DIVISION DE EDUCACION CONTINUA
CURSOS ABIERTOS

METODOS EXPERIMENTALES DE ANALISIS DE ESFUERZO

Del 7 al 11 de febrero de 1994

FECHA	HORA	TEMA	PROFESOR
Lunes 7 febrero	9:00 a 18:00 hrs.	Introducción a la Mecánica	Dr. Luis Ferrer Argote
		Teoria de Modelos	
		Fotoelasticidad (Principios Fundamentales)	
		Fotoelasticidad (2D)	Ing. Alfredo Olivares P.
Martes 8 febrero	9:00 a 18:00 hrs.	Fotoelasticidad (3D)	Dr. Luis Ferrer Argote
		Recubrimientos Fotoelasticos	Ing. Alfredo Olivares P.
		Fotoelasticidad (Aplicaciones)	Dr. Luis Ferrer Argote
		Fotoelasticidad (Técnicas de Laboratorio)	Ing. Alfredo Olivares P.
Miércoles 9 febrero	9:00 a 18:00 hrs.	Extensometros Eléctricos (S.G.)	Ing. Alfredo Olivares P.
		Extensometros Eléctricos (S.G.)	
		Extensometría (Circuitos)	
		Interpretación de Resultados	Dr. Luis Ferrer Argote
Jueves 10 febrero	9:00 a 18:00 hrs.	Extensometría (Técnicas de Laboratorio)	Ing. Alfredo Olivares P.
		Extensometría (Aplicaciones)	Dr. Luis Ferrer Argote
		Recubrimientos Fragiles	
		Transductores	Ing. Alfredo Olivares P.
Viernes 11 febrero	9:00 a 18:00 hrs.	Moire, Mallas	Dr. Luis Ferrer Argote
		Transductores	Ing. Alfredo Olivares P.
		A.O.-- Metodos Hibridos	Dr. Luis Ferrer Argote
		A.O.-- Mesa Redonda	

*rgd.

EVALUACION DEL PERSONAL DOCENTE

CURSO: **METODOS EXPERIMENTALES DE ANALISIS DE ESFUERZO**

FECHA: **7 AL 11 DE FEBRERO DE 1994.**

CONFERENCISTA	DOMINIO DEL TEMA	EFICIENCIA EN EL USO DE AYUDAS AUDIOVISUALES	MANTENIMIENTO DEL INTERES. (COMUNICACION CON LOS ASISTENTES, AMENIDAD, FACILIDAD DE EXPRESION).	PUNTUALIDAD	
DR. LUIS FERRER ARGOTE					
ING. ALFREDO OLIVARES P.					
ESCALA DE EVALUACION: 1 a 10					

EVALUACION DEL CURSO

	CONCEPTO	
1.	APLICACION INMEDIATA DE LOS CONCEPTOS EXPUESTOS	
2.	CLARIDAD CON QUE SE EXPUSIERON LOS TEMAS	
3.	GRADO DE ACTUALIZACION LOGRADO EN EL CURSO	
4.	CUMPLIMIENTO DE LOS OBJETIVOS DEL CURSO	
5.	CONTINUIDAD EN LOS TEMAS DEL CURSO	
6.	CALIDAD DE LAS NOTAS DEL CURSO	
7.	GRADO DE MOTIVACION LOGRADO EN EL CURSO	
	EVALUACION TOTAL	

ESCALA DE EVALUACION: 1 A 10

1.- ¿Qué le pareció el ambiente en la División de Educación Continua?

MUY AGRADABLE ☐ AGRADABLE ☐ DESAGRADABLE ☐

2.- Medio de comunicación por el que se enteró del curso:

PERIODICO EXCELSIOR ANUNCIO TITULADO DIVISION DE EDUCACION CONTINUA ☐

PERIODICO NOVEDADES ANUNCIO TITULADO DIVISION DE EDUCACION CONTINUA ☐

FOLLETO DEL CURSO ☐

CARTEL MENSUAL ☐

RADIO UNIVERSIDAD ☐

COMUNICACION CARTA, TELEFONO, VERBAL, ETC. ☐

REVISTAS TECNICAS ☐

FOLLETO ANUAL ☐

CARTELERA UNAM "LOS UNIVERSITARIOS HOY" ☐

GACETA UNAM ☐

3.- Medio de transporte utilizado para venir al Palacio de Minería:

AUTOMOVIL PARTICULAR ☐ METRO ☐ OTRO MEDIO ☐

4.- ¿Qué cambios haría en el programa para tratar de perfeccionar el curso?

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5.- ¿Recomendaría el curso a otras personas? ☐ SI ☐ NO

5.a. ¿Qué periódico lee con mayor frecuencia?

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6.- ¿Qué cursos le gustaría que ofreciera la División de Educación Continua?

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7.- La coordinación académica fué:

EXCELENTE ☐ BUENA ☐ REGULAR ☐ MALA ☐

8.- Si está interesado en tomar algún curso INTENSIVO ¿Cuál es el horario más conveniente para usted?

- LUNES A VIERNES DE 9 a 13 H. Y DE 14 A 18 H. (CON COMIDAD) ☐
- LUNES A VIERNES DE 17 a 21 H. ☐
- LUNES A MIERCOLES Y VIERNES DE 18 A 21 H. ☐
- MARTES Y JUEVES DE 18 A 21 H. ☐
- VIERNES DE 17 A 21 H. SABADOS DE 9 A 14 H. ☐
- VIERNES DE 17 A 21 H. SABADOS DE 9 A 13 H. DE 14 A 18 H. ☐
- OTRO ☐

9.- ¿Qué servicios adicionales desearía que tuviese la División de Educación Continua, para los asistentes?

____

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10.- Otras sugerencias:

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FACULTAD DE INGENIERIA U.N.A.M.
DIVISION DE EDUCACION CONTINUA

CURSOS ABIERTOS.

METODOS EXPERIMENTALES DE ANALISIS DE ESFUERZOS

- **FOTOELECTRICIDAD**
- **EXTENSOMETRIA ELECTRICA.**

DR. LUIS FERRER ARGOTE
ING. ALFREDO OLIVARES PONCE

NOTAS COMPLEMENTARIAS.

FEBRERO 1994.

Palacio de Minería Calle de Tacuba 5 Primer piso Deleg. Cuauhtémoc 06000 México, D.F. APDO. Postal M-2285
Teléfonos: 512-8955 512-5121 521-7335 521-1987 Fax 510-0573 521-4020 AL 26

a) Luz y Optica relacionados a la Fotoelasticidad.

a.1. Comportamiento de la luz.

Hasta la fecha no existe una teoría que explique completamente el comportamiento de la energía radiante. Para describir el fenómeno fotoelástico, la teoría electro - magnética debida a Maxwell, es usualmente usada. Esta teoría establece que la luz es una disturbación electromagnética, donde esta disturbación puede ser expresada como un vector de luz normal a la dirección de propagación. En la luz ordinaria emitida por, digamos un filamento de tungsteno incandescente, el vector luz no está restringido en ningún sentido y puede considerarse que esta formado de un número de vibraciones transversales arbitrarias, como se ilustra en la figura 20.

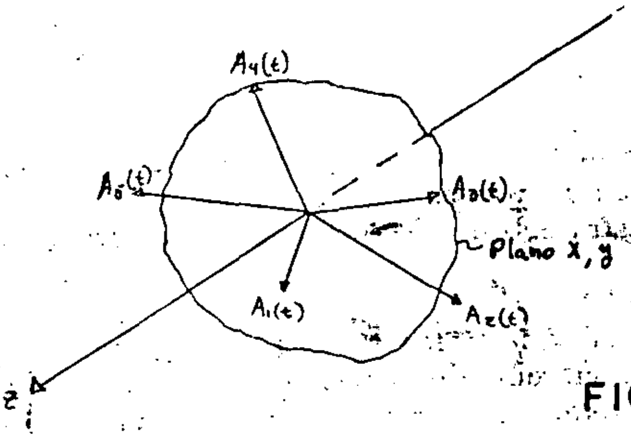


FIG-20

Ya que el disturbio productor de la luz, puede ser considerado como un movimiento ondulatorio; es posible expresar la amplitud del vector luz, en términos de una ecuación de onda unidimensional:

$$A = f(z-ct) + g(z-ct) \qquad \text{Ec. 77}$$

donde A : amplitud del vector luz o de uno de sus componentes.
z : la posición a lo largo del eje de propagación.
t : tiempo.
c : velocidad de propagación ($3\times10^{10}\ \frac{cm}{seg}$ en el vacio).

Una descripción simple del efecto fotoelástico, se obtiene considerando una componente senoidal de la luz, propagandose en la dirección positiva de z.
De esta manera la ecuación 77 puede escribirse como:

$$A = f(z-ct) = a\ \mathrm{Sen}\ \frac{2\pi}{\lambda}(z-ct) \qquad \text{Ec. 78}$$

Una representación gráfica de la amplitud del vector luz (o uno de sus componentes) conforme se propaga en la dirección positiva del eje z está dada en la figura 21.

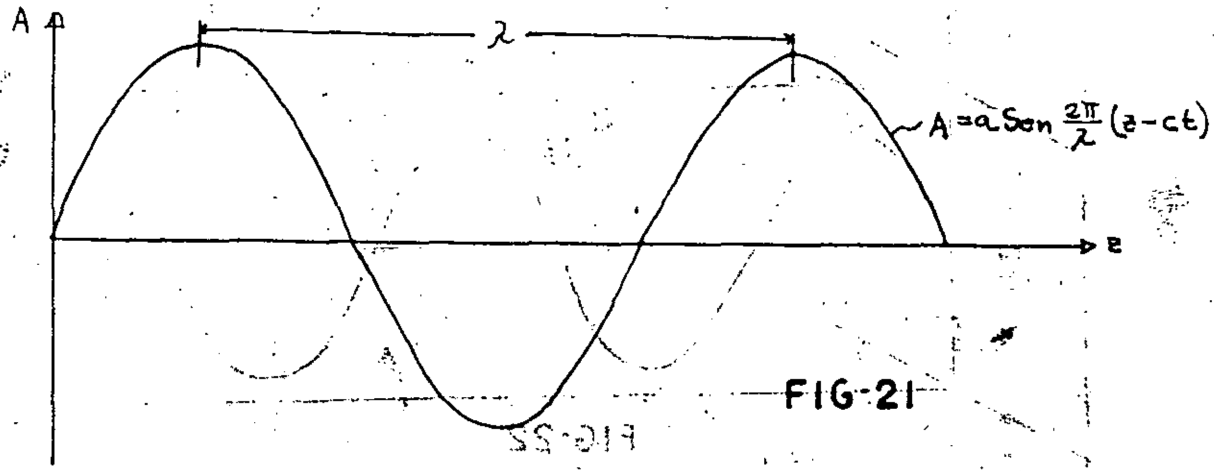


FIG-21

La longitud de pico a pico en la gráfica se define como la longitud de onda λ. El tiempo requerido para el paso de dos picos sucesivos, por algún valor fijo de z, se define como el período T y está dado por:

$$T = \lambda / c \qquad \text{Ec. 79}$$

La frecuencia del vector luz o uno de sus componentes, se define como el número de oscilaciones de la amplitud en un segundo, por lo tanto es el inverso del período.

$$f = 1/T \qquad \text{Ec. 80}$$

El color de la luz que el ojo humano reconoce, está determinado por la frecuencia de los componentes del vector luz. Los colores en el espectro visible van desde el rojo profundo, con una frecuencia de 390×10^{12} c.p.s., hasta el violeta profundo, con una frecuencia de 770×10^{12} c.p.s.

La mayoría de las investigaciones fotoelásticas se llevan a cabo con luz visible, - pero los principios de la fotoelasticidad son válidos en el rango infrarojo y ultravioleta de la energía radiante.

Cuando el vector luz está compuesto de vibraciones A_1, A_2, A_3, que tienen la misma frecuencia, el vector luz es monocromático y su color depende de la frecuencia. Si los componentes son de diferente frecuencia, los colores de los componentes se mezclan y el ojo registra esta mezcla como luz blanca.

a.2. Luz Polarizada.

Desde el punto de vista de la física clásica, la luz ordinaria consiste en ondas electromagnéticas cuya vibración es transversal a la dirección de propagación.

Cuando el patrón de vibración de una onda electromagnética exhibe una dirección - preferente de vibración, la luz es considerada como polarizada.

Hay tres diferentes formas de luz polarizada que son actualmente empleadas en los métodos fotoelásticos del análisis de esfuerzos:

1) Luz polarizada plana. Se obtiene restringiendo la vibración del vector luz en un solo plano llamado plano de polarización. Figura 22.

2) Luz polarizada circular. Se obtiene cuando la punto del vector luz describe una hélice circular conforme se propaga a lo largo del eje z. Figura 23.

3) Luz polarizada elíptica. Se obtiene cuando la punta del vector luz describe una hélice elíptica conforme se propaga en la dirección z.

Notese que los casos 1) y 2) son casos particulares del caso 3).

En la práctica la luz polarizada plana puede ser producida con un elemento óptico conocido como polarizador lineal o plano.

La producción de luz polarizada circular o elíptica, requiere del uso de dos elementos ópticos. Estos arreglos se discutirán más adelante.

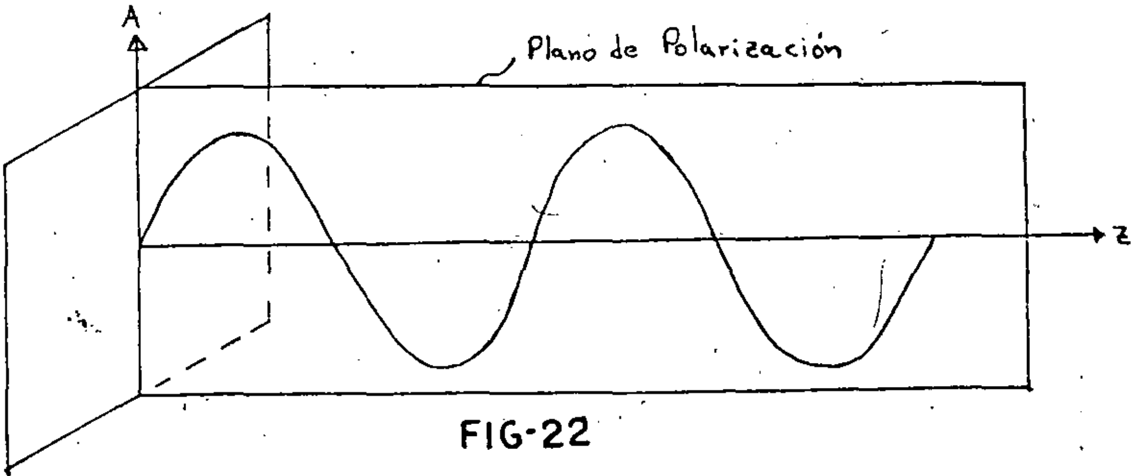


FIG-22

amp, periodo, dif.fase $\pm \frac{\pi}{2}$

$x = a \cos wt$

$y = a \operatorname{sen} wt$

$z = ct + e$

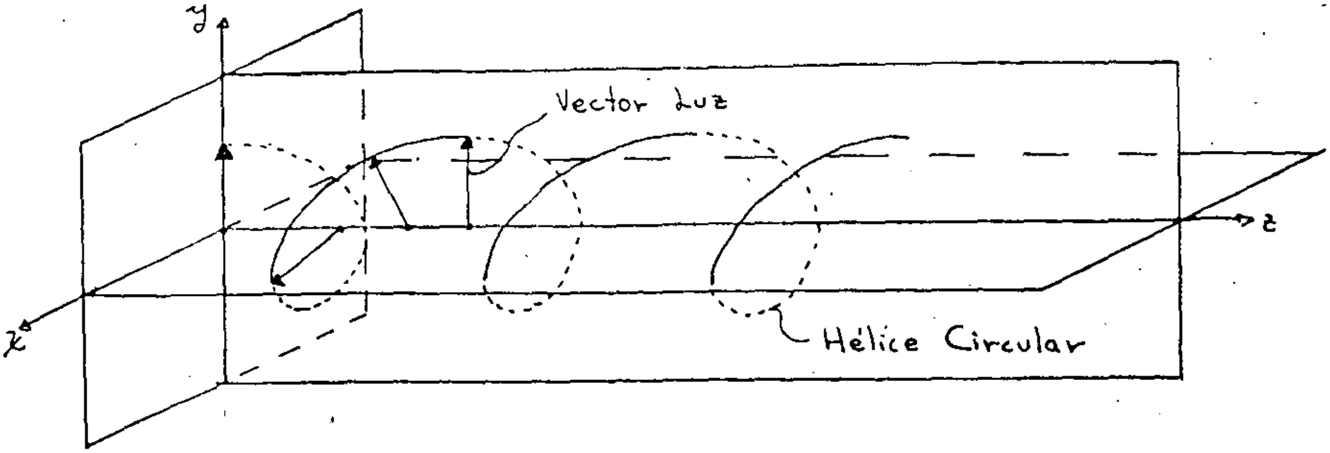


FIG-23

a.3. Polarizadores planos.

Los polarizadores planos son elementos ópticos que absorven los componentes del vector luz que no vibran en la dirección del eje del polarizador.

Cuando un vector luz pasa através de un polarizador plano, este elemento óptico absorve la componente perpendicular al eje de polarización y transmite la componente paralela, como se ilustra en la figura 24.

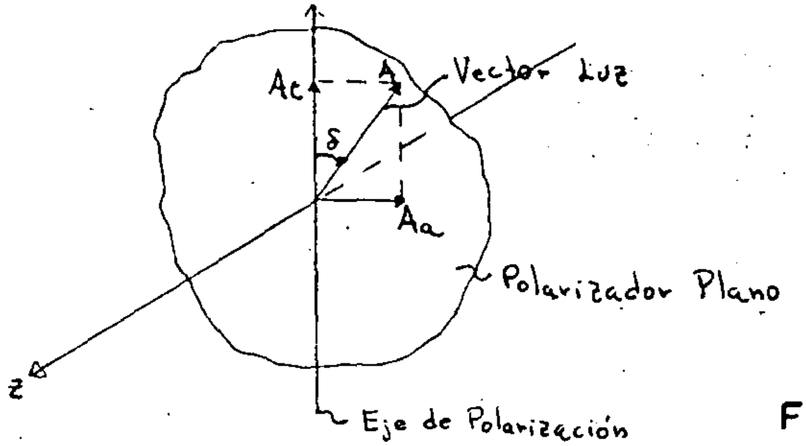


FIG-24

Si el polarizador plano está fijo en algún punto a lo largo del eje z, la ecuación para la amplitud del vector luz dada por la ecuación 78 puede ser escrita como:

$$A = a \operatorname{Sen} \frac{2\pi}{\lambda} ct$$

que puede reducirse a:

$$A = a \operatorname{Sen} 2\pi f t = \underline{a \operatorname{Sen} wt} \qquad \text{Ec. 81}$$

donde $\omega = 2\pi f$ es llamada la frecuencia circular de la luz.

Los componentes absorvido y transmitido del vector luz son:

$$A_a = a \operatorname{Sen} wt \operatorname{Sen} \delta$$
$$A_t = a \operatorname{Sen} wt \operatorname{Cos} \delta \qquad \text{Ec. 82}$$

donde δ es el ángulo entre el vector [illegible] y el eje de polarización.

En la práctica los filtros polaroid producen un amplio campo de luz muy bien polarizada a un costo relativamente bajo.

En su manufactura, una lámina de alcohol polivinílico se calienta, se alarga, e inmediatamente se deposita en una lámina de acetato o celulosa. La cara de polivinilo de este ensamble, es teñida por un líquido rico en yodo. La cantidad de yodo difuso en la placa determina su calidad. La corporación Polaroid produce tres grados de calidad: HN-22, HN-32, HN-38. La HN-22 es la más recomendada para propósitos fotoelásticos.

a.4. Placas de Onda.

Ciertos materiales tienen la propiedad de descomponer el vector luz en dos componentes ortogonales y transmitir cada uno de ellos a diferentes velocidades. Un material con esta propiedad es llamado birrefringente.

La placa birrefringente mostrada en la figura 25 tiene dos ejes principales marcados como 1 y 2.

La transmisión de la luz a lo largo del eje 1 es a una velocidad C_1 y a lo largo del eje 2 a una velocidad C_2. Como $C_1 > C_2$, al eje 1 se le llama eje rápido y al 2 eje lento.

Si la placa birrefringente es colocada en el campo de un polarizador plano, de manera que el vector luz A_t es descompuesto en dos componentes A_{t_1}, A_{t_2} a lo largo de los ejes 1 y 2 respectivamente, (nótese que el ángulo entre A_t y el eje rápido es θ), la magnitud de los componentes A_{t_1}, A_{t_2} será:

$$\begin{aligned} A_{t_1} &= A_t \cos\theta = a \cos\delta \operatorname{Sen}\omega t \cos\theta = K \operatorname{Sen}\omega t \cos\theta \\ A_{t_2} &= A_t \operatorname{Sen}\theta = a \cos\delta \operatorname{Sen}\omega t \operatorname{Sen}\theta = K \operatorname{Sen}\omega t \operatorname{Sen}\theta \end{aligned} \qquad \text{Ec. 83}$$

donde $K = a\cos\delta$.

Los componentes A_{t_1} y A_{t_2} viajan através de la placa con velocidades diferentes C_1, y C_2 respectivamente. Debido a esta diferencia de velocidades, los dos componentes emergerán de la placa en tiempos diferentes. O sea que un componente se atrasa relativamente al otro.

Este retardo puede ser manejado más eficientemente considerando el cambio relativo de fase entre los dos componentes, como se ve en la figura 26.

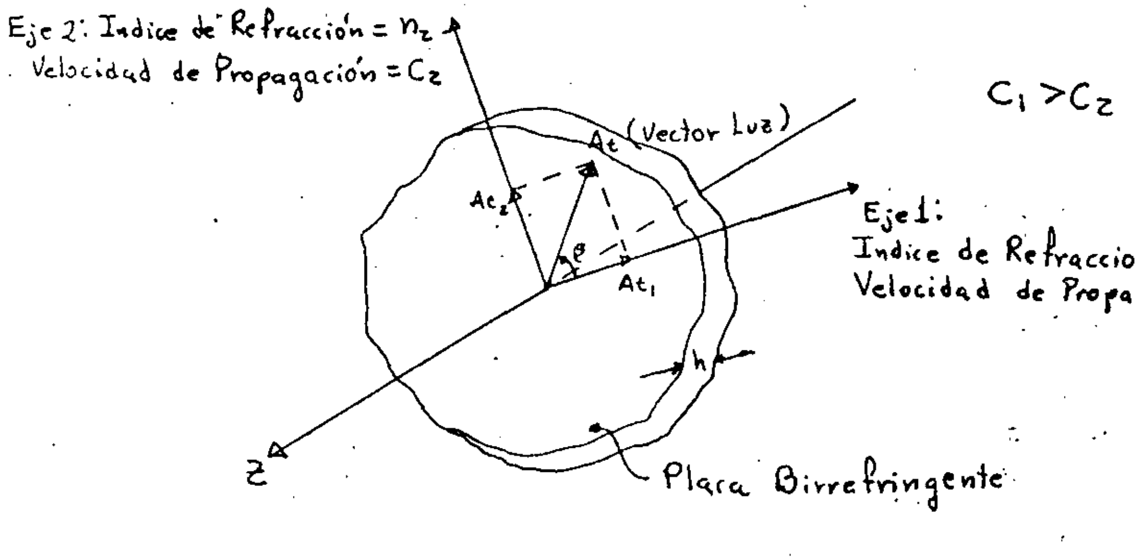


FIG-25

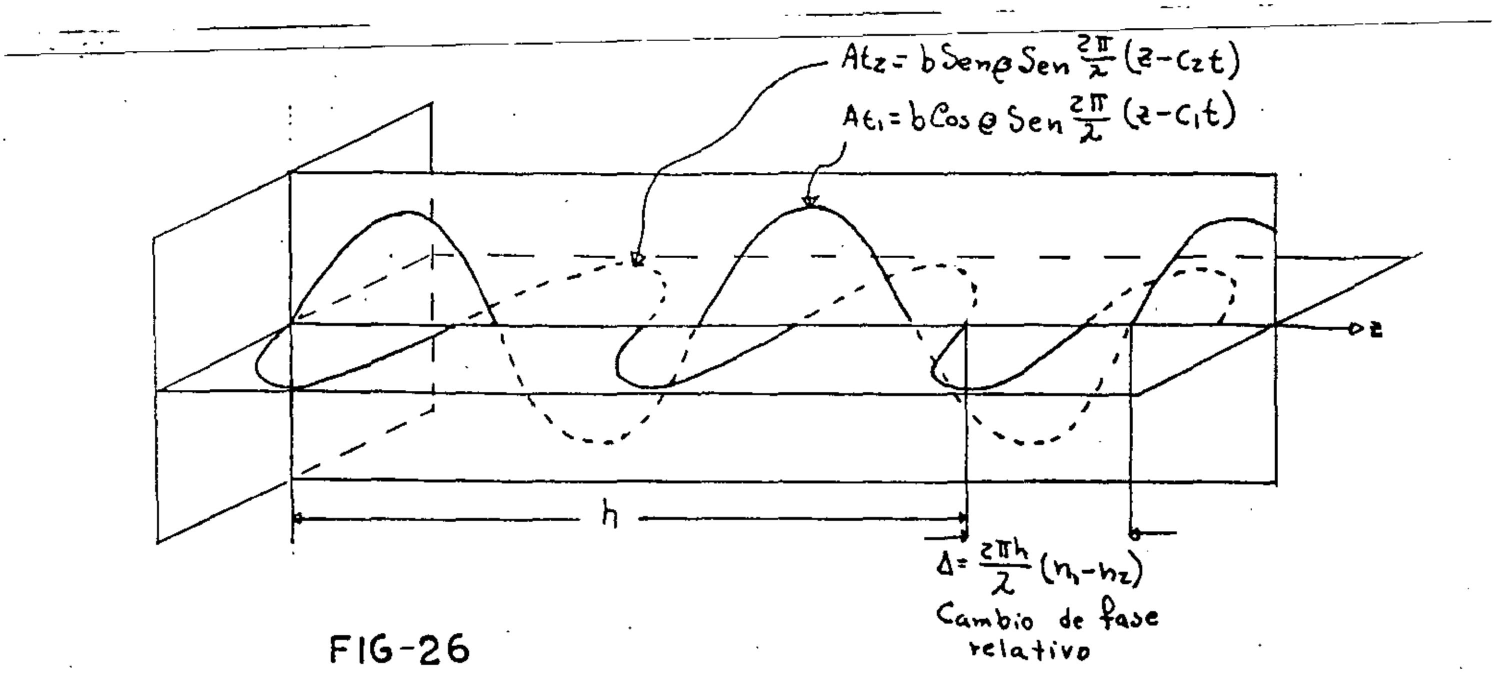


FIG-26

Para obtener este cambio de fase relativo, considere el retardo angular de cada componente, dado a continuación:

$$\Delta_1 = \frac{2\pi h}{\lambda}(n_1 - n) \qquad \Delta_2 = \frac{2\pi h}{\lambda}(n_2 - n) \qquad \text{Ec. 84}$$

donde n es el índice de refracción del aire.
La diferencia $\Delta_1 - \Delta_2$ representa el cambio de fase o la diferencia entre los dos componentes de luz cuando emergen de la placa de onda. Luego:

$$\Delta = \Delta_1 - \Delta_2 = \frac{2\pi h}{\lambda}(n_1 - n_2) \qquad \text{Ec. 85}$$

El cambio de fase relativo producido por una placa birrefringente depende de su espesor h, de la longitud de onda de la luz λ, y las propiedades de la placa $n_1 - n_2$. Cuando la placa se diseña para dar un retardo angular de $\pi/2$, se le llama placa cuarto de onda.
Al emerger de una placa birrefringente, con un retardo Δ, los componentes de la luz serán:

$$At_1' = K\,Cos\theta\,Sen(\omega t + \Delta)$$
$$At_2' = K\,Sen\theta\,Sen\,\omega t \qquad \text{Ec. 86}$$

La amplitud del vector luz producida por estos dos componentes puede expresarse como:

$$At' = \sqrt{At_1'^2 + At_2'^2} = K\sqrt{Sen^2(\omega t + \Delta)\,Cos^2\theta + Sen^2\omega t\,Sen^2\theta} \qquad \text{Ec. 87}$$

El ángulo que el vector luz que emerge de la placa forma con el eje 1 es:

$$Tan\,\gamma = \frac{At_2'}{At_1'} = \frac{Sen\,\omega t}{Sen(\omega t + \Delta)}\tan\theta \qquad \text{Ec. 88}$$

Es claro que la amplitud y el ángulo de la luz que emerge de la placa, pueden ser -- controlados por la placa de onda. Los factores de control son Δ y θ. Varias combinaciones de Δ y θ y su influencia en el tipo de polarización de la luz producida se discutirán más adelante.

Las placas de onda empleadas en fotoelasticidad consisten de una simple placa de cuarzo o calcita, cortada paralelamente al eje óptico, una placa de mica, una hoja de celofan, o una hoja de alcohol polivinílico previamente orientada.
Estas últimas son fabricadas por Polaroid Corporation, calentando y estirando unidimensionalmente la hoja de alcohol polivinílico. Como esta hoja es de solo 20 micrones de ancho, las placas comerciales son usualmente laminadas entre dos hojas de acetato o celulosa.

a.5. Luz condicionada por una serie de combinaciones de un polarizador lineal y una placa de onda.

La luz que emerge de una combinación en serie de un polarizador plano y una placa de onda, también es polarizada, sin embargo el tipo de polarización puede ser plano, circular o elíptico.
1) Luz polarizada plana:
Si el ángulo β se escoge de 0° y el retardo relativo Δ no se restringe, la amplitud y dirección del vector luz que emrge será:

$$A_t' = K \operatorname{Sen}(\omega t + \Delta) \quad ; \quad \gamma = 0$$

Ec. 89

Como $\gamma = 0$, el vector luz no rota al pasar através de la placa de onda, luego la luz que emerge sigue siendo luz polarizada plana. La placa de onda sólo retarda la luz un ángulo igual a Δ. Iguales resultados se obtienen si $\beta = \frac{\pi}{2}$.
2) Luz polarizada circular:
Si se selecciona una placa cuarto de onda ($\Delta = \pi/2$) y β se escoge de $\pi/4$, la amplitud de la luz emergente esta dada por:

$$A_t' = \frac{\sqrt{2}}{2} K \sqrt{\operatorname{Sen}^2 \omega t + \operatorname{Cos}^2 \omega t} = \frac{\sqrt{2}}{2} K$$

Ec. 90

Así que el vector luz que emerge de la placa tiene una amplitud constante. También se tendría que:

$$\operatorname{Tan} \gamma = \operatorname{Tan} \omega t \Rightarrow \gamma = \omega t$$

Ec. 91

o sea que el ángulo se incrementa continuamente.
De las ecuaciones 90 y 91, se ve que la punta del vector luz describe un círculo. Conforme la luz se propaga en el eje z, el círculo se transforma en una hélice circular con su eje coincidente con el eje z.
3) Luz polarizada elíptica:
Si se selecciona una placa cuarto de onda ($\Delta = \pi/2$), y se permite que β sea cualquier ángulo menos 0, $\pi/4$, $\pi/2$, o multiplos pares, el vector luz que emerge de la placa tendrá una amplitud:

$$A_t' = K \sqrt{\operatorname{Cos}^2 \omega t \operatorname{Cos}^2 \beta + \operatorname{Sen}^2 \omega t \operatorname{Sen}^2 \beta}$$

El ángulo de salida será:

$$\operatorname{Tan} \gamma = \operatorname{Tan} \omega t \operatorname{Tan} \beta$$

Ec. 92

Puede demostrarse que el vector luz descrito por las ecuaciones 92 constituyen luz polarizada elíptica.
Ya que la luz polarizada circular es la que se emplea más comunmente en la fotoelasticidad, es importante que la ecuación 85 se reexamine:

$$\Delta = 2\pi h/\lambda \, (n_1 - n_2)$$

Ec. 85

Recuerdese que la luz polarizada circular requiere una placa cuarto de onda, o sea que $\Delta = \pi/2$. Es claro que el espesor h puede ser determinado para que $\Delta = \pi/2$ una vez que el material $(n_1 - n_2)$ y la longitud de onda de la luz han sido seleccionadas. Sin embargo una placa cuarto de onda para una longitud de onda dada, (luz monocromática) no será muy útil para diferentes longitudes de onda.

También debe notarse que no puede diseñarse una placa cuarto de onda para luz blanca ya que sus componentes poseen deferentes longitudes de onda.

a.6. Arreglo de los elementos ópticos en un polaroscopio.

1) Polaroscopio plano.

Este es el sistema óptico más sencillo usado en la fotoelasticidad ya que consta de dos polarizadores lineales y una fuente de luz arreglados como se muestra en la figura 27.

El polarizador cercano a la fuente de luz recibe el nombre precisamente de polarizador. El polarizador más alejado de la fuente de luz se llama analizador. En el polaroscopio plano, los dos ejes de polarización están siempre cruzados, de manera que no se transmite luz através del analizador, y éste sistema óptico produce, por lo tanto, un campo obscuro.

Bajo operación, un modelo fotoelástico se introduce entre los dos elementos y se observa através del analizador. El comportamiento del modelo fotoelástico en un polaroscopio plano se verá más adelante.

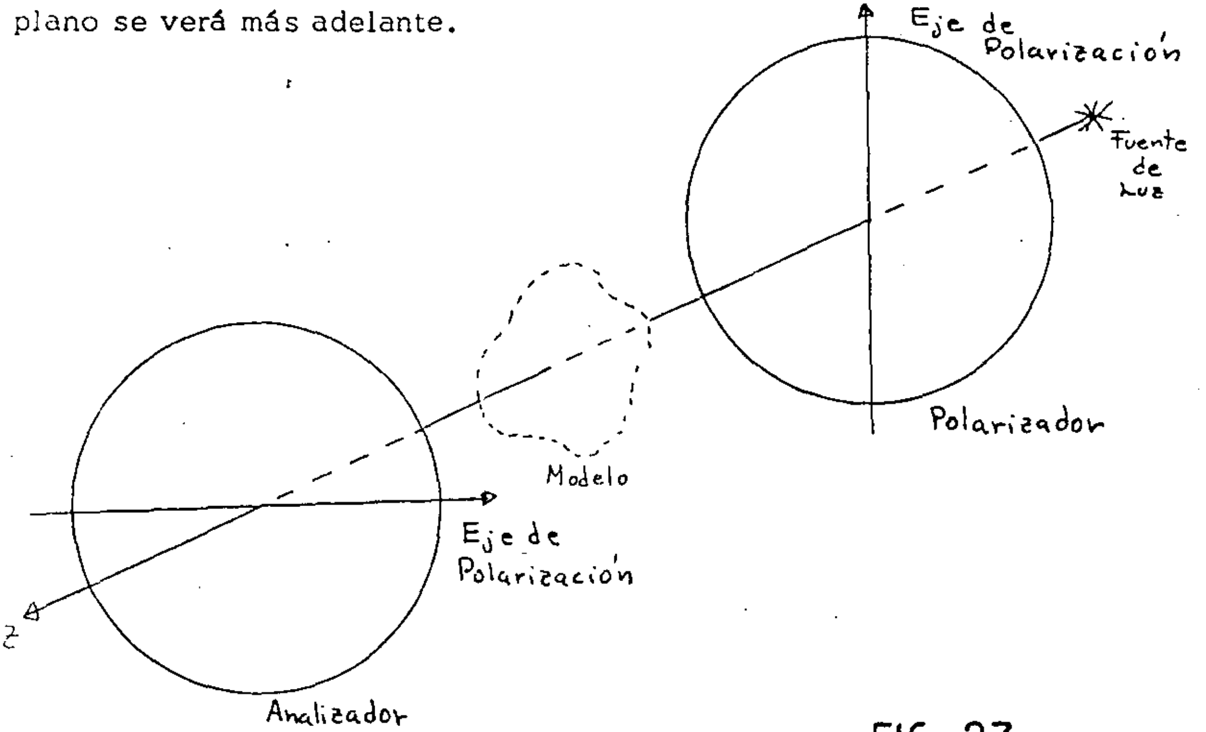


FIG-27

2) Polaroscopio circular.

Como su nombre lo indica, este polaroscopio emplea luz polarizada circular; consecuentemente el aparato posee cuatro elementos ópticos y una fuente de luz como se observa en la figura 28.

El primer elemento después de la fuente de luz se llama polarizador, el cual convierte la luz ordinaria en luz polarizada plana. El segundo elemento es una placa cuarto de onda con un ángulo $\beta = \frac{\pi}{4}$ con respecto al eje de polarización, convierte la luz polarizada plana en luz polarizada circular. El tercer elemento (placa cuarto de onda) se coloca con su eje rápido paralelo al eje lento de la placa anterior; el propósito de este elemento es convertir la luz polarizada circular en luz polarizada plana que vibra de nuevo en el plano vertical. El último elemento es el analizador con su eje de polarización horizontal, y su propósito es extinguir la luz. Esta serie de elementos ópticos producen un campo oscuro.

Actualmente se emplean cuatro arreglos de los elementos ópticos del polaroscopio circular, dependiendo de si las placas y los polarizadores son paralelos o cruzados (tabla 2).

Los arreglos A y B se recomiendan para campos oscuros y claros respectivamente, ya que el error introducido por las imperfecciones de las placas cuarto de onda, - (ambas difieren por ejemplo de $\Delta = \pi/2$ una cantidad dada), se cancelan. Ya que las placas cuarto de onda pueden ser de baja calidad, este hecho debe tenerse en cuenta.

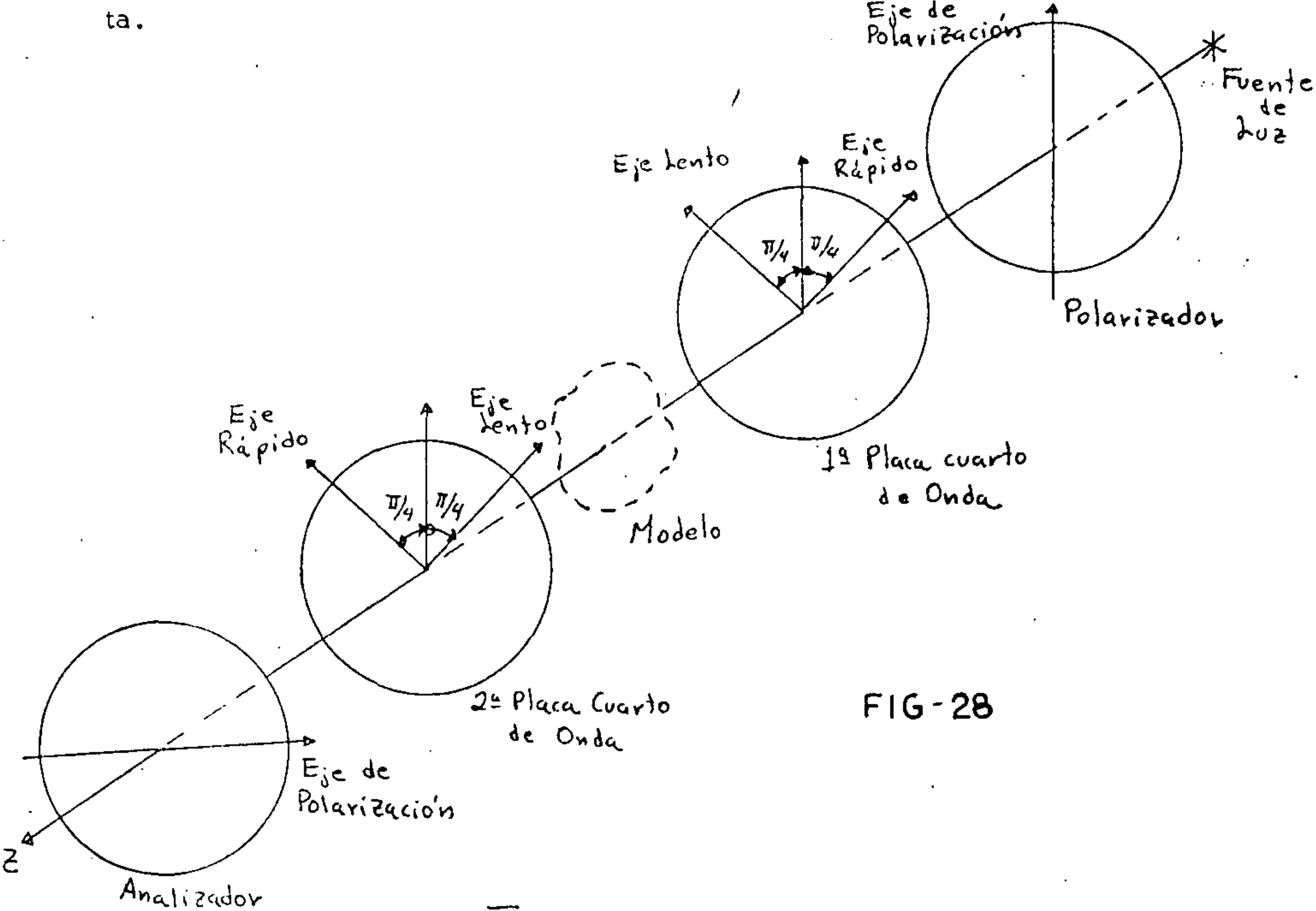


FIG-28

Tabla -2

Arreglo	Placas cuarto de Onda	Polarizador y Analizador	Campo
A*	Cruzadas	Cruzados	Obscuro
B	Cruzadas	Paralelos	Claro
C	Paralelas	Cruzados	Claro
D	Paralelas	Paralelos	Obscuro

* mostrado en la figura 28.

Los arreglos de los elementos ópticos discutidos, no son lo suficientemente completos para un buen polaroscopio de trabajo. El grado de complejidad de un polaroscopio varía desde sistemas complejos de lentes con servomotores para mover los elementos ópticos, hasta arreglos muy simples como los discutidos.

b) Teoría de la Fotoelasticidad.

El propósito es discutir la teoría de la fotoelasticidad, o en otras palabras, discutir lo que pasa en un polaroscopio cuando un modelo fotoelástico es puesto en el polaroscopio y se carga. Esta teoría se mantendrá lo más simple posible, sin embargo lo suficientemente completa para describir la mayoría de los efectos fotoelásticos observables en un polaroscopio.

b.1. La ley del esfuerzo óptico en dos dimensiones con incidencia normal.

Consideremos un modelo bidimensional maquinado de una hoja de plástico transparente. Inicialmente el modelo está libre de esfuerzos y exhibe un índice de refracción n_0 que es el mismo en todos los puntos y planos del modelo.

Sin embargo, cuando se somete a un sistema de fuerzas, un estado de esfuerzos bidimensional se induce en el modelo, y ésto cambia sus propiedades ópticas.

Opticamente el modelo se vuelve birrefringente y exhibe propiedades muy similares a las de las placas de onda.

Los ejes principales de los esfuerzos en cualquier punto del modelo, son los ejes rápido y lento de la placa; luego es evidente que el índice de refracción cambió en relación con el estado de esfuerzos inducido.

Es en esta propiedad óptica poco usual en la que se basa la teoría de la fotoelasticidad. El polaroscopio es el instrumento que nos ayuda a medir estos cambios en el índice de refracción. La teoría que relaciona los cambios del índice de refracción al estado de esfuerzos, se debe a Maxwell en 1853. Maxwell notó que el cambio en los índices de refracción eran linealmente proporcionales a los esfuerzos inducidos en el modelo y seguían las relaciones:

$$\begin{aligned} n_1 - n_0 &= c_1\sigma_1 + c_2\sigma_2 \\ n_2 - n_0 &= c_1\sigma_2 + c_2\sigma_1 \end{aligned} \qquad \text{Ec. 93}$$

donde n_0 : índice de refracción del modelo sin carga.

n_1, n_2 : índices de refracción a lo largo de los ejes principales, asociados con σ_1 y σ_2.

c_1, c_2 : coeficientes del esfuerzo óptico.

Si restamos las ecuaciones para eliminar n_0 :

$$n_1 - n_2 = (c_1 - c_2)(\sigma_1 - \sigma_2) \qquad \text{Ec. 94}$$

Ya que el modelo cargado se comporta como una placa de onda temporal, de la ecuación 85:

$$n_1 - n_2 = \frac{\lambda\,\Delta}{2\pi\,h} \qquad \text{Ec. 85}$$

De las ecuaciones 85 y 94:

$$\Delta = \frac{2\pi h}{\lambda}(c_1 - c_2)(\sigma_1 - \sigma_2) \qquad \text{Ec. 95}$$

Si $C_1 - C_2 = C$: coeficiente relativo del esfuerzo óptico, el retardo relativo Δ será:

$$\Delta = \frac{2\pi h C}{\lambda}(\sigma_1 - \sigma_2) \qquad \text{Ec. 96}$$

donde C está expresado en términos del Brewster (1 Brewster $= 10^{-13}\ \mathrm{cm^2/dina}$).

La ecuación 96 es la clásica descripción de la ley del esfuerzo óptico. El retardo relativo Δ es directamente proporcional a la diferencia de los esfuerzos principales.

Como las unidades asociadas con el Brewster no son comúnes en la Ingeniería, es más conveniente escribir la ecuación 96 como:

$$\sigma_1 - \sigma_2 = \frac{N f_\sigma}{h} \qquad Ec. 97$$

donde $N = \frac{\Delta}{2\pi}$: retraso relativo en términos de un ciclo completo de retardo 2π.
$f_\sigma = \lambda / C$: es el valor de franja del material (Psi-in).
h : espesor del modelo (in).

De la ecuación 97 es evidente que la diferencia de esfuerzos principales $\sigma_1 - \sigma_2$ en un modelo bidimensional puede ser determinado si el retardo relativo N puede ser medido y si el valor de franja del material puede ser establecido por calibración.
La función del polaroscopio es determinar el valor de N en cada punto del modelo.
Si el modelo es perfectamente elástico, puede encontrarse la diferencia entre las deformaciones principales:

$$\frac{N f_\sigma}{h} = \frac{E}{1+\nu}(\varepsilon_1 - \varepsilon_2) \qquad ó \qquad \frac{N f_\varepsilon}{h} = \varepsilon_1 - \varepsilon_2 \qquad Ec. 98, 99$$

donde: $f_\varepsilon = \frac{1+\nu}{E} f_\sigma$

Luego para un modelo fotoelástico perfectamente elástico, la determinación de N es suficiente para establecer $\sigma_1 - \sigma_2$ y $\varepsilon_1 - \varepsilon_2$ si las propiedades del material (E , ν , f_σ , o f_ε) son conocidas.

b.2. Efectos de un modelo cargado en un polaroscopio plano.

Consideremos el caso de un modelo plano cargado en un campo de un polaroscopio plano con su normal coincidente con el eje del polaroscopio (figura 29).

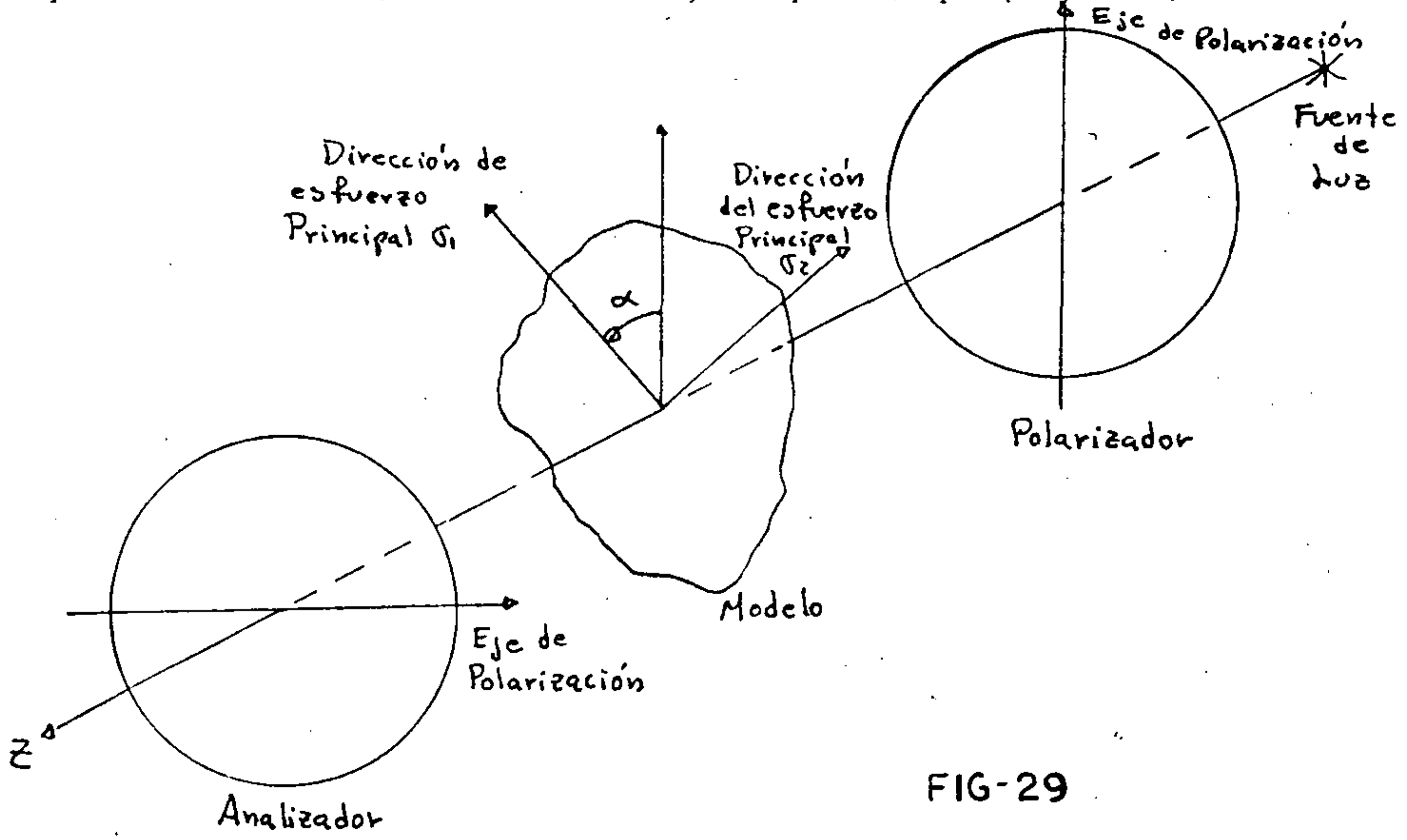


FIG-29

La luz emergente del polarizador en un estado de polarización plana vibrando en el plano vertical con una amplitud que varía con el tiempo de la siguiente manera:

$$A = k \, \mathrm{Sen}\, \omega t \qquad (a)$$

Esta luz polarizada plana penetra al modelo como muestra la figura 30.

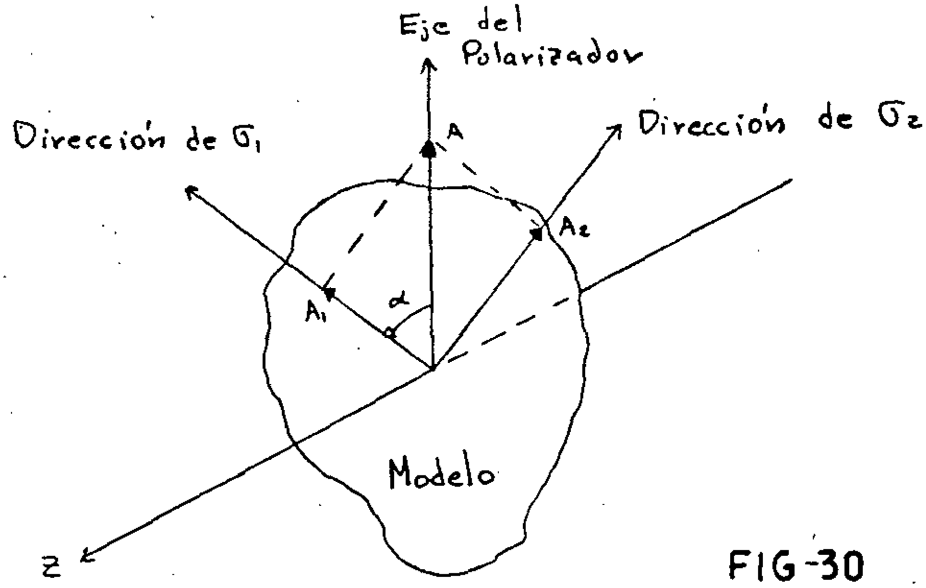


FIG-30

Como el modelo cargado se comporta como una placa de onda, el vector luz es descompuesto en dos componentes A_1 y A_2.

$$A_1 = k \, \mathrm{Sen}\, \omega t \, \mathrm{Cos}\, \alpha \qquad (b)$$

$$A_2 = k \, \mathrm{Sen}\, \omega t \, \mathrm{Sen}\, \alpha$$

Estos dos componentes se propagan através del modelo a diferentes velocidades y al salir del modelo estarán defasados. La diferencia relativa de fase entre los dos componentes será, de la ecuación 97:

$$\Delta = 2\pi N = \frac{h}{f_\sigma} (\sigma_1 - \sigma_2) \, 2\pi \qquad (c)$$

Si esta diferencia de fase relativa se divide por igual entre los dos componentes del vector de luz, al salir los componentes tendrán una amplitud dada por:

$$A_1' = k \, \mathrm{Cos}\, \alpha \, \mathrm{Sen} \left(\omega t + \frac{\Delta}{2} \right) \qquad A_2' = k \, \mathrm{Sen}\, \alpha \, \mathrm{Sen} \left(\omega t - \frac{\Delta}{2} \right) \qquad (d)$$

Los componentes A_1' y A_2' entran al analizador como se muestra en la figura 31.

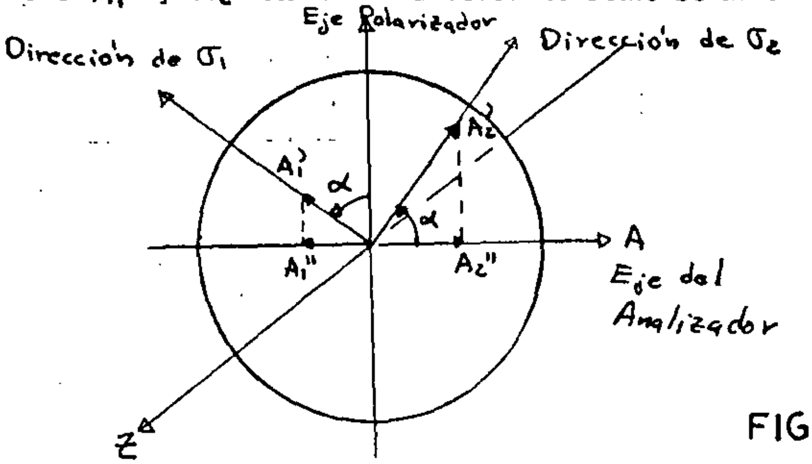


FIG-31

Los componentes A_1' y A_2' se descomponen, cuando entran al analizador, en componentes horizontales A_1'' y A_2'' , y en componentes verticales. Como los componente verticales se absorven, no se muestran en la figura 31. Los componentes horizontales de la luz, transmitidos através del analizador se superponen y resultan en un - vector luz emergente A cuya magnitud es:

$$A = A_2'' - A_1'' = A_2' \operatorname{Cos}\alpha - A_1' \operatorname{Sen}\alpha \qquad (e)$$

$$A = K \operatorname{Sen}\alpha \operatorname{Cos}\alpha \left[\operatorname{Sen}\left(wt - \frac{\Delta}{2}\right) - \operatorname{Sen}\left(wt + \frac{\Delta}{2}\right)\right] \qquad (f)$$

Mediante identidades trigonométricas, puede reducirse a:

$$A = -K \operatorname{Sen} 2\alpha \operatorname{Cos} wt \operatorname{Sen}\frac{\Delta}{2} \qquad \text{Ec. 100}$$

La intensidad de la luz es proporcional al cuadrado de la amplitud del vector luz emergiendo del analizador; luego, la intensidad de la luz emergente I está dada por:

$$I = K \operatorname{Sen}^2 2\alpha \operatorname{Sen}^2\frac{\Delta}{2} \operatorname{Cos}^2 wt \qquad \text{Ec. 101}$$

Esta ecuación muestra que la extinción (I = 0) de la luz, puede realizarse de tres maneras:

Caso 1.- Efectos de frecuencia:

Cuando $wt = \left[\frac{(2n+1)\pi}{2}\right]$, donde $n = 0, 1, 2$, etc., el $\operatorname{Cos}^2 wt = 0$ y la intensidad es cero, produciendo una condición de extinción; sin embargo la frecuencia angular ω es tan alta (por ejemplo del orden de $10^{15}\ \frac{rad}{seg}$) que cualquier tipo de equipo fotográfico de alta velocidad no puede captar esta extinción. Luego para aplicaciones en fotoelasticidad estática, este efecto puede ser completamente ignorado y la ecuación 101 puede ser escrita como:

$$I = K \operatorname{Sen}^2 2\alpha \operatorname{Sen}^2\frac{\Delta}{2} \qquad \text{Ec. 102}$$

Caso 2.- Efectos de las direcciones principales de los esfuerzos.

Cuando $2\alpha = n\pi$ donde $n = 0, 1, 2$, etc, el $\operatorname{Sen}^2 2\alpha = 0$ y la intensidad I es cero, produciendo una condición de extinción.

Este hecho implica que cuando $\alpha = 0, \frac{\pi}{2}$, ó cualquier múltiplo exacto de $\pi/2$, la dirección principal de σ_1 o σ_2 coincide con el eje del polarizador. Como este análisis puede extenderse para cubrir todos los puntos del modelo, pueden determinarse todos los puntos donde la extinción ocurre debido a este efecto.

Cuando se observa todo el modelo, resulta un patrón de franjas, las cuales se localizan en los puntos donde las direcciones principales (σ_1 o σ_2) coinciden con los ejes del polarizador.

El patrón de franjas producido por el término $\operatorname{Sen}^2 2\alpha$ en la ecuación 101 o 102 se conoce como el patrón de franjas Isóclinas.

Este campo de franjas Isóclinas se emplea para determinar las direcciones principales de los esfuerzos en un modelo fotoelástico. Como esto representa una parte muy importante de los resultados o datos obtenidos en un análisis fotoelástico, el tema de las franjas Isóclinas y su interpretación se tratará por separado más adelante.

Caso 3.- Efecto de la diferencia de los esfuerzos principales.

Cuando $\Delta/2 = n\pi$, donde $n = 0, 1, 2$, etc., el $\operatorname{Sen}^2\frac{\Delta}{2} = 0$ y la intensidad es cero produciendo una condición de extinción. Luego es claro que cuando $\frac{\Delta}{2\pi} = n$ la extinción ocurre.

De la ecuación 97 puede verse que : $\frac{\Delta}{2\pi} = n = N = h/f_\sigma\,(\sigma_1 - \sigma_2)$

Cuando la diferencia de los esfuerzos principales es tal que $h/f_\sigma(\sigma_1 - \sigma_2) = 0, 1, 2$, las condiciones de extinción son satisfechas. El orden de extinción ($N = 0, 1, 2$, etc.)está con lado por la magnitud de la diferencia de los esfuerzos principales, por el espesor del modelo y por la sensitividad del material fotoelástico, mediante el valor de f_σ.

En general, la diferencia $\sigma_1-\sigma_2$ y las direcciones principales varían de punto a punto. El análisis anterior fué hecho con la luz pasando por un solo punto del modelo. Si el análisis se extiende para cubrir cada punto y si los resultados de todos los puntos se combinan para obtener un resultado de todo el campo, las lineas de extinción se obtendrán donde $\sigma_1-\sigma_2=\frac{N}{h}f_\sigma$ con N variando como o, 1, 2, 3, etc. y donde una de las dos direcciones principales coincida con el eje de polarización del polarizador.

Los dos patrones de franjas se forman y se superponen uno con otro. Las líneas del primer tipo, llamadas franjas Isocromáticas son lineas en las cuales $\sigma_1-\sigma_2$ es igual a una constante, dependiente del orden de franja N.

El segundo tipo de líneas, que se relacionan con las direcciones principales de los esfuerzos son llamadas Isóclinas.

Desafortunadamente, los dos patrones de franjas están superpuestos y su separación requiere técnicas especiales que se describirán más adelante.

b.3. Efectos de un modelo cargado en un polaroscopio circular (arreglo en campo obscuro).

El uso de un polaroscopio circular elimina las franjas Isóclinas y mantiene las Isocromáticas, y como resultado es más usado que el polaroscopio plano.

Para ilustrar este efecto, consideremos el modelo cargado en el polaroscopio circular (arreglo A) mostrado en la figura 32.

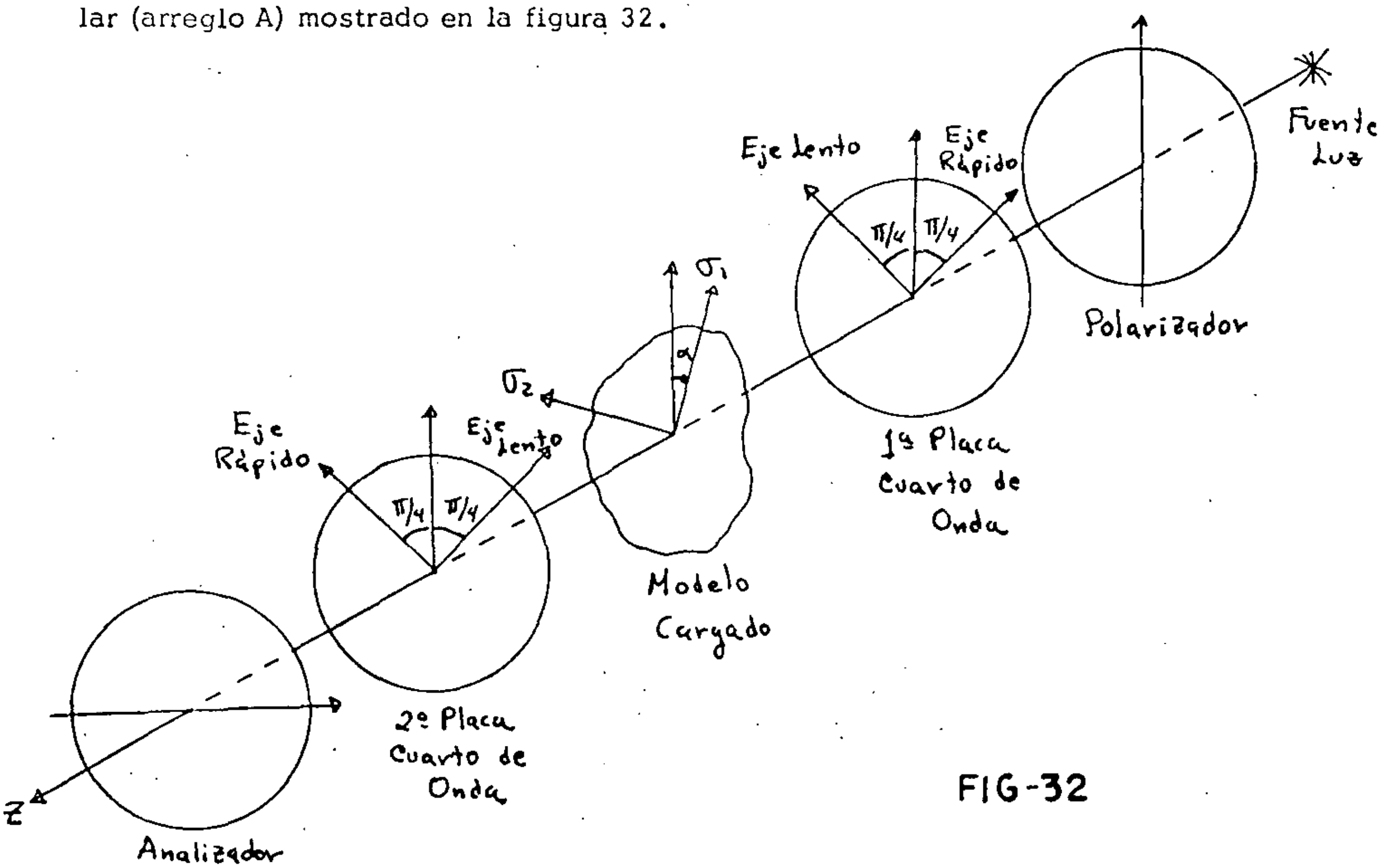


FIG-32

Empleando la ecuación 86la luz emergente de la primera placa cuarto de onda, puede expresarse como:

$$A_1' = \frac{\sqrt{2}}{2} K\,\mathrm{Sen}\left(\omega t + \frac{\pi}{2}\right) = \frac{\sqrt{2}}{2} K \cos \omega t \quad ; \quad A_2' = K \frac{\sqrt{2}}{2}\,\mathrm{Sen}\,\omega t \qquad (a)$$

Como se dijo anteriormente, la luz que emerge de la primera placa cuarto de onda, está polarizada en forma circular. El vector obtenido al combinar los componentes A_1' y A_2' es de amplitud constante y su punta describe una hélice circular conforme se propaga a lo largo del eje del polaroscopio.

Estos componentes entran al modelo como se ilustra en la figura 33.

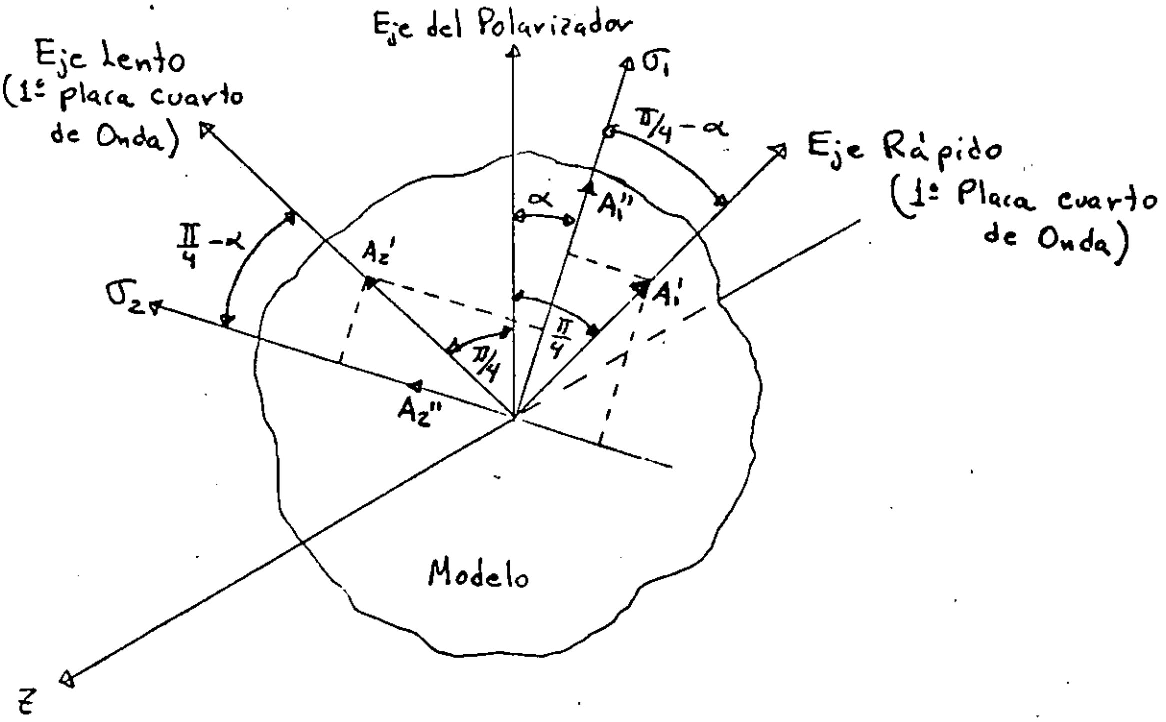


FIG-33

Los componentes A_1' y A_2' son entonces resueltos en dos nuevos componentes A_1'' y A_2'' cuando entran al modelo, a lo largo de los ejes σ_1 y σ_2.

Los componentes A_1'' y A_2'' son:

$$\begin{aligned} A_1'' &= A_1' \cos(\pi/4 - \alpha) + A_2' \,\mathrm{Sen}(\pi/4 - \alpha) \\ A_2'' &= A_2' \cos(\pi/4 - \alpha) - A_1' \,\mathrm{Sen}(\pi/4 - \alpha) \end{aligned} \qquad (b)$$

Combinando las ecuaciones a) y b) :

$$\begin{aligned} A_1'' &= \frac{\sqrt{2}}{2} K \left[\cos \omega t \cos(\pi/4 - \alpha) + \mathrm{Sen}\,\omega t\,\mathrm{Sen}(\pi/4 - \alpha)\right] \\ A_2'' &= \frac{\sqrt{2}}{2} K \left[\mathrm{Sen}\,\omega t \cos(\pi/4 - \alpha) - \cos \omega t\,\mathrm{Sen}(\pi/4 - \alpha)\right] \end{aligned} \qquad (c)$$

Como el modelo cargado tiene las características de una placa de onda, las dos -- componentes A_1'' y A_2'' se propagan através del modelo con diferentes velocidades y emergen fuera de fase con un ángulo de retraso relativo Δ que es proporcional a la diferencia $\sigma_1 - \sigma_2$ como se indica en la ecuación96. Si esta diferencia relativa de fase Δ se divide en los dos componentes, con $+\frac{\Delta}{2}$ aplicado a A_1'' y $-\frac{\Delta}{2}$ aplicado a A_2'', las amplitudes de estos componentes cuando emergen del modelo serán:

$$A_1''' = \frac{\sqrt{2}}{2} K \left[\cos\left(\omega t + \frac{\Delta}{2}\right) \cos\left(\pi/4 - \alpha\right) + \operatorname{Sen}\left(\omega t + \frac{\Delta}{2}\right) \operatorname{Sen}\left(\pi/4 - \alpha\right) \right]$$
$$A_2''' = \frac{\sqrt{2}}{2} K \left[\operatorname{Sen}\left(\omega t - \Delta/2\right) \cos\left(\pi/4 - \alpha\right) - \cos\left(\omega t - \Delta/2\right) \operatorname{Sen}\left(\pi/4 - \alpha\right) \right] \qquad (d)$$

La luz emergente del modelo, entra a la segunda placa cuarto de onda como se ilustra en la figura 34.

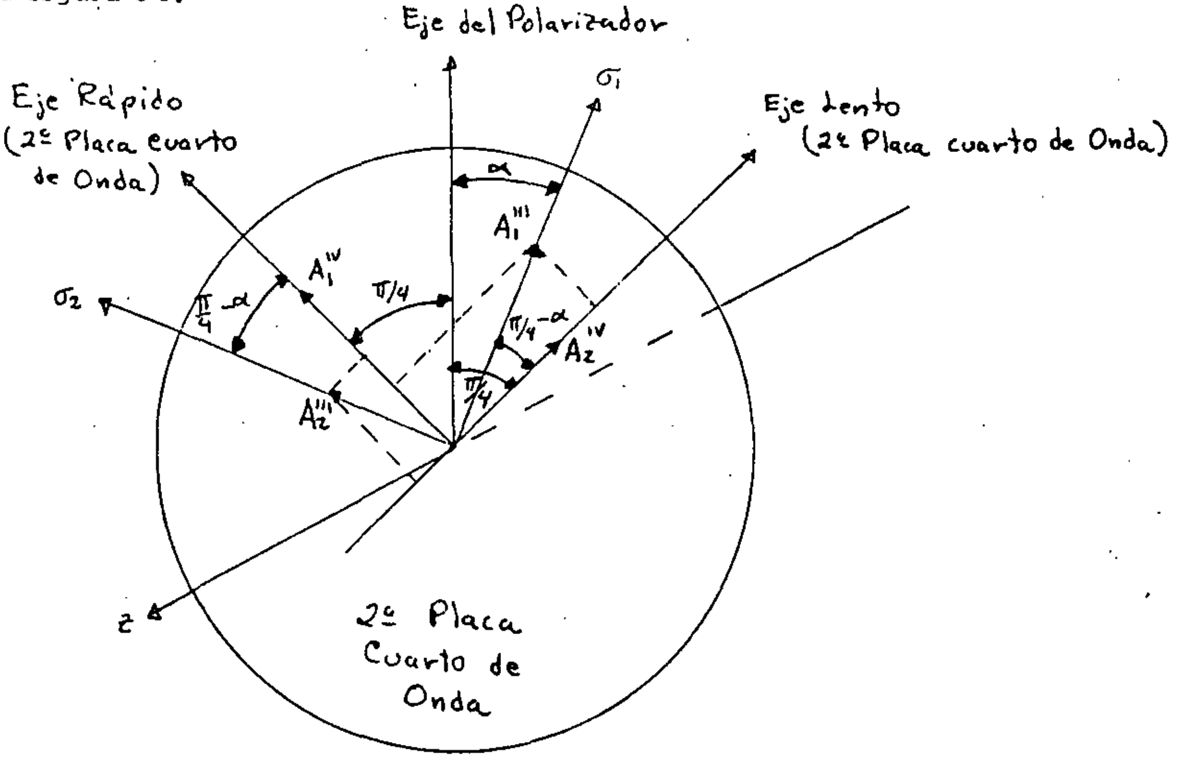


FIG-34

Los componentes A_1''' y A_2''' se descomponen en los ejes rápido y lento de la segunda placa cuarto de onda, y los denotaremos como A_1^{IV} y A_2^{IV} que pueden ser descritos por las siguientes ecuaciones:

$$A_1^{IV} = A_2''' \cos\left(\pi/4 - \alpha\right) + A_1''' \operatorname{Sen}\left(\pi/4 - \alpha\right)$$
$$A_2^{IV} = A_1''' \cos\left(\pi/4 - \alpha\right) - A_2''' \operatorname{Sen}\left(\pi/4 - \alpha\right) \qquad (e)$$

Sustituyendo las ecuaciones d) en e):

$$A_1^{IV} = \frac{\sqrt{2}}{2} K \left[\operatorname{Sen}\left(\omega t - \Delta/2\right) \cos^2\left(\frac{\pi}{4} - \alpha\right) - \cos\left(\omega t - \Delta/2\right) \cos\left(\pi/4 - \alpha\right) \operatorname{Sen}\left(\pi/4 - \alpha\right) + \right.$$
$$\left. + \cos\left(\omega t + \Delta/2\right) \cos\left(\pi/4 - \alpha\right) \operatorname{Sen}\left(\pi/4 - \alpha\right) + \operatorname{Sen}\left(\omega t + \Delta/2\right) \operatorname{Sen}^2\left(\pi/4 - \alpha\right) \right]$$
$$A_2^{IV} = \frac{\sqrt{2}}{2} K \left[\cos\left(\omega t + \Delta/2\right) \cos^2\left(\pi/4 - \alpha\right) + \operatorname{Sen}\left(\omega t + \Delta/2\right) \operatorname{Sen}\left(\pi/4 - \alpha\right) \cos\left(\pi/4 - \alpha\right) - \right.$$
$$\left. - \operatorname{Sen}\left(\omega t - \Delta/2\right) \cos\left(\pi/4 - \alpha\right) \operatorname{Sen}\left(\pi/4 - \alpha\right) + \cos\left(\omega t - \Delta/2\right) \operatorname{Sen}^2\left(\pi/4 - \alpha\right) \right] \qquad (f)$$

Si se asume que el cambio de fase relativa de $\pi/2$ que ocurre al pasar la luz através de esta placa cuarto de onda, es aplicada en sentido positivo a la componente A_1^{IV}, los componentes emergentes de la placa A_1^V y A_2^V pueden expresarse como:

$$A_1^V = \frac{\sqrt{2}}{2} k \left[\cos(\omega t - \Delta/2) \cos^2(\pi/4 - \alpha) + \operatorname{Sen}(\omega t - \Delta/2) \operatorname{Sen}(\pi/4 - \alpha) \cos(\pi/4 - \alpha) - \right.$$

$$\left. - \operatorname{Sen}(\omega t + \Delta/2) \operatorname{Sen}(\pi/4 - \alpha) \cos(\pi/4 - \alpha) + \cos(\omega t + \Delta/2) \operatorname{Sen}^2(\pi/4 - \alpha) \right]$$

$$A_2^V = \frac{\sqrt{2}}{2} k \left[\cos(\omega t + \Delta/2) \cos^2(\pi/4 - \alpha) + \operatorname{Sen}(\omega t + \Delta/2) \operatorname{Sen}(\pi/4 - \alpha) \cos(\pi/4 - \alpha) - \right. \qquad \text{Ec. 103}$$

$$\left. - \operatorname{Sen}(\omega t - \Delta/2) \cos(\pi/4 - \alpha) \operatorname{Sen}(\pi/4 - \alpha) + \cos(\omega t - \Delta/2) \operatorname{Sen}^2(\pi/4 - \alpha) \right]$$

Finalmente la luz entra al analizador como se muestra en la figura 35.

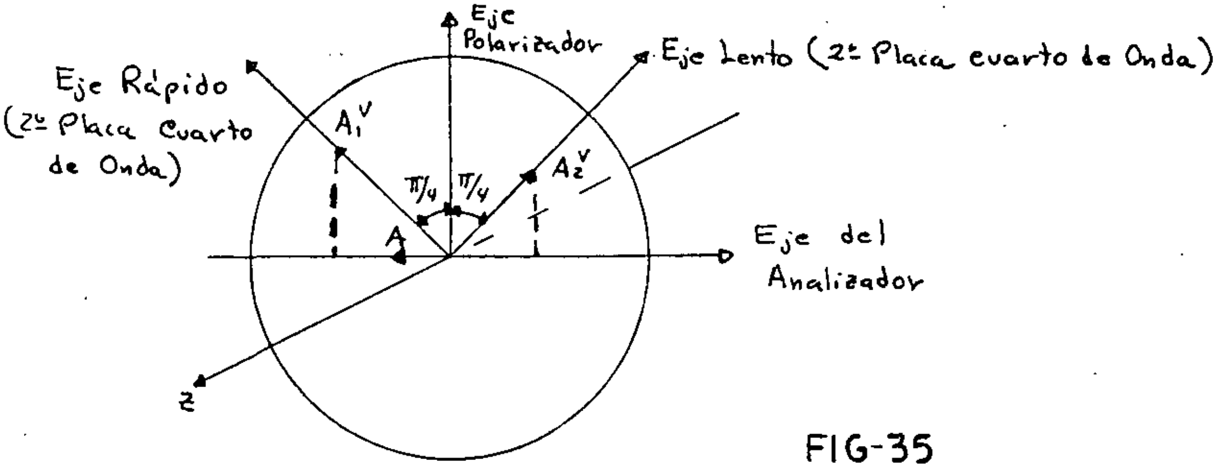


FIG-35

Los componentes A_1^V y A_2^V son descompuestos en componentes horizontales y verticales. Los componentes verticales son absorvidos en el analizador y los horizontales son transmitidos para formar el vector A :

$$A = \frac{\sqrt{2}}{2} \left(A_2^V - A_1^V \right) \qquad \text{Ec. 104}$$

Sustituyendo la ecuación 103 en la 104 y simplificando:

$$A = \frac{1}{2} k \operatorname{Sen} \frac{\Delta}{2} \left[\cos(\alpha + \omega t) - \operatorname{Sen}(\alpha - \omega t) \right] \qquad \text{Ec. 105}$$

La intensidad Ide la luz es proporcional al cuadrado de la amplitud, luego:

$$I = K \operatorname{Sen}^2 \frac{\Delta}{2} \left[\cos(\alpha + \omega t) - \operatorname{Sen}(\alpha - \omega t) \right]^2 \qquad \text{Ec. 106}$$

Una inspección de la ecuación 106 muestra que la extinción (I=0) es posible cuando

$$\operatorname{Sen}^2 \frac{\Delta}{2} = 0 \quad \text{ó} \quad \left[\cos(\alpha + \omega t) - \operatorname{Sen}(\alpha - \omega t) \right]^2 = 0$$

El término $[\cos(\alpha + \omega t) - \operatorname{Sen}(\alpha - \omega t)]^2$ no produce extinción que pueda ser registrada, ya que la frecuencia angular ω de la luz es demasiada. Por lo tanto, para efectos prácticos, éste término puede ser despreciado y la ecuación 106 puede reescribirse como:

$$I = K \operatorname{Sen}^2 \Delta/2 \qquad \text{Ec. 107}$$

Debe notarse que las direcciones de los esfuerzos no producen extinción, ya que el ángulo α está combinado con ωt .

Por lo tanto el polaroscopio circular elimina el patrón de Isóclinas.

Regresando á la ecuación 107, es claro que $I=0$ cuando $Sen^2\frac{\Delta}{2}=0$. Este hecho implica que la extinción es posible sólo cuando $\frac{\Delta}{2}=n\pi$, donde $n=0, 1, 2,$ etc. El tipo de extinción es idéntico al descrito en el caso 3 del polaroscopio plano.
La localización de estos puntos de extinción producen un patrón de franjas llamadas Isocromáticas.

b.4. Efectos de un modelo cargado en un polaroscopio circular(arreglo de campo claro).

Un polaroscopio circular es usualmente empleado tanto en un campo oscuro como en uno claro. El polaroscopio puede ser convertido de un campo oscuro a uno claro rotando el analizador 90 . La ventaja de emplear ambos campos es que se obtiene el doble de datos para la determinación de $\sigma_1-\sigma_2$ en todo el campo.
Recordemos que en el campo obscuro, el número de franja N coincide con n, y las franjas se cuentan en la secuencia 1, 2, 3, etc. Com el arreglo de campo claro, n y N no coinciden. En cambio $N=\frac{1}{2}+n$. Luego con el campo claro el número de línea se cuenta en la secuencia $\frac{1}{2}, 1\frac{1}{2}, 2\frac{1}{2}, 3\frac{1}{2},$ etc.
Para establecer el efecto de un modelo cargado en un polaroscopio circular con campo claro, sólo es necesario considerar los componentes A_1^v y A_2^v cuando entran al analizador con su nueva orientación, como se muestra en la figura 36.

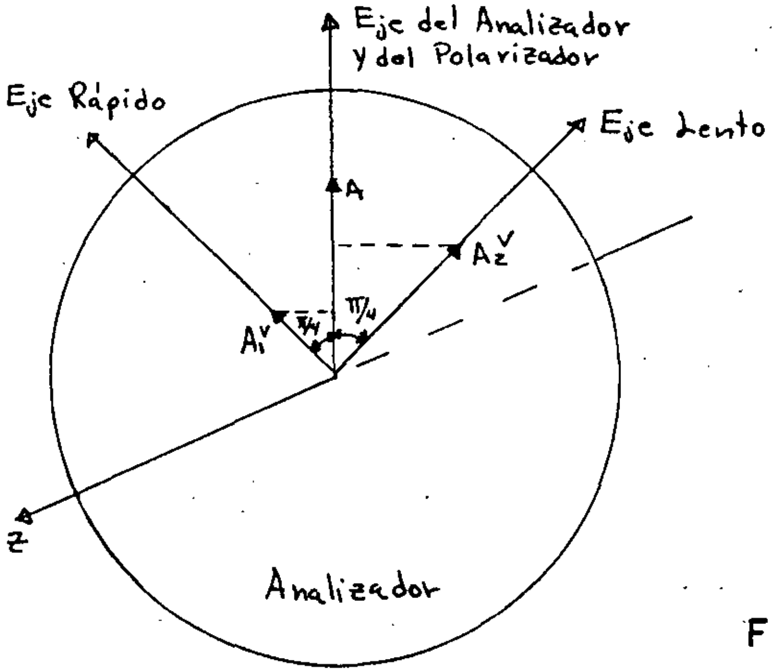


FIG 36

Los componentes horizontales de A_1^v y A_2^v son absorvidos, mientras que los componentes verticales se transmiten. El vector luz emergente estará en el plano vertical con una amplitud dada por:

$$A=\frac{\sqrt{2}}{2}\left(A_1^v+A_2^v\right) \qquad Ec. 108$$

Sustituyendo la ecuación 103 en 108 y simplificando tendremos:

$$A=2k\,Cos\,\omega t\,Cos\,\Delta/2 \qquad Ec. 109$$

y la intensidad:

$$I=K\,Cos^2\omega t\,Cos^2\Delta/2$$

El término $\cos^2\omega t$ puede despreciarse las razones ya expuestas:

$$I = K \cos^2 \Delta/2 \qquad Ec.\ 110$$

La extinción (I =0) ocurrirá cuando

$$\Delta/2 = \frac{1+2n}{2}\pi \ ; \ n = 0, 1, 2, 3, \ldots\ldots$$

pero de la ecuación97:

$$N = \frac{\Delta}{2\pi} = \frac{1}{2} + n \qquad Ec.\ 111$$

que implica que el orden o número de la primera franja observada en un polaroscopio de campo claro es $\frac{1}{2}$ que corresponde a $n = 0$. Usando los dos campos (obscuro y claro), es posible obtener dos fotografías de las franjas isocromáticas resultantes. Los datos así abtenidos, darán una representación del número de franjas separadas por $\frac{1}{2}$ orden. La interpolación entre las franjas permite a menudo una estimación del orden de franja de hasta ± 0.1 que resulta en una aproximación para la diferencia de los esfuerzos principales de $\pm 0.1\, f_\sigma/h$. Si se desea mayor exactitud, debe hacerse uso de técnicas más refinadas; algunas se describirán más adelante.

b.5. <u>Fotografía fotoelástica.</u>

En muchos análisis fotoelásticos, se toman fotos de los patrones de franjas Isóclinas e Isocromáticas. Por esta razón es importante establecer los principios básicos de la fotografía.

Una hoja de película fotográfica está preparada con un recubrimiento que contiene plata. Cuando este recubrimiento se expone a la luz, la plata sufre un cambio que es distinguible permanentemente después de un proceso de revelado fotográfico. El cambio es un proceso de oscurecimiento mediante la formación de plata metálica.

La cantidad de escurecimiento es llamada densidad.

La densidad de una película revelada, es simplemente una medida de la habilidad de la plata para prevenir la transmisión de la luz. La densidad de un tipo dado de película, es una función de la exposición (intensidad de la luz x tiempo). Las caracteristicas de la función densidad- exposición, fue primeramente establecida por Hurter y Drifrield de la manera mostrada en la figura 37. La curva de esta figura define tres características importantes de una película fotográfica, a saber: la densidad de niebla D_o , la inercia de exposición E_o , y la pendiente de la curva dada por el número γ de la película.

Cada una de estas características es importante, y deben ser consideradas al seleccionar una película para un análisís fotoelástico.

En una fotografía fotoelástica, la exposición cero ocurre siempre que la intensidad es cero (N o,1,2,....). Sin embargo la película registra valores del rango de exposición por encima del valor de inercia E_o . Es esta exposición "muerta" la que produce las franjas anchas cuando en teoría son líneas.

La pendiente de la densidad vs. Log E dada por γ determina la extención de la película. La película usual tiene $\gamma \approx 1$. Este relativamente bajo valor de γ da un amplio rango de exposición sobre el cual la película es efectiva y produce un negativo satisfactorio. Este hecho es importante en las fotografías en las que el tiempo correcto de exposición no puede determinarse.

Para fotografías fotoelásticas se emplean películas con valores de γ más altos (de 3 a 6) ya que dan un negativo de más contraste. Esto es deseable ya que las franjas tienden a adelgazar y se definen mejor. El tiempo de exposición es por supuesto más crítico, pero puede establecerse en exposiciones preliminares.

La densidad de niebla es menos importante ya que implica que existe una delgada capa uniformemente distribuida sobre la película, que absorbe la luz. Esto por supuesto va en detrimento de la brillantez del negativo, pero como es un factor relativo, no es objetable.

Para la porción lineal de la curva, densidad vs. log E, la densidad D puede expresarse como:

$$D = D_o + \gamma\left(\log E - \log E_o\right) \qquad \mathcal{E}c.\ 112$$

donde $D = \log {}^{I_i}/_{I_e}$

I_i :intensidad de la luz incidente sobre un negativo revelado.

I_e :intensidad de la luz emergente de un negativo revelado.

D_o :densidad de niebla $= \log {}^{I_i}/_{I_e'}$

I_e' :intensidad de la luz emergente de una parte no expuesta del negativo revelado.

$E = It$

I :intensidad de la luz incidente en la película.

t :tiempo de exposición.

Empleando las definiciones anteriores, la ecuación 112 puede ser escrita como:

$$\log {}^{I_i}/_{I_e} = \log {}^{I_i}/_{I_e'} + \gamma \log {}^{E}/_{E_o}$$

que puede ser reducida a:

$$1/\rho = {}^{I_e'}/_{I_e} = \left({}^{E}/_{E_o}\right)^{\gamma} \qquad \mathcal{E}c.\ 113$$

donde ρ es llamado el radio o razón de brillantez $\rho = {}^{I_e}/_{I_e'}$.

De esta definición se ve que $\rho = 1$ corresponde a la parte más brillante del negativo, mientras que $\rho = 0$ corresponde a un área opaca.

Recordando la ecuación 107:

$$I = K \operatorname{Sen}^2 \Delta/2$$

La exposición para un negativo en campo oscuro será:

$$E = It = Kt \operatorname{Sen}^2 \Delta/2 = E_\rho \operatorname{Sen}^2 \Delta/2 \qquad \mathcal{E}c.\ 114$$

donde $E_\rho = Kt$ es la exposición uniforme producida por el polaroscopio.

Combinando las ecuaciones 113 y 114:

$$1/\rho = \left({}^{E_\rho}/_{E_o}\right)^{\gamma} \operatorname{Sen}^{2\gamma} \Delta/2 \qquad \mathcal{E}c.\ 115$$

La ecuación 115 describe la brillantez de un negativo que resulta de fotografiar un modelo fotoelástico en un polaroscopio de campo oscuro.

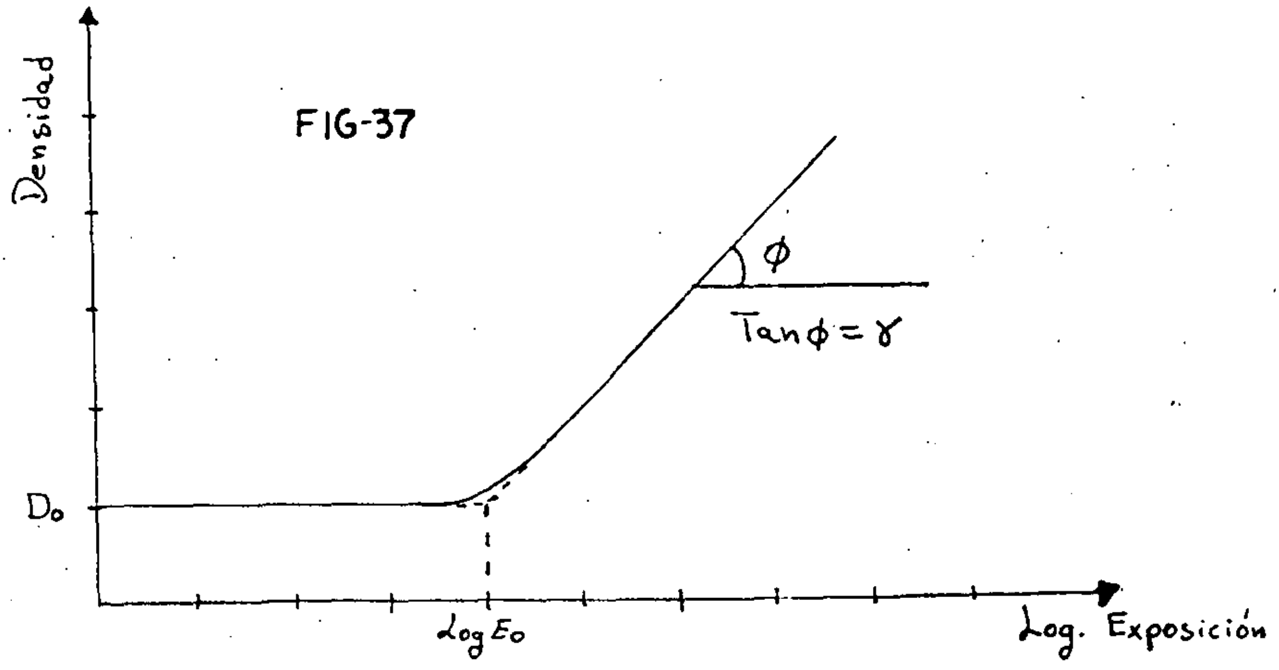


FIG-37

b.6. Multiplicación de franjas por métodos fotográficos.

Empleando procedimientos normales, pueden obtenerse dos fotos de un modelo fotoelástico (una en campo claro y otra en campo escuro), que permiten la determinación del orden de franja en la siguiente secuencia: $N = 0, 1/2, 1, 1\,1/2, 2,$ etc.

En algunas aplicaciones es deseable la determinación de ordenes de franja fraccionarios entre los ya listados. Este objetivo puede lograrse de diferentes maneras. En ésta sección se describirá una técnica fotográfica, la cual proporciona, mediante la superposición de patrones de franjas Isocromáticas ordinarias de campo claro y oscuro, un nuevo patrón de franjas de campo mixto.

Este patrón de franjas de campo mixto, junto con los de campo claro y oscuro, permite determinar el orden de franja en la secuencia $0, 1/4, 1/2, 3/4, 1,$ etc., y representa un factor de incremento de 2 en el número de franjas contables.

Recordando la ecuación 115, que describe la brillantez de un negativo obtenido en un campo oscuro:

$$1/\rho_{osc.} = \left(E\rho/E_o\right)^{\gamma} \operatorname{Sen}^{2\gamma} \Delta/2 \tag{Ec. 115}$$

Combinando las ecuaciones 113 y 114 con 110, es claro que:

$$1/\rho_{claro} = \left(E\rho/E_o\right)^{\gamma} \operatorname{Cos}^{2\gamma} \Delta/2 \tag{Ec. 116}$$

Multiplicando estas dos ecuaciones, que es matemáticamente análogo a sobreponer los dos negativos:

$$1/\rho_m = \left(1/\rho_{osc.}\right)\left(1/\rho_{claro}\right) = \left(E\rho/E_o\right)^{2\gamma} \operatorname{Sen}^{2\gamma} \Delta/2 \operatorname{Cos}^{2\gamma} \Delta/2$$

que puede reescribirse como:

$$1/\rho_m = \mathcal{E}^{2\gamma} \operatorname{Sen}^{2\gamma} \Delta/2 \operatorname{Cos}^{2\gamma} \Delta/2 \tag{Ec. 117}$$

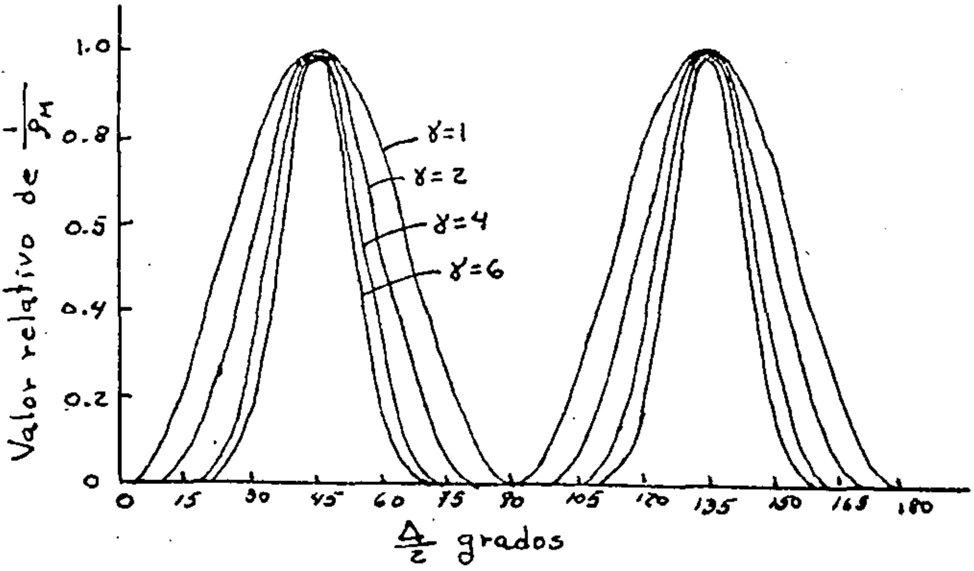
Un exámen de la ecuación 117 muestra que la característica del par de negativos superpuestos está determinado por el factor $\mathcal{E}$ (que es controlado por el tiempo de exposición y la velocidad de la película) y el factor γ (que es controlado por la película y por las propiedades del revelado). Si se emplea una película con $\gamma = 1$ la ecuación 117 se reduce a:

$$1/\rho_m = \mathcal{E}^2/8 \left[1 - \operatorname{Cos} 4\left(\Delta/2\right)\right]$$

Como al término $\mathcal{E}^2$ puede dársele cualquier valor controlando el tiempo de exposición, el término $\left[1 - \operatorname{Cos} 4\left(\Delta/2\right)\right]$ determina las características de los negativos super -- puestos. El término $\left[1 - \operatorname{Cos} 4\left(\Delta/2\right)\right]$ es uno cuando $\Delta/2 = (2n+1)\pi/4$ donde $n = 0, 1, 2, \ldots$ indicando que el patrón de franjas se registra en $N/4$, $3N/4$, $5N/4, \ldots$ como se muestra en la figura 38. Luego la posición de los ordenes de franja de $\frac{1}{4}$ pueden registrarse en todo el modelo de una forma simple y directa.

Conforme γ aumenta de valor, la cantidad $\left[\operatorname{Sen}^{2\gamma}\left(\Delta/2\right) \operatorname{Cos}^{2\gamma}\left(\Delta/2\right)\right]$ continúa exhibiendo picos en los valores de franja de $\frac{1}{4}$. Sin embargo estos picos se acentúan y los valles se aplanan. El uso de una película con un γ más alto es preferible ya que adelgaza las franjas y permite mayor exactitud en la determinación de la posición de las franjas.

FIG 38



b.7. Adelgazamiento de franjas con espejos parciales.

El ancho de las franjas Isocromáticas puede ser reducido mediante una técnica debida a Post que emplea espejos parciales en un polaroscopio circular con lentes.

Los espejos se insertan en el campo del polaroscopio en ambos lados y paralelos al modelo (figura 39).

El efecto de los espejos es hacer que la luz se propague hacia adelante y hacia atrás através del modelo en la manera ilustrada en la figura 40. Conforme la luz se refleja hacia atrás y hacia adelante entre los espejos, una porción es transmitida en cada punto de reflexión. Luego, la intensidad del rayo es progresivamente reducida. Por ejemplo, el rayo 1 es el más intenso, el 3 es menos intenso, etc.

El efecto de los espejos puede ser obtenido modificando la ecuación 107 que es válida si no hubiera espejos.

Consideremos el rayo 1 (figura 40) y reduzcamos la intensidad debido a la pérdida de luz por la reflexión en los puntos A y B. Tendremos:

$$I_1 = K(1-R)^2 \operatorname{Sen}^2 \Delta/2 = KT^2 \operatorname{Sen}^2 \Delta/2 \qquad (a)$$

donde R y T son los coeficientes de transmisión y de reflexión de los espejos.

La intensidad del rayo 3 ha pasado por dos reflexiones y dos transmisiones, luego T y R están al cuadrado. También la luz ha pasado através del modelo tres veces, y el argumento del seno ha sido multiplicado por 3 por este hecho.

$$I_3 = KT^2R^2 \operatorname{Sen}^2 3\Delta/2 \qquad (b)$$

Siguiendo este procedimiento, la intensidad del k ésimo rayo será:

$$I_k = KT^2R^{k-1} \operatorname{Sen}^2 \frac{k\Delta}{2}; \quad k=1,3,5,7\ldots \qquad \text{Ec. } 118$$

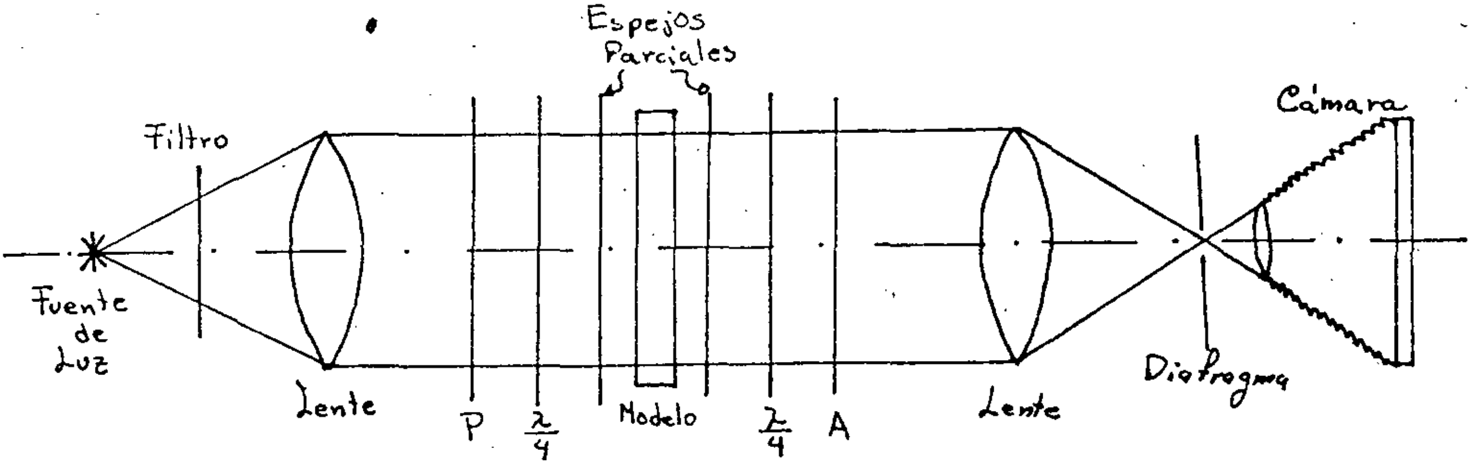

Espejos
Parciales
Filtro
Fuente
de
Luz
Lente
P
$\frac{\lambda}{4}$
Modelo
$\frac{\lambda}{4}$
A
Lente
Diafragma
Cámara

FIG-39

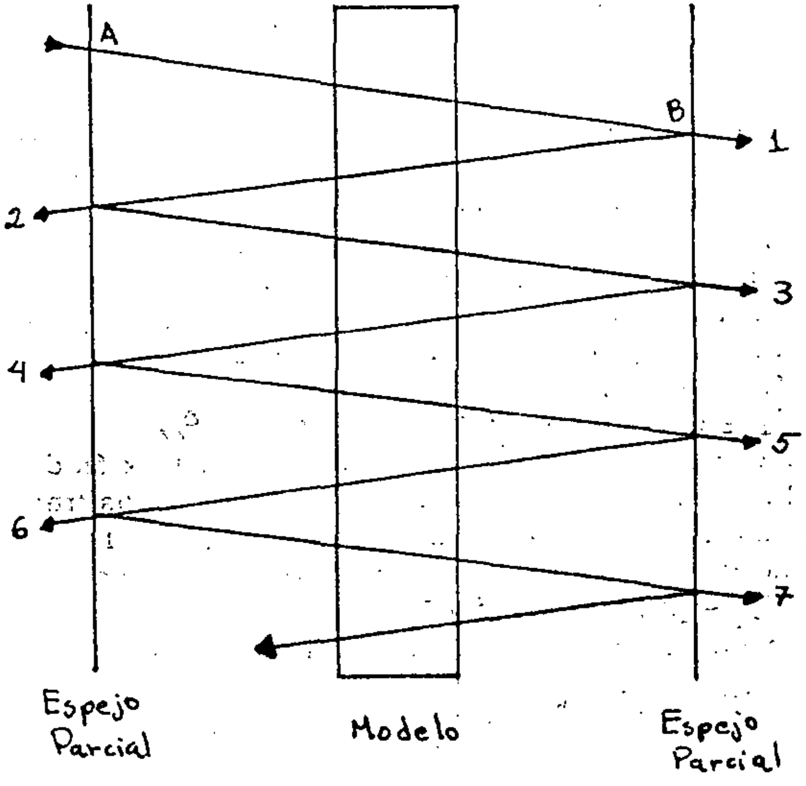

A
B
1
2
3
4
5
6
7
Espejo
Parcial
Modelo
Espejo
Parcial

FIG-40

Las intensidades I_1 , I_3 , I_5 , ... I_k se suman aritméticamente; luego la intensidad resultante de los rayos sobrepuestos está dada por la serie:

$$I = K T^2 \sum_{K=1}^{\infty} R^{K-1} \operatorname{Sen}^2 \frac{K\Delta}{2} \qquad \text{Ec. 119}$$

Si ésta relación se expande y se gráfica como función de $\frac{\Delta}{2\pi} = N$, la curva intensidad contra orden de franja es la que se obtiene (figura 41).

Cuando esta gráfica se compara con la curva convencional, se observa que las franjas se adelgazan. El ojo humano empieza a registrar una franja a una cierta intensidad mínima Io; luego la función adelgazada produce una franja mucho más angosta que la función convencional.

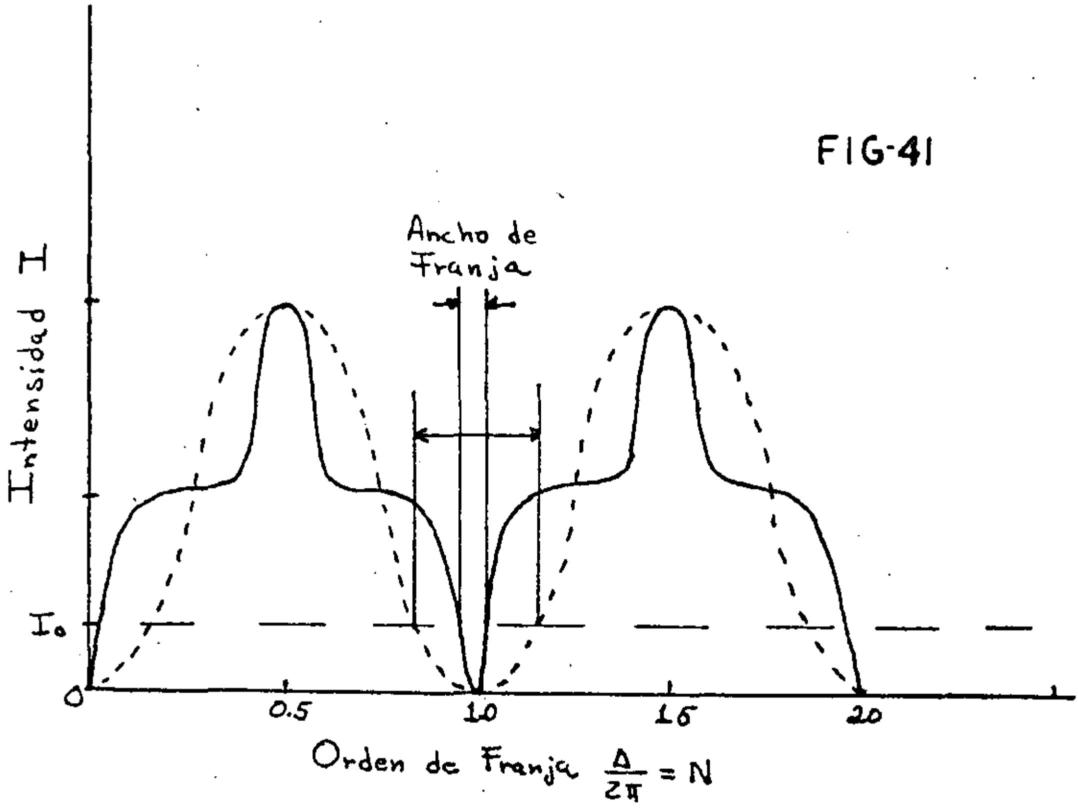


FIG-41

En una fotografía obtenida empleando este método, se observan bandas o franjas delgadas claras y oscuras separadas por anchas bandas grises. Las franjas oscuras corresponden a los valles de la figura 41 y las claras a los picos en la misma gráfica. Las bandas grises son procudidas por el rango medio de intensidades también mostrado en la figura 41. Las franjas oscuras están ordenadas con una secuencia o, 1, 2, 3, etc. y las claras con una secuencia $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$, $3\frac{1}{2}$ etc

Luego, los datos normalmente obtenidos en campos claro y oscuro convencionales están contenidos en una sola fotografía si se emplean espejos parciales en un polaroscopio circular con lentes.

b.8. Multiplicación de franjas con espejos parciales.

Post también mostró que los espejos parciales pueden ser empleados para multiplicar el número de franjas que pueden ser observadas en un modelo fotoelástico. Cuando se hace esto, los espejos son nuevamente puestos en el polaroscopio a ambos lados del modelo; sin embargo en esta aplicación uno de los espejos está ligeramente inclinado como se ve en la figura 42.

El efecto del espejo inclinado sobre la luz, al pasar hacia adelante y hacia atrás a través del modelo, se observa en la figura 43. De esta figura es claro que cada rayo de luz que emerge del espejo, sale con un ángulo que es función del número de veces que el rayo pasa através del modelo. Por ejemplo, los rayos 1, 3, 5, 7 que han atravesado el modelo el mismo número de veces que su número de rayo, emergen con ángulos $0, 2\phi, 4\phi$ y 6ϕ, además que los rayos no pasan por el mismo punto.

En la práctica, multiplicaciones por factores de 5 a 7 pueden ser obtenidos sin introducir grandes errores debido al promedio que es inherente en este método.

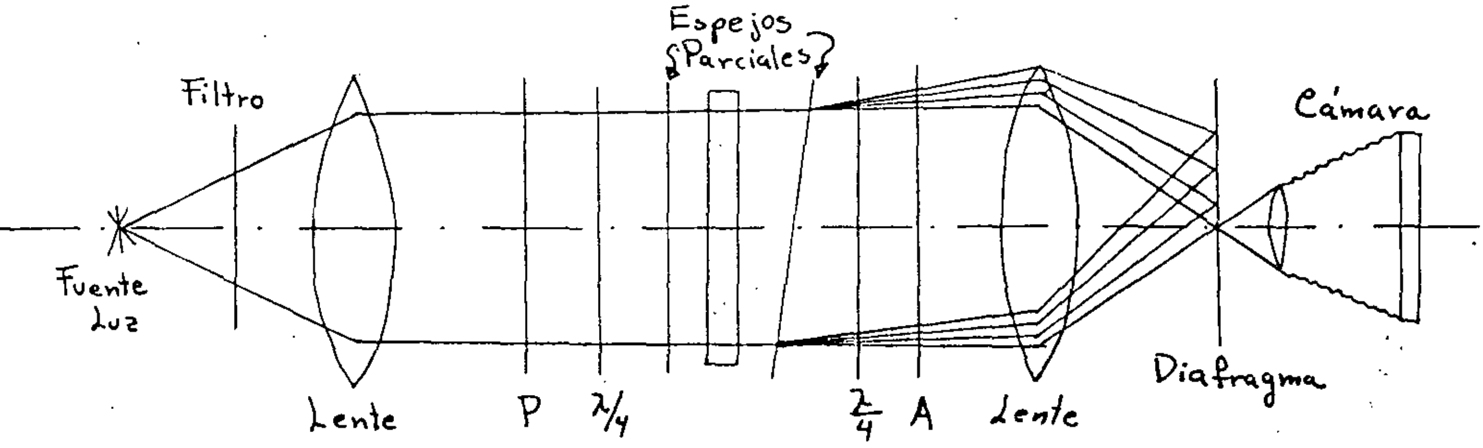


FIG 42

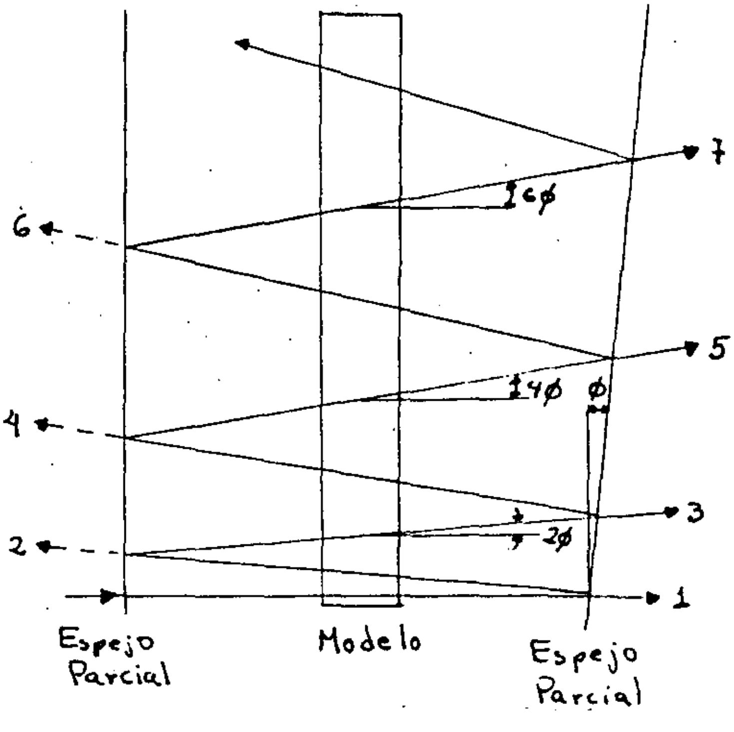


FIG 43

El hecho de que los diferentes rayos de luz estén inclinados diferentes ángulos con respecto al eje del polaroscopio, permite que cada rayo esté aislado. Los rayos son recolectados por los lentes pero afocados a diferentes puntos en el plano focal de los lentes. Cualesquiera de estos rayos pueden ser observados colocando el ojo o un lente de cámara en el punto adecuado.

En la práctica los patrones de Isocromáticas asociados con los rayos 1, 3, 5, 7, etc. pueden ser observados y fotografiados tanto en campo claro como en campo oscuro. Supongase por ejemplo que se obtienen fotografías en ambos campos de los rayos 1, 3 y 5.

El patrón de franjas en las dos fotos del rayo 1 se interpretan de manera convencional, en una secuencia $0, \frac{1}{2}, 1, \frac{3}{2}$, etc. Sin embargo, para el rayo 3, para el cual la luz ha pasado tres veces através del modelo, la secuencia de las franjas es $0, \frac{1}{6}, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}$....

Finalmente para el rayo 5, donde la luz ha atravesado el modelo 5 veces, la secuencia será $0, \frac{1}{10}, \frac{1}{5}, \frac{3}{10}, \frac{2}{5}, \frac{1}{2}$, etc.

Luego la superposición de los resultados obtenidos de estos tres rayos, es suficiente para determinar el orden de franja hasta en $\frac{1}{10}$ de orden sobre todo el modelo.

La relación para la intensidad del m ésimo rayo, donde m 1, 3, 5, etc. puede establecerse modificando la ecuación 107.

$$
\begin{aligned}
I_1 &= K T^2 \operatorname{Sen}^2 \Delta/2 \\
I_3 &= K T^2 R^2 \operatorname{Sen}^2 3\Delta/2 \\
I_5 &= K T^2 R^4 \operatorname{Sen}^2 5\Delta/2 \\
I_m &= K T^2 R^{m-1} \operatorname{Sen}^2 m\Delta/2
\end{aligned}
\qquad \text{Ec. 120}
$$

Luego, éste método de multiplicación de franjas está acompañado de una considerable pérdida de la intensidad de la luz. La intensidad del patrón multiplicado de franjas, comparado con el patrón convencional, está disminuido por el término $T^2 R^{m-1}$ que es mucho menor que uno.

c) Técnicas de Análisis.

c.1. Introducción.

En un análisis fotoelástico convencional en dos dimensiones, se fabrica un modelo, se carga, y se coloca en un polaroscopio, y los patrones de franjas son analizados y fotografiados. El siguiente paso es la interpretación de los patrones de franjas, que es el verdadero resultado de la prueba. En esta parte del trabajo se discutirán la interpretación de los patrones de franjas Isocromáticas e Isóclinas, las técnicas de compensación, de separación y la escala entre los esfuerzos del modelo y del prototipo.

c.2. Patrón de franjas Isocromático.

El patrón de franjas Isocromático obtenido de un modelo bidimensional, proporciona lineas a lo largo de las cuales la diferencia entre los esfuerzos principales $(\sigma_1-\sigma_2)$ es igual a una constante.

Cuando el orden de franja en cualquier punto del modelo ha sido establecido, es posible valuar $(\sigma_1-\sigma_2)$ de la ecuación 97.

$$\sigma_1-\sigma_2 = N f_\sigma / h$$

donde σ_1 y σ_2 son los esfuerzos principales en el plano del modelo.

El esfuerzo cortante máximo está dado por:

$$\tau_{máx} = \frac{1}{2}(\sigma_1-\sigma_2) = N f_\sigma / 2h \qquad Ec. 121$$

si σ_1 y σ_2 son de signos opuestos y $\sigma_3 = 0$; de otra manera

$$\tau_{máx} = \frac{1}{2}(\sigma_1-\sigma_3) = \frac{1}{2}\sigma_1 \qquad \text{si } \sigma_1 \text{ y } \sigma_2 \text{ son positivos}$$
$$\tau_{máx} = \frac{1}{2}(\sigma_3-\sigma_2) = \frac{1}{2}\sigma_2 \qquad \text{si } \sigma_1 \text{ y } \sigma_2 \text{ son negativos} \qquad Ec. 122$$

La diferencia entre las ecuaciones 121 y 122 está representada gráficamente en la figura 44, donde se ha dibujado el círculo de Mohr para los dos casos. Cuando $\sigma_1 > 0$ y $\sigma_2 < \sigma_3 = 0$, el esfuerzo cortante máximo es la mitad del valor de $(\sigma_1-\sigma_2)$ y puede ser determinado directamente del patrón de Isocromáticas conforme la ecuación 121. Sin embargo, cuando $\sigma_1 > \sigma_2 > \sigma_3 = 0$, el esfuerzo cortante máximo no está en el plano del modelo y la ecuación 121 proporciona τ_p y no $\tau_{máx}$. Para establecer $\tau_{máx}$ en este caso, es necesario determinar σ_1 individualmente y no $(\sigma_1-\sigma_2)$. Este es un punto importante ya que la teoría de falla del cortante máximo se usa con frecuencia en el diseño de elementos mecánicos.

En la superficie libre del modelo, σ_1 o σ_2 son iguales a cero; por lo tanto el esfuerzo tangencial a la frontera puede ser determinado directamente por

$$\sigma_1, \sigma_2 = N f_\sigma / h \qquad Ec. 123$$

El signo puede ser usualmente determinado por inspección, particularmente en las áreas críticas donde los esfuerzos en la frontera son máximos.

A lo largo de una frontera que no esté libre, por lo general se conoce la carga aplicada y por lo tanto uno de los esfuerzos, digamos σ_2 ; sea P la carga aplicada.

Luego:

$$\sigma_1-\sigma_2 = \sigma_1 + P = N f_\sigma / h \qquad ó \qquad \sigma_1 = N f_\sigma / h - P \qquad Ec. 124$$

donde $\sigma_2 = -P$ ya que la presión aplicada se considera positiva.

Concluyendo, es claro que el patrón de franjas Isocromáticas, una vez identificado, puede ser interpretado de la siguiente manera:

1. $(\sigma_1-\sigma_2)$ puede ser determinado en cualquier punto del modelo de la ecuación 97.
2. Si $\sigma_1 > 0$ y $\sigma_2 < 0$, $(\sigma_1-\sigma_2)$ puede ser relacionado al esfuerzo cortante máximo mediante la ecuación 121.

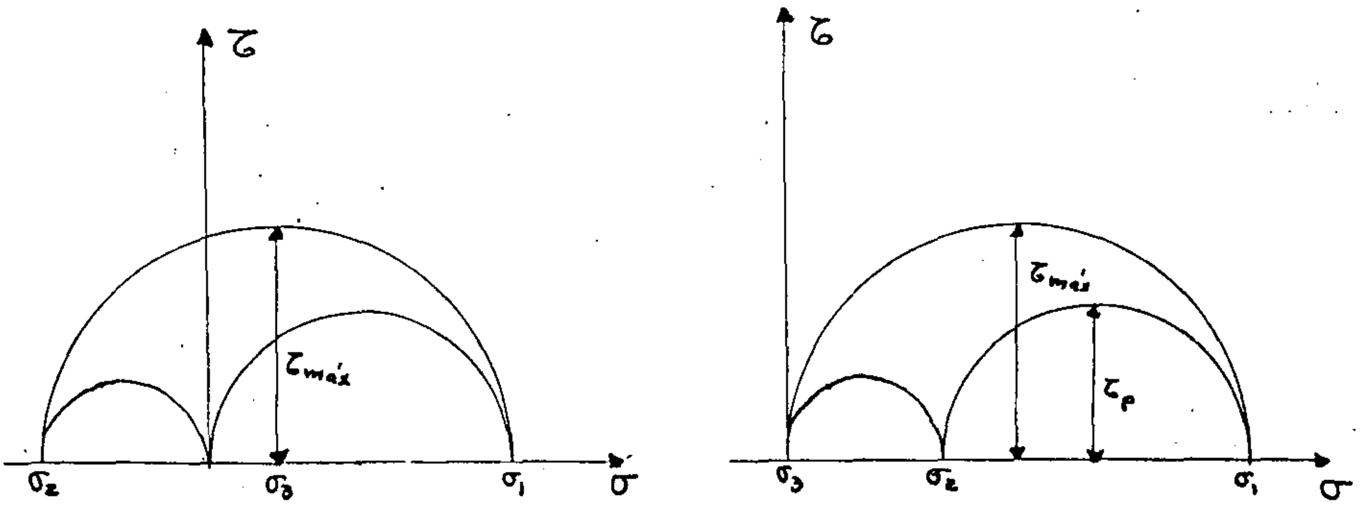


FIG 44

3. Si $\sigma_1>\sigma_2>0$ o si $0>\sigma_1>\sigma_2$, $(\sigma_1-\sigma_2)$ no puede ser referido al esfuerzo cortante máximo y es necesario determinar σ_1 y σ_2 individualmente y referir $\tau_{máx}$ a σ_1 o a σ_2 , mediante la ecuación 122.
4. Si las fronteras pueden considerarse libres (esto es si σ_1 o $\sigma_2 = 0$)el otro esfuerzo principal puede ser determinado directamente de la ecuación 123.
5. Si la frontera no está libre, pero la carga normal aplicada es conocida, entonces el esfuerzo tangencial a la frontera puede interpretarse utilizando las ecuaciones 124.
6. Si la frontera no está libre, y la carga aplicada no es conocida, deben aplicarse las técnicas de separación, las cuales se discutirán más adelante, para determinar los esfuerzos en la frontera.

c.3. Patrón de franjas Isóclinas.

El patrón de franjas Isóclinas obtenido en un polaroscopio plano es empleado para dar la dirección de los esfuerzos principales en cualquier punto del modelo. En la práctica esto puede realizarse de dos maneras. La primera es obtener un número de patrones de Isóclinas a diferentes posiciones del polaroscopio y combinar estos patrones para dar los parámetros de las Isóclinas sobre el campo completo del modelo. El segundo procedimiento consiste en aislar los puntos de interés y determinar el parámetro de Isóclinas en cada uno de estos puntos.

Hay varias reglas que deben seguirse al obtener el patrón compuesto de Isóclinas a partir de los patrones individuales. Estás reglas son:
1. Isóclinas de todos los parámetros deben pasar através de los puntos isótropos o singulares.
2. La isóclina de uno de los parámetros debe coincidir con el eje de simetría del modelo si es que existe.
3. El parámetro de una Isóclina que intersecta una superficie libre, es determinado por la pendiente de la frontera en el punto de intersección.

4. Isóclinas de todos los parámetros pasan através de los puntos de carga concentrada.

Las líneas Isóclinas, a lo largo de las cuales los esfuerzos principales tienen una inclinación constante, dan las direcciones principales de una manera que no es apreciada en el campo de la ingeniería. Por esto es un procedimiento normal presentar las direcciones principales en forma de un diagrama de Isostáticas o diagrama de trayectorias de esfuerzos, donde los esfuerzos principales son tangentes o normales a las líneas Isostáticas en cada punto.

El diagrama de Isostáticas puede ser construido de una manera directa a partir del patrón de Isóclinas utilizando el procedimiento descrito abajo e ilustrado en la figura 45. En esta técnica de construcción, las trayectorias de los esfuerzos se inician en la Isóclina de 0^{o} a partir de puntos espaciados arbitrariamente. Las líneas marcadas 1 en la figura 45 y orientedas 0^{o} de la normal, se dibujan através de cada uno de estos puntos, hasta que intersecten la Isóclina de 10^{o}. Las líneas (1) se bisectan y un nuevo set de líneas (2) se dibuja, inclinadas 10^{o} de la vertical, hasta la siguiente Isóclina. Nuevamente estas líneas se bisectan y otro conjunto de líneas (3) se dibujan orientadas un ángulo de 30^{o} con la vertical. Este procedimiento se repite hasta que el campo entero esté cubierto. Las trayectorias de los esfuerzos son trazadas utilizando las líneas 1, 2, 3, etc. como guias. Las trayectorias de los esfuerzos se dibujan tangentes a las líneas construidas en cada intersección de las Isóclinas, como se ve en la figura 45.

Los parámetros Isóclinos también son empleados para determinar los esfuerzos cortantes en un plano arbitrario definido por un sistema coordenado oxy. Recordando el hecho de que los parámetros Isóclinos dan las direcciones entre el eje x del sistema coordenado y las direcciones de σ_1 o σ_2 y recordando el círculo de Mohr y las ecuaciones de transformación de esfuerzos en función de los esfuerzos principales, es claro que:

$$\tau_{xy} = -\frac{\sigma_1-\sigma_2}{2}\,\text{Sen}\,2\theta = -\frac{N f_\sigma}{2h}\,\text{Sen}\,2\theta \qquad \text{Ec. 125}$$

donde θ es el ángulo entre el eje x y la dirección de σ_1 dado por el parámetro de la Isóclina. También:

$$\tau_{xy} = \frac{\sigma_1-\sigma_2}{2}\,\text{Sen}\,2\theta_1 = \frac{N f_\sigma}{2h}\,\text{Sen}\,2\theta_1 \qquad \text{Ec. 126}$$

donde θ_1 es el ángulo entre el eje x y la dirección de σ_2 dado por el parámetro de la Isóclina.

El uso combinado de los datos de las Isocromáticas y las Isóclinas representado en las ecuaciones 125 y 126 permite la determinación de τ_{xy}. Este valor de τ_{xy} es usado en la aplicación del método de diferencia de cortantes (que se verá posteriormente) para la determinación individual de los valores de σ_1 y σ_2.

c.4. Técnicas de compensación.

El orden de las franjas Isocromáticas puede ser determinado hasta en $\frac{1}{2}$ de orden empleando los patrones de franjas de campo claro y de campo oscuro. Una mayor exactitud en la determinación del orden de franja puede hacerse usando campos compuestos o usando el método de Post para la multiplicación de franjas.

Sin embargo cuando se necesita una mayor exactitud deben usarse técnicas de compensación de punto por punto para establecer el orden de franja N. Aquí se discutirá el más común de estos métodos, el método de Tardy.

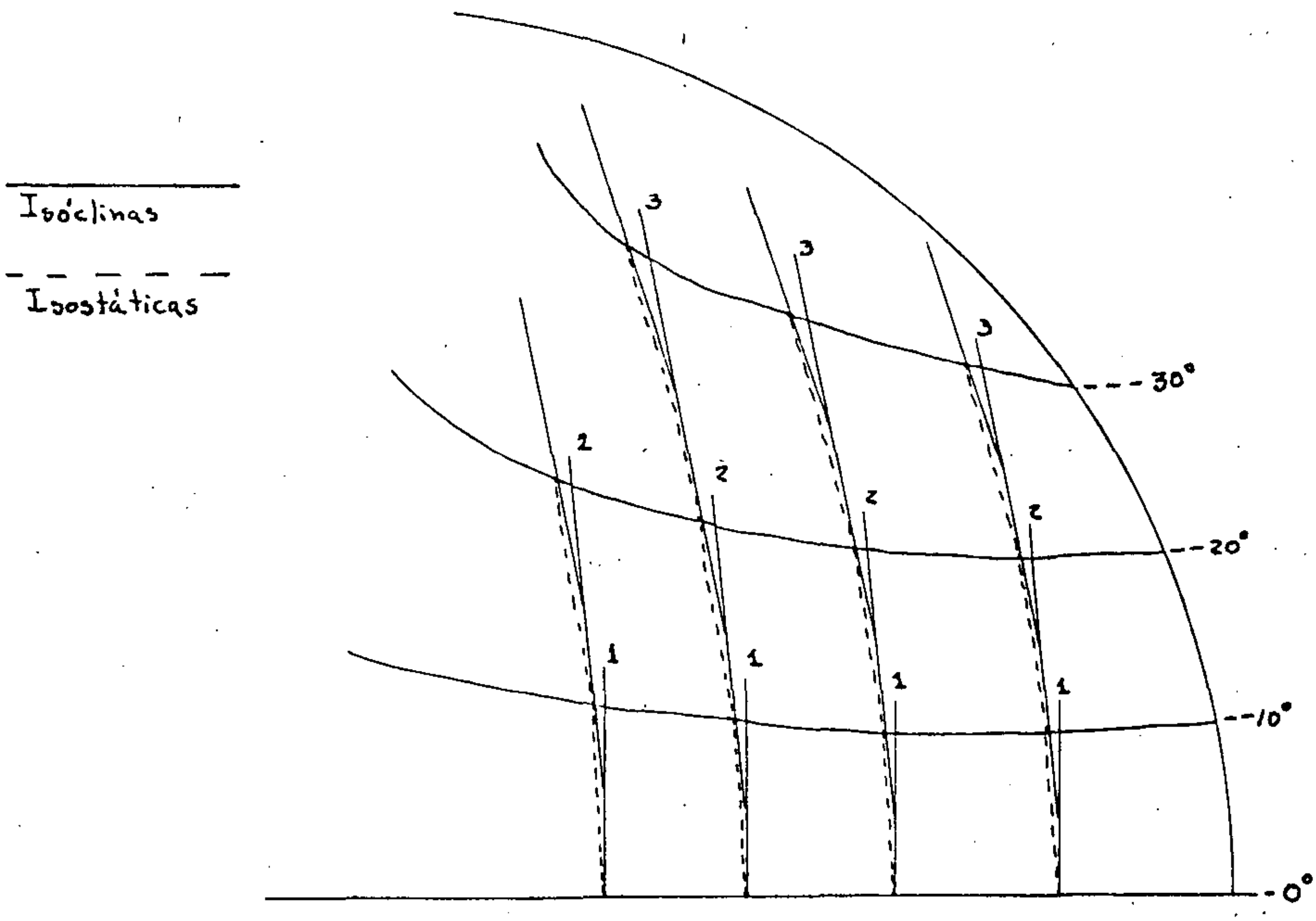


FIG 45

Método de Compensación de Tardy:

El método de compensación de Tardy es muy usado para determinar el orden de franja en un punto arbitrario del modelo. En éste método no se requiere equipo auxiliar y el analizador del polaroscopio sirve de elemento compensador.

Para emplear el método de Tardy, el polarizador del polaroscopio se alinea con la dirección de σ_1 del punto en cuestión, y todos los demás elementos del polaroscopio se rotan para obtener un campo oscuro. En esta posición del polaroscopio, se cumple el análisis presentado en la sección b.3. con el ángulo α igual a cero; por lo tanto las ecuaciones 103, que describen la luz emergente de la segunda placa cuarto de onda, pueden ser escritas como:

$$A_1^v = \frac{\sqrt{2}}{4} k \left[\mathrm{Cos}\left(\omega t - \frac{\Delta}{2}\right) + \mathrm{Sen}\left(\omega t - \frac{\Delta}{2}\right) - \mathrm{Sen}\left(\omega t + \frac{\Delta}{2}\right) + \mathrm{Cos}\left(\omega t + \frac{\Delta}{2}\right) \right]$$

$$A_2^v = \frac{\sqrt{2}}{4} k \left[\mathrm{Cos}\left(\omega t + \frac{\Delta}{2}\right) + \mathrm{Sen}\left(\omega t + \frac{\Delta}{2}\right) - \mathrm{Sen}\left(\omega t - \frac{\Delta}{2}\right) + \mathrm{Cos}\left(\omega t - \frac{\Delta}{2}\right) \right]$$

que pueden reducirse a:

$$A_1^v = \frac{\sqrt{2}}{2} K \,\mathrm{Cos}\,\omega t \left(\mathrm{Cos}\frac{\Delta}{2} - \mathrm{Sen}\frac{\Delta}{2}\right)$$

$$A_2^v = \frac{\sqrt{2}}{2} K \,\mathrm{Cos}\,\omega t \left(\mathrm{Cos}\frac{\Delta}{2} + \mathrm{Sen}\frac{\Delta}{2}\right) \qquad \text{Ec. 12}$$

Ahora consideremos los componentes de la luz entrando al analizador como se muestra en la figura 46, y determinemos el ángulo γ através del cual hay que rotar el analizador para obtener la extinción (esto es $a_1 = a_2$). La amplitud de los componentes de la luz que pasan por el analizador está dada por:

$$A = A_2^v \,\mathrm{Cos}(\pi/4 + \gamma) - A_1^v \,\mathrm{Cos}\left(\frac{\pi}{4} - \gamma\right) \qquad \text{Ec. 128}$$

Si γ se selecciona de manera que A sea cero, y sustituyendo la ecuación 127 en 128, se obtiene:

$$\left(\mathrm{Cos}\frac{\Delta}{2} + \mathrm{Sen}\frac{\Delta}{2}\right)\left(\mathrm{Cos}\,\gamma - \mathrm{Sen}\,\gamma\right) - \left(\mathrm{Cos}\frac{\Delta}{2} - \mathrm{Sen}\frac{\Delta}{2}\right)\left(\mathrm{Cos}\,\gamma + \mathrm{Sen}\,\gamma\right) = 0$$

que se reduce a:

$$\mathrm{Sen}\left(\Delta/2 - \gamma\right) = 0 \qquad \text{Ec. 129}$$

La expresión $\mathrm{Sen}\left(\frac{\Delta}{2} - \gamma\right) = 0$ cuando $\Delta/2 - \gamma = n\pi$, donde n = 0, 1, 2, ...; de manera que el orden de franja N en el punto de interés está dado por:

$$N = \Delta/2\pi = n + \gamma/\pi \qquad \text{Ec. 130}$$

Para utilizar la ecuación 130 en el método de Tardy, el valor de n se determina por la posición del punto de interés relativa a el patrón de franjas Isocromáticas en el campo oscuro. Para ilustrar este hecho consideremos el patrón de franjas hipotético y los puntos de interés mostrados en la figura 47.

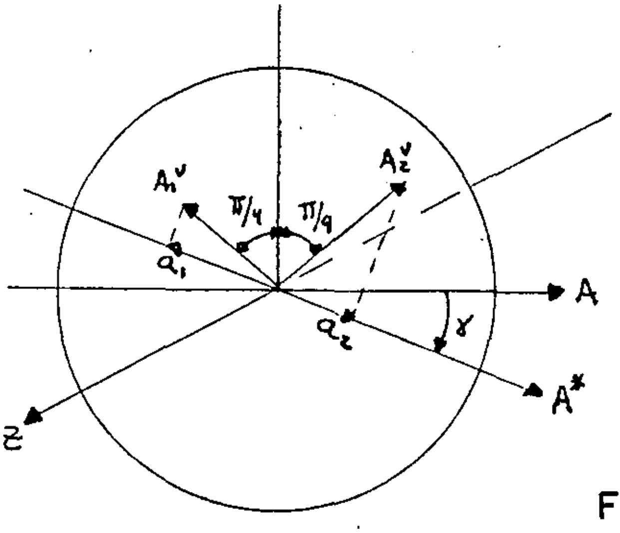


FIG 46

El punto P_1 que está entre los órdenes de franja 2 y 3, el valor asignado a n en ese punto es 2. Conforme el analizador es rotado un ángulo γ , la franja de segundo órden se moverá hacia el punto P_1 hasta que se obtenga la extinción. El órden de franja del punto P_1 será $N = 2 + \gamma/\pi$. Para el punto P_2 el valor de n se toma también como 2, y el analizador es rotado un ángulo γ_1 hasta que la franja de segundo órden provoque la extinción, dando un órden de franja de $N = 2 + \gamma_1/\pi$. En este caso n pudo haberse tomado como 3 y el analizador rotado en la dirección contraria un ángulo $-\gamma_2$, hasta que la franja de tercer órden produzca la extinción en el punto P_2. En este ca-ha sido evaluada, su influencia en el esfuerzo principal máximo es usualmente menos del 7%.

La segunda excepción de las leyes de similitud es cuando el modelo fotoelástico sufre una distorsión apreciable bajo la acción de la carga, ya que esto altera la distribución de los esfuerzos.

Como el modelo fotoelástico puede diferir del prototipo respecto a la escala, espesor, y carga aplicada, así como las constantes elásticas, es necesario extender este tratamiento para incluir las relaciones de escala. Mucho se ha escrito respecto a esto, empleando números adimensionales y el teorema π de Buckingham; sin embargo, en la mayoría de las aplicaciones fotoelásticas, relacionar los esfuerzos del modelo al prototipo es relativamente simple cuando los números adimensionales pertinentes pueden ser escritos directamente. Por ejemplo, en el caso de un modelo bidimensional con una carga aplicada P, el número adimensional para los esfuerzos es $\sigma h l / P$ y para los desplazamientos $\delta E h / P$.

Luego los esfuerzos del prototipo pueden escribirse como:

$$\sigma_p = \frac{P_p}{P_m} \frac{h_m}{h_p} \frac{l_m}{l_p} \sigma_m \qquad \text{Ec. 139}$$

y los desplazamientos del prototipo como:

$$\delta_p = \frac{P_p}{P_m} \frac{E_m}{E_p} \frac{h_m}{h_p} \delta_m \qquad \text{Ec. 140}$$

donde σ es el esfuerzo de un punto dado.
δ es el desplazamiento en un punto dado.
P es la carga aplicada.
h es el espesor.
l es una longitud típica.

los subíndices p y m se refieren al prototipo y al modelo respectivamente.

Concluyendo, el módulo de elasticidad no se considera en la determinación de la distribución de los esfuerzos, amenos que la deformación cambie la distribución de la carga (esfuerzos de contacto por ejemplo.) También el módulo de Poisson no necesita considerarse cuando el cuerpo sea simplemente conexo y las fuerzas de cuerpo no existen o son uniformes.

d) Materiales fotoelásticos para aplicaciones bidimensionales.

d.1. Criterio para la selección de materiales.

Uno de los aspectos más importantes en el análisis fotoelástico es la selección del material adecuado para el modelo fotoelástico.

Desafortunadamente no existe un material perfectamente fotoelástico y el investigador debe seleccionar de la lista de materiales disponibles el que más se adapte a sus necesidades.

La siguiente lista da las propiedades que el material fotoelástico ideal debería tener:

1. El material debe ser transparente a la luz que se usa en el polaroscopio.
2. El Material debe ser muy sensible a los esfuerzos y deformaciones , indicado por un bajo valor de f_σ o f_ε .
3. El material debe tener propiedades lineales con respecto a :
   Relaciones esfuerzo deformación.
   Relaciones esfuerzo-orden de franja.
   Relaciones deformación - orden de franja.
4. El material debe ser isótropo y homogeneo tanto mecánica como ópticamente.

5. El material no debe fluir excesivamente.
6. El material debe tener un alto módulo de elasticidad y un elevado esfuerzo último.
7. La sensitividad del material (esto es f_σ ó f_ε) no debe cambiar mucho con las variaciones pequeñas de temperatura.
8. El material no debe exhibir efectos "time-edge".
9. El material debe poderse maquinar convencionalmente.
10. El material debe estar libre de esfuerzos residuales.
11. El material no debe ser demasiado caro.

1. Transparencia.
En la mayoría de las aplicaciones, los materiales escogidos son plásticos transparentes. Estos plásticos deben ser transparentes a la luz visible, pero no deben ser claros como el cristal. En ciertas aplicaciones especiales que requieren el estudio de materiales normalmente opacos, un polaroscopio infrarojo es lo que se emplea. Unos pocos materiales son transparentes en las regiones ultravioleta o infraroja. Pueden construirse polaroscopios que operen en estas regiones cuando se necesiten longitudes de onda muy largas o muy cortas. Sin Embargo para el análisis de esfuerzos la luz visible es la más adecuada.

2. Sensitividad.
Frecuentemente se desea un material altamente sensitivo ya que esto incrementa el número de franjas que pueden ser observadas en el modelo. Si el valor de f_σ para un material es bajo, se puede obtener un patrón de franjas satisfactorio con relativamente bajas cargas. Este hecho reduce la complejidad de los sistemas de carga y la distorsión del modelo.
Materiales fotoelásticos con valores de f_σ desde menos de 0.2 hasta más de --- 2000 psi-in, están disponibles. Con respecto a los valores de f_ε , la situación no es tan satisfactoria, ya que los materiales con un valor suficientemente bajo de f_ε aún no están disponibles. (Los valores usuales de f_ε están entre 0.0002 y 0.02 in).

3. Linealidad.
Los modelos fotoelásticos son normalmente empleados para predecir los esfuerzos que ocurrirán en un prototipo de metal. Ya que una escala modelo -prototipo debe - ser usada para establecer los esfuerzos del prototipo , el modelo debe exhibir propiedades lineales de esfuerzo-deformación , esfuerzo-óptica, deformaciones-óptica. Muy poco hay en la literatura sobre las relaciones deformación-óptica; sin embargo como el método fotoelástico es usualmente empleado para determinar diferencias de esfuerzos, este hecho no es demasiado serio. Curvas típicas esfuerzo-deformación y esfuerzo-orden de franja se muestran en la figura 50, para mostrar el comportamiento característico de un material polímero fotoelástico. La mayoría de los polímeros exhiben curvas lineales en la porción inicial de la gráfica; sin embargo a valores altos del esfuerzo, el material se comporta de manera no lineal.

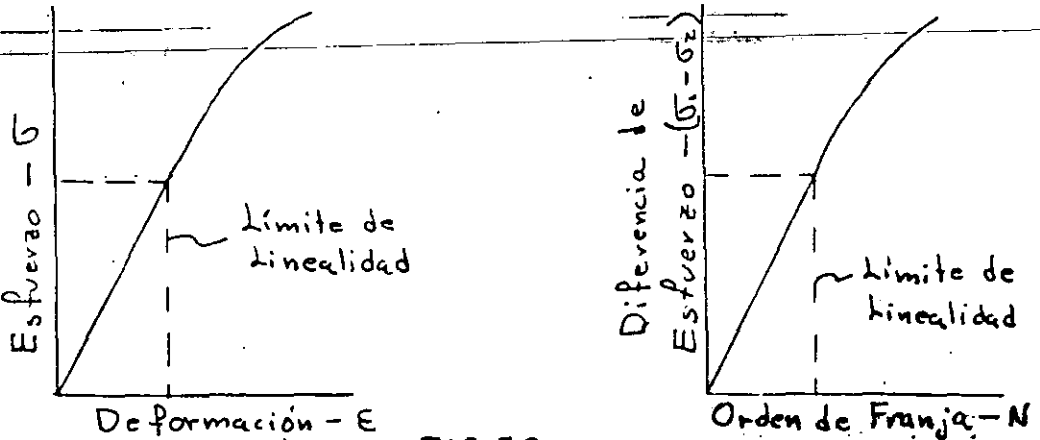


FIG 50

4. Isotropía y Homogeneidad.

Muchos de los materiales fotoelásticos son preparados de polímeros líquidos y vaciándolos entre dos placas de vidrio que forman el molde. Cuando el material fotoelástico es preparado mediante este procedimiento, las cadenas moleculares del polímero se orientan aleatoriamente, y los materiales son esencialmente isótropos y homogéneos. Sin embargo, algunos materiales son rolados o estirados durante el proceso. En ambos casos las cadenas moleculares se orientan en la dirección del rolado o del estirado. Estos materiales exhibirán propiedades no isotrópicas y no deben ser usados.

5. Fluidez.

Desafortunadamente, la mayoría de los materiales con base de polímeros fluyen tanto mecánica como ópticamente en el período de el análisis fotoelástico. Debido a ésto los polímeros no pueden ser considerados realmente como materiales elásticos, sino como viscoelásticos.

Uno de los primeros intentos para formular una teoría matemática de la fotoviscoelasticidad fué hecha por Mindlin considerando un modelo viscoelástico generalizado consistente de m elementos elásticos con un módulo cortante G_k $(k=1,2,\ldots m)$ y m elementos viscosos con un coeficiente viscoso η_k $(k=1,2,\ldots\ldots m)$ vease figura 51. Asumiendo que los efectos fotoelásticos resultan solamente de la deformación de los elementos elásticos del modelo, Mindlin mostró que el retardo relativo, expresado como (n_1-n_2) puede relacionarse con los esfuerzos y las deformaciones como:

$$(n_1-n_2)\cos 2\theta_n = R\left[(\sigma_1-\sigma_2)\cos 2\theta_\sigma\right] + 2S\left[(\varepsilon_1-\varepsilon_2)\cos 2\theta_\varepsilon\right] \qquad \text{Ec. 141}$$

donde: n_1-n_2 es el retardo relativo.

θ_n, θ_σ, θ_ε son los ángulos entre los ejes ópticos principales, los esfuerzos principales, las deformaciones principales, y el eje respectivamente.

R y S son operadores lineales del tipo que relaciona esfuerzos y deformaciones en la teoría viscoelástica.

Para un modelo estandard de 4 elementos (fig. 51), estos operadores son:

$$R=\frac{\eta_0^3}{4}\left[\frac{c_1}{G_1}+\frac{c_2}{G_2}\left(1+\frac{\eta_2}{\eta_3}+\frac{\eta_2}{G_1}\frac{d}{dt}\right)\right]$$

$$S=\frac{\eta_0^3 c_2 \eta_2}{4G_2}\frac{d}{dt} \qquad \text{Ec. 142}$$

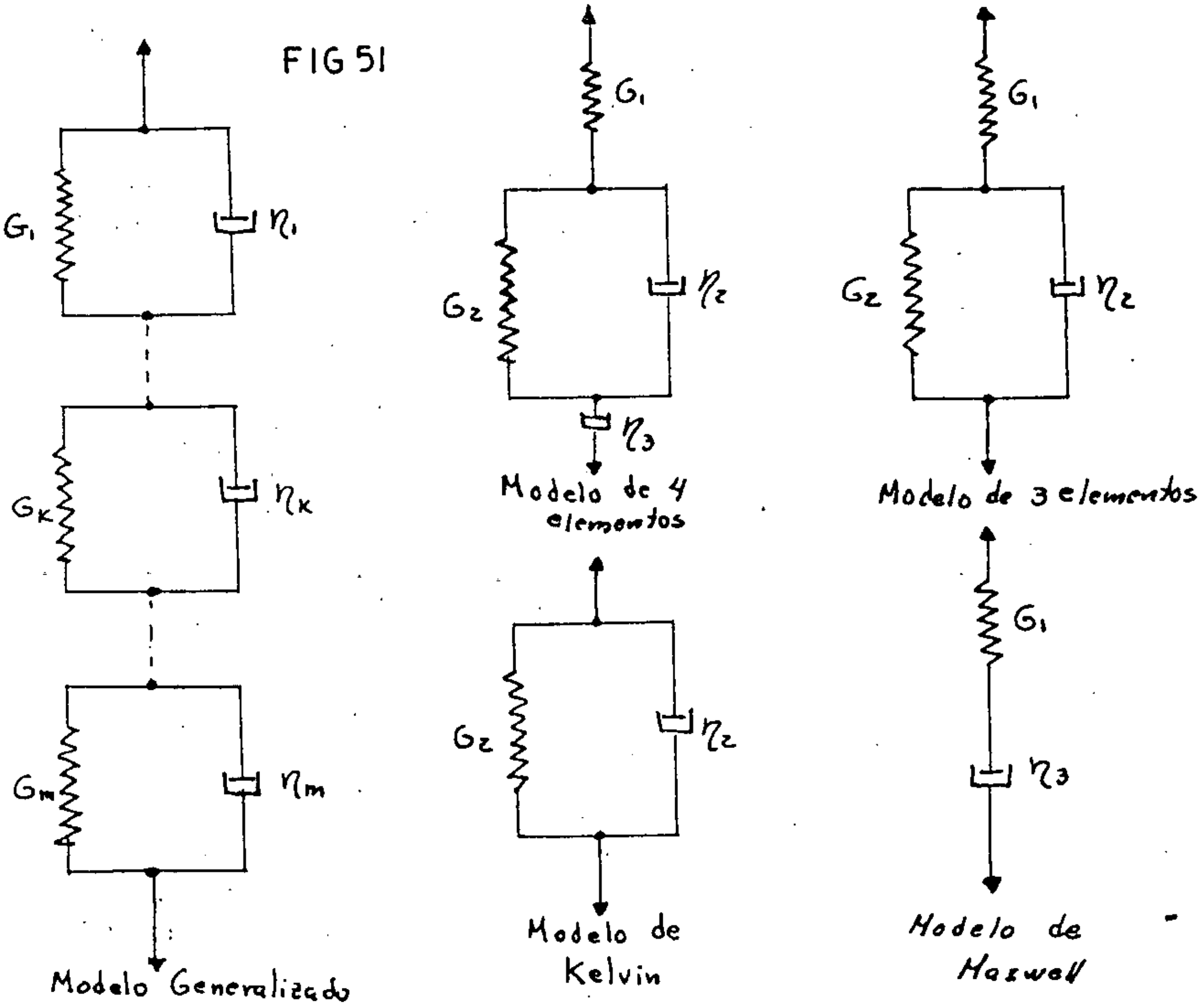
donde: C_1 y C_2 son las constantes fotoelásticas para los resortes 1 y 2 del modelo
G_1 y G_2 son los módulos cortantes para los resortes 1 y 2 del modelo.
η_2, η_3 son los coeficientes viscosos del modelo.

Puede verse de la ecuación 142 que la respuesta fotoelástica de un modelo de 4 elementos se debe a los esfuerzos, la rapidez de deformación, y la variación de los esfuerzos con respecto al tiempo. Para el modelo de tres elementos de la fig. 51 los operadores pueden expresarse como:

$$R = \frac{\eta_0^3}{4G_1}(C_1 - C_2) \qquad S = \frac{\eta_0^3}{2} C_2 \qquad \text{Ec. 143}$$

Estas ecuaciones muestran que la birrefringencia es debida a los esfuerzos y las deformaciones, pero es independiente de su variación en el tiempo. Coker y Filon encontraron que el material llamado xylonita sigue este modelo viscoelástico particular.

FIG 51



Modelo Generalizado

Modelo de 4 elementos

Modelo de 3 elementos

Modelo de Kelvin

Modelo de Maxwell

Para el modelo de Kelvin, los operadores se reducen a:

$$R = 0$$
$$S = \frac{\eta_0^3}{2} C_2 \qquad \text{Ec. 14}$$

Esta ecuación muestra que el efecto fotoelástico es función solamente de la diferencia de deformaciones.

Finalmente para el modelo de Maxwell los operadores son:

$$R = \frac{\eta_0^3 C_1}{4 G_1} \qquad S = 0 \qquad \text{Ec. 145}$$

Estas ecuaciones muestran que el efecto fotoelástico puede ser expresado como función de los esfuerzos unicamente.

Luego es claro de la discusión anterior, que la interpretación de los efectos de los esfuerzos, las deformaciones y sus variaciones con el tiempo, sobre los patrones de franjas, depende del tipo de modelo que mejor se aproxime al material fotoelástico bajo consideración.

Afortunadamente los materiales fotoelásticos comunmente empleados exhiben una propiedad importante, a saber, que los esfuerzos y las deformaciones que varían con la posición y con el tiempo, pueden representarse por el producto de dos funciones: -- una función exclusiva de las coordenadas y otra función exclusiva del tiempo, como se muestra abajo:

$$\sigma^*(x,y,t) = \sigma(x,y)\, f(t)$$
$$\varepsilon^*(x,y,t) = \varepsilon(x,y)\, g(t) \qquad \text{Ec. 146}$$

Cuando se toman las ecuaciones 146 puede demostrarse que:

$$\theta_n = \theta_\sigma = \theta_\varepsilon \qquad \text{Ec. 147}$$
$$n_2 - n_1 = C(t)(\sigma_1 - \sigma_2) \qquad \text{Ec. 148}$$
$$n_2 - n_1 = c(t)(\varepsilon_1 - \varepsilon_2) \qquad \text{Ec. 149}$$

donde

$$C(t) = R[f(t)] + \frac{1}{G_0} S[g(t)] \qquad G_0 = \frac{\sigma_1 - \sigma_2}{2(\varepsilon_1 - \varepsilon_2)}$$
$$c(t) = G_0 R[f(t)] + S[g(t)]$$

Lo que esta serie de ecuaciones implica, es que las ecuaciones 97 y 99 pueden reescribirse en la siguiente forma:

$$\sigma_1 - \sigma_2 = N/h\, f_\sigma(t)$$
$$\varepsilon_1 - \varepsilon_2 = N/h\, f_\varepsilon(t) \qquad \text{Ec. 150}$$

donde f_σ y f_ε están escritas como funciones del tiempo en vez de como constantes.

Así los materiales fotoelásticos que exhiben propiedades viscoelásticas pueden ser empleados en el análisis de la distribución de los esfuerzos elásticos si f_σ ó f_ε son determinados como función del tiempo. El procedimiento normal es calibrar el material fotoelástico como función del tiempo y graficar f_σ vs. tiempo, como se ilustra en la fig. 52. Inicialmente el valor de f_σ decrece rapidamente con el tiempo pero después de una hora, los cambios en f_σ son muy pequeños en el período de -- tiempo requerido para fotografiar el modelo. En la práctica, un modelo fotoelástico es cargado por una hora aproximadamente, luego es fotografiado y el valor de f_σ correspondiente a la calibración de una hora es usado en el análisis.

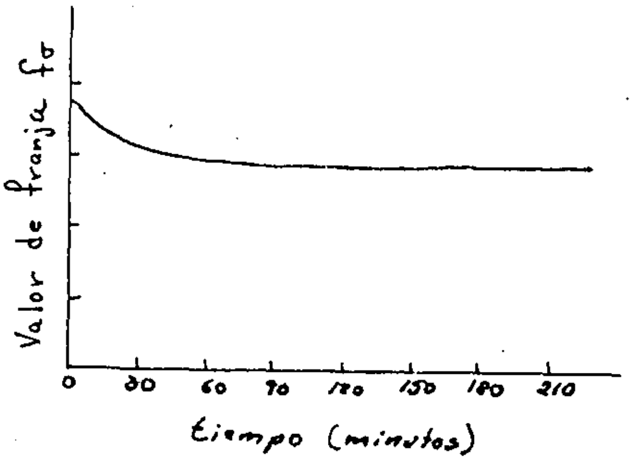


FIG 52

6. Módulo de elasticidad y esfuerzo último.

El módulo de elasticidad es importante en la selección de un material fotoelástico porque el módulo controla la distorsión del modelo debido a los esfuerzos aplicados. Si un modelo se distorsiona apreciablemente, la geometría de su frontera cambiará y la solución fotoelástica ya no será la adecuada. Errores de magnitud considerable son producidos por la distorsión del modelo, donde los cambios en la frontera influencían la determinación de la distribución de esfuerzos. El factor que puede usarse para juzgar la habilidad del material para resistir la distorsión es $1/f_\varepsilon$ o $E/f_\sigma(1+\nu)$. Los mejores materiales para resistir la distorsión, exhiben altos valores de $1/f_\varepsilon$.

El esfuerzo último de un material fotoelástico es importante en dos aspectos. Primero, un material con un alto valor del esfuerzo último puede ser cargado a un nivel más alto sin arriesgar la seguridad del modelo. Segundo, un material con un alto valor del esfuerzo último puede ser empleado para producir un patrón de franjas de mayor órden. El esfuerzo último o el límite lineal del esfuerzo se relaciona a la sensitividad del modelo. El índice de sensitividad S está dado por:

$$S = \sigma_L / f_\sigma \qquad \text{Ec. 151}$$

donde σ_L es el límite lineal o el esfuerzo último según cual sea el menor.

7. Sensitividad a la temperatura.

Si el valor de franja del material en término de los esfuerzos cambia marcadamente con la temperatura, pueden introducirse errores en el análisis fotoelástico por los cambios de temperatura, Una curva típica que muestra las características generales del cambio del valor de franja con la temperatura se representa en la fig. 53. Para la mayoría de los polímeros hay una región lineal de la curva donde f_σ decrece lentamente con la temperatura. Sin embargo a una temperatura suficientemente alta usualmente por encima de 150° F, el valor de f_σ empieza a caer rápidamente como función de la temperatura. En este rango de temperaturas, una fase del polímero se vuelve menos viscoso, y como consecuencia el valor de f_σ se influye apreciablemente. Para fotoelasticidad convencional en dos dimensiones a una temperatura en tre 70 y 80° F la pendiente de la curv [illegible] la región lineal es la característica importante. Afortunadamente la pendiente de la curva es usualmente modesta, de manera que el cambio producido en el valor de f_σ por las variaciones de temperatura del cuarto durante la prueba (usualmente menos de ± 5° F), pueden ser despreciados.

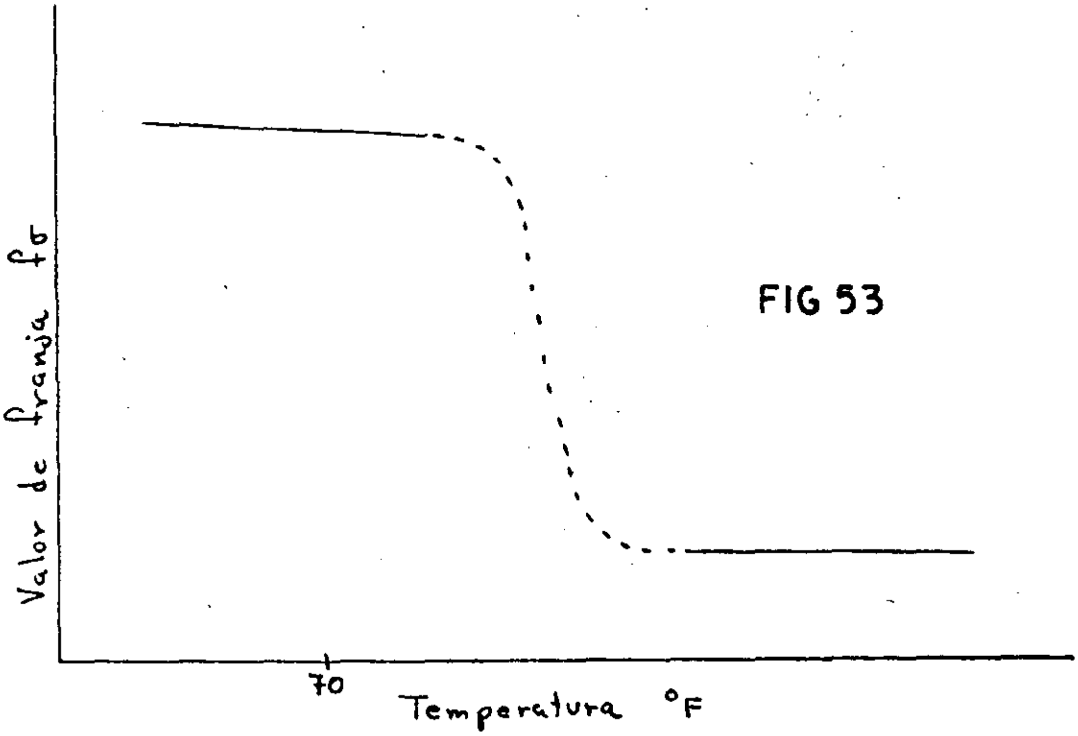


FIG 53

8. Efectos "time- edge".

Cuando un modelo fotoelástico es maquinado de una hoja de plástico y es examinado sin carga como función del tiempo, se nota que se induce un esfuerzo en la frontera que produce franjas paralelas a la frontera. La influencia de estos efectos en un análisis fotoelástico es muy importante. El patrón de franjas observado, es debido a la superposición de dos estados de esfuerzos, uno debido a la carga y otro debido a los efectos "time-edge". Como los esfuerzos debido a el efecto "time-edge" son predominantes en la frontera, los errores introducidos por estos efectos son demasiado grandes en la determinación de los extremadamente importantes esfuerzos de frontera.

Se ha establecido que los efectos "time- edge" son causados por la difusión del agua del aire en el plástico o viceversa.

Para muchos plásticos fotoelásticos, el proceso de difusión es tan lento a la temperatura ambiente que requiere muchos años para llegar al estado de equilibrio. Por esta razón un modelo recien maquinado estará usualmente en condiciones de aceptar agua del aire y los efectos "time- edge" comenzarán a revelarse. La rapidez a la cual estos efectos se presentan depende de la humedad relativa del aire y de la temperatura. Las pruebas realizadas a humedades relativas mayores del 80% son difíciles, ya que el efecto "time-edge" es muy alto en 2 o 3 horas. Para la mayoría de los materiales fotoelásticos deben seleccionarse días relativamente secos (humedad relativa menor del 40 o 50%) y fotografiar tan rápido como sea posible.

Las resinas epóxicas son diferentes a los otros materiales fotoelásticos, ya que su condición de saturación puede alcanzarse en 2 o 3 meses. Para estas resinas es posible maquinar un modelo bidimensional de una hoja de material que haya sido mantenida a una humedad constante por varios meses de manera que haya alcanzado su estado de equilibrio. Luego, si el modelo es probado bajo esta misma humedad constante el efecto "time-edge" no se presentará.

9. Maquinabilidad.

Los materiales fotoelásticos deben ser maquinables para fabricar los complejos modelos usados en el análisis fotoelástico.

La acción de una herramienta cortante sobre el plástico, produce frecuentemente calor así como fuerzas relativamente altas de corte. Como consecuencia pueden aparecer esfuerzos en las fronteras lo que hace imposible un buen análisis fotoelástico. Al maquinar modelos fotoelásticos debe tenerse cuidado de no producir grandes fuerzas o generar mucho calor. Esto puede hacerse empleando herramientas con recubrimientos de carbono, enfriamiento con aire y cortes pequeños con una velocidad de -corte mas o menos alta. Para modelos bidimensionales se recomienda emplear un --Router fig. 54

10. Esfuerzos residuales.

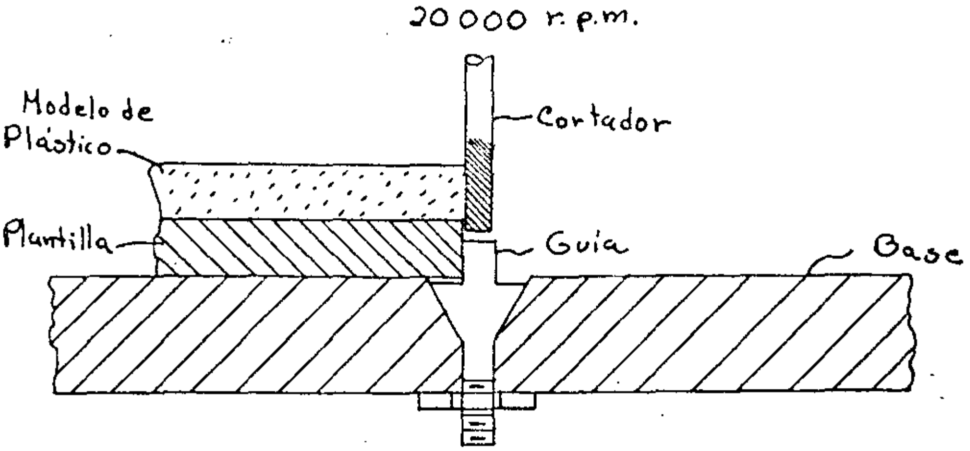
Los esfuerzos residuales se provocan a veces en el proceso de vaciado del material. Pueden observarse simplemente poniendo el material en el polaroscopio y viendo el número de franjas que aparece. La presencia de esfuerzos residuales en un modelo fotoelástico es muy nocivo ya que se superponen a los esfuerzos reales producidos al cargar el cuerpo, y esto introduce serios errores en el análisis.

En ciertos casos es posible reducir el nivel de los esfuerzos residuales templando la hoja de plástico en un baño de aceite caliente, sin embargo es imposible anularlos totalmente.

11. Costo del material

El costo de los materiales más comunmente empleados en fotoelasticidad van desde $2 hasta $20 dólares la libra siendo los más baratos el grupo de fenol formaldehidos y los más caros las resinas. Normalmente el costo del material para el modelo resenta un muy pequeño porcentaje del costo total de la investigación. Por esto el costo del material no debe ser obstáculo y debe seleccionarse el mejor material disponible. Muy pocos modelos bidimensionales requieren más de una libra de material.

FIG 54



d.2. Conclusiones de la selección del material.

Un sumario de las propiedades ópticas y mecánicas de cinco materiales fotoelásticos se presentan en la tabla 3. Un exámen de esta tabla muestra que la resina epóxica es la que más se acerca a las propiedades ideales de un material fotoelástico. El material Catalin 61-893 también es bueno, pero los efectos "time -- edge" y su escaces en grandes cantidades no lo hacen muy deseable.

El Castolite, libre de efectos "time-edge" lo hacen deseable para ciertas aplicaciones, y la altamente pulida superficie del CR-39 no puede ser ignorada en aplicaciones donde los efectos de Creep o la fluidez sean importantes. Finalmente, la goma de uretano puede ser ventajosa en fotoelasticidad dinámica y para la preparación de modelos de demostración.

Tabla 3

Material	Efectos "Time-Edge"	Fluidez	f_σ^{**} Psi-in	f_ε^{**} in	E Psi	ν	σ_L Psi	Maquinabilidad	$Q=\frac{E}{f_\sigma}$	$S=\frac{\sigma_L}{f_\sigma}$
Catalin 61-893	Malo	Bueno	86	1.91×10^{-4}	615 000	0.365	7 000	Bueno	7 160	81.5
Castolite	Excelente	Bueno	158	3.04×10^{-4}	705 000	0.355	7 400	Bueno	4 450	46.8
CR - 39	Regular	Malo	88	6.03×10^{-4}	250 000	0.42	3 000	Malo	2 840	34.2
Epoxy*	Bueno	Bueno	58	1.68×10^{-4}	475 000	0.38	- - - -	Bueno	8200	- - - -
Epoxy†	Bueno	Bueno	64	1.83×10^{-4}	475 000	0.36	8 000	Bueno	7 400	125
Uretano	Excelente	Bueno	0.9	3.24×10^{-3}	450	0.46	- - - - -	Malo	500	- - - -

* ERL-2774 con 50 partes por cien de anhidrido pentálico.

† ERL-2774 con 42 partes por cien de anhidrido pentálico

** Para luz verde ($\lambda = 5461$ Å)

d.3. Métodos de calibración.

Para determinar la distribución de esfuerzos acertadamente, se requiere una calibración cuidadosa del material, sobre todo del valor de franja del material f_σ. Aunque los valores de f_σ presentados en la tabla 3 son razonablemente ciertos, los valores de franja de los materiales varían con el proveedor, la temperatura, la edad, etc. Por esta razón es necesario calibrar cada hoja del material en el momento de la prueba. Aquí presento dos métodos de calibración igual de simples y exactos.

En cualquier técnica de calibración se debe seleccionar un cuerpo para el cual la distribución teórica de los esfuerzos sea conocida. Preferentemente el modelo debe ser fácil de maquinar y de cargar. El modelo de calibración es cargado en intervalos y el órden de franja y la carga anotados. De estos datos, el valor de franja del material puede ser determinado.

Considere primero un espécimen bajo tensión teniendo una anchura w y un espesor h, que es comunmente usado para calibraciones.

El esfuerzo axial inducido en el espécimen por la carga P puede expresarse como:

$$\sigma_1 = \frac{P}{wh} \qquad y \qquad \sigma_2 = 0 \qquad Ec.152$$

Sustituyendo la ecuación 152 en la ecuación 97 se tendrá:

$$\frac{P}{wh} = \frac{N f_\sigma}{h} \qquad ó \qquad f_\sigma = \frac{P}{wN} \qquad Ec.153$$

Esta ecuación muestra que el valor de f_σ obtenido del espécimen a tensión es totalmente independiente del espesor h. En la práctica, se grafica una curva de P como función de N (fig. 55), para 5 o 6 puntos diferentes. La pendiente de la línea recta dibujada a través de estos puntos es usada para el valor de P/N en la ecuación 153.

El disco circular cargado bajo compresión diametral es también empleado como modelo de calibración. El disco circular es algo más fácil de maquinar y de cargar que el espécimen a tensión, además, si se requiere pueden obtenerse varios puntos de calibración de una sola carga con este tipo de espécimen.

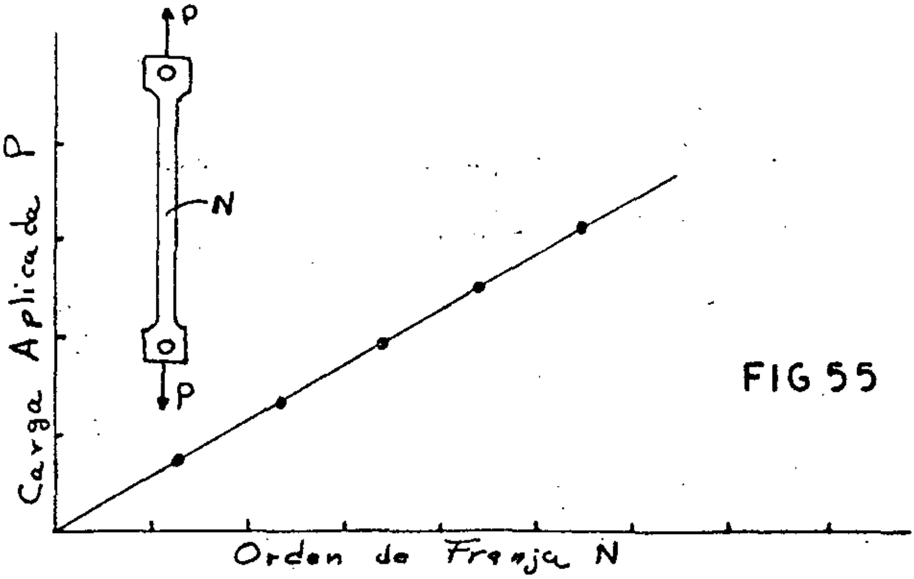


FIG 55

La distribución de esfuerzos a lo largo del diámetro horizontal (o sea y=0) está dada por:

$$\sigma_x = \sigma_1 = \frac{2P}{\pi h D}\left(\frac{D^2 - 4x^2}{D^2 + 4x^2}\right)^2$$

$$\sigma_y = \sigma_2 = -\frac{2P}{\pi h D}\left[\frac{4D^4}{(D^2+4x^2)^2} - 1\right] \qquad \text{Ec. 154}$$

$$\tau_{xy} = 0$$

donde D es el diámetro del disco.

x es la distancia a lo largo del diámetro horizontal medido desde el centro del disco.

h es el espesor del disco.

La diferencia entre los esfuerzos principales es:

$$\sigma_1 - \sigma_2 = \frac{8P}{\pi h D}\,\frac{D^4 - 4D^2x^2}{(D^2+4x^2)^2} = \frac{N f_\sigma}{h} \qquad \text{Ec. 155}$$

$$f_\sigma = \frac{8P}{\pi D N}\,\frac{D^4 - 4D^2x^2}{(D^2+4x^2)^2} \qquad \text{Ec. 156}$$

La ecuación 156 puede ser empleada para calibrar materiales fotoelásticos si una carga simple P es aplicada al disco. En este caso el órden de franja N es determinado como función de x a lo largo del diámetro horizontal. Estos valores de N y x son sustituidos en la ecuación 156 para dar varios valores de f_σ , que se promedian para reducir los errores en la lectura del orden de franja.

Sin embargo es más común usar el centro del disco como punto de calibración y varios valores de la carga se aplican al disco.

Para este caso la ecuación 156 se reduce a:

$$f_\sigma = \frac{8P}{\pi D N} \qquad \text{Ec. 15}$$

De nuevo se observa que el valor de f_σ es independiente del espesor del disco h.

El valor de P/N sustituido en esta ecuación se determina graficando varios puntos de P vs. N y estableciendo la pendiente de esta linea recta.

e) Lacas Birrefringentes.

e.1. Introducción.

En esta parte del trabajo, un área especial de la fotoelasticidad será discutida, la cual difiere, en cierto grado, de las aplicaciones más convencionales discutidas anteriormente. Este tópico especial son las lacas birrefringentes, en donde una delgada capa de plástico fotoelástico se coloca en la superficie de un espécimen metálico. Cuando el espécimen es cargado y deformado, la laca fotoelástica responde y el patrón de franjas resultante observado en un polaroscopio de luz reflejada, puede ser interpretada en términos de las deformaciones superficiales del espécimen metálico. Aunque este método fué introducido hace aproximadamente 30 años, ha sido en los últimos años que ha tenido gran publicidad, y que sus aplicaciones se han extendido.

e.2. Lacas Birrefringentes.

El método se basa en la union de una delgada hoja de plástico fotoelástico a la superficie de un espécimen metálico. La laca birrefringente actúa, en efecto, como un "strain gage", y permite la determinación de la diferencia de las deformaciones principales sobre una cierta superficie. La aplicación del método se ilustra en la figura 56, donde dos técnicas diferentes para observar el patrón de franjas en la laca están representadas.

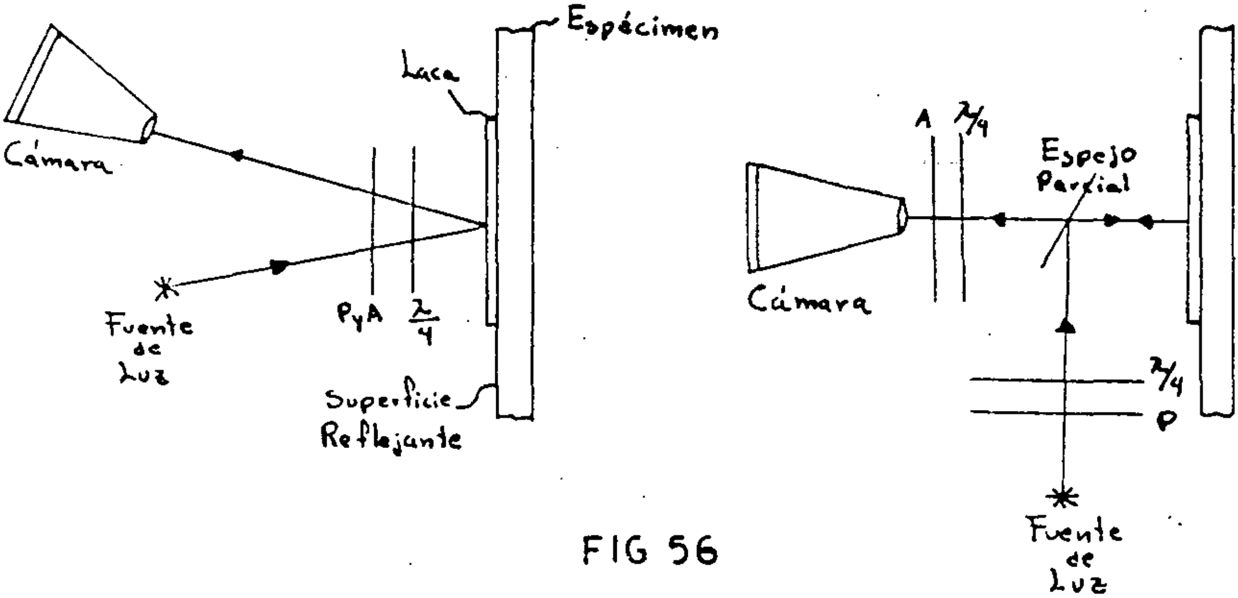


FIG 56

Cuando el espécimen se carga, los desplazamientos superficiales del espécimen se transmiten a la laca birrefringente si la union entre ellos es adecuada, conforme la laca responde a estos desplazamientos transmitidos, se inducen esfuerzos y una birrefringencia asociada. La observación de la laca mediante un polaroscopio de reflexión proporciona un patrón de franjas que se relaciona con las deformaciones superficiales del espécimen.

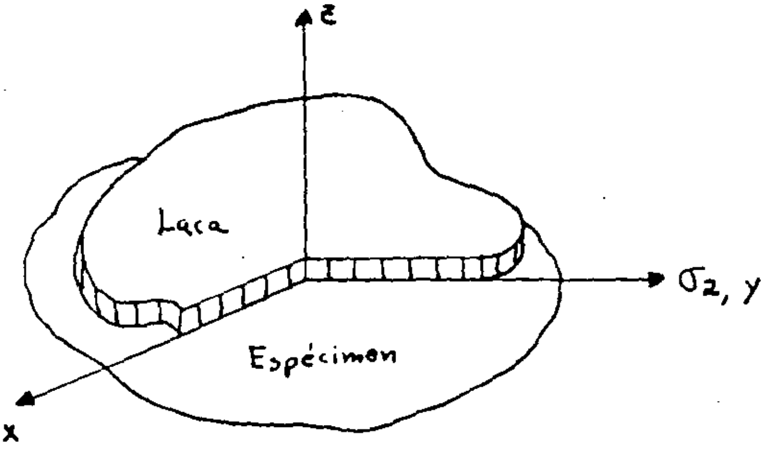
Si se asume que la laca es lo suficientemente delgada, entonces las deformaciones que ocurren en la superficie del espécimen se transmiten a la laca sin ninguna distorsión. Con esta suposición queda claro que;

$$\sigma_z = \sigma_z = 0 \qquad \text{en ambos, espécimen y laca.}$$

$$\varepsilon_1^c(x,y) = \varepsilon_1^s(x,y) \quad ; \quad \varepsilon_2^c(x,y) = \varepsilon_2^s(x,y) \qquad \text{Ec. 158}$$

donde el sistema de coordenadas es el definido en la figura 57.

FIG 57



De la ley de Hook:

$$\varepsilon_1^s = \frac{1}{E^s}(\sigma_1^s - \nu_s\sigma_2^s) \qquad \varepsilon_1^c = \frac{1}{E_c}(\sigma_1^c - \nu_c\sigma_2^c) \qquad \text{Ec. 159}$$

$$\varepsilon_2^s = \frac{1}{E_s}(\sigma_2^s - \nu_s\sigma_1^s) \qquad \varepsilon_2^c = \frac{1}{E_c}(\sigma_2^c - \nu_c\sigma_1^c)$$

Sustituyendo las ecuaciones 158 en éstas ecuaciones anteriores podemos obtener:

$$\frac{1}{E_s}(\sigma_1^s - \nu^s\sigma_2^s) = \frac{1}{E_c}(\sigma_1^c - \nu_c\sigma_2^c) \quad ; \quad \frac{1}{E_s}(\sigma_2^s - \nu_s\sigma_1^s) = \frac{1}{E_c}(\sigma_2^c - \nu_c\sigma_1^c) \qquad \text{Ec. 160}$$

Estas ecuaciones pueden resolverse para σ_1^c y σ_2^c como sigue:

$$\sigma_1^c = \frac{E_c}{E_s(1-\nu_c^2)}\left[(1-\nu_c\nu_s)\sigma_1^s + (\nu_c-\nu_s)\sigma_2^s\right] \qquad \text{Ec. 161}$$

$$\sigma_2^c = \frac{E_c}{E_s(1-\nu_c^2)}\left[(1-\nu_c\nu_s)\sigma_2^s + (\nu_c-\nu_s)\sigma_1^s\right]$$

que expresan los esfuerzos de la laca en términos de los esfuerzos en el espécimen. Restando las dos relaciones dadas en las ecuaciones 161, tenemos:

$$\sigma_1^c - \sigma_2^c = \frac{E_c}{E_s}\,\frac{1+\nu_s}{1+\nu_c}(\sigma_1^s - \sigma_2^s) \qquad \text{Ec. 162}$$

Una inspección de la ecuación 162 muestra que la diferencia de los esfuerzos principales actuantes en la laca ($\sigma_1^c - \sigma_2^c$) está relacionada linealmente a la diferencia de los esfuerzos principales actuantes en la superficie del espécimen ($\sigma_1^s - \sigma_2^s$). Las constantes elásticas E_c, E_s, ν_c, y ν_s, influencían la magnitud de ($\sigma_1^c - \sigma_2^c$). La respuesta fotoelástica de la laca se relaciona a ($\sigma_1^c - \sigma_2^c$) empleando la ecuación

$$\sigma_1^c - \sigma_2^c = \frac{N f_\sigma}{2h} = \frac{E_c}{E_s}\,\frac{1+\nu_s}{1+\nu_c}(\sigma_1^s - \sigma_2^s) \qquad \text{Ec. 163}$$

y la diferencia de los esfuerzos principales en el espécimen está dado por:

$$\sigma_1^s - \sigma_2^s = \frac{E_s}{E_c}\,\frac{1+\nu_c}{1+\nu_s}\,\frac{N f_\sigma}{2h} \qquad \text{Ec. 164}$$

Es claro que $\sigma_1^s - \sigma_2^s$ puede ser determinado por la observación del patrón de isocromáticas en la laca birrefringente si E_s, E_c, ν_s, ν_c, f_σ, y h, son conocidas. En algunos casos puede ser preferible trabajar en términos de las deformaciones en lugar de los esfuerzos. Esta transformación es muy simple ya que se ha asumido que $\varepsilon_1^c - \varepsilon_2^c = \varepsilon_1^s - \varepsilon_2^s$; luego:

$$\varepsilon_1^s - \varepsilon_2^s = \frac{N f_\varepsilon}{2h} = \frac{N}{2h}\left(\frac{1+\nu_c}{E_c}\right) f_\sigma \qquad Ec. 165a$$

Usando la ecuación 165, la laca birrefringente puede ser empleada como un "strain gage" para dar la diferencia de las deformaciones principales ($\varepsilon_1^s - \varepsilon_2^s$). La ecuación 165a se representa de una manera diferente por los fabricantes de la laca para permitir la conversión del orden de franja en la diferencia de las deformaciones -- principales sin importar la longitud de onda de la luz empleada para examinar la laca. La forma alternativa de la ecuación 165 a es:

$$\varepsilon_1^s - \varepsilon_2^s = \frac{N}{2hK} \qquad Ec. 165 b$$

donde

$$K = \lambda / f_\varepsilon$$

En esta expresión la longitud de onda de la luz se expresa en micro pulgadas.

e.3. <u>Sensitividad de las lacas birrefringentes</u>.

El término sensitividad de esfuerzos S_σ^c está dado por:

$$S_\sigma^c = \frac{N}{\sigma_1^s - \sigma_2^s} = \frac{2h}{f_\sigma} \frac{E_c}{E_s} \frac{1+\nu_s}{1-\nu_c} \qquad Ec. 166$$

y, similarmente, el término sensitividad de deformaciones S_ε^c está dado por:

$$S_\varepsilon^c = \frac{N}{\varepsilon_1^s - \varepsilon_2^s} = \frac{2h}{f_\varepsilon} = \frac{2h}{f_\sigma} \frac{E_c}{1+\nu_c} \qquad Ec. 167$$

Una inspección de las ecuaciones 166 y 167 desde el punto de vista de los parámetros de la laca, indica que h, f_σ, E_c, y ν_c, controla los dos factores de sensitividad. Queda claro que la sensitividad se incrementa linealmente con h. Sin embargo no siempre es posible incrementar h arbitrariamente hasta que se obtenga la suficiente sensitividad. Como veremos más adelante, el incrementar el espesor, produce un efecto de refuerzo, y en algunos casos distorsiona el estado de esfuerzos através del espesor de la laca. Los parámetros del material de la laca que influencían los factores de sensitividad pueden ser agrupados como:

$$Q^c = \frac{E_c}{1+\nu_c} \frac{1}{f_\sigma} = \frac{1}{f_\varepsilon} \qquad Ec. 168$$

donde Q^c se llama figura de mérito de la laca.

La figura de mérito de la laca Q^c puede emplearse efectivamente para medir la utilidad de los materiales polímeros disponibles para aplicaciones de lacas birrefringentes.

Los méritos relativos de varios materiales basados en el valor de Q^c se muestran en la tabla 4. Los epoxis y la Catalin 61-893 son más sensitivos que las lacas comerciales conocidas como Fotostress S. Es también interesante notar que el vidrio, es tan sensitivo como las lacas polímeras comercialmente disponibles hoy en día.

Tabla 4

Material	$f_\epsilon^\S$ in	$Q^c = 1/f_\epsilon$
Epoxy*	1.68×10^{-4}	5 960
Epoxy†	1.78×10^{-4}	5 610
Epoxy**	1.83×10^{-4}	5 480
Catalin 61-893	1.91×10^{-4}	5 250
Fotostress S	2.58×10^{-4}	3 980
Castolite	3.04×10^{-4}	3 300
CR-39	5.03×10^{-4}	1 980
Vidrio	1.9×10^{-4}	5 280

* ERL-2774, 50 partes por 100 de anhidrido pentálico.

† Ciba 6020, 50 partes por 100 de anhidrido pentálico.

** ERL-2774, HEX Pentálico Estandard

§ Para luz verde ($\lambda = 5461$ Å)

La aplicación de las lacas birrefringentes al problema general en el análisis experimental de esfuerzos, está comunmente limitado por la baja sensitividad inherente del método. Para ilustrar este punto, consideremos un ejemplo en el cual una laca, digamos Photostress S, se une a un espécimen de acero.

Las constantes elásticas pertinentes relacionadas a este problema son:

$E_s = 30 \times 10^6$ psi.

$\nu_s = 0.3$

$E_c = 0.420 \times 10^6$ psi.

$\nu_c = 0.36$

$f_\sigma = 78$ psi-in.

$h = 0.10$ in.

Sustituyendo estos valores en la ecuación 166 tendremos:

$$S_\sigma^c = \frac{N}{\sigma_1^s - \sigma_2^s} = 3.42 \times 10^{-5}$$

El resultado de este simple cálculo claramente indica que la respuesta de la laca birrefringente es limitada, y que la laca tiene suficiente sensitividad para una determinación de pequeños valores de $(\sigma_1^s - \sigma_2^s)$ en el campo completo.

Pueden emplearse métodos de compensación para ampliar la exactitud de la determinación del orden de franja N hasta aproximadamente 0.01, que permite la determinación de $\sigma_1^s - \sigma_2^s$ hasta aproximadamente ±300 psi 'o $\epsilon_1^s - \epsilon_2^s$ hasta aproximadamente $\pm 13\ \mu in/in$. Sin embargo, cuando tienen que emplearse tecnicas de compensación, el método no puede seguirse considerando como un método de campo completo ya que la compensación tiene una base de punto por punto.

Comunmente se utiliza luz blanca con las lacas birrefringentes para dar un patrón de isocromáticas de colores. Las franjas coloreadas pueden ser usadas para diferenciar ordenes de franja franccionarios y compensar hasta aproximadamente o.1 en una base de campo completo. Aunque la exactitud alcanzada no es tan grande como en el método convencional de compensación de punto por punto, usualmente pueden estimarse los esfuerzos en un 10% del valor real, con el método de campo completo.

La sensitividad de la laca puede ser duplicada empleando el método fotográfico de multiplicación de franjas.

e.4. Efectos reforzantes de las lacas birrefringentes.

Cuando un espécimen metálico se laquea con una laca birrefringente, y se sujeta a cargas, la laca soporta una porción de esa carga, y consecuentemente la deformación se reduce en una cierta cantidad. Es posible en muchos casos calcular los efectos reforzantes de la laca, y establecer factores de corrección que pueden ser empleados de una manera simple para tener en cuenta este refuerzo. En esta sección, el refuerzo debido a la laca será calculado para esfuerzos planos y problemas de flexión.

En el problema de esfuerzos planos, un elemento del espécimen laqueado puede aislarse como se muestra en la figura 58.

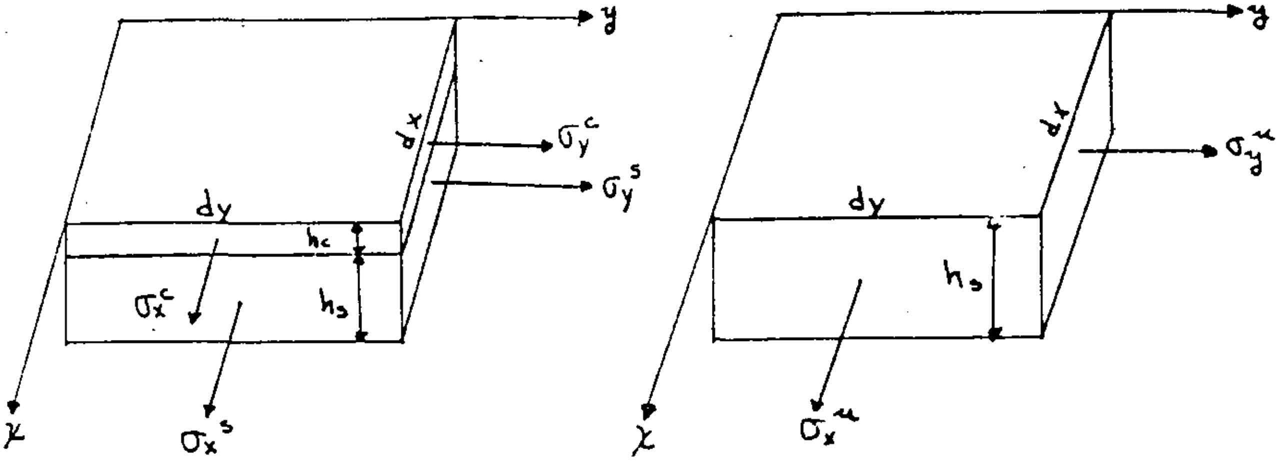


FIG 58

Un elemento similar del espécimen sin laquear también puede aislarse, y la fuerza actuante en la dirección x de ambos elementos puede igualarse para dar:

$$h_s\,dy\,\sigma_x^u = h_s\,dy\,\sigma_x^s + h_c\,dy\,\sigma_x^c$$

$$\sigma_x^u = \sigma_x^s + \frac{h_c}{h_s}\sigma_x^c \qquad \text{Ec 169 a}$$

La expresión correspondiente para las fuerzas en la dirección y es:

$$\sigma_y^u = \sigma_y^s + \frac{h_c}{h_s}\sigma_y^c \qquad \text{Ec. 169 b}$$

Si se asume nuevamente que:

$$\varepsilon_x^c = \varepsilon_x^s \qquad \sigma_z^c = \sigma_z^s = 0$$
$$\varepsilon_y^c = \varepsilon_y^s$$

y como los dos elementos están bajo [illegible] estado de esfuerzos plano:

$$\sigma_x = \frac{E}{1-\nu^2}\left(\varepsilon_x + \nu\varepsilon_y\right) \qquad \sigma_y = \frac{E}{1-\nu^2}\left(\varepsilon_y + \nu\varepsilon_x\right) \qquad \text{Ec. 170}$$

Sustituyendo las ecuaciones 170 en 169, tenemos:

$$\frac{E_s}{1-\nu_s^2}\left(\varepsilon_x^u + \nu_s\varepsilon_y^u\right) = \frac{E_s}{1-\nu_s^2}\left(\varepsilon_x^s + \nu^s\varepsilon_y^s\right) + \frac{h^c}{h_s}\frac{E_c}{1-\nu_c^2}\left(\varepsilon_x^c + \nu_c\varepsilon_y^c\right) \qquad (a)$$

$$\frac{E_s}{1-\nu_s^2}\left(\varepsilon_y^u + \nu_s\varepsilon_x^u\right) = \frac{E_s}{1-\nu_s^2}\left(\varepsilon_y^s + \nu_s\varepsilon_x^s\right) + \frac{h_c}{h_s}\frac{E_c}{1-\nu_c^2}\left(\varepsilon_y^c + \nu_c\varepsilon_x^c\right) \qquad (b)$$

Restando la ecuación b de la ecuación a y simplificando:

$$\varepsilon_x^u - \varepsilon_y^u = \left(1 + \frac{h_c}{h_s}\frac{E_c}{E_s}\frac{1+\nu_s}{1+\nu_c}\right)\left(\varepsilon_x^c - \varepsilon_y^c\right) \qquad \text{Ec. 171}$$

Esta ecuación puede escribirse como:

$$\varepsilon_x^u - \varepsilon_y^u = F_{cR}\left(\varepsilon_x^c - \varepsilon_y^c\right)$$

donde

$$F_{cR} = \left(1 + \frac{h_c}{h_s}\frac{E_c}{E_s}\frac{1+\nu_s}{1+\nu_c}\right) \qquad \text{Ec. 172}$$

El término F_{cR} representa un factor de corrección que debe ser aplicado al valor de $(\varepsilon_x^c - \varepsilon_y^c)$ obtenido de la laca birrefringente para establecer el valor real de la diferencia de deformaciones principales en el especimen sin laquear. El factor de corrección F_{cR} toma en cuenta el efecto de refuerzo debido a la presencia de la laca birrefringente.

Una gráfica que muestra F_{cR} como función de h_c/h_s es presentada para diferentes materiales del espécimen en la figura 59. Estos resultados están basados en un valor de $E_c = 420,000$ psi y $\nu_c = 0.36$, que son representativos del Photostress S, una de las lacas birrefringentes disponibles en el comercio. Una inspección de la figura 59 muestra que el factor de corrección es pequeño para valores de h_c/h_s, menores de 1, si el material del espécimen es metál. Si, sin embargo, el material del espécimen es madera, concreto, o plástico, entonces el factor de corrección es apreciablemente mayor.

Un segundo ejemplo que ilustra la influencia reforzante de la laca en el estado de esfuerzos y deformaciones en el espécimen, es el de una placa sujeta a un momento flexionante M. Considerese un elemento de la región central de ésta placa, como se indica en la figura 60. Si se asume que la distribución de esfuerzos el lineal y que es transmitido através de la intercara espécimen-laca, entonces, de la teoría elemental de las placas, la deformación en el espécimen y la laca pueden expresarse como una función de z:

$$\varepsilon_x^s = \frac{z}{\rho} \qquad \text{Para } (h_s - A) \le z \le A$$

$$\varepsilon_x^c = \frac{z}{\rho} \qquad \text{Para } A \le z \le (A + h_c) \qquad \text{Ec. 17}$$

$$\varepsilon_y^s = \varepsilon_y^c = 0 \qquad \text{Para todo } z$$

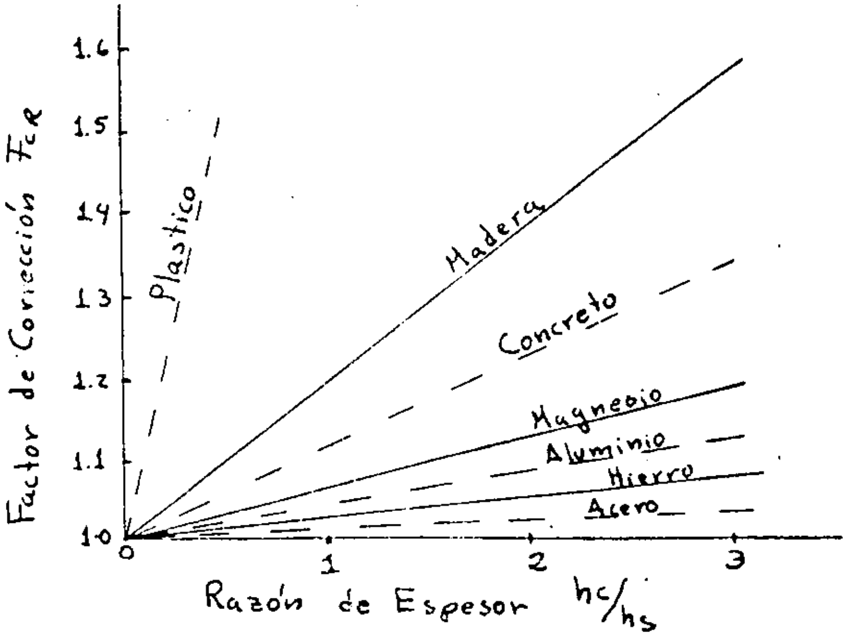

Factor de Corrección F_{cR}
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
1
2
3
Razón de Espesor h_c/h_s
Plastico
Madera
Concreto
Magnesio
Aluminio
Hierro
Acero

FIG 59

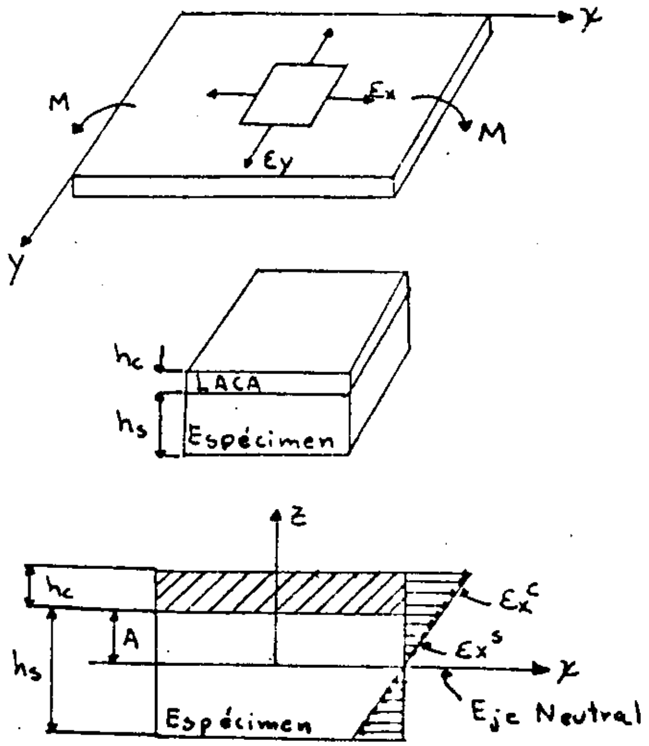

x
y
M
M
ε_x
ε_y
h_c
LACA
h_s
Espécimen
z
h_c
A
h_s
Espécimen
ε_x^c
ε_x^s
x
Eje Neutral

FIG 60

donde z es medido desde el eje neutro

A es la distancia desde el eje neutral a la intercara.

ρ es el radio de curvatura.

Como se asume que σ_3 desaparece para todos los valores de z, las ecuaciones 170 pueden emplearse con las ecuaciones 173 para expresar el esfuerzo σ_x en término de las deformaciones:

$$\sigma_x^s = \frac{E_s}{1-\nu_s^2}\,\frac{z}{\rho} \qquad \text{Para } (h_s - A) \leq z \leq A$$

$$\sigma_x^c = \frac{E_c}{1-\nu_c^2}\,\frac{z}{\rho} \qquad \text{Para } A \leq z \leq (A + h_c) \qquad \text{Ec. 174}$$

La posición del eje neutral, descrito por A, puede obtenerse considerando el equilibrio de la placa en la dirección x, como se muestra a continuación:

$$\int_{A-h_s}^{A} \sigma_x^s \, dz + \int_{A}^{A+h_c} \sigma_x^c \, dz = 0 \qquad \text{Ec. 175}$$

Sustituyendo la ecuación 174 en 175, integrando, y resolviendo para A tenemos:

$$A = \frac{h_s}{2}\,\frac{1 - BC^2}{1 + BC} \qquad \text{Ec. 176}$$

donde

$$B = \frac{E_c}{E_s}\,\frac{1-\nu_s^2}{1-\nu_c^2} \quad ; \quad C = {}^{h_c}/_{h_s}$$

El radio de curvatura ρ puede ser calculado considerando el equilibrio de los momentos donde

$$M = \int_{A-h_s}^{A} \sigma_x^s z \, dz + \int_{A}^{A+h_c} \sigma_x^c z \, dz \qquad \text{Ec. 177}$$

Sustituyendo la ecuación 174 en 177, integrando, y usando la ecuación 176 para simplificar los resultados, puede mostrarse que:

$$\frac{1}{\rho} = \frac{12\,M}{H}\,\frac{1-\nu_s^2}{E_s\,h_s^3}$$

donde

$$H = \left[4(1 + BC^3) - \frac{3(1-BC^2)^2}{1+BC} \right] \qquad \text{Ec. 178}$$

Si la laca se examina en un polaroscopio de reflexión, el patrón de franjas es proporcional al promedio de la diferenci de deformaciones $(\varepsilon_x^c - \varepsilon_y^c)$ através del espesor de la laca. Este promedio puede calcularse de las ecuaciones 173, 176, y 177 como sigue:

$$(\varepsilon_x^c - \varepsilon_y^c)_{av.} = \frac{12\,M}{H}\,\frac{1-\nu_s^2}{E_s\,h_s^3}\,\frac{1}{h_c}\int_{A}^{A+h_c} z\,dz$$

que da:

$$(\varepsilon_x^c - \varepsilon_y^c)_{av.} = \frac{6\,M}{H}\,\frac{1-\nu_s^2}{E_s\,h_s^2}\,\frac{1+C}{1+BC} \qquad \text{Ec. 179}$$

Como la diferencia real de las deformaciones en la superficie de una placa no laqueada es:

$$(\varepsilon_x^s - \varepsilon_y^s) = 6\,M\,\frac{1-\nu_s^2}{E_s\,h_s^2} \qquad \text{Ec. 180}$$

queda claro, mediante una comparación de las ecuaciones 179 y 180, que la laca no indica la diferencia real de las deformaciones superficiales. Es posible, sin embargo, corregir el error introduciendo un factor de corrección de flexión. Luego

$$(\varepsilon_x^s - \varepsilon_y^s)_{real} = F_{c\sigma}\,(\varepsilon_x^c - \varepsilon_y^c)_{av.}$$

donde el factor de corrección de flexión $F_{c\sigma}$ es:

$$F_{c\sigma} = \frac{H(1+BC)}{1+C} = \frac{1+BC}{1+C}\left[4(1+BC^3) - \frac{3(1-BC^2)^2}{1+BC}\right] \qquad Ec.\ 181$$

El factor de corrección de flexión, que es función de las razones B y C, se muestra en forma gráfica en la figura 61. Una inspección de estas curvas indica que pueden cometerse grandes errores si los resultados fotoelásticos no son correctamente corregidos. Es interesante notar que el valor de $F_{c\sigma}$ primero decrece con h_c/h_s y luego crece con posteriores incrementos de h_c/h_s. Primero, conforme el valor de -- h_c/h_s se incrementa, el plano medio de la laca se separa de la intercara, y la deformación en este plano medio(que es la deformación promedio) se incrementa relativamente a la deformación real en la superficie del espécimen no laqueado. Después, conforme la laca se vuelve más gruesa (esto es h_c/h_s se incrementa), el efecto reforzante baja la deformación promedio en la laca. Para un espécimen de aluminio los dos factores que producen el error se cancelan cuando $h_c/h_s = 1.6$; luego el valor de $F_{c\sigma}$ es 1.

e.5. <u>Efectos del espesor de las lacas birrefringentes</u>.

En la discusión de las lacas birrefringentes presentada anteriormente se ha asumido que las deformaciones se transmiten del espécimen a la laca de una manera ideal. Desafortunadamente, esta transmisión ideal de las deformaciones entre el espécimen y la laca, no siempre se verifica, y la distribución de deformaciones en la laca está influenciada por el espesor de la laca. La distorsión de la distribución de las deformaciones se conoce como el efecto de espesor. El hecho de que la distribución de deformaciones en la laca se ditorsione complica el problema de interpretación del patrón de franjas obtenido de la laca en términos de las deformaciones superficiales. La magnitud del error introducido debido al efecto de espesor, depende de cada problema en particular. A veces el error será pequeño, pero en ocasiones puede ser muy grande.

El señor Duffy y sus asociados (J. Duffy and C. Mylonas, An Experimental Study of the Effects of the Thickness of Birefringent Coatings, in "Photoelasticity"), han aproximado el problema del efecto de espesor en lacas birrefringentes para variaciones bidimensionales en las deformaciones superficiales, empleando la teoría de la elasticidad. La laca se considera como el cuerpo, con desplazamientos superficiales preescritos en la intercara (esto es, z = 0, como se define en la figura 57) como:

$$u(x,y,0) = U\ \mathrm{Sen}\ mx\ \mathrm{Cos}\ ny$$
$$v(x,y,0) = V\ \mathrm{Cos}\ px\ \mathrm{Sen}\ qy$$
$$w(x,y,0) = W\ \mathrm{Cos}\ rx\ \mathrm{Cos}\ sy$$

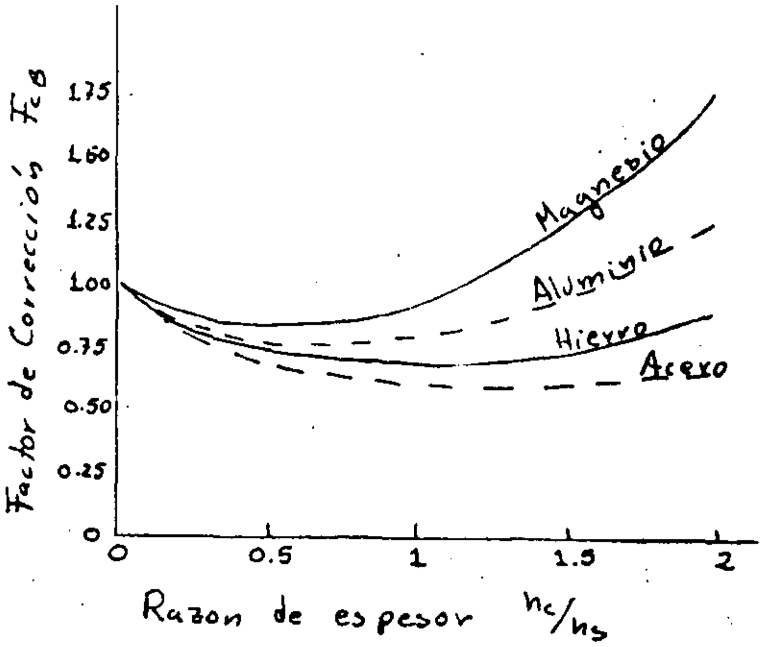

Factor de Corrección $F_{c\theta}$
1.75
1.60
1.25
1.00
0.75
0.50
0.25
0
0
0.5
1
1.5
2
Magnesio
Aluminio
Hierro
Acero
Razon de espesor h_c/h_s

FIG 61

donde U, V, W, y m, n, p, q, r, y s constantes arbitrarias usadas para describir el campo de desplazamientos en la intercara. La solución de este problema elástico muestra que el promedio de la diferencia de las deformaciones através del espesor de la laca y a lo largo del eje x puede representarse como:

$$(\varepsilon_x{}^c - \varepsilon_y{}^c)_{av.} = F(mh, nh, \nu)\,\varepsilon_x(x,0,0) - F(qh, ph, \nu)\,\varepsilon_y(x,0,0) + \frac{r^2 - s^2}{\zeta^2}\,G(\zeta h, \nu)\,\frac{w(x,0,0)}{h} \qquad \text{Ec. } 182$$

donde

$$G(\zeta h, \nu) = \frac{4\nu(1-\nu)(1-\operatorname{Cosh}\zeta h) - 2\nu\zeta h \operatorname{Senh}\zeta h + (\zeta h)^2 + \operatorname{Sinh}^2 \zeta h}{(\zeta h)^2 + (3-4\nu)\operatorname{Cosh}^2 \zeta h + (1-2\nu)^2}$$

$$F(mh, nh, \nu) = \frac{2n^2}{\xi^2}\,\frac{\tanh \xi h}{\xi h} + \frac{m^2 - n^2}{\xi^2}\left\{\frac{2\nu\xi h \cosh\xi h - 2\nu(1-2\nu)\sinh\xi h + (1-2\nu)(2\xi h + \sinh 2\xi h)}{\xi h\left[(\xi h)^2 + (3-4\nu)\cosh^2\xi h + (1-2\nu)^2\right]}\right\}$$

$$\xi = (m^2 + n^2)^{1/2} \quad ; \quad \zeta = (r^2 + s^2)^{1/2}$$

En la ecuación 182 se necesitan tres factores de corrección para ajustar el promedio de la diferencia de deformaciones a través del espesor de la laca, a aquellos que ocurren en la superficie del espécimen que esta siendo investigada. Los factores de corrección F(mh, nh, ν) y F(qh, ph, ν) se usan con los dos componentes de las deformaciones de la intercara.

Los factores de corrección pueden ser calculados para valores arbitrarios de m, n, p, q, r, y s. Un ejemplo típico de la magnitud del factor de corrección F (ξ h, 0, ν) se muestra en la figura 62 a. Una inspección de esta figura muestra que el factor de corrección varía entre 0 y 0.93 aproximadamente conforme el cociente de la longitud de onda del gradiente sinusoidal de la deformación al espesor de la laca varía de 0 a 30. Este ejemplo particular corresponde a un caso en el cual la deformación varía en la dirección x pero no en la dirección y (esto es n = 0). Para evitar los errores asociados con la distorsión de la distribución de las deformaciones através del espesor de la laca, se requieren espesores de laca muy delgados (h < π/20m).

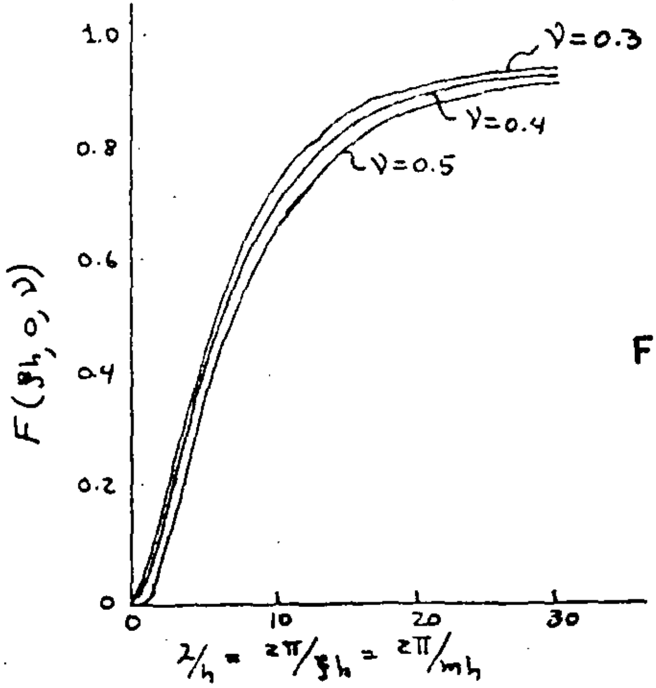


FIG 62a

TEORIA DE LAS BANDAS EXTENSOMETRICAS

1:1 Generalidades

Con el enunciamiento por Robert Hooke en 1.678 de la ley relaciona las tensiones y deformaciones en materiales sometidos a solicitaciones mecánicas y el posterior descubrimiento en 1.856 de Lord Kelvin referente a las variaciones que en su resistencia sufre un conductor eléctrico cuando se modifica su geometría, se establecieron los principios fundamentales de la extensometría eléctrica; si bién su nacimiento ha sido muy posterior, pudiendo decirse que fué a partir de la II guerra Mundial, cuando su aplicación empezó a vulgarizarse.

En su forma más elemental, una banda extensométrica (Strain-gage; jauge électrique d'extensometrie) está constituída (fig. 1) por un hilo metálico muy fino en forma de "parrilla" montado sobre un soporte, de tal manera, que la mayor parte de su longitud sea paralela a una dirección fija. Si deseamos conocer las deformaciones de una estructura según una dirección, pegaremos el extensímetro con sus hilos paralelos a dicha dirección y al deformarse aquella, producirá variaciones en la geometría del hilo del extensímetro que originarán una variación de su resistencia; por lo tanto disponiendo de instrumentos capaces de medir variaciones pequeñas de la resistencia original del extensímetro, podemos conocer las deformaciones mecánicas de la estructura en la que se pegó.

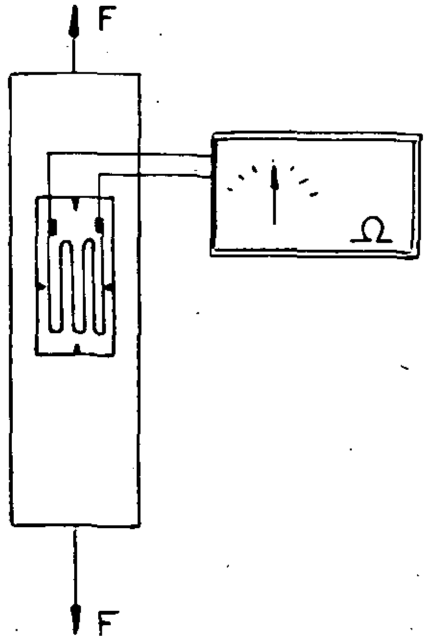


fig 1

La Resistencia de materiales nos enseña las leyes que ligan deformaciones y tensiones, siendo la extensometría la técnica que permitirá conocer el estado de tensiones de un cuerpo a partir de la medida del estado de deformaciones, sin necesidad de recurrir a ensayos destructivos, pudiendose efectuar un número ilimitado de mediciones, pués si bién el extensímetro una vez pegado es irrecuperable, sus cualidades con el tiempo perduran, dentro de los límites de utilización.

Por tanto, una banda extensométrica actua como elemento transductor, transformando la variación de una magnitud mecánica en la de una eléctrica, facultad ésta que se aprovecha para fabricar captadores sensibles a ciertos parámetros mecánicos, pudiendo así evitarse el inconveniente de su no recuperación.

Actualmente el desarrollo de las técnicas extensométricas, ha alcanzado tal grado de perfección, que normalmente los problemas de medida de deformaciones y tensiones que puedan presentarse en ingeniería tienen solución, determinándose con exactitud la evaluación de fenómenos cuya influencia en la realización de proyectos es primordial, con la ambiciosa meta de fabricación con coeficientes de seguridad próximos a la unidad, sin perdida de garantías funcionales. Reducción de costos de fabricación, control de calidad, homologación de marcas, investigación, estudios y ensayos, mejores de fabricados, nuevos diseños, etc, etc, son logros, que incluso a corto plazo, se consiguen con equipos sencillos elementales y económicos,

1.2 PRINCIPIOS TEORICOS DEL EXTENSIMETRO OHMICO

Consideremos un extensímetro formado por un solo hilo conductor unido a una estructura, de tal forma, que las deformaciones que pueden producirse sean idénticas en ambos (fig 2).

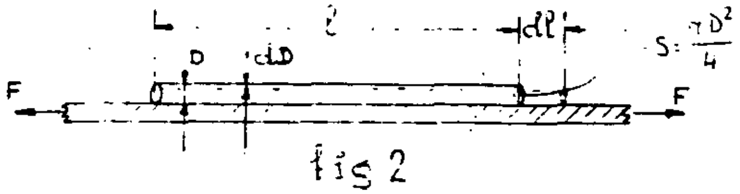


fig 2

La resistencia R del hilo tiene por valor:

$$R = \rho \frac{\ell}{S} \qquad [1]$$

(ρ = resistividad)

Si el hilo sufre una deformación (alargamiento), la longitud l aumenta, la sección S disminuye y la resistividad varía dando lugar estos cambios a una variación del valor de R que podemos obtener diferenciando (1) y después deducir la relación entre la deformación elástica del hilo y la variación relativa o unitaria de resistencia, en efecto:

$$dR = \frac{S(\ell\, d\rho + \rho\, d\ell) - \rho\, \ell\, dS}{S^2} \qquad [2]$$

Dividiendo [2] por [1]

$$\frac{dR}{R} = \frac{d\ell}{\ell} + \frac{d\rho}{\rho} - \frac{dS}{S}$$

Si el hilo es de forma cilíndrica:

$S = \frac{\pi D^2}{4}$; $dS = \frac{\pi}{2} D\, dD$ y $\frac{dS}{S} = \frac{2dD}{D}$, sustituyendo en [3]

$$\frac{dR}{R} = \frac{dl}{l} + \frac{d\rho}{\rho} - 2\frac{dD}{D} \qquad [4]$$

La (4) podemos escribirla como:

$$\frac{\frac{dR}{R}}{\frac{dl}{l}} = 1 + \frac{\frac{d\rho}{\rho}}{\frac{dl}{l}} - 2\,\frac{\frac{dD}{D}}{\frac{dl}{l}}$$

pero el último término del segundo miembro, es la expresión del coeficiente de Poisson $\frac{dD}{D} : \frac{dl}{l} = -\mu$, luego sustituyendo tendemos el valor de la relación entre la variación de resistencia y la deformación unitaria.

$$\frac{\frac{dR}{R}}{\frac{dl}{l}} = 1 + \frac{\frac{d\rho}{\rho}}{\frac{dl}{l}} + 2\mu \qquad [5]$$

al segundo miembro de (5) se llama factor de banda o de sensibilidad K;

$$K = 1 + 2\mu + \frac{\frac{d\rho}{\rho}}{\frac{dl}{l}} \qquad [6]$$

Bridgaman enunció que la variación relativa de resistividad de un conductor es proporcional a la variación relativa de volúmen de dicho - conductor

$$\frac{d\rho}{\rho} = C\,\frac{dV}{V} \quad (C = \text{Constante de Bridgman}) \qquad [7]$$

Si $V = l.S$ y sustituyendo [7] en [5]

$$\frac{dR}{R} = \left[(1+2\mu) + C\,(1-2\mu)\right]\frac{dl}{l} \qquad [8]$$

Hasta aquí, hemos considerado la sección del hilo circular, pero en las modernos bandas impresas la sección es rectangular y la variación de resistencia $\frac{dR}{R}$, función de las deformaciones que experimenta la banda en las tres dimensiones se calculará así.

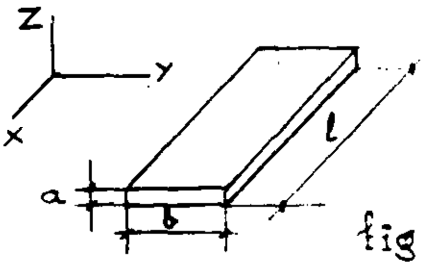


fig2a

Siendo [redacted] (fig. 2a)

$$R = \rho\,\frac{l}{a\,b} \qquad [9]$$

y las deformaciones según los ejes X,Y,Z son:

$$\varepsilon_x = \frac{dl}{l} \quad ; \quad \varepsilon_y = \frac{db}{b} \quad ; \quad \varepsilon_z = \frac{da}{a} = -\mu \frac{dl}{l} - \mu \frac{db}{b} = -\mu(\varepsilon_x + \varepsilon_y)$$

diferenciando logarítmicamente la $^{(1)}$ tendremos

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{da}{a} - \frac{db}{b} = C\frac{dV}{V} + \frac{dl}{l} - \frac{da}{a} - \frac{db}{b} =$$

$$= C\left(\frac{dl}{l} + \frac{da}{a} + \frac{db}{b}\right) + \frac{dl}{l} - \frac{da}{a} - \frac{db}{b} =$$

$$= C(\varepsilon_x - \mu\varepsilon_x - \mu\varepsilon_y + \varepsilon_y) + \varepsilon_x + \mu\varepsilon_x + \mu\varepsilon_y - \varepsilon_y =$$

$$= \varepsilon_x\left[C(1-\mu) + 1 + \mu\right] + \varepsilon_y(C-1)(1-\mu)$$

y llamando

$$K_1 = C(1-\mu) + 1 + \mu$$

$$K_2 = (C-1)(1-\mu)$$

queda

$$\frac{dR}{R} = \varepsilon_x K_1 + \varepsilon_y K_2 \qquad [10]$$

La (10) nos indica que una banda extensométrica es sensible a la deformación longitudinal según la dirección de los hilos activos, pero también a la deformación transversal, siendo esto último un inconveniente que puede introducir errores. Si el valor de la constante de Bridgman se consigue que valga la unidad, $K_2=0$, pero prácticamente es muy dificil de lograr, por lo que se tiende a buscar un compromiso que haga K_2 lo menor posible y por lo menos que permita conocer el error que su presencia introduce en la medida. Veamos como se logra.

La (10) puede escribirse:

$$\frac{dR}{R} = K_1(\varepsilon_x + K_t\varepsilon_y) \qquad [10a]$$

siendo $K_t = \frac{K_2}{K_1}$ = factor de sensibilidad transversal del extensímetro. Sustituyendo:

$$\frac{dR}{R} = K_1(\varepsilon_x - K_t\mu\varepsilon_x) = K_1(1-\mu K_t)\varepsilon_x = K\varepsilon_x \qquad [11]$$

El factor de banda dado por el fabricante es $K = K_1(1-\mu K_t)$ para $\mu = 0{,}285$

La expresión:

$$e = \frac{K_t\left(\frac{\varepsilon_y}{\varepsilon_x} + \mu\right)}{1-\mu K_t} \cdot 100 \qquad [11a]$$

nos dá el error en % que sobre la medida de la deformación según ε_x introduce el factor de sensibilidad transversal. Vemos que en el caso en que la dirección de ε_x coincide con la dirección de tensiones unidireccionales (tracción o compresión simple) el error es cero, pues se cumple que $\varepsilon_y = -\mu \varepsilon_x$, (fig 2b).

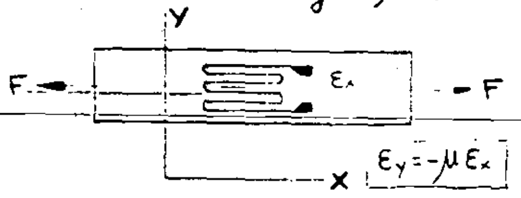


fig 2b

Según la fig. 2c vamos a medir la deformación lateral correspondiente a un estado unidireccional de tensiones, aquí por el giro dado al extensímetro, se cumple que :

$$\varepsilon_x = -\mu \varepsilon_y \quad ; \quad \frac{\varepsilon_y}{\varepsilon_x} = -\frac{1}{\mu}$$

Si consideramos $\mu = 0{,}3$ y $k_t = 3\%$ sustituyendo en (11a), el error vale:

$$e = \frac{0{,}03\left(-\frac{1}{0{,}3} + 0{,}3\right)}{1 + 0{,}3 \cdot 0{,}03} \times 100 = -9\%$$

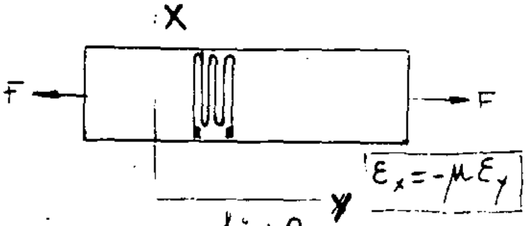


fig 2c

El error del -9% no puede despreciarse y aún cuando en el ejemplo se ha buscado un caso muy extremo, habrá que evaluar siempre la magnitud del error y considerar si debe o nó despreciarse.

El problema en el caso que se conozca la dirección principal de deformaciones (fig. 2b) no tiene importancia; pero como se verá posteriormente en el caso de rosetas de dos o tres direcciones el error por efecto de la sensibilidad lateral puede tener influencia, pués se estará siempre entre las dos posturas extremas presentadas en las fig. 2b y 2c.

1.3. OBJETO DE LAS MEDIDAS EXTENSOMETRICAS: Unidades

Los materiales empleados en la fabricación de máquinas o cualquier elemento sometido a solicitaciones externas, sufren en su estructura interna unas tensiones que deben equilibrar las cargas que soportan para que no aparezca la rotura, sobredimensionandose siempre los diseños para obtener un coeficiente de seguridad adecuado. Evidentemente el máximo conocimiento del estado de tensiones ayudará a mejorar el diseño y a reducir el coeficiente de seguridad, pero la medida directa de tensiones no siempre es posible.

Demostraremos en este capítulo, que si conocemos el estado de deformaciones en un punto, podremos calcular el estado de tensiones del mismo y determinar el valor de tensiones críticas (tensiones normales máximas o combinación, en una determinada dirección de tensiones normales y cortantes, que puedan representar un fallo).

El estado de deformaciones se determinará a partir de las medidas, que en una, dos o tres direcciones, que se efectuen con extensímetros.

Salvo casos muy especiales, la aplicación de las bandas extensométricas será siempre en la superficie de los elementos de ensayo, por lo que solo estudiaremos el estado plano o binaxial de deformaciones y tensiones en un punto.

El concepto de deformaciones es análogo al de alargamiento unitario y lo representaremos por ε midiendose en microdeformaciones $(\mu\delta)$.

$$\varepsilon \cdot 10^{6} = \frac{d\ell}{\ell} \cdot 10^{6} = \mu\delta$$ ...microdeformación (adimensional)

Diversa literatura suele expresar las deformaciones en micromilimetros/milimetro o micropulgada/pulgada, creando a veces alguna confusión, en realidad es decir lo mismo de una o de otra manera, ya que se trata de la misma unidad por lo que nosotros recomendamos referirse siempre a $\mu\delta$.

El módulo de elasticidad E y las tensiones se expresarán en daN/cm^2, aunque en algunas tablas pueden aparecer estos valores en Kp/cm^2 o Kp/mm^2.

1.4 ESTADO BIAXIAL DE DEFORMACIONES

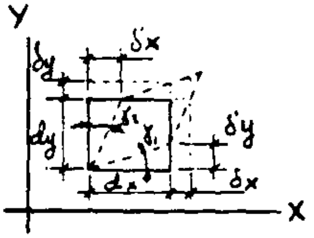


fig3

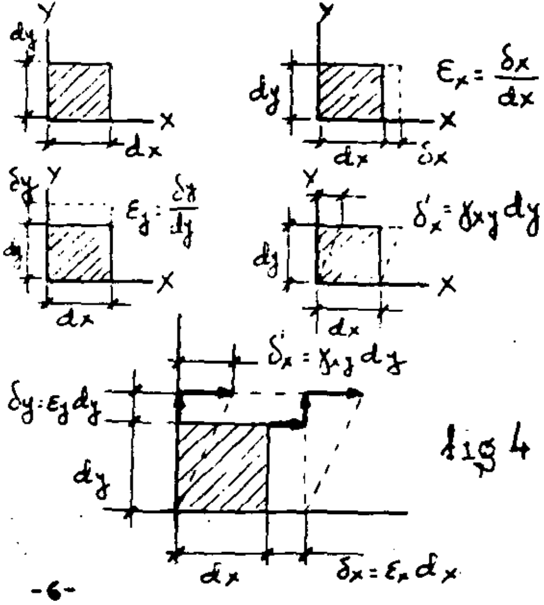
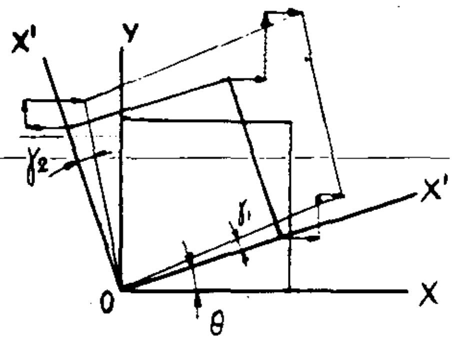


fig 4

El rectángulo elemental de la fig. 3 de lados dx y dy tiene como posibles las deformaciones lineales según los ejes X e Y ya definidas y de valor:

$$\varepsilon_x = \frac{\delta x}{dx} \qquad \varepsilon_y = \frac{\delta y}{dy}$$

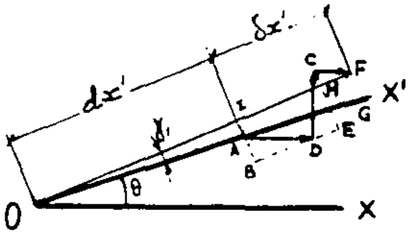
originadas cuando la dirección del alargamiento coincide con los ejes X e Y respectivamente y otro tipo de deformación llamada angular que aparece cuando hay un desplazamiento - transversal de los lados dx y dy que motiva que la forma rectangular original se convierta en rombica. La deformación angular γ_{xy} se define como la suma de los desplazamientos transversales divididos por las longitudes originales que no le son paralelas es



decir:

$$\gamma_{xy} = \frac{\delta' x}{dy} + \frac{\delta' y}{dx} = \operatorname{tg}\gamma_2 + \operatorname{tg}\gamma_1 \simeq \gamma_1 + \gamma_2$$

La deformación angular se considera positiva si supone una disminución del ángulo recto original por una extensión.



En un punto arbitrario (fig.4) de la superficie de una pieza cargada podemos aíslar un elemento infinistesimal de material para estudiar - sus deformaciones en el plano XY y para ello aplicaremos el principio de superposición, por el cual la deformación total será la suma de las deformaciones parciales, es decir, la suma de la deformación lineal según los ejes X e Y respectivamente y la deformación angular γ_{xy}.

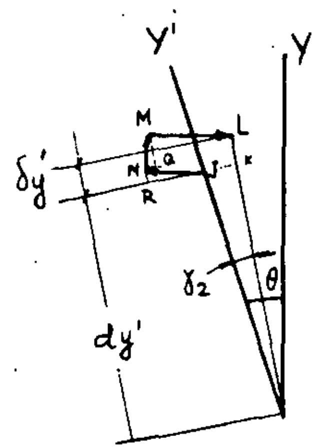


fig 5

Vamos a relacionar los valores de las deformaciones según los X-Y con otro conjunto de ejes X'-Y' que forman un ángulo θ . Al ángulo θ le consideraremos positivo en sentido contrario al de las agujas del reloj.

En la fig. 5 se observa la geometría del elemento infinitesimal referido a los nuevos ejes X'-Y', el alargamiento según el eje X' será: $\varepsilon_{x'} = \frac{\delta x'}{dx'}$

$$\delta x' = \varepsilon_{x'}\, dx' = \overline{BD} + \overline{DE} + \overline{FH}$$
$$\overline{BD} = \varepsilon_x\, dx' \cos\theta \cos\theta = \varepsilon_x\, dx' \cos^2\theta$$
$$\overline{DE} = \varepsilon_y\, dy' \operatorname{sen}\theta \operatorname{sen}\theta = \varepsilon_y\, dy' \operatorname{sen}^2\theta$$
$$\overline{FH} = dx' \operatorname{sen}\theta\, \gamma_{xy} \cos\theta$$

$$\varepsilon_x' = \varepsilon_x \cos^2\theta + \varepsilon_y \operatorname{sen}^2\theta + \gamma_{xy} \operatorname{sen}\theta\cos\theta \quad \text{- - - - - - - -} \quad [12]$$

$$\varepsilon_y' = \varepsilon_x \cos^2\left(\theta + \frac{\pi}{2}\right) + \varepsilon_y \operatorname{sen}^2\left(\theta + \frac{\pi}{2}\right) + \gamma_{xy} \operatorname{sen}\left(\theta + \frac{\pi}{2}\right)\cos\left(\theta + \frac{\pi}{2}\right) \quad .. [13]$$

La deformación angular viene expresada por: $\gamma_\theta = \gamma_1 + \gamma_2 = \frac{\overline{AI}}{dx'} + \frac{\overline{JK}}{dy'}$

$$\left.\begin{aligned} \overline{AI} &= -\overline{HC} + \overline{CE} - \overline{AB} \\ \overline{JK} &= -\overline{RJ} + \overline{NQ} + \overline{PL} \end{aligned}\right\} \quad \left.\begin{aligned} -\overline{HC} &= -dx'\gamma_{xy} \operatorname{sen}^2\theta \\ \overline{CE} &= \varepsilon_y\, d_x' \operatorname{sen}\theta\cos\theta \\ -\overline{AB} &= -\varepsilon_x\, dx' \operatorname{sen}\theta\cos\theta \end{aligned}\right\} \quad \begin{aligned} -\overline{RJ} &= -dy\,\varepsilon_x \operatorname{sen}\theta\cos\theta \\ \overline{NQ} &= dy\,\varepsilon_y \operatorname{sen}\theta\cos\theta \\ \overline{PL} &= dy\,\gamma_{xy}\cos^2\theta \end{aligned}$$

$$\gamma_\theta = -2\left(\varepsilon_x - \varepsilon_y\right) \text{sen}\,\theta \cos\theta + \gamma_{xy}\left(\cos 2\theta - \text{sen}^2\theta\right) \quad [14]$$

Si expresamos la (12 y (14) en función del ángulo doble podemos escribirlas

$$\varepsilon_{x'} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\theta + \frac{\gamma_{xy}}{2}\,\text{sen}\,2\theta \quad [15]$$

$$\frac{\gamma_\theta}{2} = \frac{\varepsilon_x - \varepsilon_y}{2}\,\text{sen}\,2\theta + \frac{\gamma_{xy}}{2}\cos 2\theta \quad [16]$$

Por ser funciones periódicas tendrán un máximo y un mínimo que calcularemos derivando la (15) respecto a θ e igualando a cero.

$$\frac{d\varepsilon_{x'}}{d\theta} = -2\,\frac{\varepsilon_x - \varepsilon_y}{2}\,\text{sen}\,2\theta + 2\,\frac{\gamma_{xy}}{2}\cos 2\theta = 0$$

$$\text{tg}\,2\,\theta_{M\cdot m} = \frac{\gamma_{xy}/2}{\frac{\varepsilon_x - \varepsilon_y}{2}} = \frac{\text{sen}\,2\theta}{\cos 2\theta} \quad [17]$$

de donde sustituyendo en (15) tenemos:

$$\varepsilon_{x'(M\text{-}m)} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{1}{4\sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2}}\left[\left(\varepsilon_x - \varepsilon_y\right)^2 + \gamma_{xy}^2\right] =$$

$$= \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad [18]$$

Los subíndices M-m indican los valores máximo y mínimo, en efecto hay dos valores de 2θ M-m que cumplen la ecuación (17) ya que $\text{tg}_M 2\theta = \text{tg}(2\theta + \pi)$ o sea que las direcciones de las deformaciones máxima y mínima son perpendiculares entre sí, verificándose además que la deformación angular es nula como se demuestra sustituyendo la (17) en la (16), la fig, 6 aclara lo expuesto.

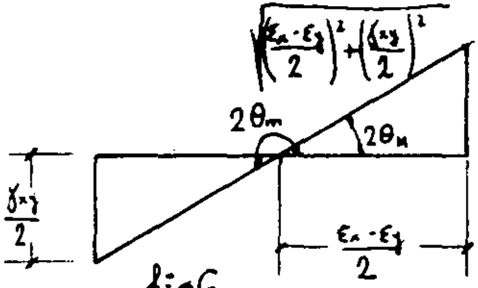


fig6

El valor máximo de la deformación angular se obtiene por el mismo procedimiento y tiene por valor:

$$\frac{\gamma\theta_{M\text{-}m}}{2} = \pm\sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad [19]$$

demostrándose que su dirección forma 45º con respecto a las direcciones principales.

Si el ángulo θ_M que el eje arbitrario X' forma con el eje X hacemos que sea nulo las expresiones (18) y (19) se pueden escribir:

$$\left.\begin{aligned} \varepsilon_{x'(M\text{-}m)} &= \frac{\varepsilon_1 + \varepsilon_2}{2} \pm \frac{\varepsilon_1 - \varepsilon_2}{2} \\ \frac{\gamma_{M\text{-}m}}{2} &= \pm\,\frac{\varepsilon_1 - \varepsilon_2}{2} \end{aligned}\right\}$$

siendo ε_1 y ε_2 las deformaciones según las direcciones principales.

Para cualquier otra dirección que forme un ángulo α respecto a las principales, las fórmulas quedarán:

$$\varepsilon_\alpha = \frac{\varepsilon_1+\varepsilon_2}{2} + \frac{\varepsilon_1-\varepsilon_2}{2}\cos 2\alpha \quad - - - - - - - - \quad [20]$$

$$\frac{\gamma_\alpha}{2} = \frac{\varepsilon_1-\varepsilon_2}{2}\,\mathrm{sen}\,2\alpha \quad - - - - - - - - - \quad [21]$$

si llamamos:

$$d = \frac{\varepsilon_1+\varepsilon_2}{2} \quad y \quad r = \frac{\varepsilon_1-\varepsilon_2}{2}, \text{ tendremos que:}$$

$$\varepsilon_\alpha = d + r\cos 2\alpha \quad - - - - - - - - - - - \quad [22]$$

$$\frac{\gamma_\alpha}{2} = r\,\mathrm{sen}\,2\alpha \quad - - - - - - - - - \quad [23]$$

1.5. ESTADO BIAXIAL DE TENSIONES

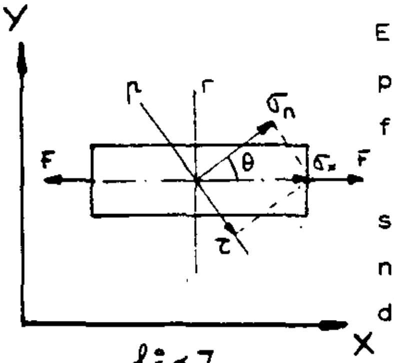


fig7

En una barra prismática sometida a una extensión pura, se llama tensión (esfuerzo o fatiga) a la fuerza que actua por unidad de superficie;

$$\sigma_x = \frac{F}{S} \quad (S: \text{sección segun } r\text{-}r')$$

si consideramos otra sección S' (según p'-p) cuya normal forma un ángulo θ con el eje de aplicación de fuerzas, la tensión según el eje X valdrá:

$$\sigma'_x = \frac{F}{S'} = \frac{F}{S}\cos\theta = \sigma_x\cos\theta$$

y descomponiéndola en las direcciones normal y tangencial respectivamente de p-p' tendremos que:

$$\sigma_n = \sigma_x\cos\theta\cos\theta = \sigma_x\cos^2\theta \quad - - - - - - - - - - \quad [24]$$

$$\tau = \sigma_x\cos\theta\,\mathrm{sen}\,\theta = \frac{1}{2}\sigma_x\,\mathrm{sen}\,2\theta \quad - - - - - - - - \quad [25]$$

llamándose el valor (24) tensión normal y al (25) tensión cortante.

Estudiaremos el estado biaxial de tensiones en la superficie de un cuerpo que no esté sometido a presiones exteriores; de forma análoga a como se desarrolla el caso de deformaciones, para ello aislemos un elemento infinitesimal de lados paralelos a unos ejes X - Y, las acciones que actuen sobre el elemento originan mas tensiones normales y cortantes que mantienen el equilibrio del sistema - (fig. 8).

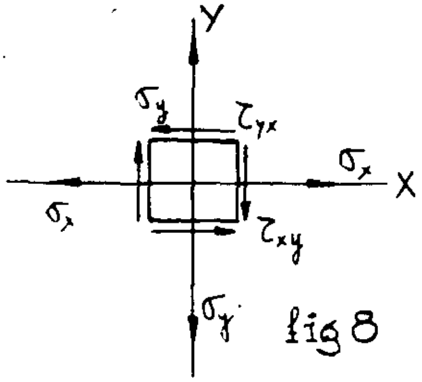


fig 8

Las tensiones normales serán positivas en caso de tracción y negativas en caso de compresión, así mismo - las tensiones cortantes se consideran positivas cuando producen un par en sentido de las agujas del reloj y negativas en caso contrario.

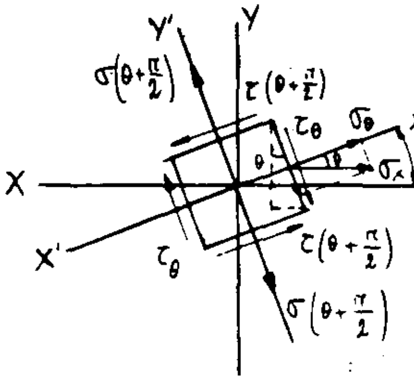


fig 9

En la fig. 9, vemos el elemento infinitesimal referenciado a unos ejes que forman un ángulo θ con los X-Y'; buscaremos el valor de las tensiones ligadas a la nueva orientación de ejes, para ello tengamos en cuenta que el equilibrio debe ser de fuerzas, en efecto:

$$\sigma_\theta S = \sigma_x S \cos\theta \cos\theta + \sigma_y S \,\text{sen}\,\theta \,\text{sen}\,\theta + \tau_{xy} S \cos\theta \,\text{sen}\,\theta + \tau_{yx} S \,\text{sen}\,\theta \cos\theta =$$

$$= \sigma_x S \cos^2\theta + \sigma_y S \,\text{sen}^2\theta + 2\tau_{xy} S \,\text{sen}\,\theta \cos\theta$$

$$\sigma_\theta = \sigma_x \cos^2\theta + \sigma_y \,\text{sen}^2\theta + 2\tau_{xy} \,\text{sen}\,\theta \cos\theta \quad \text{- - - - -} [26]$$

$$\tau_\theta = -(\sigma_x - \sigma_y) \,\text{sen}\,\theta \cos\theta \,\text{sen}\,\theta \cos\theta + \tau_{xy}(\cos^2\theta - \text{sen}^2\theta) \quad \text{- - - -} [27]$$

ecuaciones que expresadas en función del ángulo doble nos dan:

$$\sigma_\theta = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \tau_{xy} \,\text{sen}\, 2\theta \quad \text{- - - - - -} [28]$$

$$\tau_\theta = -\left(\frac{\sigma_x - \sigma_y}{2}\right) \text{sen}\, 2\theta + \tau_{xy} \cos 2\theta \quad \text{- - - - - - - -} [29]$$

Si derivamos la (28) respecto a θ e igualamos a cero, encontraremos los valores de θ que hacen máximo y mínimo a dicha ecuación:

$$\frac{d\sigma_\theta}{d\theta} = -(\sigma_x - \sigma_y) \,\text{sen}\, 2\theta + 2\tau_{xy} \cos 2\theta = 0$$

$$\text{tg}\, 2\theta_{M\text{-}m} = \frac{\text{sen}\, 2\theta_{M\cdot m}}{\cos 2\theta_{M\cdot m}} = \frac{\tau_{xy}}{\frac{\sigma_x - \sigma_y}{2}}$$

Por consideraciones análogas a las hechas en el estudio de la deformación biaxial, se deducen que hay dos planos perpendiculares que - corresponden a las direcciones en que las tensiones normales son máxima y mínima respectivamente y en las cuales las tensiones cortantes son nulas:

$$\sigma_{M\cdot m} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \left(\tau_{xy}\right)^2} \qquad [30]$$

De la misma forma encontraremos que:

$$\tau_{M\text{-}m} = \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \left(\tau_{xy}\right)^2} \qquad [31]$$

El valor máximo y mínimo de la tensión cortante se encuentra defasado 45º respecto a los valores principales de las tensiones normales.

Haciendo que el ángulo $\theta_M = 0$ tenemos que:

$$\sigma_{M\text{-}m} = \frac{\sigma_1 + \sigma_2}{2} \pm \frac{\sigma_1 - \sigma_2}{2}$$

$$\tau_{M\cdot m} = \pm \frac{\sigma_1 + \sigma_2}{2}$$

siendo σ_1 y σ_2 el valor de las tensiones normales máxima y mínima; las tensiones en cualquier dirección que formen un ángulo α con las principales, tienen de valor:

$$\sigma_\alpha = \frac{\sigma_1 + \sigma_2}{2} \pm \frac{\sigma_1 - \sigma_2}{2} \cos 2\alpha \qquad [32]$$

$$\tau_\alpha = \frac{\sigma_1 - \sigma_2}{2} \operatorname{sen} 2\alpha \qquad [32\ \text{bi}]$$

Llamando

$$\delta = \frac{\sigma_1 + \sigma_2}{2} \quad y \quad \rho = \frac{\sigma_1 - \sigma_2}{2}$$

tenemos que:

$$\sigma_\alpha = \delta + \rho \cos 2\alpha \qquad [33]$$

$$\tau_\alpha = \rho \operatorname{sen} 2\alpha \qquad [34]$$

1.6 RELACION ENTRE DEFORMACIONES Y TENSIONES

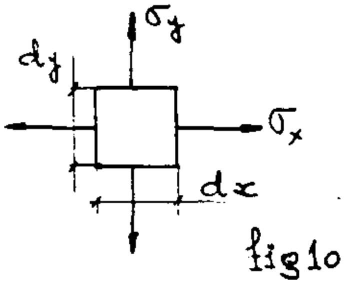


fig 10

Supongamos el elemento de la fig. 10, aplicando el teorema de la superposición encontramos que;

$$\left.\begin{aligned} \varepsilon_x &= \frac{\sigma_x}{E} - \mu \frac{\sigma_y}{E} \\ \varepsilon_y &= \frac{\sigma_y}{E} - \mu \frac{\sigma_x}{E} \end{aligned}\right\}$$

$$\sigma_x = \frac{E}{1-\mu^2}\left(\varepsilon_x + \mu\, \varepsilon_y\right) \qquad [35]$$

$$\sigma_y = \frac{E}{1-\mu^2}\left(\varepsilon_y + \mu\, \varepsilon_x\right) \qquad [36]$$

Experimentalmente se demuestra que:

$$\gamma = \frac{\tau}{G} \qquad G = \frac{E}{2(1+\mu)} \qquad [37]$$

llamándose a G coeficiente de elasticidad a cortadura.

Recordando las relaciones:

$$d = \frac{\varepsilon_1 + \varepsilon_2}{2} \qquad \delta = \frac{\sigma_1 + \sigma_2}{2}$$

$$r = \frac{\varepsilon_1 - \varepsilon_2}{2} \qquad \rho = \frac{\sigma_1 - \sigma_2}{2}$$

se deduce que:

$$\varepsilon_1 + \varepsilon_2 = \frac{\sigma_1}{E} - \mu \frac{\sigma_2}{E} + \frac{\sigma_2}{E} - \mu \frac{\sigma_1}{E} = \sigma_1 + \sigma_2 \left(\frac{1-\mu}{E} \right)$$

$$\delta = \frac{\sigma_1 + \sigma_2}{2} = \frac{\varepsilon_1 + \varepsilon_2}{2} \; \frac{E}{1-\mu} = d \, \frac{E}{1-\mu} \quad \text{- - - - - - -} \quad [38]$$

$$\varepsilon_1 - \varepsilon_2 = \sigma_1 - \sigma_2 \, \frac{1+\mu}{E}$$

$$\rho = \frac{\sigma_1 - \sigma_2}{2} = \frac{\varepsilon_1 - \varepsilon_2}{2} \; \frac{E}{1+\mu} = r \, \frac{E}{1+\mu} \quad \text{- - - - - - -} \quad [39]$$

1.7. REPRESENTACION GRAFICA DEL ESTADO BIAXIAL DE TENSIONES Y DEFORMACIONES; CIRCULOS DE MOHR

Una de las formas más sencillas y usuales de representación del estado plano de deformaciones y tensiones es el círculo de Mohr. Recordemos que la deformación en una dirección cualquiera que forma un ángulo α respecto a las direcciones principales tiene por valor:

$$\varepsilon_\alpha = \frac{\varepsilon_1 + \varepsilon_2}{2} + \frac{\varepsilon_1 - \varepsilon_2}{2} \cos 2\alpha = d + r \cos 2\alpha$$

$$\frac{\gamma_\alpha}{2} = \frac{\varepsilon_1 - \varepsilon_2}{2} \operatorname{sen} 2\alpha = r \operatorname{sen} 2\alpha$$

Podemos representar prácticamente éstas ecuaciones según la fig. 11, pués se cumple que:

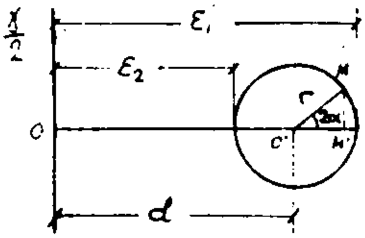


fig 11

$$\varepsilon_\alpha = \overline{OM'} = d + r \cos 2\alpha$$

$$\frac{\gamma_\alpha}{2} = \overline{MM'} = r \operatorname{sen} 2\alpha$$

Observemos que el valor máximo y el mínimo

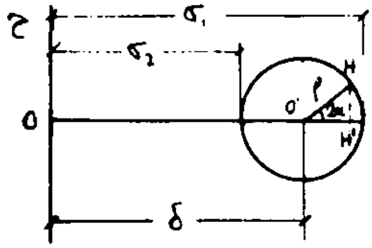


fig 12

La fig. 12 nos indica el circulo de Mohr para el estado de tensiones y vemos su similitud con el de deformaciones.

$$\sigma_\alpha = \overline{OH} = \delta + \rho \cos 2\alpha$$

$$\tau_\alpha = \overline{HH'} = \rho \operatorname{sen} 2\alpha$$

En el dominio elástico de los cuerpos isotrópicos, existe proporcionalidad entre deformaciones y tensiones, por lo que los circulos representativos de ambos valores son concéntricos. Los coeficientes de proporcionalidad han sido deducidos en el apartado 1.6 (fig. 13).

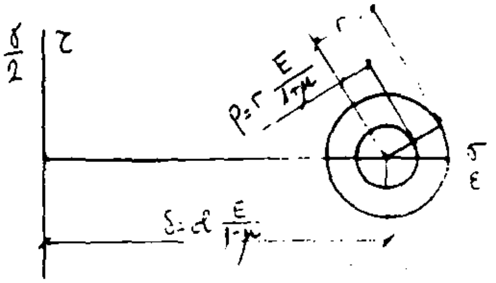
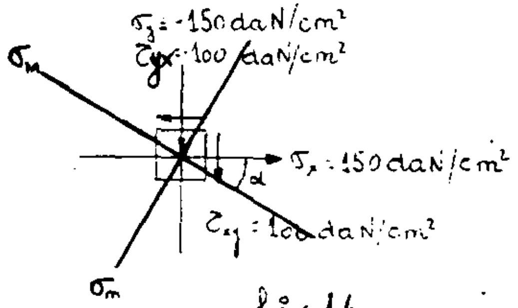


fig 13

1.8 EJEMPLOS DE APLICACION DE LOS CIRCULOS DE MOHR.

Nº 1. Sobre el elemento de la fig. 14 actuan las tensiones que se indican. Calcular analítica y gráficamente el valor y dirección de los esfuerzos principales.



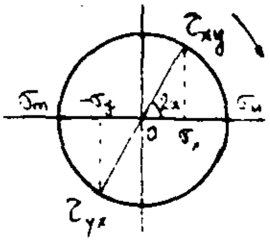
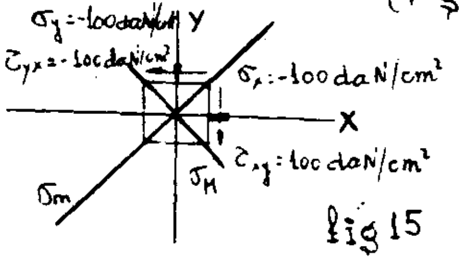


fig 14

$$\sigma_{M\cdot m} = \frac{150+(-150)}{2} \pm \sqrt{\left(\frac{150-(-150)}{2}\right)^2 + 100^2} = \underline{\underline{\pm\ 180\ daN/cm^2}}$$

$$tg\ 2\alpha = \frac{100}{\frac{150-(-150)}{2}} = 0{,}66 \qquad 2\alpha = \begin{cases} 41^\circ \\ 41^\circ + 180 \end{cases} \qquad \alpha = \begin{cases} 20.5^\circ \\ 20{,}5^\circ + 90^\circ \end{cases}$$

Nº2 Idem al anterior. (fig 15)



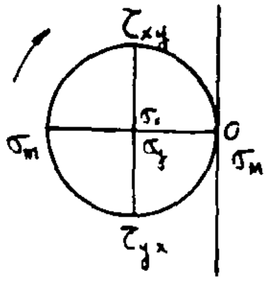


fig 15

$$\delta = \frac{-100+(-100)}{2} = -100$$

$$\rho = \pm\sqrt{\left(\frac{-100-(-100)}{2}\right)^2 + 100^2} = 100$$

$$tg\ 2\alpha = \frac{100}{\frac{-100-(-100)}{2}} = -\infty$$

$$\sigma_M = \delta + \rho = -100 + 100 = 0$$

$$\sigma_m = \delta - \rho = -100 - 100 = -200$$

$$\alpha = 45^\circ$$

Casos típicos de aplicación del circulo de Mohr.

TORSION

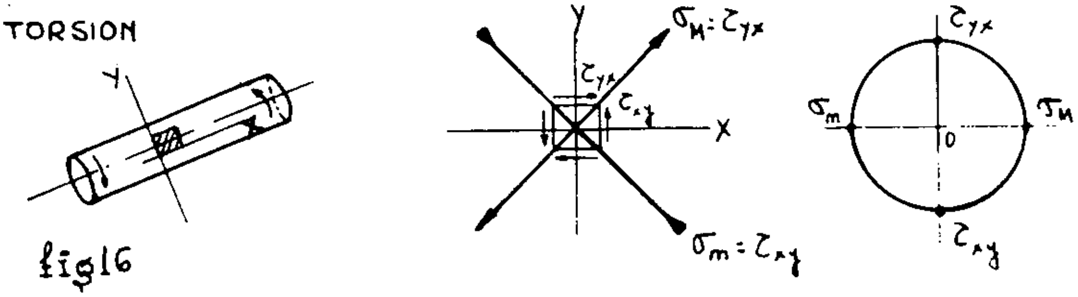


fig 16

TORSION Y TRACCION

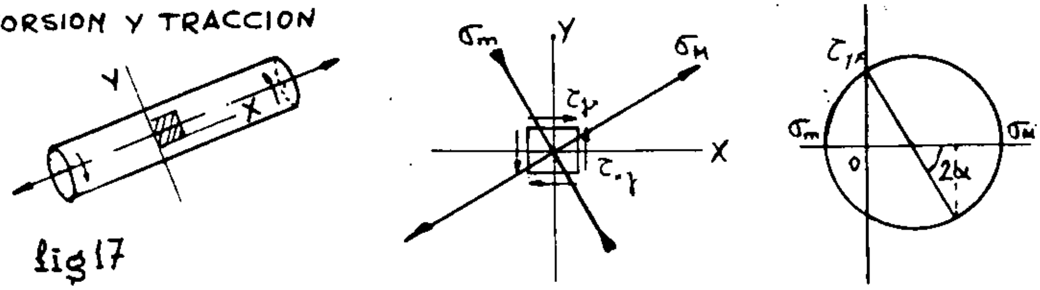


fig 17

TRACCION

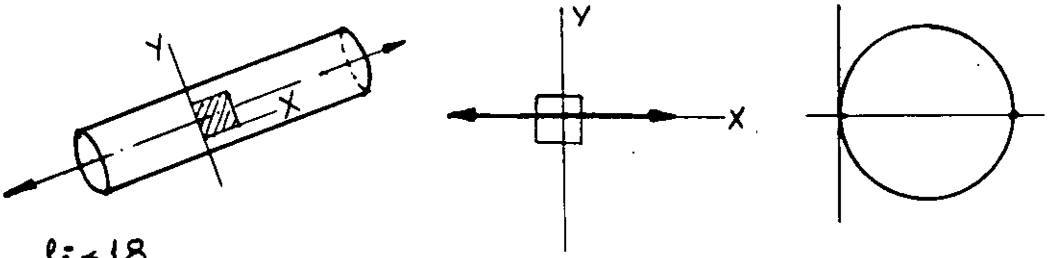


fig 18

CILINDRO BAJO PRESION

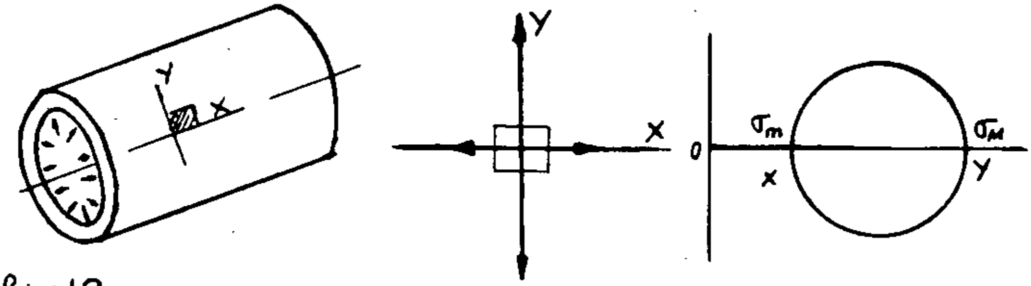


fig 19

ESFERA BAJO PRESION

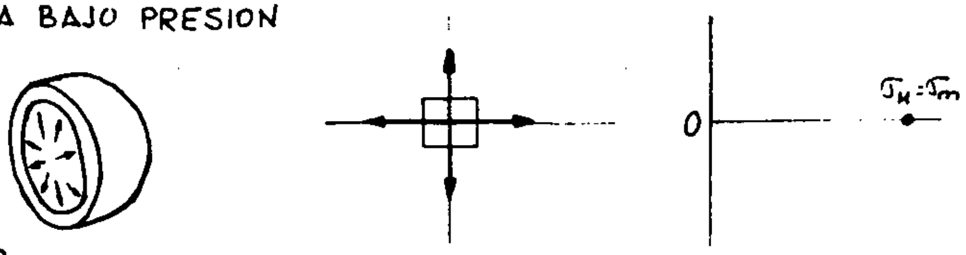


fig 20

Bandas de tres direcciones o rosetas (Rectangulares)

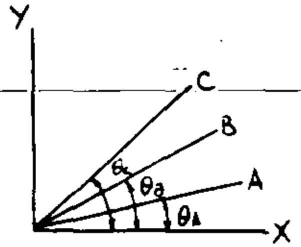


fig21

Consideremos el valor de las deformaciones (fig. 21) en direcciones A, B y C que forman los ángulos θ_A, θ_B y θ_C respectivamente con el eje X de unos ejes arbitrarios X-Y, tendremos:

$$\varepsilon_A = \frac{\varepsilon_x+\varepsilon_y}{2} + \frac{\varepsilon_x-\varepsilon_y}{2}\cos 2\theta_A + \frac{\gamma_{xy}}{2}\operatorname{sen} 2\theta_A$$

$$\varepsilon_B = \frac{\varepsilon_x+\varepsilon_y}{2} + \frac{\varepsilon_x-\varepsilon_y}{2}\cos 2\theta_B + \frac{\gamma_{xy}}{2}\operatorname{sen} 2\theta_B$$

$$\varepsilon_C = \frac{\varepsilon_x+\varepsilon_y}{2} + \frac{\varepsilon_x-\varepsilon_y}{2}\cos 2\theta_C + \frac{\gamma_{xy}}{2}\operatorname{sen} 2\theta_C$$

Si hacemos que:

$$\theta_A = 0 \quad ; \quad \theta_B = \frac{\pi}{4} \quad ; \quad \theta_C = \frac{\pi}{2}$$

nos queda:

$$\left.\begin{aligned} \varepsilon_A &= \varepsilon_x \\ \varepsilon_B &= \frac{\varepsilon_x+\varepsilon_y}{2} + \frac{\gamma_{xy}}{2} \\ \varepsilon_C &= \varepsilon_y \end{aligned}\right\} \begin{aligned} &\varepsilon_x = \varepsilon_A \\ &\varepsilon_y = \varepsilon_C \\ &\gamma_{xy} = 2\varepsilon_B - (\varepsilon_A - \varepsilon_B) = (\varepsilon_B - \varepsilon_A) + (\varepsilon_B - \varepsilon_C) \ldots [42] \end{aligned}$$

Sustituyendo las (41 y (42) en (18) y (19) y simplificando tenemos:

$$\varepsilon_M = \frac{\varepsilon_A+\varepsilon_C}{2} + \frac{1}{\sqrt{2}}\sqrt{(\varepsilon_A-\varepsilon_B)^2 + (\varepsilon_B-\varepsilon_C)^2} \quad \text{-----} \quad [43]$$

$$\varepsilon_m = \frac{\varepsilon_A+\varepsilon_C}{2} - \frac{1}{\sqrt{2}}\sqrt{(\varepsilon_A-\varepsilon_B)^2 + (\varepsilon_B-\varepsilon_C)^2} \quad \text{-----} \quad [44]$$

$$\gamma_{M \cdot m} = \pm\sqrt{2}\sqrt{(\varepsilon_A-\varepsilon_B)^2 + (\varepsilon_B-\varepsilon_C)^2} \quad \text{-----} \quad [45]$$

$$\operatorname{tg} 2\theta_M = \left[\frac{(\varepsilon_B-\varepsilon_A)+(\varepsilon_B-\varepsilon_C)}{\varepsilon_A-\varepsilon_C}\right] \quad \text{-----} \quad [46]$$

El ángulo θ_M será el que forma la dirección principal máxima con la dirección A.

Los valores de las tensiones máxima y mínima

$$\sigma_{M \cdot m} = \frac{E}{2}\left[\frac{\varepsilon_A+\varepsilon_C}{1-\mu} \pm \frac{\sqrt{2}}{1+\mu}\sqrt{(\varepsilon_A-\varepsilon_B)^2 + (\varepsilon_B-\varepsilon_C)^2}\right. \quad \text{-----} \quad [47]$$

$$\tau_M = \frac{E}{\sqrt{2}(1+\mu)}\sqrt{(\varepsilon_A-\varepsilon_B)^2 + (\varepsilon_B-\varepsilon_C)^2} \quad \text{-----} \quad [48]$$

Las fórmulas (47) y (48) dan directamente los valores de las tensiones principales a partir de los valores de las deformaciones en las direcciones A, B y C.

Las ecuaciones anteriores corresponden a una banda extensométrica roseta rectangular como la indicada en la fig. 22.

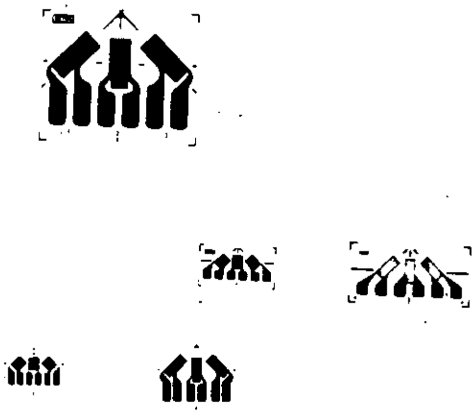


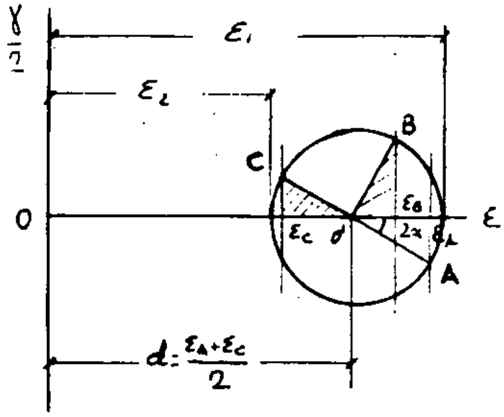
fig 22

Vamos a ver gráficamente como se determinan las deformaciones principales a partir de las deformaciones ε_A; ε_B y ε_C valiéndonos del círculo de Mohr.

Sobre el eje x (fig. 23) traslademos los valores ε_A; ε_B y ε_C . En el círculo ε_A y ε_C tienen que estar - defasados 180º; por lo que el centro del mismo será $d = \frac{\varepsilon_A + \varepsilon_C}{2}$, la dirección de ε_B estará en el círculo defasada 90º; por lo que debe cumplirse la igualdad de los triángulos $\overset{\triangle}{O'BB'} = \overset{\triangle}{O'CC'}$ con lo que hemos determinado, $r = \overline{CO'}$

En el círculo observamos que desde el punto A que corresponde a ε_A tenemos que correr un ángulo positivo 2α para llegar a $\varepsilon_1 = \varepsilon_M$; por lo tanto y sobre la banda roseta desplazaremos un ángulo α para la dirección de la deformación principal máxima. El ángulo α es el que forma la dirección principal máxima tomada como referencia y la dirección A, considerando como positivo el sentido contrario al giro de las agujas del reloj.

Conocido el círculo de Mohr de deformaciones fácilmente se deduce el de tensiones (ver. 1.6) de la fig. 23 se deduce:



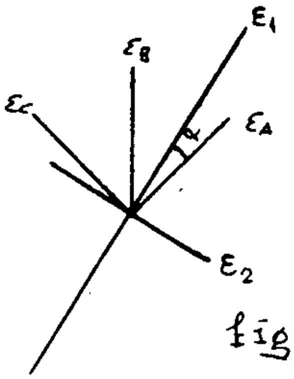


fig 23

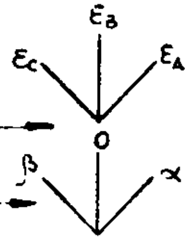
1.10 CALCULO TABULADO PARA ROSETAS RECTANGULARES

Sean ε_A, ε_B y ε_C las medidas de las bandas, A, B y C.

1) Cálculo de d: $d = \frac{\varepsilon_A + \varepsilon_C}{2}$ (con su signo)

2) Cálculo de r:

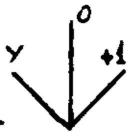
Anotar los 3 valores con su signo ⟶



Restar $(-\varepsilon_B)$ a los 3 valores, se obtiene ⟶

Anotar el signo que corresponda al mayor valor de α ó β en valor absoluto ⟹ ⊕ ⊖

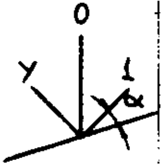
Sea, por ejemplo, α ese número. Dividir α y β por α con su signo.
Se obtiene ⟶



Y puede ser positivo o negativo, pero inferior a 1 en valor absoluto.
Buscar en la tabla I el valor W que corresponde a Y
Se tiene que: $r = |\alpha|\, W$ (Número positivo)
Las deformaciones principales son:

$$\varepsilon_1 = d + r$$
$$\varepsilon_2 = d - r$$

Buscar en la tabla II, el ángulo que corresponde a Y con su signo. α está comprendido entre 0 y 45º. Llevar el ángulo α en sentido externo (que se aleje de la referencia 0) sobre el eje marcado con el 1.



La dirección obtenida es:

Máxima si anotamos el signo + ⟸
Mínima si anotamos el signo − ⟸

TABLA Nº 1
(continuación)

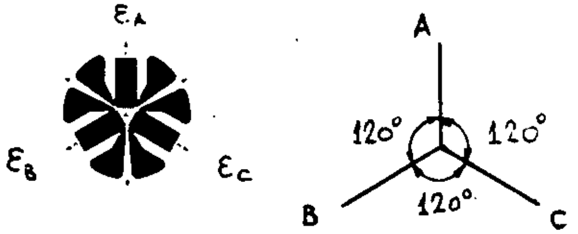
|y|	0	1	2	3	4	5	6	7	8	9
			03	07	10	14	18	22	26	30
0,65	0,8434	37	41	45	49	53	57	61	65	68
0,66	0,8472	76	80	84	88	92	94			
								00	04	08
0,67	0,8511	15	19	23	27	31	35	39	43	47
0,68	0,8551	55	59	63	67	71	75	79	83	87
0,69	0,8591	95	99							
				03	07	11	15	19	23	27
0,70	0.8631	35	39	43	48	52	56	60	64	68
0,71	0.8672	76	80	84	88	93	97			
								01	05	08
0,72	0.8713	17	21	26	30	34	38	47	46	51
0,73	0,8755	59	63	67	71	76	80	84	88	92
0,74	0,8796									
		01	05	09	13	18	22	26	30	35
0,75	0,8839	43	47	52	56	60	64	69	73	77
0,76	0,8881	86	90	94	99					
						03	07	11	16	20
0,77	0,8924	29	33	37	42	46	50	54	58	63
0.78	0,8968	72	76	81	85	89	94	98		
									03	07
0,79	0,9011	16	20	25	29	33	38	42	47	51
0,80	0,9055	60	64	69	73	77	82	86	91	95
0,81	0,9100	04	09	13	18	22	26	31	35	40
0,82	0,9144	49	53	58	62	67	71	76	80	85
0,83	0,9189	94	98							
				03	07	12	17	21	26	30
0,84	0,9235	39	44	48	53	57	62	67	71	76
0,85	0,9280	85	90	94	99					
						03	08	17	17	22
0.86	0,9326	31	36	40	45	49	54	59	63	68
0.87	0,9373	77	82	86	91	96				
							00	05	10	14
0,88	0,9419	24	28	33	38	43	47	52	57	61
0,89	0,9466	71	75	80	85	90	94	99		
									04	08
0,90	0,9513	18	23	27	32	37	42	46	51	56
0,91	0,9561	65	70	75	80	84	89	94	99	
										04
0,92	0,9608	13	18	23	27	32	37	42	47	52
0,93	0,9656	61	66	71	75	80	85	90	95	
0,94	0,9705	09	14	19	24	29	34	39	43	48
0,95	0,9753	58	63	68	73	78	82	87	92	97
0.96	0.9802	07	12	17	22	27	31	36	41	46
0.97	0.9851	56	61	66	71	76	81	86	91	96
0.98	0.9901	05	10	15	20	25	30	35	40	45
0.99	0.9950	55	60	65	70	75	80	85	90	95
1.00	1.0000									

TABLA Nº 2

y	0	1	2	3	4	5	6	7	8	9
— 1,0	0,0									
— 0,9	1,5	1,3	1,2	1,0	0,9	0,7	0,6	0,4	0,3	0,1
— 0,8	3,2	3,0	2,8	2,7	2,5	2,3	2,2	2,0	1,8	1,7
— 0,7	5,0	4,8	4,6	4,4	4,2	4,1	3,9	3,7	3,5	3,3
— 0,6	7,0	6,8	6,6	6,4	6,2	6,0	5,8	5,6	5,4	5,2
— 0,5	9,2	9,0	8,8	8,5	8,3	8,1	7,9	7,7	7,4	7,2
— 0,4	11,6	11,4	11,1	10,9	10,6	10,4	10,1	9,9	9,7	9,4
— 0,3	14,1	13,9	13,6	13,4	13,1	12,9	12,6	12,3	12,1	11,8
— 0,2	16,8	16,6	16,3	16,0	15,8	15,5	15,2	15,0	14,7	14,4
— 0,1	19,7	19,4	19,1	18,8	18,5	18,2	17,9	17,7	17,4	17,1
— 0,0	22,5	22,2	21,9	21,7	21,4	21,0	20,8	20,5	20,2	19,9
+ 0,0	22,5	22,8	23,1	23,3	23,6	24,0	24,2	24,5	24,8	25,1
+ 0,1	25,3	25,6	25,9	26,2	26,5	26,8	27,1	27,3	27,6	27,9
+ 0,2	28,2	28,4	28,7	29,0	29,2	29,5	29,8	30,0	30,3	30,6
+ 0,3	30,9	31,1	31,4	31,6	31,9	32,1	32,4	32,7	32,9	33,2
+ 0,4	33,4	33,6	33,9	34,1	34,4	34,6	34,9	35,1	35,3	35,6
+ 0,5	35,8	36,0	36,2	36,5	36,7	36,9	37,1	37,3	37,6	37,8
+ 0,6	38,0	38,2	38,4	38,6	38,8	39,0	39,2	39,4	39,6	39,8
+ 0,7	40,0	40,2	40,4	40,6	40,8	40,9	41,1	41,3	41,5	41,7
+ 0,8	41,8	42,0	42,2	42,3	42,5	42,7	42,8	43,0	43,2	43,3
+ 0,9	43,5	43,7	43,8	44,0	44,1	44,3	44,4	44,6	44,7	44,9
+ 1,0	45,0									

1.11 BANDAS DE TRES DIRECCIONES O ROSETAS (EQUIANGULARES)

Las direcciones arbitrarias de la medida de tres deformaciones en un punto podemos hacer que estén defasados 120º con lo que la banda tiene la geometría indicada en la fig. 24 y por consideraciones análogas al caso de la roseta rectangular encontramos los resultados que se indican



$$\sigma_{M-m} = \frac{E}{3}\left[\frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{1-\mu} \pm \frac{\sqrt{2}}{1+\mu}\sqrt{(\varepsilon_A-\varepsilon_C)^2+(\varepsilon_C-\varepsilon_B)^2+(\varepsilon_B-\varepsilon_A)^2}\right. \quad \ldots \; [49]$$

$$\tau = \frac{\sqrt{2}\,E}{3(1+\mu)}\sqrt{(\varepsilon_A-\varepsilon_C)^2+(\varepsilon_C-\varepsilon_B)^2+(\varepsilon_B-\varepsilon_A)^2} \quad \ldots \; [50]$$

$$\operatorname{tg} 2\theta = \frac{\sqrt{3}\,(\varepsilon_C-\varepsilon_B)}{2\varepsilon_A-\varepsilon_B-\varepsilon_C} \quad \ldots \; [51]$$

siendo θ el ángulo de la dirección principal máxima con la dirección A.

Gráficamente podemos encontrar la solución llevando sobre el eje X del diagrama de Mohr los valores de $\varepsilon_A, \varepsilon_B$ y ε_C (fig. 25).

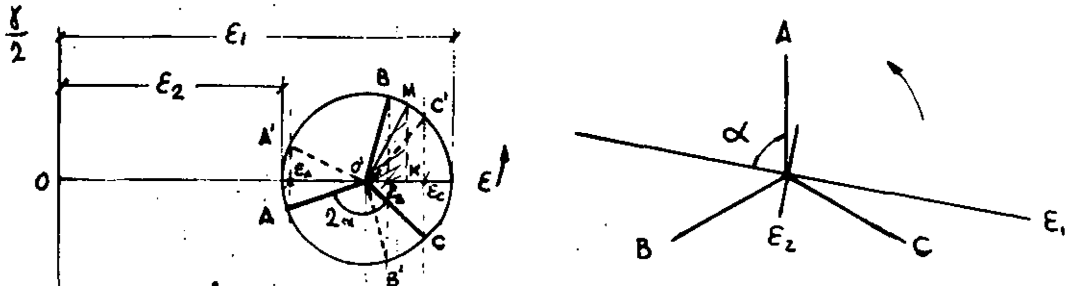


fig25

El centro del círculo sera d= $\frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3}$; sobre las dos proyecciones que queden a la derecha o a la izquierda del centro O; se levanta MM' perpendicular en el punto medio de las dos proyecciones y desde O' se traza una recta que forma 60º con el eje X, el punto de intersección M nos dá el radio del círculo $r=\overline{O'M}$. Aparentemente hay dós soluciones pero los puntos A'-B' y C' no guardan en el circulo el defase de 240º de acuerdo con la orientación de las -

direcciones de la banda

De la fig. 25 deducimos:

$$\left.\begin{aligned} d &= \frac{\varepsilon_A + \varepsilon_C + \varepsilon_B}{3} \\ r &= \frac{\varepsilon_a - d}{\cos 2\alpha} \end{aligned}\right\} \left.\begin{aligned} \varepsilon_1 &= d + r \\ \varepsilon_2 &= d - r \end{aligned}\right\} \operatorname{tg} 2\alpha = \frac{\sqrt{3}\,(\varepsilon_a - \varepsilon_b)}{2\varepsilon_A - \varepsilon_B - \varepsilon_C}$$

$$\left.\begin{aligned} \sigma_1 &= \frac{E}{1-\mu^2}\left(\varepsilon_1 + \mu\varepsilon_2\right) \\ \sigma_2 &= \frac{E}{1-\mu^2}\left(\varepsilon_2 + \mu\varepsilon_1\right) \end{aligned}\right\}$$

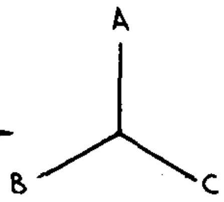
1.12 CALCULO TABULADO PARA ROSETAS EQUIANGULARES

Sean $\varepsilon_A, \varepsilon_B$ y ε_C las tres medidas con su signo

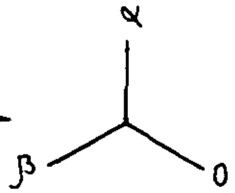
1) Cálculo de d: $d = \frac{\varepsilon_A + \varepsilon_B + \varepsilon}{3}$

2) Cálculo de r:

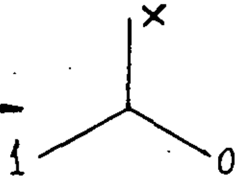
Anotar las tres medidas según su dirección ⟶



Uno al menos de los valores medios, es algebraicamente igual o menor que los otros dos. Sea por ejemplo ε_C. Se suma $(-\varepsilon_C)$ a los tres valores. Se obtiene así 0 y dos números positivos α y β ⟶



Dividimos a continuación por el número mayor α o β sea por ejemplo β ⟶



En la tabla III se obtiene un número U=f(x), tal que $r = \beta \cdot U$

$$\varepsilon_1 = d + r$$
$$\varepsilon_2 = d - r$$

3) Cálculo de φ

La tabla IV dá el ángulo en función de X. Este ángulo comprendido entre 0 y 30º se lleva sobre el esquema de direcciones haciendo girar un ángulo φ la dirección marcada con 1 en el sentido que se aproxima a la dirección marcada con 0. La dirección obtenida es la algebraicamente máxima.

1.13 ROSETA DE DOS DIRECCIONES

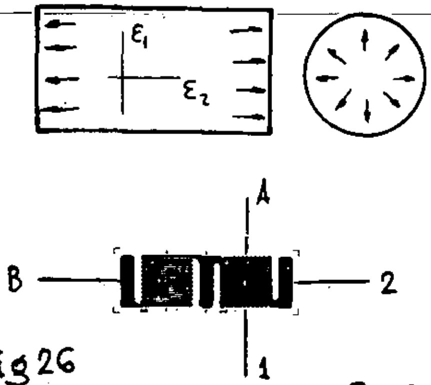


fig 26

Cuando la dirección de los ejes principales es conocida de antemano, como por ejemplo un cilindro bajo presión (fig. 26), con solo medir las deformaciones en dos direcciones perpendiculares que coincidan con las direcciones principales, será suficiente para determinar el estado de tensiones en un punto.

$$\varepsilon_1 = \varepsilon_A = \varepsilon_M \; ; \quad \varepsilon_2 = \varepsilon_B = \varepsilon_m \; ; \quad \gamma_M = \varepsilon_A - \varepsilon_B$$

$$\sigma_1 = \frac{E}{1-\mu^2}\left(\varepsilon_1 + \mu\,\varepsilon_2\right) \qquad [52]$$

$$\sigma_2 = \frac{E}{1-\mu^2}\left(\varepsilon_2 + \mu\,\varepsilon_1\right) \qquad [53]$$

$$\tau = G\gamma = G\left(\varepsilon_1 - \varepsilon_2\right) \qquad [54]$$

Se incluyen ábacos para el cálculo rápido de tensiones a partir de las lecturas en microdeformaciones.

1.14 EXTENSIMETROS UNIDIRECCIONALES

Si se conoce la dirección principal de esfuerzos y ésta es única, como en la tracción pura, la tensión es obtenida aplicando la ley de Hooke.

$$\sigma_1 = \varepsilon_1 E \qquad \varepsilon_2 = \mu\,\varepsilon_1$$
$$\sigma_2 = 0$$

1.15 CORRECCIONES DEBIDAS AL EFECTO DE LA SENSIBILIDAD TRANSVERSAL

Como vimos en el apartado 1.2 el efecto de sensibilidad transversal en el extensímetro, puede tener influencia en los resultados, sobre todo cuando se emplean bandas rosetas. A continuación se indican las correcciones que deben efectuarse sobre los valores de deformaciones principales, así como sobre la distancia del centro y radio del círculo de Mohr.

Sea $\varepsilon_M ; \varepsilon_m$ los valores de las deformaciones principales calculados y K_t el factor de sensibilidad transversal, los ver daderos valores

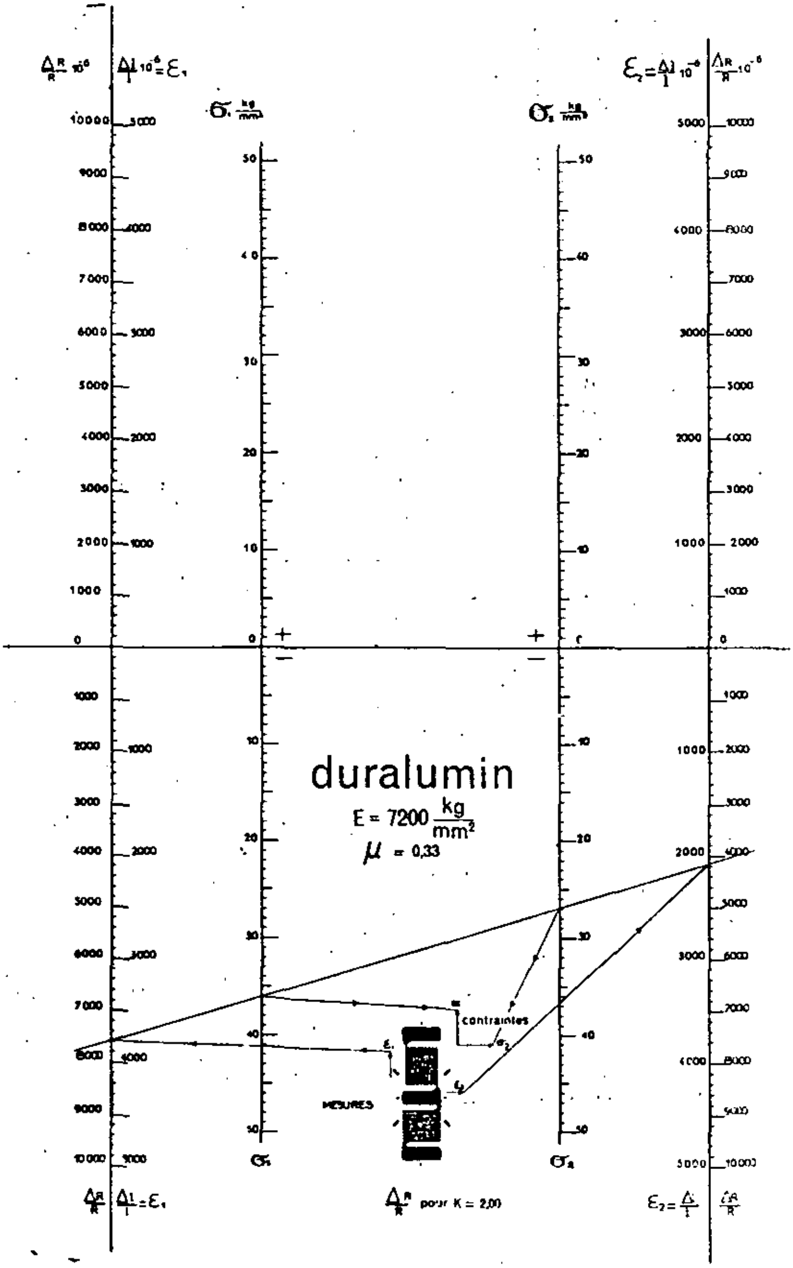
$$\varepsilon'_M = \frac{1-\mu K_t}{1+K^2}\left(\varepsilon_M - K_t\,\varepsilon_m\right) \qquad [55]$$

$$\varepsilon'_m = \frac{1-\mu K_t}{1-K_t^2}\left(\varepsilon_m - K_t\,\varepsilon_M\right) \qquad [56]$$

$$d' = d\left(1-\mu K_t\right)/\left(1+K_t\right) \qquad [57]$$

$$r' = r\left(1-\mu K_t\right)/\left(1+K_t\right) \qquad [58]$$

ABACO PARA EL
CALCULO DE
TENSIONES
(Para 2 medidas
según las direcciones
principales)



Cortesia de VISHYA MICROMESURES

PROPIEDADES DE LOS METALES DE USO MAS CORRIENTE

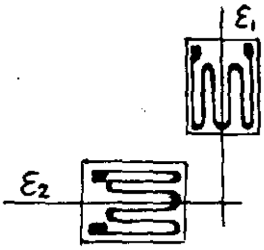
	Module d'Young E (1000 kg/mm²)	Coefficient de Poisson μ (s d)	$\frac{E}{1+\mu}$	$\frac{E}{1-\mu}$	$\frac{E}{1-\mu^2}$	σ_f	σ_r	σ_o / σ_a	Masse volumique 1000 kg/m³	Dilatation 10^{-6}/°C
Acier de Construction ...	21,0	0,285	16,34	29,37	22,87		20 à 60	1	7,80	13
Acier 45 SC 06	22,0	0,285	17,12	30,77	23,97		145	1	7,80	13
Aciers résistants usure ..	22,0	0,29	17,06	30,99	24,02			1	7,82	25
Acier inoxydable 18-10. ..	20,3	0,29	15,74	28,59	22,16		18 à 22	1	7,90	16,5
Invar	14,1	0,29	10,93	16,86	15,39		40 à 55	1		< 0,9
Fontes grises courantes ..	9 à 12	0,29	7,0 à 9,3	12,7 à 16,9	9,8 à 13,1	7 à 9	18 à 25	3,3	7,1 à 7,2	9 à 11
Fontes grises auto	10 à 13	0,29	7,7 à 10,0	14,1 à 18,3	10,9 à 14,2	10 à 15	22 à 35	3,4	7,1 à 7,4	9 à 11
Fontes grises lingotières .	5 à 8	0,29	3,9 à 6,2	7,0 à 11,2	5,4 à 6,7		8 à 12	3,5	7,1 à 7,2	9 à 11
Fonte graphite sphéroidal .	16 à 18	0,29	12,0 à 14,0	22,2 à 25,4	17,5 à 19,6	17 à 36	26 à 60	1,2	7,1 à 7,3	11 à 12
Fontes blanches non alliées	16 à 20	0,29	12,4 à 15,5	22,2 à 28,2	17,5 à 21,8		20 à 40	5	7,5 à 7,8	9 à 11
Fontes malléables	17 à 19	0,17	14 à 16	20,5 à 22,9	17,5 à 19,5	16 à 38	20 à 60	1	7,2 à 7,4	9 à 11
Titane	10,55	0,34	7,87	15,98	11,93	10 à 25	20 à 47	1	4,51	8,9
Alliage titane 6Al4V	10,9	0,34	8,13	16,52	12,33					
Alliage titane TA6V	10,5	0,34	7,83	15,91	11,88	60	90	1	4,42	8,0
Aluminium	7,05	0,34	5,26	10,68	7,98					
Alliage alu AU 4 G	7,5	0,33	5,63	11,19	8,41	12	20	1	2,8	23,5
Alliage alu AU 2 GN ...	7,5	0,34	5,60	11,36	8,48	12	37	1	2,8	22 à 24
Alliage alu AU 5 GT	7,0	0,34	5,22	10,61	7,92	10	22 à 26	1	2,8	23
Zicral AZ8GU	7,2	0,34	5,37	10,91	8,14		65	1	2,8	23,5
Cuivre	10,0	0,33	7,51	14,92	11,22		18	1,3	8,9	17
Laiton	9,2	0,33	6,92	13,73	10,33		20	1,4	7,30	18
Bronze ordinaire	10,6	0,31	8,09	15,36	11,73		24	3	8,40	17,5
Bronze au beryllium	13	0,34	9,70	19,70	14,71		80	3	8,25	17
Beryllium	30,0	0,05	28,57	31,58	30,08	20	30	1	1,85	12,4
Magnésium	4,60	0,34	3,43	6,97	5,20				1,74	25,6
Marbre	2,6	0,3	2,00	3,71	2,80		50	15	2,9	8
Béton	1,4 à 2,1	0,3	1,1 à 1,6	2,0 à 3,0	1,5 à 2,3		30	11	1,9	14
Verre	6	0,2 à 0,3	5,0 à 4,6	7,5 à 8,6	6,2 à 6,6		3 à 8	10		
Plexiglass	0,29	0,4	0,207	0,483	0,345		8	1,2	1,8	80 à 90
Araldite	0,30	0,4	0,214	0,500	0,357		5 à 8	1,2	1,15	90 à 130

1.16 PROBLEMAS DE CALCULO EXTENSOMETRICO

Problema nº 1

Una barra de acero está sometida a una tracción pura, montándose una banda en el sentido de la tracción. Calcular las tensiones principales, si leemos 1275 $\mu\delta$ y el acero de la barra tiene E= 21000 Kg/mm^2 y μ= 0,28

Problema nº 2



En un depósito cilindrico de aluminio (E= 7200 Kp/mm^2; μ= 0,33) se admite que las direcciones principales coinciden con los ejes vertical y horizontal y en tales direcciones se montan dos bandas extensométricas respectivamente. Las lecturas bajo carga son:

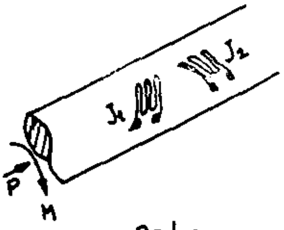
para J_1 $\varepsilon_1 = 3950\,\mu\delta$

J_2 $\varepsilon_2 = 2540\,\mu\delta$

$\tau = \frac{T \cdot P}{J}$

Calcular las tensiones en este punto.

Problema nº 3



R: 40mm

En un eje cilíndrico de acero (E= 21000 Kp/mm^2 μ= 0,28) de 80 mm de diámetro se han montado dos bandas, J_1 y J_2 a 45º respecto a su eje. El eje no sufre flexión, pero si una compresión P y un momento de torsión M.

En el curso de una primera experiencia, se obtienen como lecturas las siguientes:

$$\varepsilon_1 = -\varepsilon_2 = 1830\,\mu\delta$$

¿Cuales son las tensiones en el punto? ¿Cual la fuerza de compresión y el par?

En una segunda experiencia se obtiene

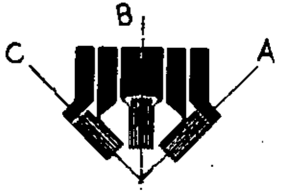
$$\varepsilon_1 = 2560\,\mu\delta \qquad y \qquad \varepsilon_2 = -1080\,\mu\delta$$

¿Cuales son la fuerza P y momento M?

Los problemas siguientes, se refieren al cálculo de rosetas, en ellos deberemos calcular:

- Direcciones principales máximas y mínimas
- Deformaciones y tensiones máxima y mínima.

Problema nº 4



Roseta de 45º
E= 7200 Kp/mm^2 μ= 0,34
Lecturas: A = - 3790 $\mu\delta$
B = - 3220 $\mu\delta$
C = - 4750 $\mu\delta$

Problema nº 5

E= 7200 Kp/mm^2 μ= 0,34
A= + 2080 $\mu\delta$
B= - 1800 $\mu\delta$
C= - 1200 $\mu\delta$

Problema nº 6

E= 21000 Kp/ mm^2 μ= 0,29
A= + 3580 $\mu\delta$
B= + 1930 $\mu\delta$
C= + 1370 $\mu\delta$

Problema nº 7

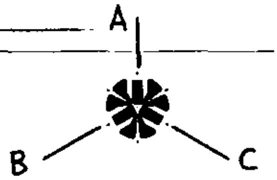
E= 21000 Kp/mm^2 μ= 0,29
A= + 1,792 $\mu\delta$
B= 817 $\mu\delta$
C= 868 $\mu\delta$

Problema nº 8

E= 21000 Kp/mm^2 μ= 0,29
A= + 340 $\mu\delta$
B= + 520 $\mu\delta$
C= - 710 $\mu\delta$

Dar directamente las tenciones, sin pasar por deformaciones.

Problema nº 9



Rosetas de 120º

E= 7200 Kp/mm^2 μ= 0,34

A= + 2400 μδ
B= + 2010 μδ
C= + 1370 μδ

Problema nº 10

E= 7200 Kp/ mm^2 μ= 0,34

A= + 4410 μδ
B= - 540 μδ
C= - 1920 μδ

Problemas nº 11

E= 21000 Kp/mm^2 μ= 0,29

A= -120 μδ
B= +540 μδ
C= +310 μδ

Problema nº 12

E= 7200 Kp/mm^2 μ= 0,34

A= + 1795 μδ
B= + 1803 μδ
C= + 1812 μδ

II TECNICA DE UTILIZACION DE LAS BANDAS EXTENSOMETRICAS

2.1. FABRICACION DE BANDAS EXTENSOMETRICAS

Una banda extensométrica está formada por dos elementos fundamentales que son el soporte y el conductor eléctrico sensible a las deformaciones, habiendo evolucionado grandemente la constitución y técnicas de fabricación de dichos elementos.

En un principio, se emplearon con gran difusión soportes de papel y conductores de sección circular colocados según la fig. 1, pero entre otros, presentaban los graves inconvenientes de la higroscopidad del papel, que hacía perder el aislamiento de la banda y el elevado factor de sensibilidad transversal en las partes curvas del conductor, intentándose compensar éste último efecto dando forma de zig-zag u otros diseños ingeniosos (fig 2). Actualmente una banda de calidad se fabrica sobre soportes de resinas epóxicas y por el procedimiento de fotograbado, se consiguen formas y dimensiones imposibles por los métodos clásicos (fig 3), ya que los modelos pueden hacerse a escalas muy aumentadas, constituyen éstas las llamadas bandas de trama pelicular o de film metálico.

fig 1

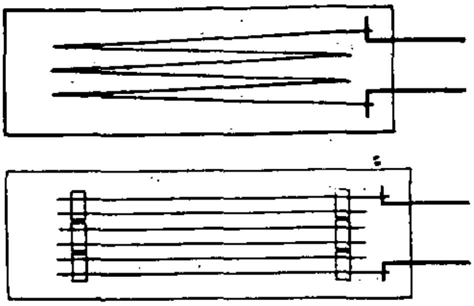


fig2

Los principios en que se basa la extensometría, suponen que las isostáticas de la estructura bajo ensayo, pasan a través de la parte activa del extensímetro y se ha podido comprobar por fotoelasticidad, que en un extensímetro pegado a una estructura, solo en sus extremidades hay distorsión de aquellas, y nó en la zona central; por dicho motivo, dando a la banda la forma indicada en la fig. 4, conseguiremos establecer en los extremos de los conductores activos una zona de anclaje en la que se inciden los isostáticas y por su mayor sección respecto a la parte activa la variación unitaria de resistencia es menor y despreciables los coeficientes de sensibilidad transversal y longitudinal.

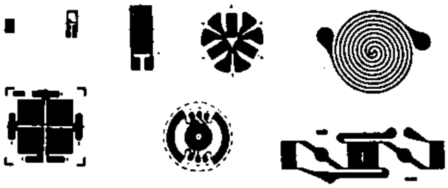


fig 3

La posibilidad de disponer de superficies adecuadas para la soldadura de los cables y la transparencia de los soportes, que permiten una colocación óptima del extensímetro, añaden ventajas a éste.

Las aleaciones del metal conductor responden a las características específicas de cada tipo, siendo a veces riguroso secreto el proceso de fabricación, en el que se incluyen técnicas sofisticadas para conseguir mejoras en la utilización de extensímetros. A título de ejemplo, en la serie CEA de la casa Vishay-Micromesures, el tratamiento dado a los extremos para soldadura de cables, hace posible que la unión soldada tenga mayor resistencia mecánica a la tracción que el cable que normalmente se utiliza, ventaja ésta que confiere seguridad a una medida extensométrica.

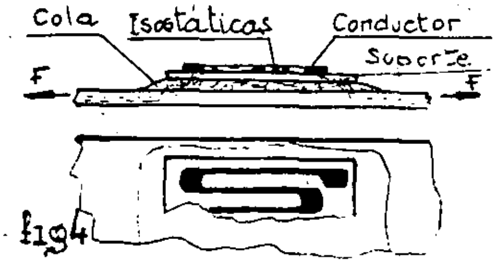


fig4

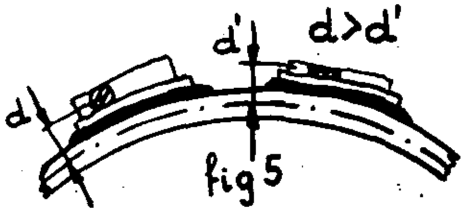


fig5

Otras ventajas de las bandas de film metálico residen, en que dado su pequeño espesor (4 micras), no introducen errores en la medida de deformaciones de secciones delgadas y se adaptan mejor sobre cualquier superficie (fig. 5).

Dejando al margen las bandas semiconductoras (de las que nos ocuparemos en otro capítulo) vemos en lo expuesto, que el verdadero sensor de las deformaciones es el conductor, siendo el soporte un medio de transición con la estructura, por lo que exige del pegado a la misma (bonded strain gauge) pero, en aplicaciones para fabricación de transductores, suele emplearse el conductor suelto montado sobre zafíros aislantes, (fig.6) que se deforma bajo estímulos mecánicos, sin necesidad del soporte propiamente dicho (unbonded - Strain-gauges).

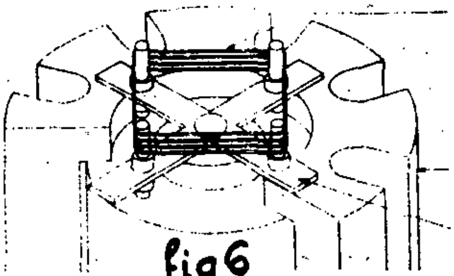


fig6

La banda puede ser posteriormente sometida a recubrimientos y opciones tales como inclusión de hilos de salida soldados, que en determinadas aplicaciones resultan de interés.

2.2 CARACTERISTICAS TECNICAS

22.1 Valor óhmico.

El valor de la resistencia óhmica de una banda viene condicionado por motivaciones de tipo eléctrico, y hay razones para que dicho valor sea elevado de una parte o pequeño de otra, por lo que debe establecerse un compromiso entre las posturas extremas.

Motivos que aconsejan un valor elevado de resistencias:

1. Señales elevadas para debiles deformaciones, en efecto, la señal es función de la tensión de excitación, por lo que conviene que ésta sea elevada, pero para que no circule una corriente excesiva, que por efecto Joule produzca un calentamiento inadecuado, el valor óhmico será alto.

2. Evitar los errores producidos por las resistencias de contacto de los conmutadores y líneas de conexión a los instrumentos, pues siendo éstos valores pequeños su influencia será menor cuando mayor sea la resistencia de la banda.

Motivos que aconsejan valores pequeños de resistencias

1. Evitar la caída de tensión interna considerando a la banda como generador de tensión.

2. Conseguir mejor aislamiento eléctrico entre la banda y la estructura.

3. Mayor robustez, pues resistencias elevadas obligan a conductores de muy pequeña sección y por tanto frágiles.

Por lo expuesto se ha establecido como valor normal y de uso más generalizado el de 120 ohmios, siendo también muy empleados los 350 (generalmente en transductores) 600 y 1000 ohmios.

Las tolerancias de fabricación son muy estrechas 0,15% con el fín de poder equilibrar los circuitos de medida, pero no sería práctico un exceso de dicha tolerancia en límites que puedan confundirse con la variación lógica, que por efecto de montaje, sufriría la banda en su instalación. La exactitud de la medida no será afectada, por ligeras dispersiones del valor nominal.

También se construyen bandas con valores nominales que son fracciones de los indicados para los casos en que la medida requiere un circuito con dos, tres ó cuatro bandas en serie (se hacen de 30, y 60 óhmios u otros valores que no suelen ser standard).

2.2.2. FACTORES DE SENSIBILIDAD

En el estudio teórico de las bandas extensométricas (1,2) vimos que hay dos factores K1 y K2 que relacionan la variación unitaria de resistencia del conductor con la deformación que sufre en sentido longitudinal y transversal respectivamente por efecto de las solicitaciones a que esté sometido el elemento donde se instala la banda.

La variación de la resistencia es motivada por el cambio de la geometría del conductor y de la conductividad, pero si bién el primer factor afecta prácticamente igual a todos los metales, el segundo es función de la aleación empleada en la fabricación del extensímetro y es por esta razón por lo que la forma y dimensiones de la banda no influyen sobre el factor de sensibilidad.

Los constructores de bandas, utilizan procesos de fabricación que mantienen el valor del factor de sentibilidad dentro de unas tolerancias estrechas en una serie, por lo que es importante en medidas con varios extensímetros procurar que no haya dispersión en dichos valores.

Por razones de la instrumentación asociado a las medidas extensométricas, se toma como valor nominal de la sensibilidad longitudinal de las bandas el de 2 y tolerancias admitidas como muy buenas son del ± 0,5%. El factor de sensibilidad transversal se expresa en tanto por ciento del longitudinal y no debe ser superior al 1%.

El fabricante indica el valor de K obtenido en unas condiciones determinadas de temperatura y sobre nedidas efectuadas con probetas de módulo de elasticidad y coeficiente de Poisson conocido, incluyendo curvas (fig. 7) donde se indica la variación del factor K respecto a variaciones de temperatura.

Para medir el factor K se utilizan balanzas de calibración basadas en producir una flexión circular a una probeta en la que se montan bandas correspondientes a una misma serie.

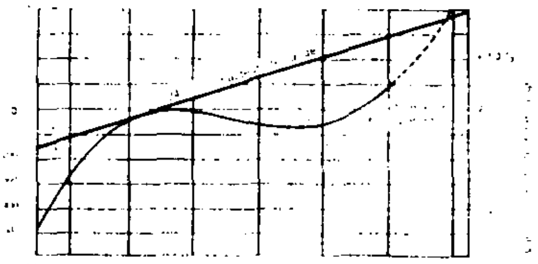


fig7

2.2.3. RESPUESTA DE TEMPERATURA

Una banda extensométrica mide todas las deformaciones que experimente el elemento sobre el que se monta, pero sabemos que las deformaciones producidas por dilataciones térmicas homogéneas no crean tensiones, por tanto (fig. 8) si consideramos una viga empotrada en un extremo sin carga alguna y hay variación de temperatura, aquella se dilatará y habrá una deformación que acusará la banda, pero por no originar tensiones, debe ser considerada como error.

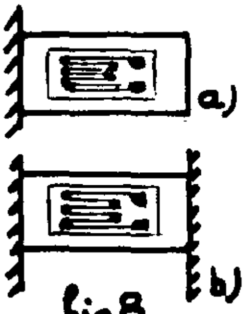


fig8

El error por variación de temperatura se corrige, dentro de ciertos límites, fabricando el conductor de la banda con coeficientes térmico de variación de la resistividad de igual valor y signo contrario al del coeficiente de dilatación lineal del cuerpo sobre el que montan.

En efecto:

$$R_0 = \rho_0 \frac{l_0}{S} \quad R_t = \rho_0 (1+\beta t) \frac{l_0(1+\alpha t)}{S}$$

$$\Delta R = R_t - R_0 = \frac{1}{S}\left[\rho_0 l_0 \alpha t + l_0 \rho_0 \beta t\right] = 0$$

$$\alpha = -\beta$$

α = coeficiente dilatación lineal
β = coeficiente de variación térmico de resistividad

La relación $\alpha = -\beta$ solo es lineal dentro de unos límites de temperatura para los cuales se dice que la banda está autocompensada, los fabricantes indican la curva de respuesta en temperatura de las bandas expresadas como microdeformaciones aparentes (fig.9).

En la fig. 8a vemos que al dilatarse la viga, si la banda es autocompensada, no experimentará variación alguna en su resistencia, por el contrario (fig.8b) si la viga está empotrada en sus extremos, se originan esfuerzos de compresión cuando dilate y la banda por tener el coeficiente $-\beta$ acusará un incremento negativo en la variación unitaria de resistencia, acusando precisamente la compresión habida.

Una banda solo puede ser compensada para materiales que tengan idéntico coeficiente de dilatación. Normalmente se compensan para acero ($\alpha = 11.10^{-6}/°C$) y aluminio ($\alpha = 23.10^{-6}/°C$).

Veremos en el capítulo de técnicas de Medida, que los efectos de origen térmico pueden compensarse con disposiciones de montaje adecuados.

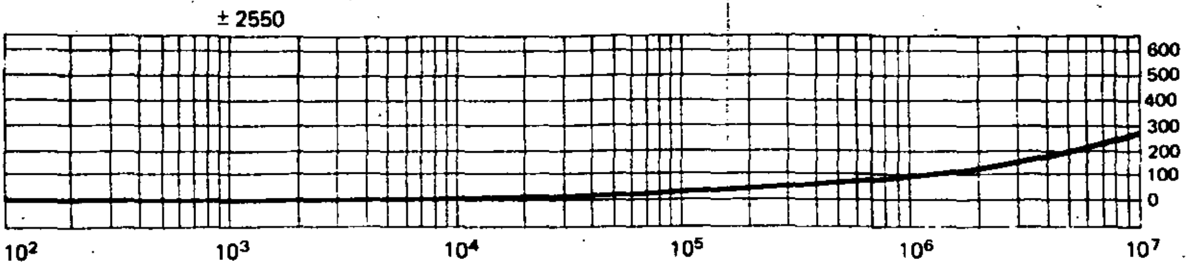


fig 10

2.2.4. LIMITES DE DEFORMACION: ESTATICA Y DINAMICA

La máxima deformación que puede soportar un extensímetro bajo carga estática se expresa en %, de la longitud de su rejilla o parte activa y depende de varios factores, entre ellos:

a) Temperatura de utilización. El valor indicado por el fabricante se refiere a temperaturas ambientes (24ºC) pero a temperaturas criogénicas, la deformación es solo una pequeña fracción de dicho valor.

b) Ductibilidad de la aleación que constituye el conductor sensible.

c) Maleabilidad del soporte de la banda y del adhesivo.

d) Forma y dimensiones del extensímetro.

e) Calidad del montaje en la extructura

Las bandas impresas de trama pelicular, admiten mayor deformación estática que las de hilo.

El fenómeno de fatiga bajo cargas alterna, presenta aspectos que influyen en las medidas y deben tenerse en cuenta pues pueden introducir errores.

El conductor metálico del extensímetro cuando se monte sobre estructuras sometidas a tensiones alternas, sufre una fatiga cuyo efecto principal es producir una deriva del valor óhmico de la banda, por èste motivo se ensayan las bandas sometiéndolas a ciclos de amplitud constante (±1500 µδ; ±1250 µδ....) observando cuando la deriva del valor óhmico representa una deformación aparente de 100 µδ, valor éste admitido como límite (fig. 10).

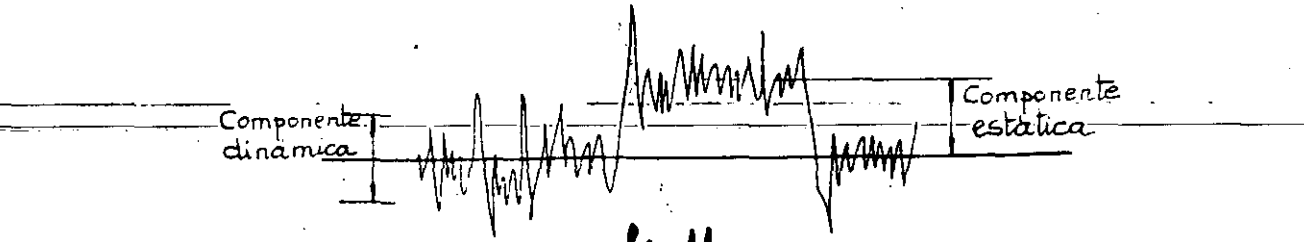


fig 11

Si en una medida dinámica queremos obtener con exactitud los valores de las componentes estáticas y dinámica (fig. 11) prestaremos especial atención en la elección del extensímetro adecuado y sobre todo se cuidará que las soldaduras de los hilos de conexión de los instrumentos a la banda sean puntuales para evitar concentración de esfuerzo en la banda y que el tamaño de la misma sea muy pequeño, ya que son los factores más influyentes para evitar llegar al límite de fatiga. En un fenómeno vibratorio la deriva no tiene gran importancia si lo que interesa conocer es solamente la amplitud de la oscilación.

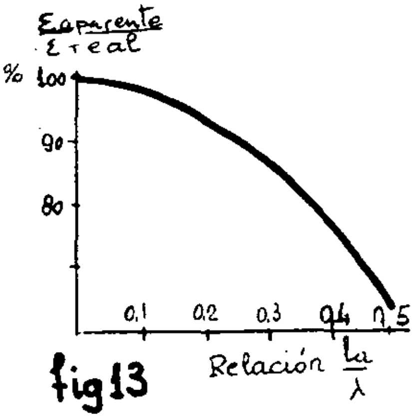


fig 13

2.2.5. LIMITE DE LA RESPUESTA EN FRECUENCIA

Una banda extensométrica por tener una longitud finita, actua como un integrador de todas las deformaciones que ocurren a lo largo de la parte activa, por esta razón si la longitud de onda del fenómeno vibratorio que se quiere medir coincide con la longitud activa de la banda (fig. 12) no acusaremos deformación alguna pues la mitad sufrirá alargamiento y la otra mitad compresión.

Las deformaciones son fenómenos que se propagan a la misma velocidad que el sonido, por tanto conocido éste valor y el de la frecuencia del fenómeno, la longitud de onda $\lambda=\frac{v}{f}$ nos indica el valor límite en el cual una banda de longitud activa=$l_a\lambda$ no causaría deformación.

Para evitar la anomalía anterior se admite como valor normal de l_a el 10% de λ con lo que el % de perdida de sensibilidad es prácticamente nulo (fig. 13),

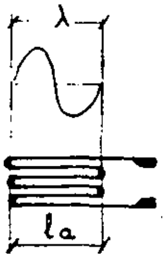


fig 12

Se fabrican bandas con longitudes activas de 0,4 mm por lo que se pueden medir en aceros ($c = 5000$ m/seg) frecuencias de 10^6 Hz aunque la limitación en éste caso estó en los instrumentos de medida.

Otros factores influyen en la limitación de la respuesta en frecuencia de las bandas, pues si bien la debil masa de inercia de la misma favorece el seguir fielmente un fenómeno dinámico, la elasticidad de adhesivos y soportes debe tenerse en cuenta, aunque su valoración es dificil de obtener de forma experimental, debiendo cuidarse la elección de adhesivos en medidas críticas.

2.2.6. FENOMENOS DE FLUENCIA E HISTERESIS

Supongamos que una probeta sobre la que hay montada una banda extensométrica es sometida a esfuerzos de tracción simple (fig 14) las deformaciones de la probeta son entonces transmitidas al conductor activo a través del adhesivo y del soporte, creandose unas solicitaciones de cortadura principalmente en los extremos de la banda, que deben compensarse con la fuerza antagonista que se origina en el conductor activo.

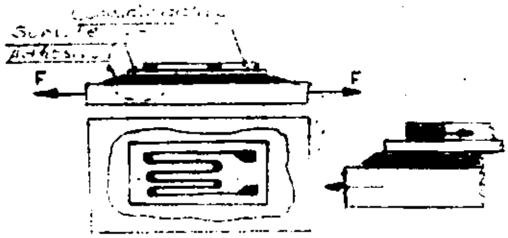


fig 14

La calidad del adhesivo y su elasticidad determinarán la magnitud de la relajación del mismo bajo las solicitaciones constantes a que esté sometido y por consiguiente que permita al conductor activo un lento retorno a su estado original. El fenómeno descrito es el de fluencia de una banda y tiene importancia considerable en medidas estáticas, no siendolo tanto en medidas dinámicas.

Por la propia naturaleza del fenómeno, se vé que la temperatura juega un papel importante en la fluencia, así como las dimensiones de la banda, participando en razón inversa al tamaño.

Es práctica muy aconsejable, someter las probetas a cargas y descargas sucesivas de magnitud lo mayor posible, antes de efectuar las medidas.

Ligado al concepto anterior puede considerarse el fenómeno de histeresis, el cual ocurre cuando queda una deformación residual después de someter a solicitaciones la probeta sobre la que está instalada la banda, siendo el principal motivo de este fenómeno que el adhesivo o soporte absorba parte de la energía de deformación y no la transmita al conductor activo.

2.2.7. NIVELES OPTIMOS DE EXCITACION

La señal eléctrica que obtendremos de cualquier circuito de medida con bandas extensométricas , será proporcional a la tensión de excitación del mismo, lo cual hace presumir el empleo de niveles elevados de excitación, sin embargo hay razones para limitar dichos niveles.

La corriente eléctrica que circula por el conductor de una banda excitada, origina por efecto Joule, una elevación de temperatura al disiparse el calor producido, por cuyo motivo pueden aparecer las perturbaciones siguientes:

a) Alterar el efecto de autocompensación, cuya estabilidad es mejor con niveles bajos de excitación.

b) Modificación del estado de tensiones de la estructura bajo ensayo, al absorber ésta el calor disipado por la banda, sobre todo en materiales plásticos.

d) Derivas del cero, sobre todo en circuitos con varios bandas y en las cuales la disipación de calor no será igual y simultánea.

Los parámetros de mayor incidencia en la determinación del nivel óptimo de excitación.de una banda son:

1.- Superficie de la rejilla, cuya influencia afecta al poder de disipación de calor.

2.- Resistencia óhmica de la banda, que limita el paso de corriente.

3.- Coeficiente de conductibilidad térmica de la estructura.

4.- Tamaño de la probeta o estructura donde se monta la banda, que determina el poder de absorción de calor.

5.- Condiciones ambientales.

6.- Calidad del montaje de la banda, cuidándose de que no hayan burbujas de aire entre el soporte y la probeta.

En la tabla I se indica la potencia por cm^2 que pueden disipar las bandas según los materiales donde estén montadas y para precisiones bajas, elevadas o medias (datos cortesia de Vishay-Micromesures).

POTENCIAS RECOMENDADAS EN WATS/CM^2

PRECISION REQUERIDA

DISIPACION DE CALOR	ESTATICAS			DINAMICAS		
	ELEVADA	MEDIA	BAJA	ELEVADA	MEDIA	BAJA
Excelente. Piezas grandes de aluminio o de cobre	0,30 ó 0,75	0,75 ó 1,5	1,5 ó 3	0,75 ó 3	1,5 ó 3	3 ó 8
Buena. Piezas grandes de acero.	0,15 ó 0,30	0,30 ó 0,75	0,75 ó 1,5	0,75 ó 1,5	1,5 ó 3	3 ó 8
Media. Piezas pequeñas de acero inoxidable o titanio.	0,08 ó 0,15	0,15 ó 0,30	0,30 ó 0,75	0,30 ó 1,5	0,75 ó 1,5	1,5 ó 3
Mala. Plásticos, resinas epoxy.	0,01 ó 0,03	0,03 ó 0,08	0,08 ó 0,15	0,08 ó 0,15	0,15 ó 0,30	0,15 ó 0,75
Muy mala. Poliestireno, materiales acrílicos.	0,001 ó 0,003	0,003 ó 0,008	0,001 ó 0,03	0,001 ó 0,008	0,003 ó 0,015	0,03 ó 0,08

La tensión de excitación se deduce a la fórmula:

Potencia disipada: $\frac{Ve^2}{4R} = We_d$ en donde

Ve= Tensióm de excitación en Voltios

R = Resistencia nominal de la banda

La potencia por unidad de superficie es

$$\frac{W_d}{S} = W$$

Siendo S la superficie de la rejilla

Si solo disponemos de una fuente de alimentación con s lida fija de tensión y esta es elevada para excitar el circuito de m dida se ponen en serie unas resistencias que produzcan una caida de tensión determinada, pero sin olvidar efectuar las correcciones adecu das por la perdida de sensibilidad que introducen las mencionadas re tencias.

2.3. PRACTICA DE MONTAJE DE BANDAS

2.3.1. Preparación de superficies

La instalación de una banda extensométrica tiene como fundamento la perfecta unión entre la banda y el cuerpo de ensayo.

Para el extensometrista cada montaje de circuitos de medida supondrá un aumento de su experiencia y una garantía de que su labor es satisfactoria, solo cuando por un exceso de confianza omite alguna de las operaciones que se indican como preceptivas, el error aparece, pero desgraciadamente no se manifiesta inutilizando la medida, sino dando como ciertos unos resultados falsos, de ahí que será criterio firme el observar toda la meticulosidad humanamente posible, con la certeza de que, si así se hace, se obtendrá resultados que justificarán el empeño puesto.

La banda puede elegirse, dentro de ciertas opciones que ofrece el fabricante, adaptada a las condiciones de utilización, pero no así la superficie donde deba instalarse, por lo que ésta última deberá ser preparada por el usuario, así como la soldadura de cables que configuran el circuito de medida.

2.5.1. Preparación de superficies

Toda superficie que debe recibir una banda se someterá generalmente a unos tratamientos mecánicos y químicos para conseguir el mayor rendimiento del adhesivo, sin que dichos tratamientos puedan suponer una modificación local de las características del cuerpo a ensayar. Dimensionalmente, se tratará una superficie doble (como mínimo) de la superficie total de la banda.

El proceso prévio será el de limpieza y desengrasado, para el que se utilizará preferentemente cloroetileno de calidad, para metales y freón para plásticos, para ello se deposita el desengrasante sobre la superficie (se facilita esta operación si viene envasado en spray) y sin dejarlo evaporar se seca con una gasa limpia y de una sola pasada, repitiendose esta operación hasta que la gasa aparezca totalmente limpia.

Conviene indicar que siempre que haya que limpiar o secar una superficie debe hacerse con una gasa limpia (no necesariamente esterilizada) o a veces con papel absorbente tipo Kleenex pero nun ca con algodones que dejarían hebras depositadas. Además la limpie se hará en una sola pasada y jamás utilizando la misma gasa para d pasadas sucesivas, las razones son obvias ya que si la gasa es rep sada sobre la superficie, en vez de limpiar por arrastre, por efec de estar impregnada de disolvente, la suciedad o grasa existente s disolvería más, entrando en las minusculas oclusiones que existan.

En montajes sobre metales, recordemos que al estar c tituidos por cristales orientados al azar, un pulido superficial p sentaría el aspecto de un espejo al quedar incluidas entre los cri tales las pequeñísimas partículas arrancadas, por lo que la adhesi y cohesión en estas zonas seria muy dudosa, por tal motivo se comb el tratamiento mecánico por abrasión con un ataque por un ácido de

El proceso de abrasión dependerá del estado inicial la superficie comenzando con papeles de carburo de silicio de gran 400, 200 o 150 respectivamente y que previamente se ha humedecido el ácido, atacando en sentidos alternativos y que formen 90º entre ellos, con el fín de en cada pasada, eliminar las "crestas" que sob el metal se van marcando; la coloración peculiar que adquiere la perficie y la desaparición de las marcas en un sentido cuando se que a 90º, indican que esta operación está concluida, debiendose p ceder inmediatamente al secado con gasas.

Posteriormente y de inmediato, la superficie se hum ce con un producto neutralizador (solución alcalina detergente) c fín de que su pH sea adecuado para recibir el adhesivo.

En resumen haremos lo siguiente:

1º Limpieza grosera, quitar óxidos pinturas, etc, en una superfic doble que la de la banda.

2º Desengrasado absoluto y secado.

3º Abrasión progresiva combinada con ácido y secado.

4º Neutralización y secado.

Lógicamente el proceso anterior es indicado para ciertos metales, siempre habrá que seguir las indicaciones concretas del fabricant de la propia experiencia.

Si se trata de superficies porosas como el caso del horigón, habrá que impermeabilizar la zona de asentamiento de la banda, onsiguiendose buenos resultados dando después de la limpieza, una caa previa de adhesivo.

En vidrio y plásticos será suficiente el empleo de freón su limpieza con gasas.

.3.2. Trazado de ejes de referencia

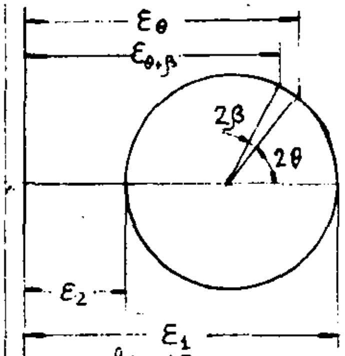


fig 15

Una mala alineación de los ejes de la banda con la dirección en la que deseamos medir las deformaciones introduce errores que son función: de la relación entre las deformaciones máximas y mínimas, del ángulo que forma la dirección en la que se desea medir y la dirección de la deformación principal máxima y del ángulo β o error de montaje de la banda (fig. 15).

Como por razones de montaje solo podemos influir sobre β , tendremos que esforzarnos en conseguir que este error sea mínio, para ello hay que determinar sobre la superficie de asentamiento e la banda, los ejes de la dirección en que deseamos medir, pero tenremos que tener en cuenta que no podemos bajo ningún pretesto, altear el estado de preparación de la superficie según se explicó en el partado anterior.

Algunos montadores utilizan (nefastamente) puntas de cero de trazar, que al producir pequeñas incisiones en el material, lteran su extructura, por tanto, nosotros recomendamos siempre que ea posible no trazar sino grabar químicamente los citados ejes.

Con los instrumentos adecuados a la precisión de la meida (escuadras, goniómetros, compás, trazadores ópticos de precisión tc. etc) buscaremos unas referencias ortogonales en los límites de a zona que se ha limpiado procurando que no haya contacto de los tiles con la superficie limpia, para evitar su contaminación; situaos las referencias tracemos con un bolígrafo de punta fina o con un apiz de grafito duro (5 ó 6) los ejes completos sobre la superficie reparada. Posteriormente, un palillo cuyo extremo lleve una bolita

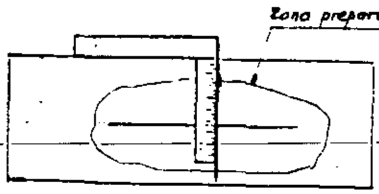


fig16

fig17

de algodón (los utilizados en Pediatría y de venta en farmacias son muy adecuados) se humedece con ácido y se pasa sobre los trazos del bolígrafo o lápiz, secando a continuación y se repite la operación pero humedeciendo un nuevo algodoncito con neutralizador; de esta forma la superficie mecánicamente no se ha modificado y sí veremos que han sido grabados los ejes de referencia, ya que la marca de grafito ha impedido la acción del ácido - sobre la propia línea y a continuación el neutralizador ha limpiado el grafito que se depositó. Este procedimiento tiene una demostrada eficacia por innumerables experiencias y es práctica su aplicación en metales.

Otra solución consiste en marcar con lápiz los ejes, pero sin que estas lleguen a cortarse dejando siempre libre la superficie - del soporte de la banda (fig. 17) pero se ve que conseguir este entraña una pericia grande y no queda exenta de problemas de contaminación de la superficie.

2.3.3. Pegado de extensímetros

El adhesivo utilizado para el pegado de bandas deberá reunir unas características adecuadas a su uso y nunca se pecará por exceso en las exigencias que en su elección hagamos. Tienen preferencia todos aquellos que solidifican por polimerización, es decir que la totalidad de los átomos que forman los componentes (normalmente dos) constituyen el sólido final, a diferencia de los pegamentos normales que solidifican por evaporación de un disolvente.

En general un buen adhesivo tendrá las siguientes características:

a) Permitir su aplicación en películas delgadas para no introducir - errores por distanciamiento de la rejilla a la superficie.

b) Ser neutro a la superficie y al soporte de la banda.

c) Transmitir los esfuerzos a la banda sin fenómenos de fluencia.

d) Técnica de aplicación facil.

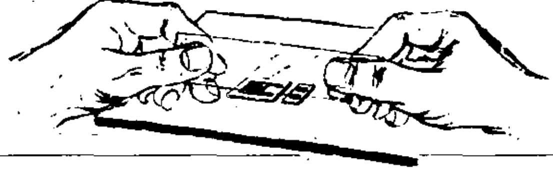
e) Utilización en un márgen lo más amplio posible respecto a condiciones ambientales.

Será dificil que un solo adhesivo cumpla en grado óptimo las condiciones anteriores, pero siempre será factible establecer un compromiso para aplicaciones concretas.

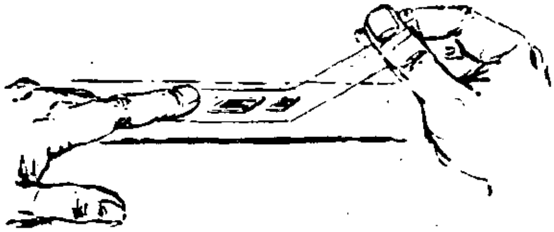
Hay pegamentos de aplicación sencilla y rápida cuyo uso es de interés en piezas grandes y usos generales donde la medida se haga a temperaturas ambientales normales (20º á 60ºC) un ejemplo de aplicación de las mismas se expone gráficamente en la fig. 18, referente al tipo M-200 de la firma Vishay-Micromesures.

Para aplicaciones que exijan una mejor precisión, como puede ser el caso de fabricación de captadores, se utilizarán adhesivos que deben someterse a un tratamiento térmico, operación que no deja de ser engorrosa. En cualquier caso, el fabricante dará normas claras de aplicación. Para usos de condiciones extremas (1000ºC) se comprende que los adhesivos se descompondrían, para ello, existen bandas encapsuladas en una vaína metálica que son fijadas por soldadura eléctrica por puntos con utensilios adecuados.

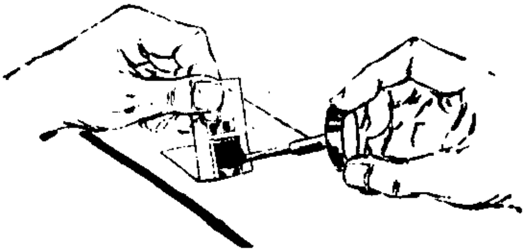
Junto con la banda, es muy práctico pegar unos soportes de terminales impresos que ayudarán a la soldadura e instalación del cableado.



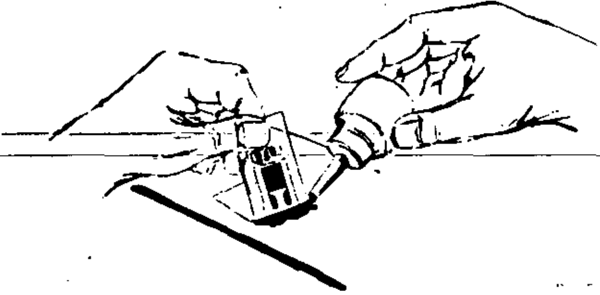
a) la banda y el terminal impreso se colocan sobre un cristal totalmente limpio y con papel transparente autoadhesivo, se cubren y se separan del cristal procurando no doblar la banda.



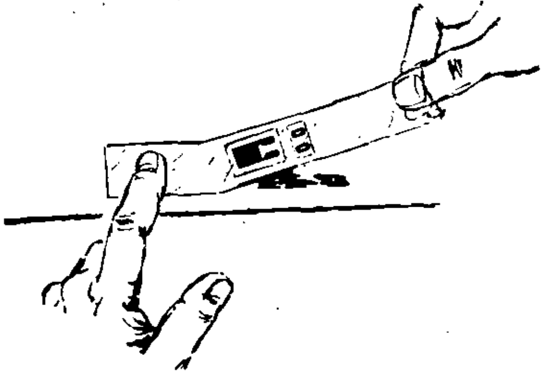
b) se situa la cinta y banda sobre el punto de medida, fijando un extremo y levantando el otro.



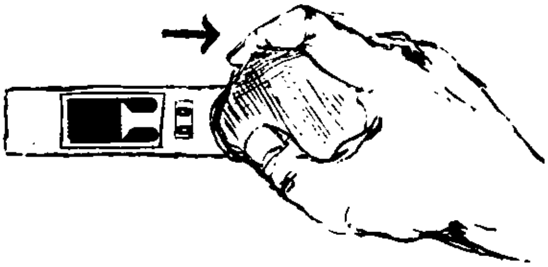
c) con el pincel del acelerador se aplica éste sobre el reverso de la banda y terminal, procurando no contaminar la banda con adhesivo de la cinta. Dejar secar un minuto.



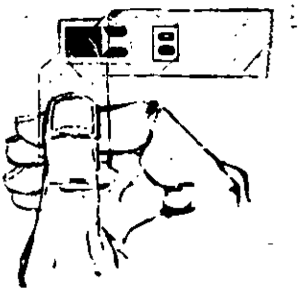
d) depositar una o dos gotas de adhesivo sobre la superficie de asentamiento.



e) se va bajando la cinta y con un dedo se hace ligera presión de izquierda a derecha y evitando tocar directamente el adhesivo.



f) una gasa se pasa varias veces para evitar se formen burbujas de aire.



g) a los 10 minutos como mínimo se puede retirar el papel transparente que ayudó a pegar la banda como se indica.

fig. 18

La soldadura de las bandas a los hilos de unión de los instrumentos de lectura, requieren una especial atención y el montador necesitará adquirir cierta expeciencia para dominar esta operación.

En la composición de las soldaduras se emplean aleaciones de plomo con estaño, plata o antimonio, que llevan o nó incorporada una resina y según las proporciones de dichas aleaciones resultan unas características determinadas de conductividad eléctrica, comportamiento a solicitaciones mecánicas, respuesta en temperatura etc. por todo ello no es recomendable el uso de soldaduras comúnes en aplicaciones de taller eléctrico o electrónico. Especial atención tiene el conocimiento de la temperatura de fusión que debe ser lo más inmediata superior a la que estará sometida el circuito de medida, con el fín de no tener que aportar más calor del necesario al efectuar las soldaduras.

Según el tipo de soldadura elegido será conveniente o necesario utilizar un fundente, sobre todo para hilos muy delgados, pero será totalmente imprescindible limpiar con un decapante adecuado los puntos de soldadura con el fín de eliminar los residuos de fundente y resina que podrían ocasionar corrosiones y fenómenos parásitos por efecto "pila" ya que evidentemente quedarían dos metales y un electrolito.

El soldador juega un papel muy importante, siendo recomendados aquellos de temperatura regulable; la punta del mismo nunca será cónica sino que tendrá una tàlla en forma de bisel. Para evitar que los cables puedan ejercer esfuerzos en la banda que pudiesen deteriorarla debe utilizarse siempre que sea posible un terminal impreso que servirá de apoyo al cable (que será de varios hilos) al que previamente se le separó un hilito y se estañó tal y como se indica en la fig. 19.

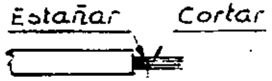


fig 19

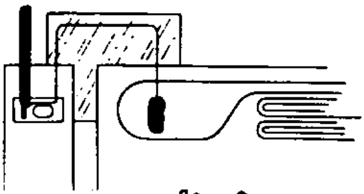


fig 20

En general seguiremos el siguiente proceso:

1º Preparar el cable según la fig. 19

2º Proteger con papel autoadhesivo debil la banda, dejando al descubierto solamente los puntos de soldadura.

3º Depositar una gota de soldadura lo más pequeña posible sin aportar excesivo calor que podría desprender la banda del soporte. No debe durar esta operación más de 2 segundos, si no se consiguen el primer intento, dejar enfriar y repetir.

4º Presentar el cable ya preparado y sin aporte de soldadura, solamente manteniendo caliente y muy limpio la punta del soldador, fijar los cables a los terminales y a la banda, tal y como se indica en la fig.20.

En la banda conviene que la gota de soldadura sea lo menor posible para evitar concentración de esfuerzos, de ahí que el procedimiento explicado favorezca ésta condición al ser más fino el hilo de unión del terminal a la banda, a la vez que se consiguen dar mayor seguridad al montaje, pues un fuerte tirón del cable rompería el terminal pero no la banda.

Hemos ofrecido unas normas generales ya que el fabricante indicará en cada caso las instrucciones concretas.

2.5.5. Comprobaciones

Una vez insralada una banda deberán efectuarse diversas comprobaciones siendo preceptivas:

1º Inspección ocular. Debe hacerse con una lupa de 20 aumentos o más para confirmar que se ha situado correctamente la banda a la vez que se observará que no han quedado bolsas de aire ni "lagunas" (zonas sin adhesivos) bajo el soporte de la misma.

2º Comprobación del aislamiento. Se utilizará un megohmetro cuya tensión no exceda los 50 V, si es de válvula mejor y jamás se hará uso de los medidores de aislamiento de tipo magneto que quemarían la banda.

El aislamiento deberá ser mejor que 100 megohms, ya que un aislamiento menor, equivale a introducir un error, por colocar en paralelo con la banda otra resistencia; se puede calcular dicho error, en efecto, consideremos un aislamiento de 2 Mohms.

3º Medida del valor óhmico de la banda. Utilizar un instrumento que aprecie decimas de ohmio como mínimo; esta comprobación tiene dos objetos; el primero saber que no está rota ni cortocircuitada la rejilla y el segundo conocer la dispersión del valor nominal, sobre todo en circuitos con varias bandas para controlar desequilibrios excesivos.

2.5.6. Protecciones

Desde medidas efectuadas en laboratorio, hasta las difíciles en los conos de cohetes o cascos de barcos, encontraremos una serie de condiciones ambientales que juntamente con la duración de la medida exigirán proteger un elemento delicado con es la banda extensométrica de forma adecuada.

Las bandas, de por sí, son presentadas bajo opciones que aportan una determinada protección, así las hay encapsuladas sobre dos láminas, una inferior que constituye el soporte y otra superior de la misma naturaleza y que deja libre solo los terminales para la soldadura de cables, ésta protección evita la proyección del estaño en la soldadura y mejora enormemente el aislamiento. Otras opciones llevan unos hilos soldados, por lo que el soporte superior cubre totalmente a la banda (fig. 21).

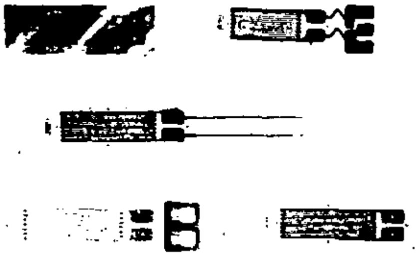


fig 21

En general la protección la consideramos bajo el aspecto de aislamiento eléctrico y de fortaleza mecánica y previamente a la instalación de la banda tendremos que conocerla, para preparar la superficie adecuadamente antes del pegado de la misma

Los criterios que debemos tener en cuenta para elegir los productos de protección estarán basados en:

a) Temperaturas extremas durante la medida, p.e. Probeta en laboratorio 22ºC ± 3ºC; estructura expuesta al sol 0-60ºC estructura de un avión en vuelo -50ºC + 120ºC.

b) Duración de las medidas, p.e. 1 hora en laboratorio; 1 año en un punto sumergido del casoo de un buque.

c) Ambiente, p,e, aire seco, aire humedo, agua, aceite, chorro de agua, gases corrosivos, hidrocarburos,

No debemos olvidar antes de la aplicación de los protectores, cercionarnos de que no hay restos de adhesivo alrededor de la zona a proteger, que se limpió bien la resina fundente de las soldaduras, que la superficie y los cables están preparados para que el protector se adhiera, que no hay humedad, etc. en una palabra, no desdeñar ningún esfuerzo que posteriormente pueda inutilizar varias horas de laboriosos trabajos.

Una práctica muy aconsejable, siempre que sea posible, será lo de conectar provisionalmente el instrumento de lectura al circuito antes de protegerlo y sometiendo aquel a alguna solicitación, observar que el funcionamiento es lógico.

Por último, no olvidar tomar datos de posición, fotos, numeración de cables, esquemas etc. antes de la protección, ya que posteriormente sería imposible, al quedar el circuito tapado por los protectores.

La aplicación del protector la haremos siguiendo siempre las indicaciones del fabricante pero como orientación tendremos presente:

1º Extender bién el producto sobre la superficie limpia y si hay que dar varias capas, que la última cubra por completo a las anteriores. Algunos productos vienen acompañados de un componente previo, que debe aplicarse sobre la superficie con pincel y dejar secar perfectamente para luego aplicar el protector y conseguir así la mejor adhesión. Vijilar que no queden bolsas de aire.

2º Cuidar que el espesor del protector sea el adecuado, muchos protectores son blandos y fácilmente las bolitas puntuales de las soldaduras, pueden atravesar el protector con pequeñas presiones, originando contactos de masa indeseados.

3º Protección del extremo de los cables de unión a instrumentos, pues de nada sirve esmerarse en la banda si dejamos opción a que por la vaina de los cables queden huecos por donde se perdería la protección.

La fig. 22 indica un acabado tipo de protección.

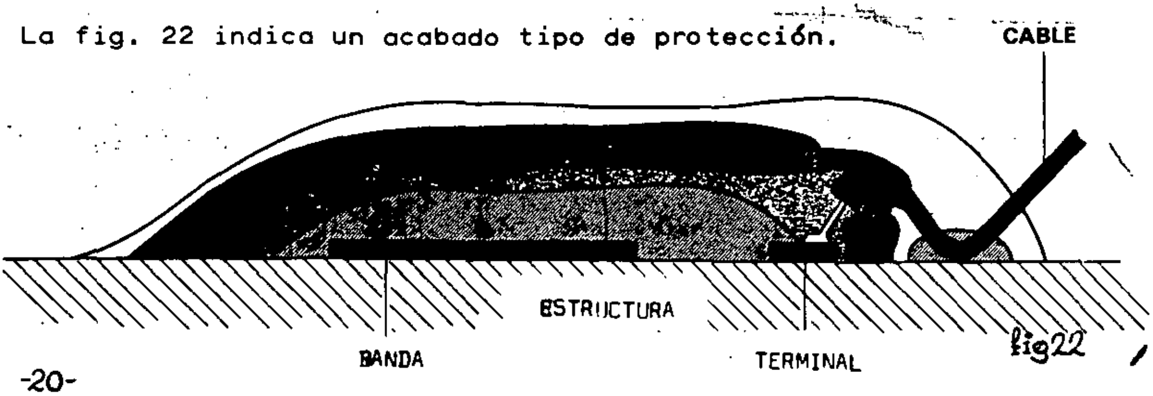


fig22

2.6.1. Indicadores de propagación de fisuras

Dos son los motivos que pueden hacer necesario el uso de estos sensores: detectar la aparición de una fisura o determinar la velocidad de propagación de la misma, en ambos casos, si bien el sensor será el mismo, variarán los instrumentos de lectura.

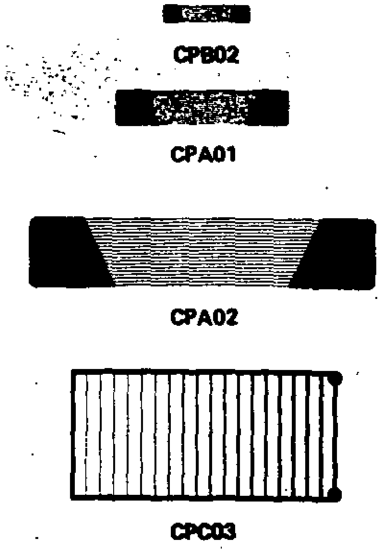


fig 23

Estos indicadores están formados por una serie de hilos en paralelo (fig. 23) montados en un soporte similar al de los extensímetros, que se pega en el punto donde se producirá la fisura, y que cuando aparezca, romperá un determinado número de conductores, deduciéndose la longitud de la fisura por medida de la resistencia con un ohmetro; si por el contrario el momento de aparición de la fisura es registrado de forma contínua por un oscilógrafo, deduciremos la velocidad con que se propaga (fig. 24).

La aleación de la que están constituidos es suficiente para soportar deformaciones superiores a ± 2000 μδ más de 10^8 ciclos y son montados con técnicas similares a las utilizadas en los extensímetros.

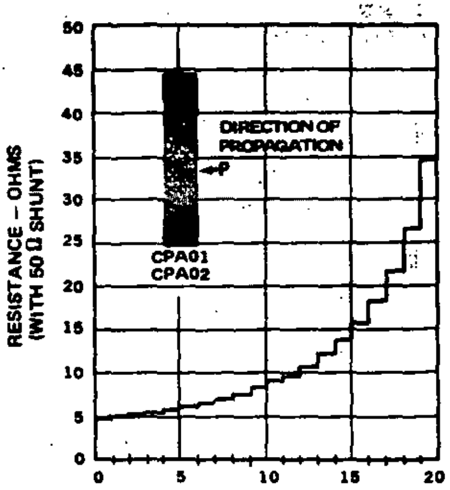


fig 24

Los efectos de temperatura tienen poca influencia.

2.6.2. Indicadores de fatiga

Al contrario que las bandas extensométricas, que miden deformaciones por variaciones instantáneas de su resistencia, los indicadores de fatiga (S/N) guardan "en memoria" todas las deformaciones experimentadas después de su instalación. La memoria aludida viene representada por una modificación permanente del valor nominal de su resistencia, que es función de la amplitud de las deformaciones y de la frecuencia con que se producen.

Las leyes de Wöhler nos dicen que:

1º En una pieza sometida a cargas alternas, la carga de rotura disminuye.

2º El número de alternancias que hay que producir para la rotura es tanto menor, cuanto mayor es la amplitud de las mismas.

3º Existe un valor de deformación máximo para el cual no se produce rotura sea cúal sea el número de ciclos con que se aplique.

En la fig. 25 se expresa gráficamente lo expuesto.

Estudios realizados por Miner, permiten afirmar que el porcentaje de vida de una pieza sometida a tensiones variables, es el mismo si aumentando la amplitud de las tensiones disminuimos su frecuencia o viceversa, siguiendo la proporción obtenida según los criterios de Wöheler.

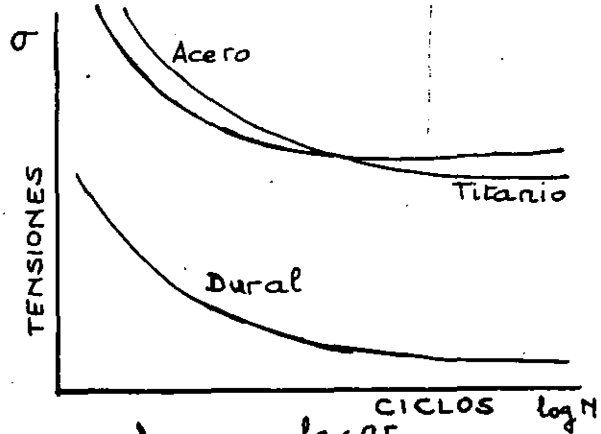


fig 25

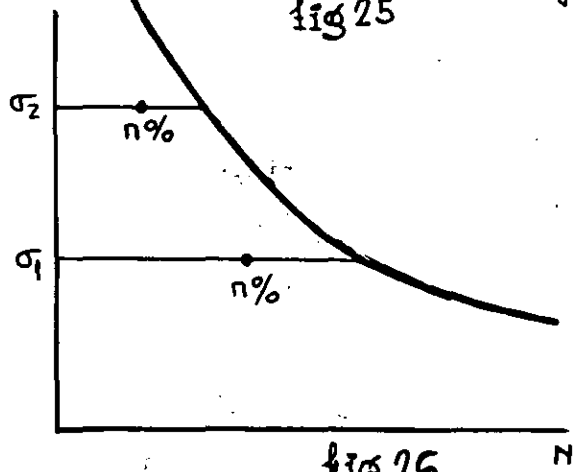


fig 26

En la fig. 26 vemos que el tanto por ciento de envejecimiento de una pieza es el mismo sometido a la tensión σ_1 y C_1, ciclos que si se somete a la tensión σ_2 y C_2 ciclos.

Se considera que las tensiones aplicadas escilan entre un valor σ máximo y un mínimo O, si así no fuese, logicamente habrá que considerar los efectos de una componente contínua más la carga variable.

Si bién en su aspecto los indicadores de fatiga (fig. 27) son semejantes a las bandas extensométricas, la constitución de su elemento sensible es bién distinta, ya que la aleación de la rejilla persigue aumentar al máximo el efecto que en los extensímetros se trataba de eliminar; en efecto recordemos (2.2.4.) que en las bandas se establece como límite deformaciones dinámicas, aquel que produce una deriva de

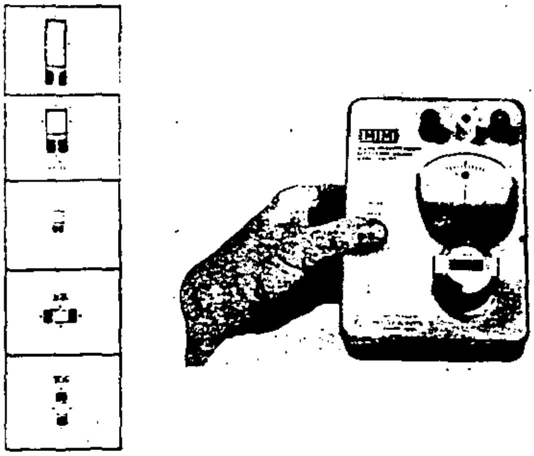


fig 27

$100\,\mu\delta$, equivalente a un incremento de 0,024 ohms en una banda de 120 ohms, mientras que ahora pretendemos que estos valores sean del orden de 7 a 10 ohm. Se constituyen en aleación de constantan con valor nominal de 100 ohm.

La variación de la resistencia del indicador de fatigas es producida por una distorsión de su red cristalina y por la aparición de microfisuras de la aleación de que se compone su rejilla y ha podido demostrarse experimentalmente que en algunos metales, empleados en construcción normalmente, se produce el mismo fenómeno; de ahí que estos sensores cuando son montados sobre piezas mecánicas puedan indicar con gran fidelidad el estado de envejecimiento de los materiales midiendo la desviación del valor nominal de la resistencia del sensor.

Si el envejecimiento de la aleación del sensor es distinto del material sobre el que se monta, la concordancia anterior se pierde y los resultados no tendrán valor alguno, ya que si, por ejemplo la deformación máxima capáz de desviar el valor de la resistencia del sensor, (3º ley de Wöhler) es superior a la deformación que producirá la rotura de la pieza de ensayo, el indicador de fatiga jamás acusaría desviación de su resistencia; para evitarlo se fabrican sensores multiplicadores los cuales por diversos procedimientos de fabricación se consiguen adaptar la respuesta del sensor a los materiales en que se montan (fig 28a)

La fig. 28 dá una respuesta de los sensores FWA de Vishay-Micromesures.

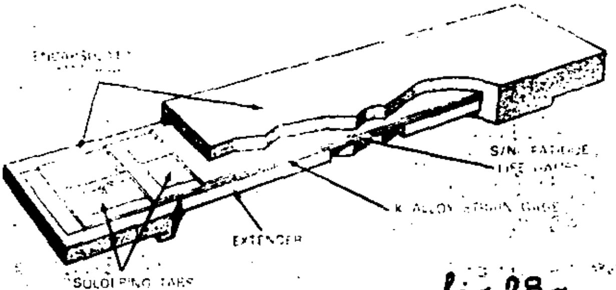


fig 28a

TABLAS PARA EL CALCULO CON ROSETAS DE 120º

TABLA Nº 3

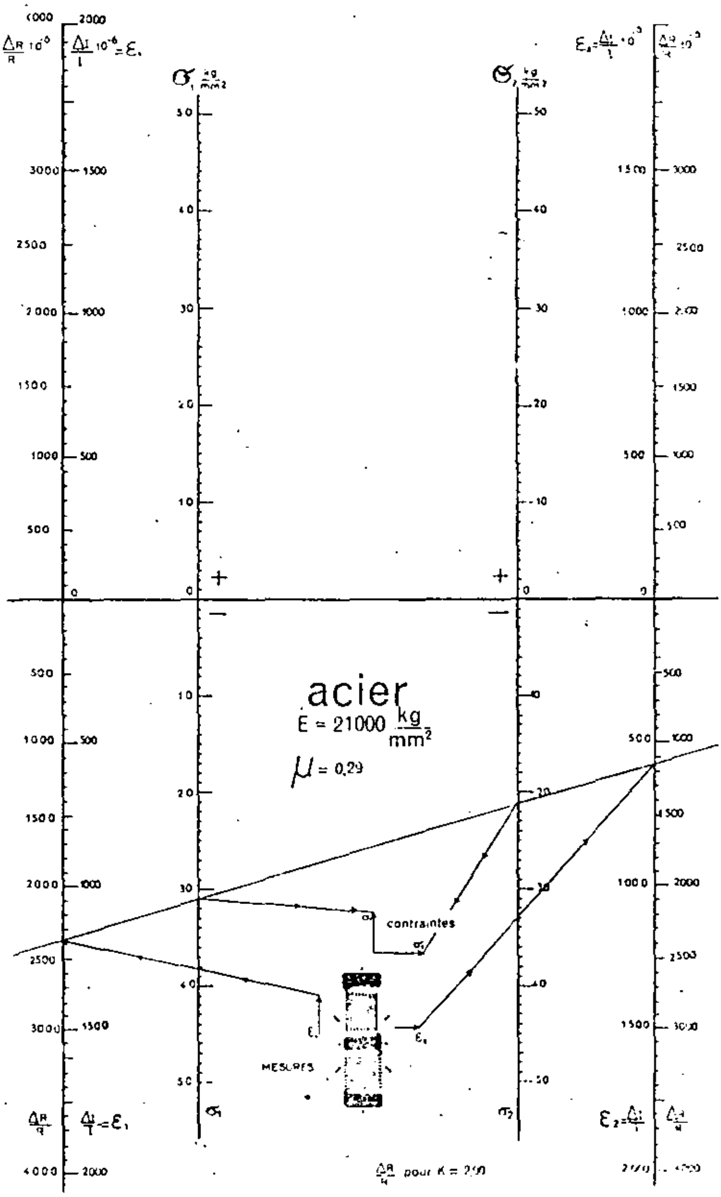
x	0	1	2	3	4	5	6	7	8	9		
0,00	0,6667	63	60	57	53	50	47	43	40	39	0,6634	0,99
0,01	34	30	27	24	20	17	13	10	07	04	01	0,98
0,02	01											
		98	95	91	88	85	82	79	75	72	0,6569	0,97
0,03	0,6569	66	63	59	56	53	50	47	44	41	37	0,96
0,04	37	34	31	28	25	22	19	16	13	09	06	0,95
0,05	06	03	00									
				97	94	91	88	85	82	79	0,6476	0,94
0,06	0,6476	73	70	67	64	61	58	55	52	40	46	0,93
0,07	46	43	40	37	34	31	28	25	22	20	17	0,92
0,08	16	14	11	08	05	02						
							99	96	94	91	0,6387	0,91
0,09	0,6388	85	82	79	76	74	71	68	65	62	60	0,90
0,10	60	57	54	51	48	46	43	40	37	35	32	0,89
0,11	32	29	26	24	21	18	16	13	10	08	04	0,88
0,12	05	02										
			99	97	94	92	89	86	84	81	0,6278	0,87
0,13	0,6278	76	73	70	68	65	63	60	58	55	52	0,86
0,14	52	50	47	45	42	40	37	35	32	30	27	0,85
0,15	27	25	22	20	17	15	12	10	07	04	02	0,84
0,16	02	00										
			98	95	93	90	88	86	83	81	0,6178	0,83
0,17	0,6178	76	74	71	69	67	64	62	60	57	55	0,82
0,18	55	53	50	48	46	44	41	39	37	34	32	0,81
0,19	32	30	28	26	23	21	19	17	14	12	10	0,80
0,20	10	08	06	04	01							
						99	97	95	93	91	0,6089	0,79
0,21	0,6089	86	84	82	80	78	76	74	72	70	68	0,78
0,22	68	66	64	62	60	58	56	54	52	50	48	0,77
0,23	48	46	44	42	40	38	36	34	32	30	28	0,76
0,24	28	26	24	22	20	19	17	15	13	11	09	0,75
0,25	09	07	05	03	02	00						
							98	96	95	93	0,5991	0,74
0,26	0,5991	89	88	86	84	82	80	79	77	75	74	0,73
0,27	74	72	70	69	67	65	64	62	60	59	57	0,72
0,28	57	55	54	52	50	49	47	46	44	42	41	0,71
0,29	41	39	38	36	35	33	32	30	28	27	25	0,70
0,30	25	24	22	21	20	18	17	15	14	13	11	0,69
0,31	10	09	08	07	05	04	02	01				
									99	98	0,5897	0,68
0,32	0,5897	96	94	93	92	90	89	88	86	85	84	0,67
0,33	64	82	81	80	79	77	76	75	74	72	71	0,66
0,34	71	70	69	68	66	65	64	63	62	60	59	0,65
0,35	59	58	57	56	55	54	53	52	51	50	48	0,64
0,36	48	47	46	45	44	43	42	41	40	39	38	0,63
0,37	38	37	36	35	34	33	32	31	30	30	29	0,62
0,38	29	28	27	26	25	24	23	22	22	21	20	0,61
0,39	20	19	18	17	17	16	15	14	13	13	12	0,60
0,40	12	11	10	10	09	08	07	07	06	05	05	0,59
0,41	05	04	03	03	02	01	01	00				
									99	99	0,5798	0,58
0,42	0,5798	97	97	96	96	95	95	94	93	93	92	0,57
0,43	92	92	91	91	90	90	89	89	88	88	87	0,56
0,44	87	87	86	86	86	85	85	84	84	83	83	0,55
0,45	83	83	82	82	82	81	81	81	80	80	80	0,54
0,46	80	79	79	79	78	78	78	78	77	77	77	0,53
0,47	77	77	77	76	76	76	76	76	75	75	75	0,52
0,48	75	75	75	75	74	74	74	74	74	74	74	0,51
0,49	74	74	74	74	74	74	74	74	74	73	0,5773	0,50
		9	8	7	6	5	4	3	2	1	0	x

TABLA Nº 4

x	0	1	2	3	4	5	6	7	8	9
0,0	0,00	0,25	0,50	0,76	1,01	1,28	1,53	1,80	2,07	2,33
0,1	2,61	2,88	3,16	3,43	3,72	3,99	4,28	4,58	4,87	5,15
0,2	5,45	5,74	6 04	6,34	6,64	6,95	7,26	7,57	7,92	8,18
0,3	8,50	8,82	9,13	9,45	9,77	10,09	10,41	10,73	11,06	11,38
0,4	11,70	12,03	12,36	12,69	13,02	13,35	13,68	14,01	14,24	14,67
0,5	15,00	15,33	15,66	15,99	16,32	16,65	16,98	17,31	17,64	17,97
0,6	18,30	18,62	18,94	19,27	19,59	19,91	20,23	20,55	20,87	21,18
0,7	21,50	21,82	22,08	22,43	22,74	23,05	23,36	23,66	23,96	24,26
0,8	24,55	24,85	25,13	25,42	25,72	26,01	26,28	26,57	26,84	27,12
0,9	27,39	27,67	27,93	28,20	28,47	28,72	28,99	29,24	29,50	29,75
1 0	30,00									

ABACO PARA EL CALCULO DE TENSIONES

(Para 2 medidas
según las direcciones
principales)



Cortesia de VISHAY MICROMESURES

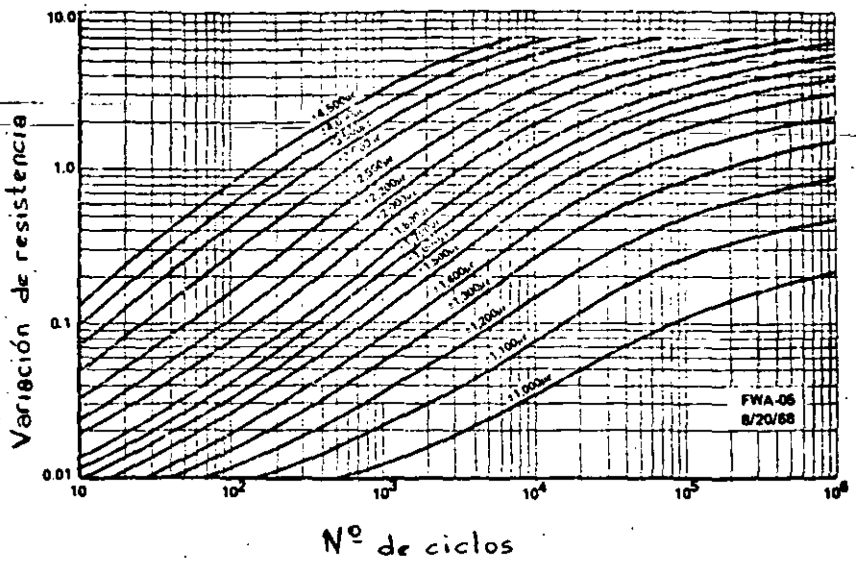


fig28

Los indicadores de fatiga son verdaderos integradores de los efectos producidos por cargas alternas, sea cual sea su amplitud así pués, si después de 10.000 ciclos de ± 2000/uδ producen una desviación de la resistencia de 1,9 ohm y 100 ciclos de ± 3000/uδ 0,8ohm, la indicación final será de 2,7 ohm.

Al montaje de estos indicadores habrá que tener en cuenta que su eje sensible coincida con el eje de esfuerzo principal máximo, determinado previamente por cualquier procedimiento (extensométrico, fotoelasticidad, etc).

2.6.3. Sensores de temperatura

Siguiendo el mismo procedimiento de fabricación de las bandas extensométricas, pero haciendo que la aleación de la rejilla sea de niquel, se obtienen sensores cuya variación de resistencia es altamente sensible a las variaciones de temperatura siendo este fenómeno muy estable y repetitivo, de ahí que se utilice profusamente en la medida de temperaturas por contacto y utilizando las mismas técnicas de instalación que las expuestas para extensímetros. La curva ΔR-t° (fig. 29), tiene una pendiente considerable por lo que se obtienen señales de alto nivel, pudiendose medir con gran precisión, exactitud y poder de resolución, temperaturas comprendidas entre -300 y + 500ºF.

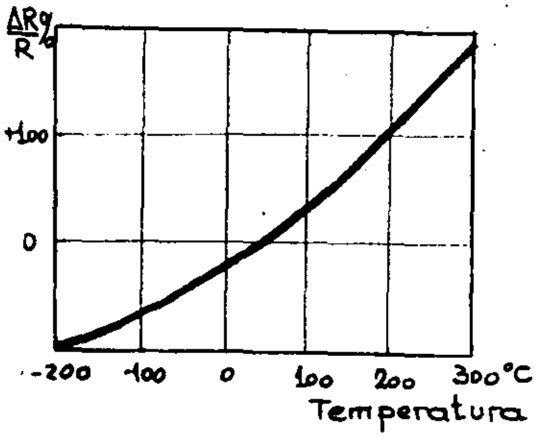


fig 29

Generalmente son fabricados para que a la temperatura ambiente (23,9ºC su resistencia nominal sea de 50 ohm y conociendo la curva , poder conocer la temperatura midiendo por cualquier procedimiento las desviaciones de la resistencia.

Estos sensores a diferencia de los termopares que generan una f.e.m. son pasivos, necesitando de una fuente de alimentación, por eso (fig. 30) si es excitado con una fuente de intensidad constante 1mA) la lectura directa de un milivoltímetro nos valdría para conocer los Δ R directamente, no obstante como la respuesta no es lineal siempre tendríamos que tener tablas o curvas de respuesta para conocer el verdadero valor de la temperatura en ºC ó ºF. El inconveniente anterior ha sido subsanado introduciendo circuitos linealizadores en los cuales, si bién se pierde sensibilidad, la respuesta es lineal, por lo que los instrumentos de lectura pueden ir tarados directamente en escalas termométricas.

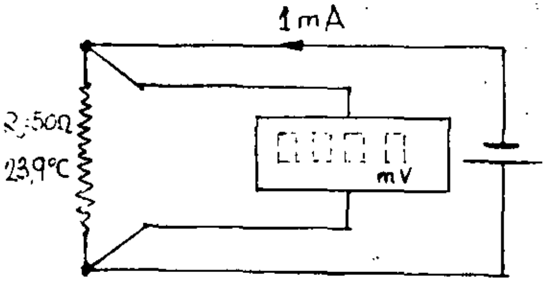


fig 30

Con el fín de utilizar para la medida de temperaturas los mismos instrumentos que para medir deformaciones, los circuitos linealizadores se calculan de tal forma que el sensor constituye una rama de un puente de Whearstone (fig. 31), de tal forma, que al leer un número entero de microdeformaciones equivalga a la variación de 1grado centígrado o Farenheit, Normalmente se fabrican redes para:

$$10\mu\delta <> 1^{\circ}C <> 1^{\circ}F$$

$$100\mu\delta <> 1^{\circ}C <> 1^{\circ}F.$$

FACULTAD DE INGENIERIA U.N.A.M.
DIVISION DE EDUCACION CONTINUA

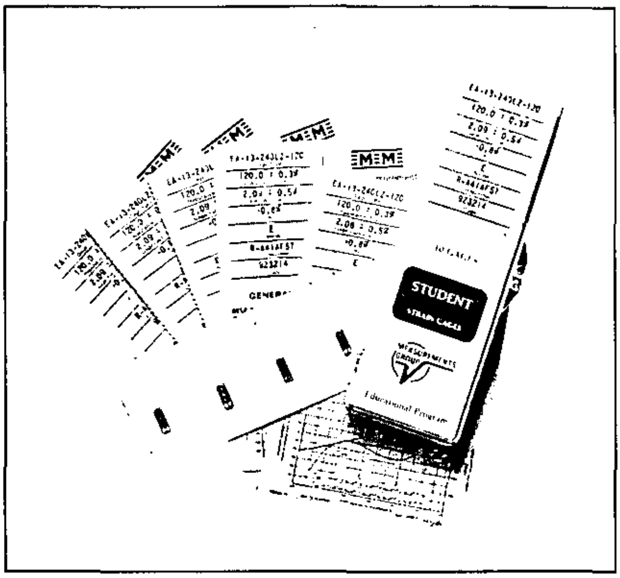
CURSOS ABIERTOS

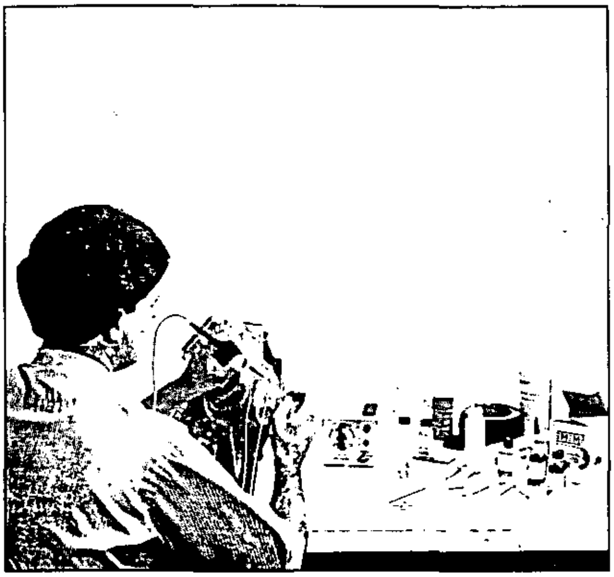
METODOS EXPERIMENTALES DE ANALISIS DE ESFUERZOS

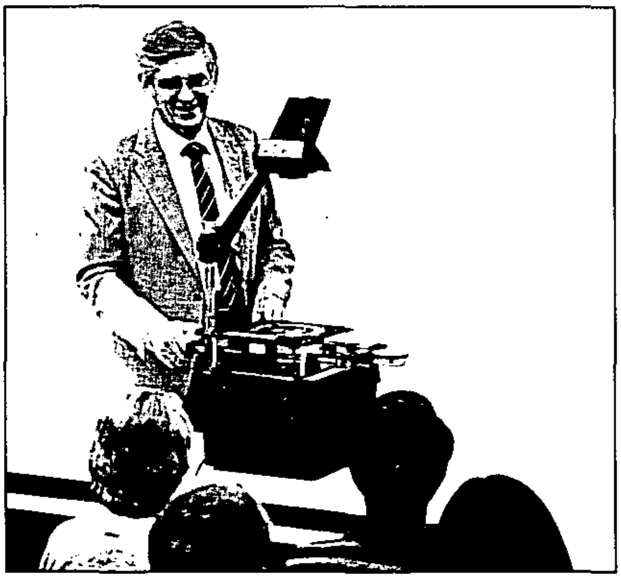
ANEXO

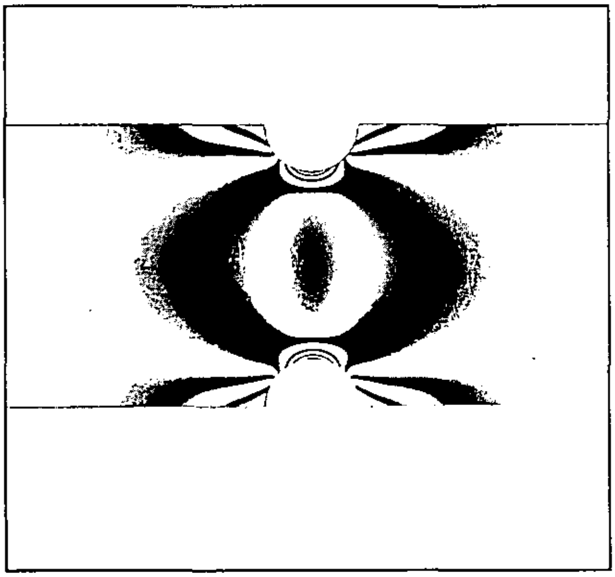
FEBRERO DE 1994

Palacio de Minería Calle de Tacuba 5 Primer piso Deleg. Cuauhtémoc 06000 México, D.F. APDO. Postal M-2285
Teléfonos: 512-8955 512-5121 521-7335 521-1987 Fax 510-0573 521-4020 AL 26









Teaching/Learning Aids for Experimental Stress Analysis

MEASUREMENTS GROUP VISHAY

EDUCATION DIVISION

Education Division

Teaching/Learning Aids

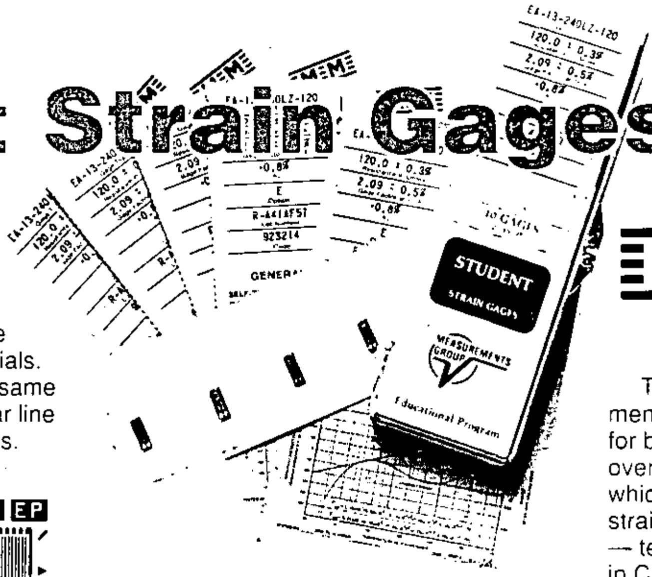
Through its Micro-Measurements, Instruments, and Photolastic Divisions, the Measurements Group is dedicated to developing, manufacturing, and marketing high-quality materials and equipment for precision strain measurement and stress analysis testing. In addition to offering a broad range of products, the Measurements Group also provides extensive collateral support for those practicing experimental stress analysis. Training programs in the techniques of stress analysis, a full-time staff of applications engineers, and an extensive selection of up-to-date technical and product literature are available to assist you in the application of experimental stress analysis technology.

The Measurements Group is equally dedicated to serving the special needs of the educational community. The Education Division was established with a commitment to providing an outlet for the resources of the Measurements Group to engineering and technology students and teachers at schools, colleges and universities around the world. In addition to offering a unique line of high-quality instructional materials and equipment, the Education Division serves as your channel to the full range of Measurements Group experimental stress analysis products and services.

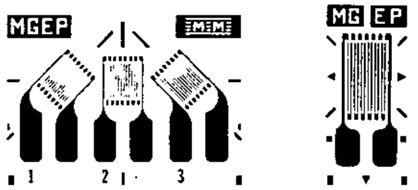
This brochure describes a selection of Measurements Group products with exceptional utility as teaching and learning aids. These technically sound and academically effective instructional materials and equipment are now in use in hundreds of technical high schools, technical institutes, engineering colleges, and universities.

The teaching and learning aids described in this brochure are fully compatible with the entire range of Measure-

Student Strain Gages



Student Gages are a group of ten Micro-Measurements EA-Series and CEA-Series strain gage types specially designed for student use. These strain gages are manufactured from the same materials, by the same processes, and to the same high-quality standards as the regular line of Micro-Measurements strain gages.



Like others in the EA Series, Student Gages have constantan metal foil grids and tough, flexible polyimide backings. Student Gages are produced in three single-element linear patterns (LZ) and in a three-element rectangular rosette (RZ). The LZ patterns are available with 0.060-, 0.120-, and 0.240-in *(1.5-, 3-, and 6-mm)* active gage lengths. The RZ rosette is designed with 0.060 in *(1.5 mm)* active grid lengths. CEA-Series Student Gages are available only in a linear pattern (UZ) with 0.240-in *(6-mm)* active gage length. All patterns of Student Gages are produced in 06 and 13 ppm/°F self-temperature-compensations for use on most steels and on aluminum alloys, respectively. All gages are 120Ω in resistance and all include a polyimide encapsulation of the grid. The CEA-Series gages feature extra-large copper-coated solder tabs.

Student Gages are supplied in a standard package quantity of ten gages. Each package of gages contains ten engineering data forms with gage type, resistance, gage factor, transverse sensitivity, and thermal output data which have been compiled specifically for the gages in the package.

Because costs are heavily subsidized, Student Gages are provided exclusively for use in those teaching and learning activities which are an integral part of a formal course of study.

For information on how to qualify for Student Gages, ask for Bulletin 307 or write to the Education Program Coordinator.

MM Strain Gages

The complete line of Micro-Measurements precision strain gages is available for both teaching and research uses. With over 250,000 possible gage types from which to select, a Micro-Measurements strain gage for every measurement need — teaching or research — can be found in Catalog 500.

Practice Patterns

Practice Patterns are uniquely designed for developing strain gage bonding and soldering techniques. They are similar in appearance to EA-Series strain gages and are constructed of the same materials. Because they contain inactive grids, Practice Patterns cannot be used to measure strain.

These training aids are ideally suited to first-time strain gage users. Write to the Education Program Coordinator for more details.

ments Group products for strain measurement and stress analysis testing. In fact, they are differentiated only by their usefulness in teaching and learning activities.

Student Understanding

Measurements Group teaching and learning aids are directed toward improving and deepening student understanding of stresses and strains by emphasizing:

- how, why, and where they occur
- their relevance to the design of safe, economical components, machines, and structures
- how to measure them
- how to control and limit them

Such understanding is critical for students who will become technicians or engineers. Therefore, these educational aids are particularly relevant and beneficial to those courses in:

- mechanics of deformable solids (strength of materials)
- machine design
- experimental stress analysis
- materials science
- measurements and instrumentation
- structures and structural design
- design for safety and reliability
- value engineering
- failure analysis

Teaching/Learning Aids

Measurements Group instructional products have been designed for maximum adaptability in supplementing and enriching established courses without revamping or restructuring them.

The educational products utilize strain gage and photoelastic stress analysis techniques as vehicles for accomplishing their tutorial purposes. Basic products for strain gage and photoelastic techniques are also available separately.

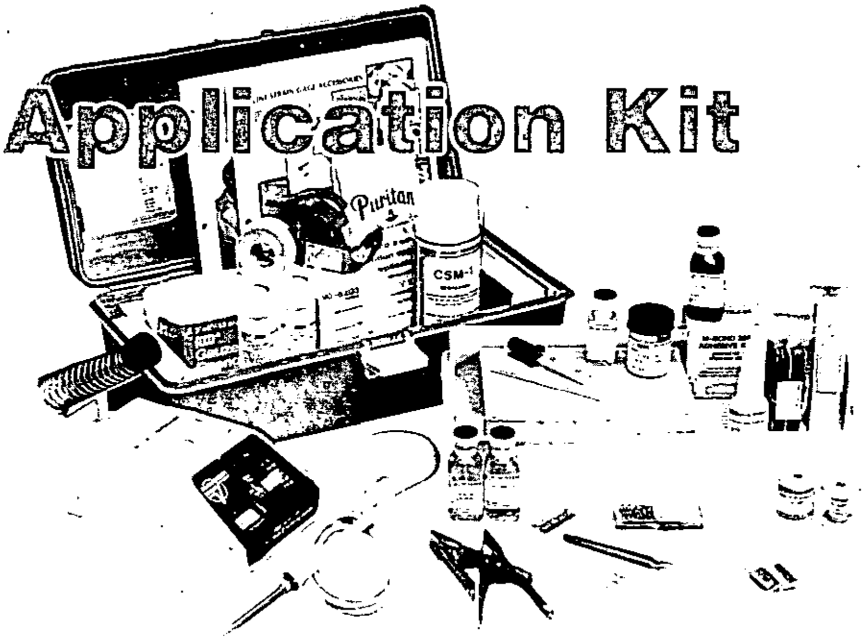
Learning Is Faster and More Complete

Learning is faster, easier, and in greater depth when the principles of mechanics, mechanical design, structures, and stress analysis are actually experienced by the student.

Measurements Group teaching/learning aids are intended to generate student interest, provide motivation, and develop comprehension of stress and strain concepts which otherwise tend to remain abstractions.

The learning aids described in this brochure are flexible and can be employed in a purely illustrative or demonstrative fashion or as fundamental components of course content. Most of them are also open-ended, and provide the means for the imaginative teacher (or student) to explore advanced areas.

Application Kit



The **Student Strain Gage Application Kit** contains an assortment of those Micro-Measurements *M-LINE* Accessories necessary for making successful strain gage installations in the laboratory. In addition to the materials for preparing the specimen surface for bonding, the kit includes both the popular, fast-curing M-Bond 200 cyanoacrylate and the durable, creep-free M-Bond AE-10 epoxy strain gage adhesive systems. All the tools and materials for bonding and soldering strain gages — including a controlled-temperature soldering iron — are provided. Designed with the student in mind, each kit comes complete with practice materials for developing strain gage installation techniques. Up to four students can work from one kit. The Student Strain Gage Application Kit is packaged in a durable storage box. All items are fully compatible with, and may be supplemented by, the complete line of Micro-Measurements *M-LINE* Strain Gage Accessories. All consumables in the kit are replaceable from standard Micro-Measurements stock. For a complete list of contents, ask for Bulletin 310.

M-LINE Accessories

Making accurate and reliable measurements with electrical resistance strain gages in the classroom or laboratory requires installation with high-quality accessory tools, materials, and supplies qualified for making strain gage installations. Ask for Catalog A-110 which describes the complete line of Micro-Measurements *M-LINE* Strain Gage Accessories.

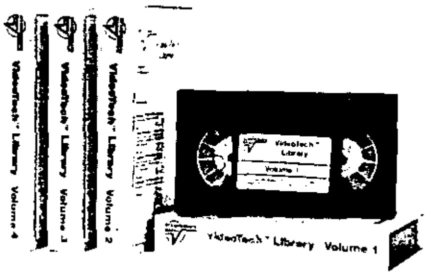
VideoTech™ Libraries

The VideoTech Library is a series of instructional VHS videotapes for strain gage installation.

The procedures outlined in the VideoTech Library will help both novice and experienced strain gage users to make reliable, professional-caliber strain gage installations every time.

The videotape presentation format of these dependable, proven, state-of-the-art methods can be adapted with equal success to individual, self-taught programs, or to group training sessions. Each tape contains instruction for general-purpose surface preparation, gage bonding, leadwire attachment, and typical environmental protections. Organized in detailed, fully illustrated steps, each tape concludes with an example of a successful strain gage installation.

With the VideoTech Library at hand, the student *learns by doing* each of the prescribed steps to reproduce the actual installation. For additional details concerning these instructional videotapes, request Bulletin 318.



Experiments In Mechanics

Experiments In Mechanics — Strain Gage Series are six complete experiments designed by C.C. Perry around the simple cantilever beam. (They are intended to teach mechanics, using experimental stress analysis technology as the teaching medium.) Presented in a logical, easy-to-follow format on 8-1/2 x 11 in. *(216 x 279 mm)* pages, each experiment will yield consistently accurate and meaningful results when the instructions are carefully followed. Necessary supplemental information such as wiring diagrams, work sheets, graphs, and illustrations is included. Additionally, a list of the learning opportunities embodied in the experiment, as well as sources of errors and estimates of time required to perform the experiment, are contained in separate "Notes to the Instructor" provided with each set of experiments.

Experiments in Mechanics are complete exercises requiring a minimum of preparation time for the instructor. The experiments employ conventional strain gage technology and are coordinated with the beams described below.

Experiments in Mechanics are available separately or in complete sets.

Experiment E-101
Modulus of Elasticity — Flexure
Designed for use with Pregaged Beam B-101.

With a single strain gage mounted along the axis and near the fixed end of a cantilever beam, the student determines modulus of elasticity of the beam material by:

1. Measuring the beam dimensions.
2. Applying a known load to the free end of the beam.
3. Calculating the stress at the strain gage location from (1) and (2) with the flexure formula.
4. Measuring the strain along the beam axis.
5. Calculating the modulus of elasticity from (3) and (4) using Hooke's law.

Experiment E-102
Poisson's Ratio — Flexure
Designed for use with Pregaged Beam B-102.

In this experiment, two strain gages are used, one along the axis on the upper surface of the beam, and one transversely oriented at the same section on the lower surface on the beam.

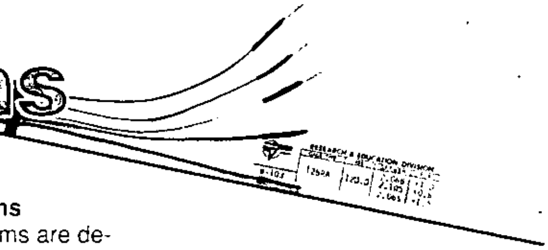
After applying an arbitrary displacement or load to the beam, the two strains are measured, and the Poisson's ratio of the beam material is calculated from these data.

Experiment E-103 Principal Strains and Stresses — Flexure
Designed for use with Pregaged Beam B-103.

A three-element strain gage rosette is mounted on a cantilever beam for this experiment. The rosette is oriented so that none of the element axes coincide with the axes of symmetry of the beam.

After applying a known load to the beam, the student measures the strains along the three rosette axes and calculates the principal strains from the strain transformation relationships. Using the biaxial Hooke's law, the student calcu-

Cantilever Beams



Cantilever Beams, designed for use with the Flexor, are coordinated with **Experiments in Mechanics**, but can be used separately for other demonstrations or experiments. All beams are manufactured from 2024-T6 high-strength aluminum alloy and are 1 in *(25.4 mm)* wide by 12.5 in *(317.5 mm)* long. Beams designed for Experiments E-101 and E-103 are 0.125 in *(3.18 mm)* thick. All others are 0.250 in *(6.35 mm)* thick.

Ungaged Beams

Ungaged Beams permit specialized instruction and are particularly valuable when instructional time is sufficient to allow students to mount their own strain gages.

Catalog No.	Description	For Use With Experiment No.
UB-01	0.125 in *(3.18 mm)* thick rectangular beam	E-101, E-103
UB-02	0.250 in *(6.35 mm)* rectangular beam	E-102, E-105

Special Configuration Beams

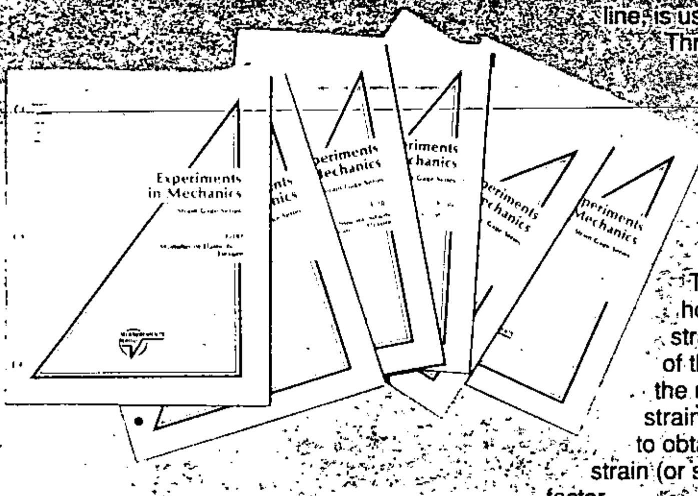
Special Configuration Beams are designed for advanced work in measuring stress concentrations. They are ungaged to afford students the opportunity to position and mount their own strain gages.

Catalog No.	Description	For Use With Experiment No.
UBS-01	Stress Concentration — with a 1/4 in *(6.35 mm)* drilled and reamed hole	E-104
UBS-02	Stress Concentration — with accurately milled symmetrical U-Notches	E-104
UBS-03	Constant Stress — two-stage tapered beam with two constant-stress levels	E-106

Pregaged Beams

Pregaged Beams are instrumented with Micro-Measurements temperature-compensated foil strain gages. The strain gage installations are fully wired and are covered with a clear protective coating. In addition, all installations are factory tested for resistance, stability, and freedom from creep.

Catalog No.	For Use With Experiment No.	Number Of Gages	Gage Type	Gage Length (in)
B-101	E-101	1	Linear	0.125
B-102	E-102	2	Linear	0.125
B-103	E-103	1	3-Element Rosette	0.125
B-104	E-104	3 1	Linear Linear	0.030 0.125
B-105	E-105	3	Linear	0.125
B-106	E-106	4	Linear	0.125



lates the principal stresses from the principal strains. These results are compared with the stress calculated from the flexure equations for the known load and measured beam dimensions.

Experiment E-104
Stress and Strain Concentration

Designed for use with Pregaged Beam B-104.

A cantilever beam with a hole through the thickness of the beam, on the center-line, is used in this experiment. Three very small strain gages are mounted at varying distances from the edge of the hole to permit measuring the local increase in strain due to the presence of the hole. The student is shown how to extrapolate the strain data to the edge of the hole, and compare the result to the nominal strain at the same section to obtain a measure of the strain (or stress) concentration factor.

Experiment E-105
Cantilever Flexure

Designed for use with Pregaged Beam B-105.

This experiment provides a practical demonstration of the relationship between the vertical shear force and bending moment distributions in a beam. It exploits the fact that the derivative (slope) of the bending moment distribution is equal to the vertical shear force. The student is shown how to measure the slope of the moment distribution with two strain gages mounted at different points along the beam axis and connected to the strain indicator in a half-bridge arrangement. The output of the strain indicator is then directly proportional to the vertical shear force. This technique can be used to make a load or force transducer for which the output is independent of the point of load application, as long as it is not between the two strain gages.

Experiment E-106
Constant Stress Beams

Designed for use with Pregaged Beam B-106.

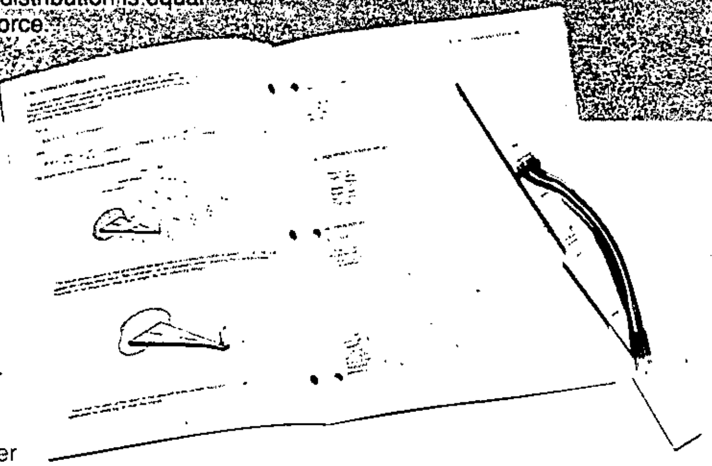
The constant stress beam is employed in this experiment as a vehicle for teaching the relationships among bending moment, section modulus, and stress or strain in a beam while, at the same time, introducing the student to the concept of efficient beam design.

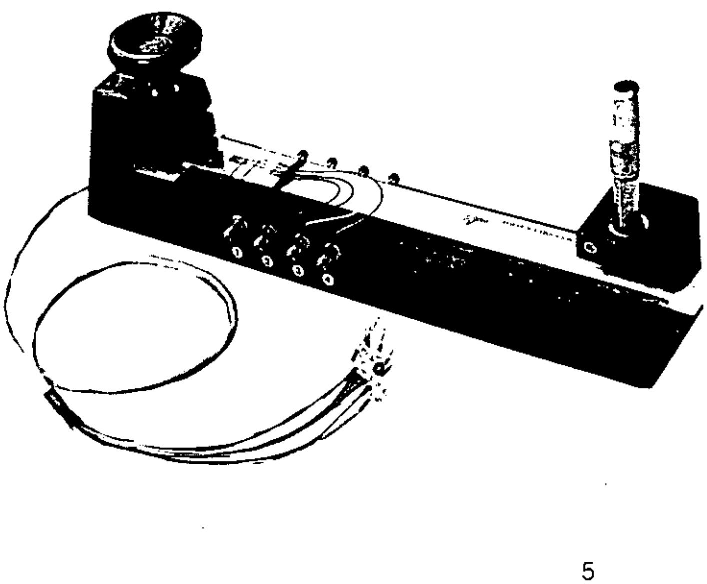
Flexor

The **Flexor**, a cantilever flexure frame, is a simple, versatile, and portable all-in-one fixture for loading beams.

The cantilever-beam principle is particularly appropriate for measuring basic materials properties, and for performing strain gage and other stress analysis experiments. The test specimens are inexpensive and simple to fabricate, and only modest forces are required to develop large strains and high stresses.

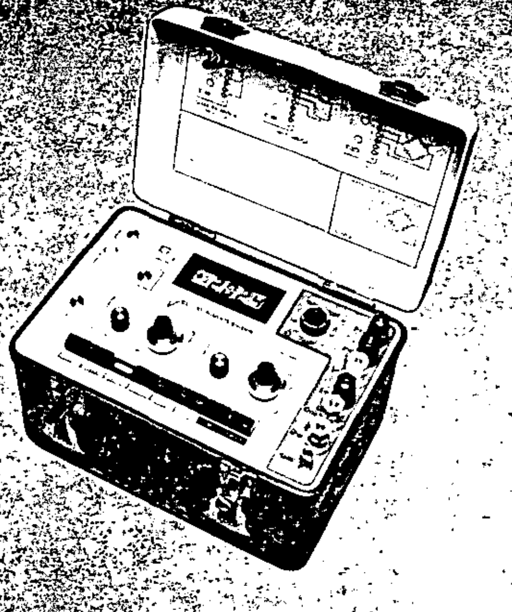
Since the cantilever beam is a fundamental and widely used structural element, the Flexor offers numerous associated advantages as a technical teaching aid.





Deflections are produced and measured by a micrometer, and strains of up to 2500με can be obtained on a 0.250 in *(6.35 mm)* thick beam. The Flexor can also be used with deadweights. Eight integral push-clamp binding posts on the side of the Flexor are used for intermediate connections to the gaged beams. The binding posts are prewired to an attached instrument cable which conveniently connects to a strain indicator. The Flexor is 13-1/4 in *(335 mm)* long, 4-3/4 in *(120 mm)* high and 2-1/2 in *(65 mm)* deep. It weighs 3-1/2 lb *(1.6 kg)*. Three ungaged high-strength aluminum alloy beams, a weight hook, and user's manual are provided with each Flexor. The Flexor is recommended for all **Experiments in Mechanics.**

Strain Gage Instrumentation



A wide range of state-of-the-art strain gage instrumentation is available from the Measurements Group Instruments Division. Many of these instruments are ideally suited for use in the classroom or teaching laboratory. The **Model P-3500 Strain Indicator**, for example, is a portable, lightweight, rugged instrument which can be used both for stress analysis testing and strain-gage-based transducers. Featuring an LCD (or optional LED) readout, the P-3500 will accept full-, half-, or quarter-bridge strain gage inputs, and provides direct readings of strain, pressure, torque, load, and other engineering variables. An auxiliary analog output for driving an external oscilloscope or recorder is also provided. The bridge excitation potential of 2 Vdc results in low bridge operating power and negligible drift due to gage self-heating. The P-3500 Strain Indicator is the most easy-to-use instrument of its kind. By following a logical sequence of set-up steps and activating color-coded push-button controls, even the most inexperienced user can rapidly prepare the instrument for making accurate and reliable measurements.

For making dynamic measurements, the **2100 System** is designed to accept inputs from strain gages; load, pressure and dc-displacement transducers; and nickel temperature sensors. With a standard bandpass of dc to 5 kHz minimum at −0.5 dB, the 2100 System accepts low-level signals, and conditions and amplifies them into high-level outputs suitable for multi-channel simultaneous dynamic recording. The system is com-

Teaching Polariscope

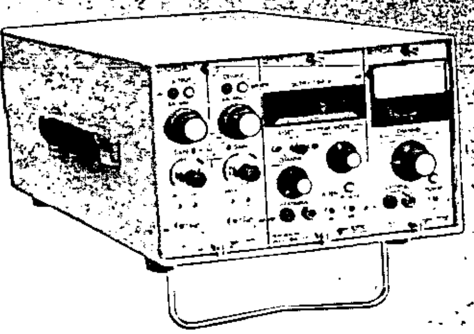
Photoelastic methods of stress analysis provide a complete "picture" of the stress distributions in a structure. As a result, they have become increasingly important elements in the design of modern products. The **080 Series Teaching Polariscope System** will enable you to give your students a firm foundation in this valuable technology and will add new understanding to courses in design and strength of materials.

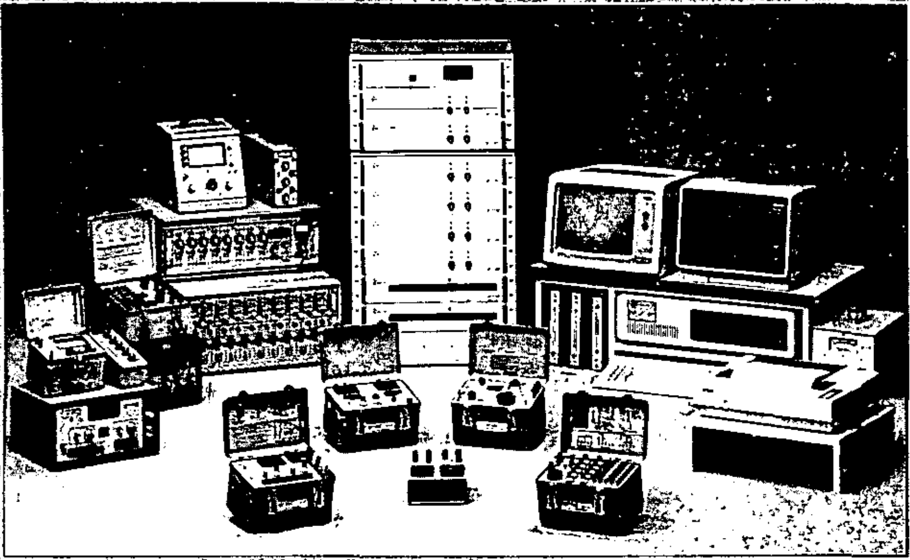
The Model 081 Teaching Polariscope is a complete working polariscope which can be used to graphically demonstrate and teach the principles of photoelasticity and its application to stress analysis. Because it has all the elements of a bench-mounted laboratory instrument, the 081 is also an excellent device for teaching the theory and operation of a polariscope.

The 081 can be easily carried to the classroom and quickly set up for use. It is designed to be placed on an overhead projector and allows students to observe the different measuring operations necessary to determine the stress directions and magnitudes of the projected photoelastic pattern. Quantitative measurements are made through the use of a transparent dial which surrounds the projected pattern.

The Polariscope consists of a sturdy anodized metal frame, two plane polarizing filters, two removable quarter-wave filters, and the transparent numbered dial. A mechanical drive system is provided for rotating all four filters simultaneously. The filters are laminated in glass for excellent light transmission as well as durability.

A full line of accessories is also available to extend the usefulness of the polariscope in teaching and research. The recommended 080 System would include a straining frame with mechanical force dial indicator, support stage for stress-frozen models, uniform-field digital compensator, monochromator, and a set of educational models. For additional information on the 080 Series Teaching Polariscope System, ask for Bulletin 306. For information about other reflection and transmission polariscopes and photoelastic materials and supplies, ask for short form catalog SFC-300.



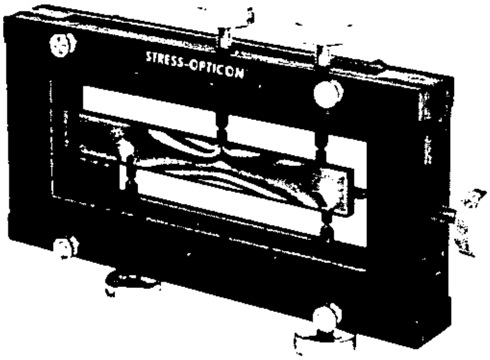


patible with galvanometers, computers, and strip-chart, magnetic tape, and X-Y recorders. Each 2110A power supply module will power up to five 2120A dual channel conditioner/amplifier modules (ten channels total). With the optional 2130/2131 digital readout module, the 2100 System can also function as a direct-reading static strain indicator.

Also available is a complete line of accessories and auxiliary instruments, including strain-indicator calibrators and a gage installation tester.

For information about the complete line of strain gage instrumentation – including the System 4000 computer-based stress analysis data system – consult your Strain Gage Technology Master Binder or ask for short-form catalog SFC-600.

Stress-Opticon



The **Stress-Opticon** is a unique, textbook size instrument which can be used to demonstrate the fundamental principles of stress analysis, mechanics of materials and the general nature of stress distribution in various structural shapes. Its five movable loading screws allow an infinite variety of loading modes – e.g., cantilever bending, column, statically indeterminate beam, and eccentrically loaded column — to be studied on a single prismatic model.

Each of the eight models available for the Stress-Opticon is a separate structural shape which can be easily correlated to standard textbook examples.

The Stress-Opticon is effective in room lighting, requiring no special light source. For lecture purposes, it can be used with an overhead projector for particularly dramatic presentations. In addition, it is lightweight, yet rugged enough to be passed from student to student during laboratory courses.

The Stress-Opticon is 9 in *(229 mm)* long, 6 in *(150 mm)* high and 1-1/2 in *(38 mm)* deep. The device comes complete with a detailed instruction manual and structural Model No. M-241.

Each Stress-Opticon model is a specific structural shape which can be subjected to a variety of different loading arrangements.

The models are machined from Type PSM-1 Plastic, a durable, non-brittle photoelastic material that is high in photoelastic sensitivity and free from time-edge effects.

PSM-1 Plastic is also available for custom designing photoelastic models and comes complete with machining instructions for producing models without initial fringes.

The accompanying photographs show the stress distribution for only one of the many loading conditions possible with each model.

Stress-Opticon Models

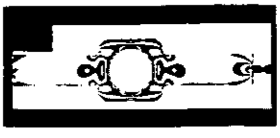
Model M-241: Standard prismatic model for teaching beam and column theories, St.Venant's principle, and others.

Model M-242: Standard model with 3/16 in *(4.8 mm)* diameter central hole . . . for teaching stress concentration. Elastic stress concentration factor (K_t) approximately 2.43 for axial load.

Model M-243: Standard model with 3/8 in *(9.5 mm)* diameter central hole . . . for teaching stress concentration. Elastic stress concentration factor (K_t) approximately 2.16 for axial load.

Model M-244: Model with symmetrical semicircular notches . . . for teaching stress concentration. Elastic stress concentration factor approximately 1.9, axial; 1.6, bending.

Model M-245: Dual section structural member . . . for teaching relationship between stress and cross-sectional properties, as well as stress concentration in fillets.



Model M-246: Representative mechanical component configuration . . . for teaching photoelastic stress measurement in arbitrary shapes.

Model M-247: Knee frame . . . for teaching stress distribution in typical structural shapes.

Model M-248: Arch . . . for teaching stress distribution in classical structural member.

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Bulletin 309C

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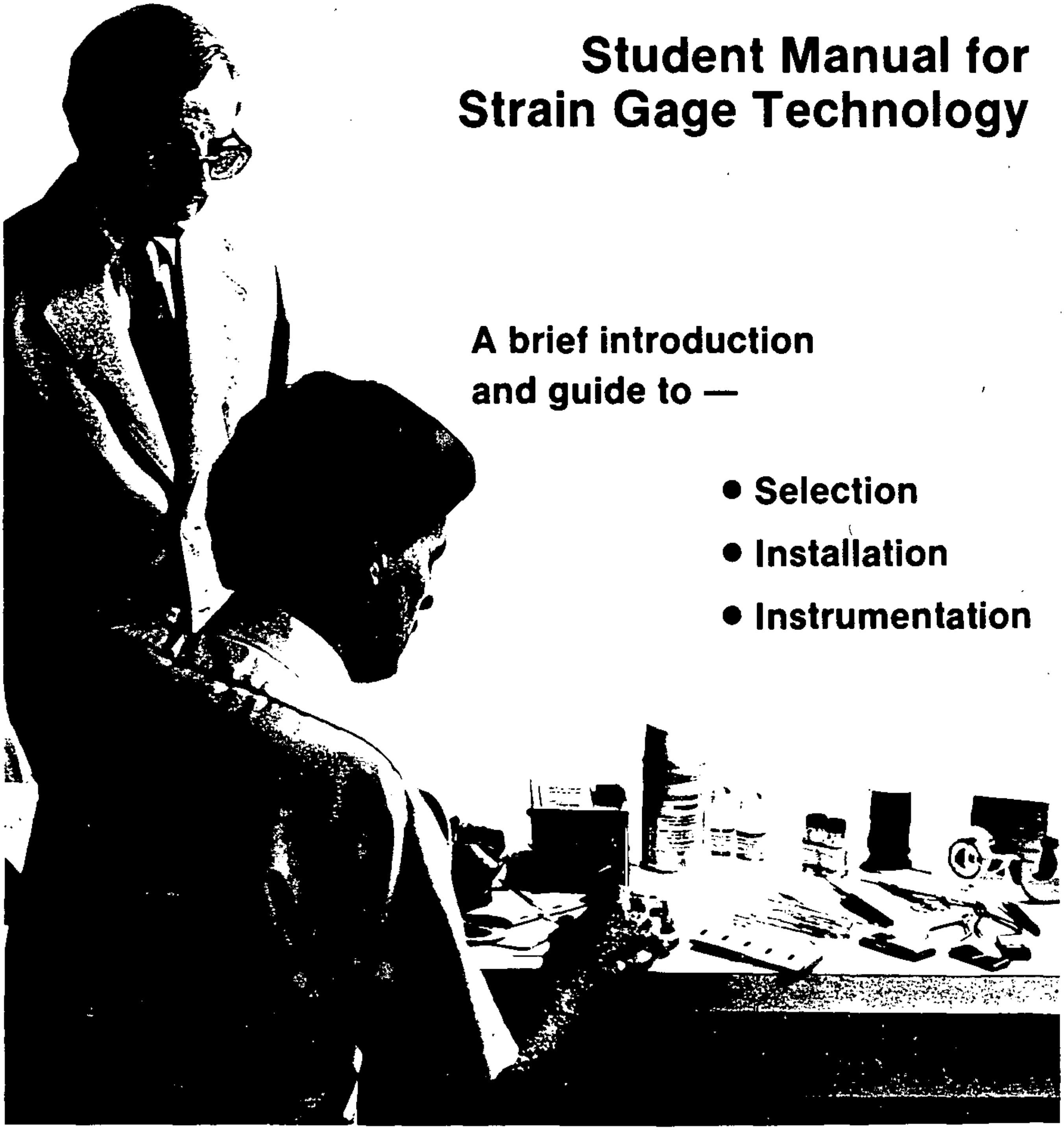
Education Division



Student Manual for Strain Gage Technology

A brief introduction
and guide to —

- Selection
- Installation
- Instrumentation

Introduction to Strain Gage Technology

Experimental Stress Analysis is an established, popular engineering tool, routinely used in the design of safe and reliable products and engineering structures. The techniques of experimental stress analysis may be applied at different stages in the life of a product: from preliminary design concepts to testing of the finished product; in proof and overload testing; and in failure analysis of products already in service. Within the broad field of experimental stress analysis, several practical techniques are available, including photoelastic coatings and models, moiré, and electrical resistance strain gages.

Of these techniques, the modern bonded electrical resistance strain gage is widely recognized as the most practical technology for testing of load-bearing parts, members, and structures. Because both excellent accuracy and repeatability can be achieved, strain gages are also becoming increasingly important as primary sensing elements in load cells as well as in pressure, force, torque, displacement, and other specialized transducers.

To make strain measurements of acceptable quality — whether for structural testing or for transducer applications — requires the consideration of several well-defined parameters: quality of the strain gage itself; proper selection of the strain gage, bonding adhesive, environmental protection, and other strain gage accessories; proper circuit design, proper installation of the strain gage; and quality of the strain gage instrumentation. While the importance of these parameters is well understood by the experienced stress analyst, their significance may be less obvious to those unfamiliar with strain gage technology. The purpose of this manual is to familiarize students with the proper techniques of strain measurements with electrical resistance strain gages.

In addition to providing high-quality, state-of-the-art strain gages and strain gage instrumentation, the Measurements Group maintains an extensive selection of technical and product literature describing the techniques, equipment, and practical application of strain gage technology. This manual is a compendium of the Measurements Group strain gage literature, specially selected to provide the student with a sound introduction to the hardware and procedures of strain gage methods. It includes the following topics:

- **Strain Gage Selection Criteria, Procedures, Recommendations:** The parameters for gage selection — including strain sensing alloy, backing material, gage length and pattern, self-temperature compensation, gage resistance, and gage options — are detailed. Examples are given of gage selections made in actual application.

- **Strain Gage Installations with M-Bond 200 and AE-10 Adhesive Systems:** Steps used by professional stress analysts in preparing the test specimen and making gage installations with both M-Bond 200 cyanoacrylate and M-Bond AE-10 epoxy adhesive systems are described in detail. Also included is a section of two- and three-leadwire strain gage circuits and a troubleshooting guide. By following the detailed, illustrated steps, the first-time strain gage user can make dependable installations.

In the later sections, the hardware of strain gage technology is described:

- **Description of Strain Gages and Accessories:** Partial listings of Micro-Measurements strain gages show the range of modern foil strain gage sizes and geometries. Included are linear patterns, three-element rosettes, pressure diaphragm gages, shear patterns, and others. Also included is a description of the accessory materials and equipment necessary for making good, sound installations.

- **Description of Strain Gage Instrumentation:** The range of instrumentation — including static, dynamic, and computer-controlled stress analysis systems — is shown. A selection chart is provided as a guide in determining the type of instrumentation best suited to a specific measurement application.

- **Reading List:** Additionally, a reading list of recommended references is provided for supplemental study.

This manual has been provided as part of the Measurements Group Educational Program for Strain Gage Technology.

— Reprint of —

MEASUREMENTS GROUP

TECH NOTE

Strain Gage Selection
Criteria, Procedures, Recommendations

1.0 Introduction

The initial step in preparing for any strain gage installation is the selection of the appropriate gage for the task. It might at first appear that gage selection is a simple exercise, of no great consequence to the stress analyst; but quite the opposite is true. Careful, rational selection of gage characteristics and parameters can be very important in: optimizing the gage performance for specified environmental and operating conditions, obtaining accurate and reliable strain measurements, contributing to the ease of installation, and minimizing the *total* cost of the gage installation.

The installation and operating characteristics of a strain gage are affected by the following parameters, which are selectable in varying degrees:

- strain-sensitive alloy
- backing material (carrier)
- gage length
- gage pattern
- self-temperature-compensation number
- grid resistance
- options

Basically, the gage selection process consists of determining the particular available combination of parameters which is most compatible with the environmental and other operating *conditions*, and at the same time best satisfies the installation and operating *constraints*. These constraints are generally expressed in the form of requirements such as:

- accuracy
- stability
- temperature
- elongation
- test duration
- cyclic endurance
- ease of installation
- environment

The cost of the strain gage itself is not ordinarily a prime consideration in gage selection, since the significant economic measure is the total cost of the complete installation, of which the gage cost is usually but a small fraction. In many cases, the selection of a gage series or optional feature which increases the gage cost serves to decrease the total installation cost.

It must be appreciated that the process of gage selection generally involves compromises. This is because parameter choices which tend to satisfy one of the constraints or requirements may work against satisfying others. For example, in the case of a small-radius fillet, where the space available for gage installation is very limited, and the strain gradient extremely high, one of the shortest available gages might be the obvious choice. At the same time, however, gages shorter than about 0.125 in *(3 mm)* are generally characterized by lower maximum elongation, reduced fatigue life, less stable behavior, and greater installation difficulty. Another situation which often influences gage selection, and leads to compromise, is the stock of gages at hand for day-to-day strain measurements. While compromises are almost always necessary, the stress analyst should be fully aware of the effects of such compromises on meeting the requirements of the gage installation. This understanding is necessary to make the best overall compromise for any particular set of circumstances, and to judge the effects of that compromise on the accuracy and validity of the test data.

The strain gage selection criteria considered here relate primarily to stress analysis applications. The selection criteria for strain gages used on transducer spring elements, while similar in many respects to the considerations presented here, may vary significantly from application to application and should be treated accordingly. The Measurements Group's Transducer Applications Department can assist in this selection.

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2.0 Gage Selection Parameters

2.1 Strain-Sensing Alloys

The principal component which determines the operating characteristics of a strain gage is the strain-sensitive alloy used in the foil grid. However, the alloy is not in every case an independently selectable parameter. This is because each of Micro-Measurements strain gage series (identified by the first two, or three, letters in the alphanumeric gage designation — see diagram on page 11) is designed as a complete system. That system is comprised of a particular foil and backing combination, and usually incorporates additional gage construction features (such as encapsulation, integral leadwires, or solder dots) specific to the series in question.

Micro-Measurements supplies a variety of strain gage alloys as follows (with their respective letter designations):

A: Constantan in self-temperature-compensated form.

P: Annealed constantan.

D: Iso-Elastic.

K: Nickel-chromium alloy, a modified Karma in self-temperature-compensated form.

2.1.1 Constantan Alloy

Of all modern strain gage alloys, constantan is the oldest, and still the most widely used. This situation reflects the fact that constantan has the best overall combination of properties needed for many strain gage applications. This alloy has, for example, an adequately high strain sensitivity, or *gage factor*, which is relatively insensitive to strain level and temperature. Its resistivity is high enough to achieve suitable resistance values in even very small grids, and its temperature coefficient of resistance is not excessive. In addition, constantan is characterized by good fatigue life and relatively high elongation capability. It must be noted, however, that constantan tends to exhibit a continuous drift at temperatures above +150° F *(+65° C)*; and this characteristic should be taken into account when zero stability of the strain gage is critical over a period of hours or days.

Very importantly, constantan can be processed for self-temperature-compensation (see box at right) to match a wide range of test material expansion coefficients. Micro-Measurements A alloy is a self-temperature-compensated form of constantan. A alloy is supplied in self-temperature-compensation (S-T-C) numbers 00, 03, 05, 06, 09, 13, 15, 18, 30, 40 and 50, for use on test materials with corresponding thermal expansion coefficients (expressed in ppm/° F).

For the measurement of very large strains, 5% (50 000$\mu\epsilon$) or above, annealed constantan (P alloy) is the grid material normally selected. Constantan in this form is very ductile; and, in gage lengths of 0.125 in *(3 mm)* and longer, can be strained to >20%. It should be borne in mind, however, that under high *cyclic* strains the P alloy will exhibit some permanent resistance change with each cycle, and cause a corresponding zero shift in the strain gage. Because of this characteristic, and the tendency for premature grid failure with repeated straining, P alloy is not ordinarily recommended for cyclic strain applications. P alloy is available with S-T-C numbers of 08 and 40 for use on metals and plastics, respectively.

2.1.2 Iso-Elastic Alloy

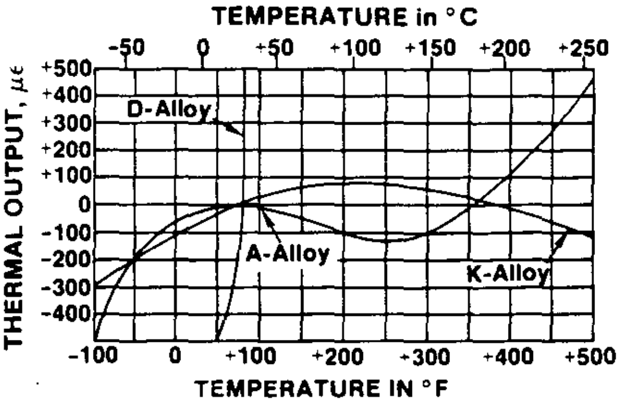
When purely dynamic strain measurements are to be made — that is, when it is not necessary to maintain a stable reference zero — Iso-Elastic (D alloy) offers certain advantages. Principal among these are superior fatigue life, compared to A alloy, and a high gage factor (approximately 3.2) which improves the signal-to-noise ratio in dynamic testing.

Self-Temperature-Compensation

An important property shared by constantan and modified Karma strain gage alloys is their responsiveness to special processing for self-temperature-compensation. Self-temperature-compensated strain gages are designed to produce minimum thermal output (temperature-induced apparent strain) over the temperature range from about -50° to +400° F *(-45° to +200° C)*. When selecting either constantan (A-alloy) or Karma (K-alloy) strain gages, the self-temperature-compensation (S-T-C) number must be specified. The S-T-C number is the approximate thermal expansion coefficient in ppm/° F of the structural material on which the strain gage will display minimum thermal output.

The accompanying graph illustrates typical thermal output characteristics for A and K alloys. The thermal output of uncompensated Iso-Elastic alloy is included in the same graph for comparison purposes. In normal practice, the S-T-C number for an A- or K-alloy gage is selected to most closely match the thermal expansion coefficient of the test material. However, the thermal output curves for these alloys can be rotated about the room-temperature reference point to favor a particular temperature range. This is done by intentionally mismatching the S-T-C number and the expansion coefficient in the appropriate direction. When the selected S-T-C number is lower than the expansion coefficient, the curve is rotated counterclockwise. An opposite mismatch produces clockwise rotation of the thermal output curve. Under conditions of S-T-C mismatch, the thermal output curves for A and K alloys (supplied with each package of strain gages) do not apply, of course, and it will generally be necessary to calibrate the installation for thermal output as a function of temperature.

For additional information on strain gage temperature effects, see Measurements Group Tech Note TN-504.



D alloy is not subject to self-temperature-compensation. Moreover, as shown in the graph (see box), its thermal output is so high [about 80$\mu\epsilon$/°F *(145$\mu\epsilon$/°C)*] that this alloy is not normally usable for static strain measurements. There are times, however, when D alloy finds application in special-purpose transducers where a high output is needed, and where a full-bridge arrangement can be used to achieve reasonable temperature compensation within the circuit.

Other properties of D alloy should also be noted when considering the selection of this grid material. It is, for instance, magnetoresistive; and its strain-sensitive response is somewhat nonlinear, becoming significantly so at strains beyond ±5000$\mu\epsilon$.

2.1.3 Karma Alloy

Modified Karma, or K alloy, with its wide areas of application, represents an important member in the family of strain gage alloys. This alloy is characterized by good fatigue life and excellent stability; and is the preferred choice for accurate static strain measurements over long periods of time (months or years) at room temperature, or lesser periods at elevated temperature. It is recommended for extended static strain measurements over the temperature range from –452° to +500° F *(-269° to +260° C)*. For short periods, encapsulated K-alloy strain gages can be exposed to temperatures as high as +750° F *(+400° C)*. An inert atmosphere will improve stability and extend the useful gage life at high temperatures.

Among its other advantages, K alloy offers a much flatter thermal output curve than A alloy, and thus permits more accurate correction for thermal output errors at temperature extremes. Like constantan, K alloy can be self-temperature-compensated for use on materials with different thermal expansion coefficients. The available S-T-C numbers in K alloy are limited, however, to the following: 00, 03, 05, 06, 09, 13, and 15. K alloy is the normal selection when a temperature-compensated gage is required that has environmental capabilities and performance characteristics not attainable in A-alloy gages.

Due to the difficulty of soldering directly to K alloy, the duplex copper feature, which was formerly offered as an option, is now standard on all Micro-Measurements open-faced strain gages produced with K alloy. The duplex copper feature is a precisely formed copper soldering pad (DP) or dot (DD), depending on the available tab area. All K-alloy gages which do not have leads or solder dots are specified with DP or DD as part of the designation (in place of, or in addition to, the option specifier). The specific style of copper treatment will be advised when the Order Service Department is contacted. Open-faced K-alloy gages may also be ordered with solder dots.

2.2 Backing Materials

Conventional foil strain gage construction involves a photoetched metal foil pattern mounted on a plastic backing or carrier. The backing serves several important functions:

- provides a means for handling the foil pattern during installation
- presents a readily bondable surface for adhering the gage to the test specimen
- provides electrical insulation between the metal foil and the test object

Backing materials supplied on Micro-Measurements strain gages are of two basic types: polyimide and glass-fiber-reinforced epoxy-phenolic. As in the case of the strain sensitive alloy, the backing is not completely an independently specifiable parameter. Certain backing and alloy combinations, along with special construction features, are designed as systems, and given gage *series* designations. As a result, when arriving at the optimum gage type for a particular application, the process does not permit the arbitrary combination of an alloy and a backing material, but requires the specification of an available gage series. Micro-Measurements gage series and their properties are described in the following ***Section 2.3***. Each series has its own characteristics and preferred areas of application; and selection recommendations are given in the table on page 5. The individual backing materials are discussed here, as the alloys were in the previous section, to aid in understanding the properties of the series in which the alloys and backing materials occur.

The Micro-Measurements polyimide E backing is a tough and extremely flexible carrier, and can be contoured readily to fit small radii. In addition, the high peel strength of the foil on the polyimide backing makes polyimide-backed gages less sensitive to mechanical damage during installation. With its ease of handling and its suitability for use over the temperature range from –320° to +350° F *(-195° to +175° C)*, polyimide is an ideal backing material for general-purpose static and dynamic stress analysis. This backing is capable of large elongations, and can be used to measure plastic strains in excess of 20%. Polyimide backing is a feature of Micro-Measurements EA-, CEA-, EP-, EK-, S2K-, N2A-, J2A- and ED-Series strain gages.

For outstanding performance over the widest range of temperatures, the glass-fiber-reinforced epoxy-phenolic backing material is the most suitable choice. This backing can be used for static and dynamic strain measurement from –452° to +550° F *(-269° to +290° C)*. In short-term applications, the upper temperature limit can be extended to as high as +750° F *(+400° C)*. The maximum elongation of this carrier material is limited, however, to about 1 to 2%. Reinforced epoxy-phenolic backing is employed on the following gage series: WA, WK, SA, SK, WD, and SD.

2.3 Gage Series

As noted in ***Sections 2.1*** and ***2.2***, the strain-sensing alloy and backing material are not subject to completely independent selection and arbitrary combination. Instead, a selection must be made from among the available gage systems, or *series*, where each series generally incorporates special design or construction features, as well as a specific combination of alloy and backing material. For convenience in identifying the appropriate gage series to meet specified test requirements, the information on gage series performance and selection is presented here, in condensed form, in two tables.

The table on the following page gives brief descriptions of all general-purpose Micro-Measurements gage series — including in each case the alloy and backing combination and the principal construction features. This table defines the performance of each series in terms of operating temperature range, strain range, and cyclic endurance as a function of strain level. It must be noted, however, that the performance data are *nominal*, and apply primarily to gages of 0.125 in *(3 mm)* or longer gage length.

SERIES	DESCRIPTION AND PRIMARY [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
EA	Constantan foil in combination with a tough, flexible, polyimide backing. Wide range of options available. Primarily intended for general-purpose static and dynamic stress analysis. Not recommended for highest accuracy transducers.	Normal: -100° to +350°F *(-75° to +175°C)* Special or Short-Term: -320° to +400°F *(-195° to +205°C)*	±3% for gage lengths under 1/8 in *(3.2 mm)* ±5% for 1/8 in and over	±1800 ±1500 ±1200	10^5 10^6 10^8
CEA	Universal general-purpose strain gages. Constantan grid completely encapsulated in polyimide, with large, rugged copper-coated tabs. Primarily used for general-purpose static and dynamic stress analysis. 'C'-Feature gages are specially highlighted throughout the gage listing sections of Catalog 500, Part A — *Strain Gage Listings.*	Normal: -100° to +350°F *(-75° to +175°C)* Stacked rosettes limited to +150°F *(+65°C)*	±3% for gage lengths under 1/8 in *(3.2 mm)* ±5% for 1/8 in and over	±1500 ±1500 *Fatigue life improved using low-modulus solder.	10^5 10^6*
N2A	Open-faced constantan foil gages with a thin, laminated, polyimide-film backing. Primarily recommended for use in precision transducers, the N2A Series is characterized by low and repeatable creep performance. Also recommended for stress analysis applications employing large gage patterns, where the especially flat matrix eases gage installation.	Normal Static Transducer Service: -100° to +200°F *(-75° to +95°C)*	±3%	±1700 ±1500	10^6 10^7
J2A	Constantan foil gages with a thin, laminated, polyimide backing and encapsulating film. Exposed solder tabs for direct leadwire attachment. Primarily recommended for precision transducers; the encapsulating film provides a more rugged gage than the N2A Series, but may increase reinforcement of thin transducer flexures.	Normal Static Transducer Service: -100° to +200°F *(-75° to +95°C)*	±2%	±1700 ±1500	10^6 10^7
ED	Iso-Elastic foil in combination with tough, flexible polyimide film. High gage factor and extended fatigue life excellent for dynamic measurements. Not normally used in static measurements due to very high thermal-output characteristics.	Dynamic: -320° to +400°F *(-195° to +205°C)*	±2% Nonlinear at strain levels over ±0.5%	±2500 ±2200	10^6 10^7
WA	Fully encapsulated constantan gages with high-endurance leadwires. Useful over wider temperature ranges and in more extreme environments than EA Series. Option W available on some patterns, but restricts fatigue life to some extent.	Normal: -100° to +400°F *(-75° to +205°C)* Special or Short-Term: -320° to +500°F *(-195° to +260°C)*	±2%	±2000 ±1800 ±1500	10^5 10^6 10^7
EK	Karma foil in combination with a tough, flexible polyimide backing. Primarily used where a combination of higher grid resistances, stability at elevated temperature, and greatest backing flexibility are required.	Normal: -320° to +350°F *(-195° to +175°C)* Special or Short-Term: -452° to +400°F *(-269° to +205°C)*	±1.5%	±1800	10^7
WK	Fully encapsulated K-alloy gages with high-endurance leadwires. Widest temperature range and most extreme environmental capability of any general-purpose gage when self-temperature-compensation is required. Option W available on some patterns, but restricts both fatigue life and maximum operating temperature.	Normal: -452° to +550°F *(-269° to +290°C)* Special or Short-Term: -452° to +750°F *(-269° to +400°C)*	±1.5%	±2400 ±2200 ±2000	10^6 10^7 10^8
EP	Special annealed constantan foil with tough, high-elongation polyimide backing. Used primarily for measurements of large post-yield strains in metals or on low-modulus materials (polymers). Available with Options E, L, and LE (may restrict elongation capability).	-100° to +400°F *(-75° to +205°C)*	±10% for gage lengths under 1/8 in *(3.2 mm)* ±20% for 1/8 in and over	±1000 EP gages show zero shift under high-cyclic strains.	10^4
SA	Fully encapsulated constantan gages with solder dots. Same matrix as WA Series. Same uses as WA Series but derated somewhat in maximum temperature and operating environment because of solder dots.	Normal: -100° to +400°F *(-75° to +205°C)* Special or Short-Term: -320° to +450°F *(-195° to +230°C)*	±2%	±1800 ±1500	10^6 10^7
S2K	Karma foil laminated to 0.001 in *(0.025 mm)* thick, high-performance polyimide backing, with a laminated polyimide overlay fully encapsulating the grid and solder tabs. Provided with large solder pads for ease of leadwire attachment.	Normal: -100° to +250°F *(-75° to +120°C)* Special or Short-Term: -300° to +300°F *(-185° to +150°C)*	±1.5%	±1800 ±1500	10^6 10^7
SK	Fully encapsulated K-alloy gages with solder dots. Same uses as WK Series, but derated in maximum temperature and operating environment because of solder dots.	Normal: -452° to +450°F *(-269° to +230°C)* Special or Short-Term: -452° to +500°F *(-269° to +260°C)*	±1.5%	±2200 ±2000	10^6 10^7
WD	Fully encapsulated Iso-Elastic gages with high-endurance leadwires. Used in wide-range dynamic strain measurement applications in severe environments.	Dynamic: -320° to +500°F *(-195° to +260°C)*	±1.5% — nonlinear at strain levels over ±0.5%	±3000 ±2500 ±2200	10^5 10^7 10^8
SD	Equivalent to WD Series, but with solder dots instead of leadwires.	Dynamic: -320° to +400°F *(-195° to +205°C)*	±1.5% See above note	±2500 ±2200	10^6 10^7

Strain Gage Series and Adhesive Selection Reference Table

TYPE OF TEST OR APPLICATION	OPERATING TEMPERATURE RANGE	TEST DURATION IN HOURS	ACCURACY REQUIRED**	CYCLIC ENDURANCE NEEDS		TYPICAL SELECTION	
				Maximum Strain, με	Number of Cycles	Gage Series	M-Bond Adhesive
GENERAL STATIC OR STATIC-DYNAMIC STRESS ANALYSIS*	-50° to +150°F *(-45° to +65°C)*	$<10^4$	Moderate	±1300	$<10^6$	CEA, EA	200 or AE-10
		$>10^4$	Moderate	±1300	$<10^6$	CEA, EA	AE-10 or AE-15
		$>10^4$	High	±1600	$>10^6$	WA, SA	AE-15 or 610
		$>10^4$	Very High	±2000	$>10^6$	WK, SK	AE-15 or 610
	-50° to +400°F *(-45° to +205°C)*	$<10^3$	Moderate	±1600	$<10^6$	WA, SA	600 or 610
		$>10^3$	High	±2000	$<10^6$	WK, SK	600 or 610
	-452° to +450°F *(-269° to +230°C)*	$>10^3$	Moderate	±2000	$>10^6$	WK, SK	610
	<600°F *(<315°C)*	$<10^2$	Moderate	±1800	$<10^6$	WK	610
	<700°F *(<370°C)*	<10	Moderate	±1500	$<10^6$	WK	610
HIGH-ELONGATION (POST-YIELD)	-50° to +150°F *(-45° to +65°C)*	<10	Moderate	±50 000	1	CEA, EA	AE-10
		$>10^3$	Moderate	±100 000	1	EP	AE-15
		$>10^3$	Moderate	±200 000	1	EP	A-12
	0° to +500°F *(-20° to +260°C)*	$<10^2$	Moderate	±15 000	1	SA, SK, WA, WK	610
	-452° to +500°F *(-269° to +260°C)*	$<10^3$	Moderate	±10 000	1	SK, WK	600 or 610
DYNAMIC (CYCLIC) STRESS ANALYSIS	-100° to +150°F *(-75° to +65°C)*	$<10^4$	Moderate	±2000	10^7	ED	200 or AE-10
		$<10^4$	Moderate	±2400	10^7	WD	AE-10 or AE-15
	-320° to +500°F *(-195° to +260°C)*	$<10^4$	Moderate	±2000	10^7	WD	600 or 610
		$<10^4$	Moderate	±2300	$<10^5$	WD	600 or 610
TRANSDUCER GAGING	-50° to +150°F *(-45° to +65°C)*	$<10^4$	1 to 5%	±1300	$<10^6$	CEA, EA	AE-10 or AE-15
		$<10^6$	1 to 5%	±1300	$<10^6$	CEA	AE-15
	-50° to +200°F *(-45° to +95°C)*	$<10^4$	Better than 0.2%	±1500	10^6	N2A	600, 610 or 43-B
	-50° to +300°F *(-45° to +150°C)*	$<10^4$	0.2 to 0.5%	±1600	10^6	WA, SA	610
	-320° to +350°F *(-195° to +175°C)*	$<10^4$	Better than 0.5%	±1800	10^6	WK, SK	610

* This category includes most testing situations where some degree of stability under static test conditions is required. For absolute stability with constantan gages over long periods of usage and temperatures above +150°F *(+65°C)*, it may be necessary to employ half- or full-bridge configurations. Protective coatings may also influence stability in cases other than transducer applications where the element is hermetically sealed.

** It is inappropriate to quantify "accuracy" as used in this table without consideration of various aspects of the actual test program and the instrumentation used. In general, "moderate" for stress analysis purposes is in the 2 to 5% range, "high" in the 1 to 3% range, and "very high" 1% or better.

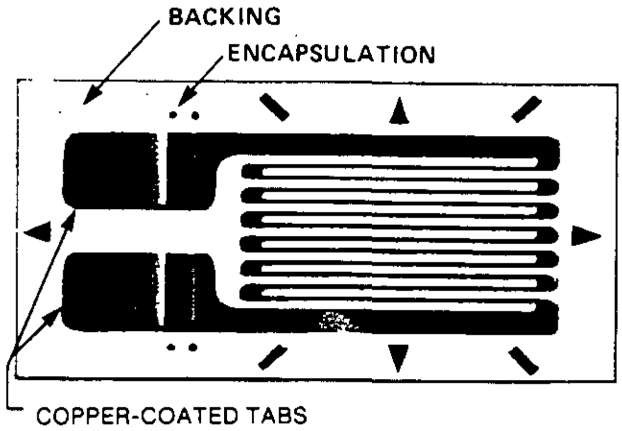
The above table gives the recommended gage series for specific test "profiles," or sets of test requirements, categorized by the following criteria:

- type of strain measurement (static, dynamic, etc.)
- operating temperature of gage installation
- test duration
- accuracy required
- cyclic endurance required

This table provides the basic means for preliminary selection of the gage series for most conventional applications. It also includes recommendations for adhesives, since the adhesive in a strain gage installation becomes part of the gage system, and correspondingly affects the performance of the gage. This selection table, supplemented by the information in the table on page 4, is used in conjunction with Catalog 500, Part A — *Strain Gage Listings* to arrive at the complete gage selection. The procedure for accomplishing this is described in ***Section 3.0*** of this Tech Note.

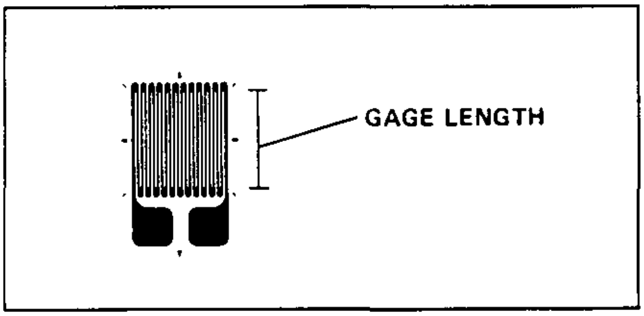
When a test profile is encountered that is beyond the ranges specified in the above table, it can usually be assumed that the test requirements approach or exceed the performance limitations of available gages. Under these conditions, the interactions between gage performance characteristics become too complex for presentation in a simple table. In such cases, the user should consult the Applications Engineering Department of Micro-Measurements for assistance in arriving at the best compromise.

As indicated in the previous table, the CEA Series is usually the preferred choice for routine strain-measurement situations, not requiring extremes in performance or environmental capabilities (and not requiring the very smallest in gage lengths, or specialized grid configurations). CEA-Series strain gages are polyimide-encapsulated A-alloy gages, featuring large, rugged, copper-coated tabs for ease in soldering leadwires directly to the gage (photograph below). These thin, flexible gages can be contoured to almost any radius. In overall handling characteristics, for example, convenience, resistance to damage in handling, etc., CEA-Series gages are outstanding.

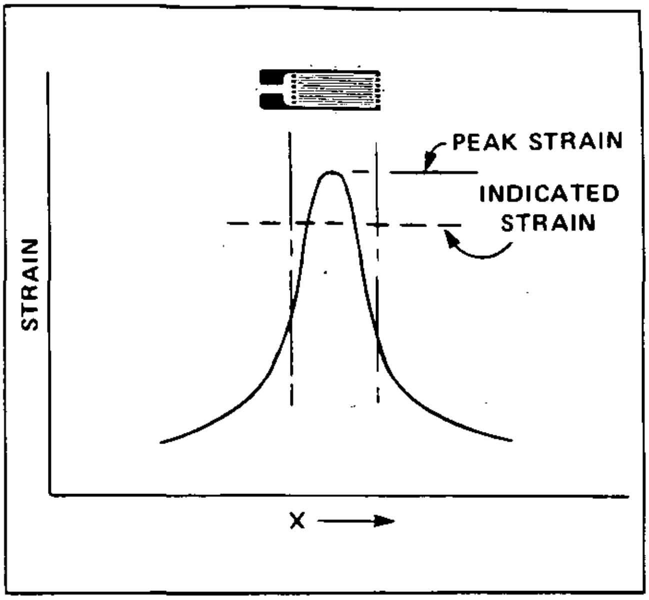


2.4 Gage Length

The gage length of a strain gage is the active or strain-sensitive length of the grid, as shown below. The endloops and solder tabs are considered insensitive to strain because of their relatively large cross-sectional area and low electrical resistance. To satisfy the widely varying needs of experimental stress analysis and transducer applications, the Micro-Measurements Division offers gage lengths ranging from 0.008 in *(0.2 mm)* to 4 in *(100 mm)*.



Gage length is often a very important factor in determining the gage performance under a given set of circumstances. For example, strain measurements are usually made at the most critical points on a machine part or structure — that is, at the most highly stressed points. And, very commonly, the highly stressed points are associated with stress concentrations, where the strain gradient is quite steep and the area of maximum strain is restricted to a very small region. The strain gage tends to integrate, or average, the strain over the area covered by the grid. Since the average of any nonuniform strain distribution is always less than the maximum, a strain gage which is noticeably larger than the maximum strain region will indicate a strain magnitude which is too low. The sketch below illustrates a representative strain distribution in the vicinity of a stress concentration, and demonstrates the error in strain indicated by a gage which is too long with respect to the zone of peak strain.



As a rule of thumb, *when practicable*, the gage length should be no greater than 0.1 times the radius of a hole, fillet, or notch, or the corresponding dimension of any other stress raiser at which the strain measurement is to be made. With stress-raiser configurations having the significant dimension less than, say, 0.5 in *(13 mm)*, this rule of thumb can lead to very small gage lengths. Because the use of a small strain gage may introduce a number of other problems, it is often necessary to compromise.

Strain gages of less than about 0.125 in *(3 mm)* gage length tend to exhibit degraded performance — particularly in terms of the maximum allowable elongation, the stability under static strain, and endurance when subjected to alternating cyclic strain. When any of these considerations outweigh the inaccuracy due to strain averaging, a larger gage may be required.

When they can be employed, larger gages offer several advantages worth noting. They are usually easier to handle (in gage lengths up to, say, 0.5 in or *13 mm*) in nearly every aspect of the installation and wiring procedure than miniature gages. Furthermore, large gages provide improved heat dissipation because they introduce, for the same nominal gage resistance, lower wattage per unit of grid area. This consideration can be very important when the gage is installed on a plastic or other substrate with poor heat transfer properties. Inadequate heat dissipation causes high temperatures in the grid, backing, adhesive, and test specimen surface, and may noticeably affect gage performance and accuracy (see Measurements Group Tech Note TN-502, *Optimizing Strain Gage Excitation Levels*).

Still another application of large strain gages — in this case, often very large gages — is in strain measurement on nonhomogeneous materials. Consider concrete, for example, which is a mixture of aggregate (usually stone) and cement. When measuring strains in a concrete structure it is ordinarily desirable to use a strain gage of sufficient gage length to span several pieces of aggregate in order to measure the representative strain in the structure. In other words, it is usually the *average* strain that is sought in such instances, not the severe local fluctuations in strain occurring at the interfaces between the aggregate particles and the cement. In general, when measuring strains on structures made of composite materials of any kind, the gage length should normally be large with respect to the dimensions of the inhomogeneities in the material.

As a generally applicable guide, when the foregoing considerations do not dictate otherwise, gage lengths in the range from 0.125 to 0.25 in *(3 to 6 mm)* are preferable. The largest selection of gage patterns and stock gages is available in this range of lengths. Furthermore, larger or smaller sizes generally cost more, and larger gages do not noticeably improve fatigue life, stability, or elongation, while shorter gages are usually inferior in these characteristics.

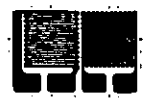
2.5 Gage Pattern

The gage pattern refers cumulatively to the shape of the grid, the number and orientation of the grids in a multiple-grid gage, the solder tab configuration, and various construction features which are standard for a particular pattern. All details of the grid and solder tab configurations are illustrated in the "Gage Pattern" columns of Catalog 500, Part A — *Strain Gage Listings*. The wide variety of patterns in the list is designed to satisfy the full range of normal gage installation and strain measurement requirements.

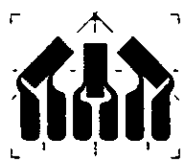
With single-grid gages, pattern suitability for a particular application depends primarily on the following:

> *Solder tabs* — These should, of course, be compatible in size and orientation with the space available at the gage installation site. It is also important that the tab arrangement be such as to not excessively tax the proficiency of the installer in making proper leadwire connections.
>
> *Grid width* — When severe strain gradients perpendicular to the gage axis exist in the test specimen surface, a narrow grid will minimize the averaging error. Wider grids, when available and suitable to the installation site, will improve the heat dissipation and enhance gage stability — particularly when the gage is to be installed on a material or specimen with poor heat transfer properties.
>
> *Gage resistance* — In certain instances, the only difference between two gage patterns available in the same series is the grid resistance — typically 120 ohms vs. 350 ohms. When the choice exists, the higher-resistance gage is preferable in that it reduces the heat generation rate by a factor of three (for the same applied voltage across the gage). Higher gage resistance also has the advantage of decreasing leadwire effects such as circuit desensitization due to leadwire resistance, and unwanted signal variations caused by leadwire resistance changes with temperature fluctuations. Similarly, when the gage circuit includes switches, slip rings, or other sources of random resistance change, the signal-to-noise ratio is improved with higher resistance gages operating at the same power level.

In experimental stress analysis, a single-grid gage would normally be used only when the stress state at the point of measurement is known to be uniaxial and the directions of the principal axes are known with reasonable accuracy (±5°). These requirements severely limit the meaningful applicability of single-grid strain gages in stress analysis; and failure to consider biaxiality of the stress state can lead to large errors in the stress magnitude inferred from measurements made with a single-grid gage.

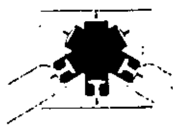

90-degree rosette

For a biaxial stress state — a common case necessitating strain measurement — a two- or three-element rosette is required in order to determine the principal stresses. When the directions of the principal axes are known in advance, a two-element 90-degree (or "tee") rosette can be employed with the gage axes aligned to coincide with the principal axes. The directions of the principal axes can sometimes be determined with sufficient accuracy from one of several considerations. For example, the shape of the test object and the mode of loading may be such that the directions of the principal axes are obvious from the symmetry of the situation, as in a cylindrical pressure vessel. The principal axes can also be defined by testing with photoelastic coating.


45-degree rosette


60-degree rosette

In the most general case of surface stresses, when the directions of the principal axes are not known from other considerations, a three-element rosette must be used to obtain the principal stress magnitudes. The rosette can be installed with any orientation, but is usually mounted so that one of the grids is aligned with some significant axis of the test object. Three-element rosettes are available in both 45-degree rectangular and 60-degree delta configurations. The usual choice is the rectangular rosette since the data-reduction task is somewhat simpler for this configuration.


Stacked rosette

When a rosette is to be employed, careful consideration should always be given to the difference in characteristics between single-plane and stacked rosettes. For any given gage length, the single-plane rosette is superior to the stacked rosette in terms of heat transfer to the test specimen, generally providing better stability and accuracy for static strain measurements. Furthermore, when there is a significant strain gradient perpendicular to the test surface (as in bending), the single-plane rosette will produce more accurate strain data because all grids are as close as possible to the test surface. Still another consideration is that stacked rosettes are generally less conformable to contoured surfaces than single-plane rosettes.

On the other hand, when there are large strain gradients in the plane of the test surface, as is often the case, the single-plane rosette can produce errors in strain indication because the grids sample the strain at different points. For these applications the stacked rosette is ordinarily preferable. The stacked rosette is also advantageous when the space for mounting the rosette is limited.

2.6 Optional Features

Micro-Measurements offers a selection of optional features for its strain gages and special sensors. The addition of options to the basic gage construction usually increases the cost, but this is generally offset by the benefits. Examples are:

- Significant reduction of installation time and costs
- Reduction of the skill level necessary to make dependable installations
- Increased reliability of applications
- Simplified installation of sensors in difficult locations on components or in the field
- Increased protection, both in handling during installation and shielding from the test environment
- Achievement of special performance characteristics

Availability of each option varies with gage series and pattern. Standard options are noted for each sensor in Catalog 500, Part A — *Strain Gage Listings.*

Shown below is a summary of the optional features offered.

Standard Catalog Options

OPTION	BRIEF DESCRIPTION
W	Integral Terminals and Encapsulation
E	Encapsulation with Exposed Tabs
SE	Solder Dots and Encapsulation
L	Preattached Leads
LE	Preattached Leads and Encapsulation

Option *W* | **Series Availability: EA, EP, WA, ED, EK, WK**

General Description: This option provides encapsulation, and thin, printed circuit terminals at the tab end of the gage. Beryllium copper jumpers connect the terminals to the gage tabs. The terminals are 1.4 mil [0.0014 in *(0.036 mm)*] thick copper on polyimide backing about 1.5 mil [0.0015 in *(0.038 mm)*] thick. Option W gages are rugged and well protected, and permit the direct attachment of larger leadwires than would be possible with open-faced gages. This option is primarily used on EA-Series gages for general-purpose applications. **Solder:** +430° F *(+220° C)* tin-silver alloy solder joints on E-backed gages. +570° F *(+300° C)* lead-tin-silver alloy solder joints on W-backed gages. **Temperature Limit:** +400° F *(+200° C)* for E-backed gages, +500° F *(+260° C)* for W-backed gages. **Grid Protection:** Entire grid and part of terminals are encapsulated with polyimide. **Fatigue Life:** Some loss in fatigue life unless strain levels at the terminal location are below ±1000$\mu\epsilon$. **Size:** Option W extends from the soldering tab end of the gages and thereby increases gage size. With some patterns width is slightly greater. **Strain Range:** With some gage series, notably E-backed gages, strain range will be reduced. This effect is greatest with EP gages, and Option W should be avoided with them if possible. **Flexibility:** Option W adds encapsulation, making gages slightly thicker and stiffer. Conformance to curved surfaces will be somewhat reduced. In the terminal area itself, stiffness is markedly increased. **Resistance Tolerance:** On E-backed gages, resistance tolerance is normally doubled.

Option *E* | **Series Availability: EA, ED, EK, EP**

General Description: Option E consists of a protective encapsulation of polyimide film approximately 1 mil [0.001 in *(0.025 mm)*] thick. This provides ruggedness and excellent grid protection, with little sacrifice in flexibility. Soldering is greatly simplified since the solder is prevented from tinning any more of the gage tab than is deliberately exposed for lead attachment. Option E contributes significantly to long-term gage stability, because the grid cannot be contaminated by fingerprints or other agents during installation. Heavier leads may be attached directly to the gage tabs for simple static load tests. Supplementary protective coatings should still be applied after lead attachment in most cases. **Temperature Limit:** No degradation. **Grid Protection:** Entire grid and part of tabs are encapsulated. **Fatigue Life:** When gages are properly wired with small jumpers, maximum endurance is easily obtained. **Size:** Gage size is not affected. **Strain Range:** Strain range of gages will be reduced because the additional reinforcement of the polyimide encapsulation can cause bond failure before the gage reaches its full strain capability. **Flexibility:** Option E gages are almost as conformable on curved surfaces as open-faced gages, since no internal leads or solder are present at the time of installation. **Resistance Tolerance:** Resistance tolerance is normally doubled when Option E is selected.

Option *SE*

Series Availability: EA, ED, EK, EP

General Description: Option SE is the combination of solder dots on the gage tabs with a 1-mil [0.001-in *(0.025-mm)*] polyimide encapsulation layer that covers the entire gage. The encapsulation is removed over the solder dots, providing access for lead attachment. These gages are very flexible, and well protected from handling damage during installation. Option SE is primarily intended for small gages that must be installed in restricted areas, since leadwires can be routed to the exposed solder dots from any direction. The option does not increase overall gage dimensions, so the matrix may be field-trimmed very close to the actual pattern size. Option SE is sometimes useful on miniature transducers of medium or low accuracy class, or in stress analysis work on miniature parts. **Solder:** +570° F *(+300° C)* lead-tin-silver alloy. To prevent loss of long-term stability, gages with Option SE must be soldered with noncorrosive (rosin) flux, and all flux residue should be carefully removed with *M-LINE* Rosin Solvent after wiring. Protective coatings should then be used. **Temperature Limit:** No degradation. **Grid Protection:** Entire gage is encapsulated. **Fatigue Life:** When gages are properly wired with small jumpers, maximum endurance is easily obtained. **Size:** Gage size is not affected. **Strain Range:** Strain range of gages will be reduced because the additional reinforcement of the polyimide encapsulation can cause bond failure before the gage reaches its full strain capability. **Flexibility:** Option SE gages are almost as conformable on curved surfaces as open-faced gages. **Resistance Tolerance:** Resistance tolerance is normally doubled when Option SE is selected.

Option *L*

Series Availability: EA, ED, EK, EP

General Description: Option L is the addition of soft copper lead ribbons to open-faced polyimide-backed gages. The use of this type of ribbon results in a thinner and more conformable gage than would be the case with round wires of equivalent cross section. At the same time, the ribbon is so designed that it forms almost as readily in any desired direction. **Leads:** Nominal ribbon size is 0.012 wide x 0.004 thick in *(0.30 x 0.10 mm)*. Leads are approximately 0.8 in *(20 mm)* long. **Solder:** +430° F *(+220° C)* tin-silver alloy. The solder is confined to small, well-defined areas at the end of each ribbon. **Temperature Limit:** +400° F *(+200° C)*. **Fatigue Life:** Fatigue life will normally be degraded by Option L. This occurs primarily because the copper ribbon has limited cyclic endurance. When it is possible to carefully dress the leads so that they are not bonded in a high strain field, the performance limitation will not apply. Option L is not often recommended for very high endurance gages such as the ED Series. **Size:** Matrix size is unchanged. **Strain Range:** Strain range will usually be reduced by the addition of Option L. **Flexibility:** Gages with Option L are not as conformable as standard gages. **Resistance Tolerance:** Not affected.

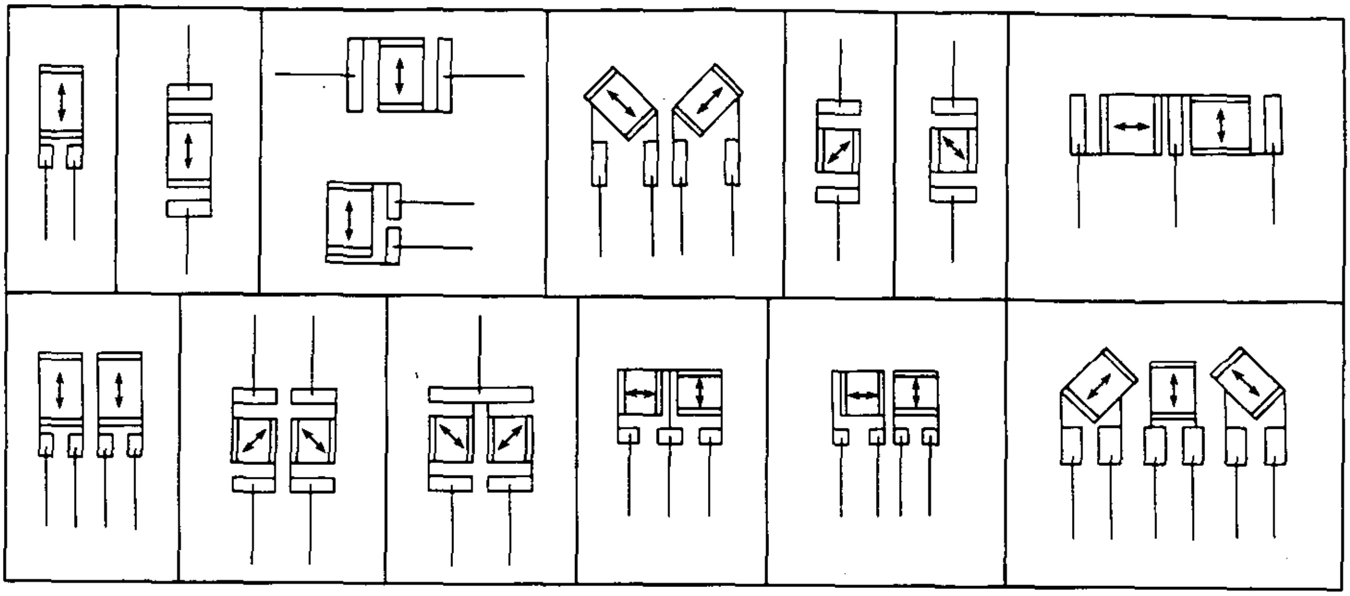
Option *LE*

Series Availability: EA, ED, EK, EP

General Description: This option provides the same conformable soft copper lead ribbons as used in Option L, but with the addition of a 1-mil [0.001-in *(0.025-mm)*] thick encapsulation layer of polyimide film. The encapsulation layer provides excellent protection for the gage during handling and installation. It also contributes greatly to environmental protection, though supplementary coatings are still recommended for field use. Gages with Option LE will normally show better long-term stability than open-faced gages which are "waterproofed" only after installation. A good part of the reason for this is that the encapsulation layer prevents contamination of the grid surface from fingerprints or other agents during handling and installation. The presence of such contaminants will cause some loss in gage stability, even though the gage is subsequently coated with protective compounds. **Leads:** 0.012 wide x 0.004 thick in *(0.30 x 0.10 mm)* copper ribbons. Leads are approximately 0.8 in *(20 mm)* long. **Solder:** +430° F *(+220° C)* tin-silver alloy. The solder is confined to small, well-defined areas at the end of each ribbon. **Temperature Limit:** +400° F *(+200° C)*. **Grid Protection:** Entire gage is encapsulated. A short extension of the backing is left uncovered at the leadwire end to prevent contact between the leadwires and the specimen surface. **Fatigue Life:** Fatigue life will normally be degraded by Option LE. This occurs primarily because the copper ribbon has limited cyclic endurance. Option LE is not often recommended for very high endurance gages such as the ED Series. **Size:** Matrix size is unchanged. **Strain Range:** Strain range will usually be reduced by the addition of Option LE. **Flexibility:** Gages with Option LE are not as conformable as standard gages. **Resistance Tolerance:** Resistance tolerance is normally doubled by the addition of Option LE.

Leadwire Orientation for Options L and LE

These illustrations show the standard orientation of leadwires relative to the gage pattern geometry for Options L and LE. The general rule is that the leads are parallel to the longest dimension of the pattern. The illustrations also apply to leadwire orientation for WA-, WK-, and WD-Series gages, when the pattern shown is available in one of these series.



2.7 Characteristics of Standard Catalog Options on EA-Series Gages

As in other aspects of strain gage selection, the choice of options ordinarily involves a variety of compromises. For instance, an option which maximizes a particular gage performance parameter such as fatigue life may at the same time require greater skill in installing the gage. Because of the many interactions between installation attributes and performance parameters associated with the options, the relative merits of all standard options are summarized qualitatively in the chart below as an aid to option selection. For comparison purposes, the corresponding characteristics of the CEA Series are given in the right-most column of the table.

Since, in strain measurement for stress analysis, the standard options are most frequently applied to EA-Series strain gages, the information supplied in this section is directed primarily toward such option applications.

When contemplating the application of an EA-Series gage with an option, the first consideration should usually be whether there is an equivalent CEA-Series gage that will satisfy the test requirements. Comparing, for example, an EA-Series gage equipped with Option W and a similar CEA-Series pattern, it will be found that the latter is characterized by lower cost, greater flexibility and conformability, and superior fatigue life. The only possible advantages for the selection of Option W are the wider variety of available patterns and the occasional need for large soldering terminals.

It should also be noted that many standard strain gage types, without options, are normally available from stock; while gages with options are commonly manufactured to order, and may thus involve a minimum order requirement.

In the table below, the respective performance parameters for an open-faced EA-Series gage without options are arbitrarily assigned a value of 5. Numbers greater than 5 indicate a particular parameter is improved by addition of the option, while smaller numbers indicate a reduction in performance.

INSTALLATION ATTRIBUTE OR PERFORMANCE PARAMETER	STANDARD OPTIONS					CEA SERIES
	W	E	SE	L	LE	
Overall Ease of Gage Installation	8	7	6	5	6	10
Ease of Leadwire Attachment	10	8	7	7	8	10
Protection of Grid from Environmental Attack	8	8	8	5	8	8
Cyclic Strain Endurance	2	7	8	3	4	4
Elongation Capability	2	3	3	4	3	3
Resistance Tolerance	3	3	3	5	3	3
Reinforcement Effects	2	3	3	5	3	3

3.0 Gage Selection Procedure

The performance of a strain gage in any given application is affected by every element in the design and manufacture of the gage. Micro-Measurements offers a great variety of gage types for meeting the widest range of strain measurement needs. Despite the large number of variables involved, the process of gage selection can be reduced to only a few basic steps. From the diagram below that explains the gage designation code, it is evident that there are but five parameters to select, not counting options. These are: the gage series, the S-T-C number, the gage length and pattern, and the resistance.

Of the preceding parameters, the gage length and pattern are normally the first and second selections to be made, based on the space available for gage mounting and the nature of the stress field in terms of biaxiality and expected strain gradient. A good starting point for initial consideration of gage length is 0.125 in *(3 mm)*. This size offers the widest variety of choices from which to select remaining gage parameters such as pattern, series and resistance. The gage and its solder tabs are large enough for relatively easy handling and installation. At the same time, gages of this length provide performance capabilities comparable to those of larger gages.

The principal reason for selecting a longer gage would commonly be one of the following: (a) greater grid area for better heat dissipation; (b) improved strain averaging on inhomogeneous materials such as fiber-reinforced composites; or (c) slightly easier handling and installation [for gage lengths up to 0.50 in *(13 mm)*]. On the other hand, a shorter gage length may be necessary when the object is to measure localized peak strains in the vicinity of a stress concentration, such as a hole or shoulder. The same is true, of course, when the space available for gage mounting is very limited.

In selecting the gage pattern, the first consideration is whether a single-grid gage or rosette is required (see ***Section 2.5***). Single-grid gages are available with different aspect (length-to-width) ratios and various solder tab arrangements for adaptability to differing installation requirements. Two-element 90-degree rosettes, when applicable, can also be selected from a number of different grid and solder tab configurations. With three-element rosettes (rectangular or delta), the primary choice in pattern selection, once the gage length has been determined, is between planar and stacked construction, as described in ***Section 2.5***.

The format of Catalog 500, Part A — *Strain Gage Listings* is designed to simplify selection of the gage length and pattern. Similar patterns available in each gage length are grouped together, and listed in order of size. The strain gages in the Super Stock section of the catalog are the most widely used for stress analysis applications. This section should always be reviewed first to locate an appropriate gage.

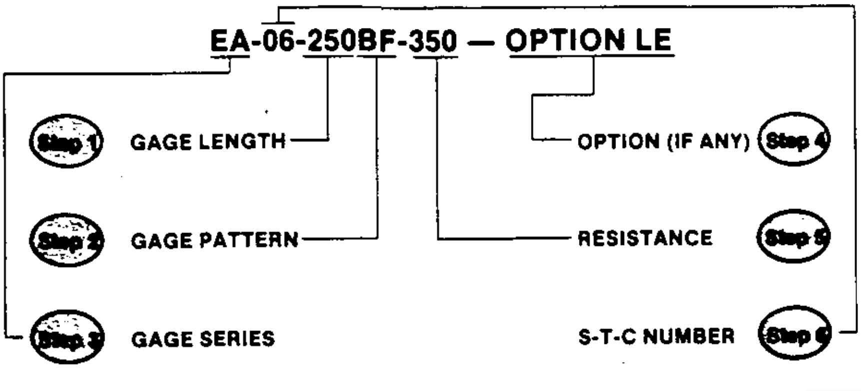
With an initial selection of the gage size and pattern completed, the next step is to select the gage series, thus determining the foil and backing combination, and any other features common to the series. This is accomplished by referring to the chart on page 5, which gives the recommended gage series for specific test "profiles", or sets of test requirements. If the gage series is to have a standard option applied, the option should be tentatively specified at this time, since the availability of the desired option on the selected gage pattern in that series requires verification during the procedure outlined in the following paragraph.

After selecting the gage series (and option, if any), reference is made again to Catalog 500, Part A — *Strain Gage Listings* to record the gage designation of the desired gage size and pattern in the recommended series. If this combination is not listed as available in the catalog, a similar gage pattern in the same size group, or a slightly different size in an equivalent pattern, can usually be selected for meeting the installation and test requirements. In extreme cases, it may be necessary to select an alternate series and repeat this process. Quite frequently, and especially for routine strain measurement, more than one gage size and pattern combination will be suitable for the specified test conditions. In these cases, it is wise to select a gage from the Super Stock Listings to eliminate the likelihood of extended delivery time or a minimum order requirement.

As noted under the gage pattern discussion on page 7, there are often advantages from selecting the 350-ohm resistance if this resistance is compatible with the instrumentation to be used. This decision may be influenced, however, by cost considerations, particularly in the case of very small gages. Some reduction in fatigue life can also be expected for the high-resistance small gages. Finally, in recording the complete gage designation, the S-T-C number should be inserted from the list of available numbers for each alloy given on page 4 of Catalog 500, Part A — *Strain Gage Listings*.

This completes the gage selection procedure. In each step of the procedure, the Strain Gage Selection Checklist on page 12 should be referred to as an aid in accounting for the test conditions and requirements which could affect the selection.

Strain Gage Selection Steps



4.0 Strain Gage Selection Checklist

This checklist is provided as a convenient, rapid means for helping make certain that no critical requirement of the test profile which could affect gage selection is overlooked. It should be borne in mind in using the checklist that the "considerations" listed apply to relatively routine and conventional stress analysis situations, and do not embrace exotic applications involving nuclear radiation, intense magnetic fields, extreme centrifugal forces, and the like.

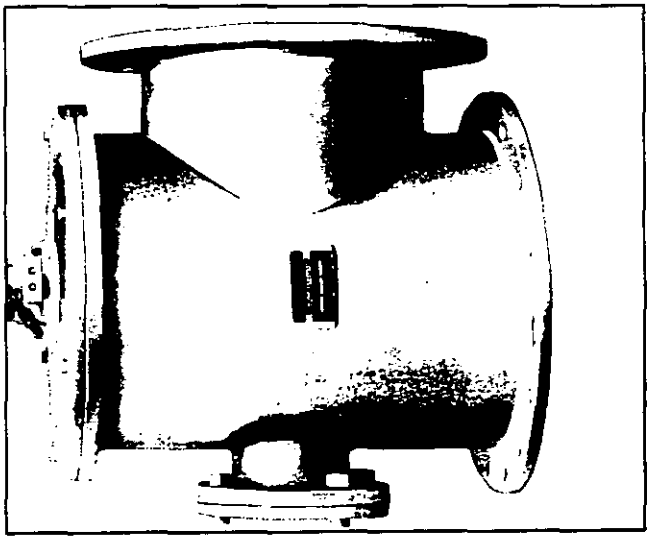
	CONSIDERATIONS FOR PARAMETER SELECTION
Selection Step: **1** *Parameter:* **Gage Length**	☐ strain gradients ☐ area of maximum strain ☐ accuracy required ☐ static strain stability ☐ maximum elongation ☐ cyclic endurance ☐ heat dissipation ☐ space for installation ☐ ease of installation
Selection Step: **2** *Parameter:* **Gage Pattern**	☐ strain gradients (in-plane and normal to surface) ☐ biaxiality of stress ☐ heat dissipation ☐ space for installation ☐ ease of installation ☐ gage resistance availability
Selection Step: **3** *Parameter:* **Gage Series**	☐ type of strain measurement application (static, dynamic, post-yield, etc.) ☐ operating temperature ☐ test duration ☐ cyclic endurance ☐ accuracy required ☐ ease of installation
Selection Step: **4** *Parameter:* **Options**	☐ type of measurement (static, dynamic, post-yield, etc.) ☐ installation environment — laboratory or field ☐ stability requirements ☐ soldering sensitivity of substrate (plastic, bone, etc.) ☐ space available for installation ☐ installation time constraints
Selection Step: **5** *Parameter:* **Gage Resistance**	☐ heat dissipation ☐ leadwire desensitization ☐ signal-to-noise ratio
Selection Step: **6** *Parameter:* **S-T-C Number**	☐ test specimen material ☐ operating temperature range ☐ accuracy required

5.0 Gage Selection Examples

In this section, three examples are given of the gage-selection procedure in representative stress analysis situations. An attempt has been made to provide the principal reasons for the particular choices which are made. It should be noted, however, that an experienced stress analyst does not ordinarily proceed in the same step-by-step fashion illustrated in these examples. Instead, simultaneously keeping in mind the test conditions and environment, the gage installation constraints, and the test requirements, the analyst reviews Catalog 500, Part A — *Strain Gage Listings*, and quickly segregates the more likely candidates from among the available gage-pattern and series combinations in the appropriate sizes. The selection criteria are then refined in accordance with the particular strain-measurement task to converge on the gage or gages to be specified for the test program. Whether formally or otherwise, the knowledgeable practitioner does so in the light of parameter selection considerations such as those itemized in the preceding checklist.

A. Design Study of a Pressure Vessel

Strain measurements are to be made on a scaled-down plastic model of a pressure vessel. The model will be tested statically at, or near, room temperature; and, although the tests may be conducted over a period of several months, individual tests will take only a few hours to run.



Gage Selection:

1. *Gage Length* — Very short gage lengths should be avoided in order to minimize heat dissipation problems caused by the low thermal conductivity of the plastic. The model is quite large, and apparently free of severe strain gradients; therefore, a 0.25-in *(6.3-mm)* gage length is specified, because the widest selection of gage patterns is available in this length.
2. *Gage Pattern* — In some areas of the model, the directions of the principal axes are obvious from considerations of symmetry, and single-grid gages can be employed. Of the patterns available in the selected gage length, the 250BF pattern is a good compromise because of its high grid resistance which will help minimize heat dissipation problems.

In other areas of the model, the directions of the principal axes are not known, and a three-element rosette will be required. For this purpose, a "planar" rosette should be selected, since a stacked rosette would contribute significantly to reinforcement and heat dissipation problems. Because of its high-resistance grid, the 250RD pattern is a good choice.

3. *Gage Series* — The polyimide (E) backing is preferred because its low elastic modulus will minimize reinforcement of the plastic model. Because the normal choice of grid alloy for static strain measurement at room temperature is the A alloy, the EA Series should be selected for this application.

4. *Options* — Excessive heat application to the test model during leadwire attachment could damage the material. Option L (preattached leads) is therefore selected so that the instrument cable can be attached directly to the leads without the application of a soldering iron to the gage proper. Option L is preferable over Option LE because the encapsulation in the latter option would add reinforcement.

5. *Resistance* — In this case, the resistance was determined in Step 2 when the higher resistance alternative was selected from among the gage patterns; i.e., in selecting the 250BF over the 250BG, and the 250RD over the 250RA. The selected gage resistance is thus 350 ohms.

6. *S-T-C Number* — Ideally, the gages should be self-temperature-compensated to match the model material, but this is not always feasible, since plastics — particularly reinforced plastics — vary widely in thermal expansion coefficient. For unreinforced plastic, S-T-C 30, 40 or 50 should usually be selected. If a mismatch between the model material and the S-T-C number is necessary, S-T-C 13 should be selected (because of stock status), and the test performed at constant temperature.

Gage Designations:

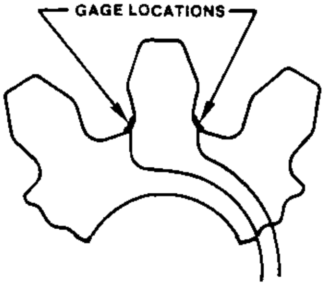
From the above steps, the strain gages to be used are:

EA-30-250BF-350/Option L (single-grid)
EA-30-250RD-350/Option L (rosette)

See page 15 for a description of the strain gage types mentioned in this section.

B. Dynamic Stress Analysis Study of a Spur Gear in a Hydraulic Pump

Strain measurements are to be made at the root of the gear tooth while the pump is operating. The fillet radius at the tooth root is 0.125 in (or about *3 mm*) and test temperatures are expected to range from 0° to +180°F *(-20° to +80°C)*.



Gage Selection:

1. *Gage Length* — A gage length which is small with respect to the fillet radius should be specified for this application. A length of 0.015 in *(0.38 mm)* is preferable, but reference to Catalog 500, Part A — *Strain Gage Listings*, indicates that such a choice severely limits the available gage patterns and grid alloys. Anticipating problems which would otherwise be encountered in Steps 2 and 3, a gage length of 0.031 in *(0.8 mm)* is selected.

2. *Gage Pattern* — Because the gear is a spur gear, the directions of the principal axes are known, and single-grid gages can be employed. A gage pattern with both solder tabs at the same end should be selected so that leadwire connections can be located in the clearance area along the root circle between adjacent teeth. In the light of these considerations, the 031CF pattern is chosen for the task.

3. *Gage Series* — Low strain levels are expected in this application; and, furthermore, the strain signals must be transmitted through slip rings or through a telemetry system to get from the rotating component to the stationary instrumentation. Iso-Elastic (D alloy) is preferred for its higher gage factor (nominally 3.2, in contrast to 2.1 for A and K alloys). Because the gage must be very flexible to conform to the small fillet radius, the E backing is the most suitable choice. The maximum test temperature is not a consideration in this case, since it is well within the recommended temperature range for any of the standard backings. The combination of the E backing and the D alloy defines the ED gage series.

4. *Options* — For protection of the gage grid in the test environment, Option E, encapsulation, should be specified. Because of the limited clearance between the outside diameter of one gear and the root circle of the mating gear, a particularly thin gage installation must be made; and very small leadwires will be attached to the gage tabs at 90° to the grid direction, and run over the sides of the gear for connection to larger wires. This requirement necessitates attachment of the small leadwires after gage bonding, and prevents the use of preattached leads.

5. *Resistance* — In the ED-Series version of the 031CF gage pattern, Catalog 500, Part A — *Strain Gage Listings*, lists the resistance as 350 ohms. The higher resistance should usually be selected whenever the choice exists, and will be advantageous in this instance in improving the signal-to-noise ratio when slip rings are used.

6. *S-T-C Number* — D alloy is not subject to self-temperature-compensation, nor is compensation needed for these tests since only dynamic strain is to be measured. In the ED-Series designation the two-digit S-T-C number is replaced by the letters DY for "dynamic."

Gage Designation:

Combining the results of the above selection procedure, the gage to be employed is:

ED-DY-031CF-350/Option E

C. Flight-Test Stress Analysis of a Titanium Aircraft Wing Tip Section — With, and Without, a Missile Module Attached

The operating temperature range for strain measurements is from -65° to +450° F *(-55° to +230° C)*, and will be a dominant factor in the gage selection.

Gage Selection:

1. *Gage Length* — Preliminary design studies using the PhotoStress® photoelastic coating technique indicate that a gage length of 0.062 in *(1.6 mm)* represents the best compromise in view of the strain gradients, areas of peak strain, and space for gage installation.

2. *Gage Pattern* — With information about the stress state and directions of principal axes gained from the photoelastic coating studies, there are some areas of the wing tip where single-grid gages and two-element "tee" rosettes can be employed. In other locations, where principal strain directions vary with the nature of the flight maneuver, 45°-degree rectangular rosettes are required. The strain gradients are sufficiently steep that stacked rosettes should be selected. From Catalog 500, Part A —*Strain Gage Listings*, the foregoing requirements suggest the selection of 060WT and 060WR gage patterns for the stacked rosettes, and the 062AP pattern for the single-grid gage. In making this selection, attention was given to the fact that all three patterns are available in the WK Series, which is compatible with the specified operating temperature range.

3. *Gage Series* — The maximum operating temperature, along with the requirement for static as well as dynamic strain measurement, clearly dictates use of K alloy for the grid material. Either the SK or WK Series could be selected, but the WK gages are preferred because they have integral leadwires.

4. *Options* — For ease of gage installation, Option W, with integral soldering terminals, is advantageous. This option is not applicable to stacked rosettes, however, and is therefore specified for only the single-grid gages.

5. *Resistance* — When available, as in this case, 350-ohm gages should be specified because of the benefits associated with the higher gage resistance.

6. *S-T-C Number* — The titanium alloy used in the wing tip section is the 6Al-4V type, with a thermal expansion coefficient of 4.9 x 10^{-6} per ° F *(8.8 x 10^{-6} per ° C)*. K alloy of S-T-C number 05 is the appropriate choice.

Gage Designations:

WK-05-062AP-350/Option W

WK-05-060WT-350

WK-05-060WR-350

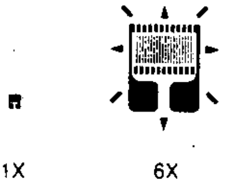
Strain gages referenced on pages 13 and 14.

GAGE PATTERN — **Actual Size Shown. Enlarged When Necessary For Definition.**

ES = Each Section
S = Section (S1 = Sec 1)
CP = Complete Pattern
M = Matrix

inches
millimetres

031CF

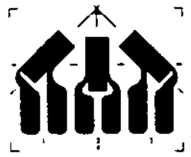


GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.031	0.076	0.062	0.062
0.79	*1.93*	*1.57*	*1.57*
Matrix Size	0.19L x 0.14W		***4.8L x 3.5W***

250BF

GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.250	0.375	0.125	0.125
6.35	*9.53*	*3.18*	*3.18*
Matrix Size	0.52L x 0.22W		***13.2L x 5.6W***

250RD



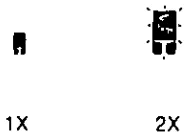
GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.250 ES	0.550 CP	0.125 ES	0.847 CP
6.35 ES	*13.79 CP*	*3.18 ES*	*21.51 CP*
Matrix Size	0.78L x 0.93W		***19.8L x 23.6W***

GAGE PATTERN — **Actual Size Shown. Enlarged When Necessary For Definition.**

ES = Each Section
S = Section (S1 = Sec 1)
CP = Complete Pattern
M = Matrix

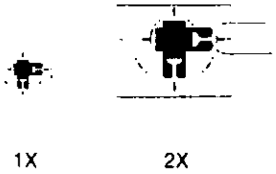
inches
millimetres

062AP



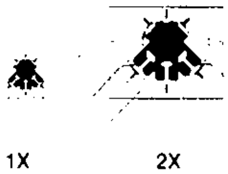
GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.062	0.114	0.062	0.062
1.57	*2.90*	*1.57*	*1.57*
Matrix Size	0.26L x 0.16W		***6.6L x 4.1W***

060WT



GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.060 ES	0.240 M	0.060 ES	0.300 M
1.52 ES	*6.1 M*	*1.52 ES*	*7.6 M*
Matrix Size	0.24L x 0.30W		***6.1L x 7.6W***

060WR



GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.060 ES	0.24 M	0.060 ES	0.030 M
1.52 ES	*6.1 M*	*1.52 ES*	*7.6 M*
Matrix Size	0.24L x 0.30W		***6.1L x 7.6W***

***M-LINE* ACCESSORIES**

Student Instruction Bulletin

Strain Gage Installations with M-Bond 200 and AE-10 Adhesive Systems

1.0 INTRODUCTION

Because the strain gage is an extremely sensitive device capable of registering the smallest effects of an imperfect bond, considerable attention to detail must be taken to assure stable, creep-free installations. However, the techniques involved are very simple, and readily mastered.

This manual gives explicit step-by-step instructions for making consistently successful strain gage installations with M-Bond 200 and M-Bond AE-10 Adhesives. These directions should be followed precisely. More detailed information may be found in the Measurements Group VideoTech™ Library and in the following publications:

- Instruction Bulletin B-129, *Surface Preparation for Strain Gage Bonding.*
- Instruction Bulletin B-127, *Strain Gage Installations with M-Bond 200 Adhesive.*
- Instruction Bulletin B-137, *Strain Gage Installations with M-Bond AE-10/15 and M-Bond GA-2 Adhesive Systems.*

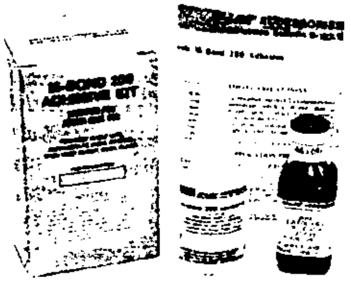
All operations described in this manual can be performed with the use of the Student Strain Gage Application Kit. The procedures outlined here are ideally suited to the classroom or teaching laboratory. For most teaching/learning activities involving strain gage technology, the specially priced, first-quality *Student Gages* manufactured by Micro-Measurements Division of the Measurements Group may be used with excellent results.

2.0 STRAIN GAGE ADHESIVES

Because consistently successful installation of strain gages requires the use of an adhesive certified for strain gage use, Micro-Measurements *M-LINE* adhesives undergo extensive laboratory testing to ensure reliability and consistency of those properties required in strain gage bonding. To assure accurate and reliable strain gage measurements, it is strongly recommended that a certified adhesive such as M-Bond 200 methyl-2-cyanoacrylate or M-Bond AE-10 epoxy adhesive be selected for most general laboratory installations.

2.1 M-Bond 200

Micro-Measurements certified M-Bond 200 is an excellent general-purpose laboratory adhesive because of its fast room-temperature cure and ease of application. It is compatible with all Micro-Measurements strain gages and all common structural materials. M-Bond 200 Adhesive can be used for high-elongation tests (+60 000$\mu\epsilon$), for fatigue studies, and for one-cycle proof tests within a normal operating temperature range of -25° to +150°F *(-32° to +65°C).*



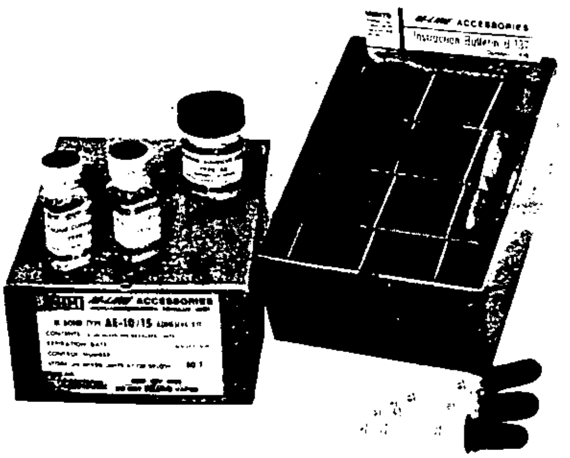
The catalyst supplied with M-Bond 200 is specially formulated to control the reactivity rate. For best results, the catalyst should be used sparingly. Since M-Bond 200 bonds are weakened by exposure to high humidity, adequate protective coatings are essential. Because this adhesive will become harder and more brittle with time, M-Bond 200 is not generally recommended for permanent installations over one or two years in duration.

HANDLING PRECAUTIONS

M-Bond 200 is a cyanoacrylate compound. *Immediate bonding of eye, skin, or mouth may result upon contact. Causes irritation.* The user is cautioned to (1) *avoid contact with skin;* (2) *avoid prolonged or repeated breathing of vapors;* and (3) *use with adequate ventilation. For additional health and safety information, consult the material safety data sheet which is available upon request.*

The shelf life of M-Bond 200 is six months when stored under normal laboratory conditions. Life of *unopened* material can be extended by refrigeration [+40°F *(+5°C)*]. Due to possible condensation problems, care should be taken to allow the unopened bottle to return to room temperature before opening. Refrigeration after opening is not recommended.

2.2 M-Bond AE-10



Micro-Measurements certified M-Bond AE-10 is a 100% solids epoxy system for use with strain gages. It offers the advantages of high elongation (10%) and wider operating temperature range [-320° to +200°F *(-195° to +95°C)*]. Because it is highly resistant to moisture and most chemicals, M-Bond AE-10 is recommended for permanent installations over one year in duration.

M-Bond AE-10 Adhesive is supplied in kit form with preweighed resin and sufficient curing agent for six separate mixes of adhesive. Allow the materials to attain room temperature before opening the containers. Each of the individual units of resin can be separately activated by filling one of the calibrated droppers with curing agent *exactly* to the number 10 and dispensing the contents into the center of the jar of resin. *Immediately cap the bottle of curing agent to avoid moisture absorption.* Mix the resin and curing agent for five minutes, using one of the plastic stirring rods. The pot life or working time after mixing is 15 to 20 minutes at +75°F *(+24°C)*. The pot life can be somewhat extended by occasionally stirring the mixture, by cooling the jar, or by spreading the adhesive on a chemically clean aluminum plate. Discard the dropper and stirring rod after use.

HANDLING PRECAUTIONS

While M-Bond AE-10 is considered relatively safe to handle, *contact with skin and inhalation of its vapors should be avoided.* Immediately washing with ordinary soap and water is effective in cleansing should skin contact occur. For eye contact, rinse thoroughly with copious amounts of water and consult a physician. For additional health and safety information, consult the material safety data sheet which is available upon request.

The shelf life of unmixed components is one year at room temperature. During storage, crystals may form in the resin. These crystals do not affect adhesive performance, but should be reliquefied prior to mixing by warming the resin jar to +120°F *(+50°C)* for approximately one-half hour. Because excess heat will shorten pot life, allow the resin to return to room temperature before adding the curing agent.

3.0 SURFACE PREPARATION

Strain gages can be bonded satisfactorily to almost any solid material if the material surface is properly prepared. While there are many surface preparation techniques available, the specific procedures and techniques described here are a carefully developed and thoroughly proven system. They are ideal for both M-Bond 200 and M-Bond AE-10 Strain Gage Adhesives.

The purpose of surface preparation is to develop a chemically clean surface having a roughness appropriate to the gage installation requirements, a surface alkalinity of the correct pH, and visible gage layout lines for locating and orienting the strain gage. The Micro-Measurements system of surface preparation will accomplish these objectives for aluminum alloys and steels in five basic operations:

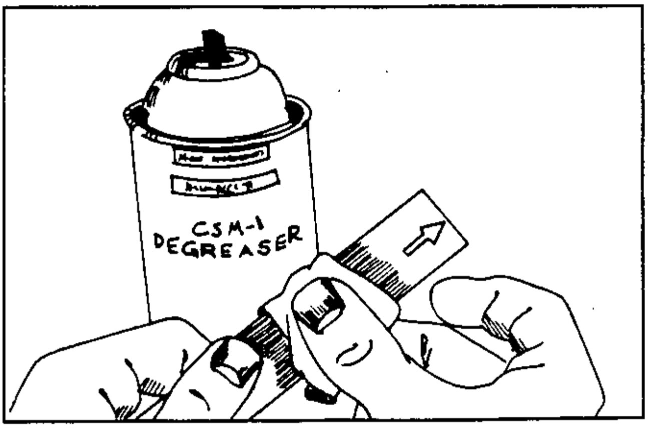
- Solvent degreasing
- Surface abrading
- Application of gage layout lines
- Surface conditioning
- Neutralizing

To ensure maximum cleanliness and best results, the following should be avoided in all steps:

- Touching the surface with the fingers
- Wiping back and forth or reusing swabs or sponges
- Dragging contaminants into the cleaned area from the uncleaned boundary of that area
- Allowing a cleaning solution to evaporate on the surface
- Allowing partially prepared surface to sit between steps in the preparation process or a prepared surface to sit before bonding

Consult Instruction Bulletin B-129 for other test materials and for special precautions and considerations for surface preparation.

3.1 Solvent Degreasing

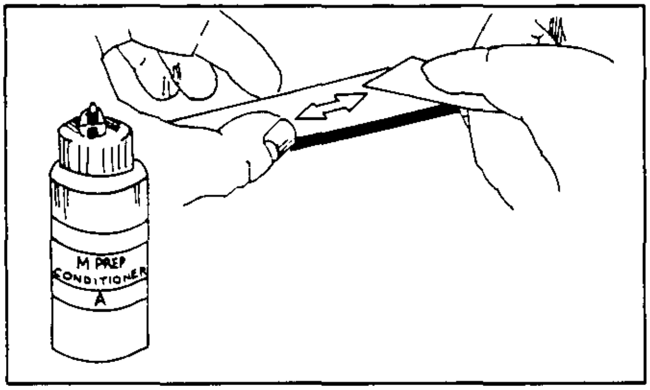


Degreasing is performed to remove oils, greases, organic contaminants, and soluble chemical residues. Degreasing should *always* be the first operation.

Degreasing can be accomplished using a solvent such as CSM-1 Degreaser. Spray applicators are preferred to avoid back-contamination of the parent solvent. Use a clean gauze sponge to clean the entire specimen, if possible, or an area covering 4 to 6 in *(100 to 150 mm)* on all sides of the gage location.

3.2 Surface Abrading

The surface is abraded to remove any loosely bonded adherents (scale, rust, paint, coatings, oxides, etc.), and to develop a surface texture suitable for bonding. For rough or coarse surfaces it may be necessary to start with a grinder, disc sander, or file; but, for most specimens a suitable surface can be produced with only silicon-carbide paper of the appropriate grit.



Place a liberal amount of M-Prep Conditioner A in the gaging area and wet-lap with clean 320-grit silicon-carbide paper for aluminum, or 220-grit for steel. Add Conditioner A as necessary to keep the surface wet during the lapping process.

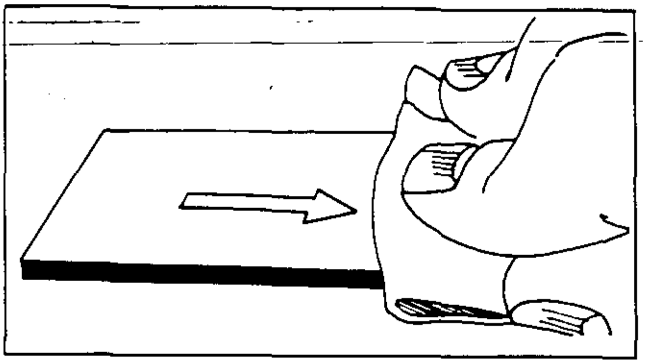
When a bright surface is produced, wipe the surface dry with a clean gauze sponge. A clean surface of the gauze should be used with each wiping stroke. A sufficiently large area should be cleaned to ensure that contaminants will not be dragged back into the gaging area during the steps to follow.

Repeat the above step, using 400-grit silicon-carbide paper for aluminum, or 320-grit for steel.

3.3 Layout Lines

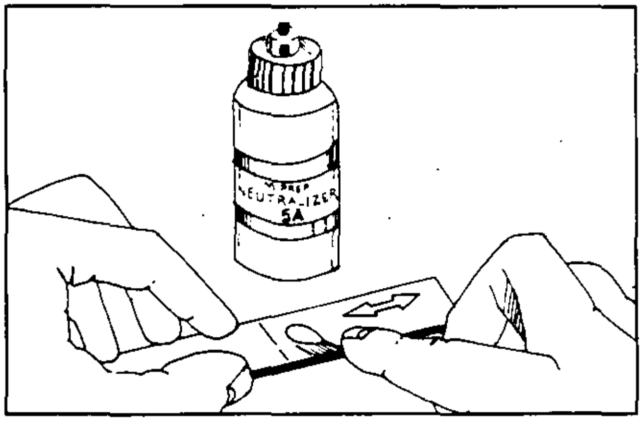
The desired location and orientation of the strain gage on the test surface should be marked with a pair of crossed, perpendicular reference lines. The reference or layout lines should be *burnished*, rather than scored or scribed, on the surface. For aluminum, a medium-hard drafting pencil is satisfactory. For most steels, a ball-point pen or a tapered brass rod may be used. All residue from the burnishing operations should be removed in the following step.

3.4 Surface Conditioning



After the layout lines are marked, Conditioner A should be applied repeatedly, and the surface scrubbed with cotton-tipped applicators until a clean tip is no longer discolored by scrubbing. The surface should be kept constantly wet with Conditioner A until the cleaning is completed. When clean, the surface should be dried by wiping through the cleaned area with a *single* slow stroke of a gauze sponge. The stroke should begin inside the cleaned area to avoid dragging contaminants in from the surrounding area. Throw the used gauze away and, with a fresh gauze, make a *single* slow stroke in the opposite direction. Throw the second gauze away.

3.5 Neutralizing



To provide optimum alkalinity for Micro-Measurements strain gage adhesives, the cleaned surfaces must be neutralized. This can be done by applying M-Prep Neutralizer 5A liberally to the cleaned surface, and scrubbing the surface with a clean cotton-tipped applicator. The cleaned surface should be kept completely wet with Neutralizer 5A throughout this operation. When neutralized, the surface should be dried by wiping through the cleaned area with a *single* slow stroke of a clean gauze sponge. Throw the gauze away and with another fresh gauze sponge, make a *single* stroke in the opposite direction. Always begin within the cleaned area to avoid recontamination from the uncleaned boundary.

If the foregoing instructions have been followed precisely, the surface is now properly prepared for gage bonding. The gages should be installed within 30 minutes on aluminum or 45 minutes on steel.

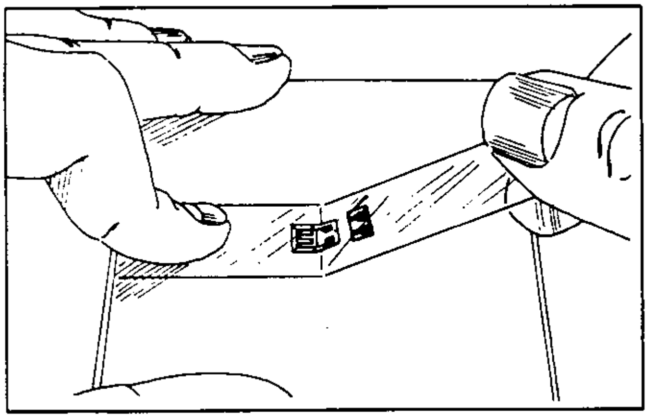
4.0 STRAIN GAGE BONDING

The electrical resistance strain gage is capable of making accurate and sensitive indications of strains on the surface of the test part. Its performance is absolutely dependent on the bond between itself and the test part. The procedures outlined below will help ensure satisfactory bonds when using M-Bond 200 or AE-10 Adhesives. While the steps may appear unduly elaborate, these techniques have been used repeatedly in strain gage installations which have yielded consistent and accurate results. The steps shown assume that a terminal strip will be used. When CEA-Series gages are used, no strip is required.

4.1 Handling and Preparation

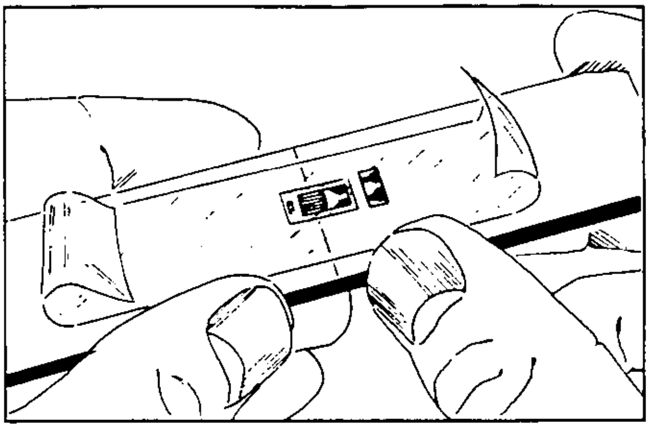
Micro-Measurements strain gages are specially treated for optimum bond formation with all appropriate gage adhesives. No further cleaning is necessary if contamination of the prepared bonding surface is avoided during handling. (Should contamination occur, clean with a cotton swab moistened with a low residue solvent such as *M-LINE* Neutralizer 5A or GC-6 Isopropyl Alcohol. Allow the gage to dry for several minutes before bonding.) Gages should never be touched with the hands.

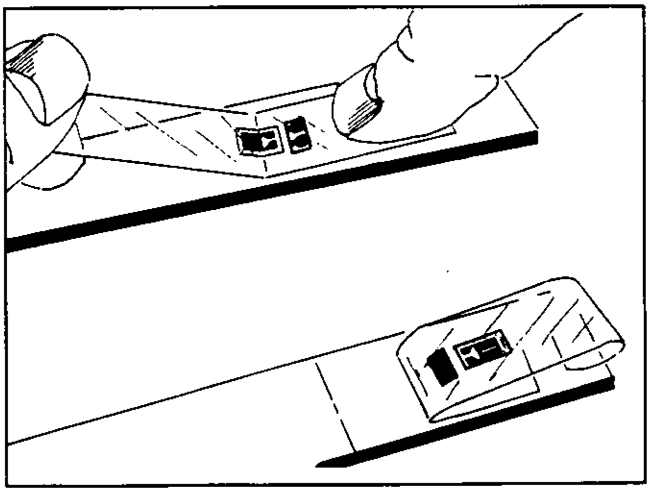
Remove the strain gage from its acetate envelope by grasping the edge of the gage backing with tweezers, and place on a chemically clean glass plate (or empty gage box) with the bonding side of the gage down. Place the appropriate terminals (if any) next to the strain gage solder tabs, leaving a space of approximately 1/16 in *(1.5 mm)* between the gage backing and terminal.



Using a 4-to-6-in *(100-to-150-mm)* length of *M-LINE* PCT-2A cellophane tape, anchor one end of the tape to the glass plate behind the gage and terminal. Wipe the tape firmly down over the gage and terminals. Pick the gage and terminals up by carefully lifting the tape at a shallow angle (30 to 45 degrees) until the tape comes free with the gage and terminal attached. (The shallow angle is important to avoid over-stressing the gage and causing permanent resistance changes.) **Caution: Some tapes may contaminate the bonding surface or react with the bonding adhesive. Use only tapes certified for strain gage installations.**

The strain gage is now prepared for positioning on the test specimen. Position the gage/tape assembly so the triangle alignment marks on the gage are over the layout lines on the specimen. Holding the tape at a shallow angle, wipe the assembly onto the specimen surface. If the assembly is misaligned, lift the tape again at a shallow angle until the assembly is free of the specimen. Reposition and wipe the assembly again with a shallow angle.

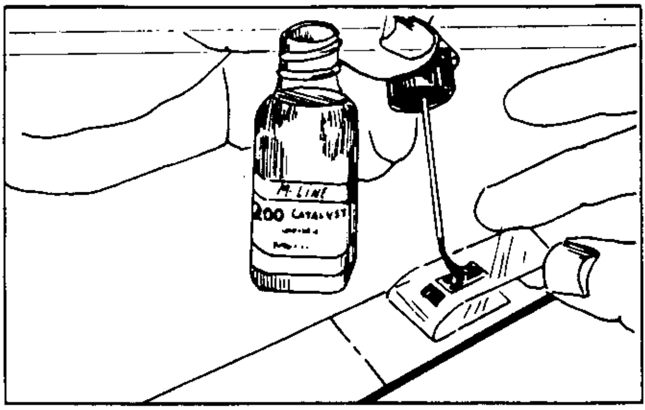




In preparation for applying the adhesive, lift the end of the tape opposite the solder tabs at a shallow angle until the gage and terminal are free of the specimen. Tack the loose end of the tape under and press to the surface so the gage lies flat with the bonding side exposed.

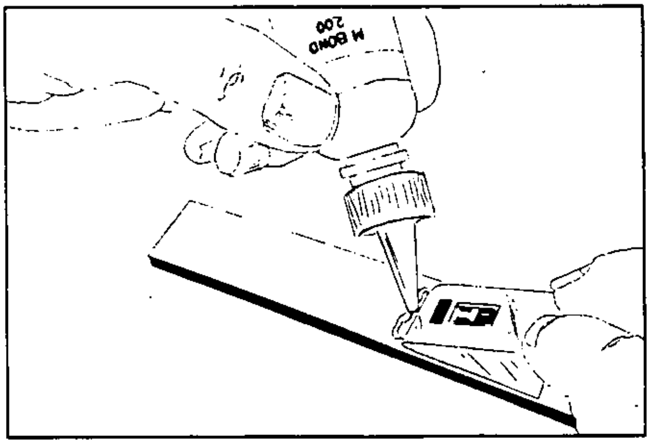
The appropriate adhesive may now be applied. The procedures for M-Bond 200 and M-Bond AE-10 are described in the two sections which follow.

4.2 Bonding with M-Bond 200



M-Bond 200 Catalyst should be applied sparingly in a thin uniform coat. Wipe the brush against the lip of the bottle approximately ten times to remove most of the catalyst. Set the brush down on the gage and swab the gage backing by sliding — not brushing in the painting style — the brush over the entire gage surface. Move the brush to an adjacent tape area prior to lifting from the surface. Allow the catalyst to dry at least one minute under normal ambient laboratory conditions.

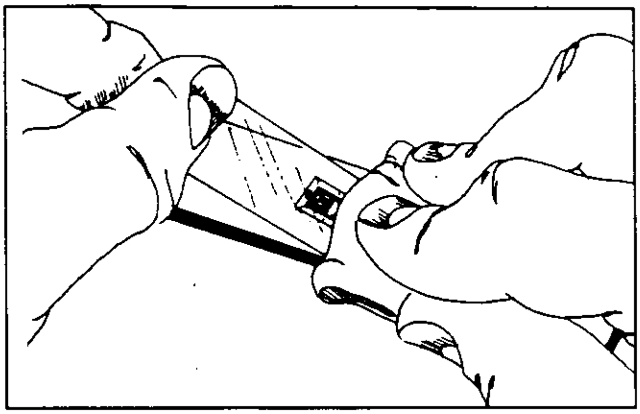
The next three steps must be completed in sequence within three to five seconds. Read these steps before proceeding.



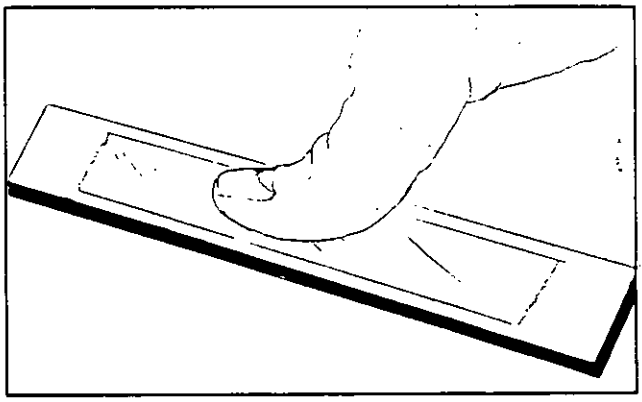
Lift the tucked-under tape. Holding the gage/tape assembly in a fixed position, apply one or two drops of M-Bond 200 Adhesive at the junction of the tape and specimen surface, about 1/2 in *(13 mm)* outside the actual gage installation area.

Immediately rotate the tape to approximately a 30-degree angle so that the gage is bridged over the installation area.

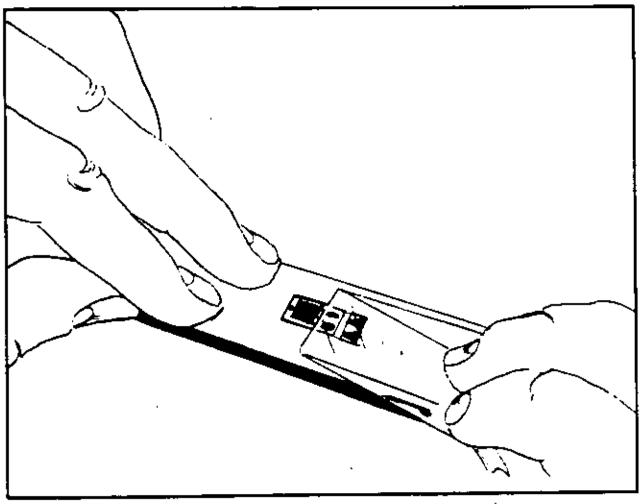
Holding the tape slightly taut and beginning from the tab end of the gage, slowly and *firmly* make a single wiping stroke over the gage/tape assembly with a clean gauze sponge to bring the gage back down over the alignment marks on the specimen. Release the tape.



Immediately upon completion of the above step, *discard the gauze* and apply firm thumb pressure to the gage and terminal area. This pressure should be held for at least one minute. Wait two minutes before the next step (tape removal).

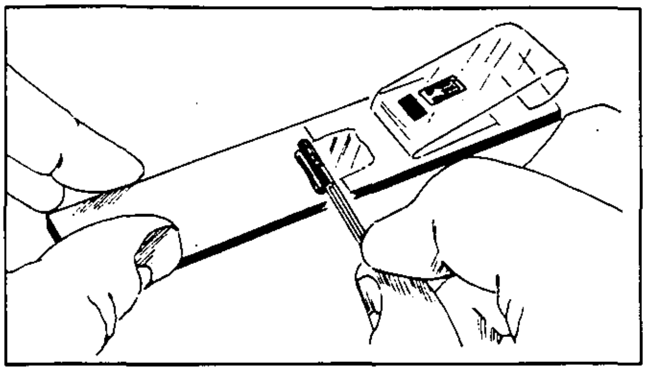


The gage and terminals should now be bonded to the specimen. To remove the tape, pull it back directly over itself, *peeling* it slowly and steadily off the surface.

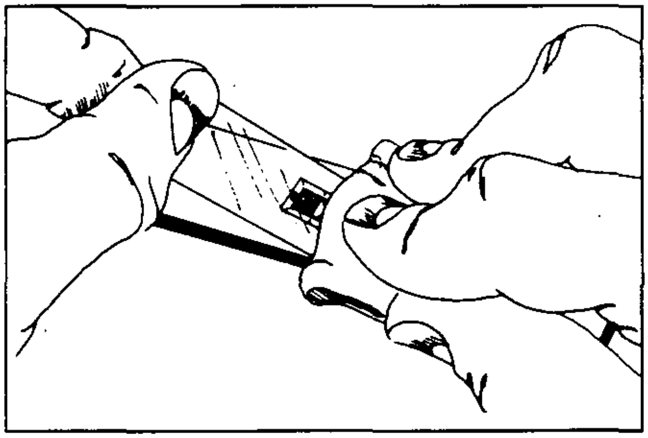


4.3 Bonding with M-Bond AE-10

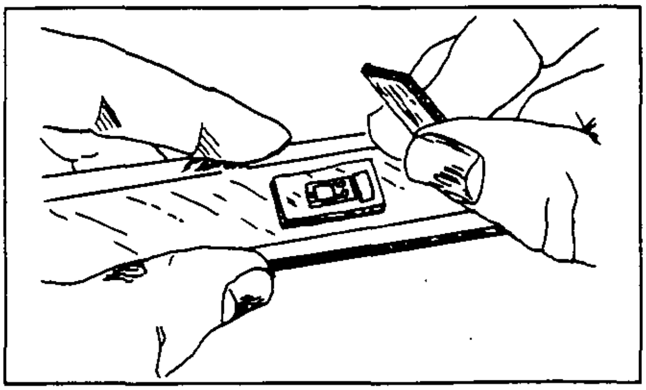
(This section follows 4.1 when using M-Bond AE-10 Adhesive.) Mix the Resin AE with Curing Agent Type 10 per the instructions in Instruction Bulletin B-137 supplied with the adhesive.



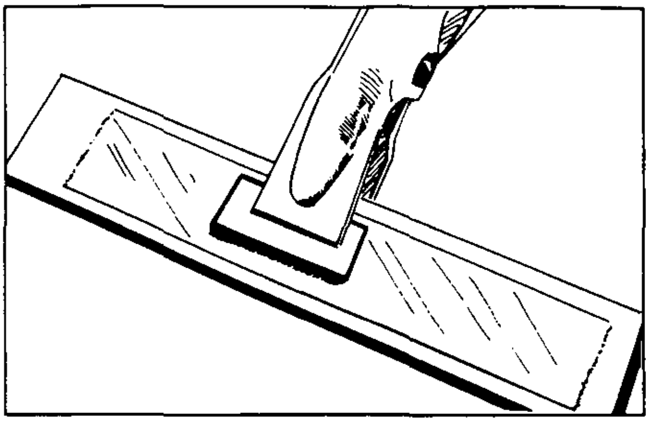
Coat the specimen and back of the gage and terminal with the prepared M-Bond AE-10 Adhesive. The mixing rod may be used to apply a thin layer of adhesive over both surfaces. *Be careful not to pick up any unmixed components of the adhesive.* To ensure this, wipe the mixing rod clean and then pick up a very small amount of adhesive from the central area of the adhesive jar. After applying the adhesive, proceed immediately to the next step.



Lift the tucked-over end of the tape and bridge over the specimen installation area at approximately a 30-degree angle. Beginning from the tab end of the gage and using a clean gauze sponge, slowly and firmly make a single wiping stroke over the gage/tape assembly to bring the gage back down over the alignment marks on the specimen.

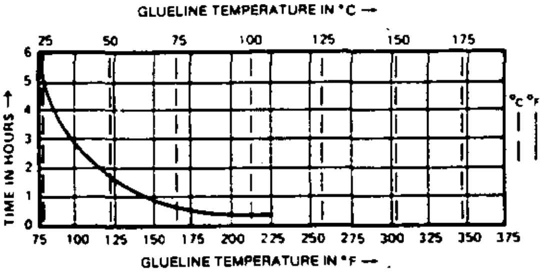


Place a silicone rubber pad and a back-up plate over the gage installation. Apply force by dead weight or spring clamp until a pressure of 5 to 20 psi *(35 to 135 kN/M²)* is attained. Take care to ensure the pressure is equal over the entire gage surface.



The M-Bond AE-10 Adhesive will develop adequate bonding strength in six hours at room temperature [+75° F *(+24° C)*]. The time may be reduced by increasing the temperature of the glueline per the schedule below. **Warning: For curing temperature above +150° F *(+66° C)* a special mylar tape must be used for gage handling, and a Teflon® strip should be placed between the gage and the silicone rubber pad.**

RECOMMENDED CURE SCHEDULE



After the adhesive is cured, remove the clamps or weights, the silicone pads and Teflon strip (if used). To remove the tape, pull it back directly over itself, *peeling* it slowly and steadily off the surface.

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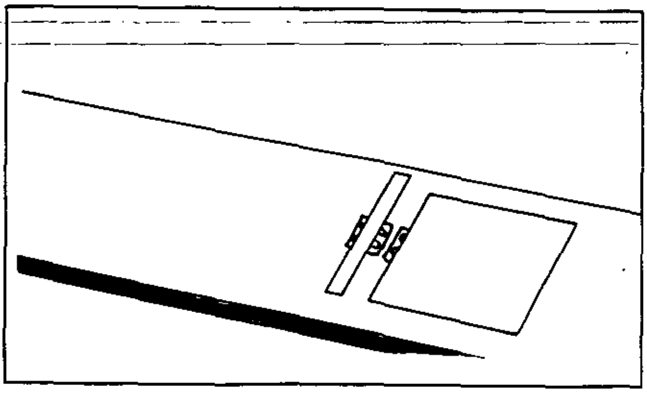
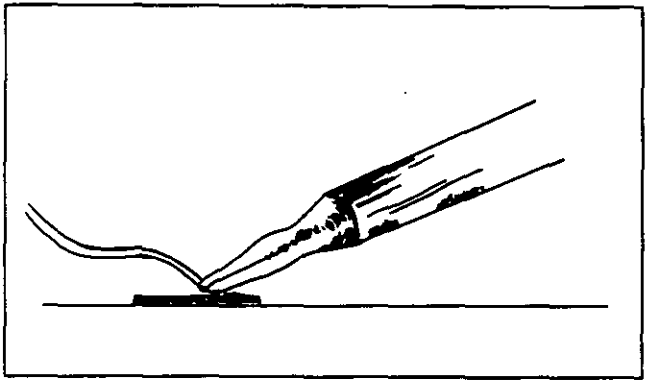
5.0 SOLDERING TECHNIQUES



If the strain gage is without encapsulation or preattached lead ribbons, mask the gage grid area with drafting tape, leaving only the tabs exposed.

After the soldering iron has reached operating temperature, clean the tip with a gauze sponge and tin it with fresh solder. Tin the gage tabs and terminal tabs (if used). Melt a small amount of solder on the tip of the soldering iron, lay the rosin-core solder wire across the gage tab or copper terminal. Firmly apply the iron tip for one second, then *simultaneously* lift both solder and tip. A bright, shiny, even mound of solder should have been deposited on the tab. If not, repeat the process. If spikes are formed rather than smooth beads, it is a sign of inadequate flux, dwelling too long with the iron, and/or an improper iron temperature. Feeding the cored solder into the tab area during heat application will increase the amount of flux available.

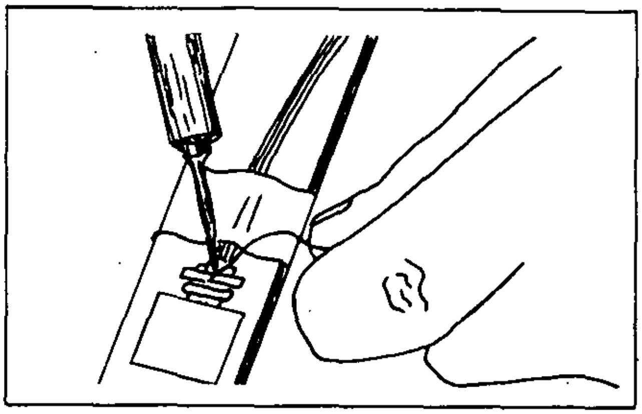


For a three-conductor lead-in wire, separate the individual leads for 3/4 in *(20 mm)*. Strip away 1/2 in *(13 mm)* of insulation by using the soldering tip to melt the insulation on both sides of each end of the wire 1/2 in *(13 mm)* from the ends and quickly pulling off the insulation. **Warning: Do not use a knife or other blade to cut the insulation.** When the main leadwire is stranded and terminal strips are used, it is often convenient to cut all strands but one to fit the size of the copper pad. The long strand can then be used as the jumper wire. Soldering is made considerably easier by this method. This is unnecessary when the leadwires are bonded directly to the solder tabs on CEA-Series strain gages.

Holding the tip of a finger on the tip of the tinned wire for safety, cut each wire with diagonal wire cutters leaving 1/8 in *(3 mm)* of exposed, tinned wire.

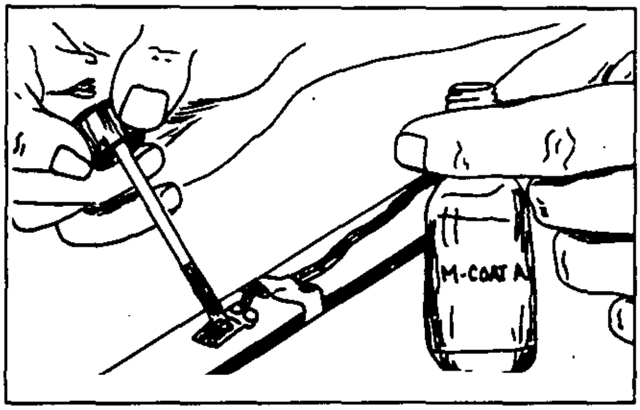
Tack the lead-in wires to the specimen with drafting tape so the tinned end of the wire is spring-loaded in contact with the solder bead. Complete the solder connection as before by applying solder and iron tip for one second and removing simultaneously.

Apply rosin solvent liberally to the solder joints. Drafting tape may be removed by loosening the mastic with rosin solvent. Remove all solvent with a gauze sponge, using a dabbing action. Repeat.



Tape or otherwise secure the lead-in wires to the specimen to prevent the wires from being accidentally pulled from the tabs. A stress relief "loop" should be placed between the tape and the solder connections.

Apply a protective coating over the entire gage and terminal area. For most laboratory uses, M-Coat A will provide adequate long-term protection. The coating should be continuous up to and over at least the first 1/8 in *(3 mm)* of leadwire insulation.

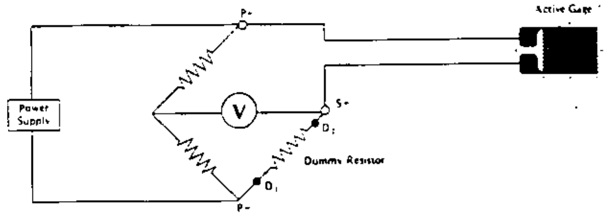


The properly installed strain gage will have a resistance to ground of at least 10 000 to 20 000 megohms. Checking leakage resistance with the Model 1300 Gage Installation Tester is highly recommended.

6.0 TWO-AND THREE-WIRE CIRCUITS

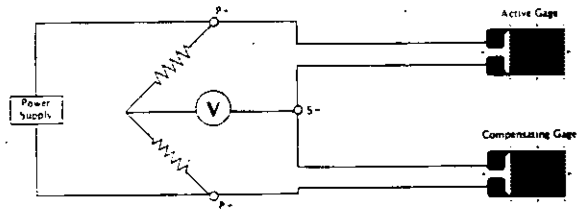
All commercial static strain indicators employ some form of the Wheatstone bridge circuit to detect the resistance change in the gage with strain.

When a single active gage is connected to the Wheatstone bridge with only two wires, as shown in the accompanying schematic, both the wires will be in series with the gage in the same arm of the bridge circuit. One of the effects of this arrangement is that temperature-induced resistance changes in the leadwires are manifested as thermal output by the strain indicator.



Two-wire circuit for single active gage (quarter bridge)

The errors due to leadwire resistance changes in single-gage installations with two-wire circuits can be minimized by minimizing the total leadwire resistance; that is, by using short leadwires of the largest practicable cross-section.

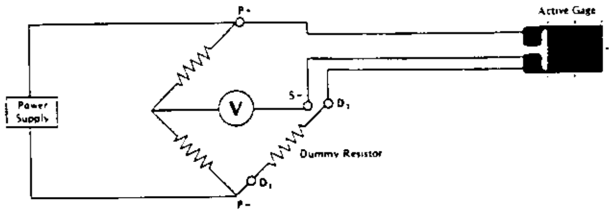


Two-wire circuit for two gages (half bridge)

When two matched gages are connected as adjacent arms of the bridge circuit (with the same length leadwires, maintained at the same temperature), the temperature effects cancel since they are the same in each arm, and "like" resistance changes in adjacent arms of the bridge circuit are self-nullifying.

Leadwire effects can be virtually eliminated in single active gage installations by use of the "three-wire" circuit. In this case a third lead, representing the centerpoint connection of the bridge circuit, is brought out to one of the gage terminals. Resistance changes in the bridge centerpoint lead do not affect bridge balance.

For this method of leadwire compensation to be effective, the two leadwires in the adjacent bridge arms should be the same length, and should be maintained at the same temperature. The three-wire circuit is the standard method of connection for a single active temperature-compensated strain-gage in a quarter-bridge arrangement.



Three-wire circuit for single active gage (quarter bridge)

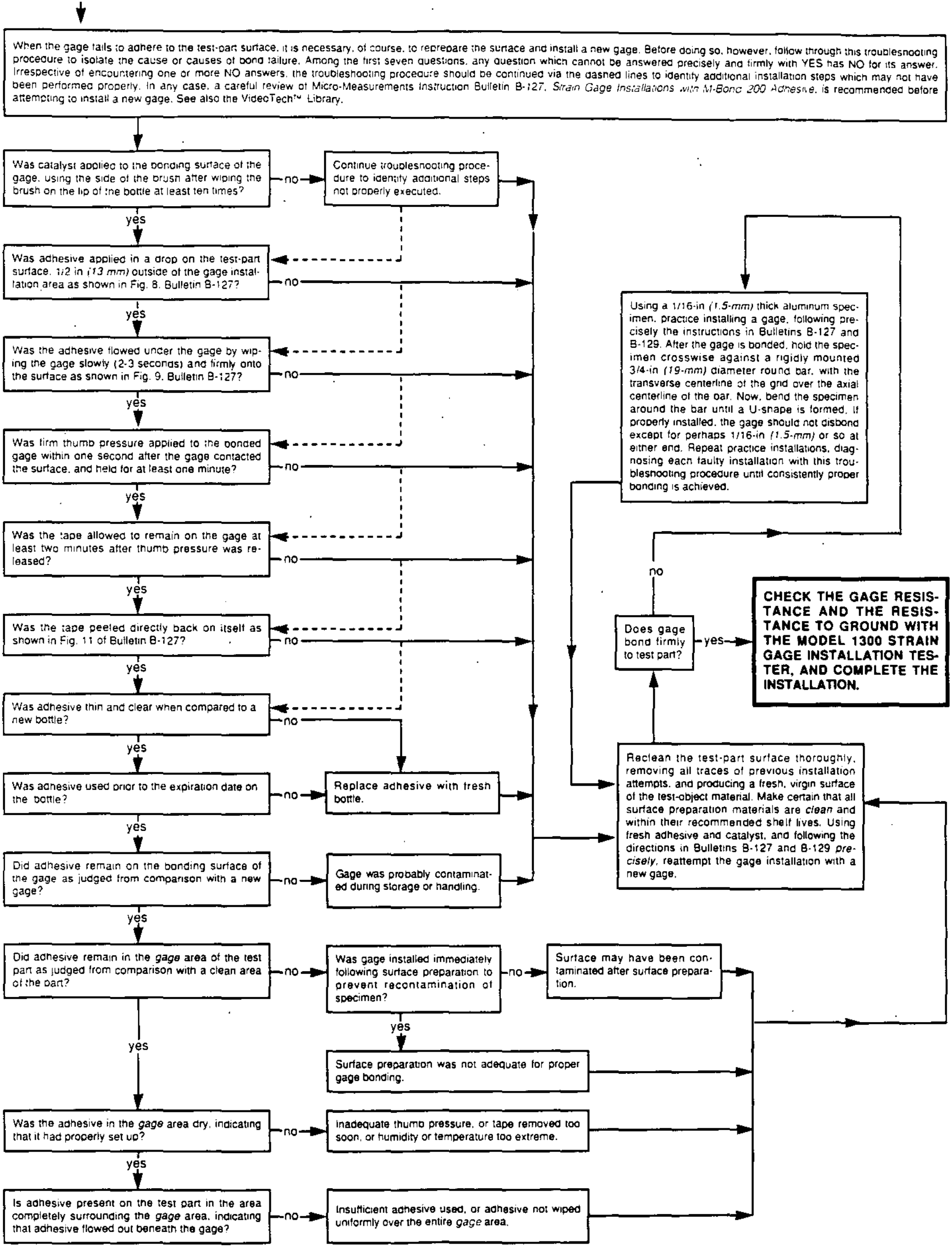
Contact resistance at mechanical connections within the Wheatstone bridge circuit can lead to errors in the measurement of strain. Connections should be snugly made. Following bridge balance, a "wiggle" test should be made on wires leading to mechanical connections. No change in balance should occur if good connections have been made.

If necessary, contact surfaces may be cleaned of oils with a low residue solent such as isopropyl alcohol. If long periods of disuse have caused contact surfaces to tarnish, clean them by scraping lightly with a knife blade.

7.0 TROUBLESHOOTING PROCEDURE

M-Bond 200 Gage Installation

I attempted to install a strain gage with M-Bond 200 Adhesive, but the gage unbonded from the test surface when I removed the handling tape. *What should I do?*



When the gage fails to adhere to the test-part surface, it is necessary, of course, to reprepare the surface and install a new gage. Before doing so, however, follow through this troubleshooting procedure to isolate the cause or causes of bond failure. Among the first seven questions, any question which cannot be answered precisely and firmly with YES has NO for its answer. Irrespective of encountering one or more NO answers, the troubleshooting procedure should be continued via the dashed lines to identify additional installation steps which may not have been performed properly. In any case, a careful review of Micro-Measurements Instruction Bulletin B-127, *Strain Gage Installations with M-Bond 200 Adhesive*, is recommended before attempting to install a new gage. See also the VideoTech™ Library.

Was catalyst applied to the bonding surface of the gage, using the side of the brush after wiping the brush on the lip of the bottle at least ten times?

Continue troubleshooting procedure to identify additional steps not properly executed.

Was adhesive applied in a drop on the test-part surface, 1/2 in *(13 mm)* outside of the gage installation area as shown in Fig. 8, Bulletin B-127?

Was the adhesive flowed under the gage by wiping the gage slowly (2-3 seconds) and firmly onto the surface as shown in Fig. 9, Bulletin B-127?

Was firm thumb pressure applied to the bonded gage within one second after the gage contacted the surface, and held for at least one minute?

Was the tape allowed to remain on the gage at least two minutes after thumb pressure was released?

Was the tape peeled directly back on itself as shown in Fig. 11 of Bulletin B-127?

Was adhesive thin and clear when compared to a new bottle?

Was adhesive used prior to the expiration date on the bottle?

Replace adhesive with fresh bottle.

Did adhesive remain on the bonding surface of the gage as judged from comparison with a new gage?

Gage was probably contaminated during storage or handling.

Did adhesive remain in the *gage* area of the test part as judged from comparison with a clean area of the part?

Was gage installed immediately following surface preparation to prevent recontamination of specimen?

Surface may have been contaminated after surface preparation.

Surface preparation was not adequate for proper gage bonding.

Was the adhesive in the *gage* area dry, indicating that it had properly set up?

Inadequate thumb pressure, or tape removed too soon, or humidity or temperature too extreme.

Is adhesive present on the test part in the area completely surrounding the *gage* area, indicating that adhesive flowed out beneath the gage?

Insufficient adhesive used, or adhesive not wiped uniformly over the entire *gage* area.

Using a 1/16-in *(1.5-mm)* thick aluminum specimen, practice installing a gage, following precisely the instructions in Bulletins B-127 and B-129. After the gage is bonded, hold the specimen crosswise against a rigidly mounted 3/4-in *(19-mm)* diameter round bar, with the transverse centerline of the grid over the axial centerline of the bar. Now, bend the specimen around the bar until a U-shape is formed. If properly installed, the gage should not disbond except for perhaps 1/16-in *(1.5-mm)* or so at either end. Repeat practice installations, diagnosing each faulty installation with this troubleshooting procedure until consistently proper bonding is achieved.

Does gage bond firmly to test part?

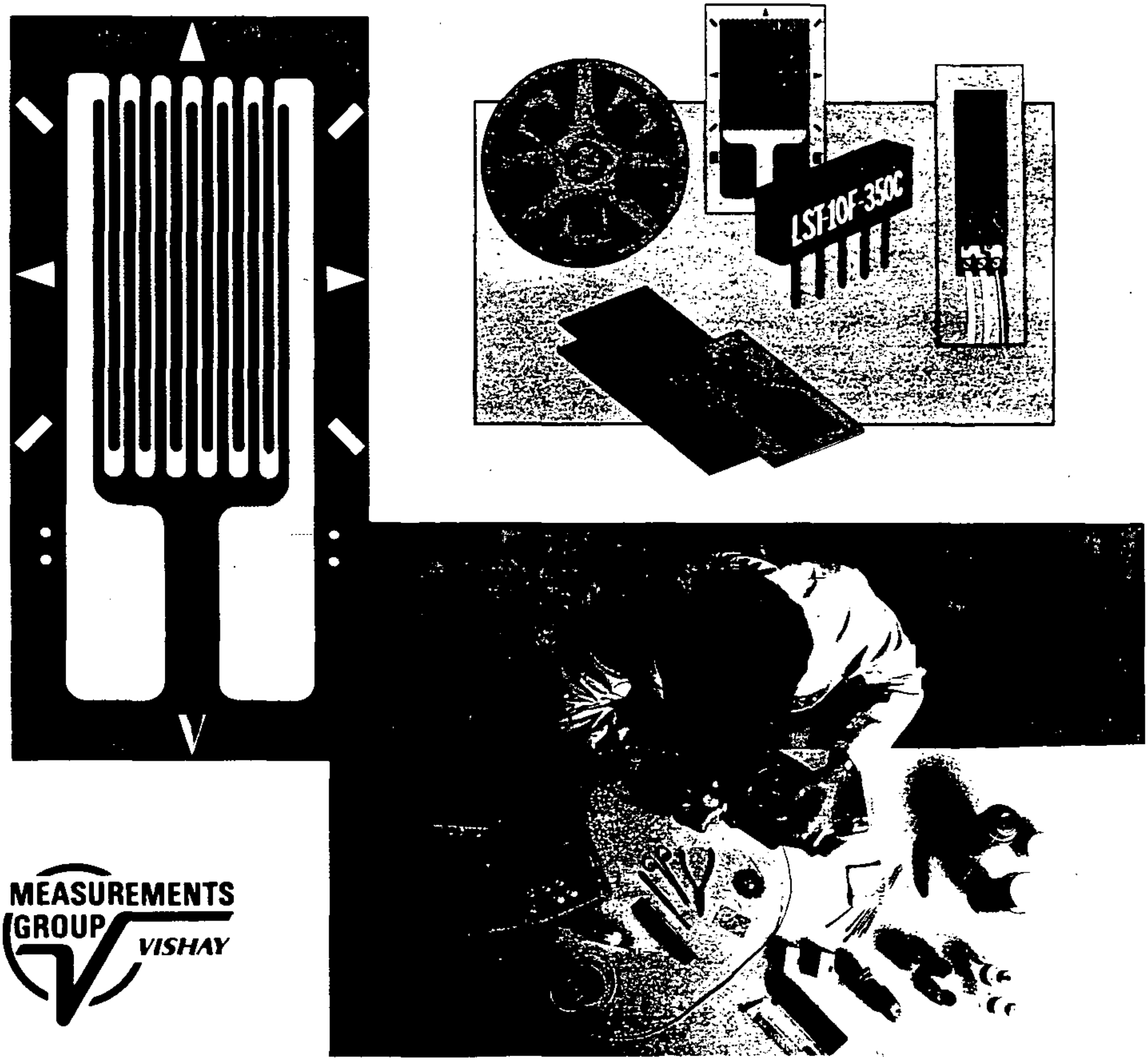
CHECK THE GAGE RESISTANCE AND THE RESISTANCE TO GROUND WITH THE MODEL 1300 STRAIN GAGE INSTALLATION TESTER, AND COMPLETE THE INSTALLATION.

Reclean the test-part surface thoroughly, removing all traces of previous installation attempts, and producing a fresh, virgin surface of the test-object material. Make certain that all surface preparation materials are *clean* and within their recommended shelf lives. Using fresh adhesive and catalyst, and following the directions in Bulletins B-127 and B-129 *precisely*, reattempt the gage installation with a new gage.

Micro-Measurements

MM

- **Strain Gages**
  - **Special Sensors**
    - **Installation Accessories**



MEASUREMENTS GROUP VISHAY

The Broadest Range Of Strain Gages And Accessories Available

Micro-Measurements has been a trusted name in the field of Strain Gage Technology for many years. We are proud of our worldwide reputation as a premier supplier of high-quality precision strain gages and strain gage accessories, and are fully committed to maintaining our position as the leader in this field. This short-form catalog of Micro-Measurements strain gages and related products is intended to provide a condensed overview of the sensors, supplies, and tools commonly needed for typical strain gage applications.

Micro-Measurements was independently founded and operated in the early 1960's. A few years later it became a part of Vishay Intertechnology, Inc. and, in late 1973, was incorporated with the other stress analysis divisions of Vishay into a single entity — The Measurements Group. All divisions of the Measurements Group are now located in our world headquarters facility near Raleigh, North Carolina. Micro-Measurements maintains an additional strain gage production facility in Romulus, Michigan.

Customer Support Services

The common denominator in all Micro-Measurements products and services is our dedication to helping you achieve consistently accurate and reliable strain measurements. And we've made some significant commitments to help ensure your success:

We publish the widest range of technical reference literature in the strain gage field — available through the Measurements Group's Technical Data Mailing Program.

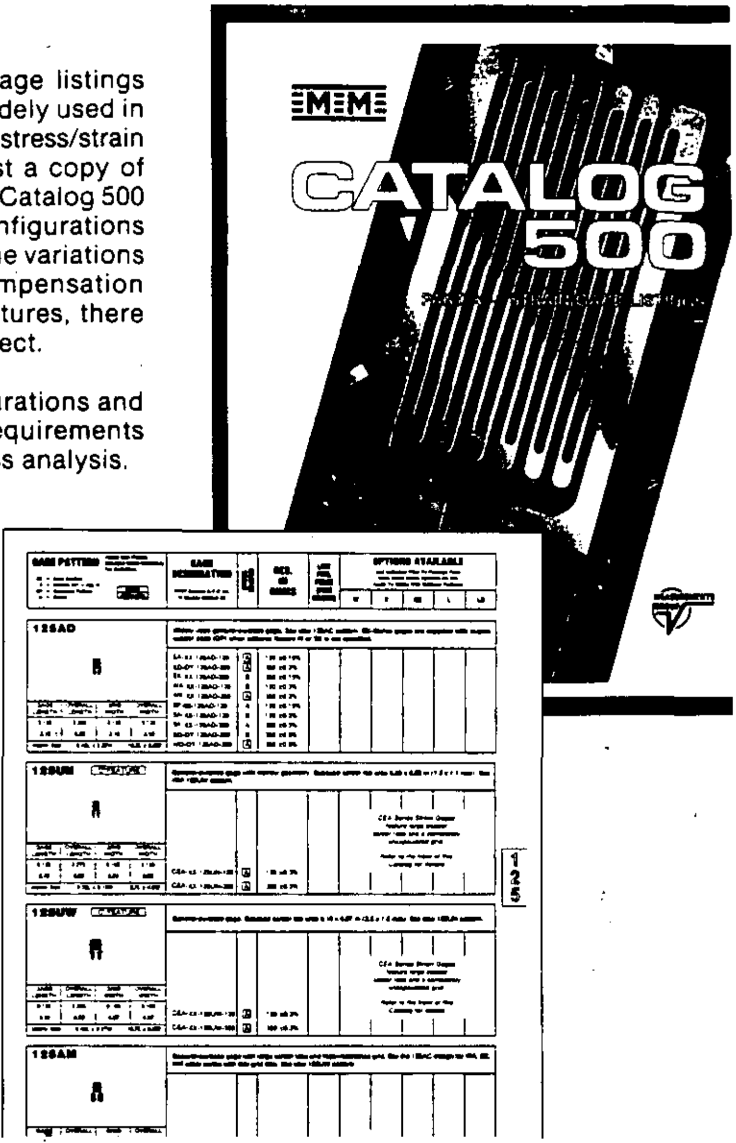
We respond quickly to requests for "specials" to suit individual requirements.

An experienced and friendly Applications Engineering staff is readily available by phone or letter.

We offer a variety of comprehensive technical training programs from beginner to advanced levels in strain gage technology. The Measurements Group regularly conducts workshops and technical seminars in our Technical Training Center in Raleigh, North Carolina and at locations throughout the U.S. and the world.

At Micro-Measurements, Your Success Is Our Goal

Master Strain Gage Catalog
Catalog 500



This introductory catalog contains abridged strain gage listings which are representative of the types and sizes most widely used in stress analysis applications. For those involved in extensive stress/strain measurement programs, it is advantageous to request a copy of Micro-Measurements Catalog 500. The gage listings in Catalog 500 include essentially all standard types and pattern configurations manufactured by Micro-Measurements. Considering the variations in pattern design, grid alloys, self-temperature-compensation (S-T-C) numbers, backing materials, and optional features, there are over 100,000 possible gage types from which to select.

Catalog 500 contains a broad range of pattern configurations and sizes, designed to meet the many and varied test requirements encountered throughout the field of experimental stress analysis.

> A special group of strain gages — *Transducer-Class®* — has been developed specifically for transducer applications. *Transducer-Class* strain gages, described in separate Micro-Measurements literature, are a select group of standard and special gage patterns designed for optimum cost/performance ratio (in transducer service) in high-volume production quantities.

Gage Listings

Reproduced below is a sample Catalog 500 listing for a single, representative gage pattern. The listing includes a tabulation of all gage series in which the pattern is available, as well as optional features applicable to each series. Complete descriptions of the gage series, options, etc. are provided in the introductory section of Catalog 500.

GAGE PATTERN ES = Each Section S = Section (S1 = Sec 1) CP = Complete Pattern M = Matrix inches *millimetres*	GAGE DESIGNATION Insert Desired S-T-C No. in Spaces Marked XX		RES. IN OHMS	W	E	SE	L	LE
125AD 	Widely used general-purpose gage. See also 125AC pattern. EK-Series gages are supplied with duplex copper pads (DP) when optional feature W or SE is not specified.							
	EA-XX-125AD-120	A	120 ±0.15%					
	ED-DY-125AD-350	A	350 ±0.3%					
	EK-XX-125AD-350		350 ±0.15%					
	WA-XX-125AD-120		120 ±0.3%					
	WK-XX-125AD-350	A	350 ±0.3%					
	EP-08-125AD-120		120 ±0.15%					
	SA-XX-125AD-120		120 ±0.3%					
	SK-XX-125AD-350		350 ±0.3%					
	SD-DY-125AD-350		350 ±0.6%					
	WD-DY-125AD-350	A	350 ±0.6%					

GAGE LENGTH	OVERALL LENGTH	GRID WIDTH	OVERALL WIDTH
0.125	0.250	0.125	0.125
3.18	*6.35*	*3.18*	*3.18*

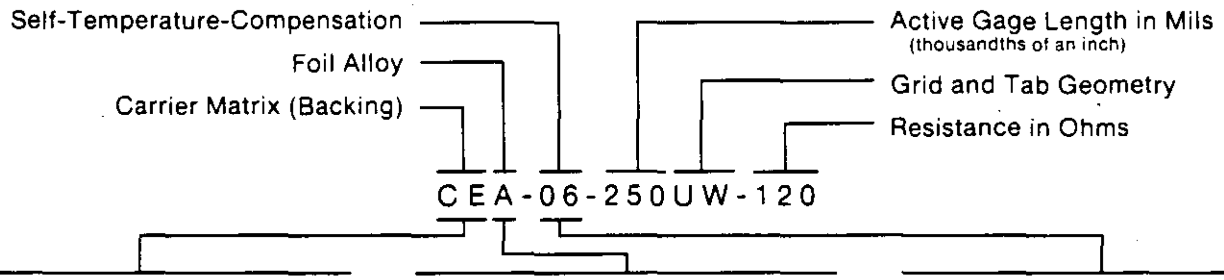
Matrix Size 0.40L x 0.22W *10.2L x 5.6W*

Strain Gage Designation System and Selection Chart

In selecting the most suitable strain gage for each application, consideration must be given to the variations in pattern design, grid alloy, self-temperature-compensation (S-T-C), backing material, and optional features. The gage designation system and standard strain gage selection chart shown on this page present a partial summary of the many combinations of these factors available in Micro-Measurements strain gages. For brevity, this summary is limited to those gage series and optional features listed in this catalog only. When selecting or ordering a strain gage from this catalog, these charts will provide a key to choosing the appropriate gage for your application.

A complete, detailed designation system and selection chart are included in Catalog 500.

When test conditions are severe, or when there are unusually stringent demands on accuracy and stability, selection of the optimum gage parameters to satisfy the test specifications can involve a number of subtle considerations. As an aid in systematically arriving at the most appropriate gage type, given a specific measurement task, Measurements Group Tech Note TN-505, *"Strain Gage Selection Criteria, Procedures, Recommendations"*, available on request from the Measurements Group's Applications Engineering Department, will provide a valuable reference for use in conjunction with these selection criteria and charts.



E: Open-faced, cast polyimide backing.

W: Fully encapsulated; glass-fiber-reinforced epoxy-phenolic resin. High-endurance leadwires.

CE: Thin, flexible gages with a cast polyimide backing and encapsulation featuring large, rugged, copper-coated solder tabs. This construction provides optimum capability for direct leadwire attachment.

A: Constantan alloy in self-temperature-compensated form.

P: Annealed Constantan.

D: Isoelastic alloy.

K: Modified Karma alloy.

The S-T-C number is the approximate therm expansion coefficient in PPM/°F of the structur material on which the gage is to be used. The following standard compensations are available:

A and K alloys: 06, 13.

P alloy: 08.

The D alloy is not available in self-temperature-compensated form. 'DY' is used instead.

Gage Series	DESCRIPTION AND PRIMARY APPLICATION	TEMPERATURE RANGE	STRAIN RANGE	FATIGUE LIFE	
				Strain Level in με	Number of Cycles
EA	General-purpose static and dynamic stress analysis. Wide range of options available.	Normal: -100° to +350°F *(-75° to +175°C)* Special or Short Term: -320° to +400°F *(-195° to +205°C)*	±3% for gage lengths under 1/8 in *(3.2 mm)*. ±5% for 1/8 in & over.	±1800 ±1500 ±1200	10^5 10^6 10^8
CEA	**Universal general-purpose strain gages. Constantan grid completely encapsulated in polyimide, with large, rugged, copper-coated tabs. Primarily used for general-purpose static and dynamic stress analysis.**	**Normal: -100° to +350°F *(-75° to +175°C)* Stacked rosettes limited to +150°F *(+65°C)***	**±3% for gage lengths under 1/8 in *(3.2 mm)*. ±5% for 1/8 in & over.**	±1500 ±1500	10^5 10^6*
ED	Excellent for dynamic measurements. High gage factor and extended fatigue life.	Dynamic: -320° to +400°F *(-195° to +205°C)*	±2% Nonlinear at strain levels over ±0.5%.	±2500 ±2200	10^6 10^7
WA	Stress analysis and transducer applications. Wide temperature range and extreme environmental capability. High-endurance leadwires.	Normal: -100° to +400°F *(-75° to +205°C)* Special or Short-Term: -320° to +500°F *(-195° to +260°C)*	±2%	±2000 ±1800 ±1500	10^5 10^6 10^7
WK	Widest temperature range and most extreme environmental capability. High-endurance leadwires.	Normal: -452° to +550°F *(-269° to +290°C)* Special or Short-Term: -452° to +750°F *(-269° to +400°C)*	±1.5%	±2400 ±2200 ±2000	10^6 10^7 10^8
EP	High-elongation measurements (post yield). Only available in 08 S-T-C value.	-100° to +400°F *(-75° to +205°C)*	±10% for gage lengths under 1/8 in *(3.2 mm)*. ±20% for 1/8 in & over.	±1000 EP gages show zero shif under high-cyclic strains.	10^4
WD	For wide-range dynamic strain measurements in severe environments. High-endurance leadwires.	Dynamic: -320° to +500°F *(-195° to +260°C)*	±1.5% Nonlinear at strain levels over ±0.5%.	±3000 ±2500 ±2200	10^5 10^7 10^8

*Fatigue life improved using low-modulus solder.

Super Stock Gage Listings Section

The gages listed on this and the following page represent the most widely used types for general-purpose experimental stress analysis. Gage lengths range from 0.015 to 0.500 in *(0.4 to 13 mm)* in a wide range of pattern configurations. In addition to single-element gages in a variety of sizes and aspect ratios, the list includes two- and three-element rosettes for use in biaxial stress fields. There are also twin-element chevron patterns for measuring shear strain or torque. Grid resistances of 120, 350, and 1000 ohms are available.

Selection of gages from this list will generally lead to the best delivery and, in many cases, to a price advantage as well. The "C"-feature, or CEA-Series, strain gages are normally the first choice because of the ease of installation. These gages have rugged, copper-coated solder tabs, permitting direct leadwire attachment.

All gages in this list are classified as *Super Stock*. This means that Micro-Measurements guarantees to maintain stock for off-the-shelf delivery of at least 10 packages of any type listed in 06 and 13 self-temperature-compensation numbers (except 08 S-T-C for P alloy and DY for Isoelastic). There are no Minimum Order Requirements for gages selected under the above conditions.

If your application requires a gage that is not listed here, you should refer to Micro-Measurements Catalog 500, which includes all standard, general-purpose Micro-Measurements strain gages. All gage patterns are shown at actual size except where enlargement is necessary for geometry definition.

GAGE DESIGNATION AND PATTERN
CEA-XX-**015UW**-120 Micro-miniature pattern with large exposed solder tabs for high-strain-gradient applications. Exposed tab area is 0.06 x 0.04 in *(1.5 x 1.0 mm)*.  4X
CEA-XX-**032UW**-120 Short gage length pattern with large exposed solder tabs for high-strain-gradient applications. Exposed tab area is 0.07 x 0.04 in *(1.8 x 1.0 mm)*.  2X
EA-XX-**031DE**-120 Miniature pattern for positioning adjacent to high stress concentrations, e.g., holes, fillets, etc.  4X
WA-XX-**060WR**-120 Small 3-element 45° rectangular stacked rosette.  2X
EA-XX-**062AK**-120 Small general-purpose pattern with elongated solder tabs.  2X

GAGE DESIGNATION AND PATTERN
EA-XX-**062AP**-120 WK-XX-**062AP**-350 Compact small general-purpose pattern. Select WK gage for wide temperature range applications.  2X
EA-XX-**062AQ**-350 Same size as 062AP pattern but with high-resistance grid in EA Series.  2X
CEA-XX-**062UW**-120 CEA-XX-**062UW**-350 Small general-purpose gage with large exposed solder tabs. Exposed tab area is 0.07 x 0.04 in *(1.8 x 1.0 mm)*.  2X
EA-XX-**062TV**-350 Small 2-element 90° torque gage.  2X
EA-XX-**062TT**-120 Small general-purpose 90° 'tee' rosette. Sections are electrically independent.  2X

GAGE DESIGNATION AND PATTERN
EA-XX-**125AC**-350 Widely used general-purpose pattern with high-resistance grid. 
EA-XX-**125AD**-120 ED-DY-**125AD**-350 WD-DY-**125AD**-350 WK-XX-**125AD**-350  Widely used, general-purpose pattern. Select ED- or WD-DY gages for fatigue applications; WK for wide temperature range static or dynamic measurements.
CEA-XX-**125UN**-120 CEA-XX-**125UN**-350 Narrow general-purpose gage pattern. Exposed tab area is 0.06 x 0.05 in *(1.5 x 1.1 mm)*. 
CEA-XX-**125UW**-120 CEA-XX-**125UW**-350 Most widely used general-purpose gage in CEA Series. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*. 
EA-XX-**125BB**-120 Narrow general-purpose pattern with elongated tabs. 

Super Stock Gage Listings Section

GAGE DESIGNATION AND PATTERN

EA-XX-**125BT**-120

General-purpose pattern with narrow grid and compact geometry.

EA-XX-**125BZ**-350

Narrow high-resistance pattern with compact geometry.

EA-XX-**125RA**-120

General-purpose 3-element 45° rectangular rosette. Compact geometry.

CEA-XX-**125UR**-120
CEA-XX-**125UR**-350

General-purpose 45° single-plane rosette. Compact geometry. Exposed tab area is 0.08 x 0.06 in *(2.0 x 1.5 mm)*.

EA-XX-**125TM**-120

General-purpose 2-element 90° 'tee' rosette. Sections are electrically independent.

CEA-XX-**125UT**-120
CEA-XX-**125UT**-350

2-element 90° 'tee' rosette for general-purpose use. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

EA-XX-**125TK**-350

High-resistance 2-element 90° gage for torque applications.

GAGE DESIGNATION AND PATTERN

CEA-XX-**187UV**-120
CEA-XX-**187UV**-350

2-element 90° rosette for torque and shear-strain measurements. Sections have a common electrical connection. Exposed tab area is 0.13 x 0.08 in *(3.3 x 2.0 mm)*.

EA-XX-**250AE**-350

Large general-purpose gage. Used when high power-dissipation is required.

EA-XX-**250AF**-120

Large general-purpose gage. Used when high power-dissipation is required.

EA-XX-**250BG**-120
EP-08-**250BG**-120
WA-XX-**250BG**-120
WK-XX-**250BG**-350

Widely used general-purpose pattern. EP Series capable of elongation > 20%.

EA-XX-**250BF**-350

General-purpose pattern with high-resistance grid. Compact geometry. Similar to 250BG pattern except for resistance.

CEA-XX-**250UN**-120
CEA-XX-**250UN**-350

Narrow general-purpose gage pattern. Exposed tab area is 0.08 x 0.05 in *(2.0 x 1.1 mm)*.

CEA-XX-**250UW**-120
CEA-XX-**250UW**-350

Larger grid and tab than 250UN pattern. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

GAGE DESIGNATION AND PATTERN

EA-XX-**250BK**-10C

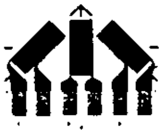
Very high-resistance (1000Ω) pattern. Recommended for high bridge voltages or for use on plastics.

CEA-06-**W250A**-120
CEA-06-**W250A**-350

Lowest-cost, most flexible and conformable linear weldable gage pattern. See page 8 for more details.

CEA-XX-**250UR**-120
CEA-XX-**250UR**-350

Large 3-element 45° single-plane rosette. Exposed tab area is 0.13 x 0.08 in *(3.3 x 2.0 mm)*.



EA-XX-**500BH**-120

Long general-purpose gage in a compact geometry.

CEA-XX-**500UW**-120

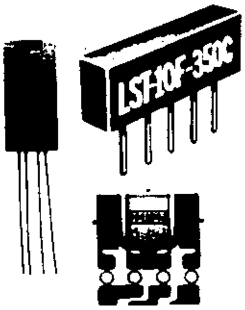
Widely used long gage pattern. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

Special-Purpose Gages, Sensors, and Equipment

In addition to providing the stress analyst with a vast selection of standard strain gage types, Micro-Measurements offers a variety of products designed to meet special needs and perform special functions in experimental stress analysis. Although space in this introductory catalog permits neither a full listing of these products, nor complete descriptions, a few types of special sensors are briefly noted.

Full information on any of these products, along with detailed technical specifications, can be obtained by requesting Catalog 500, or by contacting the Measurements Group's Applications Engineering Department.

Temperature Sensors



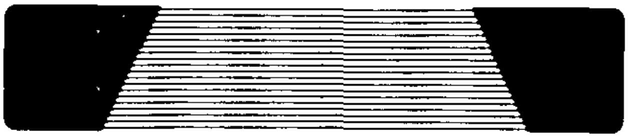
TG Temperature Sensors, with a grid of ultra-pure nickel foil, are recommended for general-purpose temperature measurement from -320° to +500°F *(-195° to +260°C)*. For application at extremely low temperatures, two alloys — nickel and manganin — are combined to produce the CLTS-2B (cryogenic linear temperature sensor). The duplex construction of this sensor results in an essentially linear change of overall resistance with temperature, from -452° to +100°F *(-269° to +40°C)*.

Reusable LST matching networks are available for half-bridge connection of temperature sensors to strain indicators. With these accessories, the strain indicator registers temperature directly, at a scale factor of 10 or 100 microstrain per °F or °C.

Crack Detection

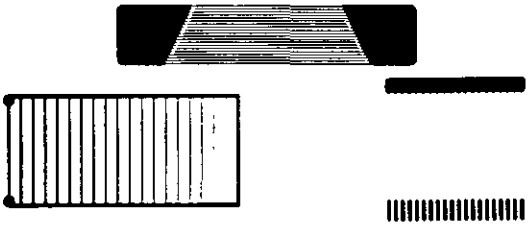
CD-Series Crack Detection Gages are designed to provide a convenient, economical method of indicating the presence of a crack, or indicating when a crack has progressed to a predetermined location on a test part or structure. By employing several CD gages, it is also possible to monitor the rate of crack growth.

Crack detection gages are available with various strand lengths; from 0.4 to 2.0 in *(10 to 50 mm)*.



Crack Propagation

Crack Propagation Gages accurately indicate rate of crack propagation in a specimen material over a very small distance. These sensors are often used adjacent to notches, fillets, or other types of discontinuities in structures. Several sizes and geometries are available.



Strain Gages for Residual Stress Determination

EA Series **CEA Series** **TEA Series**

approximately 2X actual size

The most widely used practical technique for measuring residual stresses is the hole-drilling strain gage method described in ASTM Standard E837. With this method, a specially configured electrical resistance strain gage rosette is bonded to the surface of the test object, and a small, shallow hole is introduced through the center of the gage, using a precision drilling apparatus such as the Measurements Group's RS-200 Milling Guide. After drilling, the strain in the immediate vicinity of the hole is measured, and the relaxed residual stresses are computed from these measurements.

For further details, request Bulletin 304.

Weldable Strain Gages and Temperature Sensors

Weldable gages are precision foil sensors bonded to a metal carrier for spot welding to structures and components. These sensors are easy to install and require minimal surface preparation. Installation is accomplished without adhesives, eliminating heat curing problems on massive structures. They are also well suited to laboratory test programs requiring elevated-temperature testing and minimal installation time.

SPECIFICATIONS

Sensor	Standard S-T-C	Resistance In Ohms	Gage Factor	Temperature Range
CEA	06,09	120 ± 0.4% 350 ± 0.4%	2.0	-100° to +200° F *(-75° to +95° C)*
LWK	06,09	350 ± 0.4%	2.1	-320° to +500° F *(-195° to +260° C)*
WWT	N/A	50 ± 0.4% @ +75° F *(+24° C)*	N/A	-320° to +500° F *(-196° to +260° C)*

SENSOR DESCRIPTIONS

CEA-Series Weldable Strain Gage: Constantan alloy sensing grid completely encapsulated in polyimide. Very flexible. In most cases can be contoured to radii as small as 1/2 in *(13 mm)*. Rugged, copper-coated tabs for convenient leadwire attachment.

W250A

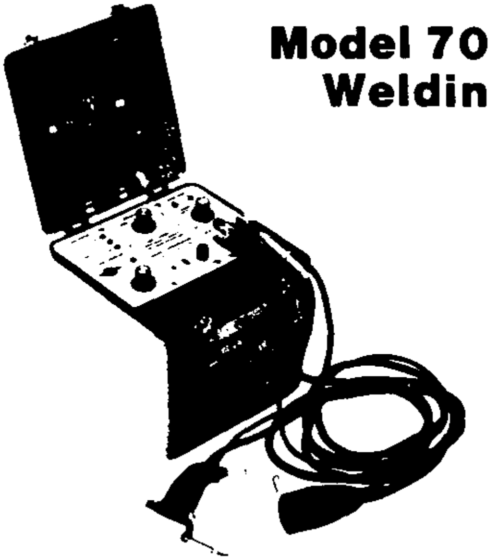
LWK-Series Weldable Strain Gage: Modified Karma (K-alloy) sensing grid completely encapsulated in a fiberglass-reinforced epoxy-phenolic matrix. Integral three-wire lead system consists of 10 in *(250 mm)* flexible etched Teflon®-insulated leadwires. Installation radius generally limited to 2 in *(50 mm)* or larger in the direction of the grid axis.

W250B

WWT-Series Weldable Temperature Sensor: High-purity nickel sensing grid completely encapsulated in a fiberglass-reinforced epoxy-phenolic matrix. Integral three-tab printed circuit terminals for convenient leadwire attachment.

W200B

®Registered Trademark of DuPont



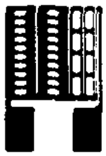
Model 700 Portable Strain Gage Welding and Soldering Unit

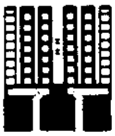
The Model 700 is a completely portable, capacitance-discharge spot welder, designed for efficient installation of weldable strain gages and temperature sensors. Supplied in a rugged, gasketed case, the battery-powered unit can be used under field conditions where no power lines are available.

A temperature-controlled soldering pencil, operated from the main battery supply, is an integral part of the Model 700. The lightweight pencil can be adjusted to a wide range of tip temperatures for both gage soldering and leadwire splicing.

For further details, request Bulletin 302.

Bondable Resistors





Micro-Measurements manufactures a variety of fixed, adjustable, and combination bondable resistors for use in many applications where precise resistance is required. Appropriate patterns are available in both low and high temperature-coefficient-of-resistance types. Widest use is in transducer bridge circuits to compensate for small temperature-induced errors and to adjust bridge balance.

Various alloys, sizes, and patterns are available, allowing selection of the optimum resistor for specific applications. Resistors are normally produced open-faced on a polyimide carrier. The recommended temperature range is from 0° to +300° F *(-20° to +175° C)*. *For further details, request Transducer-Class Catalog TC-116.*

Micro-Measurements Strain Gage Accessories

Micro-Measurements strain gages are produced under rigidly controlled manufacturing conditions, with the utmost care and attention given to ensuring the high level of quality and precision for which these gages have gained world-wide recognition. However, the gages' full potential for accurate strain measurement can be realized only when they are properly installed. There are, in fact, three principal components in every strain gage installation: (1) the strain gage itself, (2) the tools, materials, and supplies (accessories) needed to install the gage, and (3) the techniques employed in performing the installation. Professional stress analysts have learned from experience that compromising any of these may lead to compromising the quality of the installation and the accuracy of the strain data.

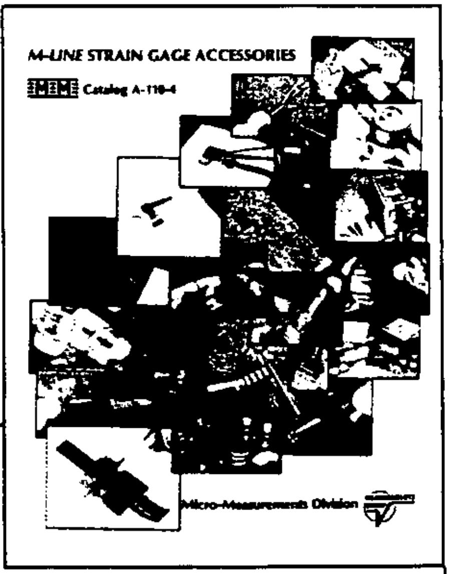
The well-established formula for making consistently successful strain gage installations is quite simple:

- select high-quality precision strain gages.
- select professional-caliber accessories which have been laboratory-tested and field-proven for effectiveness and compatibility with the strain gages.
- follow the installation procedures recommended by the manufacturer of the gages and accessories.

Featured on the following two pages is a small sample of Micro-Measurements *M-LINE* strain gage installation accessories. As indicated, the appropriate materials, supplies, and tools are provided for each important step in the gage installation process — from preparing the surface of the test piece to applying a protective coating over the bonded and wired gage. All accessory items, whether manufactured directly by Micro-Measurements or specified for purchase from an outside supplier, are of the highest quality, and have been designed or selected specifically to help ensure successful installation of Micro-Measurements strain gages.

Regular users of strain gages will want to request a copy of Catalog A-110. This 40-page, fully illustrated catalog describes the complete line of gage installation accessories and related equipment. In addition to detailed product descriptions and specifications, it includes, where applicable, extensive recommendations for the appropriate selection and application of the accessories.

Catalog A-110 is available on request from our Applications Engineering Department.

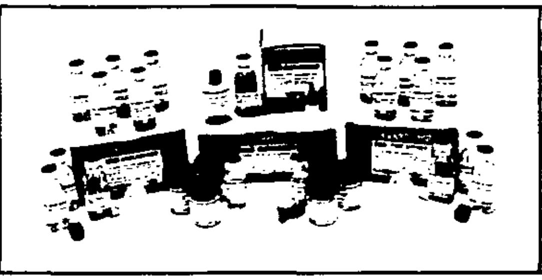


6 Simple Steps To Successful

Surface Preparation

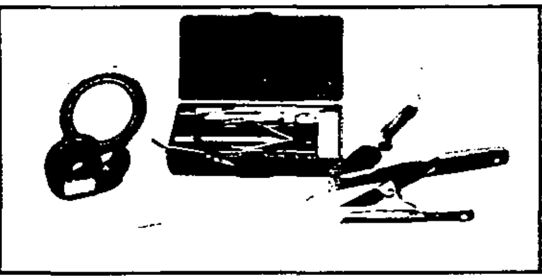
CSM-1 Degreaser
M-Prep Conditioner A
M-Prep Neutralizer 5A
Silicon-Carbide Paper
Cotton Swabs
Gauze Sponges

Adhesive Selection



M-Bond 200
M-Bond AE-10
M-Bond AE-15
M-Bond 600
M-Bond 610

Gage Handling and Bonding



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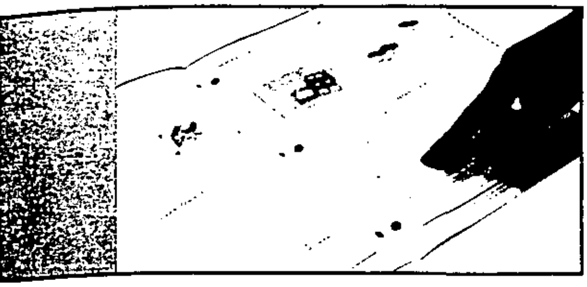
Leadwire Attachment

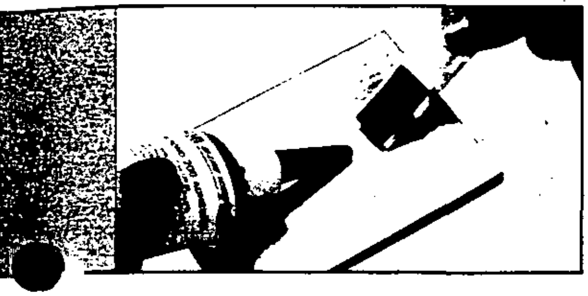
Protective Coating Application

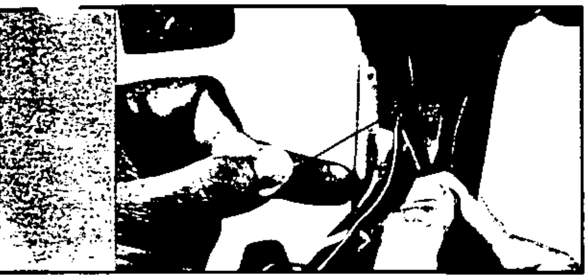
Gage Installation Tester

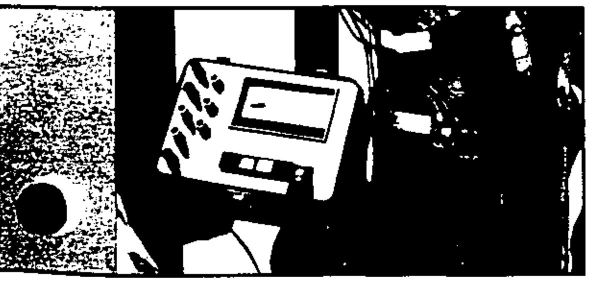
. . . With *M-LINE* Accessories

Strain Gage Installations . . .

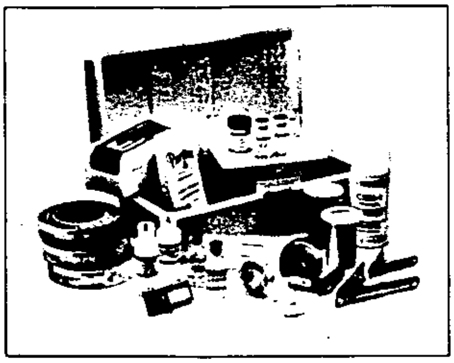








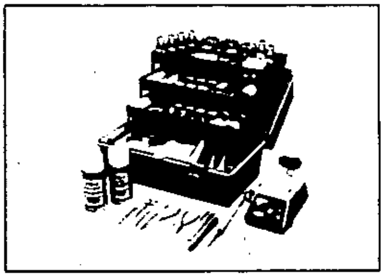
General Application Kits



It is often of greatest convenience for the strain gage user to purchase all of the needed accessory supplies and materials in a single package.

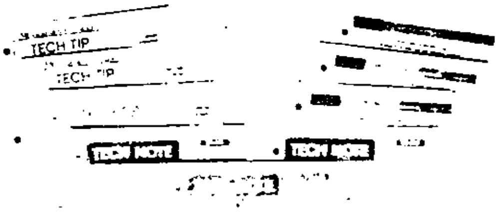
GAK-2 Series Kits provide specific selections of *M-LINE* accessories for making basic strain gage installations with the M-Bond 200, AE-10/15, or 610 adhesives.

The ultimate in gage installation capability is provided by the **MAK-1, Master Strain Gage Application Kit.** The MAK-1 includes all of the supplies and special tools necessary for making a wide range of gage installations for both laboratory and field applications.



Instructional Materials

Because technique is such an important ingredient in successful strain gage installation, detailed **Instruction Bulletins** have been prepared for virtually all Micro-Measurements strain gage installation products.



In addition, a library of **Tech Notes** and **Tech Tips** is available for reference on a broad range of subjects within Strain Gage Technology.

Tech Tips present practical strain gage application techniques for "out-of-the-ordinary" situations, and represent, as much as possible, a practical "how-to" approach to strain gage installation.

Tech Notes contain in-depth technical treatments of specific subjects having direct or indirect bearing on the successful application of stress/strain measurement technology.

— Lab-Tested — Field-Proven

Ordering Information

The Measurements Group Order Service Department can provide immediate stock and delivery information. Most products are available for same-day shipment or can be produced on short delivery cycles. Measurements Group, Inc. maintains regional sales representatives throughout the world to further assist you. For additional information on any of our product lines, contact us or our representative serving your area.

Quantity discounts are available on strain gages and special sensors. All other items are sold on a net basis only. All prices are subject to change without notice.

Micro-Measurements Warranty Policy

The Micro-Measurements Division of Measurements Group, Inc., warrants that the products sold under its name, are fit for the purpose for which they were intended by the supplier and guarantees said items against defects in workmanship or material for a period of ninety (90) days, or otherwise specified limits, from date of delivery. Every reported case of non-standard material is thoroughly investigated by our Quality Assurance Department. It should be recognized that there is no method to 100% test our type of products since many tests would be destructive. Both Micro-Measurements and the purchasers must depend upon statistical sampling techniques that have in the past proved to be reliable and economical in respect to the cost of the product.

This warranty is in lieu of any other warranties, expressed or implied, including any implied warranties of merchantability or fitness for a particular purpose. There are no warranties which extend beyond the description on the face hereof. Purchaser acknowledges that all goods purchased from Measurements Group are purchased as is, and buyer states that no salesman, agent, employee or other person has made any such representations or warranties or otherwise assumed for Measurements Group any liability in connection with the sale of any goods to the Purchaser. Buyer hereby waives all rights buyer may have arising out of any breach of contract or breach of warranty on the part of Measurements Group, to any incidental or consequential damages, including but not limited to damages to property, damages for injury to the person, damages for loss of use, loss of time, loss of profits or income, or loss resulting from personal injury.

Some states do not allow the exclusion or limitation of incidental or consequential damages for consumer products, so the above limitations or exclusions may not apply to you.

The Purchaser agrees that the Purchaser is responsible for notifying any subsequent buyer of goods manufactured by Measurements Group of the warranty provisions, limitations, exclusions and disclaimers stated herein prior to the time any such goods are purchased by such buyers, and the Purchaser hereby agrees to indemnify and hold Measurement Group harmless from any claim asserted against or liability imposed on Measurements Group occasioned by the failure of the Purchaser to so notify such buyer. This provision is not intended to affort subsequent purchasers any warranties or rights not expressly granted to such subsequent purchasers under the law.

The Measurements Group is solely a manufacturer and assumes no responsibility of any form for the accuracy or adequacy of any test results, data, or conclusions which may result from the use of its equipment.

The manner in which the equipment is employed and the use to which the data and test results may be put are completely in the hands of the purchaser. Measurements Group, Inc. shall in no way be liable for damages consequential or incidental to defects in any of its products.

LIMITATION OF REMEDY: In the event any discrepancy is found to be Micro-Measurements' responsibility, the buyer's sole and exclusive remedy will be the replacement of, or full credit for the discrepant product.

We will provide immediate assistance to the best of our ability in locating and identifying the source of any difficulties involving our product.

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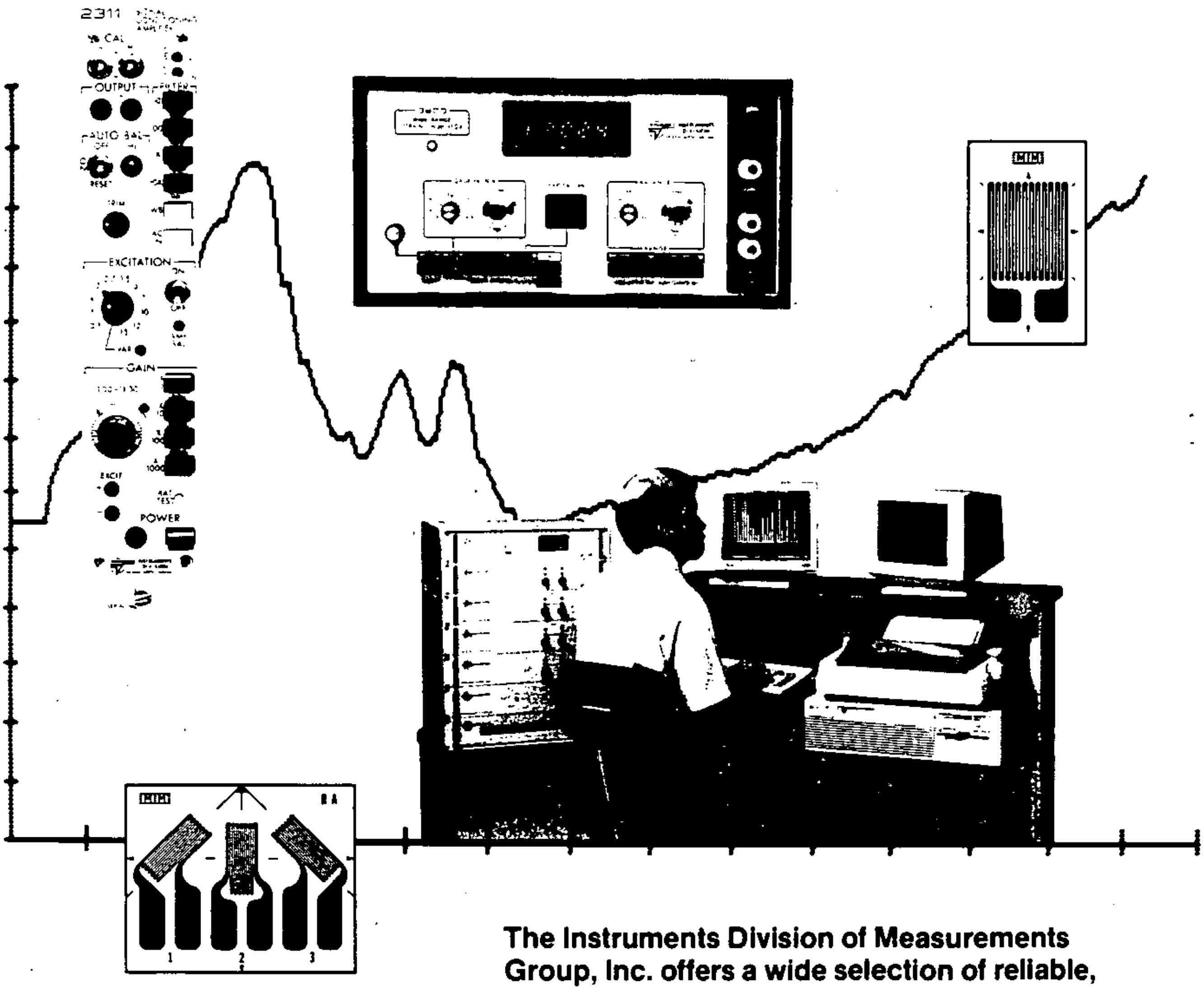
STRAIN GAGE INSTRUMENTATION



The Instruments Division of Measurements Group, Inc. offers a wide selection of reliable, precision strain gage instrumentation for stress analysis, structural, and materials testing.

This short-form catalog will introduce you to our instruments, and assist you in selecting those most appropriate for your measurement needs.

MEASUREMENTS GROUP VISHAY

STATIC MEASUREMENTS

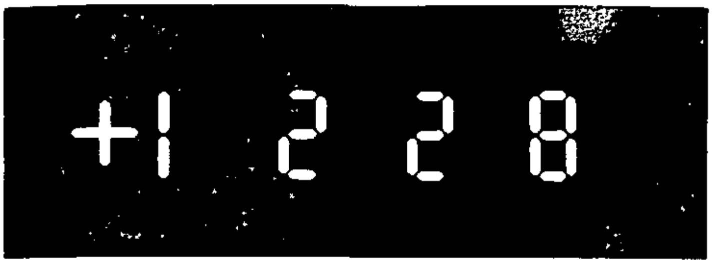
DISPLAY	OPERATION	BRIDGE EXCITATION	INPUT POWER	INSTRUMENT MODEL NO.	MULTI-CHANNEL	REMARKS
Digital	Manual, Direct-Reading	2.0 Vdc	Battery (AC Optional)	P-3500	Manual*	Portable, 0.05% Accuracy
		DC Step Selectable 1.0-15.0V	AC	3800	Manual*	Wide-Range, High-Precision Laboratory Strain Indicator
	Automatic	DC Selectable	AC	System 4000	Automatic	Computer-Based Software/Hardware System

*Switch and balance units are used to read sequentially the outputs of two or more strain gages on a single indicator.
See Special-Purpose Instrumentation on back cover.

DYNAMIC MEASUREMENTS

FREQUENCY RESPONSE**	OUTPUT (±)	AMPLIFIER GAIN	BRIDGE EXCITATION	INPUT POWER	INSTRUMENT MODEL NO.	REMARKS
DC 17 kHz, -0.5 dB DC 50 kHz, -3 dB	10V at 100 mA	Continuously Variable 1-2100	DC 0.5-12V	AC or Battery	2100 System	General-Purpose Signal Conditioner
DC 50 kHz, -0.5 dB DC 100 kHz, -3 dB	10V at 10 mA and 1 Vrms at 10 mA	Continuously Variable 1-3300	DC: 0.5-15V or 0.5-15 mA	AC	2200 System	High Performance, for Demanding Environments
DC 25 kHz, -0.5 dB DC 65 kHz, -3 dB	10V at 5 mA 1 Vrms at 5 mA 10V at 75 mA	Continuously Variable 1-11 000	DC 0.5-15V	AC	2300 (2310) System	Multi-Feature Signal Conditioner
DC 50 kHz, -0.5 dB DC 125 kHz, -3 dB	10V at 5 mA 1 Vrms at 5 mA 10V at 75 mA	Continuously Variable 1-11 000	DC: 0.5-15V 0.3-6V variable	AC	2300 (2311) System	High Freq. Resp. Multi-Feature Signal Conditioner
DC 50 kHz, -0.5 dB DC 100 kHz, -3 dB	10V at 10 mA and 1 Vrms at 10 mA	1 to 3000 digitally controlled	DC: 0.25-15.75V or 1.0 to 63 mA	AC	2400 System	High Performance, Computer-Controlled Signal Conditioner

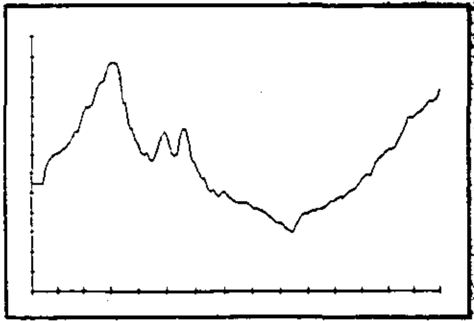
**Typical — see specific product bulletin and/or instruction manual for detailed performance specifications.



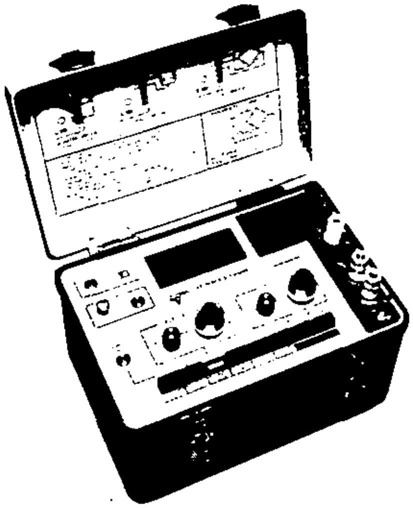
Static signals are essentially constant, while quasi-static signals vary slowly, typically at a few cycles per minute (e.g., 0.1 Hz). Basic instrumentation requirements call for stability, accuracy and high resolution, particularly where measurements are to be taken over long periods of time.

If test conditions involve predominantly static or quasi-static measurements, the first choice for a measuring instrument will ideally incorporate a digital or analog display, direct or null-balance reading, and, depending on the degree of sophistication, output to a printer, microprocessor or computer. Multi-channel capability can be provided by manual or automatic switching/multiplexing units, which may include balance and/or span control facilities.

Many static strain measuring instruments have an analog output available for making single-channel dynamic measurements in conjunction with, for example, an oscilloscope, recorder, or peak-read indicator. However, this dynamic capability may have limitations with respect to frequency response and amplifier gain compared to an instrument designed specifically for dynamic measurements.



Dynamic signals vary continuously at frequencies above 0.1 Hz, or are transients. Under these conditions, measuring instrumentation requires adequate frequency response, and a wide amplifier gain range for output to the appropriate recording or display instrument. A dynamic instrument consists of an amplifier and signal conditioner with a built-in or shared power supply. Individual units are normally required for each channel when simultaneous recording or multiple channels are needed. With the output sent to a suitable display device, dynamic instrumentation can be used for making static measurements, when maximum stability and accuracy are not primary considerations.

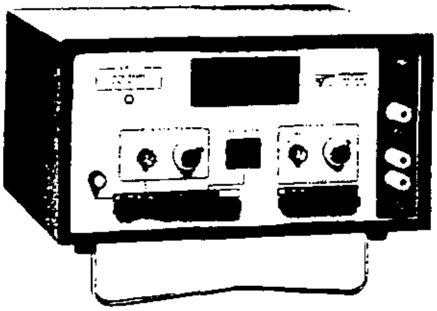


P-3500

The P-3500 is a portable, battery-powered precision instrument featuring a 4-1/2 digit LCD readout (optional LED available). Color-coded push-button controls provide an easy-to-follow, logical sequence of setup and operational steps. A transducer input connector facilitates connection of strain gage based transducers. *Request Bulletin 245.*

3800

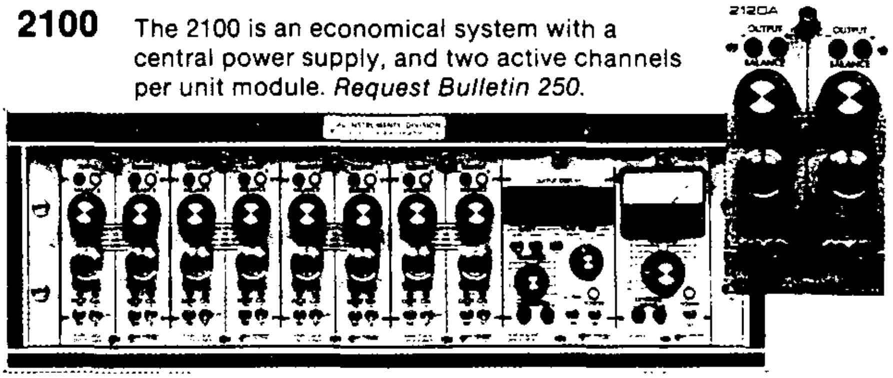
The 3800 is a high-precision, laboratory-type digital display strain indicator. It features extremely wide-range gage factor, balance, and bridge excitation controls. The wide-range feature enables measurement resolution of 0.1$\mu\epsilon$. The 3800 can also be used as a high-performance transducer indicator. *Request Bulletin 249.*

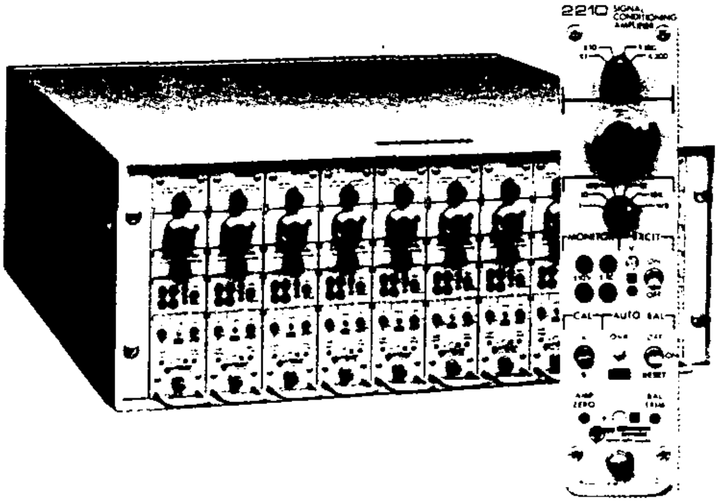


The 2100, 2200, 2300, and 2400 Systems accept low-level signals, and condition and amplify them into high-level outputs suitable for multiple-channel simultaneous dynamic recording. These systems can be used in conjunction with various recording devices.

2100

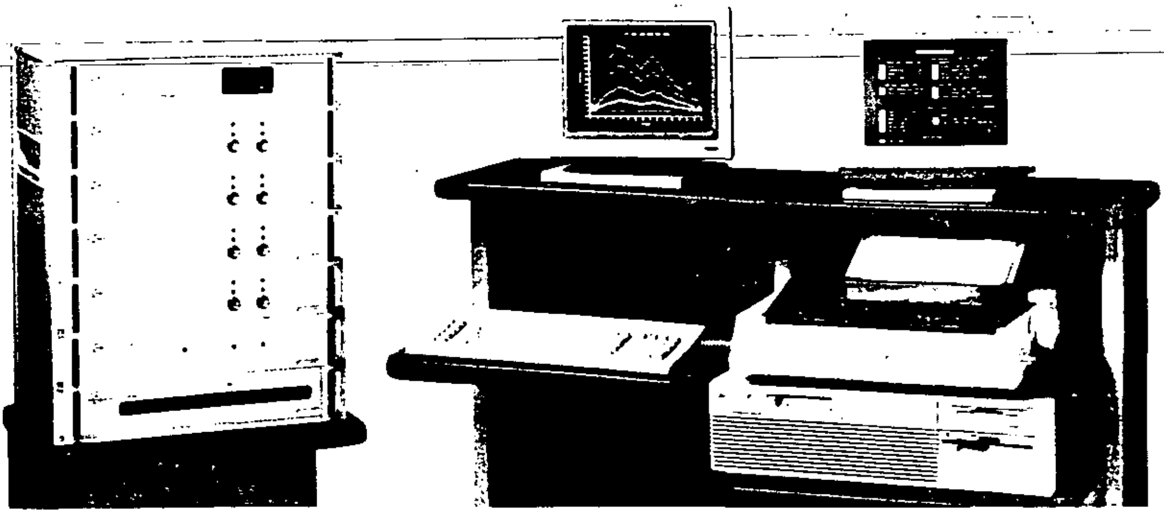
The 2100 is an economical system with a central power supply, and two active channels per unit module. *Request Bulletin 250.*





2200

The 2200 System offers high performance in the most severe operating environments. Among its features are isolated constant-voltage/constant-current excitation, guarded input structure with ±350V common-mode capability, automatic wide-range bridge balance, and four-pole Bessel low-pass filter. The plug-in amplifiers are removable from the rack mount without having to disconnect the input wiring. *Request Bulletin 252.*

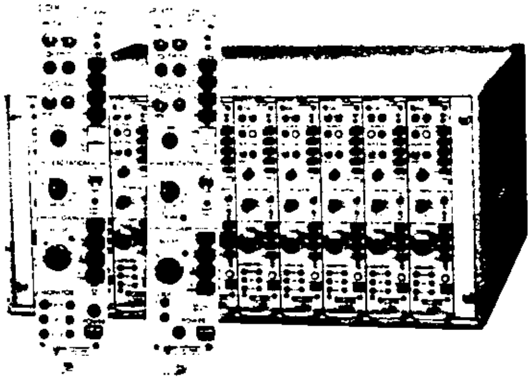


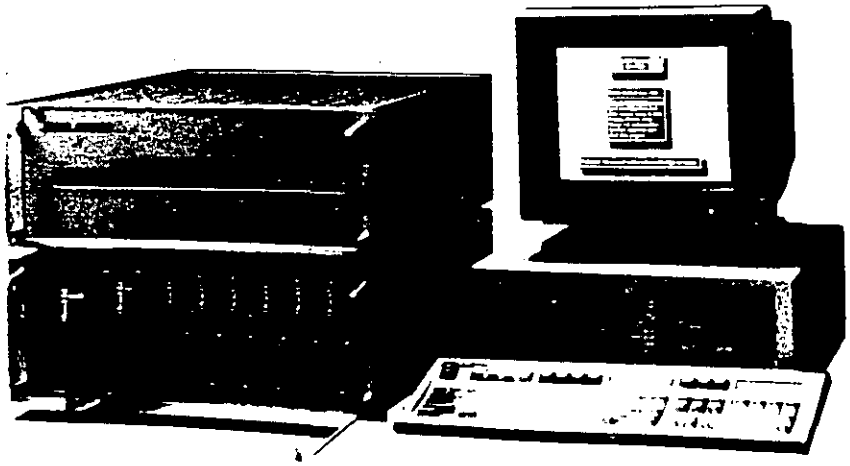
SYSTEM 4000

Featuring an extensive, preprogrammed software package, System 4000 is a state-of-the-art computer-based data system for stress analysis and structural materials testing. The most significant feature of System 4000 is its unique 4216 Executive Unit, including the system's comprehensive operating software which addresses virtually every variable that must be considered in stress analysis testing — from initial data entry, to data acquisition and conditioning, to on-line and off-line presentation of results. System 4000 will accept inputs from strain gages, thermocouples, LVDT's, load cells, and other transducers. Simple to operate, System 4000 provides maximum stress analysis testing capability with minimum investment. *Request Bulletin 235.*

2300

The 2300 is a sophisticated system incorporating such advanced features as an individual power supply per channel, active filtering, three simultaneous outputs, tape playback mode, wide frequency response, and electronic bridge balance.
Request Bulletin 251.





2400

The 2400 System is an expandable strain gage signal conditioning/amplifier system which allows the user to configure individual signal conditioners from any host computer with IEEE-488 or RS-232 capability. Programmed functions include amplifier gain, excitation, filter selection, and auto-balancing.
Request Bulletin 253.

SPECIAL-PURPOSE INSTRUMENTATION

SB-10

The SB-10 is a high-quality, 10-channel switch and balance unit for use with strain indicators. It features gold-plated binding posts for reliable connection of input circuits, and incorporates fine-balance control with turns-counting dials for each individual channel. *Request Bulletin 247.*

3650

The 3650 Peak-Read Indicator is a portable, battery-powered instrument for capturing peak values of dynamic signals. The instrument is designed to be used in conjunction with any static strain gage indicator, transducer indicator, or signal conditioning system. The 3650 features dual LCD readouts for simultaneously displaying the most positive and most negative readings, and easy-to-use color-coded push-button controls. *Request Bulletin 246.*

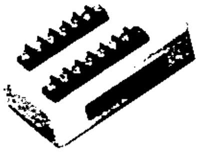
1300

The 1300 Gage Installation Tester is used to verify the quality of an installed strain gage, as well as the complete gage installation, including leadwires. A carefully selected individualized test voltage is used for each measurement mode. Operation is by push buttons. *Request Bulletin 301.*

1550A

A true Wheatstone-bridge simulator, the 1550A Strain Indicator Calibrator presents known and repeatable resistance changes to the input of the indicator. Three decades of push buttons are used to produce incremental resistance changes. The 1550A is NIST-traceable. *Request Bulletin 313.*

1601 LVDT ADAPTER MODULE



The 1601 Adapter Module provides an interface and direct compatibility between the strain indicator and a wide variety of LVDT displacement transducers.

V/E-40

This decade resistor/strain gage simulator can be used as a resistance standard, decade box, instrumentation calibrator, strain simulator, or investigative tool. It is also useful in measurement of arbitrary resistances and large strains. *Request Bulletin 316.*

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RECOMMENDED REFERENCE LITERATURE

The Strain Gage Primer, by C.C. Perry and H.R. Lissner.

Explains the use of bonded wire and foil resistance strain gages for solving problems in experimental stress analysis. Covers all phases, from selecting the proper gage through interpreting readings in terms of significant stresses.

Strain Gauge Technology, edited by A.L. Window and G.S. Holister.

Thorough, practical review of contemporary strain gage technology. Includes a chapter on gage use in hostile environments, and one on errors and uncertainties in strain measurements.

Handbook on Experimental Mechanics, edited by A.S. Kobayashi.

Twenty-one chapters contributed by twenty-five prominent authors cover well-known traditional disciplines as well as new experimental techniques. Extensive lists of references are provided.

Experimental Stress Analysis, by J.W. Dally and W.F. Riley.

Prepared to serve as a teaching text for courses in experimental stress analysis. Topics covered include elementary elasticity, brittle coatings, photoelasticity, strain gages, and related instrumentation.

Formulas for Stress and Strain, by R.J: Roark and W.C. Young.

A comprehensive summary of the formulas, facts, and principles pertaining to the strength of materials, for the design engineer and stress analyst.

Experimental Stress Analysis and Motion Measurement, by R.C. Dove and P.H. Adams.

A thorough discussion of stress analysis and strain measurement, with proper attention to new experimental methods including moiré fringes and semiconductor gages. Part two covers techniques and instruments used for measuring and analyzing displacements, velocities, and accelerations.

Stress Concentration Factors, by R.E. Peterson.

The most complete and authoritative compilation of stress concentration factors available in the published literature. Data are included for most commonly encountered geometric configurations and design details.

A broader selection of Experimental Stress Analysis related literature is available from:

Society for Experimental Mechanics
7 School Street
Bethel, Connecticut 06801
Telephone (203) 790-6373

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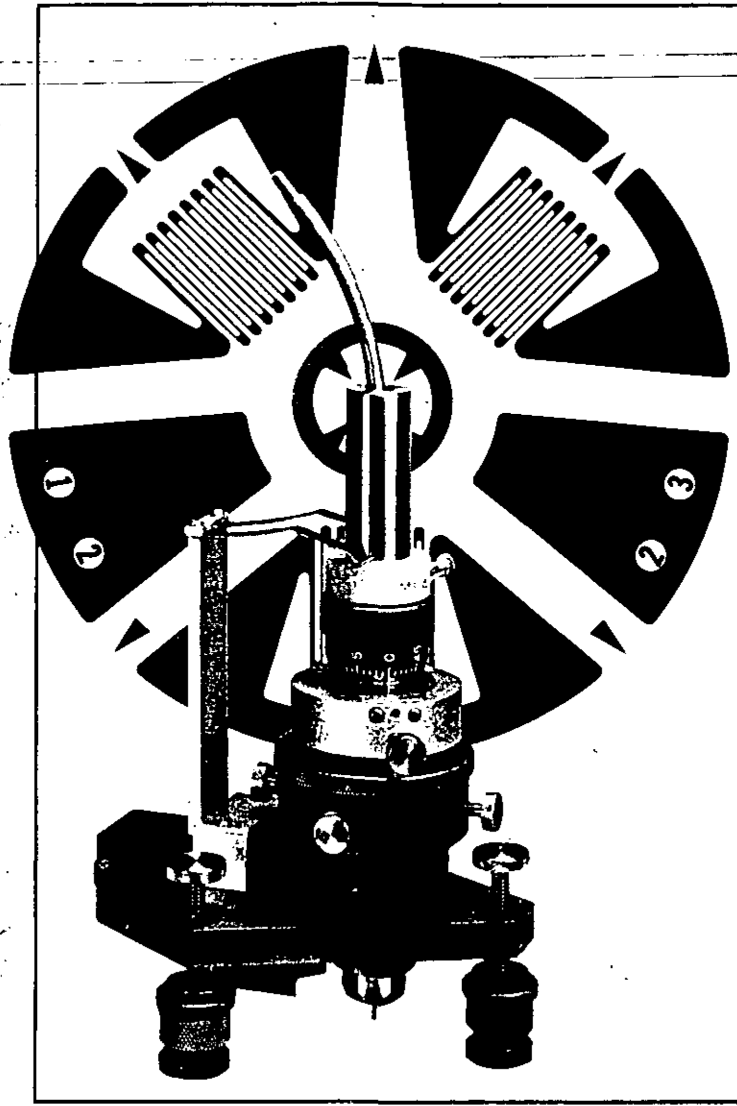
BULLETIN 304-F



Strain Gages
and
Instrumentation
for
Residual Stress Measurements

A predominant factor contributing to the structural failure of machine parts, pressure vessels, framed structures, etc., may be the *residual "locked-in" stresses* that exist in the object prior to its being put into service. These residual stresses are usually introduced during manufacturing, and are caused by processes such as casting, welding, machining, heat treating, molding, etc.

Residual stress can neither be detected nor evaluated by conventional surface measurement techniques, since the strain sensor (strain gage, photoelastic coating, etc.) can only respond to strain changes that occur after the sensor is installed.

The most widely used practical technique for measuring residual stresses is the hole-drilling strain gage method described in ASTM Standard E837. With this method, a specially configured electrical resistance strain gage rosette is bonded to the surface of the test object, and a small shallow hole is drilled through the center of the rosette. The local changes in strain due to introduction of the hole are measured, and the relaxed residual stresses are computed from these measurements. Measurements Group Tech Note TN-503, *Measurement of Residual Stresses By The Hole-Drilling Strain Gage Method,* presents a detailed discussion of the theory and application of this technique.

The hole-drilling method is generally considered semidestructive, since the drilled hole may not noticeably impair the structural integrity of the part being tested. Depending on the type of rosette gage used, the drilled hole is typically 0.062 or 0.125 in *(about 1.5 or 3.0 mm),* both in diameter and depth. In many instances, the hole can also be plugged, if necessary, to return the part to service after the residual stresses have been measured.

The practicality and accuracy of this method is directly related to the precision with which the hole is drilled through the center of the strain gage rosette. The Measurements Group RS-200 optical milling guide described herein provides a practical means to accomplish this task.

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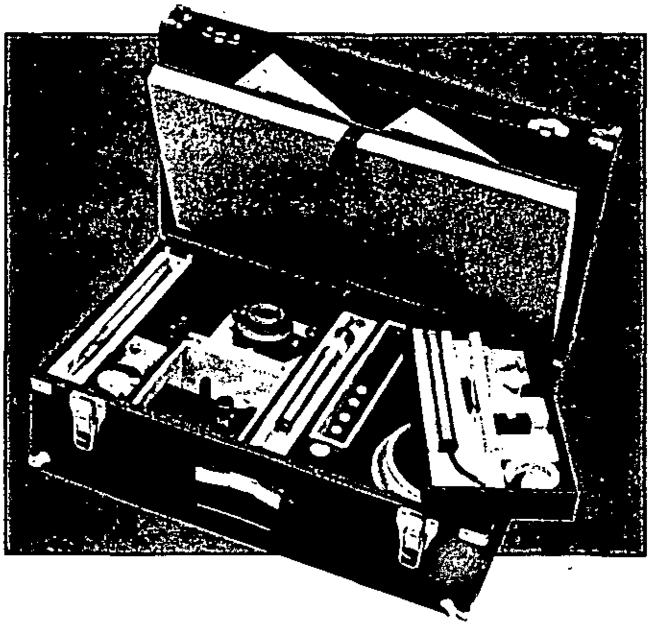
Equipment



The RS-200 Milling Guide is a precision fixture for the accurate positioning and drilling of a hole through the center of the strain gage rosette. Principal features and components of the milling guide assembly are shown in the photos below. When installed on the workpiece, the guide is supported by three leveling screws which are footed with swivel mounting pads to facilitate attachment to uneven surfaces.

Alignment of the milling guide relative to the strain gage rosette is accomplished by inserting a special-purpose microscrope into the guide's centering journal, and then positioning the guide precisely over the center of the rosette by means of four X-Y adjusting screws. The microscope assembly, consisting of a polished steel housing with eyepiece, reticle, and objective lens, permits alignment to within 0.0015 in *(0.038 mm)* of the gage center. The microscope is also used to measure the diameter of the hole after it is drilled. An illuminator attaches to the base of the guide to aid in the optical alignment procedure.

After alignment is achieved, the microscope is removed from the guide, and the milling bar inserted in its place for slow-speed drilling of the hole. Two standard milling cutters are supplied: 0.062 and 0.125 in *(1.6 and 3.2 mm)* diameter. The milling bar is equipped with a universal joint for flexible connection to a drill motor.

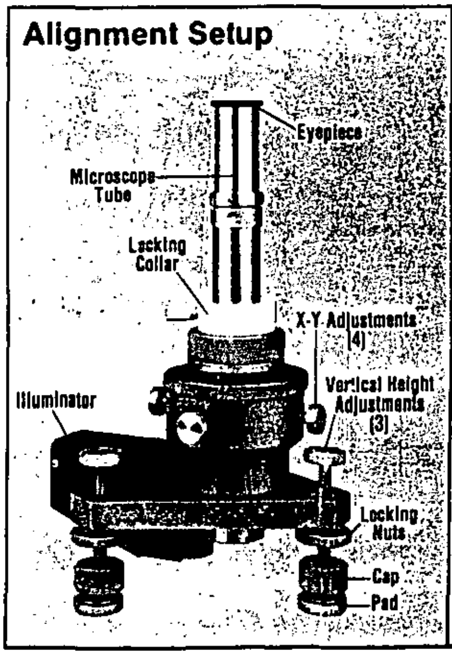
Conventional slow-speed milling may be satisfactory on some mild steels and aluminum alloys. But high-speed drilling is generally the most convenient and practical method for introducing the hole in all test materials. (When residual stresses are to be measured on materials such as stainless steels, nickel-based alloys, etc., ultra-high-speed drilling techniques are preferred.) For this purpose, a high-speed air-turbine assembly is supplied for use with the milling guide, along with a supply of tungsten carbide-tipped cutters [ten each 0.031 in *(0.8 mm)* diameter and 0.062 in *(1.6 mm)* diameter]. A foot pedal control is included for operating the air turbine.

Also part of the milling guide assembly is a micrometer depth set attachment. This device is used for incremental drilling in those cases when information on the variation of residual-stress-with-depth is considered essential.

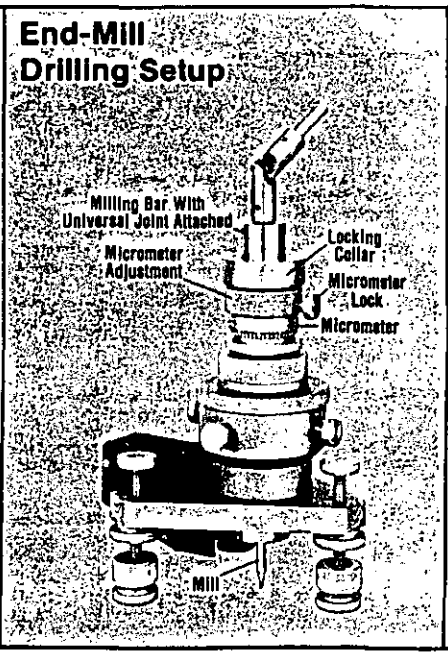
Other items supplied include a plastic template for the proper location of the milling guide foot pads on the test part and a special break-off tool which is used to remove the foot pads from the part after the test is completed. All components are housed in a sturdy carrying case. The guide is approximately 9 in *(230 mm)* high, and 4.5 in *(114 mm)* wide at the base.

A fast-setting-cement kit, used to firmly attach the guide to the test part, is available as an accessory item.

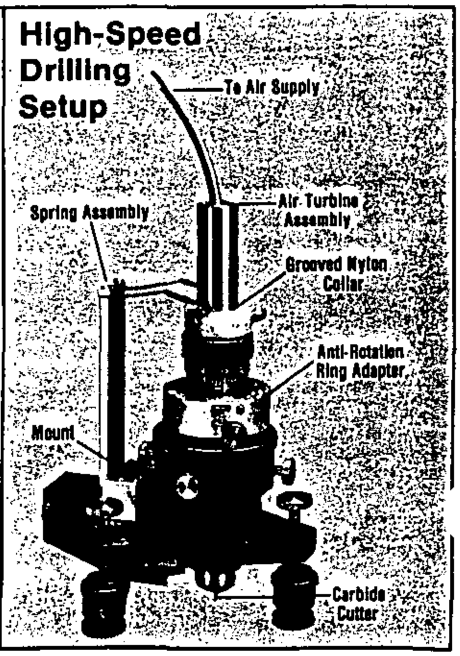
Alignment Setup



End-Mill Drilling Setup

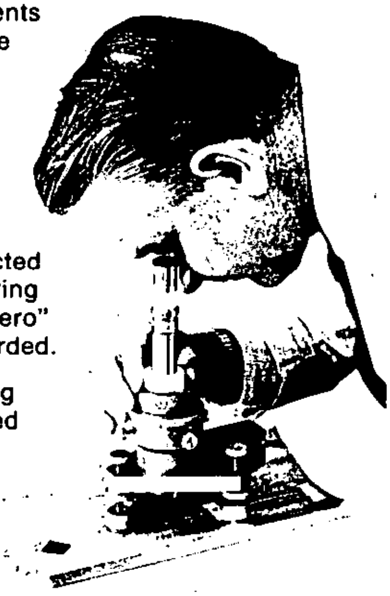


High-Speed Drilling Setup

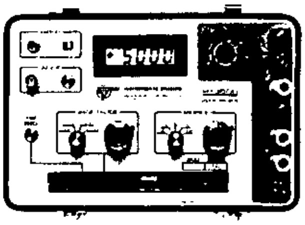


Residual Stress Measurement Procedure

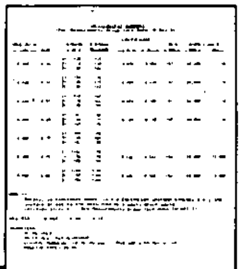
Making residual stress measurements with the RS-200 Milling Guide consists of the following steps:

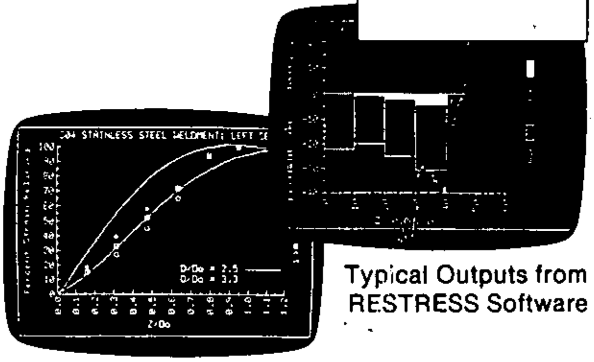


1. A special three-element Micro-Measurements strain gage rosette is bonded to the test part at points where residual stresses are to be determined.
2. Each rosette grid element is connected to a strain measuring instrument and "zero" readings are recorded.
3. The RS-200 Milling Guide is positioned over the center of the gage and securely attached to the test part.
4. The RS-200 is optically aligned so that its drilling axis is precisely positioned over the target at the center of the strain gage rosette.
5. A hole is drilled through the center of the rosette and into the test part.
6. Strain gage instrumentation is used to obtain strain readings.
7. Residual stresses are then computed, either manually or by using the Measurements Group's RESTRESS software program. RESTRESS is available on either 5-1/4 in or 3-1/2 in disks for use with most MS-DOS PC-compatible computers. RESTRESS provides data reduction in accordance with ASTM Standard Method E837, as well as approximate determination of residual stress variation with depth. (Refer to TN-503).



Model P-3500 Strain Indicator for Manual Data Acquisition





Typical Outputs from RESTRESS Software

Accessories and Replacement Parts for the RS-200

Listed below are accessory items and replacement parts for the RS-200 Milling Guide.

Double-Ended Boring Mills

Although boring mills are supplied as standard equipment with the basic guide, replacement will be necessary after prolonged usage. These mills, of high-speed steel, are available in two sizes:
HS-200-125, 0.125 in *(3.2 mm)* diameter.
HS-200-062, 0.062 in *(1.6 mm)* diameter.

Cutters For High-Speed Air Turbine

Cutters are inverted-cone, carbide-tipped:
ATC-200-062, 0.062 in *(1.6 mm)* diameter.
ATC-200-031, 0.031 in *(0.8 mm)* diameter.

Type RM-1 Motor for High-Speed Air Turbine

Cement Kit

A fast-setting (15 minutes) two-component resinous-type dental cement especially suited for firmly attaching the milling guide to the test part. Standard packaging is approximately two ounces. One package is sufficient for ten guide mountings.

A full line of strain gage instruments for measuring the strain magnitude is also available from the Measurements Group.

M=M Special Rosette Strain Gages

All gages are constructed of self-temperature-compensated constantan foil, mounted on a flexible polyimide carrier. Since their application is generally associated with a precision alignment milling guide, each incorporates a centering target. The unique features of each construction are:

EA Series: Normally supplied "open-faced", but also available with solder dots and encapsulation (Option SE).

TEA Series: Fully encapsulated with easily accessible copper terminals to facilitate installation.

CEA Series: Incorporates all the advantages of Micro-Measurements' popular 'C' Feature gages. Pattern is specifically designed for applications where it is impractical to use RE or RK configurations (i.e., adjacent to weldments, corners, and intersecting surfaces). Care must be exercised when using this pattern, however, as limitations may exist in data reduction equations.

Refer to Micro-Measurements Catalog A-110 for detailed information concerning strain gage installation accessories. Refer to Catalog 500 for detailed information about rosette specifications.

GAGE PATTERN AND DESIGNATION [illegible]	RES. IN OHMS	DIMENSIONS (inches / *millimetres*)					
		GAGE LENGTH	GRID CTR'LINE DIA.	TYPICAL HOLE DIA.		MATRIX	
				Min.	Max.	Length	Width
EA-XX-031RE-120 EA-XX-031RE-120/Option SE	120 ±0.2% 120 ±0.4%	0.031	0.101	0.03	0.04	0.29	0.29
		0.79	*2.56*	*0.8*	*1.0*	*7.4*	*7.4*
		Due to small pattern size, measurement error can be magnified by slight mislocation of drill hole. Pattern not recommended for general-purpose applications.					
EA-XX-062RE-120 EA-XX-062RE-120/Option SE	120 ±0.2% 120 ±0.4%	0.062	0.202	0.06	0.08	0.42	0.42
		1.57	*5.13*	*1.5*	*2.0*	*10.7*	*10.7*
		Most widely used RE pattern for general-purpose residual stress measurement applications.					
EA-XX-125RE-120 EA-XX-125RE-120/Option SE	120 ±0.2% 120 ±0.4%	0.125	0.404	0.12	0.16	0.78	0.78
		3.18	*10.26*	*3.0*	*4.1*	*19.8*	*19.8*
		Larger version of the 062RE pattern.					
TEA-XX-062RK-120	120 ±0.4%	0.062	0.202	0.06	0.08	0.60	0.60
		1.57	*5.13*	*1.5*	*2.0*	*15.2*	*15.2*
		Fully encapsulated, with copper terminals for ease of soldering. Same pattern geometry as 062RE pattern.					
CEA-XX-062UM-120	120 ±0.4%	0.062	0.202	0.06	0.08	0.38	0.48
		1.57	*5.13*	*1.5*	*2.0*	*9.6*	*12.2*
		Fully encapsulated with large copper-coated soldering tabs and special trim alignment marks. Trim line spaced 0.068 in *(1.73 mm)* from hole center.					

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BULLETIN 313-C

MODEL 1550A

STRAIN INDICATOR CALIBRATOR

A laboratory standard for verifying the calibration of strain and transducer indicators.

- **True Wheatstone Bridge Circuitry**
- **Simulates Quarter, Half & Full Bridge — both 120Ω/350Ω**
- **3 Decades of Push Buttons**
  - **Strain Range Direct Reading: ±99 900$\mu\epsilon$... Increments of 100$\mu\epsilon$**
  - **Transducer Range: ±49.95 mV/V... Increments of 0.05 mV/V**
- **Reversing Switch for Plus and Minus Calibration**
- **High Precision Vishay Resistors used throughout to ensure Excellent Stability**
- **Accuracy 0.025 Percent — Traceable to the U.S. National Institute of Standards and Technology**

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DESCRIPTION

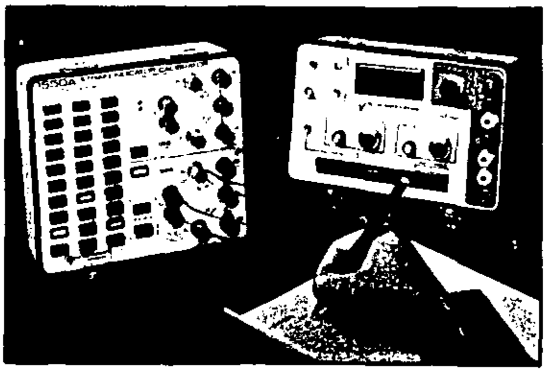
Sound engineering and laboratory practices require that the instrumentation used to make critical strain measurements be periodically calibrated to verify that it is within the manufacturer's original specifications. Additionally, each type of strain indicator exhibits some degree of nonlinearity, especially for large strains during quarter-bridge operation. Since this is the most common stress analysis application of strain gages, it is important that the strain indicator be calibrated in this mode. Instrumentation span should also be checked at a number of points before each important test to avoid inaccurate data.

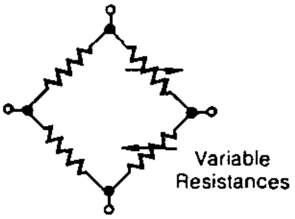
The Model 1550A calibrator is a Wheatstone bridge and generates a true change of resistance in one or two arms of the bridge. It simulates the actual behavior of a strain gage in both positive and negative strain.

The 'star network' used in certain other commercial calibrators provides a substantially lower cost instrument design, because component specifications are less critical, and fewer components are required.

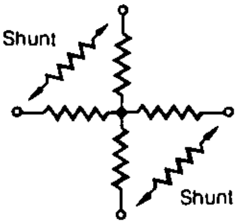
However, the 'star network' cannot simulate quarter-bridge strain gage behavior, and cannot simulate positive strain. Another serious problem with this circuit is that the bridge input and output resistances change in an abnormal manner, leading to inaccuracies in calibration under some conditions.

A calibrator based on the Wheatstone bridge principle requires stable components. A total of 66 ultra-stable Vishay precision resistors are used in the Model 1550A calibrator to provide the stability, repeatability, accuracy and incremental steps required in a laboratory standards instrument.


Calibration verification of a P-3500 Portable Strain Indicator before an important test.



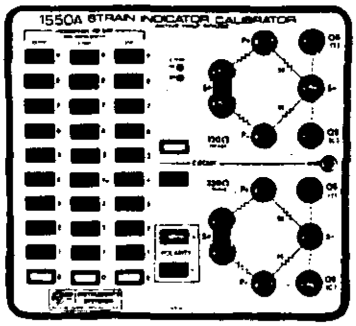
WHEATSTONE BRIDGE



'STAR NETWORK'

SPECIFICATIONS

Accuracy:	0.025% of setting ±1με (0.0005 mV/V), max. Traceable to United States National Institute of Standards and Technology.
Repeatability:	±1με (0.0005 mV/V), max.
Stability:	(0.001% of setting ±1με)/°C, max.
Thermal EMF:	0.5 μV/V of excitation, max.
Bridge Resistances:	120Ω and 350Ω. Input resistance: ±0.05%, max., from nominal at all output settings. Output resistance: ±0.05%, max., from nominal at "000" με, -0.25% at ±99 900με.
Circuit:	True ±ΔR in two adjacent arms (opposite signs), plus two fixed arms for bridge completion.
Simulation:	Quarter bridge, one active arm. Half bridge, one or two active arms. Full bridge, two active arms.
Range:	Two active arms. 0 to ±99 900με in steps of 100με @ GF=2.00. 0 to ±49.95 mV/V in steps of 0.05 mV/V. One active arm: 0 to ±49 950με in steps of 50με @ GF=2.00.
Excitation:	To meet accuracy and repeatability specifications: 120Ω: 0-10V ac or dc. 350Ω: 0-15V ac or dc. Maximum permissible: 120Ω: 25V ac or dc. 350Ω: 30V ac or dc.
Output @ 000:	50με (0.025 mV/V), max. in full-bridge mode.
Environment:	Temperature: 0° to +120°F *(-18° to +49°C)*. Humidity: Up to 70% RH, non-condensing.
Size:	Aluminum case (separable lid). 5-3/4 H x 8-1/4 W x 7-3/4 D in *(145 x 210 x 195 mm)*.
Weight:	4.8 lbs *(2.2 kg)*.



A Certificate of Calibration is provided with each Model 1550A Calibrator.

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MODEL V/E-40

STRAIN GAGE SIMULATOR

A precision decade resistor for accurately simulating the behavior of strain gages and RTD's.

- **5 Decade Selector Switches**
- **Resistance Range: 30.00 to 1111.10Ω in 0.01Ω steps**
- **High Precision Vishay Resistors used throughout to ensure Excellent Stability**
- **Accuracy 0.02% of Setting**
- **Simulates Tension and Compression Strain for most widely used Strain Gage Resistance Values**
- **Simulates a Broad Range of RTD's for Instrumentation Set Up and Calibration**

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DESCRIPTION

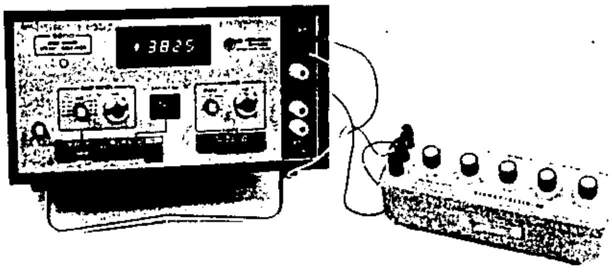
The V/E-40 Strain Gage Simulator is an accurate, stable, compact, five-decade resistor specially designed to simulate the behavior of strain gages and RTD's, and for use in a broad range of measurement and calibration applications.

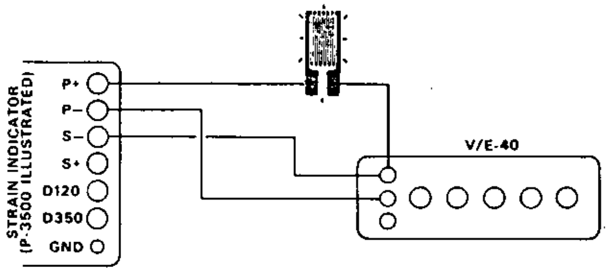
As a precision strain gage simulator, the V/E-40 can be used to **measure nonlinearity of the instrumentation** in quarter-bridge operation, or to **verify instrument calibration** over the anticipated measurement range. It is also well-suited to **measuring desensitization of the strain gage circuit** due to the finite resistance of the strain gage leadwire system.

In a similar manner, the V/E-40 can be temporarily substituted for an RTD over a resistance range of 30.00 to 1111.10 ohms to **verify calibration of temperature measurement instrumentation.**

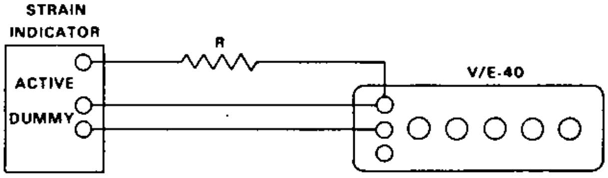
The V/E-40 can also be used in conjunction with a conventional Wheatstone bridge strain indicator to **measure arbitrary resistances** between 30.00 and 1111.10 ohms, or to **eliminate Wheatstone bridge nonlinearity effects when measuring high post-yield strains in quarter-bridge operation.** In this mode, the resistance or strain gage to be measured is connected as one arm of a Wheatstone bridge, the V/E-40 is used as a decade resistor in an adjacent arm, and the strain measuring instrument as a null detector.

Other applications include use as an investigative tool to troubleshoot faulty strain gage installations, or as a precision decade resistor.





V/E-40 used for large strain measurement



V/E-40 used to measure arbitrary resistance value, *R*.

SPECIFICATIONS

Accuracy:	0.02% of reading.	Environment:	0° to +120°F *(−18° to +49°C)*, up to 70% relative humidity, non-condensing.
Maximum Current:	To meet accuracy and repeatability specifications: 120Ω: 65 mA; 350Ω: 55 mA; 1000Ω: 25 mA.	Size:	3-7/8 H x 9-1/8 W x 3-1/8 D in *(98 x 232 x 89 mm)*.
Stability:	±3 ppm/°C max.		
Resistance Range:	30.00 to 1111.10Ω in 0.01Ω steps.	Weight:	1.9 lb *(0.85 kg)*.

All specifications are nominal or typical at +23°C *(+73°F)*.

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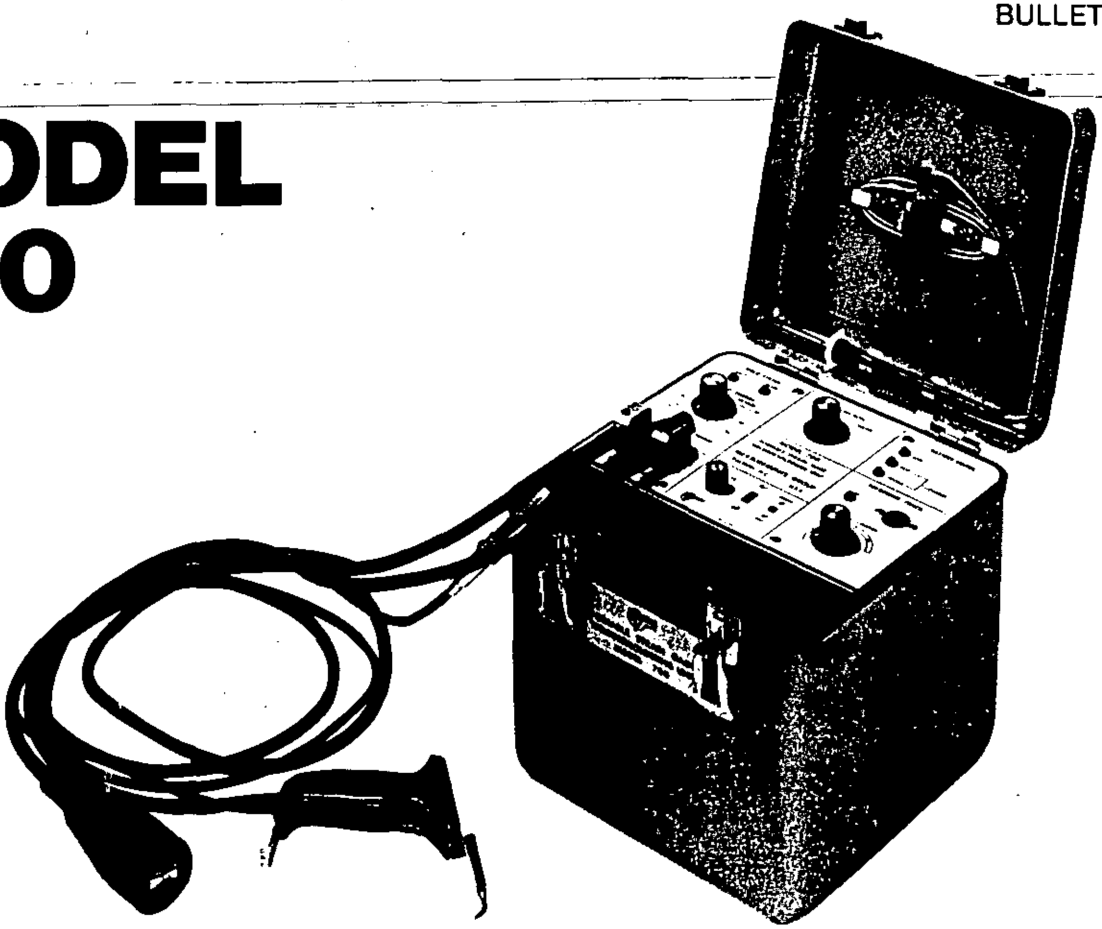
BULLETIN 302-B

MODEL 700



PORTABLE STRAIN GAGE WELDING AND SOLDERING UNIT

A battery-operated capacitive discharge spot welder for attaching and wiring weldable strain gages and temperature sensors.

- **Separate visual and audible indicators monitor welder status** — Weld energy is continuously adjustable from 3 to 50 joules, making the Model 700 an excellent choice for installing weldable strain gages and temperature sensors, as well as small thermocouples and light-gauge metal.
- **Supplied with a lightweight soldering pencil** —A front-panel control adjusts soldering tip temperature for a wide range of soldering applications in the field or in the laboratory.
- **"Low-battery" light to warn the user when the internal, sealed lead-acid battery requires charging** — A built-in charger operates automatically when plugged into 115 or 230 Vac, to ensure full battery charge with no danger of overcharging. Indicator lights monitor battery charge rate.
- **Convenient storage space for cables and instruction manual.**

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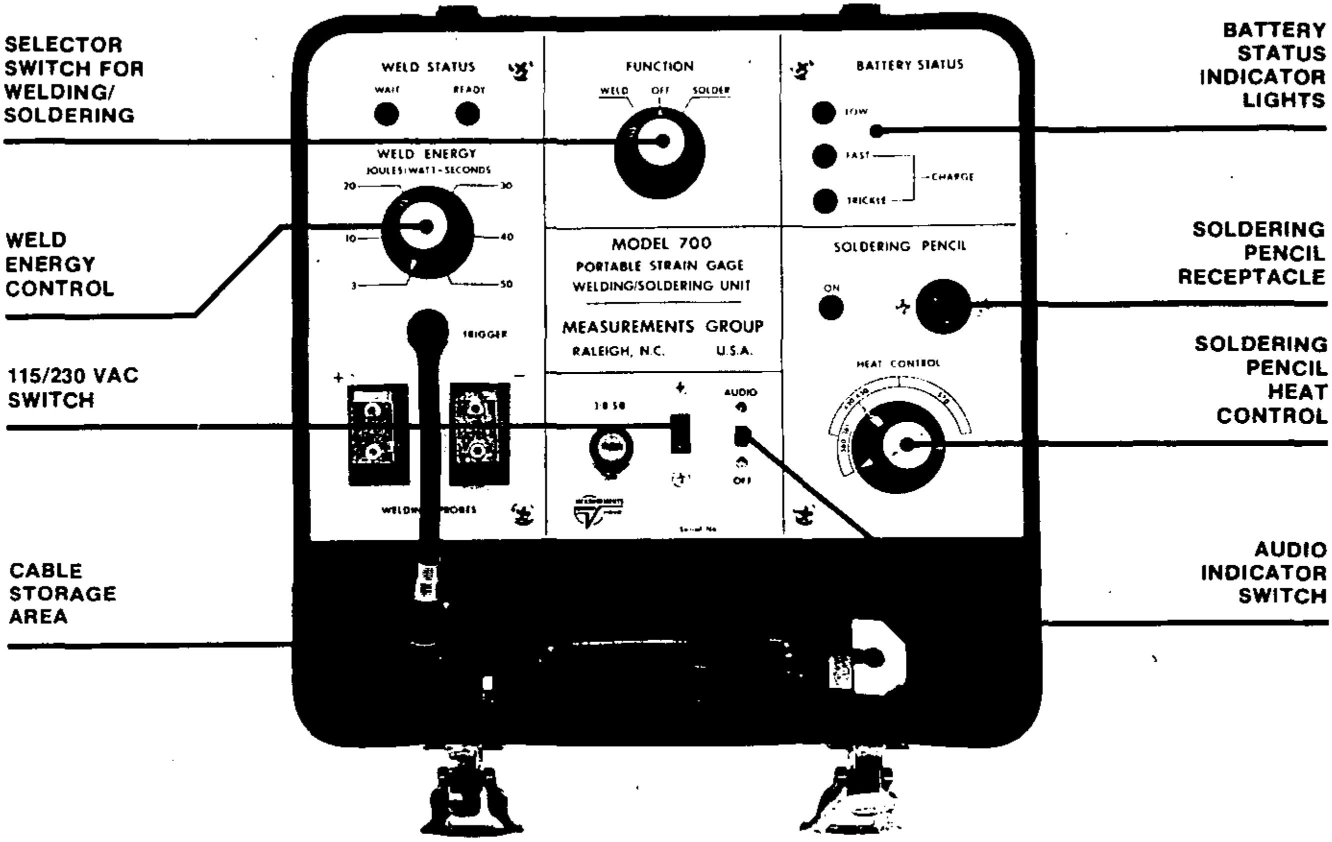
PANEL CONTROL FEATURES



SPECIFICATIONS

WELDING

WELD ENERGY RANGE
3 to 50 joules, continuously adjustable by front-panel control.

MAXIMUM WELD REPETITION RATE
20 per minute at 30 joules, typical.

NUMBER OF WELDS PER BATTERY CHARGE
Approximately 2000 at weld energy setting of 30 joules. This is equivalent to 40 Micro-Measurements weldable gage installations.

BATTERY CHARGE TIME (from full discharge)
12 hours to 75% full charge; 18 hours to full charge.

BATTERY
One sealed, rechargeable lead-acid (non-liquid) type, 12 volt, 5 ampere-hour.

WELDING PROBE
Manually fired with trigger control and "steady-rest."

WELDING CABLES
Two 5 ft *(1.5 m)*, fully flexible.

WELD ENERGY MONITOR
Calibrated front-panel control with READY and WAIT indicators; audible indication selectable.

SOLDERING

TEMPERATURE CONTROL
Continuously variable with bands indicating melting range of solders.

SOLDERING PENCIL
1.1 oz *(31 gm)*, rated at 25 watts, 12 volt operation. Tip temperature adjustable from +200° to +900°F *(+90° to +480°C)*.

SOLDERING DURATION
4 hours using +361°F *(+183°C)* melting point solders (with initial full charge).

GENERAL

OVERALL SIZE
9 L x 9 W x 9-3/4 H in (230 x 230 x 250 mm).

WEIGHT
21 lb *(9.5 kg)*.

INPUT POWER FOR RECHARGING
115 Vac or 230 Vac, 50-60 Hz.

OPERATING AND STORAGE TEMPERATURE RANGE
0° to +120°F *(-20° to +50°C)*.

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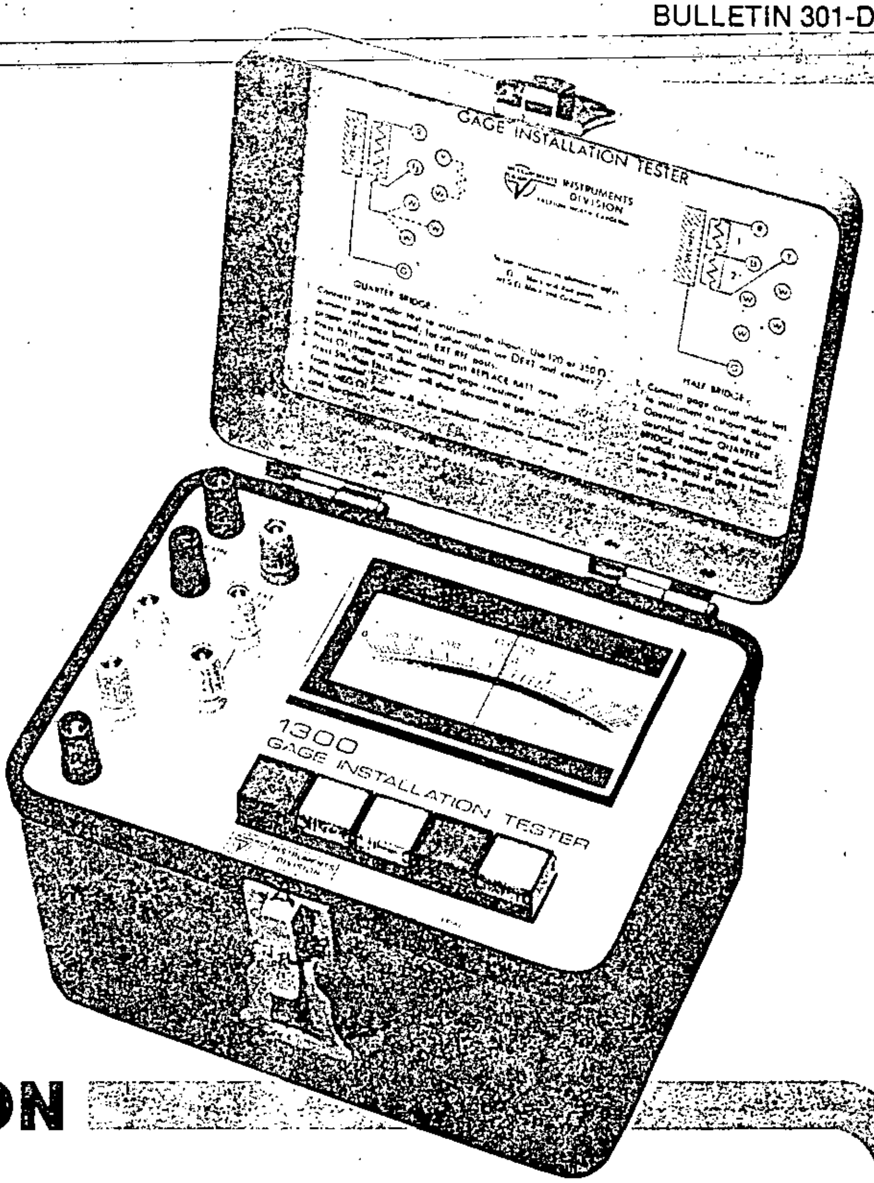
BULLETIN 301-D

MODEL 1300



GAGE INSTALLATION TESTER

A compact, battery-powered instrument used to verify the electrical quality of a strain gage installation BEFORE it is placed in service.

- **Reads with the Push of a Button: No Warm-Up.**
- **Reads Insulation Resistance (Leakage) to 20 000 Megohms with 15 Vdc.**
- **Measures Deviation of Installed Gage Resistance from Precise Standards to a Resolution of 0.02 Percent.**
- **Ohmmeter Scale for Troubleshooting Questionable Installations.**
- **Verifies the Complete Gage Circuit Including Leadwires.**

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DESCRIPTION

Two of the most important measurements used to verify the quality of a strain gage installation are insulation resistance (leakage to ground) and shift in gage resistance due to installation procedures. While these two measurements are not a complete guarantee of eventual proper strain gage performance, any installation which produces questionable values should not be relied upon where accuracy of results is necessary.

Several sources of variations in insulation resistance and shifts in gage resistance are:

> Insulation resistance in excess of 20 000 megohms should be expected for foil strain gages when installed under laboratory conditions. A value of 10 000 megohms should be considered minimum. A reading below this value generally indicates trapped foreign matter, moisture, residual flux or backing damage due to soldering, as well as incomplete solvent evaporation from an overcoating.
>
> Deterioration of the insulation resistance with time may be an indication of an improperly coated installation.
>
> At higher test temperatures, particularly above +300°F *(+150°C)*, it is normal to expect lesser values. Ten megohms is considered to be the lower allowable value.
>
> A voltage difference between the specimen and strain gage frequently exists. A very high insulation resistance will help keep this voltage differential from introducing extraneous signals during strain measurement.
>
> Shifts in gage resistance during installation should not normally exceed 0.5% when using room-temperature-curing adhesives. Resistance shifts greater than 0.5% generally indicate damage to the gage due to improper handling or clamping. However, strain gages installed using elevated-temperature-curing adhesives may exhibit greater shifts in resistance due to adhesive lock-up at elevated temperatures (difference in linear coefficient of thermal expansion between the strain gage and specimen). These shifts will vary depending upon the specific cure temperature and materials used. The shifts should never exceed 2% and should be uniform within 0.5%.

The Model 1300 was jointly designed by the Micro-Measurements and Instruments Divisions of the Measurements Group for maximum usability. The unit's payback is very short as it will identify faulty gage installations that could ruin a costly test program.

Complete strain gage installation is easily verified using the Model 1300. Once initial wire connections are made, measurements are accomplished simply by pushing the appropriate buttons.

SPECIFICATIONS

INPUT CIRCUITS
Gages: 3-wire quarter bridge (120 and 350Ω) and half bridge. Other value quarter bridges using customer's reference, at readily accessible panel terminals. As ohmmeter: 2 leads (500Ω and 500 MΩ midscale).

INPUT LEADS
4-ft *(1.2-m)* 4-conductor AWG #26 *(0.4-mm dia.)* twisted Teflon®-insulated cable supplied (with ground clip and 3 tinned leads).

METER
3.5-in size [3.00-in *(76-mm)* scale length] with mirror. Tracking accuracy ±1% full range.

MODE SWITCH
5 momentary push buttons: battery check, ±5% deviation, ±1% deviation, gage resistance (ohms), and insulation resistance (megohms).

DEVIATION MODE
Two ranges, ±1% and ±5% F.S. (50 graduations either side of zero).
Accuracy: 1% range: 0.04% ΔR (2 meter graduations)
5% range: 0.2% ΔR (2 meter graduations)
Excitation: 1.0 Vdc per gage.

INSULATION RESISTANCE MODE
Graduated 5 MΩ to 20 000 MΩ (500 MΩ mid-scale).
Accuracy: 1 scale div.
Test Voltage: 15 Vdc open circuit.

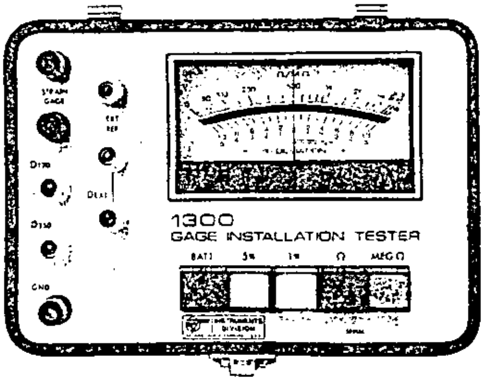
OHM MODE
Graduated 5Ω to 20 kΩ (500Ω mid-scale).
Accuracy: 1 scale div.
Test Voltage: 2 Vdc open circuit (0.4 Vdc @ 120Ω).

ENVIRONMENTAL
+15° to +125°F *(-10° to +50°C)*; up to 90% relative humidity, non-condensing.

SIZE
Aluminum case (separable lid)
5 H x 7 W x 5 D in with lid
(125 x 180 x 125 mm).

WEIGHT
3.6 lb *(1.6 kg)* with batteries

POWER SUPPLY
Four 9V NEDA 1604 batteries (Eveready 216 or equiv.)
Life: Will fully test 1000-5000 installations.



Momentary action, color-coded push-button switches enable easy selection of meter scales—ohms/megohms, ±1% deviation, ±5% deviation and battery check.

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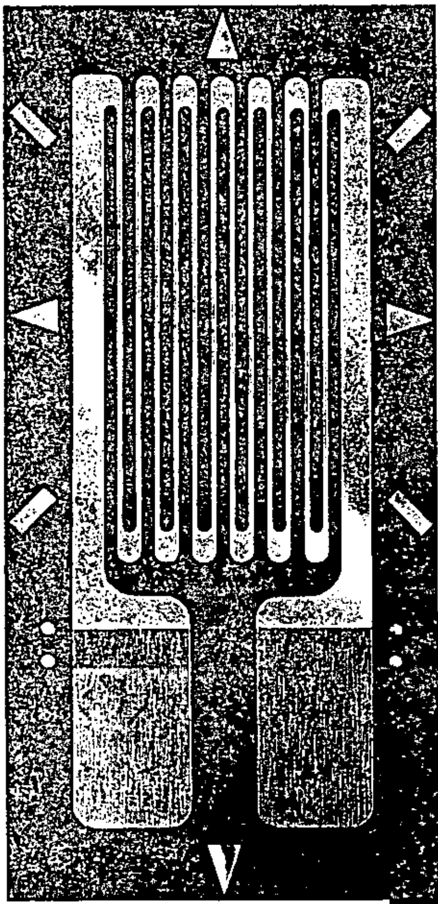
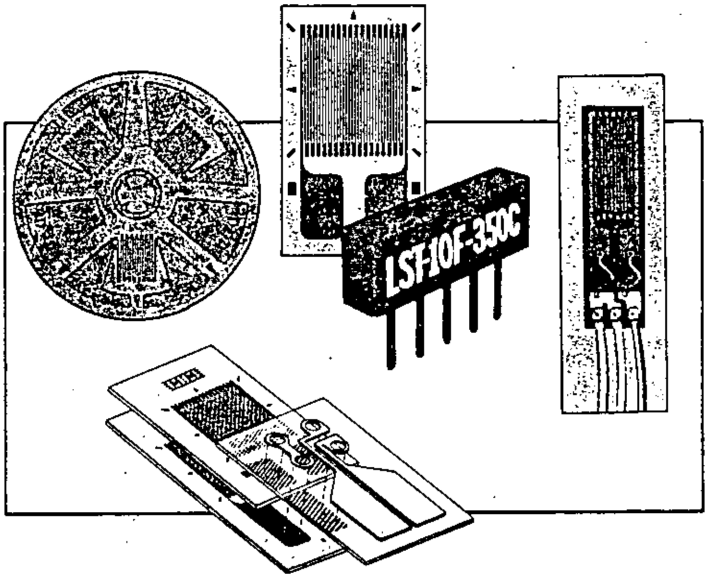
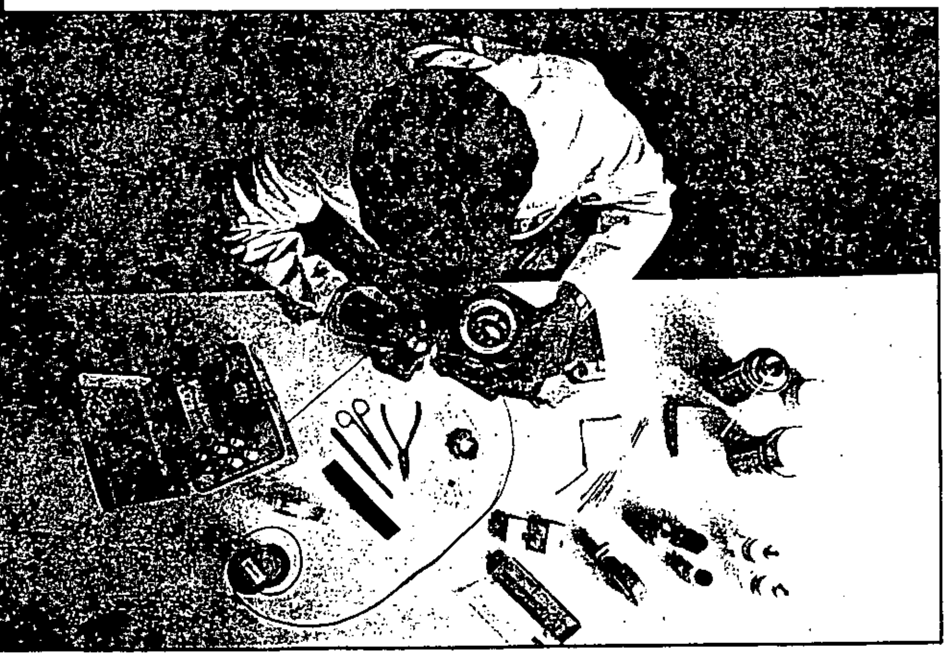
An Introduction to . . .

Micro-Measurements

- **Strain Gages**
- **Special Sensors**
- **Installation Accessories**







MEASUREMENTS
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The Broadest Range Of Strain Gages And Accessories Available

Micro-Measurements has been a trusted name in the field of Strain Gage Technology for many years. We are proud of our worldwide reputation as a premier supplier of high-quality precision strain gages and strain gage accessories, and are fully committed to maintaining our position as the leader in this field. This short-form catalog of Micro-Measurements strain gages and related products is intended to provide a condensed overview of the sensors, supplies, and tools commonly needed for typical strain gage applications.

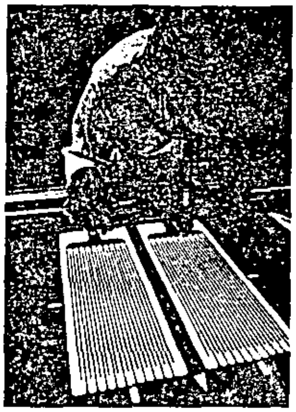
Micro-Measurements was independently founded and operated in the early 1960's. A few years later it became a part of Vishay Intertechnology, Inc. and, in late 1973, was incorporated with the other stress analysis divisions of Vishay into a single entity — The Measurements Group. All divisions of the Measurements Group are now located in our world headquarters facility near Raleigh, North Carolina. Micro-Measurements maintains an additional strain gage production facility in Romulus, Michigan.

Customer Support Services

The common denominator in all Micro-Measurements products and services is our dedication to helping you achieve consistently accurate and reliable strain measurements. And we've made some significant commitments to help ensure your success:

We publish the widest range of technical reference literature in the strain gage field — available through the Measurements Group's Technical Data Mailing Program.

We respond quickly to requests for "specials" to suit individual requirements.



An experienced and friendly Applications Engineering staff is readily available by phone or letter.

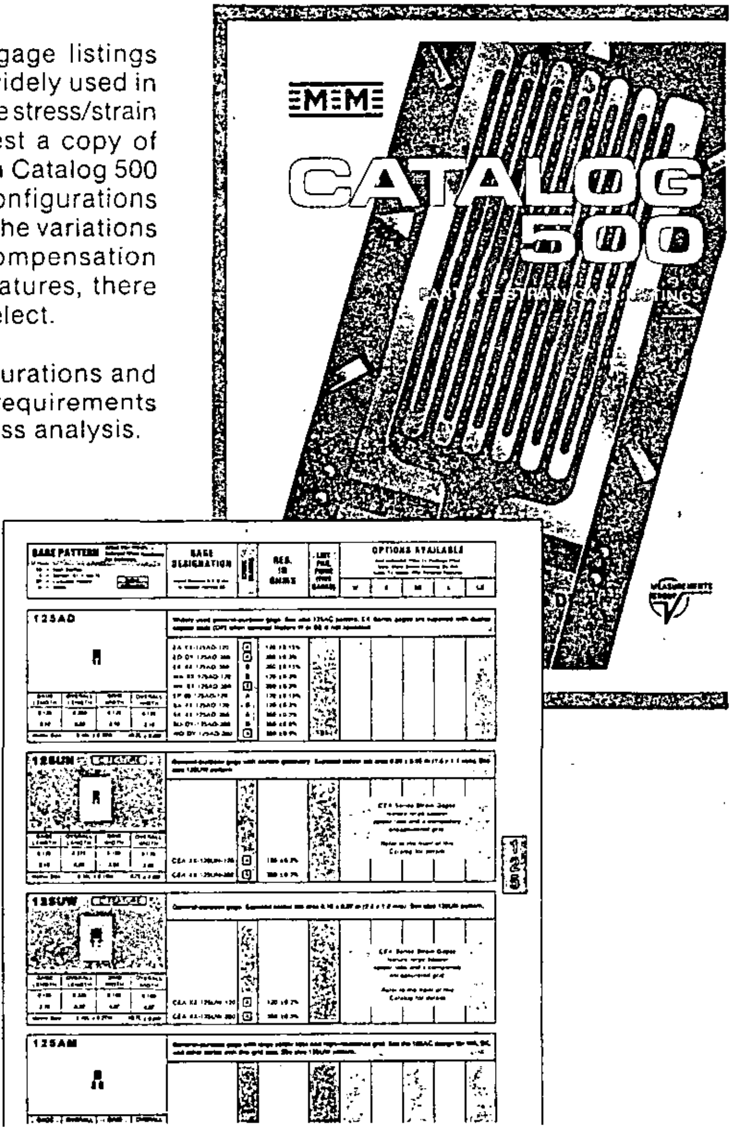
We offer a variety of comprehensive technical training programs from beginner to advanced levels in strain gage technology. The Measurements Group regularly conducts workshops and technical seminars in our Technical Training Center in Raleigh, North Carolina and at locations throughout the U.S. and the world.

At Micro-Measurements, Your Success Is Our Goal

Master Strain Gage Catalog
Catalog 500

This introductory catalog contains abridged strain gage listings which are representative of the types and sizes most widely used in stress analysis applications. For those involved in extensive stress/strain measurement programs, it is advantageous to request a copy of Micro-Measurements Catalog 500. The gage listings in Catalog 500 include essentially all standard types and pattern configurations manufactured by Micro-Measurements. Considering the variations in pattern design, grid alloys, self-temperature-compensation (S-T-C) numbers, backing materials, and optional features, there are over 100,000 possible gage types from which to select.

Catalog 500 contains a broad range of pattern configurations and sizes, designed to meet the many and varied test requirements encountered throughout the field of experimental stress analysis.



> A special group of strain gages — *Transducer-Class®* — has been developed specifically for transducer applications. *Transducer-Class* strain gages, described in separate Micro-Measurements literature, are a select group of standard and special gage patterns designed for optimum cost/performance ratio (in transducer service) in high-volume production quantities.

Gage Listings

Reproduced below is a sample Catalog 500 listing for a single, representative gage pattern. The listing includes a tabulation of all gage series in which the pattern is available, as well as optional features applicable to each series. Complete descriptions of the gage series, options, etc. are provided in the introductory section of Catalog 500.

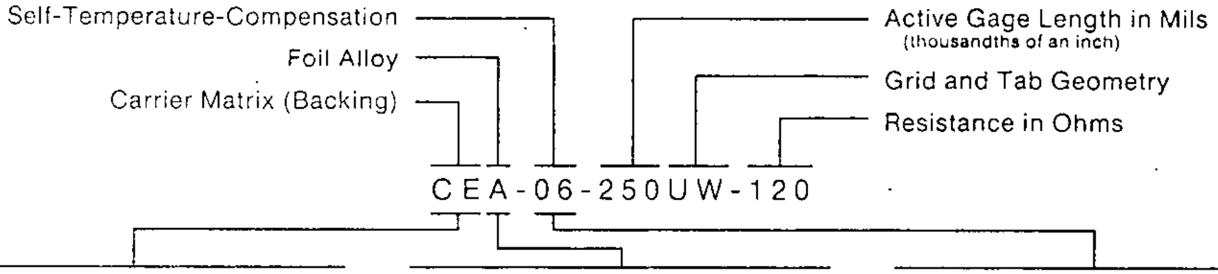
GAGE PATTERN Actual Size Shown. Enlarged When Necessary For Definition. ES = Each Section S = Section (S1 = Sec 1) CP = Complete Pattern M = Matrix inches *millimetres*	**GAGE DESIGNATION** Insert Desired S-T-C No. in Spaces Marked XX	**STOCK STATUS**	**RES. IN OHMS**	**LIST PKG. PRICE (FIVE GAGES)**	**OPTIONS AVAILABLE** Add Indicated Price To Package Price. Note: Stock Status Symbols Do Not Apply To Gages With Optional Features W	E	SE	L	LE
125AD  GAGE LENGTH: 0.125 / *3.18* OVERALL LENGTH: 0.250 / *6.35* GRID WIDTH: 0.125 / *3.18* OVERALL WIDTH: 0.125 / *3.18* *Matrix Size* 0.40L x 0.22W / *10.2L x 5.6W*	Widely used general-purpose gage. See also 125AC pattern. EK-Series gages are supplied with duplex copper pads (DP) when optional feature W or SE is not specified.								
	EA-XX-125AD-120	$\boxed{A}$	120 ±0.15%						
	ED-DY-125AD-350	$\boxed{A}$	350 ±0.3%						
	EK-XX-125AD-350	B	350 ±0.15%						
	WA-XX-125AD-120	B	120 ±0.3%						
	WK-XX-125AD-350	$\boxed{A}$	350 ±0.3%						
	EP-08-125AD-120	A	120 ±0.15%						
	SA-XX-125AD-120	B	120 ±0.3%						
	SK-XX-125AD-350	A	350 ±0.3%						
	SD-DY-125AD-350	B	350 ±0.6%						
	WD-DY-125AD-350	$\boxed{A}$	350 ±0.6%						

Strain Gage Designation System and Selection Chart

In selecting the most suitable strain gage for each application, consideration must be given to the variations in pattern design, grid alloy, self-temperature-compensation (S-T-C), backing material, and optional features. The gage designation system and standard strain gage selection chart shown on this page present a partial summary of the many combinations of these factors available in Micro-Measurements strain gages. For brevity, this summary is limited to those gage series and optional features listed in this catalog only. When selecting or ordering a strain gage from this catalog, these charts will provide a key to choosing the appropriate gage for your application.

A complete, detailed designation system and selection chart are included in Catalog 500.

When test conditions are severe, or when there are unusually stringent demands on accuracy and stability, selection of the optimum gage parameters to satisfy the test specifications can involve a number of subtle considerations. As an aid in systematically arriving at the most appropriate gage type, given a specific measurement task, Measurements Group Tech Note TN-505, *"Strain Gage Selection Criteria, Procedures, Recommendations"*, available on request from the Measurements Group's Applications Engineering Department, will provide a valuable reference for use in conjunction with these selection criteria and charts.



E: Open-faced, cast polyimide backing.

W: Fully encapsulated; glass-fiber-reinforced epoxy-phenolic resin. High-endurance leadwires.

CE: Thin, flexible gages with a cast polyimide backing and encapsulation featuring large, rugged, copper-coated solder tabs. This construction provides optimum capability for direct leadwire attachment.

A: Constantan alloy in self-temperature-compensated form.

P: Annealed Constantan.

D: Isoelastic alloy.

K: Modified Karma alloy.

The S-T-C number is the approximate thermal expansion coefficient in PPM/°F of the structural material on which the gage is to be used. The following standard compensations are available:

A and K alloys: 06, 13.

P alloy: 08.

The D alloy is not available in self-temperature-compensated form. 'DY' is used instead.

Gage Series	DESCRIPTION AND PRIMARY APPLICATION	TEMPERATURE RANGE	STRAIN RANGE	FATIGUE LIFE	
				Strain Level in $\mu\epsilon$	Number of Cycles
EA	General-purpose static and dynamic stress analysis. Wide range of options available.	Normal: -100° to +350°F *(-75° to +175°C)* Special or Short Term: -320° to +400°F *(-195° to +205°C)*	±3% for gage lengths under 1/8 in *(3.2 mm)*. ±5% for 1/8 in & over.	±1800 ±1500 ±1200	10^5 10^6 10^8
CEA	Universal general-purpose strain gages. Constantan grid completely encapsulated in polyimide, with large, rugged, copper-coated tabs. Primarily used for general-purpose static and dynamic stress analysis.	Normal: -100° to +350°F *(-75° to +175°C)* Stacked rosettes limited to +150°F *(+65°C)*	±3% for gage lengths under 1/8 in *(3.2 mm)*. ±5% for 1/8 in & over.	±1500 ±1500	10^5 10^6*
ED	Excellent for dynamic measurements. High gage factor and extended fatigue life.	Dynamic: -320° to +400°F *(-195° to +205°C)*	±2% Nonlinear at strain levels over ±0.5%.	±2500 ±2200	10^6 10^7
WA	Stress analysis and transducer applications. Wide temperature range and extreme environmental capability. High-endurance leadwires.	Normal: -100° to +400°F *(-75° to +205°C)* Special or Short-Term: -320° to +500°F *(-195° to +260°C)*	±2%	±2000 ±1800 ±1500	10^5 10^6 10^7
WK	Widest temperature range and most extreme environmental capability. High-endurance leadwires.	Normal: -452° to +550°F *(-269° to +290°C)* Special or Short-Term: -452° to +750°F *(-269° to +400°C)*	±1.5%	±2400 ±2200 ±2000	10^6 10^7 10^8
EP	High-elongation measurements (post yield). Only available in 08 S-T-C value.	-100° to +400°F *(-75° to +205°C)*	±10% for gage lengths under 1/8 in *(3.2 mm)*. ±20% for 1/8 in & over.	±1000 EP gages show zero shift under high-cyclic strains.	10^4
WD	For wide-range dynamic strain measurements in severe environments. High-endurance leadwires.	Dynamic: -320° to +500°F *(-195° to +260°C)*	±1.5% Nonlinear at strain levels over ±0.5%.	±3000 ±2500 ±2200	10^5 10^7 10^8

*Fatigue life improved using low-modulus solder.

Super Stock Gage Listings Section

The gages listed on this and the following page represent the most widely used types for general-purpose experimental stress analysis. Gage lengths range from 0.015 to 0.500 in *(0.4 to 13 mm)* in a wide range of pattern configurations. In addition to single-element gages in a variety of sizes and aspect ratios, the list includes two- and three-element rosettes for use in biaxial stress fields. There are also twin-element chevron patterns for measuring shear strain or torque. Grid resistances of 120, 350, and 1000 ohms are available.

Selection of gages from this list will generally lead to the best delivery and, in many cases, to a price advantage as well. The "C"-feature, or CEA-Series, strain gages are normally the first choice because of the ease of installation. These gages have rugged, copper-coated solder tabs, permitting direct leadwire attachment.

All gages in this list are classified as *Super Stock*. This means that Micro-Measurements guarantees to maintain stock for off-the-shelf delivery of at least 10 packages of any type listed in 06 and 13 self-temperature-compensation numbers (except 08 S-T-C for P alloy and DY for Isoelastic). There are no Minimum Order Requirements for gages selected under the above conditions.

If your application requires a gage that is not listed here, you should refer to Micro-Measurements Catalog 500, which includes all standard, general-purpose Micro-Measurements strain gages. All gage patterns are shown at actual size except where enlargement is necessary for geometry definition.

GAGE DESIGNATION AND PATTERN

CEA-XX-015UW-120

Micro-miniature pattern with large exposed solder tabs for high-strain-gradient applications. Exposed tab area is 0.06 x 0.04 in *(1.5 x 1.0 mm)*.

4X

CEA-XX-032UW-120

Short gage length pattern with large exposed solder tabs for high-strain-gradient applications. Exposed tab area is 0.07 x 0.04 in *(1.8 x 1.0 mm)*.

2X

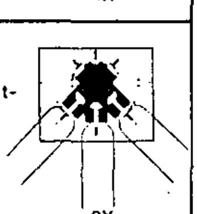
EA-XX-031DE-120

Miniature pattern for positioning adjacent to high stress concentrations, e.g., holes, fillets, etc.

4X

WA-XX-060WR-120

Small 3-element 45° rectangular stacked rosette.



2X

EA-XX-062AK-120

Small general-purpose pattern with elongated solder tabs.

2X

GAGE DESIGNATION AND PATTERN

EA-XX-062AP-120
WK-XX-062AP-350

Compact small general-purpose pattern. Select WK gage for wide temperature range applications.

2X

EA-XX-062AQ-350

Same size as 062AP pattern but with high-resistance grid in EA Series.

2X

CEA-XX-062UW-120
CEA-XX-062UW-350

Small general-purpose gage with large exposed solder tabs. Exposed tab area is 0.07 x 0.04 in *(1.8 x 1.0 mm)*.

2X

EA-XX-062TV-350

Small 2-element 90° torque gage.

2X

EA-XX-062TT-120

Small general-purpose 90° 'tee' rosette. Sections are electrically independent.

2X

GAGE DESIGNATION AND PATTERN

EA-XX-125AC-350

Widely used general-purpose pattern with high-resistance grid.

EA-XX-125AD-120
ED-DY-125AD-350
WD-DY-125AD-350
WK-XX-125AD-350

Widely used, general-purpose pattern. Select ED- or WD-DY gages for fatigue applications; WK for wide temperature range static or dynamic measurements.

CEA-XX-125UN-120
CEA-XX-125UN-350

Narrow general-purpose gage pattern. Exposed tab area is 0.06 x 0.05 in *(1.5 x 1.1 mm)*.

CEA-XX-125UW-120
CEA-XX-125UW-350

Most widely used general-purpose gage in CEA Series. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

EA-XX-125BB-120

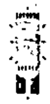
Narrow general-purpose pattern with elongated tabs.

Super Stock Gage Listings Section

GAGE DESIGNATION AND PATTERN

EA-XX-125BT-120

General-purpose pattern with narrow grid and compact geometry.



2X

EA-XX-125BZ-350

Narrow high-resistance pattern with compact geometry.

2X

EA-XX-125RA-120

General-purpose 3-element 45° rectangular rosette. Compact geometry.

CEA-XX-125UR-120
CEA-XX-125UR-350

General-purpose 45° single-plane rosette. Compact geometry. Exposed tab area is 0.08 x 0.06 in *(2.0 x 1.5 mm)*.

EA-XX-125TM-120

General-purpose 2-element 90° 'tee' rosette. Sections are electrically independent.

CEA-XX-125UT-120
CEA-XX-125UT-350

2-element 90° 'tee' rosette for general-purpose use. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

EA-XX-125TK-350

High-resistance 2-element 90° gage for torque applications.

GAGE DESIGNATION AND PATTERN

CEA-XX-187UV-120
CEA-XX-187UV-350

2-element 90° rosette for torque and shear-strain measurements. Sections have a common electrical connection. Exposed tab area is 0.13 x 0.08 in *(3.3 x 2.0 mm)*.

EA-XX-250AE-350

Large general-purpose gage. Used when high power-dissipation is required.

EA-XX-250AF-120

Large general-purpose gage. Used when high power dissipation is required.

EA-XX-250BG-120
EP-08-250BG-120
WA-XX-250BG-120
WK-XX-250BG-350

Widely used general-purpose pattern. EP Series capable of elongation > 20%.

EA-XX-250BF-350

General-purpose pattern with high-resistance grid. Compact geometry. Similar to 250BG pattern except for resistance.

CEA-XX-250UN-120
CEA-XX-250UN-350

Narrow general-purpose gage pattern. Exposed tab area is 0.08 x 0.05 in *(2.0 x 1.1 mm)*.

CEA-XX-250UW-120
CEA-XX-250UW-350

Larger grid and tab than 250UN pattern. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

GAGE DESIGNATION AND PATTERN

EA-XX-250BK-10C

Very high-resistance (1000Ω) pattern. Recommended for high bridge voltages or for use on plastics.

CEA-06-W250A-120
CEA-06-W250A-350

Lowest-cost, most flexible and conformable linear weldable gage pattern. See page 8 for more details.

CEA-XX-250UR-120
CEA-XX-250UR-350

Large 3-element 45° single-plane rosette. Exposed tab area is 0.13 x 0.08 in *(3.3 x 2.0 mm)*.

EA-XX-500BH-120

Long general-purpose gage in a compact geometry.

CEA-XX-500UW-120

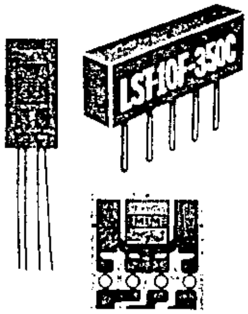
Widely used long gage pattern. Exposed tab area is 0.10 x 0.07 in *(2.5 x 1.8 mm)*.

Special-Purpose Gages, Sensors, and Equipment

In addition to providing the stress analyst with a vast selection of standard strain gage types, Micro-Measurements offers a variety of products designed to meet special needs and perform special functions in experimental stress analysis. Although space in this introductory catalog permits neither a full listing of these products, nor complete descriptions, a few types of special sensors are briefly noted.

Full information on any of these products, along with detailed technical specifications, can be obtained by requesting Catalog 500, or by contacting the Measurements Group's Applications Engineering Department.

Temperature Sensors



TG Temperature Sensors, with a grid of ultra-pure nickel foil, are recommended for general-purpose temperature measurement from −320° to +500°F *(−195° to +260°C)*. For application at extremely low temperatures, two alloys — nickel and manganin — are combined to produce the CLTS-2B (cryogenic linear temperature sensor). The duplex construction of this sensor results in an essentially linear change of overall resistance with temperature, from −452° to +100°F *(−269° to +40°C)*.

Reusable LST matching networks are available for half-bridge connection of temperature sensors to strain indicators. With these accessories, the strain indicator registers temperature directly, at a scale factor of 10 or 100 microstrain per °F or °C.

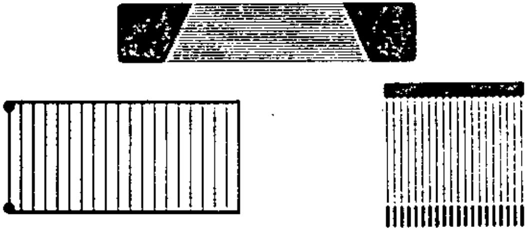
Crack Detection

CD-Series Crack Detection Gages are designed to provide a convenient, economical method of indicating the presence of a crack, or indicating when a crack has progressed to a predetermined location on a test part or structure. By employing several CD gages, it is also possible to monitor the rate of crack growth.

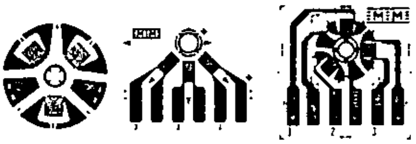
Crack detection gages are available with various strand lengths; from 0.4 to 2.0 in *(10 to 50 mm)*.

Crack Propagation

Crack Propagation Gages accurately indicate rate of crack propagation in a specimen material over a very small distance. These sensors are often used adjacent to notches, fillets, or other types of discontinuities in structures. Several sizes and geometries are available.



Strain Gages for Residual Stress Determination



EA Series **CEA Series** **TEA Series**

approximately 2X actual size

The most widely used practical technique for measuring residual stresses is the hole-drilling strain gage method described in ASTM Standard E837. With this method, a specially configured electrical resistance strain gage rosette is bonded to the surface of the test object, and a small, shallow hole is introduced through the center of the gage, using a precision drilling apparatus such as the Measurements Group's RS-200 Milling Guide. After drilling, the strain in the immediate vicinity of the hole is measured, and the relaxed residual stresses are computed from these measurements.

For further details, request Bulletin 304.

Weldable Strain Gages and Temperature Sensors

Weldable gages are precision foil sensors bonded to a metal carrier for spot welding to structures and components. These sensors are easy to install and require minimal surface preparation. Installation is accomplished without adhesives, eliminating heat curing problems on massive structures. They are also well suited to laboratory test programs requiring elevated-temperature testing and minimal installation time.

SPECIFICATIONS

Sensor	Standard S-T-C	Resistance In Ohms	Gage Factor	Temperature Range
CEA	06,09	120 ± 0.4% 350 ± 0.4%	2.0	-100° to +200°F *(-75° to +95°C)*
LWK	06,09	350 ± 0.4%	2.1	-320° to +500°F *(-195° to +260°C)*
WWT	N/A	50 ± 0.4% @ +75°F *(+24°C)*	N/A	-320° to +500°F *(-195° to +260°C)*

SENSOR DESCRIPTIONS

CEA-Series Weldable Strain Gage: Constantan alloy sensing grid completely encapsulated in polyimide. Very flexible. In most cases can be contoured to radii as small as 1/2 in *(13 mm)*. Rugged, copper-coated tabs for convenient leadwire attachment.

W250A

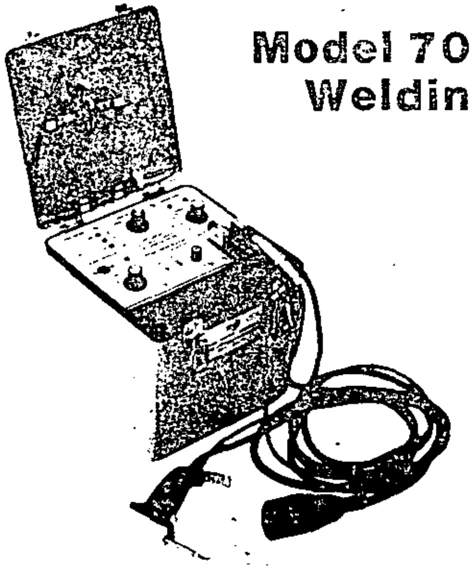
LWK-Series Weldable Strain Gage: Modified Karma (K-alloy) sensing grid completely encapsulated in a fiberglass-reinforced epoxy-phenolic matrix. Integral three-wire lead system consists of 10 in *(250 mm)* flexible etched Teflon®-insulated leadwires. Installation radius generally limited to 2 in *(50 mm)* or larger in the direction of the grid axis.

W250B

WWT-Series Weldable Temperature Sensor: High-purity nickel sensing grid completely encapsulated in a fiberglass-reinforced epoxy-phenolic matrix. Integral three-tab printed circuit terminals for convenient leadwire attachment.

W200B

®Registered Trademark of DuPont



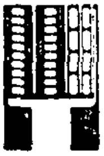
Model 700 Portable Strain Gage Welding and Soldering Unit

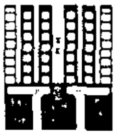
The Model 700 is a completely portable, capacitance-discharge spot welder, designed for efficient installation of weldable strain gages and temperature sensors. Supplied in a rugged, gasketed case, the battery-powered unit can be used under field conditions where no power lines are available.

A temperature-controlled soldering pencil, operated from the main battery supply, is an integral part of the Model 700. The lightweight pencil can be adjusted to a wide range of tip temperatures for both gage soldering and leadwire splicing.

For further details, request Bulletin 302.

Bondable Resistors





Micro-Measurements manufactures a variety of fixed, adjustable, and combination bondable resistors for use in many applications where precise resistance is required. Appropriate patterns are available in both low and high temperature-coefficient-of-resistance types. Widest use is in transducer bridge circuits to compensate for small temperature-induced errors and to adjust bridge balance.

Various alloys, sizes, and patterns are available, allowing selection of the optimum resistor for specific applications. Resistors are normally produced open-faced on a polyimide carrier. The recommended temperature range is from 0° to +300°F *(-20° to +175°C). For further details, request Transducer-Class Catalog TC-116.*

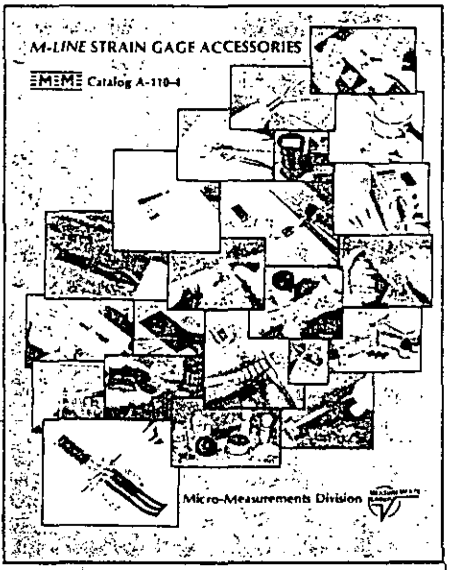
Micro-Measurements Strain Gage Accessories

Micro-Measurements strain gages are produced under rigidly controlled manufacturing conditions, with the utmost care and attention given to ensuring the high level of quality and precision for which these gages have gained world-wide recognition. However, the gages' full potential for accurate strain measurement can be realized only when they are properly installed. There are, in fact, three principal components in every strain gage installation: (1) the strain gage itself, (2) the tools, materials, and supplies (accessories) needed to install the gage, and (3) the techniques employed in performing the installation. Professional stress analysts have learned from experience that compromising any of these may lead to compromising the quality of the installation and the accuracy of the strain data.

The well-established formula for making consistently successful strain gage installations is quite simple:

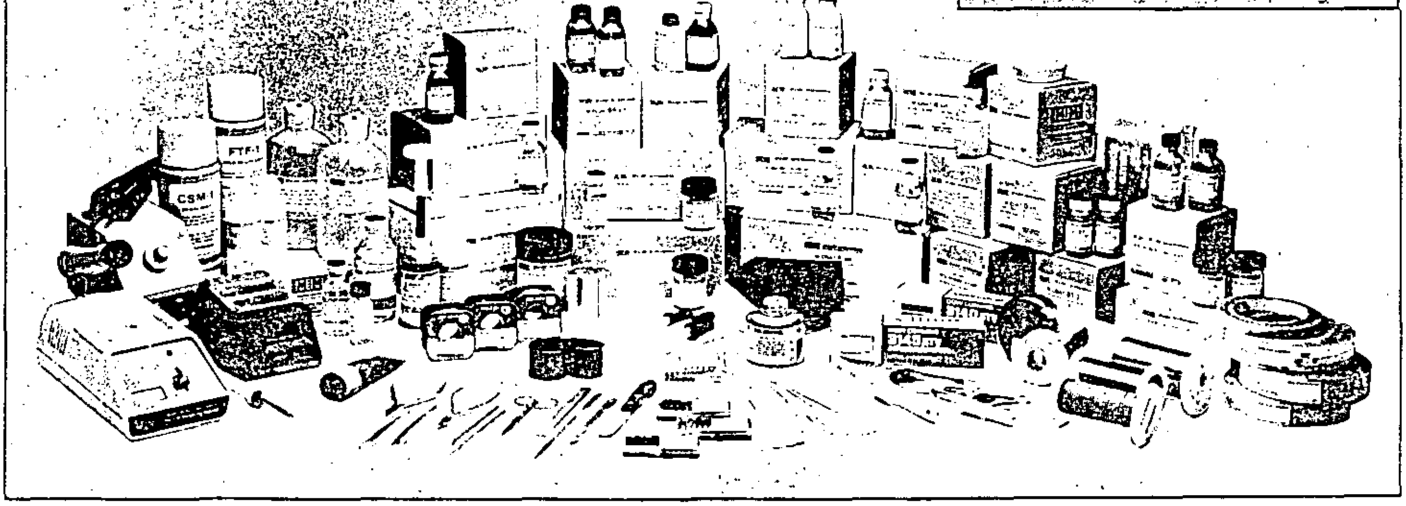
- select high-quality precision strain gages.
- select professional-caliber accessories which have been laboratory-tested and field-proven for effectiveness and compatibility with the strain gages.
- follow the installation procedures recommended by the manufacturer of the gages and accessories.

Featured on the following two pages is a small sample of Micro-Measurements *M-LINE* strain gage installation accessories. As indicated, the appropriate materials, supplies, and tools are provided for each important step in the gage installation process — from preparing the surface of the test piece to applying a protective coating over the bonded and wired gage. All accessory items, whether manufactured directly by Micro-Measurements or specified for purchase from an outside supplier, are of the highest quality, and have been designed or selected specifically to help ensure successful installation of Micro-Measurements strain gages.



Regular users of strain gages will want to request a copy of Catalog A-110. This 40-page, fully illustrated catalog describes the complete line of gage installation accessories and related equipment. In addition to detailed product descriptions and specifications, it includes, where applicable, extensive recommendations for the appropriate selection and application of the accessories.

Catalog A-110 is available on request from our Applications Engineering Department.

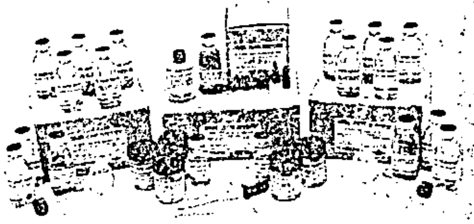


6 Simple Steps To Successful

Surface Preparation

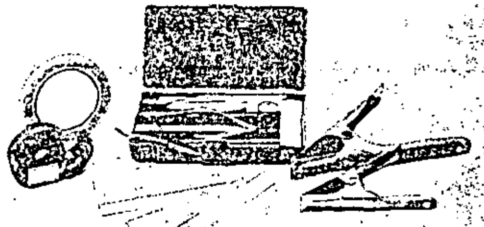
- CSM-1 Degreaser
- M-Prep Conditioner A
- M-Prep Neutralizer 5A
- Silicon-Carbide Paper
- Cotton Swabs
- Gauze Sponges

Adhesive Selection



- M-Bond 200
- M-Bond AE-10
- M-Bond AE-15
- M-Bond 600
- M-Bond 610

Gage Handling and Bonding

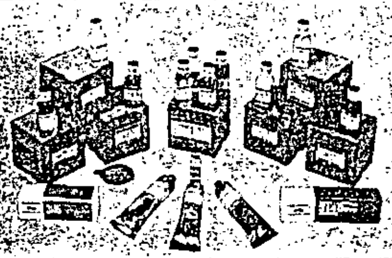


- Cellophane Tape
- Mylar JG Tape
- Spring Clamps
- Teflon Film
- Silicone Rubber
- Application Tools

Leadwire Attachment

- Solder Terminals
- Wires, Cables — Solid, Stranded, Tinned
- Solders
- Soldering Station
- Wiring Tools

Protective Coating Application



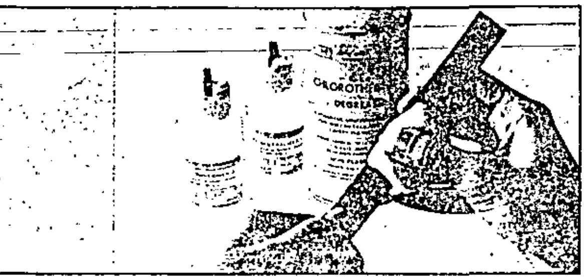
- M-Coat A Polyurethane
- M-Coat B Nitrile Rubber
- M-Coat C Silicone Rubber
- M-Coat D Acrylic
- M-Coat W-1 Microcrystalline Wax

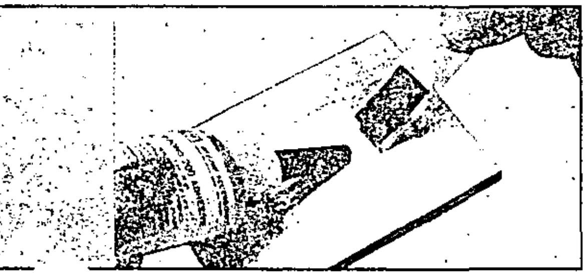
Gage Installation Tester

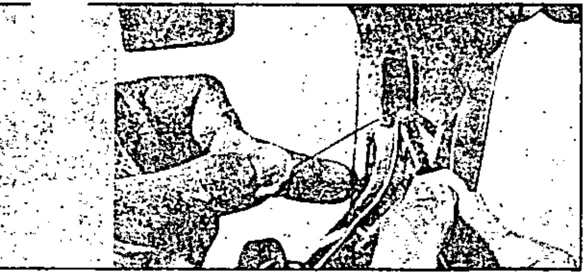
- Reads insulation resistance (leakage) to 20 000 MΩ with 15 Vdc.
- Measures deviation of installed gage resistance from precise standards to a resolution of 0.02%.
- Auxiliary ohmmeter scale for troubleshooting questionable installations.
- Reads with the push of a button.
- Verifies the complete gage circuit including leadwires.

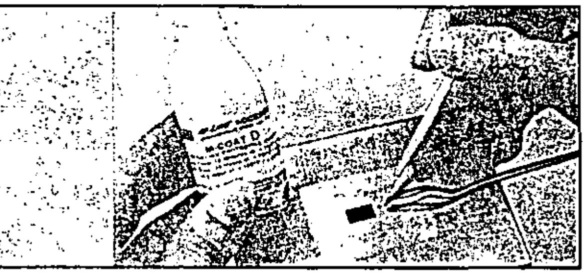
. . . With *M-LINE* Accessories

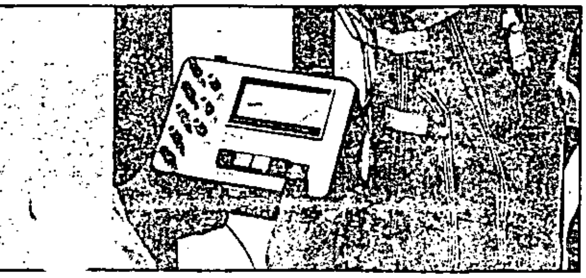
Strain Gage Installations . . .



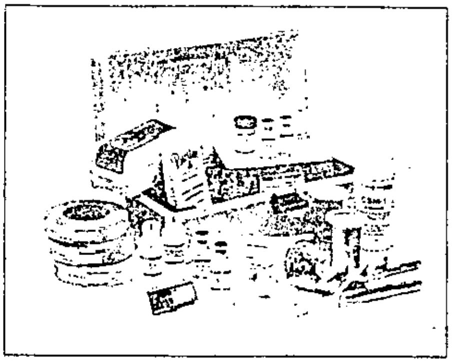








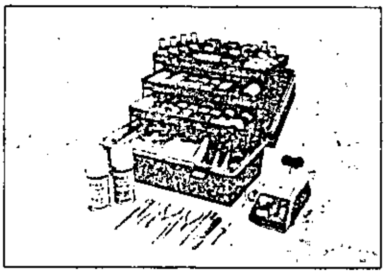
General Application Kits



It is often of greatest convenience for the strain gage user to purchase all of the needed accessory supplies and materials in a single package.

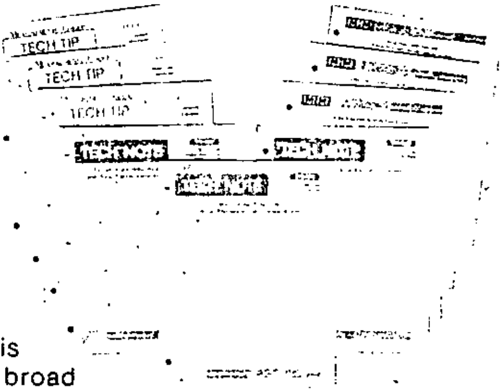
GAK-2 Series Kits provide specific selections of *M-LINE* accessories for making basic strain gage installations with the M-Bond 200, AE-10/15, or 610 adhesives.

The ultimate in gage installation capability is provided by the **MAK-1, Master Strain Gage Application Kit.** The MAK-1 includes all of the supplies and special tools necessary for making a wide range of gage installations for both laboratory and field applications.



Instructional Materials

Because technique is such an important ingredient in successful strain gage installation, detailed **Instruction Bulletins** have been prepared for virtually all Micro-Measurements strain gage installation products.



In addition, a library of **Tech Notes** and **Tech Tips** is available for reference on a broad range of subjects within Strain Gage Technology.

Tech Tips present practical strain gage application techniques for "out-of-the-ordinary" situations, and represent, as much as possible, a practical "how-to" approach to strain gage installation.

Tech Notes contain in-depth technical treatments of specific subjects having direct or indirect bearing on the successful application of stress/strain measurement technology.

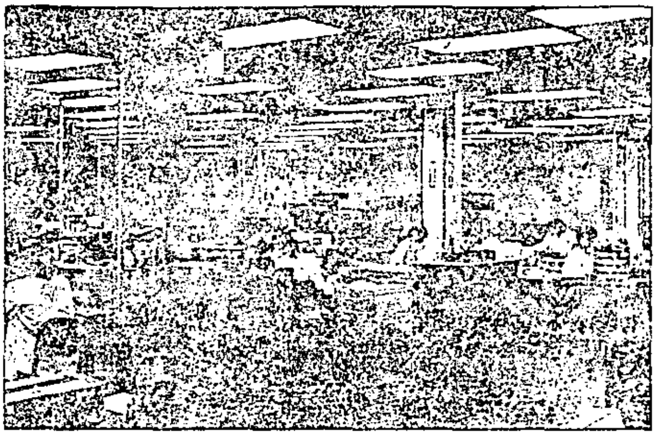
— Lab-Tested — Field-Proven

Ordering Information

All Micro-Measurements products shown in this catalog can be ordered from the accompanying price list.

The Measurements Group Order Service Department can provide immediate stock and delivery information. Most products are available for same-day shipment or can be produced on short delivery cycles. Measurements Group, Inc. maintains regional sales representatives throughout the world to further assist you. For additional information on any of our product lines, contact us or our representative serving your area.

Quantity discounts are available on strain gages and special sensors. All other items are sold on a net basis only. All prices are subject to change without notice.



Micro-Measurements Warranty Policy

The Micro-Measurements Division of Measurements Group, Inc., warrants that the products sold under its name, are fit for the purpose for which they were intended by the supplier and guarantees said items against defects in workmanship or material for a period of ninety (90) days, or otherwise specified limits, from date of delivery. Every reported case of non-standard material is thoroughly investigated by our Quality Assurance Department. It should be recognized that there is no method to 100% test our type of products since many tests would be destructive. Both Micro-Measurements and the purchasers must depend upon statistical sampling techniques that have in the past proved to be reliable and economical in respect to the cost of the product.

This warranty is in lieu of any other warranties, expressed or implied, including any implied warranties of merchantability or fitness for a particular purpose. There are no warranties which extend beyond the description on the face hereof. Purchaser acknowledges that all goods purchased from Measurements Group are purchased as is, and buyer states that no salesman, agent, employee or other person has made any such representations or warranties or otherwise assumed for Measurements Group any liability in connection with the sale of any goods to the Purchaser. Buyer hereby waives all rights buyer may have arising out of any breach of contract or breach of warranty on the part of Measurements Group, to any incidental or consequential damages, including but not limited to damages to property, damages for injury to the person, damages for loss of use, loss of time, loss of profits or income, or loss resulting from personal injury.

Some states do not allow the exclusion or limitation of incidental or consequential damages for consumer products, so the above limitations or exclusions may not apply to you.

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Bulletin 251-A

2300 SYSTEM

SIGNAL CONDITIONING AMPLIFIER

A versatile, multi-channel, dynamic instrumentation system that generates high-level signals from strain gages (or strain gage based transducers) for display or recording of data on external equipment.

MEASUREMENTS GROUP
VISHAY

Sophisticated / Uncomplicated

The 2300 Signal Conditioning Amplifier System combines the latest in electronic sophistication with simplicity in setup and operation

The 2300 System conditions and amplifies low-level signals to high-level outputs for multiple-channel, simultaneous dynamic recording or display on external devices.

Among its advanced features, each 2310/2311 Module includes a built-in power supply, active filtering, three simultaneous outputs, playback mode, wide frequency response, and electronic bridge balance. Socket-mounted integrated circuits and discrete components achieve the demanding specifications listed while providing ease of serviceability.

Up to ten 2310/2311 Modules can be mounted in a Model 2350 Rack Adapter; or up to four modules in a Model 2360 Portable Enclosure; or, a single 2310/2311 can serve as a stand-alone unit.

While the Model 2311 provides wider frequency response and more versatile excitation, the basic 2310 and 2311 Signal Conditioner/Amplifier Modules accept inputs from strain gages, load/pressure/dc displacement transducers, potentiometers, thermocouples (with Model 1611 Adapter), RTD's and nickel temperature sensors, without any internal modification.

Controls on the 2310/2311 are arranged in sections, permitting easy setup. Clearly marked push-button and single-purpose switches minimize the possibility of operator error during use. With the exception of the playback switch, all operational and monitor controls are on the front panel. Switches for selecting remote sense and specific shunt calibration configurations are located on the printed circuit board inside the unit.

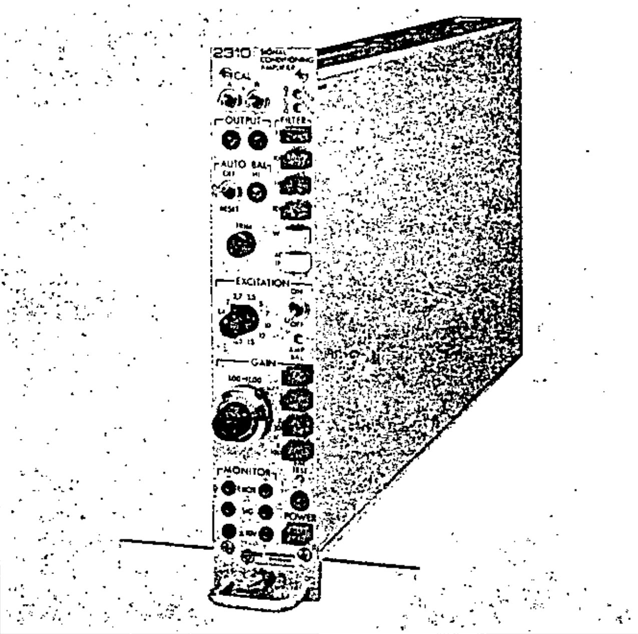
Typical 2300 System configurations are shown on the facing page. The operating features of the basic 2310 and 2311 Modules (shown actual size) are illustrated and described on pages 4 and 5. Complete specifications are given on page 7.

Features

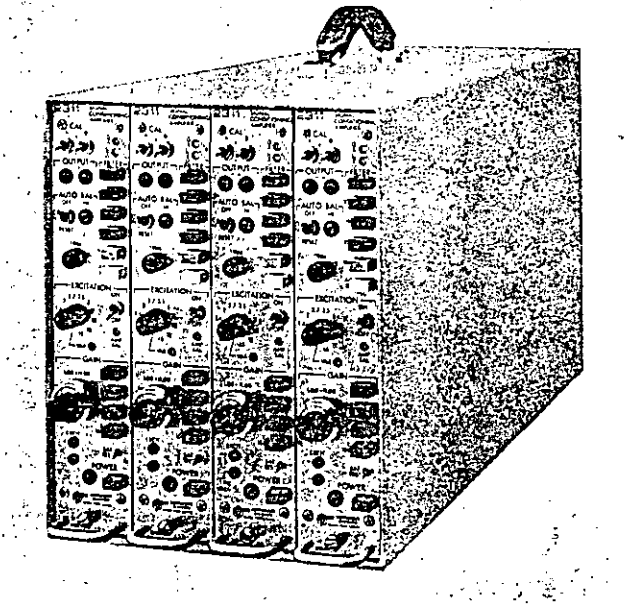
- **Selectable bridge excitation, 0.5 to 15 Vdc (0.3 to 15 Vdc for Model 2311).**
- **Fully adjustable calibrated gain from 1 to 11 000.**
- **Dual-range (±5000 and ±25 000$\mu\epsilon$) automatic bridge balance, with "keep-alive" power to preserve balance for months without external power.**
- **All bridge completion built in, including 120 and 350 ohm dummies.**
- **Dual polarity, two-step double-shunt calibration.**
- **Bandpass:**
  - **2310: 25 kHz (-0.5 dB)**
  - **65 kHz (-3.0 dB)**
  - **2311: 50 kHz (-0.5 dB)**
  - **125 kHz (-3.0 dB).**
- **Switchable active filter — up to six poles.**
- **Three simultaneous buffered outputs.**
- **Playback mode to filter and observe or re-record previously recorded magnetic tape data.**
- **Input impedance above 10 megohms at all times.**

Configurations

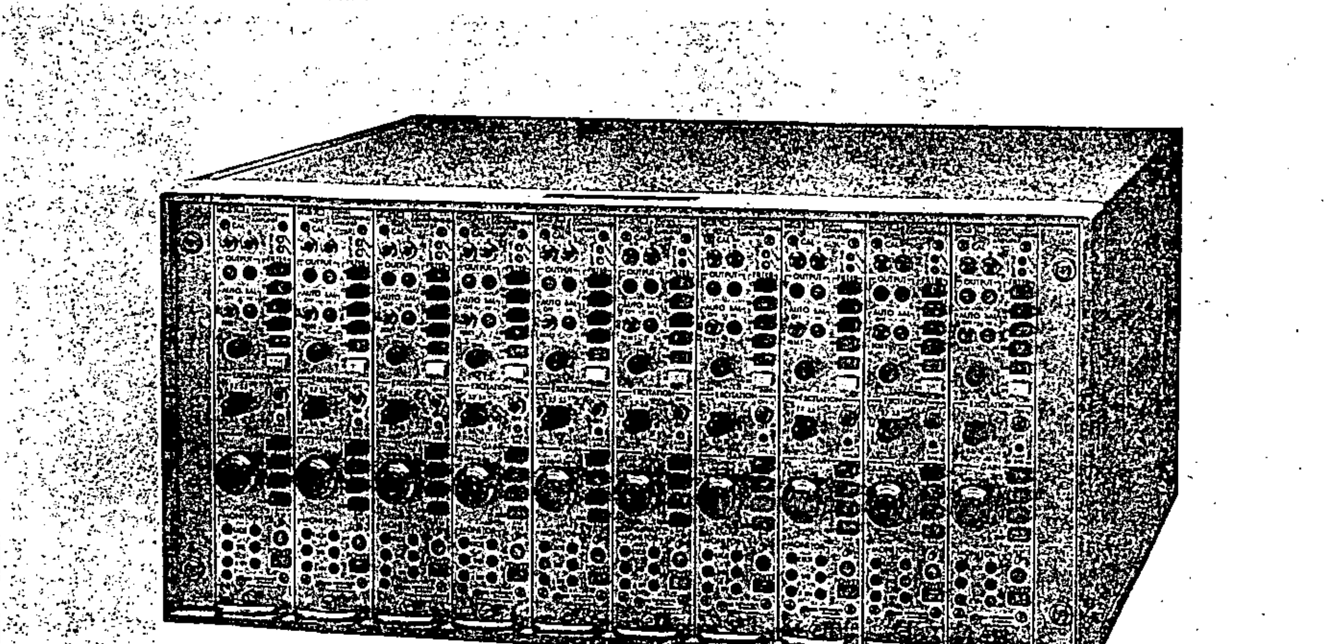
The 2310/2311 Amplifier Modules can be used as stand-alone, single-channel instruments, or can be configured into racks for multi-channel testing.



Stand-alone, single-channel instrument used with the Model 2310-A20 line cord and stabilizer bar accessory package.

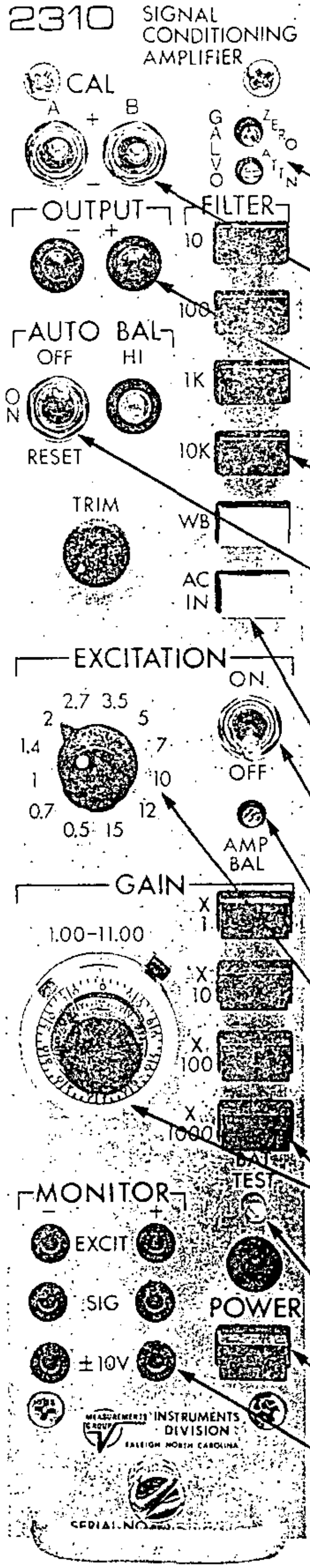


Model 2360 Portable Enclosure includes all ac wiring. Accepts up to four amplifier modules.



Ten-Channel System (including Model 2350 Rack Adapter) shown with the Model 2355 Enclosure. The Model 2350 Rack Adapter fits standard 19-in *(483-mm)* electronic equipment rack. All wiring is built-in to accept adjacent ten-channel systems.

Front-Panel Controls



Shown actual size

The principal differences between the 2310 and 2311 amplifiers are the 2311's wider frequency response and broader range of excitation settings. See specifications on page 7.

GALVANOMETER: Electronic adjustment for zero positioning and span of the galvanometer, remote from recorder.

CALIBRATION: Momentary two-position switches, ±A and ±B, control shunt calibration levels; 4 point.

LED DISPLAY: Set up indicator for amplifier balance, bridge balance and for monitoring the output level.

FILTER SECTION: Push-button controls for activating appropriate low-pass active filter, or selecting wide-band operation (WB).

ELECTRONIC BRIDGE BALANCE SECTION: Three-position switch — OFF, ON, RESET — for electronic bridge balance; auto ranging up to ±25 000$\mu\epsilon$ with nonvolatile zero storage; yellow light indicates high-range operation or overrange condition. Vernier TRIM control is used to refine bridge balance when desired.

AC IN: Capacitive coupling in the amplifier; eliminates static component of the signal.

BRIDGE EXCITATION: ON-OFF switch for removing bridge excitation from the strain gage or transducer.

AMPLIFIER BALANCE: Adjusts any amplifier offset.

EXCITATION LEVEL: Twelve-position switch; values arranged for doubling power with each step.

2311 — Same as 2310 except 0.5 replaced by variable setting: 0.3 to 6 Vdc.

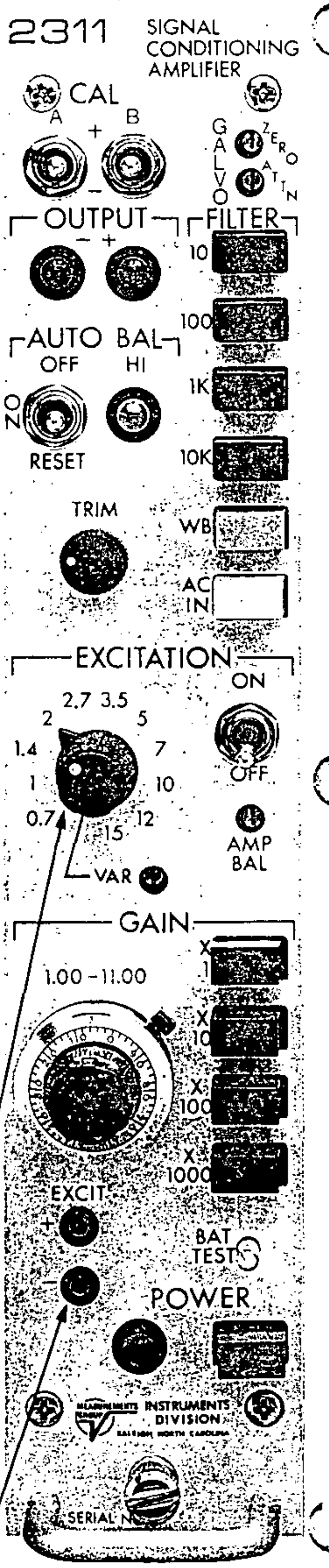
AMPLIFIER GAIN SECTION: Continuously variable potentiometer (1.00 to 11.00) plus push-button multipliers control amplifier gain; direct-reading.

BATTERY TEST: Momentary push button determines battery level for bridge zero storage.

MAIN POWER: Turns unit on/off; LED pilot light.

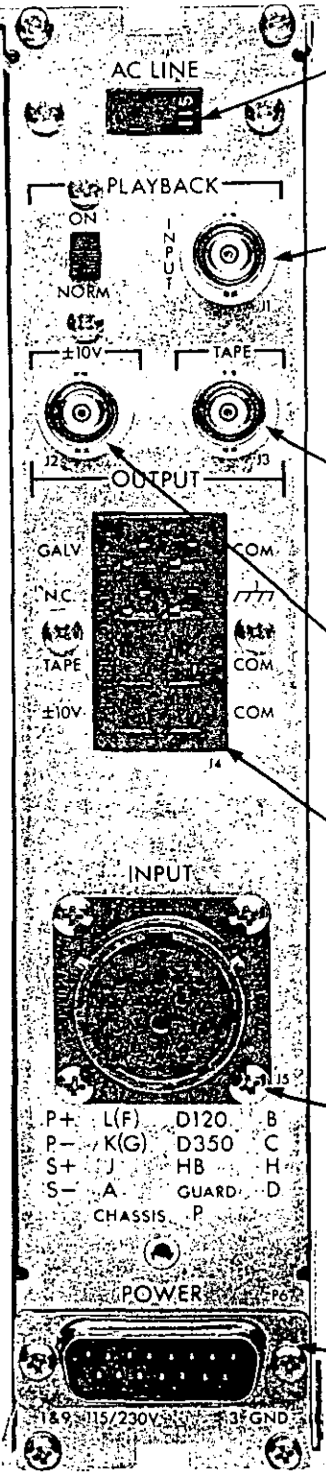
PIN JACKS: Monitoring of EXCITATION, UNAMPLIFIED INPUT, AMPLIFIED OUTPUT.

Excitation pin jacks only for Model 2311.



Shown actual size

Back-Panel Controls — 2310/2311



Shown actual size

AC LINE SWITCH: Selects nominal 115 or 230 Vac operation. Recessed to eliminate inadvertent movement.

TAPE PLAYBACK SECTION: Slide switch activates magnetic tape-playback operating mode. Connects the input to the filter circuits and post amplifiers. BNC input connector.

MAGNETIC TAPE OUTPUT: Full-scale ±1.4V level available at this BNC connector for driving magnetic tape recorder.

HIGH-LEVEL OUTPUT: Full-scale ±10V level available at this BNC connector for driving an oscilloscope, DPM, etc.

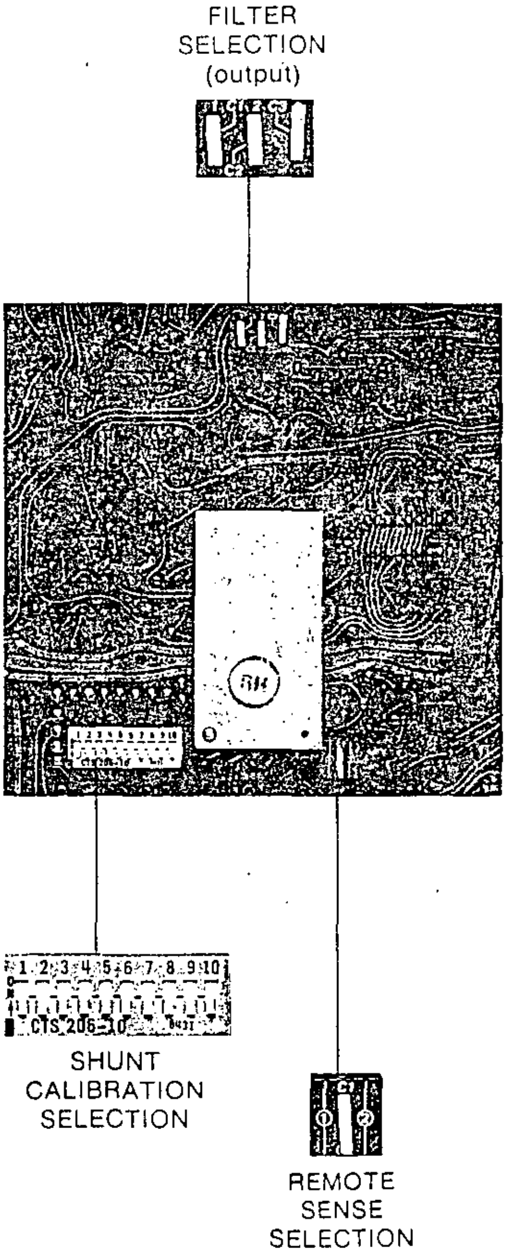
OUTPUT RECEPTACLE: All three outputs available at this connector for those who prefer to hard wire their connections *(mating plug included)*. Outputs are 75 mA for galvanometers, ±1.4V, and ±10V.

INPUT RECEPTACLE: All sensor inputs made through this 15-pin quarter-turn connector. Pin selection determines mode of operation *(mating plug included)*.

POWER CONNECTOR: Main power input from the rack adapter, portable enclosure or individual line plug. Additional pins for optional remote operation of shunt calibration, bridge excitation (ON/OFF), and electronic bridge balance.

PC-Board Controls

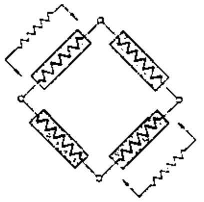
Conveniently located switches on the printed circuit board permit easy setup for filtering of outputs, shunt calibration, and remote sense selection.



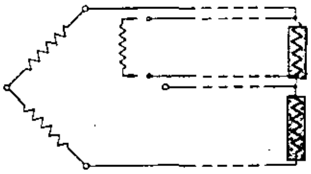
Technical Notes

CALIBRATION

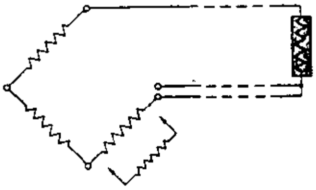
The shunt calibration technique is customarily used to calibrate and introduce gage factor into the system. Two front-panel switches, A and B, activate two pairs of fixed resistors mounted in sockets on the printed circuit (PC) board. These are the shunt calibration resistors, and their values determine the calibration levels. Additionally, a multiple switch assembly on the PC board controls which Wheatstone bridge arm(s) is being shunted, and selects local or remote wiring to these arms. Multiple shunt configurations are possible by simply moving the selector switches — rewiring is not necessary. The specific test conditions dictate the best configuration. Several of the more important configurations are illustrated below:



FULL BRIDGE: Double shunt; recommended for high-accuracy transducer applications.

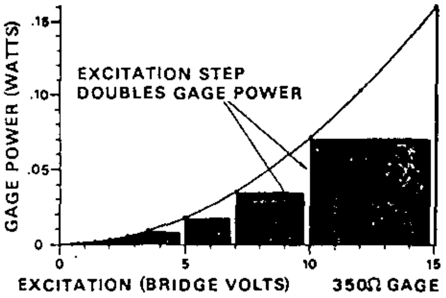


HALF BRIDGE: Shunt active gage with dedicated leads; used on some transducers and some stress analysis applications; eliminates leadwire influences on calibration.



QUARTER BRIDGE: Shunt dummy gage; recommended for stress analysis applications to compensate for leadwire desensitization.

EXCITATION



Power dissipation is an important consideration for obtaining optimum stability and performance from strain gages, strain gage based transducers and similar devices.

The excitation steps on the 2310/2311 have been carefully chosen and arranged to provide power doubling with each step, starting with an extremely low excitation. The power-versus-voltage graph illustrates this important feature. The step excitation switch allows quick and certain repositioning of the excitation level; and, in combination with a continuously variable gain, provides excellent measurement flexibility.

REMOTE SENSE: Serious full-bridge measurement inaccuracies can be caused by voltage losses due to cable resistance and variations of that resistance. To minimize this problem the 2310/2311 is equipped with a REMOTE SENSE feature. When used, it automatically senses the voltage at the transducer and regulates the voltage of the power supply to achieve the preset level at the transducer.

OPTION Y — REMOTE OPERATION: Remote calibration by external command is an optional feature for the 2300 System. This option adds six internal relays enabling the user to remotely operate: Shunt Calibration (+A, -A, +B, and -B), Auto Balance Reset, and Bridge Excitation ON/OFF (to check amplifier balance).

For single-channel applications, the internal power supply may be used to energize these relays. More than one 2310/2311 can be operated with a single set of switches (or external relays); an external 5 Vdc power supply is required (250 mA for each ten channels). If Option Y is specified for the 2310/2311, it must also be specified for the accompanying Rack Adapter (2350), or Portable Enclosure (2360), to ensure that the necessary internal cabling, receptacle and mating connector are supplied.

ELECTRONIC BRIDGE BALANCE

Setting the initial test condition to zero output (balance) is normally done before each test. With the 2310/2311, balance is automatically achieved by pushing the momentary switch to the RESET position. The OFF position disables the auto balance circuit.

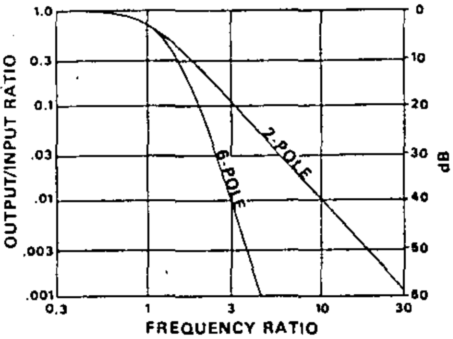
The voltage injection technique is used to set zero. With this technique a voltage is generated which is essentially equal (but of opposite sign) to the unbalanced bridge output; this voltage is injected into the amplifier to produce zero net output voltage. The main advantage of this technique over the conventional potentiometer-resistive-balance method is that it does not load the bridge — a necessary requirement for accurate full-bridge operation and good common-mode rejection. The injection voltage, although analog in form, is digitally generated and digitally stored. Internal batteries preserve the zero when the main power to the unit is interrupted or turned off.

When balance cannot be achieved on the low range, the 2310/2311 will auto range to the high range, which is indicated by a steady yellow panel light. The high range provides greater range with less resolution.

Although not normally used, a TRIM control is provided for that demanding measurement where zero must be precisely set.

Balance by external command is an optional feature.

FILTERING



When the measurement does not require the full bandwidth, a built-in low-pass filter can be used to suppress high-frequency components of the input signal. The standard 2310/2311 has a two-pole low-pass active Butterworth filter with selectable frequencies. Greater suppression above the cutoff frequency can be obtained by specifying Option V. This option increases the standard two-pole filter to a four- or six-pole filter with characteristics similar to the Butterworth.

A graph illustrating the roll-off characteristics of the 2- and 6-pole filters is shown.

Push buttons control the cutoff frequency, while the wide band (WB) position allows the amplifier to operate at its fullest capacity.

The ac position is used to eliminate the static (dc) component of the signal and pass only the dynamic component. In this circuit configuration, the amplifier is capacitively coupled after the preamplifier.

Specifications

2310/2311 SIGNAL CONDITIONING AMPLIFIER

INPUT

Strain Gages: Quarter (120 and 350Ω), half or full bridge (50 to 1000Ω). Dummy resistors installed.

Transducers: Foil or piezoresistive strain gage types.

Potentiometer.

DCDT displacement transducer.

EXCITATION

2310 — 12 settings: 0.5, 0.7, 1, 1.4, 2, 2.7, 3.5, 5, 7, 10, 12 and 15 Vdc ±1%, max.

2311 — Same as 2310 except 0.5 replaced by variable setting: 0.3 to 6 Vdc.

Current: 0-100 mA, limited at 175 mA, max.

Regulation (0-100 mA, ±10% line change): ±0.5 mV ±0.04%, max measured at remote sense point. (Local sense: -5 mV, typical, @ 100 mA, measured at plug.)

Remote Sense Error: 0.0005%/Ω of lead resistance (350Ω load).

Noise and Ripple: 0.05% p-p, max (dc to 10 kHz).

Stability: 0.02%/°C.

Level: Normally symmetrical about ground; either side can be grounded with no effect on performance.

BRIDGE BALANCE

Method: Counter-emf injection at preamp; automatic electronic; dual range; can be disabled on front panel.

Ranges (auto ranging):
 ±5000µε (1% bridge unbalance or 2.5 mV/V), resolution 2.5µε (0.0012 mV/V).
 ±25 000µε (5% bridge unbalance or 12.5 mV/V), resolution 12.5µε (0.006 mV/V).

Balance Time: 2 seconds, typical.

Manual Vernier Balance: ±50µε (± 0.025 mV/V).

Interaction: Essentially independent of excitation and amplifier gain.

Storage: Digital; up to 2 years without line power.

SHUNT CALIBRATION

Circuit (2-level, dual polarity):
 Single-shunt (for stress analysis) across any bridge arm, including dummy gage.
 Double-shunt (for transducer) across opposite bridge arms.

Provision for 4 dedicated leads to shunt external arms.

Cal circuit selected by switches on PC board.

Standard Factory-Installed Resistors (±0.1%) Simulate:
 ±200 and ±1000µε @ GF=2 across dummy half bridge;
 +1000µε @ GF=2 across dummy gage (120 and 350Ω);
 ±1 mV/V (double-shunt) for 350Ω transducer.

Remote-Operation Relays (Option Y): 4 relays (plus remote-reset relay for bridge balance and relay for excitation on/off). Each requires 10 mA @ 5 Vdc, except excitation on/off 25 mA.

AMPLIFIER

Gain: 1 to 11 000 continuously variable. Direct-reading.
 2310: ±1% max. of reading
  ±0.5% max. of full scale vernier setting.
 2311: ±1% max. of reading.

Ten-turn counting knob (X1 to X11) plus decade multiplier (X1 to X1000).

2310 Frequency Response (all gains >5, full output):
 dc coupled: dc to 25 kHz, -0.5 dB max.
  dc to 65 kHz, -3 dB (typical at 40% output).
 ac coupled: 5 Hz to 25 kHz, -0.5 dB.

2311 Frequency Response (all gains, full output):
 dc coupled: dc to 50 kHz, -0.5 dB max.
  dc to 125 kHz, -3 dB max.
 ac coupled: 1.7 Hz to 125 kHz, -3 dB max.

2311 Frequency Response, Reduced Output (2 Vrms max):
 Bandwidth (-3 dB) @ Gain of: 1-11, 200 kHz; 10-110, 170 kHz; 100-1100, 135 kHz; 1000-11000, 125 kHz.

All Specifications are nominal or typical at +23°C unless noted.

Input Impedance: 100 MΩ, min, differential or common-mode, including bridge balance circuit.

Bias Current: ±50 nA, typical each input.

Source Impedance: 0 to 1000Ω each input.

Common-Mode Voltage: ±10V.

Common-Mode Rejection (gain over X100):
 Shorted input: 100 dB, min, at dc; 90 dB, min, dc to 1 kHz.
 350Ω balanced input: 90 dB, typical, at 1 kHz.

Stability (gain over X100): ±2 µV/°C, max, referred to input (RTI).

Noise (gain over X100, all outputs):
 0.01 to 10 Hz: 1 µV p-p RTI.
 0.5 Hz to 125 kHz: 5 µVrms, max, RTI.

FILTER

Characteristic: Low-pass active 2-pole Butterworth standard.

Frequencies (-3 ±1 dB): 10, 100, 1000 and 10 000 Hz and wide-band.

Outputs Filtered: Any 1 or 2 or all (switch-selected on PC board).

NOTE: Consult Applications Engineering Department concerning optional filter characteristics and frequencies.

AMPLIFIER OUTPUTS

Standard Output: ±10V @ 5 mA, min.

Tape Output: ±1.414V (1 Vrms) @ 5 mA, min.

Galvanometer Output: ±10V at 75 mA, min, current-limited at 100 mA, max (minimum load resistance for 0.05% linearity: 50Ω).

Galvanometer attenuator (0-100%) and zero adjust (±1V) on front panel.

Linearity @ dc: 0.02%.

Any output can be short-circuited with no effect on others.

PLAYBACK

Input: ±1.414V full scale; input impedance 20 kΩ.

Gain: X1 to tape output; X7.07 to standard output.

Filter Selection: As specified above.

Outputs: All three as specified above.

POWER

105 to 125V or 210 to 250V (switch-selected), 50/60 Hz, 10 watts, max.

Keep-Alive Supply (for bridge balance): 2 Eveready S76E or equal. Shelf-life (approx. 2 years).

SIZE & WEIGHT

Panel: 8.75 H x 1.71 W in *(222 x 43.3 mm).*

Case Depth Behind Panel: 15.9 in *(404 mm).*

Weight: 6 lb *(2.7 kg).*

2350 RACK ADAPTER

POWER

2-ft *(0.6-m)* 3-wire line cord; 10-ft *(3-m)* extension cord supplied.

Fuse: 1A size 3AG *(32 x 6.4 dia mm).*

Receptacle to accept line cord from adjacent 2350 Rack Adapter.

Wiring for remote calibration with Option Y.

SIZE & WEIGHT

8.75 H x 19 W x 19.06 D in *(222 x 483 x 484 mm).*

13.5 lb *(6.1 kg).*

2360 PORTABLE ENCLOSURE

POWER

8-ft *(2.4-m)* detachable 3-wire cord.

Fuse: 1/2A size 3AG *(32 x 6.4 dia mm).*

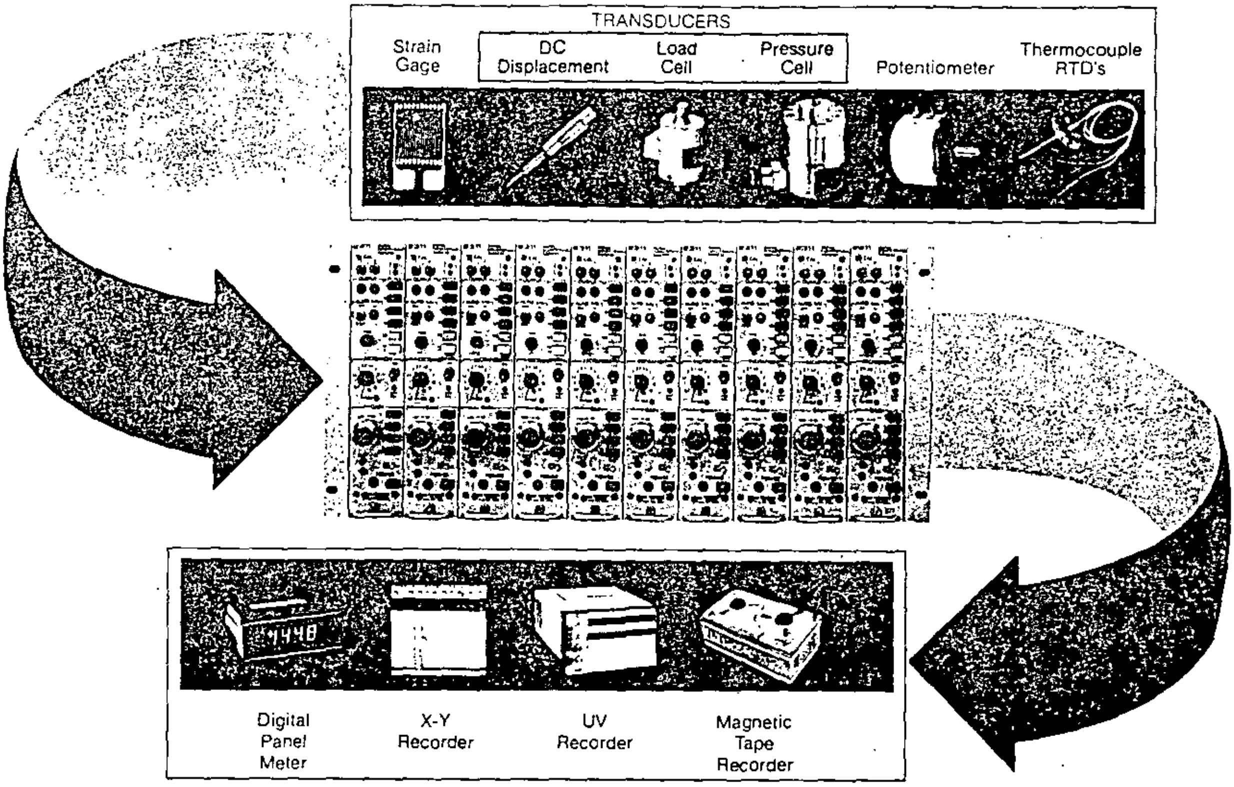
Wiring for remote calibration with Option Y.

SIZE & WEIGHT

9.06 H x 7.20 W x 18.90 D in *(229 x 183 x 480 mm).*

6.75 lb *(3.1 kg).*

2300 System with I/O Devices



The 2300 System provides better data . . .

A **separate bridge power switch** removes bridge excitation, enabling the operator to detect unwanted signals due to electrical interference and/or noise, thermocouple effects, and shifts of the instrument zero during a long-term test. This feature is an absolute must for dynamic testing, and for validating test results.

The **low temperature coefficient** of the instrument permits large changes in ambient temperature with only minor shifts in instrument zero and span. The **low noise level** allows good resolution of very small signals.

An **individual power supply** for each channel provides the ultimate in channel isolation and eliminates any potential interaction.

Very **low excitation settings** of 0.5, 0.7 and 1 volt allow small strain gages, such as 0.015 in *(0.38 mm)*, to be properly excited without any overpowering or self-heating. Additionally, this feature allows for any special consideration which may be dictated by the test material; for example, poor thermal conductivity normally associated with plastics and composites.

An **electronic balance with LED indication** is used to set the initial test condition to zero output. Balance accuracy is independent of the operator. And the high input impedance (above 10 megohms) of this circuit eliminates any loading of the transducer.

The **bandpass at full output is independent of the gain settings.** This permits the selection of the optimum bridge excitation level and gain setting without being concerned about the obtainable frequency response.

The 10-Hz **filter** position can be used to collect quasi-static data. 60-Hz pick-up is rejected by a 30:1 ratio (2-pole filter). 60-Hz ripple is not present in the recorded data.

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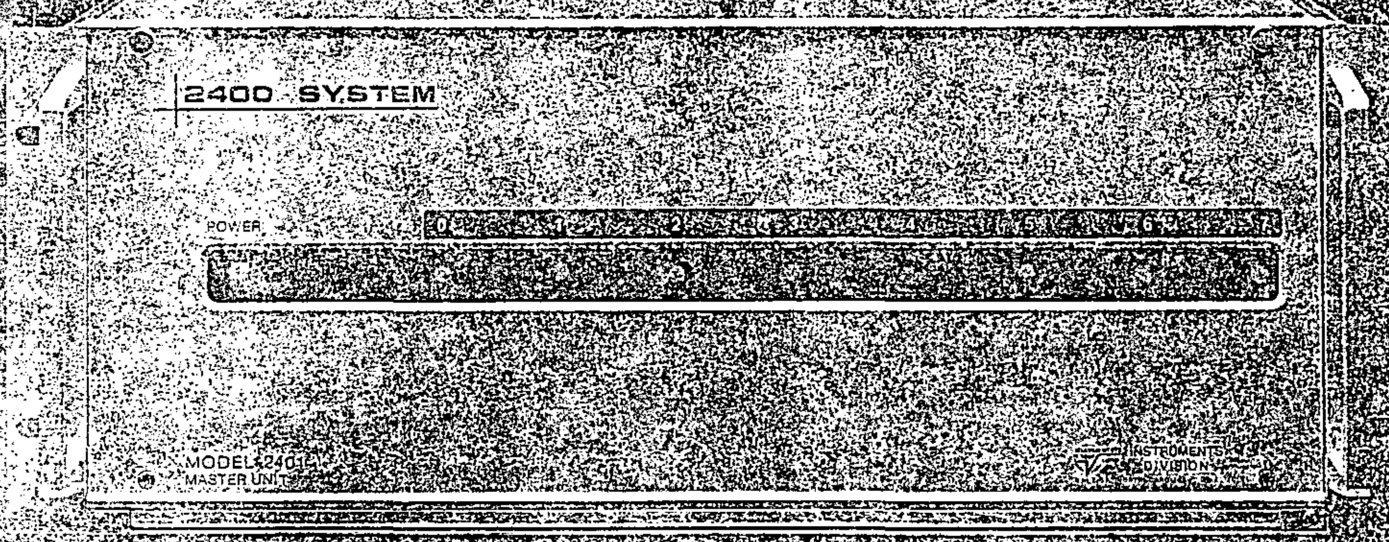
2400 SYSTEM

SIGNAL CONDITIONING AMPLIFIER



A high-performance computer-controlled, dynamic instrumentation system for conditioning and amplification of signals from strain gages and transducers.

MEASUREMENTS GROUP
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2400 SYSTEM

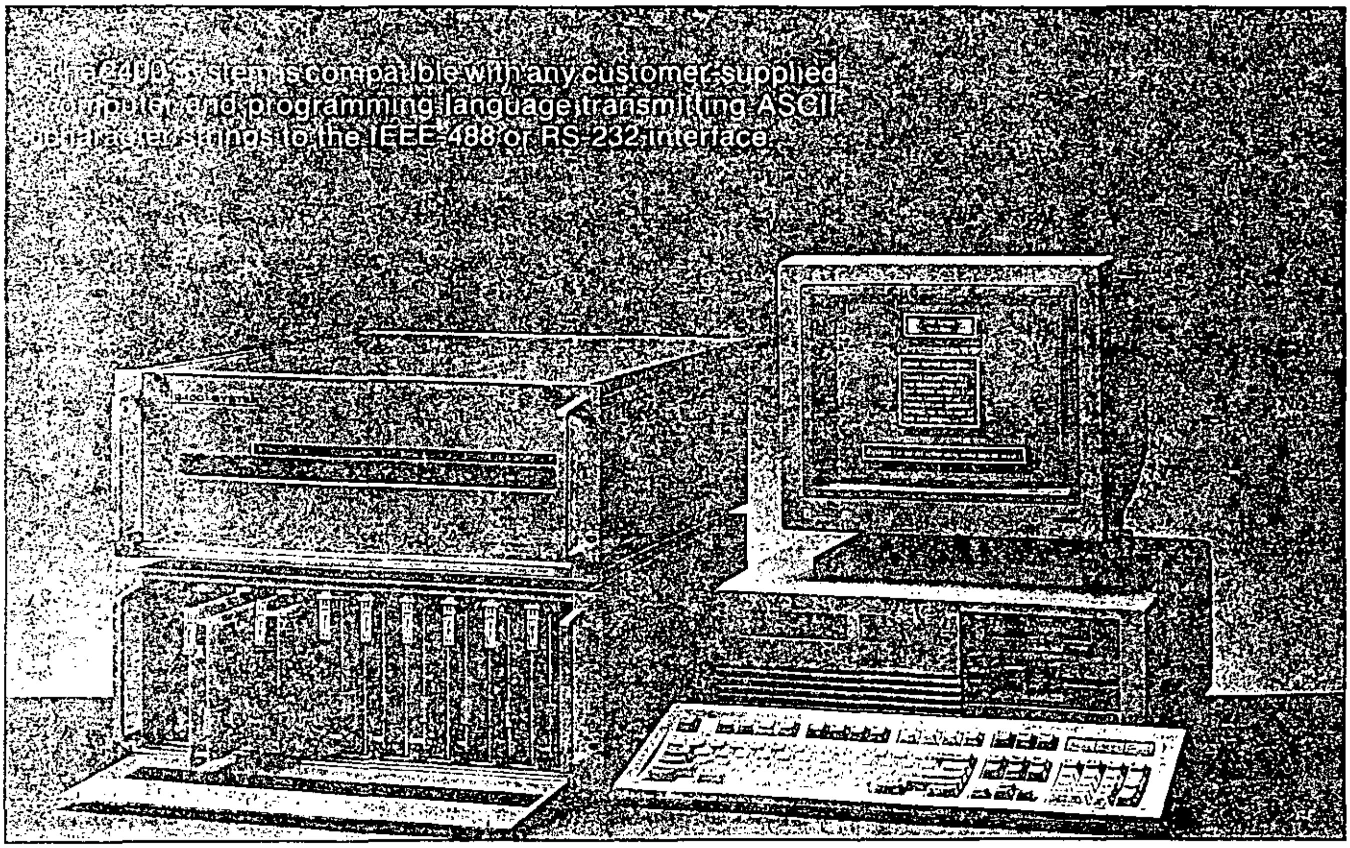
The computer-controlled 2400 Signal Conditioning Amplifier System offers high performance in the most demanding environments

The 2400 Signal Conditioning System incorporates, as standard, all the features necessary for precise conditioning of strain gage and transducer inputs combined with the convenience and speed of computer-controlled setup. The 2400 System allows the user to configure individual signal conditioners from any host computer with an IEEE-488 or RS-232 communications link.

Among the features of the 2410 Amplifier are isolated constant-voltage/constant-current excitation, guarded input structure with ±350V common-mode capability, ±10V and tape outputs, automatic wide-range bridge balance and four-pole Bessel low-pass filters.

A basic system consists of a Model 2401 Master Unit which accommodates up to eight (8) Model 2410 Signal Conditioning Amplifiers. The system may be expanded to 256 channels by adding a Model 2402 Expansion Unit for each additional eight-channel rack. The system may be expanded beyond 256 channels by using an additional IEEE-488 address or RS-232 port.

Each master and expansion unit is housed in a standard 19-in *(483-mm)* rack adapter which occupies 7 in *(178 mm)* of rack space. Attractive panels are supplied with each rack unit for those applications where tabletop mounting is desirable. Expansion units may be separated from the master unit and from succeeding expansion units by up to 100 ft *(30.5 m)*.



The 2400 System is compatible with any customer-supplied computer and programming language transmitting ASCII character strings to the IEEE-488 or RS-232 interface.

Input/output signal, control, and power connectors are mounted on the rear panel of the rack mounting assembly. All mating connectors (except signal output) and power cords are supplied. Installation or removal of individual channel modules is accomplished from the front of the rack without requiring rear access or removal of mating connectors. An optional rack-mounted power control panel is available to provide front-panel access to the power switch.

Programmable functions and status outputs are compatible with the IEEE-488 and/or RS-232 protocols. No additional hardware is required to operate in either mode. Individual channels may be addressed, or an "all-channel" command may be utilized to address every channel simultaneously for fast initial setup.

All programmed functions may be read back from individual signal conditioners at any time without altering any programmed setting.

In addition to the user-selected settings described below, the following flags are provided to enable the operator to easily determine the channel status:

- Excitation ON or OFF
- Autobalance ON or OFF
- Autobalance Range Low or High
- Autobalance Sequence Inrange or Overrange
- Excitation Constant-Voltage or Constant-Current
- Input dc-coupled or ac-coupled
- Addressed Channel Valid or Invalid
- Power Interrupt

A hardware reset capability is provided so that the amplifier will power up with the excitation reduced to zero. This capability guarantees that sensitive strain gages or other input devices will not be damaged by high excitation voltages (or currents). Likewise, a power interruption will cause all programmable functions to reset to the off state and will set the power-interrupt flag.

Features

- **Set-up and monitoring of all channel input parameters from any host computer with IEEE-488 or RS-232 communications link.**
- **Plug-in amplifier design; amplifiers are removable from the master unit without affecting input/output connections.**
- **Programmable constant-voltage or constant-current excitation; 0.25 to 15.75V or 1.0 to 63 mA.**
- **Programmable gain from 1 to 3000.**
- **Electronically injected, automatic wide-range bridge balance with battery backup to retain balance in power-off condition.**
- **Input coupling; hardware selectable ac or dc.**
- **Fully guarded input amplifier; ±350Vdc or peak ac common-mode operating voltage.**
- **Full-power bandwidth of 100 kHz at all gain settings; slew rate of 6.3 V/μsec.**
- **Programmable four-pole Bessel low-pass filters with cutoff frequencies of 1 Hz, 10 Hz, 100 Hz, 1 kHz and 10 kHz.**
- **Two simultaneous buffered outputs; ±10V and tape 1.0 Vrms; will drive up to 0.15 μF without instability.**
- **Stable, proprietary bridge completion module for quarter- and half-bridge 120- and 350-ohm strain gage and transducer circuits.**
- **120-ohm dummy easily configured for 1000-ohm completion.**
- **Built-in programmable shunt calibration circuits; internal user-selectable configurations to provide two-point shunting of any bridge component or two-point double shunt calibration of transducers.**
- **Documented system software commands for maximum flexibility of user programming.**
- **Initial set-up programs provided for system checkout.**

INPUT

Input Impedance:
dc-coupled: 22 MΩ.
ac-coupled: 1.1 μF in series with 20 kΩ;
low frequency cutoff (3 dB) 8 Hz nom.

Source Current: ±10 nA typical; ±20 nA max.

Configuration: 2- to 10-wire plus guard shield to accept quarter-, half-, or full-bridge strain gage or transducer inputs. Internal bridge completion with temperature stability better than 3.0 ppm/°C for dummy 120Ω, 350Ω, and 1000Ω completion gages and internal half bridge. Accepts inputs from ground-referenced or isolated devices.

Differential Input: Maximum differential input voltage of ±30 Vdc or peak ac.

Common-Mode Input: Maximum common-mode input voltage of ±350 Vdc or peak ac.

Guard Impedance: >250 kΩ to output common; >1000 MΩ to power and rack ground.

AMPLIFIER

Gain: 1 to 3000. Coarse Gain Steps X1, X10, X100, X200. Fine Gain 0 to 15, 16 steps incremental. Overall accuracy ±0.2%.

Linearity: ±0.02% of full scale at dc.

Frequency Response:
dc to 100 kHz: 3 ±0.2 dB at all gain settings and full output;
dc to 50 kHz: 0.5 dB max at all gain settings and full output.

Slew Rate: 6.3 V/μsec min at all gain settings.

Noise: (350Ω source impedance, dc-coupled).

Referred-to-Input (RTI):
1 μV 0.1 Hz to 10 Hz p-p;
2 μV 0.1 Hz to 100 Hz p-p;
3 μV 0.1 Hz to 100 kHz rms.

Referred-to-Output (RTO):
FG = fine gain setting
200 μV + (FG x 100 μV) 0.1 Hz to 10 Hz p-p;
500 μV + (FG x 200 μV) 0.1 Hz to 100 Hz p-p;
600 μV + (FG x 300 μV) 0.1 Hz to 100 kHz rms.

Zero Stability: ±2 μV RTI, ±200 μV RTO at constant temp.

Temperature Coefficient of Zero: ±1 μV/°C RTI
±200 μV/°C RTO; -10° to 60°C.

Common-Mode Rejection:

GAIN	CMR (dB)	GAIN	CMR (dB)
X1	82	X100	122
X10	102	X200	128

Common-Mode Voltage: ±350 Vdc or peak ac, max operating.

Standard Output: ±10V @ 10 mA max.

Tape Output: 1.0 Vrms @ 10 mA max.

Output Isolation: Isolated from power and rack ground; >1000 MΩ.

Output Protection: Protected against continuous short.

Capacitive Loading: Up to 0.15 μF.

Filter: Four-pole Bessel low-pass filter with selectable 3 dB bandwidths of 1 Hz, 10 Hz, 100 Hz, 1 kHz and 10 kHz.

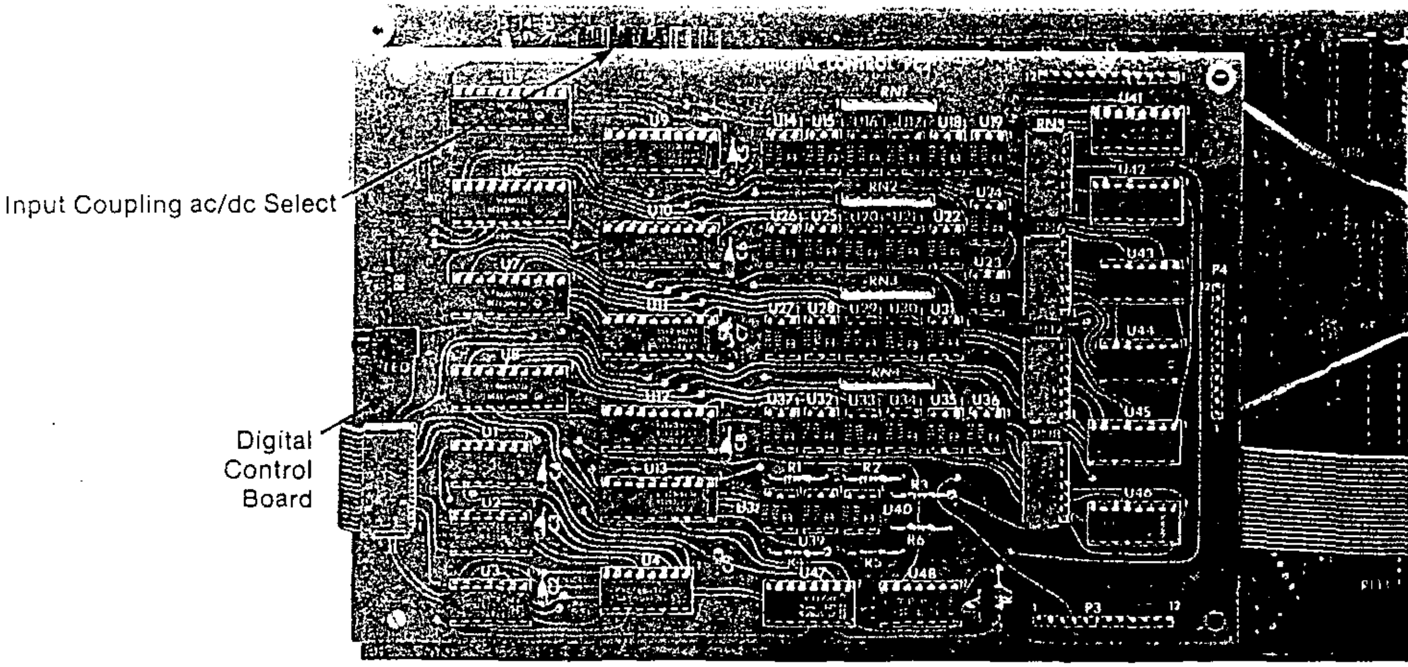
CONSTANT-VOLTAGE EXCITATION

Range: 0.25 to 15.75 Vdc @ 85 mA max, 0.25V increments.

Accuracy: ±0.10% ±5 mV.

Noise: 100 μV ±0.002% p-p dc to 20 kHz.

Line Regulation: ±200 μV ±0.01% max for line voltage change of 10% from nom.



"Piggyback-mounting" of the Model 2410's printed circuit boards affords compac design, yet provides for easy access when internal configuration changes ar required to meet specific test applications.

FICATIONS

Load Regulation: ±200 μV ±0.01% max for load variation of 10% to 90% of full load.

Remote Sense: Excitation error <0.0005%/Ω of lead resistance.

Temperature Stability: ±0.01%/° C.

Monitoring: Front-panel monitoring jacks.

Isolation: Isolated from power ground and output common; floats with Guard.

CONSTANT-CURRENT EXCITATION

Range: 1.00 to 63.0 mA dc. 1.0 mA increments. Compliance voltage 15.75V; max open circuit voltage 21.0V.

Accuracy: ±0.10% ±5 μA.

Noise: (1 μA + 10μV) p-p; dc to 20 kHz.

Line Regulation: ±1 μA ±0.01% max for line voltage change of ±10% from nom.

Load Regulation: ±1 μA ±0.01% max for 100% load change.

Monitoring: Front-panel monitoring jacks.

Isolation: Isolated from power ground and output common; floats with Guard.

Temperature Stability: ±0.01%/° C

AUTOMATIC BALANCE

Method: Electronically injected automatic balance.

Activation: Programmable.

Storage: Digital storage with battery backup. Battery life 2 to 4 years.

Balance Time: 4 seconds typical; 8 seconds max.

Range: ±15 000με (7.5 mV/V) RTI Low Range; ±45 000με (22.5 mV/V) RTI High Range.

Resolution: 0.5με RTI Low Range; 1.5με RTI High Range.

Accuracy: ±3 mV RTO; ±3 με RTI.

NOTE: Range, Resolution, and Accuracy specifications apply to gain ranges of X10, X100, X200. On gain range of X1, all RTI specifications are multiplied X10

CALIBRATION

Four internal shunt calibration resistors, ±0.1% tolerance:

174.8K	1000με (0.50 mV/V)	350Ω; (2 each)
874.8K	200με (0.10 mV/V)	350Ω;
59.94K	1000με (0.50 mV/V)	120Ω.

Internal selector switches for selection of two-point unipolar, bipolar, or two-point double-shunt calibration circuits.

External static or dynamic calibration signals are also program selectable.

ENVIRONMENTAL

Temperature:
Operating Range −10° C to 60° C;
Storage Range −20° C to 70° C;
Humidity to 95% without condensation.

SIZE

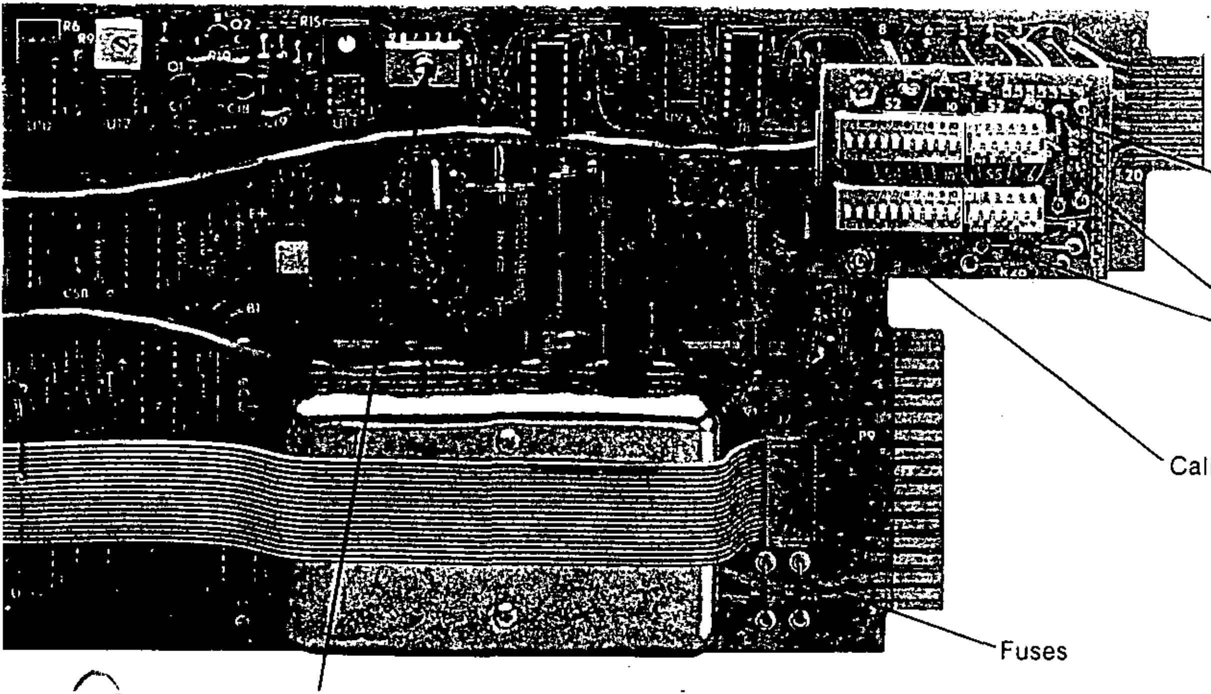
5.69 H x 1.87 W x 20.37 D in *(145 x 48 x 518 mm)*.

WEIGHT

2.6 lb *(1.17 kg)*.

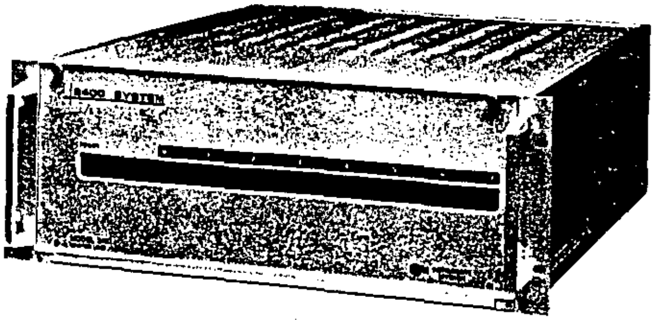
All references to microstrain assume a gage factor of 2.00.

All specifications nominal or typical at +25° C unless noted.



Model 2401 Master Unit

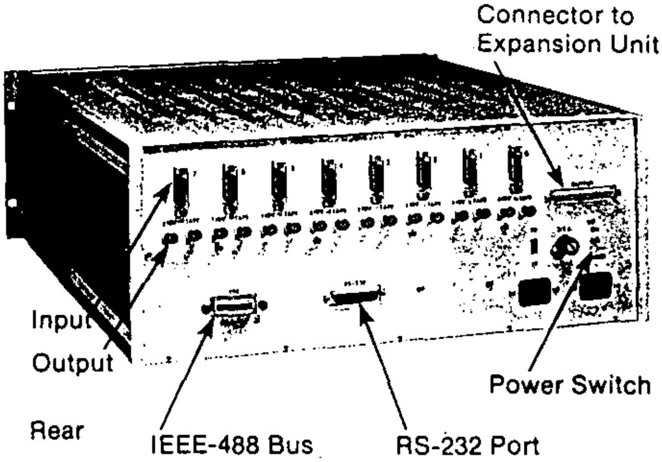
The Model 2401 Master Unit contains the system control circuitry. It accepts up to eight (8) Model 2410 Signal Conditioning Amplifiers and provides the required input/output rear-panel connections. The front panel has silk-screened channel identification (0 to 7). The master unit is attractively styled for tabletop mounting, or it can be rack mounted in a standard 19-in *(483-mm)* equipment rack.



Front

Specifications

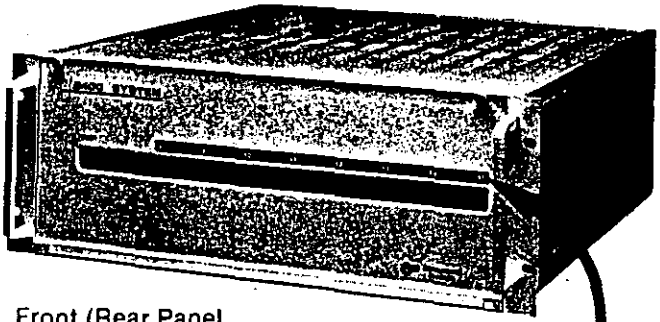
Input:	Input plugs are provided for eight Model 2410 Amplifiers.
Output:	Standard (±10V) and tape (1.0 Vrms) output for each channel; BNC receptacle.
Computer Interface:	Connector for interfacing to RS-232 port. Connector for interfacing to IEEE-488 bus.
Power:	115/230 Vac, 50-60 Hz, 120W max Fuse: 1.5A, 3AG (115V) or 3/4 A, 3AG (230V).
Size:	7 H x 19 W x 21.5 D in *(178 x 483 x 546 mm)*.
Weight:	17 lb *(7.7 kg)*.



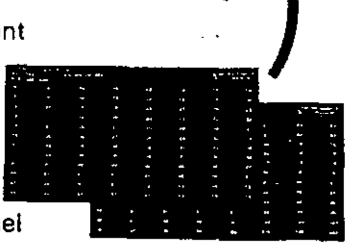
Rear

Model 2402 Expansion Unit

The Model 2402 Expansion Unit allows the addition of up to eight (8) Model 2410 Amplifiers to a system. All required control and interface circuits are included. This unit can be stacked for tabletop mounting with the Model 2401, or rack mounted. The Model 2402 is supplied with pre-numbered, reusable "customer-installed", self-adhesive channel identification strips.



Front (Rear Panel Input/Output Arrangement Similar to Master Unit)



Reusable Self-Adhesive Channel Identification Strips — Provided for Both Front and Rear Panel on Expansion Units.

Specifications

Input: Input plugs are same as the Model 2401.

Output: Same as the Model 2401.

Specifications for Power, Size, and Weight are same as the Model 2401.

Programmable Functions

Communication with the 2400 System is accomplished by sending simple ASCII commands to the Model 2401 Master Unit. All commands are well documented to provide sufficient information for developing user-written programs.*

INPUT

Selectable input configurations are:

- Standard — connected to the external S+, S- bridge input;
- AUX 1 — connected to the external auxiliary input #1;
- AUX 2 — connected to the external auxiliary input #2.

The auxiliary inputs are connected through the rear-panel input connector. Inputs may be dynamic signals for calibration of recorders, oscilloscopes and other devices, or direct current calibration voltages within specified accuracy limits. Also, an auxiliary input can be shorted to provide a reliable amplifier zero reference point.

AMPLIFIER GAIN

Coarse Gain (CG) steps of X1, X10, X100, X200.

Fine Gain (FG) steps of 0 to 15.

Total amplifier gain is the product of CG and FG. Overall accuracy ±0.2%.

A fine gain setting of zero allows operator to observe output noise independent of the input circuit.

CALIBRATION

Two low-thermal EMF, shielded, guarded relays are utilized. Selectable configurations are:

- Calibration OFF
- Shunt Cal A
- Shunt Cal B
- Shunt Cal A & B simultaneously

Four shunt calibration resistors are provided for calibration of 350Ω and 120Ω bridges. These resistors are easily changeable (without soldering) so that user-selected values can be substituted as desired.

Board-mounted dip switches allow the user to select any desired calibration configuration for Shunt Cal A and Shunt Cal B; i.e., shunt dummy resistor, shunt active gage, shunt internal half bridge, etc. Also, the relays can be configured to shunt remote or local resistors across external bridge components or transducers as in double-shunt calibration of transducers.

External calibration sources can be used by connection to the auxiliary inputs.

*A demonstration program for initial setup and control of all programmable functions, through the RS-232 port, is provided with each system.

EXCITATION

Constant voltage or constant current excitation is selected by a board-mounted toggle switch. A status bit is set to allow operator monitoring of the existing setting.

Constant voltage, 0.25 to 15.75 Vdc in 0.25V increments, 85 mA max.

Constant current, 1.0 to 63 mA in 1.0 mA increments, 15.75V compliance voltage, 21.0V max.

A separate on/off function reduces excitation to zero without altering the previously programmed excitation level, with the on/off status available for review.

FILTER AND OUTPUT

Selectable four-pole Bessel low-pass filters of 1 Hz, 10 Hz, 100 Hz, 1 kHz and 10 kHz are provided. The wideband (WB) output can also be selected.

Outputs of ±10V and Tape (1 Vrms) are standard. The filtered or WB output can be independently routed to the ±10V and/or the Tape output by the filter program command. For example, a wideband tape output may be viewed or recorded while the ±10V output is used for monitoring quasi-static or filtered signals.

Both outputs are capable of driving large capacitive loads as in the case of long coaxial output cables.

AUTOMATIC BALANCE

The autobalance circuit provides balance ranges of ±15 000$\mu\epsilon$ (7.5 mV/V) and ±45 000$\mu\epsilon$ (22.5 mV/V), with resolutions of 0.50$\mu\epsilon$ and 1.50$\mu\epsilon$, respectively. The autobalance circuit is fully programmable as follows:

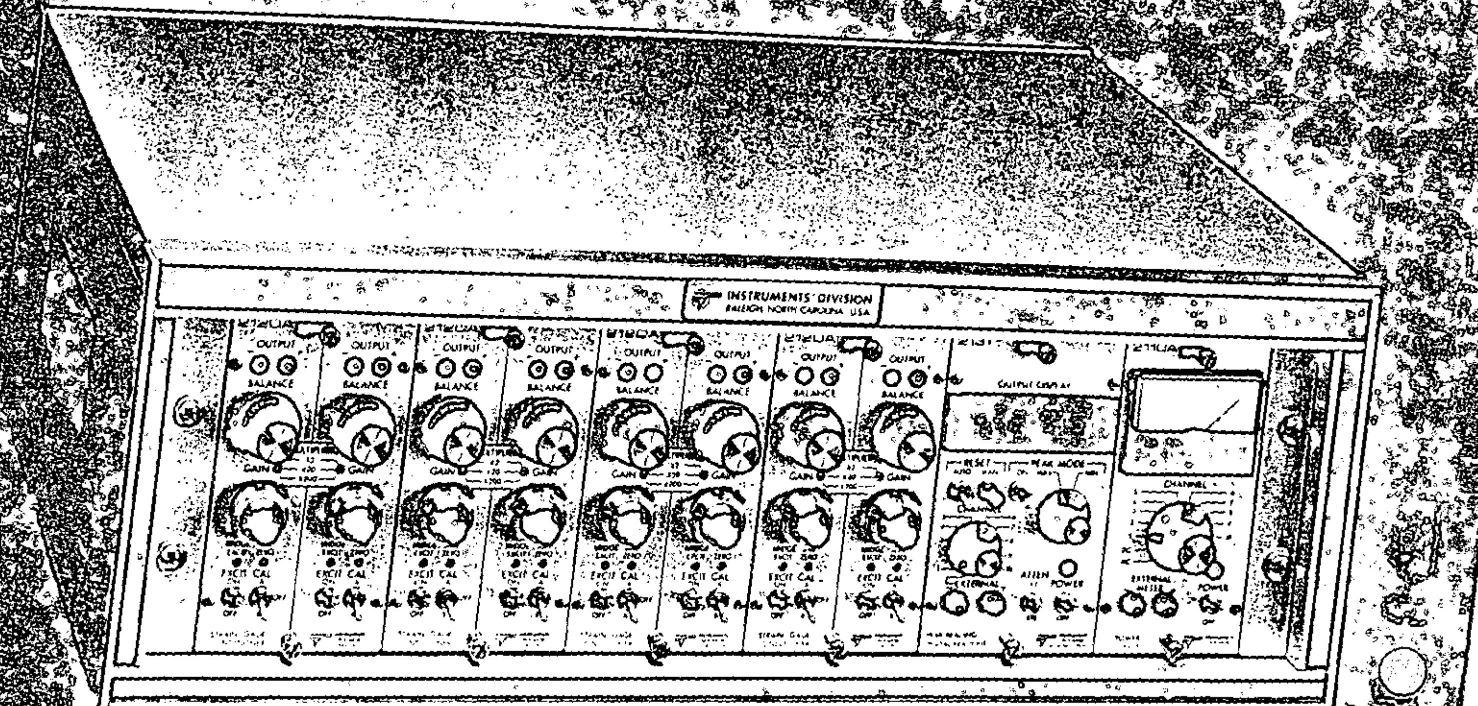
OFF	Autobalance injection voltages are removed. In this mode, raw input unbalances may be read and the input circuit evaluated.
ON-LOW	Autobalance voltages are injected and the low (±15 000$\mu\epsilon$) range is selected.
ON-HIGH	Autobalance voltages are injected and the high (±45 000$\mu\epsilon$) range is selected.
ON-Restart	The autobalance voltage is reset to zero, and a new autobalance sequence is initiated.

The autobalance circuit is fully ratiometric. Injected voltages are derived from the sensed (local or remote) voltages. Also, when constant current excitation is used, the autobalance circuit remains fully ratiometric and undesirable fixed offset voltages are not used.

Status "flags" are provided to allow monitoring of autobalance range (low/high), autobalance on/off, and autobalance overrange.

Autobalance readings are stored and memory is battery backed. Battery life is 2 to 4 years.

Bulletin 250-B



Eight-channel system
with digital output display

2100 SYSTEM

MULTI-CHANNEL SIGNAL CONDITIONER/AMPLIFIER

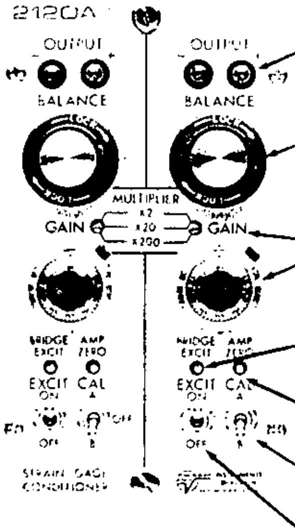
Conditions signals from strain gages and transducers when multiple-channel simultaneous dynamic recording is required

MEASUREMENTS GROUP
VISHAY

Model 2120A Strain Gage Conditioner/Amplifier

A two-channel plug-in module which includes bridge completion, bridge balance, amplifier, amplifier balance, excitation regulator and shunt calibration.

FRONT



LED DISPLAY: Setup/indicator for amplifier balance, bridge balance, tension/compression.

BRIDGE BALANCE: Resistively balances the bridge; standard locking knob; digital locking knob ("K" option).

GAIN RANGE AND VERNIER: Varies amplifier gain between 1-2100.

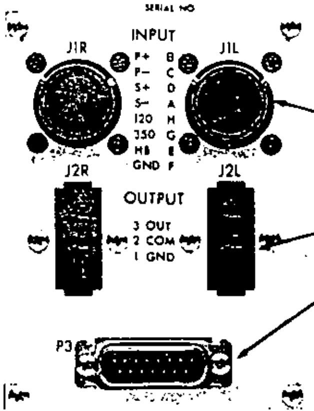
BRIDGE EXCITATION: Varies bridge excitation between 0.5-12 Vdc.

AMPLIFIER BALANCE: Adjusts amplifier offset.

SHUNT CALIBRATION: (2 points).

BRIDGE EXCITATION (on/off): Removes bridge excitation.

REAR

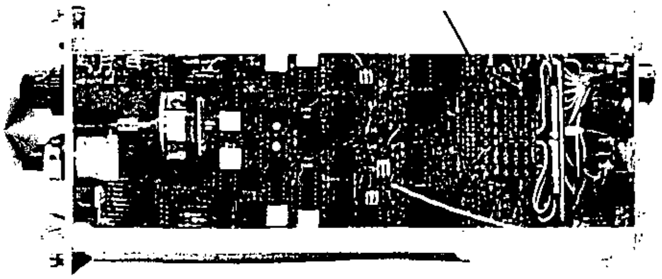


STRAIN GAGE/TRANSDUCER INPUT: Quarter (120Ω, 350Ω), half, and full bridge.

OUTPUT: ±10 Vdc, ±100 mA.

POWER RECEPTACLE

SPECIAL PORTION OF PRINTED CIRCUIT BOARD FOR SHUNT CALIBRATION RESISTORS AND JUMPERS



Specifications

These specifications apply for each of two independent channels per module.

INPUTS	Quarter (120Ω and 350Ω), half and full bridge (50-1000Ω). Quarter-bridge dummy gages provided.
BRIDGE EXCITATION	0.5 to 12 Vdc (adjustable for each channel) with 120Ω full-bridge load. Short-circuit current: <40 mA. Ripple, noise, and 10% line change: ±2 mV max. Load regulation: ±0.2% no-load to 120Ω load (10% line cnange).
BRIDGE BALANCE	±2000$\mu\epsilon$ (quarter, half, or 350Ω full bridge), range can be changed by internal jumper to ±4000$\mu\epsilon$ or ±6000$\mu\epsilon$.
CALIBRATION	Two-position (center off) toggle switch. Standard factory-installed resistors (±0.1%) simulate ±1000$\mu\epsilon$ at GF=2.
AMP GAIN	1 to 2100 continuously adjustable, ±0.5%.
BANDPASS	DC to 5 kHz (min): −0.5 dB (−5%). DC to 15 kHz: −3 dB. Can be extended by internal jumper to: DC to 17 kHz −0.5 dB; DC to 50 kHz −3 dB.
AMP INPUT	Temperature Coefficient of Zero: ±1 μV/°C RTI*, ±210 μV/°C RTO**; −10° to +60°C (after 30 minute warm-up). Noise RTI: (350Ω source impedance) 1 μV p-p at 0.1 Hz to 10 Hz; 2 μV p-p at 0.1 Hz to 100 Hz; 2 μVrms at 0.1 Hz to 50 kHz. Noise RTO: 50 μV p-p at 0.1 Hz to 10 Hz; 80 μV p-p at 0.1 Hz to 100 Hz; 100 μVrms at 0.1 Hz to 15 kHz; 200 μVrms at 0.1 Hz to 50 kHz. Input Impedance: >100 MΩ (balance limit resistor disconnected). Common-Mode Rejection: (dc to 60 Hz).

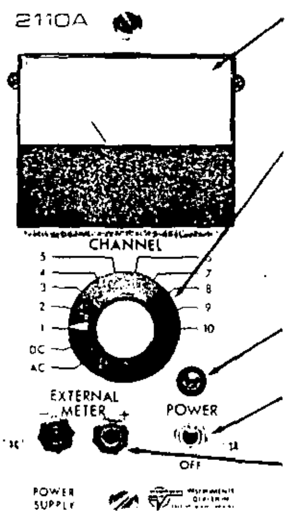
Gain Multiplier	CMR (dB)
X2	67
X20	87
X200	100

	Source Current: ±10 nA typical; ±40 nA max.
OUTPUT	±10V (min) at ±100 mA. Current limit: 140 mA.
OPTIONAL FEATURE	May be ordered with, or be field upgraded for, remote-operation relays for control of shunt calibration and excitation (off). Remote-operation capability is required in the Model 2150 or 2160 also. Contact Measurements Group for details.
SIZE	5.25 H x 2.94 W x 10.97 D in *(133 x 75 x 279 mm).*
WEIGHT	2.2 lb *(1.0 kg).*

**Referred to input* ***Referred to output*

All specifications in this bulletin are nominal or typical at +23°C unless noted.

Model 2110A Power Supply



BRIDGE-VOLTS METER: Used to set up/monitor bridge excitation, also line and power supply levels.

CHANNEL SELECTOR: AC monitors AC line input. DC monitors the power supplies. Positions 1-10 select and display bridge excitation for each channel.

PILOT LAMP: Indicates main power.

POWER SWITCH: Main power on-off.

EXTERNAL METER: Used with an external digital voltmeter to precisely adjust bridge excitation.

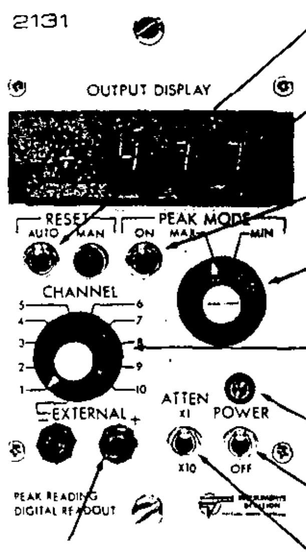
A plug-in module capable of powering up to ten channels (five Model 2120A modules) at maximum rated voltage or current. Provides initial bridge and amplifier voltages. All supplies are current-limited against amplifier malfunction.

Specifications

OUTPUTS	±15V at 1.2A and +17.5V at 1.1A; all regulators current-limited against overload.
INPUT	107, 115, 214, 230 Vac ±10% 50/60 Hz (selected internally). Power: 40W typical, 100W max.
METER	0 to 12 Vdc (with switch) to read bridge excitation. Also AC input and DC output go/no-go monitor.
SIZE	5.25 H x 2.44 W x 12.34 D in *(133 x 62 x 313 mm).*
WEIGHT	6.7 lb *(3.1 kg).*

Model 2130/2131 Digital Display

A plug-in module that provides real-time digital readout on channel-by-channel basis. Will accept and switch up to 10 inputs. Peak hold/retention capability is provided with the Model 2131. (The Model 2131 is shown below.)



PEAK RESET: Provides manual or automatic reset.

DIGITAL DISPLAY: 3-1/2 Digit LED, ±1999 counts.

PEAK MODE ON: On/off switch.

PEAK MODE MAX/MIN: Selector for maximum or minimum peak mode.

CHANNEL SELECTOR: Positions 1-10 select input channel for display.

PILOT LAMP: Indicates main power.

POWER SWITCH: Main power on-off.

ATTENUATOR: Attenuates input signal to increase measurement range.

EXTERNAL: Front-panel jacks accept input, typically bridge voltage from 2110A external meter jacks.

Specifications

2130/2131 SPECIFICATIONS

INPUT CAPACITY	10 channels, BNC (rear panel). 1 channel, banana jacks (front panel).
SWITCH OUTPUT	Not attenuated, BNC (rear panel).
UPDATE RATE	3 readings/sec, nominal.
INPUT VOLTAGE RANGE	±1999 mV (X1 range) — 2130/2131. ±19 990 mV (X10 range) — 2130. ±10V (X10 range) — 2131.
INPUT IMPEDANCE	100 kΩ — 2130. Greater than 1 MΩ — 2131.
COMMON MODE INPUT RANGE	±100 mV (rear-panel input) min — 2130. ±10V (rear-panel input) — 2131.
ACCURACY	±(0.05% reading +0.05% full scale) or better (Peak Mode Off — 2131).
SIZE	5.25 H x 2.94 W x 10.97 D in *(133 x 75 x 279 mm).*
WEIGHT	2 lb *(0.8 kg).*

2131 SPECIFICATIONS

STEP/INPUT RESPONSE	±5 counts for 10 msec full-scale step input (worst case).
STORAGE STABILITY	±3 counts/min (max).
PEAK MODES	MAX (usually positive) excursion and MIN (usually negative) excursion.
PEAK RESET	Manual or Automatic.

Model 2111 DC-Operated Power Supply

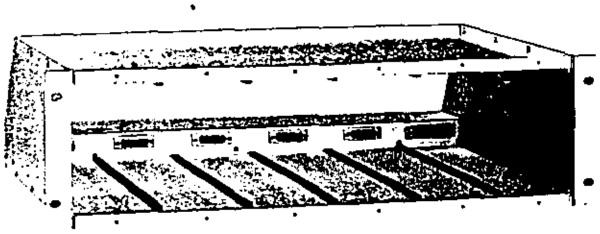
A plug-in module capable of powering up to eight channels (four Model 2120A modules) at maximum rated bridge voltage and output current, or up to ten channels when maximum bridge voltage and output current are not required. The 2111 functions similarly to the 2110A Power Supply, with the exception of the 12 Vdc nominal input which supports battery operation only. The front panel is similar in appearance to the Model 2110A.

Specifications

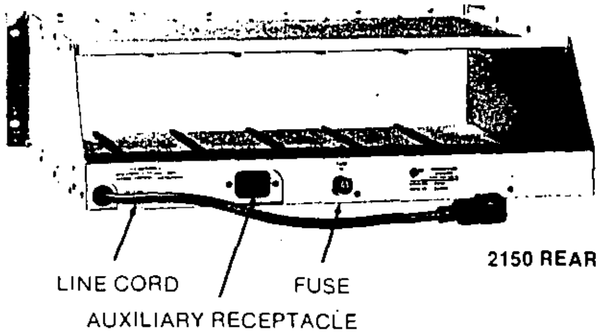
OUTPUTS	±15 Vdc at 1.0A and +17.5 Vdc at 1.0A; outputs are protected against overload.
INPUT	12 Vdc nominal (9 to 18 Vdc range). Power: 60W max; 78% efficiency at full load. Reverse polarity protection: Internal shunt diode.
METER	0 to 12 Vdc (with switch) to read bridge excitation. DC output go/no-go monitor.
SIZE	5.25 H x 2.44 W x 12.34 D in *(133 x 62 x 313 mm).*
WEIGHT	3.0 lb *(1.4 kg).*

Model 2150 Rack Adapter, Model 2155 Enclosure, and Model 2160 Portable Enclosure

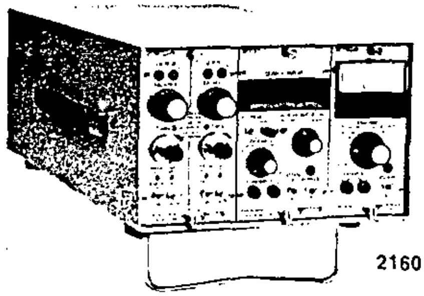
Model 2150: A prewired rack adapter which accepts one Model 2110A or 2111, and any combination of five Model 2120A, 2130, or 2131 plug-in modules. It has its own fuse and power cord and can be housed in any standard 19-in *(483-mm)* electronic equipment rack.



2150 FRONT



2150 REAR



2160

Model 2155: A sturdy cabinet (shown on front cover) for enclosing a complete eight- or ten-channel system for free-standing operation, while providing additional mechanical protection and increased portability. A Model 2150 is required.

Model 2160: A prewired, fused enclosure which houses one Model 2110A or 2111, one 2130 or 2131, and one 2120A module. A carrying handle ensures maximum portability. An additional snap-down bail support on the bottom can be used to elevate the 2160 for excellent work efficiency during bench-top operation. The Model 2160 (shown with the 2110A, 2131, and 2120A modules) would be substituted for the Model 2150 when two or four channels and maximum portability are required.

Specifications

2150 SPECIFICATIONS

POWER	2-ft *(0.6-m)* 3-wire line cord; 10-ft *(3-m)* extension available. Fuse: 1A size 3 AG *(32 x 6.5 dia. mm).* Receptacle to accept line cord from adjacent 2150 Rack Adapter.
SIZE	5.25 H x 19 W x 14.17 D in *(133 x 483 x 360 mm).*
WEIGHT	6.6 lb *(3.0 kg).*

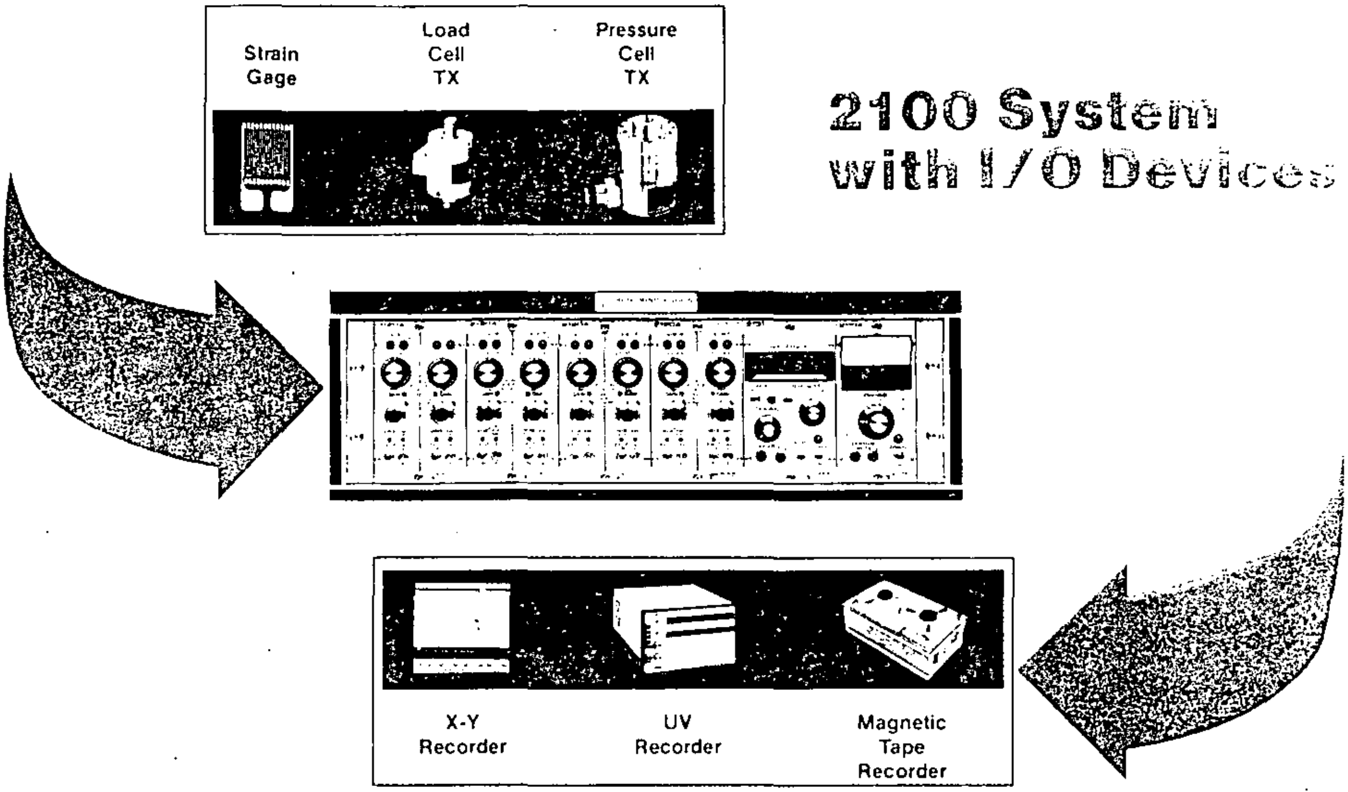
2155 SPECIFICATIONS

SIZE	5.25 H x 19 W x 13 D in *(133 x 483 x 330 mm).*
WEIGHT	18.8 lb *(9.5 kg).*

2160 SPECIFICATIONS

SIZE	5.55 H x 8.75 W x 13.80 D in *(141 x 222 x 350 mm).*
WEIGHT	5.2 lb *(2.4 kg).*

2100 System with I/O Devices



The 2100 System provides better data . . .

A **separate bridge power switch** removes bridge excitation, enabling the operator to detect unwanted signals due to electrical interference and/or noise, thermocouple effects, and shifts of the instrument zero during a long-term test. This feature is an absolute must for dynamic testing, and for validating test results.

An **adjustable bridge excitation control** on each channel permits excitation to be set as specified by the strain gage or transducer manufacturer. It also allows for any special consideration which may be dictated by the test material; for example, the poor thermal conductivity normally associated with plastics.

In addition to adjustable bridge excitation, each channel has its own **regulator circuit**. This prevents interaction of adjacent channels during setup or operation.

Each channel has a **continuously variable gain control**. In combination with recommended excitation, the independent gain control can provide a large output signal so that small signals can be resolved without overpowering the strain gage or transducer.

An **LED display for each channel** gives positive indication of amplifier and resistive balance. This capability accelerates setup, minimizes the risk of destroying galvanometers, and verifies tension/compression loading.

Easily read **reference marks** on the setup meter indicate acceptable line voltage and proper operation of internal power supplies.

A switch contained in the Model 2110A Power Supply allows adjustment when the **line voltage** is too high or too low.

The 2100 System provides **true quarter-bridge, three-leadwire capability**, including internal dummies and sufficient plug connections for remote shunt calibration.

A convenient network in the Model 2120A Strain Gage Conditioner/Amplifier **allows the operator to change the factory-supplied shunt values**, as well as shunt any arm of the bridge, as required.

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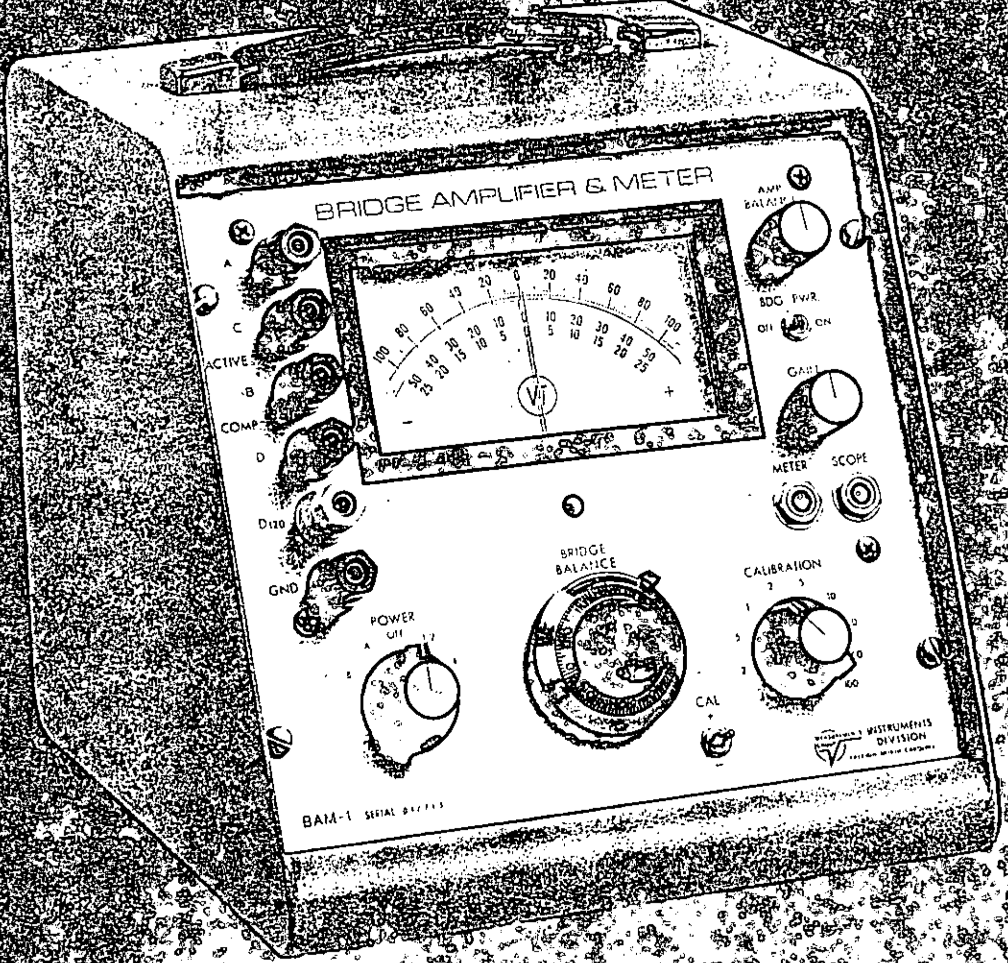

BAM-1

A portable battery-powered universal strain measuring instrument

MEASUREMENTS GROUP

DESCRIPTION

The BAM-1 is a battery-powered universal strain measuring instrument and signal conditioner containing a DC amplifier, bridge completion, and indicating meter. Additional features include a separate bridge excitation switch, variable gain control, initial bridge balance control, shunt calibration switch, and amplifier balance control.

Static measurements are made directly on the instrument's analog meter. If desired, a standard digital voltmeter can be used with the BAM-1 to provide a digital output.

For dynamic testing, two outputs are provided: The SCOPE signal provides DC to 20 000 Hz at high source impedance, while the METER signal is a low source impedance output for oscillographs. The dynamic range can be increased to 100 000 Hz by specifying Option B (BAM-1B).

An independent bridge power switch makes the BAM-1 an excellent instrument for long-term testing. With this feature, amplifier balance can be checked and corrections made at any time during a test by temporarily turning off bridge power and resetting the amplifier balance if the output has deviated from zero. Thus, during long-term measurements, the user has the ability to electrically maintain the original zero of the instrument, and separate any instrumentation drift from the desired test measurement signal.

Calibration of the BAM-1 for static or dynamic work is accomplished by using a ten-point shunt CALIBRATION switch, and system GAIN (span) control. The GAIN control is adjustable over a wide range by changing bridge excitation and, in the case of static measurements, by attenuating the meter signal. The BAM-1 can be adjusted to read directly in strain, psi, or any other desired engineering unit.

Applications with the BAM-1 or BAM-1B include measuring or monitoring signals from strain gages, transducers, temperature sensors, and thermocouples on an oscilloscope, oscillographic recorder, or directly on the meter of the instrument.

FEATURES

- **Static and Dynamic Measuring Capability**
- **Battery Operation with AC Option**
- **Separate Bridge Excitation Switch plus Variable Gain Control**
- **DC to 20 000 Hz std.**
  100 000 Hz with "B" Option
- **Built-in Ten-point Shunt Calibration Switch**

SPECIFICATIONS

INPUT CIRCUITS

Strain gages/transducers, 50 to 2000Ω, and thermocouples.

Half or full bridges; 120Ω quarter-bridge operation with the provided 120Ω dummy (internal) resistor.

Bridge Balance: Ten-turn potentiometer with counting dial, ±8% for half
bridge, or ±7% for 350Ω full bridge.

BRIDGE EXCITATION

Half or Quarter Bridge (excitation per gage): 120Ω, 0.25 to 2.5 Vdc;
350Ω, 0.7 to 5.6 Vdc.

Full Bridge: 120Ω, 0.5 to 6 Vdc; 350Ω, 1.4 to 9 Vdc.

Gage Current: Max 25 mA depending on gage resistance and GAIN setting using recommended procedures.

AMPLIFIER

Direct-coupled, solid state.

Balanced differential input, approximately 20kΩ impedance.

Noise: 2μVrms RTI.

Stability: ±1μV/hr max at input after 1/2 hour warm-up.
Drift: ±0.5μV/°F max at input (32° to 77°F)
[±0.9μV/°C max at input (0° to 25°C)].
±25μV max at input from turn-on and 32° to 77°F
(0° to 25°C) change.

Gain: 125 at SCOPE jack; 250 at METER jack.

Bandpass (-0.5 dB or 5%): SCOPE jack DC to 20 000 Hz;
METER jack DC to 2000 Hz.

Output Impedance: SCOPE 30kΩ single ended; METER 250Ω differential.

Linear Output: SCOPE ±3V into 500kΩ load;
METER ±5V into 100kΩ load, or ±0.5 mA into 1kΩ or less.

CALIBRATION

Ten 1% shunt-calibration resistors.

Half or Quarter Bridge: Simulates ±20 to 20 000με (GF=2)
by shunting internal 400Ω half bridge.

Full Bridge: Shunts one arm of external bridge.

METER

Taut Band Movement, Linearity: ±1 graduation.

Scale 3.5 in *(89 mm)*, 100 total graduations; with mirror.

Sensitivity attenuated 15:1 with GAIN control.

SYSTEM SENSITIVITY USING METER

Half or Quarter Bridge, 120Ω, 1 active gage, GF=2: ±100 to ±15 000με F.S.

Full Bridge: 120Ω, ±0.1 to 10 mV/V F.S.
350Ω, ±0.05 to ±4 mV/V F.S.

DC Input: ±350 to 5000μV F.S.

POWER SUPPLY

Internal Batteries (standard): Two 6V NEDA No. 920, 200 hr;
One 22-1/2V NEDA No. 710, 500 hr.

PHYSICAL

Weight: 12 lb *(5.4 kg)* with batteries.

Case Dimensions: 9 L x 9 W x 10 H in *(228.6 x 228.6 x 254 mm).*

ACCESSORY

AC Power Pack (replaces batteries): Model 4008, 115 Vac, 50-60 Hz, 2W;
Model 4008Z, 230 Vac, 50-60 Hz, 2W.

All specifications nominal or typical at +23°C unless noted.

The Measurements Group is a leading supplier of strain gage instrumentation. Available instruments include portable indicators, signal conditioners/amplifiers, strain gage installation tester, instrument calibrator, and sophisticated computer-controlled systems for the acquisition, storage and reduction of test data. Call or write for all of your strain gage instrumentation needs.

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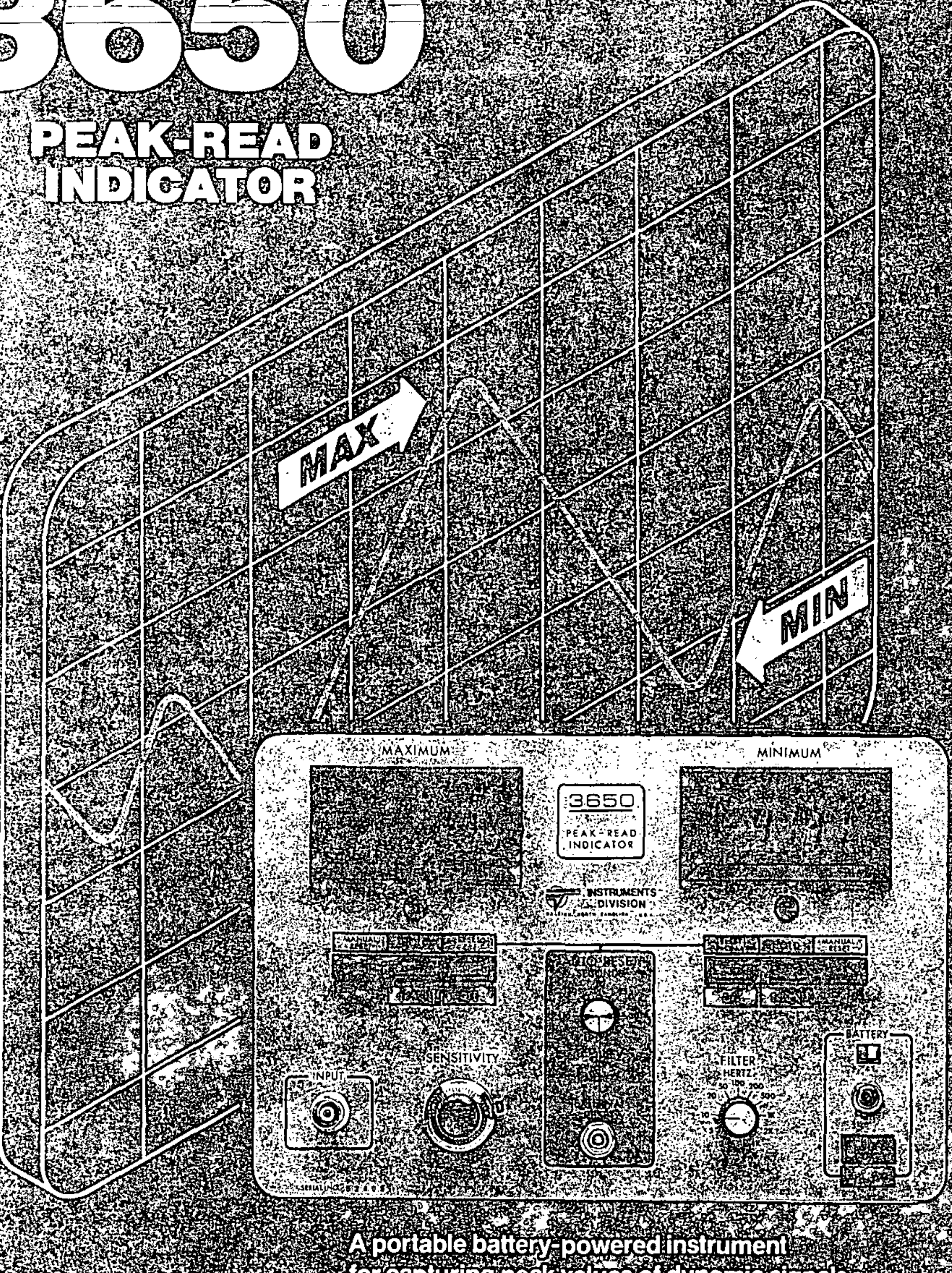
Bulletin 246-B

3650

PEAK-READ INDICATOR



A portable battery-powered instrument
for capturing peak values of dynamic signals.

MEASUREMENTS
GROUP
VISHAY

MODEL 3650
DUAL PEAK-READ INDICATOR

This instrument is designed to simultaneously display both the maximum (most positive excursion) and minimum (most negative excursion) values of a transient waveform. The primary application is to display the peak values of dynamic mechanical strains measured by strain indicators such as the Measurements Group's P-3500 and Model 3800.

A typical example of such usage is the measurement of maximum forces developed in the structure of mechanical presses during each load cycle. In this case, strain gages are installed at appropriate locations on the press, and the Model 3650 utilizes the analog output signal from the strain indicator as its input signal. The Model 3650 is equipped with an extremely versatile system of meter display and reset, which allows easy and accurate monitoring of the variable force occurring with each strike of the press.

While the Model 3650 is primarily intended to operate from the DC analog output signal obtained from suitable strain gage indicators or conditioners, it may also be used to capture and display dynamic voltage signals obtained from other sources, so long as these signals lie within its operating range (typically, instruments that provide an analog output in the 1.0 to 11.0-volt range).

The Model 3650 features dual LCD digital displays with a full-scale range of ±19 999 counts. Color-coded push-button controls are easy to use, and allow the operator to determine the operating mode at a glance.

The instrument is powered from an internal battery pack consisting of six alkaline "C" cells, which are readily available anywhere in the world when replacement is required. Battery life is approximately 250 hours of continuous use. An external line-voltage adapter is also available (115 or 230 Vac, 50 to 60 Hz).

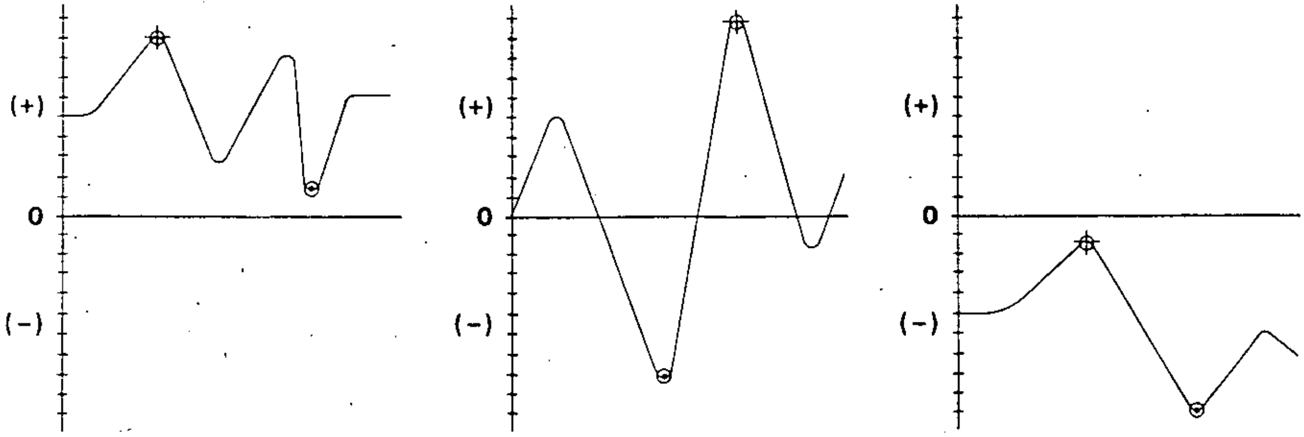
As a dynamic analog signal is fed into the Model 3650, an instantaneous comparison is made to the previously stored values. When the stored values are exceeded, they are immediately replaced with updated values and displayed. The new values are retained until they are exceeded, or reset occurs.

Reset is accomplished either manually with a push-button switch, automatically by a selectable timing circuit, or externally by contact closure or TTL low-logic level. Reset simply changes the stored values to the values of the input signal.

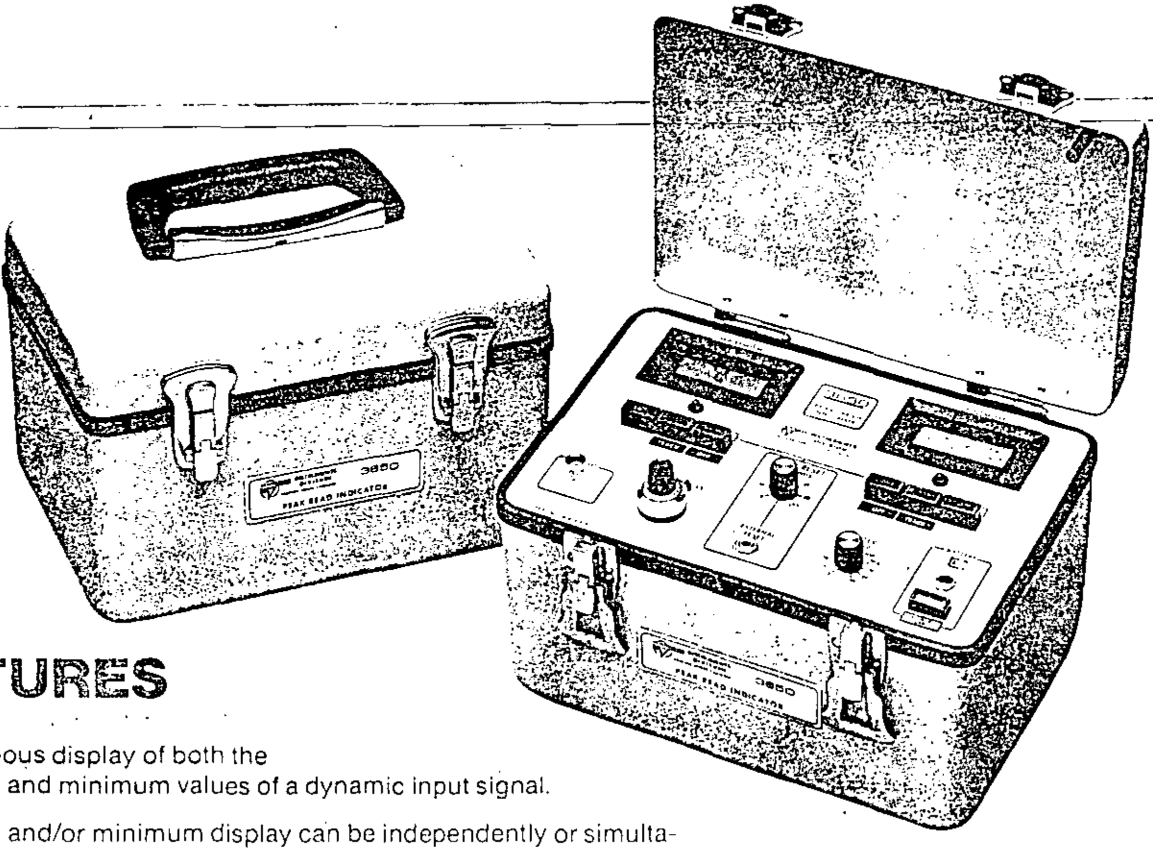
For suppression of voltage transients (noise), often encountered during strain gage measurements in shop environments, a four-pole Bessel low-pass filter with switchable cutoff frequencies from 2 to 4000 Hz is built into the instrument.

To measure the amplitude of dynamic voltages, the use of peak-capturing meters, such as the 3650, often requires special precautions to ensure that the input signal is sufficiently "clean" (free of noise), and that the signal duration is sufficient to permit proper measurement accuracy. While the Model 3650 demonstrates repetitive accuracies approaching 0.1% during calibration on ideal waveforms, such accuracies should not be expected in practical dynamic strain measurement. Because of parasitic strains from loose or badly fitting parts of a moving structure, excessive electrical noise, etc., practical repetitive peak measurement accuracies may range from 0.5% to 5%, or even 10%, of the transient maximum strain value.

It should also be noted that the "response time" of this instrument, which determines the minimum duration of the pulse that can be measured with suitable accuracy, has been designed for typical dynamic *mechanical* phenomena. The Model 3650 is therefore not generally intended for high-speed electrical waveforms that are of interest in various electronic circuit developments.



The Model 3650 simultaneously displays both the maximum (most positive excursion) and minimum (most negative excursion) values of a transient waveform, as illustrated in the above diagram.



FEATURES

- Simultaneous display of both the maximum and minimum values of a dynamic input signal.
- Maximum and/or minimum display can be independently or simultaneously reset by manual push buttons, externally generated reset pulse, or periodic automatic internal reset.
- Selectable four-pole Bessel low-pass filter to discriminate against undesirable high-frequency interference.
- Color-coded push-button controls for simple operation and minimum operator training.
- Compatibility with most instruments that provide an analog output signal.

SPECIFICATIONS

Range and Display:

Dual direct-reading liquid crystal display. ±19 999 counts full scale.

Overload Indication: All-zero display with two flashing columnar indicators.

Sensitivity:

±1.0 to ±11V nominal for full-scale indication (±19 999 counts).

Resolution:

1 count, 50 to 550μV.

Accuracy:

Step Input: ±0.1% ±4 counts for step input of >4 milliseconds duration.

Repetitive Step Input: ±0.2% ±4 counts for repetitive step inputs of >200 microseconds duration. Number of steps required $\geq \frac{\text{4 milliseconds}}{\text{Pulse Duration}}$.

Input Circuit:

Isolated; input impedance >20 000Ω; either side may be connected to system ground.

Hold Stability:

4 counts/minute maximum, averaged over 5-minute period.

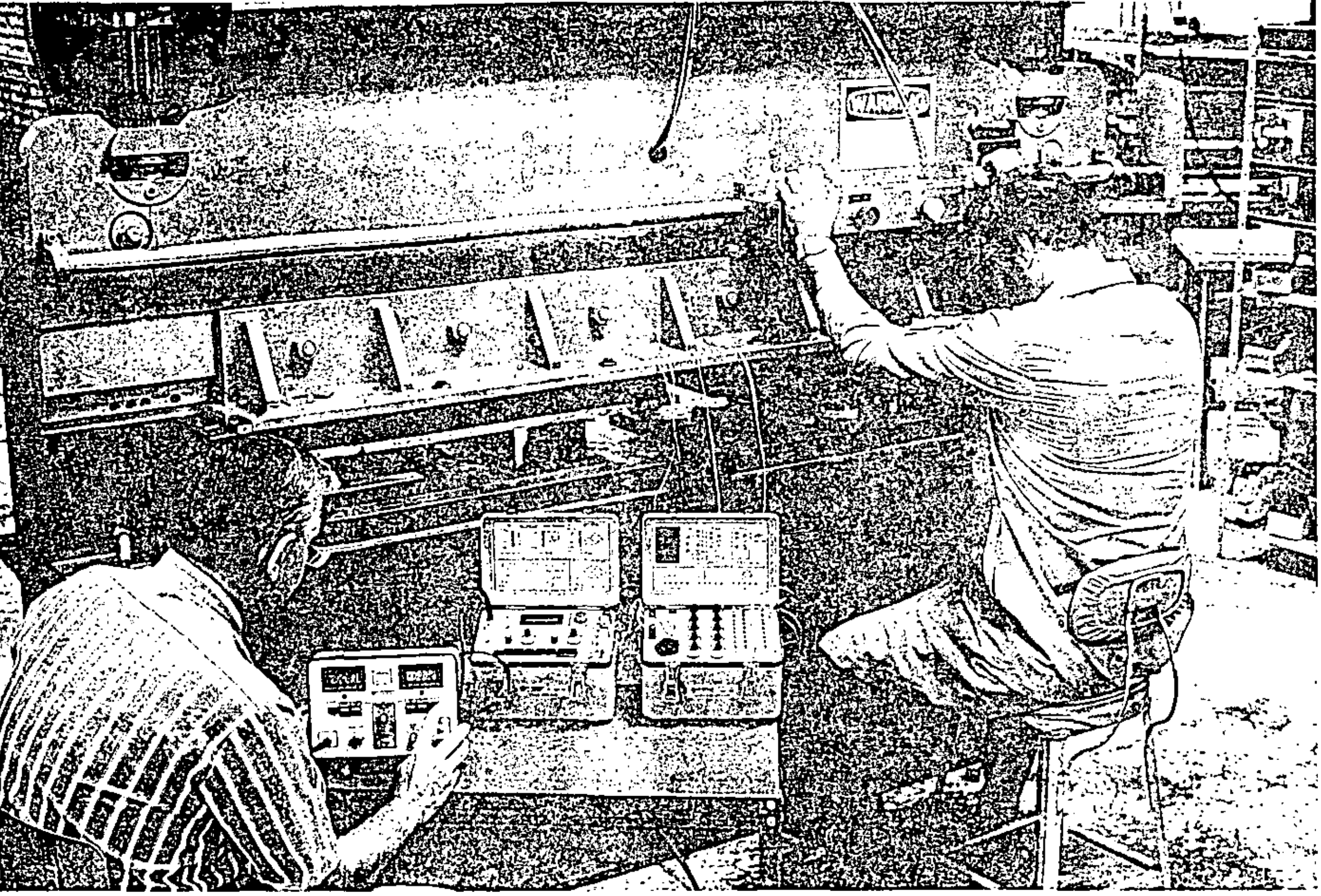
Reset Capability:

Independent or simultaneous reset of maximum and/or minimum by manual push buttons; automatic timed reset; or external contact closure or low TTL level.

Size and Weight:

6 H x 9 W x 6 D in *(152 x 228 x 152 mm)*.
5.5 lb *(2.5 kg)*.

All specifications nominal or typical at +23°C unless noted.



Model 3650 Peak-Read Indicator, used in conjunction with P-3500 Strain Indicator and SB-10 Switch and Balance Unit, to measure peak strains on press platen during metal punching operation.

Other applications include, but are not limited to:

- **Rolling Mills**
- **Ship Propellers**
- **Production Machinery**
- **Vehicle Testing**
- **Aircraft Landing Gear**
- **Hydraulic Systems**
- **Structures Testing**
- **Cranes, Derricks**
- **Off-The-Road Machinery**
- **And More...**

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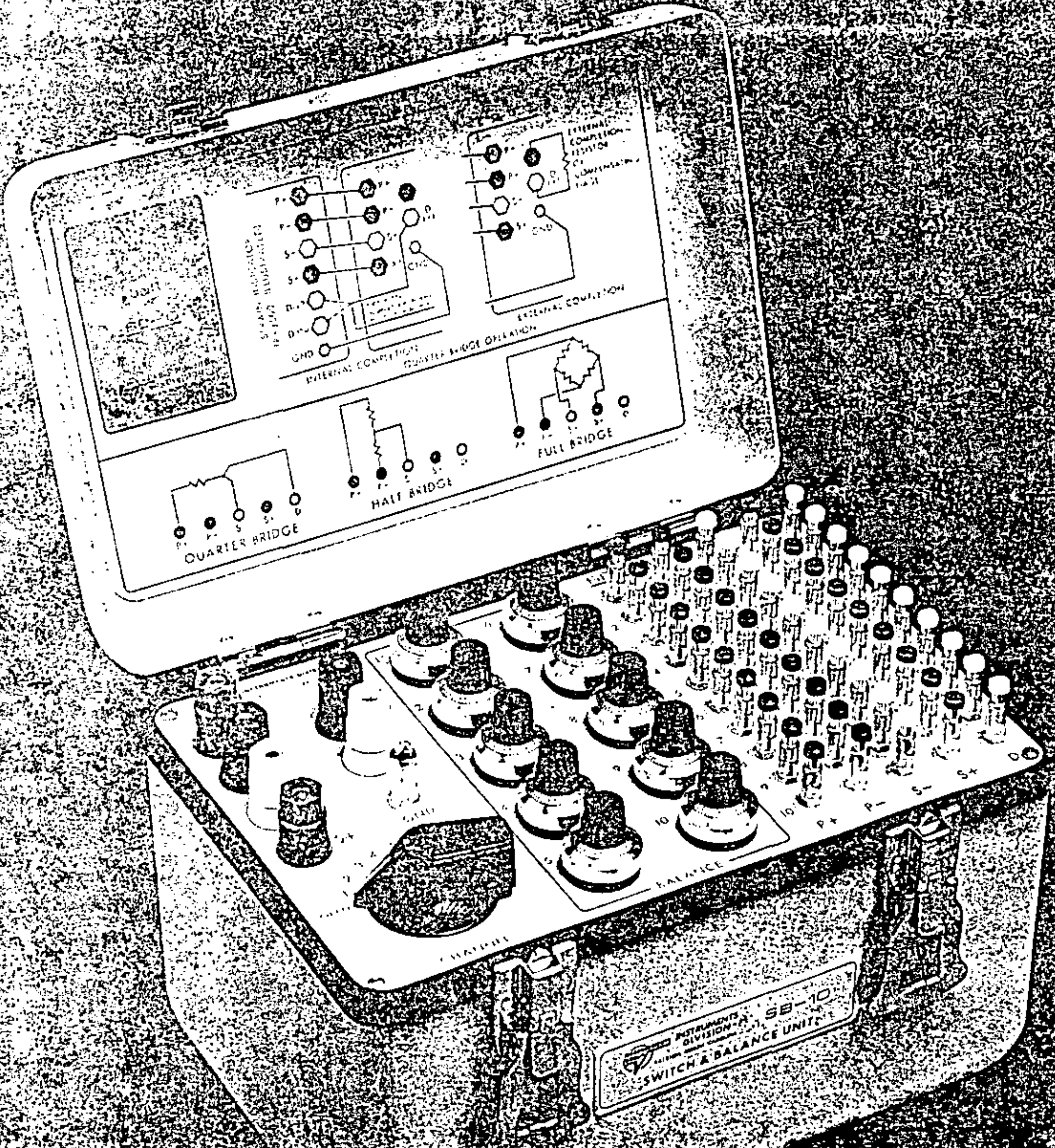


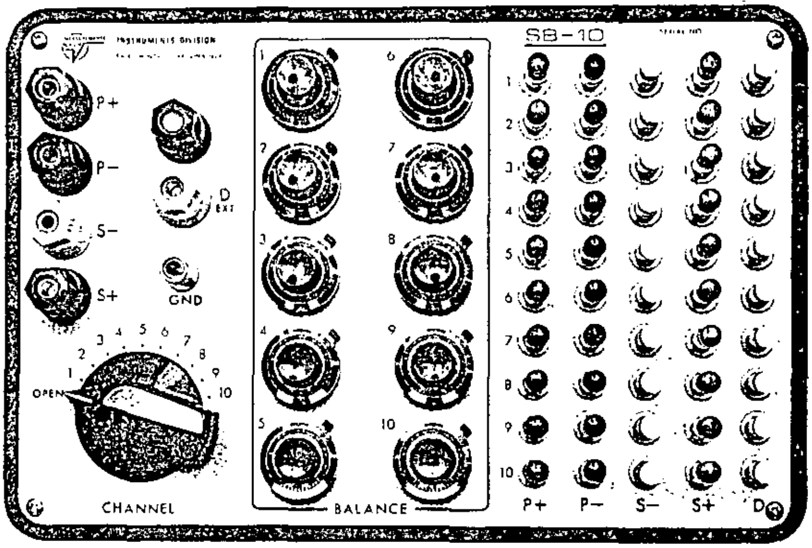
SB-10

SWITCH AND BALANCE UNIT

Provides portable, ten-channel
switching and balancing capability
for strain indicators

MEASUREMENTS GROUP VISHAY

MODEL SB-10
SWITCH AND BALANCE UNIT



The SB-10 Switch and Balance Unit provides a convenient means for strain measurement when more than one strain gage is involved. While designed for use primarily with the Measurements Group P-3500 Strain Indicator, the SB-10 can also be used with other types of strain indicators.

An updated version of the time-proven SB-1K Switch and Balance Unit, the SB-10 features gold-plated push/clamp binding posts to allow fast, convenient, and reliable connection of input circuits, and individual ten-turn locking potentiometers with turns-counting dials for fine-balance adjustment. Also available is the SB-10L, a basic version of the SB-10. It also features locking potentiometers, but without turns-counting dials. (SB-10 front panel is shown.)

The channel selector switch of the SB-10 has negligible switch resistance, and provides an open position to allow the use of additional SB-10's with a single strain indicator. The SB-10 also incorporates a common dummy position for use with other than 120- or 350-ohm strain gages.

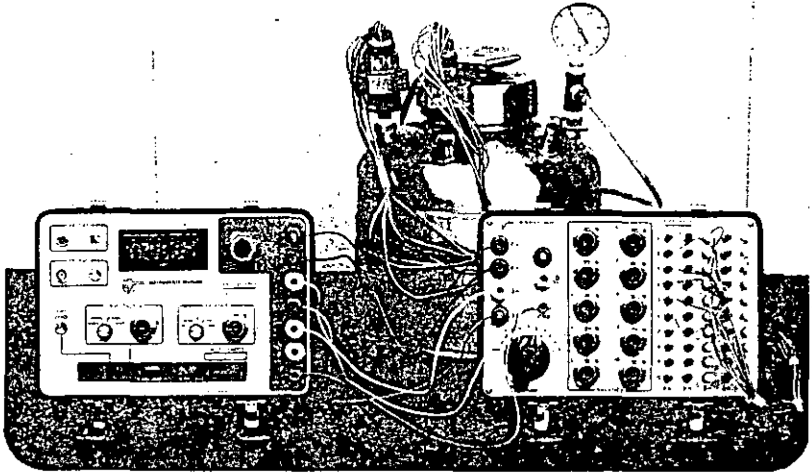
Ruggedly built and lightweight, the SB-10 is ideal for use in harsh field environments.

SPECIFICATIONS

Circuits:	10 channels plus OPEN position.
Inputs*:	Will accept quarter-, half- or full-bridge circuits in any combination, including three-wire quarter bridges.
Balance Range*:	
Quarter and Half Bridge:	±2000με with 350Ω half bridge in strain indicator.
Full Bridge:	±2000με for 350Ω bridge. Range proportional to bridge resistance.
Switching Repeatability:	Better than 1με for gage resistance of 120Ω or higher.
Size & Weight:	9 × 6 × 6 in *(230 × 150 × 150 mm)*. 5.5 lb *(2.5 kg)*.

*when used with Model P-3500

All specifications nominal or typical at +23°C unless noted.



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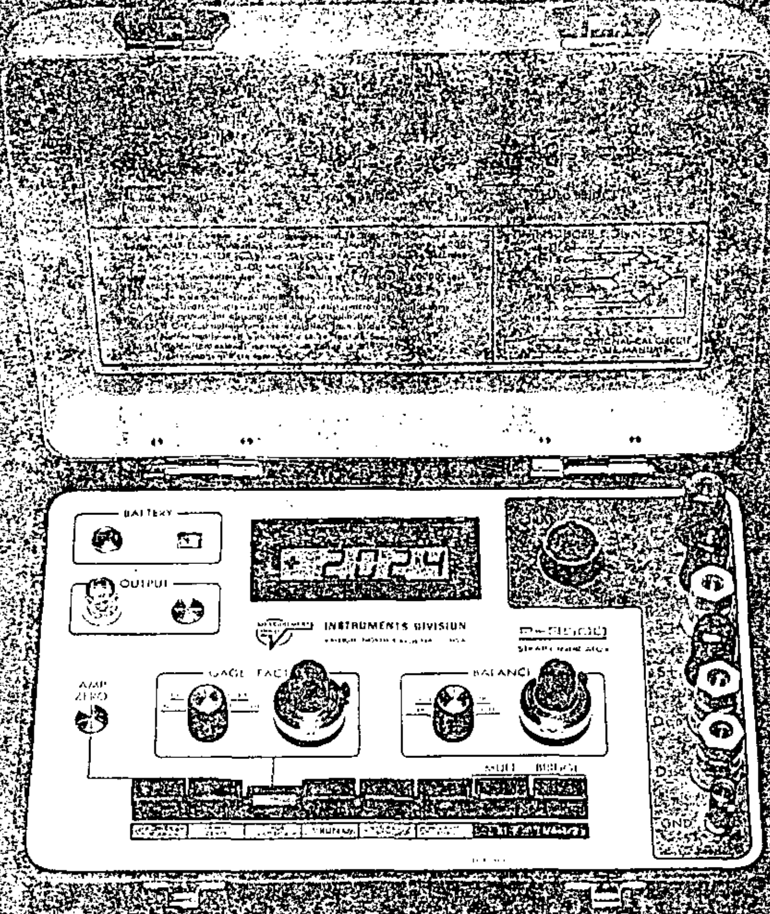
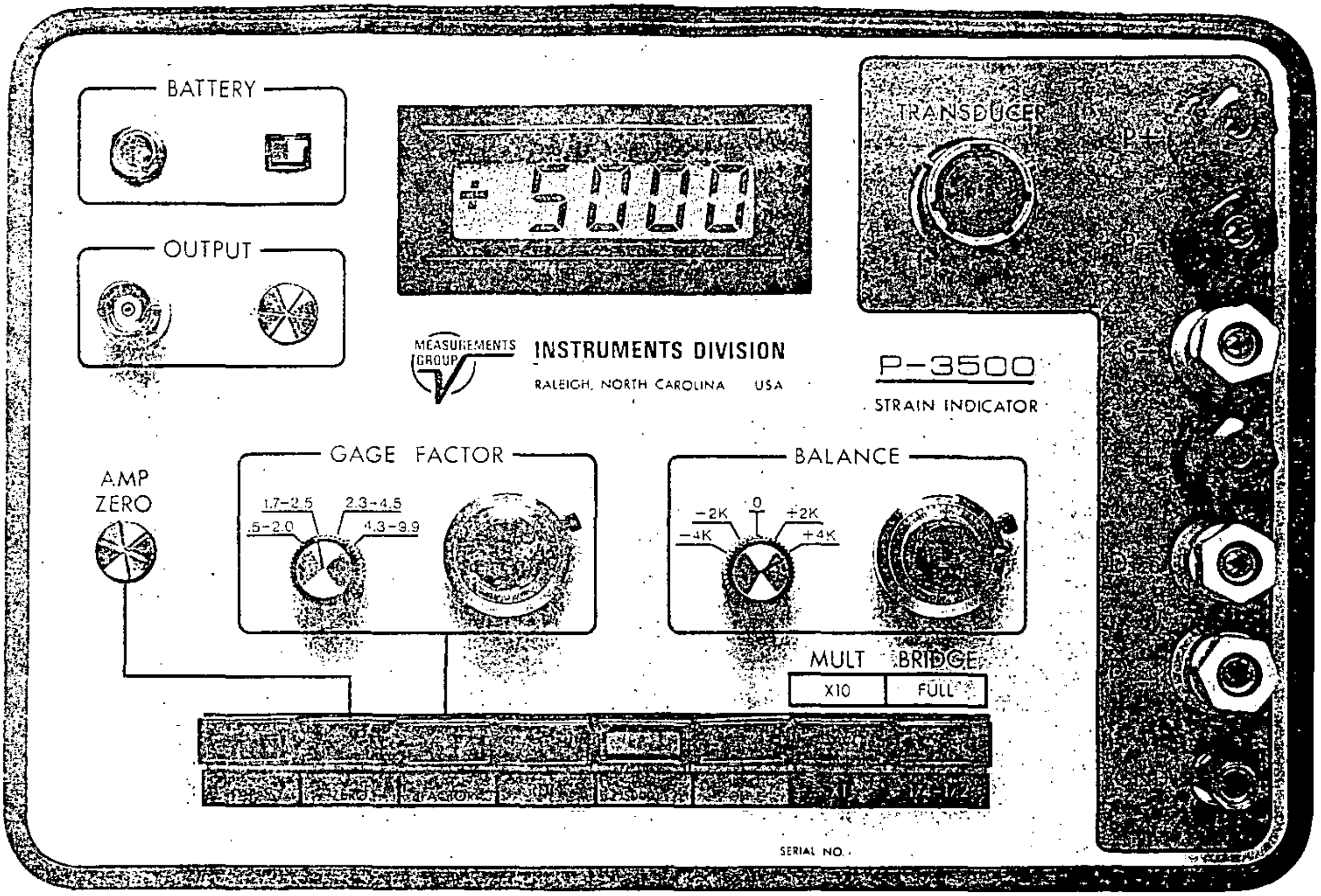


P-3500

PORTABLE STRAIN INDICATOR

Featuring advanced electronic design and unique easy-to-understand operating controls *for making accurate and reliable measurements.*

MEASUREMENTS GROUP
VISHAY



The Model P-3500 Strain Indicator is a portable, battery-powered instrument with unique features for use in stress analysis testing, and for use with strain gage based transducers. The P-3500 offers a choice of LCD or LED readouts, and incorporates many unique operating features that make it the most advanced and easy-to-use instrument of its kind. In use, the operator follows a logical sequence of setup steps by activating color-coded push-button controls to prepare the instrument for making accurate and reliable measurements.

The P-3500 also incorporates a highly stable DC amplifier, precisely regulated bridge excitation supply, and precisely settable gage factor controls.

Static measurements are displayed directly on the indicator's readout with 1$\mu\epsilon$ resolution. An analog output with a −3 dB bandwidth of 4 kHz is provided to drive an external oscilloscope or recorder for dynamic measurements. The instrument will accept full-, half-, or quarter-bridge strain gage inputs, and all required bridge completion components for 120, 350 and 1000Ω gages are built in.

Bridge excitation is 2 Vdc, resulting in low gage power and negligible drift due to gage self-heating. The P-3500 operates in fully ratiometric mode. Minute changes in bridge excitation due to drift or battery deterioration do not affect accuracy of reading.

Gage factor is precisely settable (to a resolution of 0.001) by a front-panel 10-turn potentiometer, and is displayed on the digital readout when the gage factor push button is depressed.

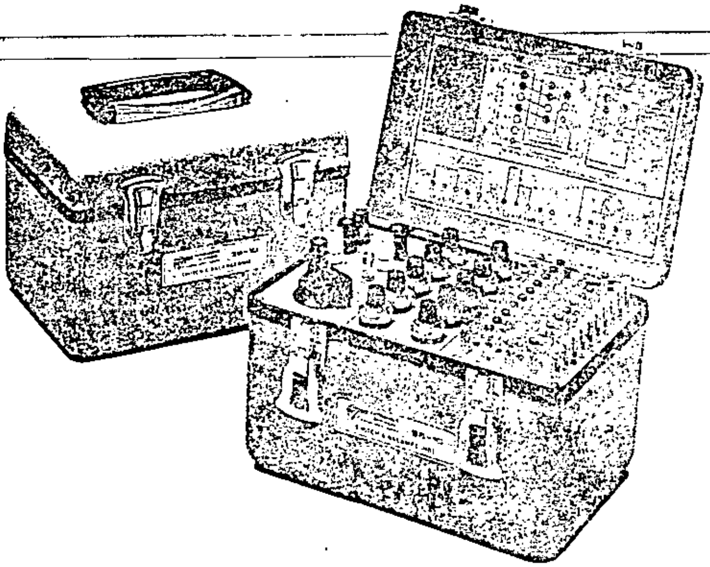
The P-3500 operates from an internal battery pack consisting of six "D" cells, which are readily available worldwide when replacement is required. Battery life is approximately 250 to 300 hours of continuous use (approximately 200 hours with LED readout). Battery condition is monitored by a miniature front-panel meter while the instrument is on. An external line-voltage adapter is also available (115 or 230 Vac, 50 to 60 Hz).

An optional transducer input connector facilitates connection of four- or six-wire strain gage based transducers. The P-3500's unique remote-sense feature is operational whenever the remote-sense leads are connected, and no switching is required. A remote calibration resistor is also accessible via a contact closure at the transducer connector.

FEATURES

- **Choice of 4-1/2 Digit LCD or LED Readout**
- **Direct Reading of Strain, Pressure, Torque, Load, and Other Engineering Variables**
- **Battery or Line-Voltage Operation**
- **Convenient Color-Coded Push-Button Controls**
- **Gage Factor Setting (to four significant digits) Displayed on Readout**
- **Quarter-, Half-, and Full-Bridge Circuits**
- **Built-in 120, 350 and 1000Ω Bridge Completion**
- **Separate Bridge Excitation On/Off Control**
- **Transducer Connector with Remote-Sense**
- **Balance by Voltage Injection**
- **Analog Output**
- **ANSI/SEM Color-Coded Bridge Connection Terminals**
- **Portable, Lightweight, Rugged for Field Use**

MODEL SB-10
COMPANION SWITCH AND BALANCE UNIT FOR THE MODEL P-3500



The SB-10 Switch and Balance Unit features gold-plated push/clamp binding posts to allow fast, convenient, and reliable connection of input circuits, and individual 10-turn potentiometers with turns-counting dial for fine-balance adjustments.

The channel switch of the SB-10 has an OPEN position to allow the use of additional SB-10's with a single P-3500 Strain Indicator. The SB-10 also incorporates a common dummy position for use with other than 120, 350 or 1000Ω gages.

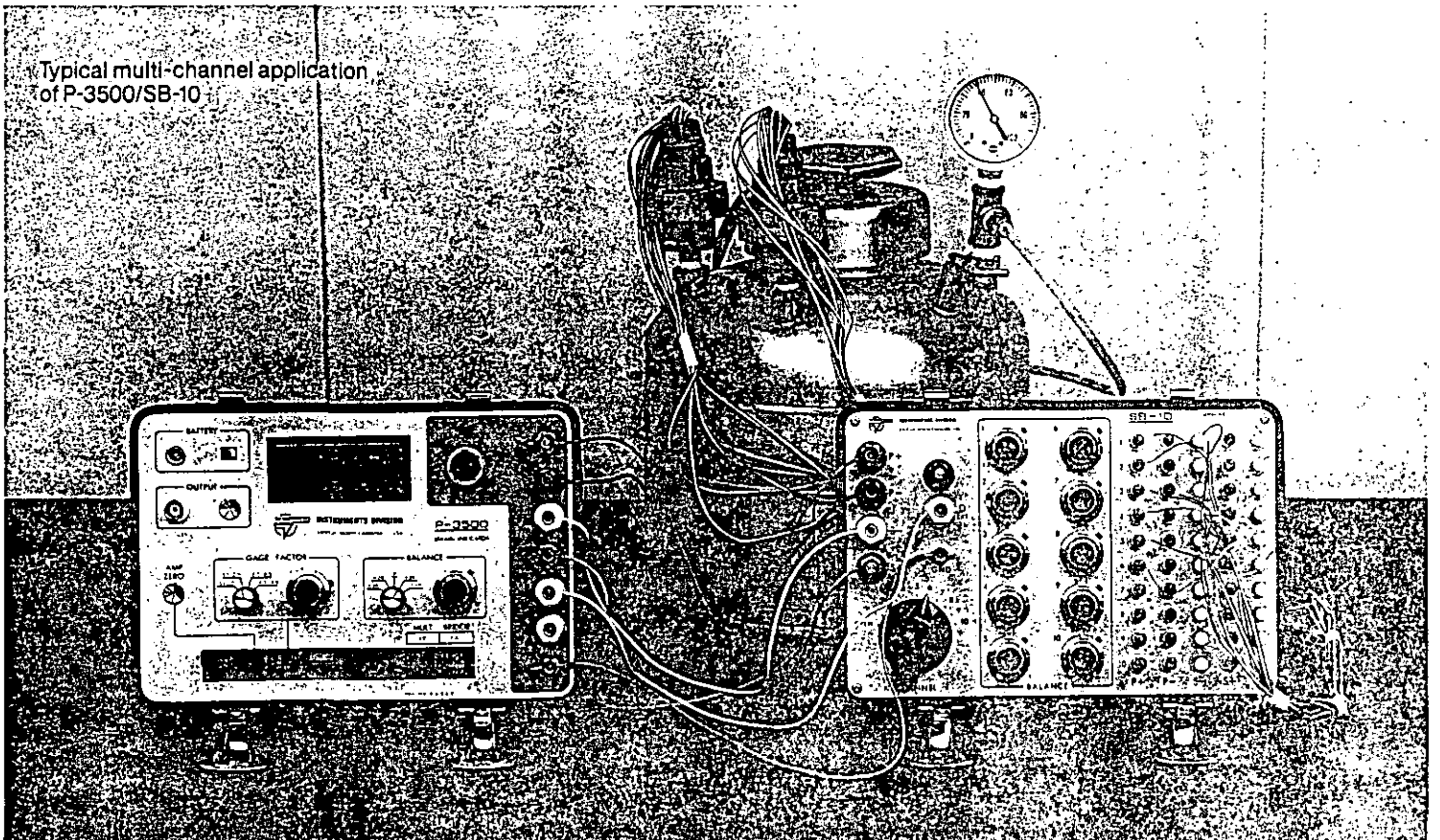
The combination of a P-3500 and SB-10 allows the operator to intermix, in a single 10-channel system, quarter-, half-, and full-bridge circuits. This feature is not found in most portable strain gage instrumentation.

Quarter and half bridges of the same resistance (e.g., all 120 or all 350Ω) can be intermixed in any combination without alteration of either instrument. If the installation makes use of both 120 and 350Ω gages, it is necessary only to connect to the dummy binding post corresponding to the selected gage resistance as the channel is changed.

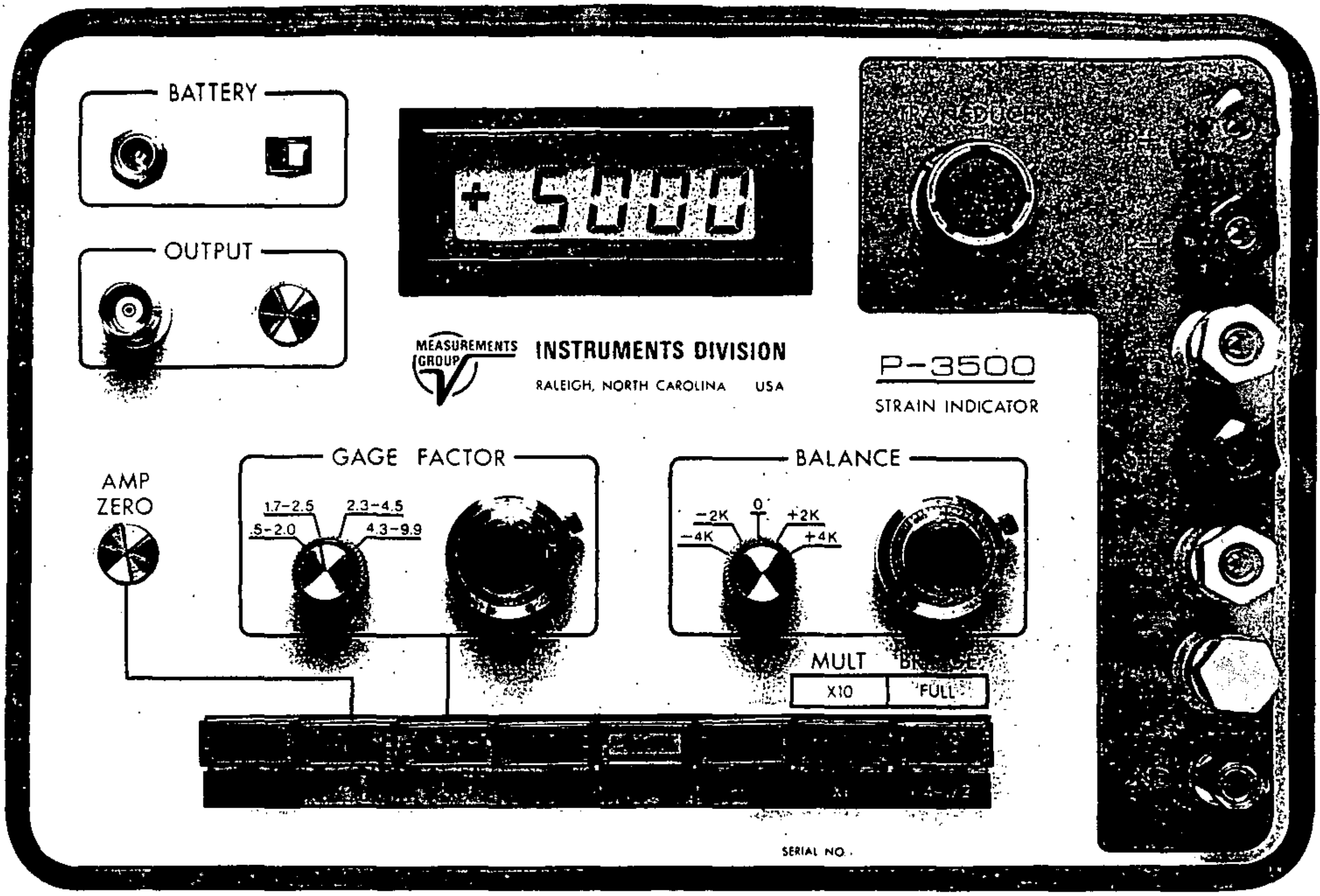
Full bridges can also be intermixed in any combination. In this case, the operator needs only to depress the P-3500 BRIDGE push button to FULL position when a full-bridge channel is selected.

FEATURES

- **10 Channels plus OPEN Position**
- **Gold-Plated Push/Clamp Binding Posts**
- **Rugged, Lightweight**
- **Intermix Quarter, Half and Full Bridges**
- **Negligible Switching Resistance**
- **Switching Repeatability Better than 1$\mu\epsilon$**



Typical multi-channel application of P-3500/SB-10



The Model P-3500 Strain Indicator is a portable, battery-powered instrument with unique features for use in stress analysis testing, and for use with strain gage based transducers. The P-3500 offers a choice of LCD or LED readouts, and incorporates many unique operating features that make it the most advanced and easy-to-use instrument of its kind. In use, the operator follows a logical sequence of setup steps by activating color-coded push-button controls to prepare the instrument for making accurate and reliable measurements.

The P-3500 also incorporates a highly stable DC amplifier, precisely regulated bridge excitation supply, and precisely settable gage factor controls.

Static measurements are displayed directly on the indicator's readout with $1\mu\epsilon$ resolution. An analog output with a –3 dB bandwidth of 4 kHz is provided to drive an external oscilloscope or recorder for dynamic measurements. The instrument will accept full-, half-, or quarter-bridge strain gage inputs, and all required bridge completion components for 120, 350 and 1000Ω gages are built in.

Bridge excitation is 2 Vdc, resulting in low gage power and negligible drift due to gage self-heating. The P-3500 operates in fully ratiometric mode. Minute changes in bridge excitation due to drift or battery deterioration do not affect accuracy of reading.

Gage factor is precisely settable (to a resolution of 0.001) by a front-panel 10-turn potentiometer, and is displayed on the digital readout when the gage factor push button is depressed.

The P-3500 operates from an internal battery pack consisting of six "D" cells, which are readily available worldwide when replacement is required. Battery life is approximately 250 to 300 hours of continuous use (approximately 200 hours with LED readout). Battery condition is monitored by a miniature front-panel meter while the instrument is on. An external line-voltage adapter is also available (115 or 230 Vac, 50 to 60 Hz).

An optional transducer input connector facilitates connection of four- or six-wire strain gage based transducers. The P-3500's unique remote-sense feature is operational whenever the remote-sense leads are connected, and no switching is required. A remote calibration resistor is also accessible via a contact closure at the transducer connector.

FEATURES

- **Choice of 4-1/2 Digit LCD or LED Readout**
- **Direct Reading of Strain, Pressure, Torque, Load, and Other Engineering Variables**
- **Battery or Line-Voltage Operation**
- **Convenient Color-Coded Push-Button Controls**
- **Gage Factor Setting (to four significant digits) Displayed on Readout**
- **Quarter-, Half-, and Full-Bridge Circuits**
- **Built-in 120, 350 and 1000Ω Bridge Completion**
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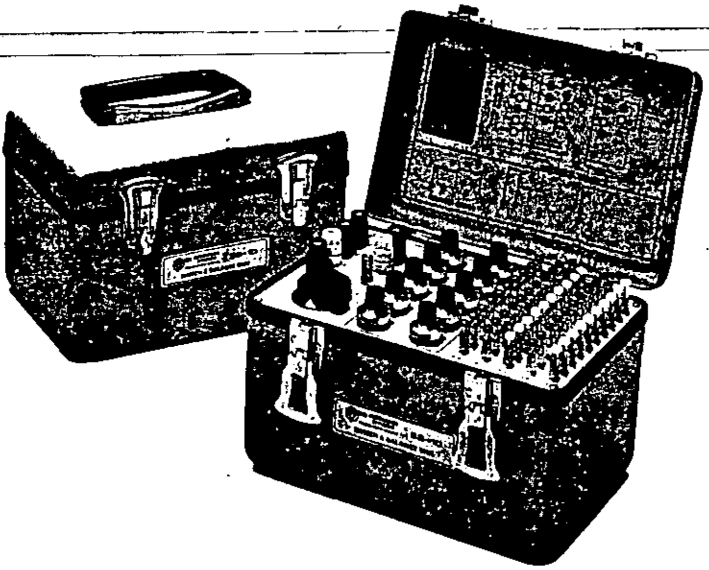
- **Transducer Connector with Remote-Sense**
- **Balance by Voltage Injection**
- **Analog Output**
- **ANSI/SEM Color-Coded Bridge Connection Terminals**
- **Portable, Lightweight, Rugged for Field Use**

MODEL SB-10
COMPANION SWITCH AND BALANCE UNIT FOR THE MODEL P-3500



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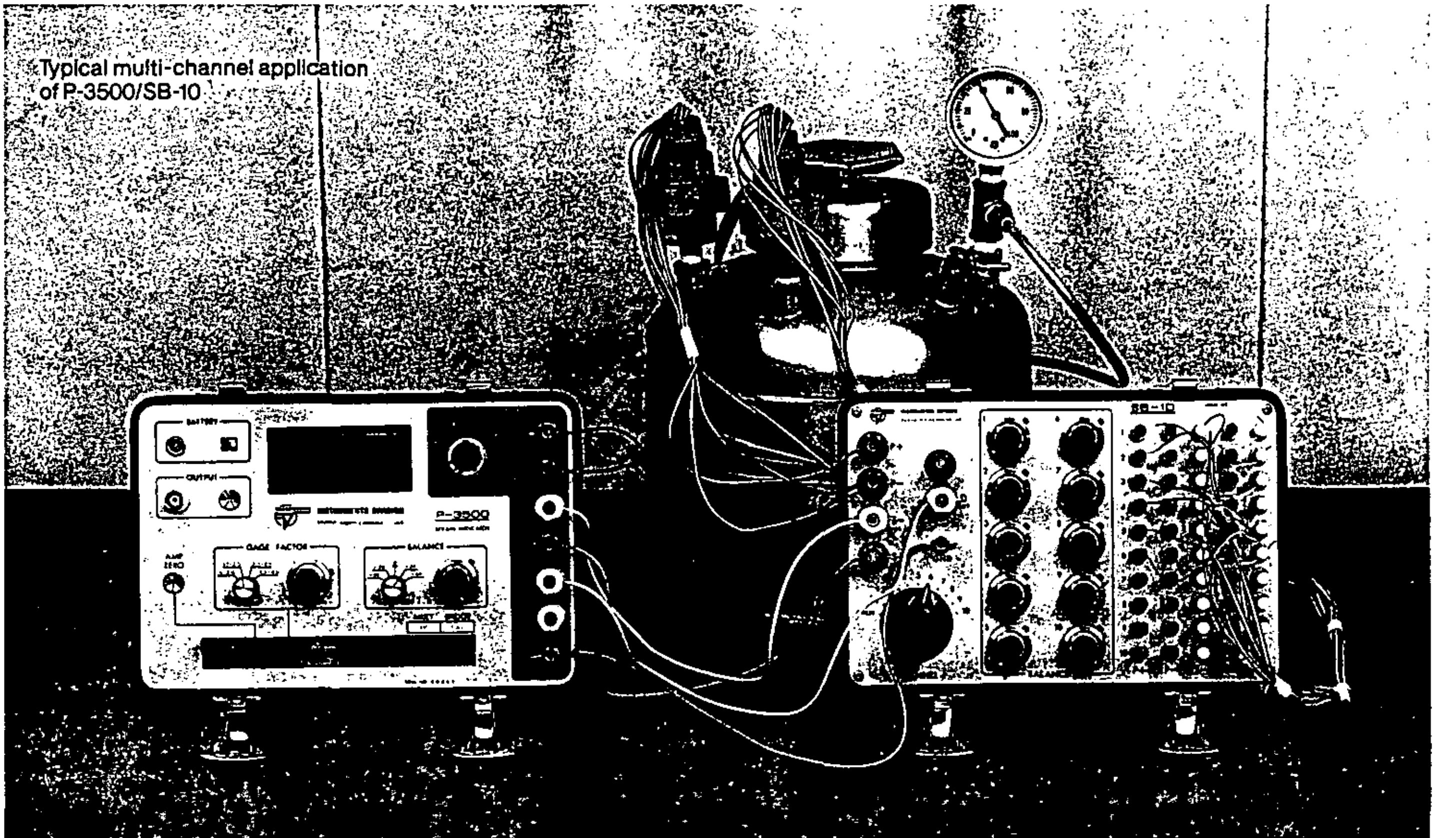
Quarter and half bridges of the same resistance (e.g., all 120 or all 350Ω) can be intermixed in any combination without alteration of either instrument. If the installation makes use of both 120 and 350Ω gages, it is necessary only to connect to the dummy binding post corresponding to the selected gage resistance as the channel is changed.

Full bridges can also be intermixed in any combination. In this case, the operator needs only to depress the P-3500 BRIDGE push button to FULL position when a full-bridge channel is selected.

FEATURES

- **10 Channels plus OPEN Position**
- **Gold-Plated Push/Clamp Binding Posts**
- **Rugged, Lightweight**
- **Intermix Quarter, Half and Full Bridges**
- **Negligible Switching Resistance**
- **Switching Repeatability Better than 1$\mu\epsilon$**


Typical multi-channel application of P-3500/SB-10

SPECIFICATIONS

MODEL P-3500

Range:

±19 999$\mu\epsilon$ at Gage Factor <6.000.

$\pm\frac{6.000}{G \cdot F} \times 19\,999\mu\epsilon$ at Gage Factor >6.000.

Above ranges increased by factor of 10 when using X10 multiplier switch. Example: ±199 990 at Gage Factor <6.000.

Accuracy:

±0.05% of reading ±3$\mu\epsilon$ for Gage Factor settings of 1.000 to 9.900.

±0.05% of reading ±10$\mu\epsilon$ for Gage Factor settings of 1.000 to 9.900 when using X10 multiplier.

Sensitivity (Resolution):

±1$\mu\epsilon$ at all Gage Factor settings.

±10$\mu\epsilon$ when using X10 multiplier.

Gage Factor:

Range 0.500 to 9.900. Precisely settable to a resolution of 0.001 by 10-turn potentiometer and four-position switch. Gage Factor accuracy ±0.02% at all settings. Displayed on digital readout.

Balance:

Coarse: 5 switch positions: Off, ±2000$\mu\epsilon$, and ±4000$\mu\epsilon$ (GF=2.000). Tolerance ±1% nominal.

Fine: 10-turn potentiometer with turns-counting dial, ±1050$\mu\epsilon$ min. range (GF=2.000). Zero position of potentiometer calibrated for zero ±2$\mu\epsilon$.

All balance voltages are electronically injected at input of amplifier. No bridge loading by balance controls, and no compromise of measurement range.

Bridge Excitation:

2.0 Vdc ±0.1%. Temperature stability better than ±0.02% per °C. Readings are fully ratiometric, and not degraded by variation in excitation voltage.

Bridge Configurations:

Quarter-, half-, and full-bridge circuits. Internal bridge completion provided for 120, 350, and 1000Ω quarter bridges. 60 to 2000Ω half or full bridge.

Amplifier:

Warm-up drift: Less than ±3 counts at GF=2.000, cold start to ten min.

Random drift at constant ambient temperature: Less than ±1 count at GF=2.000.

Common-mode rejection: Greater than 90 dB, 50 to 60 Hz.

Temperature effect on zero: Less than 1 μV/°C referred to input.

Temperature effect on span: Less than 0.005%/°C.

Input impedance: Greater than 30 MΩ.

All specifications nominal or typical at +23°C unless noted.

Calibration:

Shunt calibration across 120 and 350Ω dummy gages to simulate 5000$\mu\epsilon$ (±0.05%).

Analog Output:

Linear ±2.50V max. Adjustable from 40 $\mu V/\mu\epsilon$ to 440 $\mu V/\mu\epsilon$, nominal. Output load 2 KΩ min. Bandwidth, DC to 4 kHz, −3 dB nominal. Noise: Less than 400 μV rms at 40 $\mu V/\mu\epsilon$ output level.

Remote Sense:

Provided at the transducer connector. Remote-sense error less than 0.001%/Ω of lead resistance.

Power:

Internal battery pack using six "D" cells. Battery life 300 hours nominal (200 hours with LED readout).

Case:

Aluminum.

Size and Weight:

9 x 6 x 6 in *(228 x 152 x 152 mm)*. 6.3 lb *(2.9 kg)* including batteries.

Accessories:

Line voltage adapter for 115V or 230V, 50 or 60 Hz operation.

Transducer input connector.

MODEL SB-10

(when used with Model P-3500)

Circuits:

10 channels plus OPEN position.

Inputs:

Will accept quarter-, half- or full-bridge circuits in any combination, including three-wire quarter bridges.

Balance Range:

±5800$\mu\epsilon$ for quarter-, half-, and 350Ω full-bridge inputs.

±2000$\mu\epsilon$ for 120Ω full-bridge inputs.

Switching Repeatability:

Better than 1$\mu\epsilon$.

Size and Weight:

9 x 6 x 6 in *(228 x 152 x 152 mm)*. 5.5 lb *(2.5 kg)*.

The Measurements Group is a leading supplier of strain gage instrumentation. Available instruments include portable indicators, signal conditioners/amplifiers, strain gage installation tester, instrument calibrator, and sophisticated computer-controlled systems for the acquisition, storage and reduction of test data. Call or write for all of your strain gage instrumentation needs.

MEASUREMENTS GROUP VISHAY

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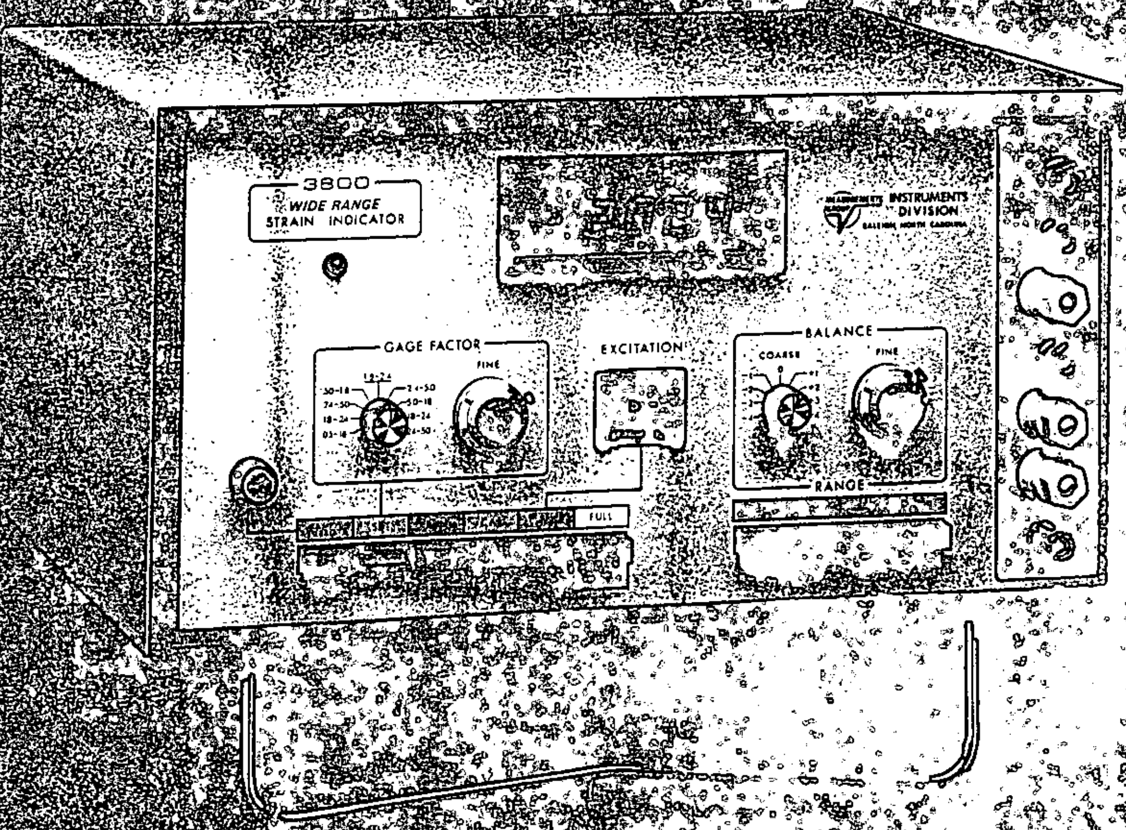
Telex 802-502 • FAX (919) 365-3945

021621HP
Printed in USA

Bulletin 249



3800

WIDE RANGE STRAIN INDICATOR

A versatile high-performance laboratory-type instrument featuring wide-range operating controls for handling the most critical strain measuring tasks.

MEASUREMENTS GROUP VISHAY

NEW HORIZONS IN RANGE • RESOL

NEVER BEFORE ACHIEVED IN A LABORATORY INSTRUMENT

The Model 3800 *Wide Range* Strain Indicator is a versatile, high-precision laboratory-type instrument designed for use with strain gages and strain-gage-based transducers.

Principal features of the Model 3800 are wide-range control of gage factor; excitation precisely settable over 1—15 volt range; and wide balance range with no bridge loading effect.

With these extended operating capabilities, the Model 3800 can be used for the most demanding measurement tasks which are not possible with conventional strain measuring instruments and general-purpose transducer indicators. Resolutions achievable with the Model 3800 are 0.10$\mu\varepsilon$ when used as a strain indicator, and 0.10 μV/V when used as a transducer indicator (0.025 μV/V with suppressed zero).

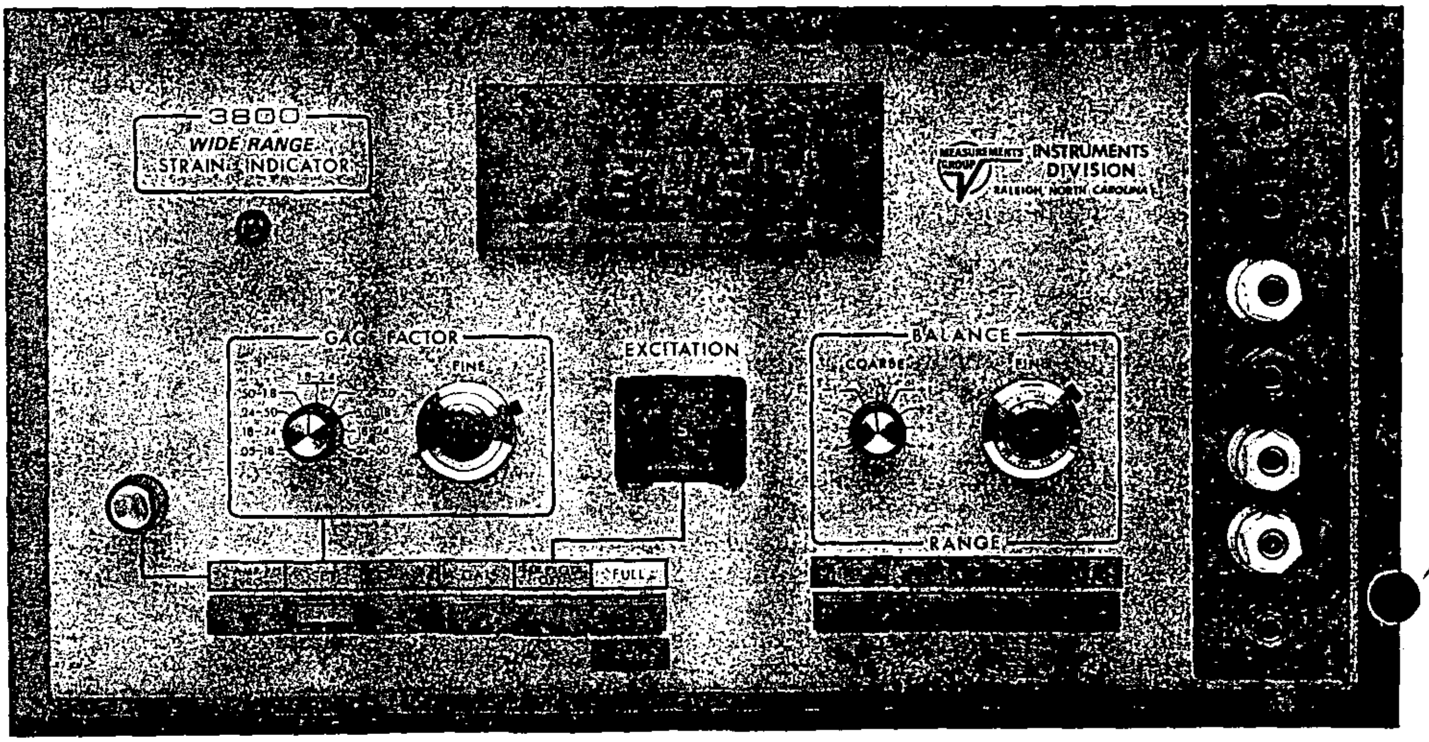
In addition to the wide-range features, the Model 3800 incorporates simplified operating controls that minimize set-up time, and promote measurement accuracy. The operator follows a logical sequence of steps to configure the instrument for the desired measurement. Color-coded interlocked push-button controls minimize operator errors, and make the operating mode instantly recognizable.

Gage factor on the Model 3800 is settable by front panel controls over a range of 0.0500 to 50.00, and is displayed by the LED readout when in the SET position. The instrument allows full range display (±19 999 counts) over the complete gage factor range.

Excitation voltage is precisely settable over a range of 1—15 volts in 1-volt increments by a front-panel thumbwheel switch. The output display automatically tracks the excitation setting so that gage factor does not vary with bridge voltage.

The balance system in the Model 3800 has four ranges which are selected by the BALANCE RANGE push buttons. Each range is further divided into four sub-ranges by the COARSE balance switch. The FINE balance control provides an additional adjustment range that overlaps the COARSE balance switch positions. This unique system provides a total of 32 overlapping ranges for achieving precise balance settings and resolution. All balance voltages are electronically injected into the input amplifier to eliminate bridge loading errors and preserve full measurement range.

FRONT PANEL



ION VERSATILITY

Input circuitry includes an ultra-stable internal half-bridge, as well as internal 120- and 350-ohm dummy gages for bridge completion. Shunt-calibration resistors across the internal dummy gages are provided on the rear panel. Two remote calibration resistors, also mounted on the rear panel, are automatically actuated by the front-panel calibration button.

Virtually all strain-gage-based transducers can be used with the Model 3800 via the rear-panel transducer connector. This connector provides precision remote-sense capability, as well as access to the remote calibration resistors. Full-scale resolutions of 0.10 μV/V are routinely possible. By using the wide-range balance controls to suppress zero, resolutions to 0.025 μV/V can be achieved.

In addition to the digital LED display, the Model 3800 provides an analog output available at the rear panel. A separate analog level control totally independent of the digital display is also provided.

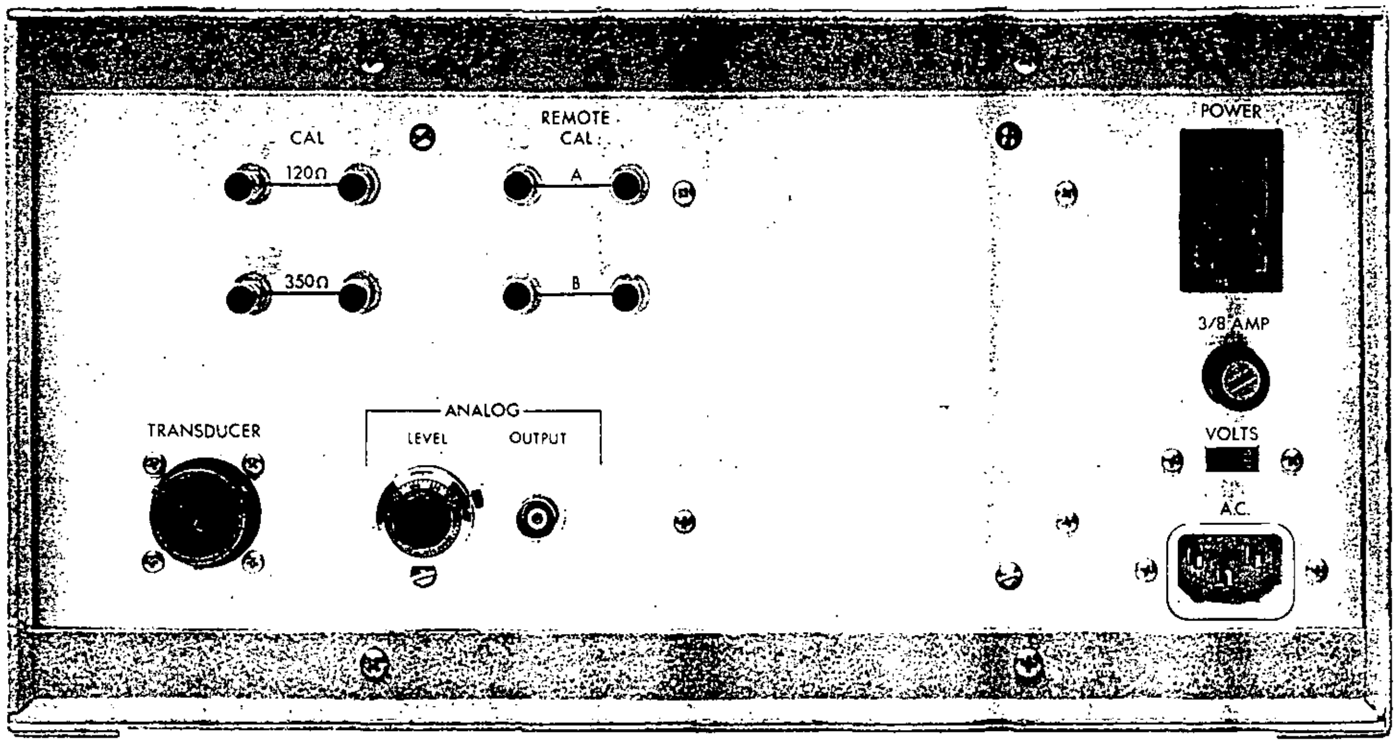
The Model 3800 *Wide Range* Strain Indicator is an exceptional, high-resolution instrument that will make a valuable contribution to any experimental stress analysis or transducer development laboratory.

FEATURES

- 4-1/2 Digit LED Display
- ANSI/SEM Color-Coded Bridge Connection Terminals
- Analog Output
- Transducer Connector with Remote Sense
- Direct Reading of Strain, Pressure, Torque, Load, and other Engineering Variables
- Convenient Color-Coded Push-Button Controls
- Gage Factor Range from 0.0500 to 50.00 Displayed on LED Readout (to four significant digits)
- Bridge Excitation Range from 1.000 to 15.000 Vdc
- Extremely Wide Balance Range. Balance by Voltage Injection.
- Quarter-, Half-, and Full-Bridge Circuits
- Separate Bridge Excitation On/Off Control
- Built-in 120- and 350-ohm Dummy Gages

Complete specifications for the Model 3800 are given on the back of this bulletin.

REAR PANEL



SPECIFICATIONS

Range and Display:

±19 999 counts direct-reading LED display.

Resolution:

1με at any Gage Factor from 0.0500 to 50.00.
0.10 μV/V as a transducer indicator.

Linearity:

±0.01% of full scale.

Balance Range:

Coarse Balance: ±2.5% to ±100% of full scale per step, in 32 total steps.

Fine Balance: ±1.25% to ±50% of full scale; overlaps each coarse balance step.

Balance Method:

Electronically injected counter-emf.

Gage Factor:

Range: 0.0500 to 50.00; displayed by LED readout when in the SET position.

Resolution: 0.0001 from GF of 0.0500 to 0.5000.
0.001 from GF of 0.500 to 5.000.
0.01 from GF of 5.00 to 50.00.

Linearity: ±0.05% of full scale.

Accuracy: ±1 least significant digit.

Excitation Voltage:

1.000 to 15.000 Vdc ±1 mV ±0.02%. Settable in 1V increments by front-panel thumbwheel switch.

Temperature Stability: ±0.01%/°C.

Amplifier:

Temperature Effect on Zero: ±1.0 μV/°C RTI† max.;
±0.50 μV/°C RTI† typical.

Temperature Effect on Span: ±0.005%/°C max.

Warm-up Drift: Less than ±3 μV RTI† from turn-on to 5 minutes.

Random Drift at Constant Ambient Temperature:
Less than ±1 μV RTI†.

Common-Mode Rejection: Greater than 100 dB at 50-60 Hz.

Common-Mode Voltage: ±8V max.

Input Impedance:
Greater than 100 MΩ differential and common mode.

Input Circuits:
60 to 10 000Ω half or full bridge. Internal dummy gages are provided for 120Ω and 350Ω quarter bridges.

Calibration:
Shunt calibration resistors are provided across internal 120Ω and 350Ω dummy gages to simulate 5000με ±0.05%. Calibration resistors are located on the rear of instrument and may be changed to suit specific requirements.

Contact closures are provided for two rear-panel-mounted resistors to facilitate any calibration configuration. Typical use is double-shunt calibration of transducers.

Analog Output:

Linear Output: ±10.00V max; adjustable over 11:1 range by a ten-turn potentiometer mounted on the rear panel.

Output Load: 2 kΩ min.

Bandwidth: GF > 0.500, DC to 4.5 kHz (−3 dB nominal).
GF < 0.500, DC to 2.0 kHz (−3 dB nominal).

Output Noise: Less than 2.5 μV peak to peak 0.10 to 10 Hz, RTI†. Less than 2 μV rms dc to 5 kHz, RTI†, plus 0.005% of full scale, RTO (referred to output).

Remote Sense:

Remote sense connections provided at transducer connector.

Remote Sense Error: Less than 0.0005%/Ω of lead resistance. Maximum lead resistance 40Ω or less.

Power:

115/230 Vac, 50—60 Hz, less than 10 volt-amperes.

Size and Weight:

6.5 H x 11.0 W x 12.5 D in *(165 x 280 x 318 mm).*
10.2 lb *(4.6 kg).*

Companion instruments for use with the Model 3800

Model SB-10—A high-quality 10-channel Switch and Balance Unit that allows multiple gage hook-up to the Model 3800 Strain Indicator.

Model V/E-40 Decade Resistor Strain Gage Simulator, and Model 1550A Strain Indicator Calibrator—with these specialized instruments, the capabilities and sensitivity of the Model 3800 can be further extended by making critical measurements through precise strain simulation.

---

† *Referred to input*

All specifications are nominal or typical at +23°C unless noted.

The Measurements Group is a leading supplier of strain gage instrumentation. Available instruments include portable indicators, signal conditioners/amplifiers, strain gage installation tester, instrument calibrator, and sophisticated computer-controlled systems for the acquisition, storage and reduction of test data. Call or write for all of your strain gage instrumentation needs.

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Printed in USA

Bulletin 235-E

System 4000

Unique Power and Simplicity in a Data System for Stress Analysis, Structural and Materials Testing

```
                  SENSOR INFO-ENTRY MENU                9:24:24 AM

========================[ Strain Gage Scanner ]========================
   STRAIN GAGE CHANNEL INFO               ROSETTES
<GF>  Gage Factor                   <RO>  Rosette Types and Elements
<TC>  Temperature Corrections       <KT>  Kt (Transverse Sensitivity)
<SH>  Shunt Calibration (ue)        <MP>  Material Properties
<AA>  Active Arms                   <MA>  Material Assignment to Channels

   NON-GAGF       INFO                   GAGE LOTS
<MT>  =MM=       e S                      Enter                 GF
<ST>  Stra       nsc                      Enter                 s
                                          Therm                 ession
```

MEASUREMENTS GROUP
VISHAY

System 4000 — It Pays

. . . with dividends like weight reduction and material savings, performance improvements and failure prevention, and shortened design-to-development time. In today's demanding world of product and structural design, payoffs like these can make a big difference.

Experimental Stress Analysis (ESA) is often called the **quality control of design** because it assures maximum reliability with minimum material and weight. Even with recent advances in analytical methods using finite-element analysis and high-speed computers, essential data which can affect not only design results but also product life, liability, and profitability, can be provided only by ESA technology.

The leaders in nearly every industry depend on the Measurements Group for the equipment and expertise to apply the quality-control benefits of ESA to their designs. And the System 4000 approach to stress analysis provides these benefits more effectively — and economically — than ever before.

Unique Power and Simplicity

. . . to meet today's measurement challenges. System 4000 is completely preprogrammed to perform all system functions. It accepts and stores test parameters, controls the scanning operations, records input signals, and corrects and reduces the data to provide directly usable engineering information.

The System's hardware incorporates all of those features that strain gage users have come to expect from the Measurements Group for more than 30 years, including precision bridge completion for quarter- and half-bridge circuits, and selectable bridge excitation. And, for maximum stability and noise rejection, System 4000 incorporates a 14-bit (plus sign), dual-slope integrating A/D converter, synchronized to line frequency for data acquisition.

In addition to its many special features which simplify the acquisition and reduction of strain gage data, System 4000 is also equipped to handle inputs from the other types of sensors commonly used in stress analysis and structural testing, including thermocouples, RTD's, LVDT's, load cells, DCDT's, potentiometers and other transducers.

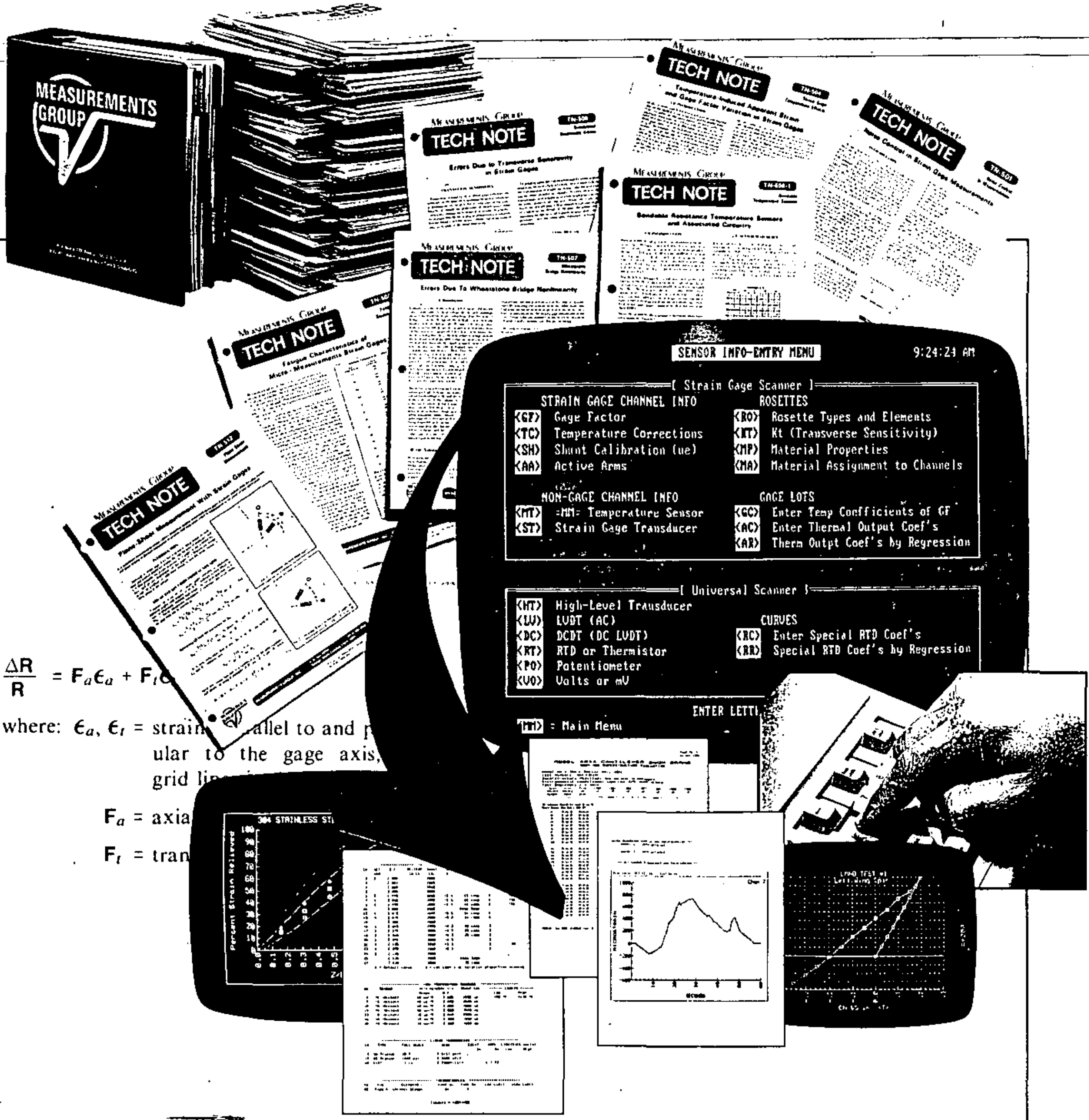
The Premier Data System

. . . today and tomorrow. System 4000 has been acknowledged by hundreds of users as the world's premier data system for stress analysis, structural and materials testing since its introduction in 1981. In the years since, both hardware and software have been enhanced and refined, through significant commitments we've made to ensure that System 4000 remains the world's premier data system.

About This Brochure

The Measurements Group's commitment to System 4000 is long term. In this brochure, you will read about some of our ongoing programs and development efforts which we believe will keep System 4000 the world's premier data system for stress analysis and structural testing. Operating software enhancements and new hardware developments are but a few of the programs in place to keep System 4000 expansion in pace with the needs of its users.

Because of the ongoing nature of these programs, this brochure can serve only as an introduction to the concept behind System 4000. To keep System 4000 users informed of important developments, *System 4000 Update — the Users Group Newsletter*, is published periodically and distributed to all System 4000 users throughout the world. As you are reading this, chances are that new and more powerful aspects of System 4000 are *already* available.



Strain gage technology has developed into the world's most widely used precision stress/strain measurement technique. Over the years, through our Technical Data Mailing Program, we have treated technical matters relating to stress analysis in a practical, usable fashion that we hope most benefits you, the user, in your stress analysis applications. The primary factors affecting strain gage and instrumentation performance are covered in the *Tech Note* portion of the Measurements Group's Strain Gage Technology literature binder, recognized and used as the authoritative reference for strain gage measurement by practitioners throughout the world.

Virtually all of the materials included in the Measurements Group's Strain Gage Technology Tech Note library are incorporated into System 4000's extensive software package, designed by Measurements Group engineers. Now, you can apply these techniques directly to your test measurements.

Computer technology has impacted virtually all disciplines of engineering, primarily through the greatly expanded potential for computational speed, accuracy, and flexibility provided by software. While the System 4000 hardware is designed for the highest performance/cost ratio possible, it is the software that provides the true power behind System 4000.

The System

4220
CONTROLLER

Serves as the interface between the Executive Unit and the System's scanners, providing primary system power, channel display, and analog-to-digital conversion.

4270A
STRAIN GAGE SCANNER

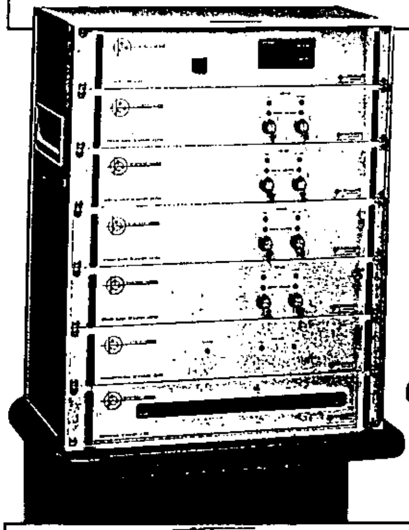
Each scanner accommodates 20 channels of strain gage inputs (quarter, half, or full bridge). Switch-selectable bridge excitation is provided for each block of 10 channels.

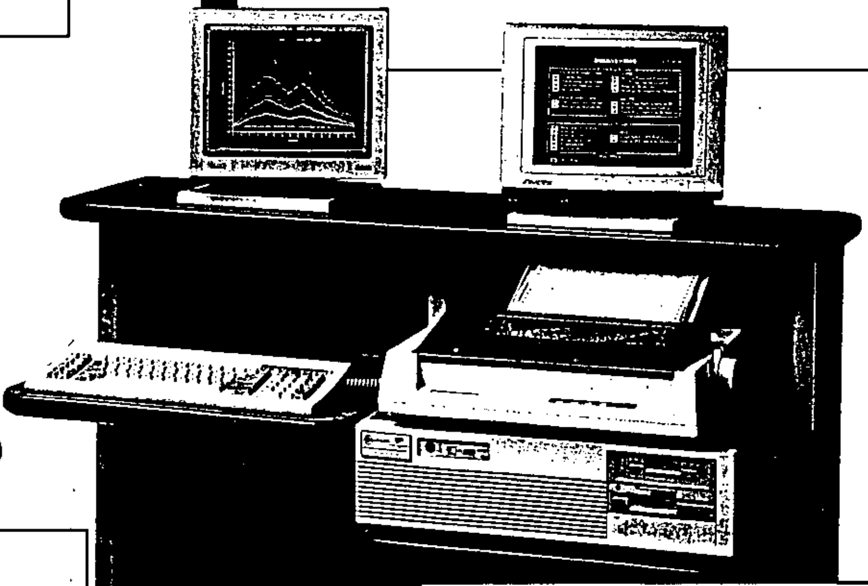
SOFTWARE/HARDWARE CONFIGURATIONS

The heart of System 4000 is the extensive software that organizes, processes, and presents test data in various modes as required by the user. **Model 610 Standard System Software** operates on a wide range of customer-supplied, general-purpose personal computers, including laptops.

For tests requiring more modest capabilities, the lower cost **Model 605 Data Logger Software** is also available. *A listing of specific hardware component requirements for both software packages is available, upon request, from our Applications Engineering Department.*

Additionally, the **Model 4216 Executive Unit** (shown here), consisting of Model 510 Standard System Software and Model 4202 Computer Hardware Components, is available to those wishing to purchase a complete, dual-monitor turn-key system.





4280
UNIVERSAL SCANNER

Capacity for 10 channels of mixed inputs, including thermocouples, LVDT's, RTD's, DCDT's, semiconductor transducers, potentiometers and voltage inputs.

4290
THERMOCOUPLE SCANNER

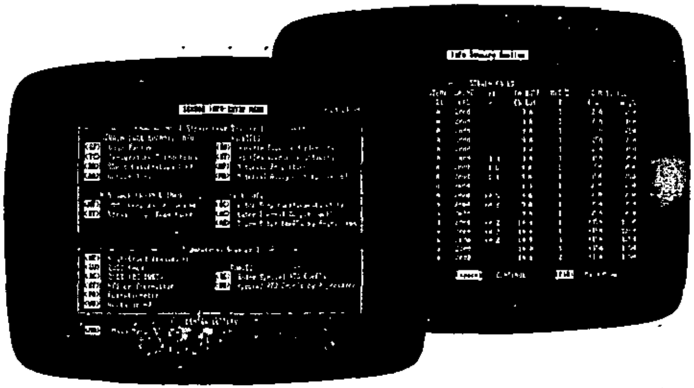
Provides dedicated capability for 20 channels of thermocouple inputs (Types J, K, T, E, R, S, B). Type is selectable for each block of 10 channels.

PRINCIPAL FEATURES

- Complete, preprogrammed software
- Inputs accepted from strain gages, strain gage based transducers, LVDT's, DCDT's, potentiometers, thermocouples, and RTD's
- Input capacity from 1 to 1000 channels — expandable as needed at any time
- Scanning speed up to 30 channels per second (25 channels per second for 50 Hz operation)
- Automatic bridge balance (offset values stored in memory and/or permanently recorded)
- Switch-selectable excitation voltage (1, 2, 5, 10 Vdc)
- Built-in bridge completion for all 120 and 350Ω strain gage channels (quarter and half bridges)
- PC-compatible for user-preferred off-line data handling

TEST INFORMATION ENTRY

- Channel assignment
- Gage Factor
- Thermal output coefficients
- Gage factor temperature coefficient
- Transducer input/output specifications
- Control limits (by channel or by groups) (except Model 605)
- Active bridge arms
- Transverse sensitivity
- Modulus of elasticity
- Poisson's ratio



SOFTWARE CAPABILITIES

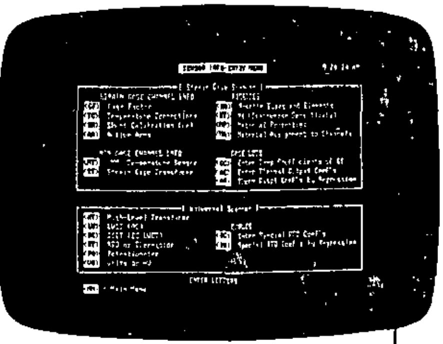
The scope and capabilities of System 4000's standard, preprogrammed stress analysis software far exceed those of other commercially available packages, which are generally designed for narrowly defined applications only.

- Rosette data reduction (delta, rectangular, biaxial) and conversion of strains to stress
- Thermal output correction
- Correction for gage factor temperature coefficient
- Scaling for number of active bridge arms
- Wheatstone bridge nonlinearity correction
- RTD linearization
- Transverse sensitivity correction
- Thermocouple linearization
- Alarm or control limits (print or initiate scan) (except Model 605)
- On-line monitoring of key channels and/or rosette solutions in numeric and graphic (except Model 605) formats
- Reduced data can be printed for up to 1000 channels
- Automatic or manual data scan and record
- Data storage for later analysis or processing
- Off-line plot generation on color monitor or optional plotter (except Model 605)

Optional software packages for specialized test requirements are also available.

Add to Your Test Program

ACCURACY



Accurate strain gage measurements require that attention be paid to characteristics unique to the strain gage itself — characteristics such as thermal output, transverse sensitivity, nonlinearity of output from the Wheatstone bridge, temperature coefficient of gage factor, and grid power dissipation. In addition, care must be taken to apply corrections at the appropriate stage in the measurement process. System 4000 can take into account as many — or as few — of these potential error sources as your test requires.

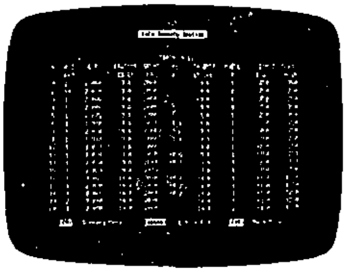
For thermocouple measurements, a unique, isothermal strip eliminates temperature gradients between input terminals.

The System's specially selected analog-to-digital converter uses a dual-slope conversion technique to integrate the analog signal over a complete powerline cycle, making it possible to achieve the high resolution and excellent noise rejection essential for accurate strain measurements.

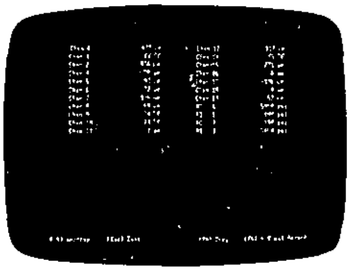
Through its unique software and hardware, System 4000 provides the test operator with the tools to obtain the most accurate test data possible.

ON-LINE MONITORING

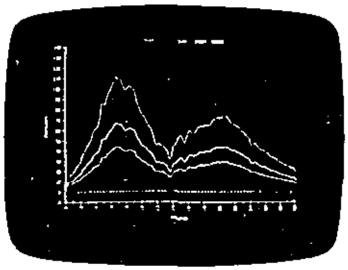
System 4000 provides a wide range of options for monitoring test parameters and data, including:



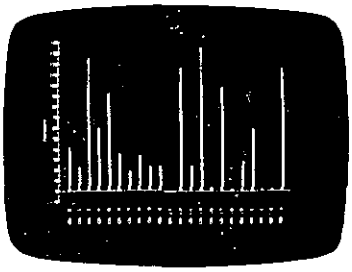
Test parameters reviewed through a screen display before testing is begun.



Up to 44 key channels of corrected and reduced data simultaneously displayed and updated.

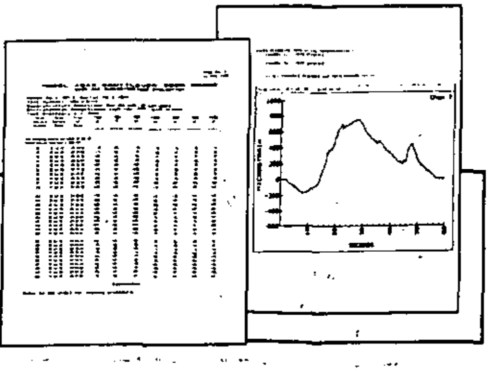


Up to 12 line plots of data (vs. data or time) displayed (except Model 605).



Up to 44 bar graphs that change color when user-defined trip levels are exceeded — allowing for fast recognition of critical test conditions (except Model 605).

FLEXIBILITY IN DATA PRESENTATION



Through the System's Data Translation Program, data files can be transformed into ASCII, DIF, or WKS formats, allowing for easy manipulation and presentation of data with commercial software packages or user-developed programs.

Worldwide, System 4000 Users* Are Putting Power, Accuracy, and Simplicity Into Their Stress/Strain Measurement Programs

In Industry and Research . . .

- AM General
- AT&T Bell Laboratories
- Admiralty Marine Technology Est.
- Aerospatiale
- Agency for Defense Development
- Alcoa Technical Center
- Alfa Romeo S.P.A.
- Alsthom Atlantique La Rochelle
- American Sterilizer
- Amp
- Armco Steel
- Astech
- Avions Huret/Dubois
- Baker Tubular Services
- Beech Aircraft
- Bender Machine Services
- Bendix Aerospace
- Blue Bird Body Company
- Boeing
- Borg-Warner
- British Nuclear Fuels
- British Steel Corporation
- Brookhaven Laboratories
- L.J. Broutman & Associates
- CASA
- CNERIB Alger
- Cameron Iron Works
- Canocean Resources
- Chrysler Corporation
- Clark Michigan Company
- Crown-Zellerbach
- Cummins Engine
- Daimler-Benz AG
- Defense Product Assurance Agency
- Delas Weir
- Dominion Engineering
- Dow Chemical
- Dow Corning Wright
- Dunlop Aviation Division
- E. I. DuPont Company
- E.C.A.N.
- ETSI Industriales
- Eaton Axle Division
- Electricite de France
- Equipos Nucleares
- Etablissement Central de L'Carmement Naval de Nantes
- Exxon
- Fiberglas
- Fisher Controls
- Flxible Corporation
- Ford Aerospace
- Ford Motor Company
- GEC Research Centre
- GM, Allison Gas Turbine Division
- GM, Chevrolet Division
- GM Technical Center
- Garrett Turbine Engine Company
- General Dynamics
- General Electric Company
- Gilbarco
- Gradall Company
- Graviner Limited
- Groupe P.S.A.
- Grove Manufacturing
- Grumman
- Hamilton Standard
- Harris Corporation
- Hindustan Motors
- Hughes Aircraft
- Hughes Offshore
- Hunting Oilfield Services
- Hyundai
- IBM
- IMPA, SPA
- Institute for Industrial Research & Standards, Ireland
- Israel Aircraft Industries
- Isringhausen Railroad Products
- J.A. Jones Applied Research
- Jin Hae Machine Depot
- Korea Institute of Mining & Metals
- Knolls Atomic Power Labs
- Koch Fiberglass
- Kon Mij de Schelde
- Laboratoire du Baltiment et Travaux Publics a Libreville
- Laboratorio Ensayo Investigacion Industrial
- Laboratoire des Ponts et Chaussées de Toulouse
- McDonnell Douglas
- Marshalls of Cambridge Engr.
- Martin Marietta Aerospace Co.
- Martin Marietta Energy Systems
- Massachusetts General Hospital
- Menasco
- Metalastik Vibration Control Sys.
- Metallurgical Engineers
- Michelin Tire
- Ministry of Defence, France
- Motor Wheel Corporation
- NASA
- National Aeronautical Lab (India)
- National Crane Company
- National Forge Company
- National Research Council of Canada
- Naval Ocean Systems Ctr. (U.S.)
- Naval Science & Technological Lab (India)
- Naval Surface Weapons Ctr. (U.S.)
- Navistar International
- Neil F. Lampson
- Newport News Shipbuilding
- O'Donnell & Associates
- Olkon Corporation
- Omark Industries
- Ontario Hydro
- PPG Industries
- Pettibone-Tiffin
- Piasecki Aircraft
- Picker International
- Pratt & Whitney Aircraft Co.
- Precision Medical Instruments
- Pullman Technology
- Research & Development Establishment (India)
- Richards Medical
- Rockwell Intl, Rocketdyne Div.
- SEMAT
- SNECMA Villaroche
- SPAR Aerospace
- STE Alkan Aeronautique
- STE Beta
- STE Elmex Paris
- STE Eternit
- STE Hermex
- STE Messier Aeronautique
- STE Thomson
- Samsung
- Shell Development Company
- A.O. Smith
- Southwest Research Institute
- Specialty Measurements
- Steiger Tractor
- Stress Engineering Services
- Tadiran
- Tennessee Eastman
- Terex Corporation
- Textron Lycoming
- Thrall Car Manufacturing Co.
- Trinity Engineering
- U.S. Air Force
- U.S. Army
- U.S. Marine Corps
- U.S. Navy
- VME America
- Volvo Flygmotor AB
- WSM Industries
- Water Research Center
- Waukesha Engine
- Weber Aircraft
- Westinghouse Electric
- Whitehead Motofides S.P.A.

In Education . . .

- American University of Beirut
- Auburn University
- Beijing Aeronautical Institute
- California Polytechnic State Univ.
- Carleton University
- The Citadel
- Columbia University
- Dublin College of Technology
- Ecole Centrale de Lyon
- Ecole D'Ingenieures de Yamoussoukro
- Ecole Superieure D'Ingenieurs des Techniques du Bois
- Electronics & Telecommunication Research Institute
- Enit Tunisia University
- General Motors Institute
- Howard University
- Indian Institute of Technology
- Institut Francais de Petrole
- Institut National de Genie Mecanique Algiers
- Institut Nationale de Toulouse
- Institut Universitaire de Bordeaux
- Institut Universitaire de Bourges
- Institut Universitaire de Reims
- Kuwait University
- Metropolitan Medical Center
- Michigan State University
- Nan Yang Technical Institute
- Oklahoma State University
- Rochester Institute of Technology
- Southern Illinois University
- Swarthmore College
- U.S. Naval Post-graduate School
- Universidad de Oviedo
- Universite de Lille
- University of Bari
- University of Bridgeport
- University of California
- University of Dayton
- University of Delaware
- University of Grenoble
- University of Illinois
- University of Louisville
- University of Maryland
- University of Miami
- University of Michigan
- University of Nova Scotia
- University of Petroleum & Minerals
- University of Pittsburgh
- University of South Florida
- University of Toledo
- University of Trieste
- University of Wisconsin
- Villanova University
- Virginia Polytechnic Institute and State University
- Washington University
- Youngstown State University

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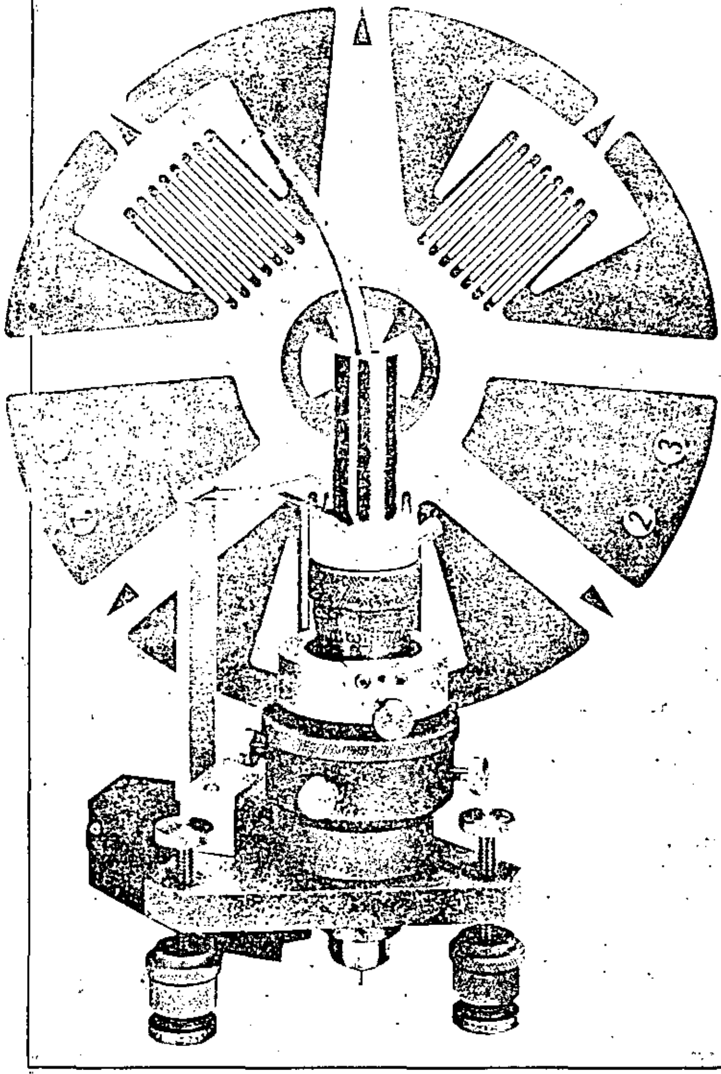
*The listing represents a selection of organizations using System 4000 at the time this brochure was printed. Inclusion does not imply endorsement.

. . . Shouldn't You?



Strain Gages and Instrumentation for Residual Stress Measurements

A predominant factor contributing to the structural failure of machine parts, pressure vessels, framed structures, etc., may be the residual "locked-in" stresses that exist in the object prior to its being put into service. These residual stresses are usually introduced during manufacturing, and are caused by processes such as casting, welding, machining, heat treating, molding, etc.

Residual stress can neither be detected nor evaluated by conventional surface-measurement techniques, since the strain sensor (strain gage, photoelastic coating, etc.) can only respond to strain changes that occur after the sensor is installed.

The most widely used practical technique for measuring residual stresses is the hole-drilling strain gage method described in ASTM Standard E837. With this method, a specially configured electrical resistance strain gage rosette is bonded to the surface of the test object, and a small shallow hole is drilled through the center of the rosette. The local changes in strain due to introduction of the hole are measured, and the relaxed residual stresses are computed from these measurements. Measurements Group Tech Note TN-503, *Measurement of Residual Stresses By The Hole-Drilling Strain Gage Method*, presents a detailed discussion of the theory and application of this technique.

The hole-drilling method is generally considered semi-destructive, since the drilled hole may not noticeably impair the structural integrity of the part being tested. Depending on the type of rosette gage used, the drilled hole is typically 0.062 or 0.125 in *(about 1.5 or 3.0 mm)*, both in diameter and depth. In many instances, the hole can also be plugged, if necessary, to return the part to service after the residual stresses have been measured.

The practicality and accuracy of this method is directly related to the precision with which the hole is drilled through the center of the strain gage rosette. The Measurements Group RS-200 optical milling guide described herein provides a practical means to accomplish this task

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