



Misure Meccaniche e Collaudi

(A. A. 2020/21)

Estensimetri elettrici a resistenza – Strain gauge

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ESTENSIMETRI

- u **meccanici (leva meccanica)**
- u **ottici (leva ottica, fotoelastici, interferometrici)**
- u **acustici**
- u **a resistenza elettrica (RE)**

u Quando si devono misurare deformazioni





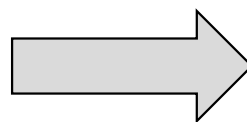
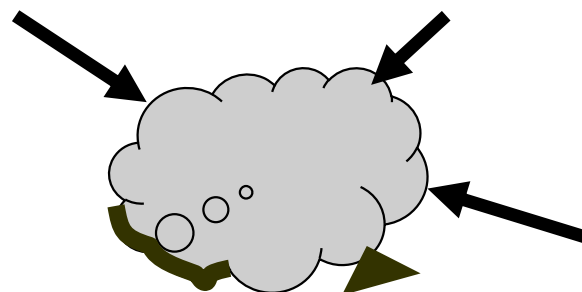
Strain - gauge **modello**

Meccanica dei Continui

Lineari Elastici

- Fenomeno = comportamento meccanico strutturale di un componente
- Modello = Meccanica dei continui
 - omogenei; isotropi; lineari; elastici
- geometria
- condizioni di carico
- condizioni di vincolo

- equazioni di congruenza
- equazioni di equilibrio
- **relazioni costitutive**



**stato di tensione e
di deformazione**

Meccanica dei continui

Lineari Elastici

□ Geometria

□ Vincoli

□ Carichi

□ Materiale E , ν , σ_{sn}

□ Spostamenti

(deformata) u , f

□ Tensioni σ

□ Deformazioni ε

Deformazioni ε

□ **Lagrange**

$$\varepsilon_L = \frac{\Delta l}{l_0}$$

□ **Eulero**

$$\varepsilon_E = \int_{l_0}^l \frac{dl}{l} = \ln \frac{l}{l_0}$$

$$\varepsilon_E = \ln \frac{l}{l_0} = \ln \left[\frac{\Delta l}{l_0} + 1 \right] = \varepsilon_L + \frac{\varepsilon_L^2}{2} + \dots$$

□ **Lagrange \cong Eulero**

$$\varepsilon = \frac{\Delta l}{l_0}$$

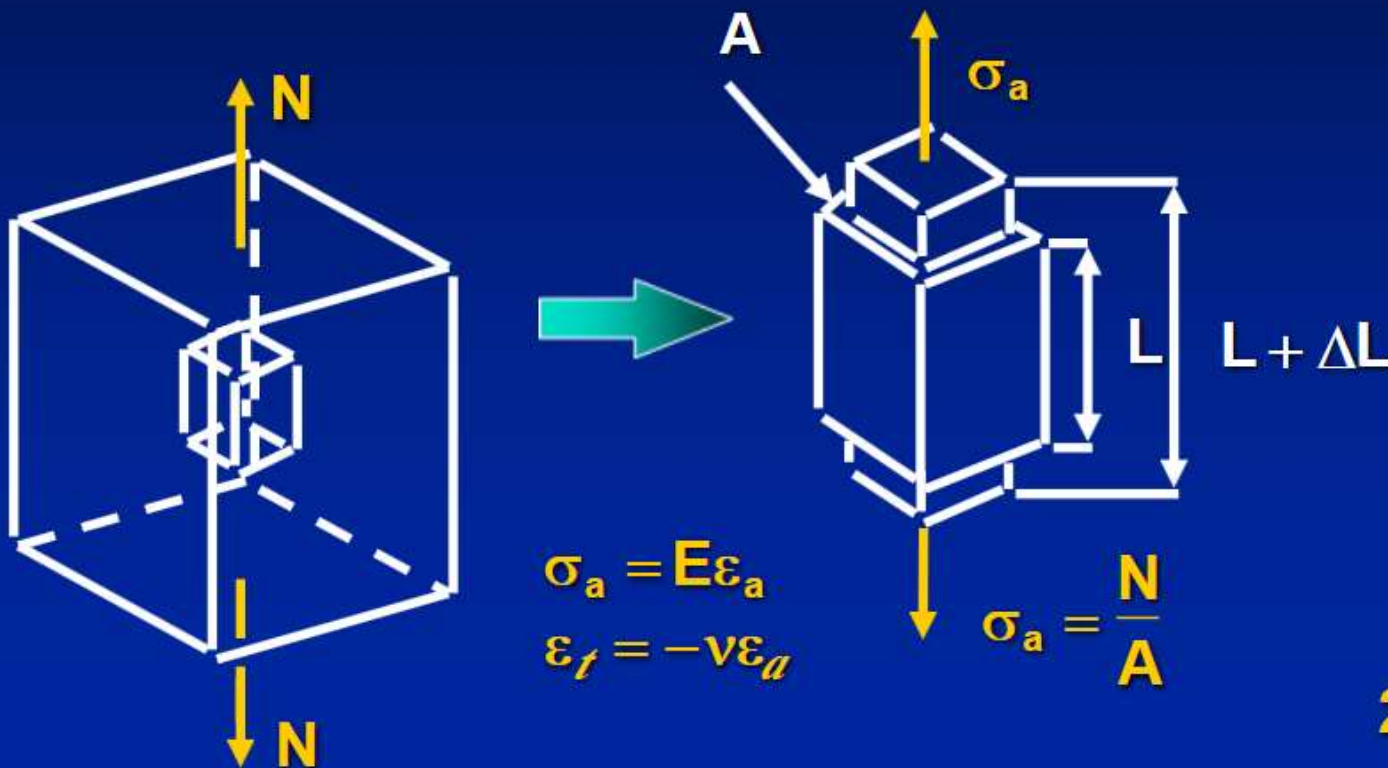
E = modulo di elasticità

acciaio: 210000 MPa (N/mm²)

ν = coefficiente di Poisson

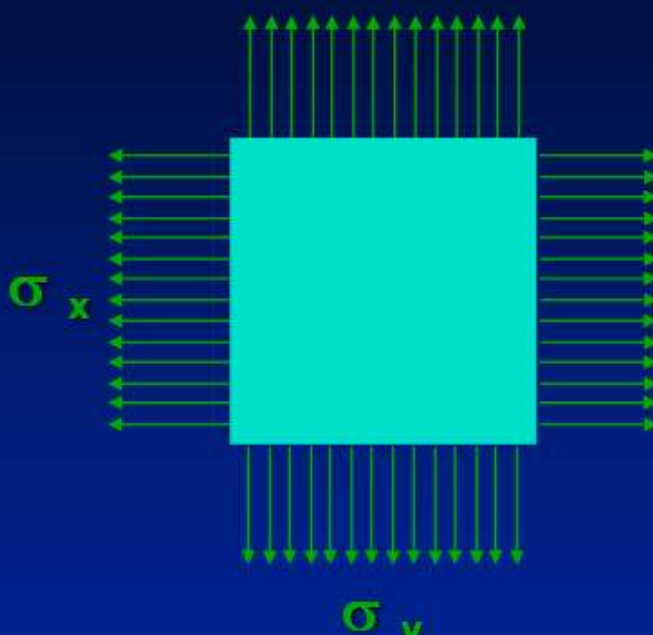
acciaio: 0,3

$$\varepsilon = \frac{\Delta L}{L}$$



2

$\sigma_z = 0$


$$\varepsilon_y = \frac{\sigma_y}{E} - \nu \frac{\sigma_x}{E}$$
$$\varepsilon_x = \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E}$$
$$\sigma_x = \frac{E(\varepsilon_x + \nu \varepsilon_y)}{1 - \nu^2}$$
$$\sigma_y = \frac{E(\varepsilon_y + \nu \varepsilon_x)}{1 - \nu^2}$$
$$\gamma_{xy} = \frac{1}{G} \tau_{xy}$$
$$G = \frac{E}{2(1 + \nu)}$$

$$\varepsilon = \frac{\Delta l}{l_0}$$

□ unità di misura

$$1 \mu\varepsilon \text{ (microepsilon)} = 1 * 10^{-6}$$

$$\varepsilon = 10^{-2} = 0,01 = 1\% = 10000 \mu\varepsilon$$

□ range

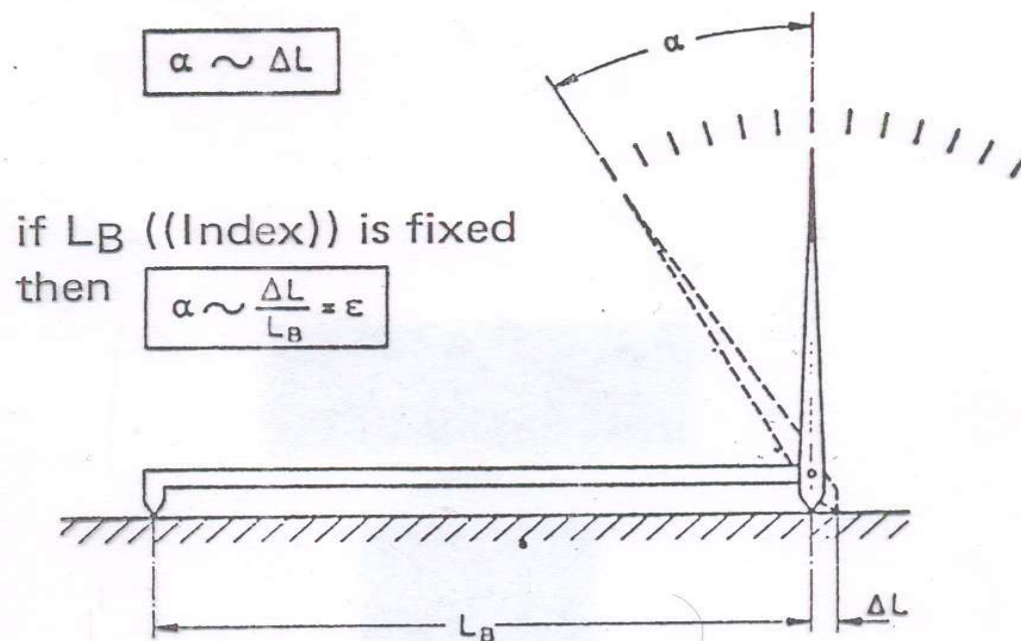
$$\sigma = 0 - 600 \text{ MPa} ; E = 200 \text{ GPa}$$

$$\varepsilon = 0 \div 3000 - 5000 \mu\varepsilon$$

□ risoluzione

$$\sigma = 5 - 10 \text{ MPa} \Rightarrow \varepsilon = 2 - 5 \mu\varepsilon$$

$$\varepsilon = \frac{\Delta l}{l_0}$$



□ **solidarietà sensore - struttura**

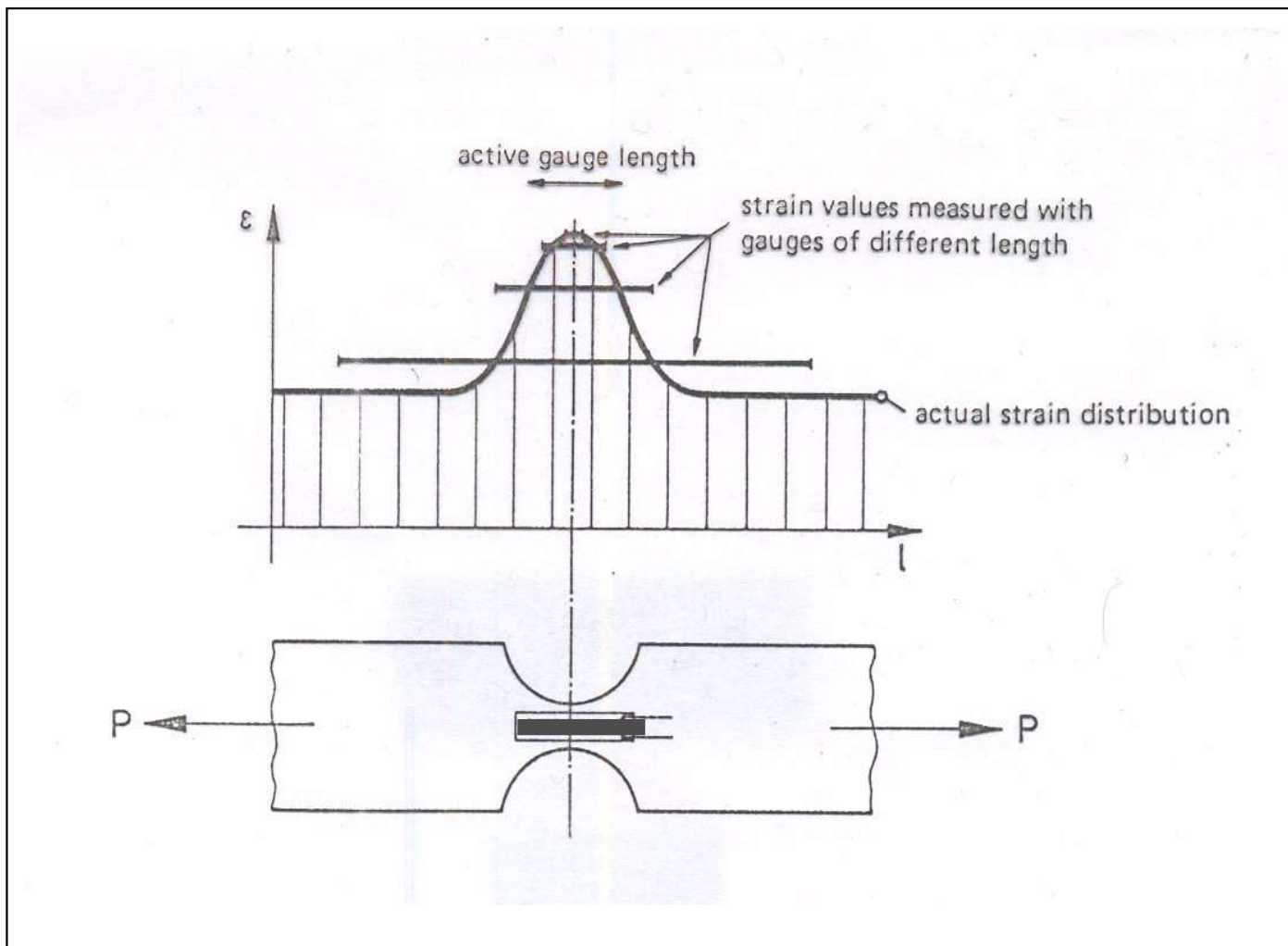
→ Δl struttura = Δl sensore

□ **direzionale**

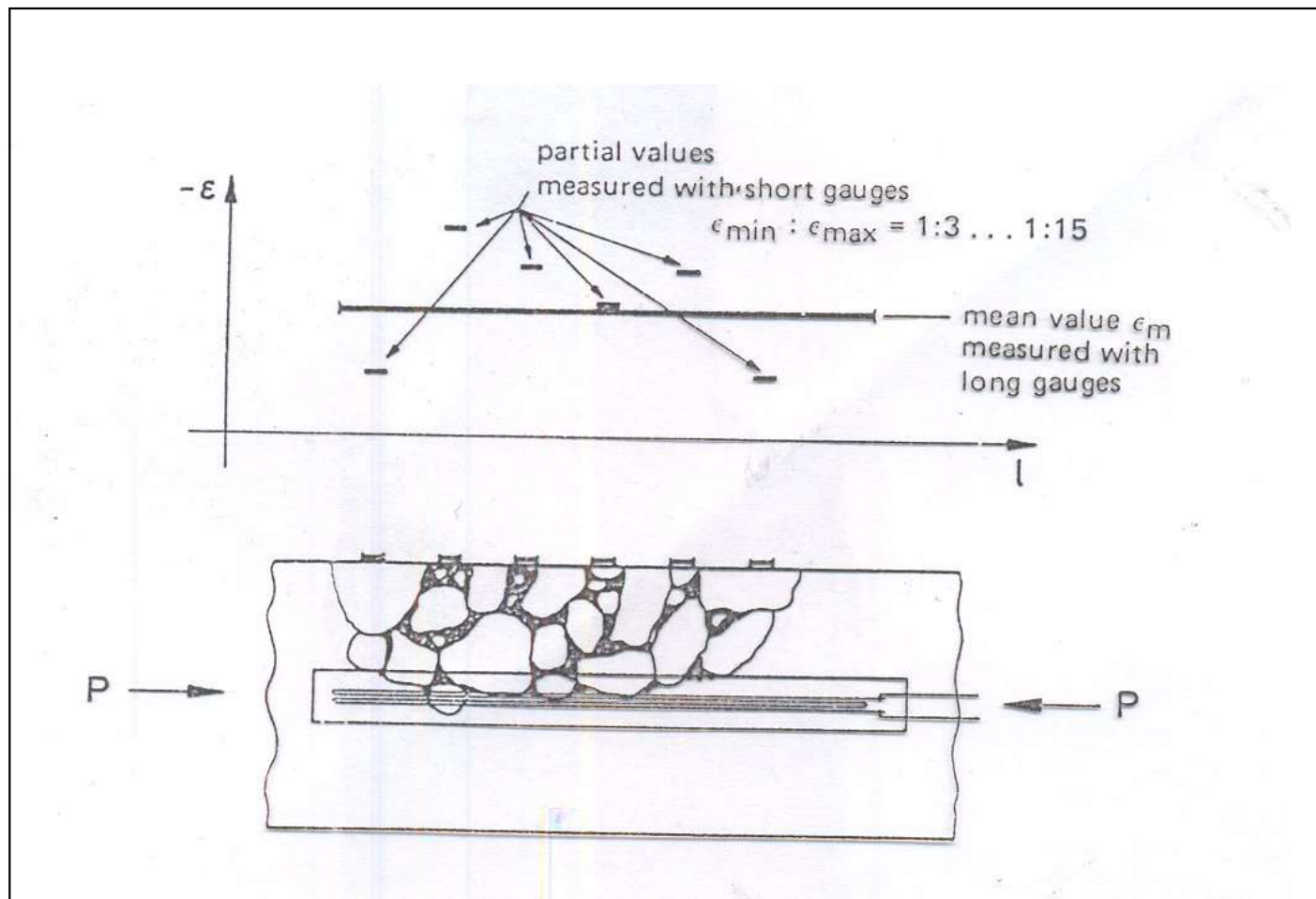
□ $\varepsilon = \Delta l / l_0$

l_0 = base di misura $\Rightarrow \Delta l$ medio

$\varepsilon = 5 * 10^{-6}$; $\Delta l = 10^{-2}$ mm $\Rightarrow l_0 = 2000$ mm



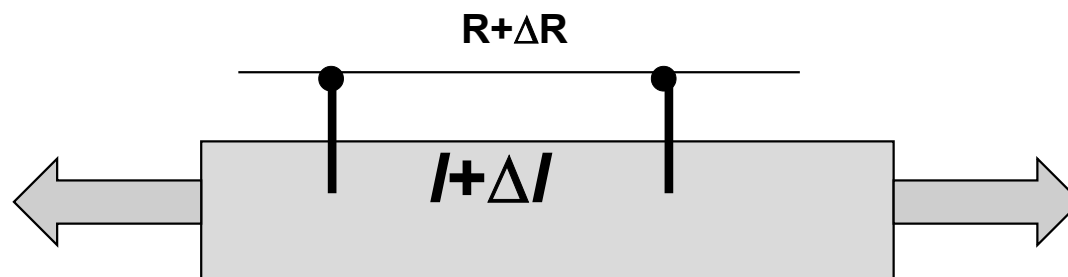
$$\varepsilon = \frac{\Delta l}{l_0}$$



$$\epsilon = \frac{\Delta l}{l_0}$$

Materiali "continuo" volume "rappresentativo"

Materiali		Disomogeneità	Cubo elementare
Metalli e leghe	cristallo	1 μm - 0,01 mm	0,1 mm
Polimeri	molecole	10 μm - 0,05 mm	1 mm
Legno	fibre	0,1 mm - 1 mm	1 cm
Calcestruzzo	grani	1 cm	10 cm



□ legge di Ohm

$$R = \frac{\rho l}{S}$$

$$\frac{dR}{R} = k \varepsilon$$

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

$$\frac{dl}{l} \Rightarrow \varepsilon$$

$$\frac{dS}{S} \Rightarrow [S = \pi r^2] \Rightarrow 2 \frac{dr}{r} = -2\nu \varepsilon$$

$$\frac{d\rho}{\rho} \text{ materiale \& volume}$$

$$k = \frac{\Delta R / R}{\Delta L / L} = 1 + 2\nu + \frac{\Delta \rho / \rho}{\varepsilon}$$

Strain - gauge

- 1827 - legge di Ohm (Berlino)
- 1843 - ponte di Wheatstone resistenze dei fili (UK)
- 1856 - Thomson (lord Kelvin) misura utilizzando il ponte di Wheatstone variazioni di lunghezza di un filo utilizzando le variazioni di resistenza
- 1938 - Rouge del MIT valuta vibrazioni di una struttura soggetta a sisma incollando un filo sulla struttura e valutando le variazioni di resistenza
- 1938 - Simons al California Institute of Technology costruisce un dinamometro utilizzando estensimetri elettrici
- 1939 - Rouge offre alla Baldwin (industria ferroviaria) il brevetto - contenzioso Rouge / Simons / MIT / California Institute - accordo SR-4

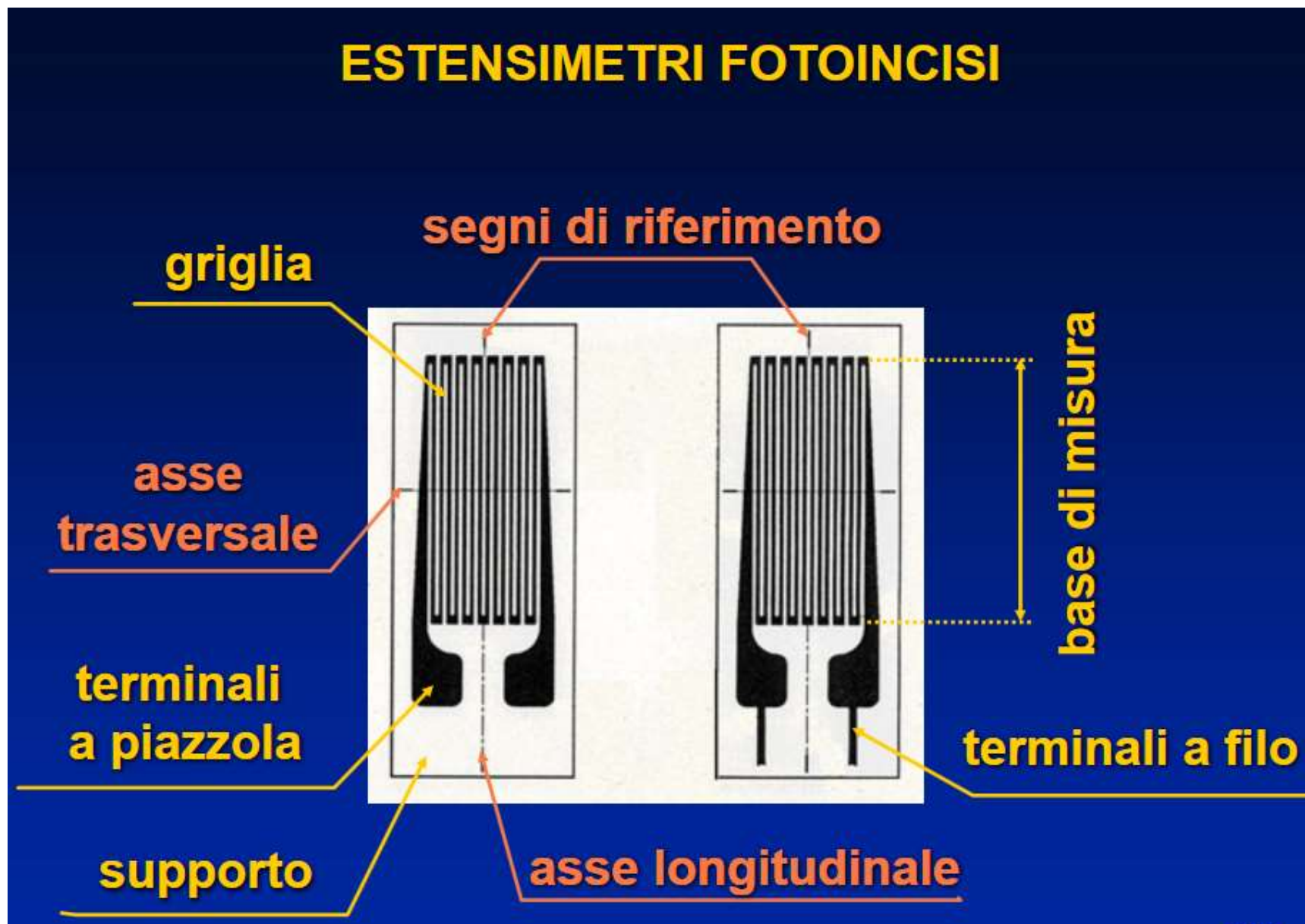
Strain - gauge

- 1939 - 1944 - utilizzazione (USA & UK) nella industria bellica aeronautica
- 1946 - Hottinger (responsabile misure meccaniche della Luftwaffe) in USA - al rientro 1950 fonda la Hottinger Messtechnik Company - 1963 HBM Hottinger Baldwin Messtechnik
- 1952 - estensimetri su pellicola fotoincisi
- 1950 - prof. Anthos Bray (Istituto di Metrologia “G. Colonnetti” del CNR), sigg. G. Artusio e G. Boano (Centro Ricerche Fiat) introducono in Italia l’uso degli estensimetri (Boano fonderà una ditta per la costruzione e commercializzazione degli estensimetri)
- 1996 - 1999 (1-6) - prove non distruttive UNI 10478 - norma UNI sugli estensimetri elettrici a resistenza



Strain - gauge

Estensimetro elettrico a resistenza



Gauge Factor $K \approx 2$

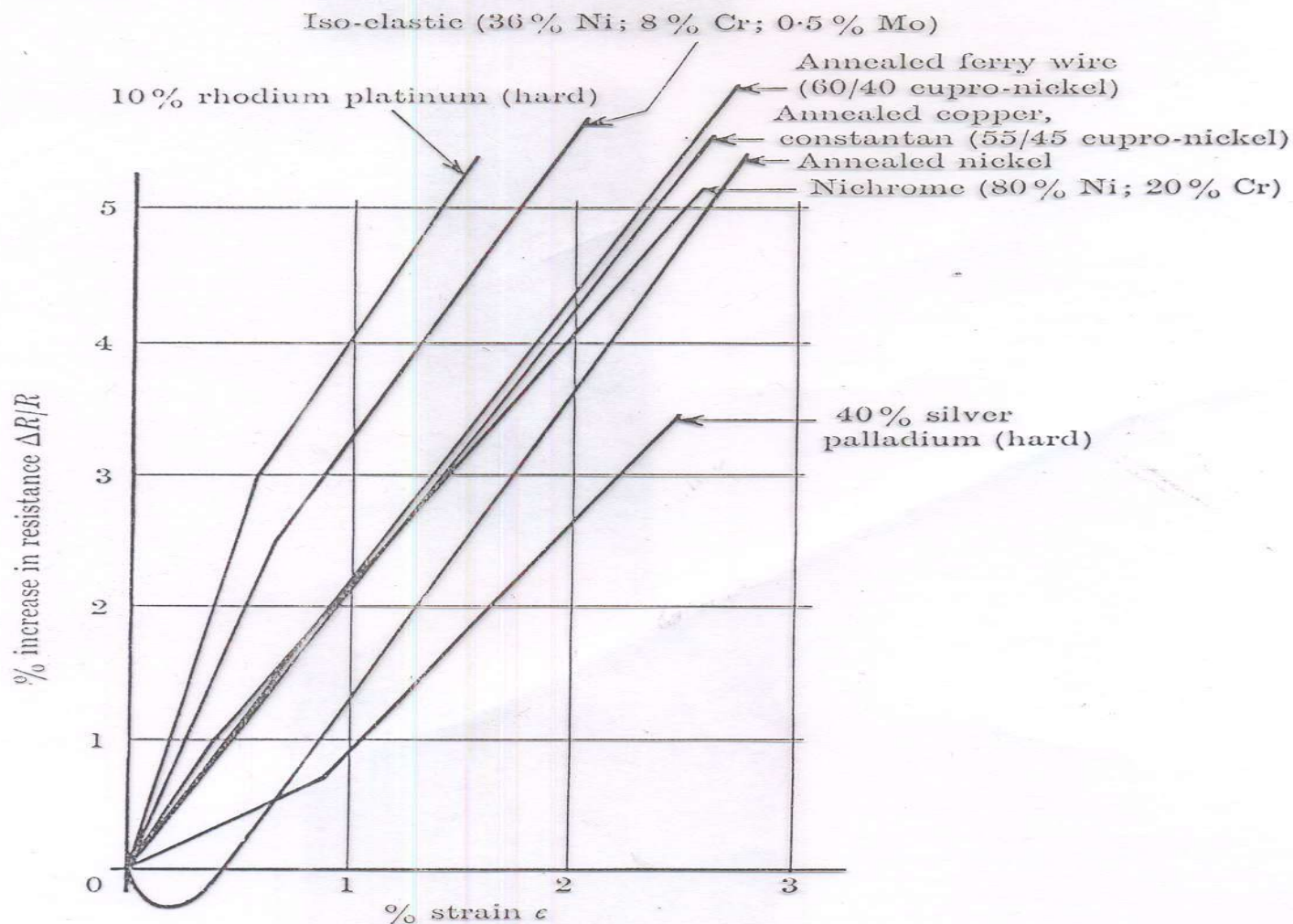
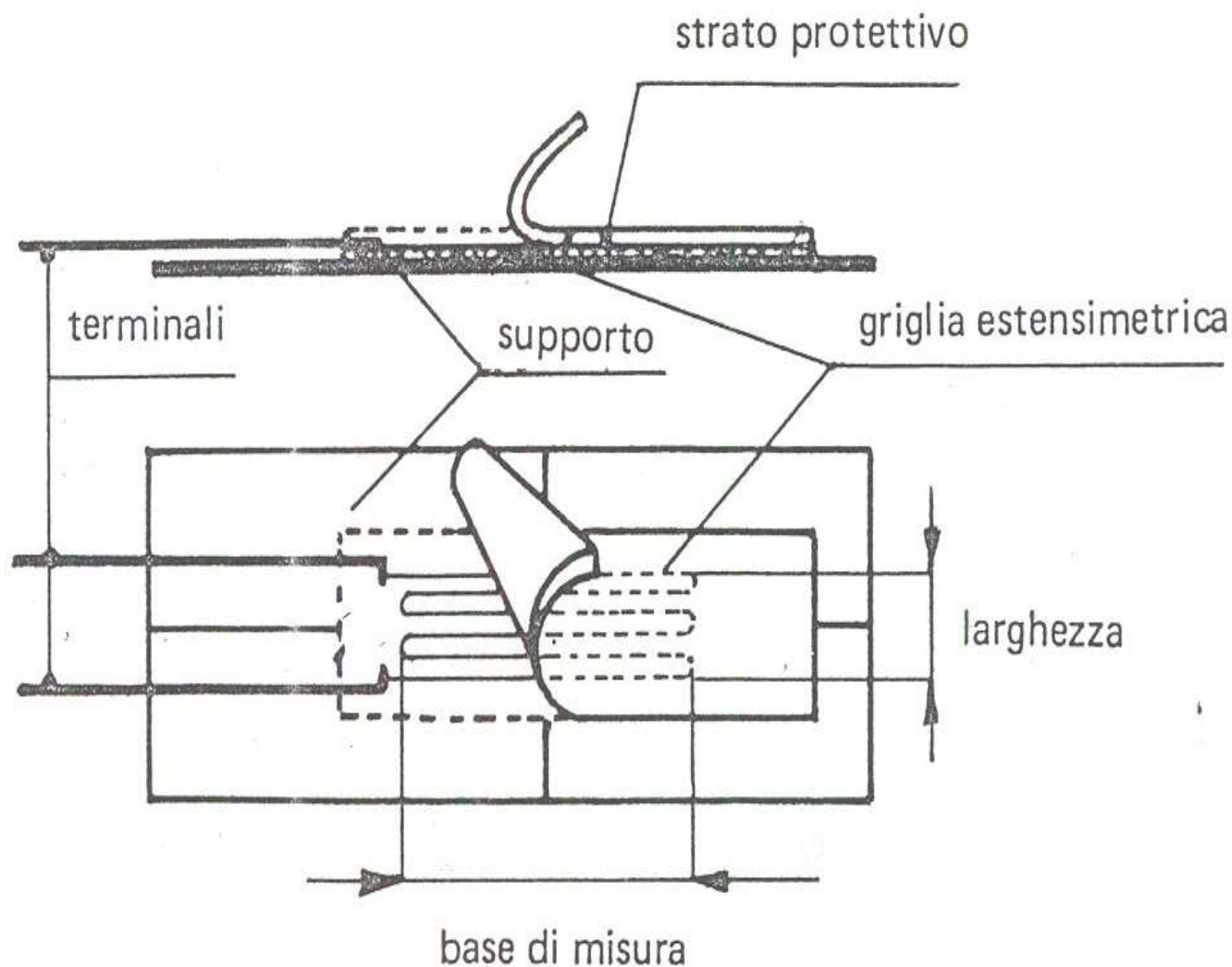


Fig. 2.1. $K = (\Delta R/R)/(\Delta L/L) = \text{slope of graphs.}$
(Courtesy of Murray & Stein, 1958.)

Strain - gauge



- Griglia
- Supporto
- Terminali
- Adesivo
- Protettivo

Griglia

Lega	Composizione	
Costantana Advance	Ni 45 - Cu 55	Uso generale (-70/ + 200 °C)
Nicromo	Ni 80 - Cr 20	Uso generale
Karma	Ni 74 - Cr 20 - Fe 3 - Al 3	Trasduttori / misure di lunga durata
Isoelastic	Ni 36 - Fe 55.5 - Cr 8 - Mo 0,5	Prove dinamiche
Platino Tungsteno	Pt 92 - W 8	Alte temperature (-200 / +650 °C)

Resistenza

$$\frac{\Delta R}{R} = k \varepsilon$$

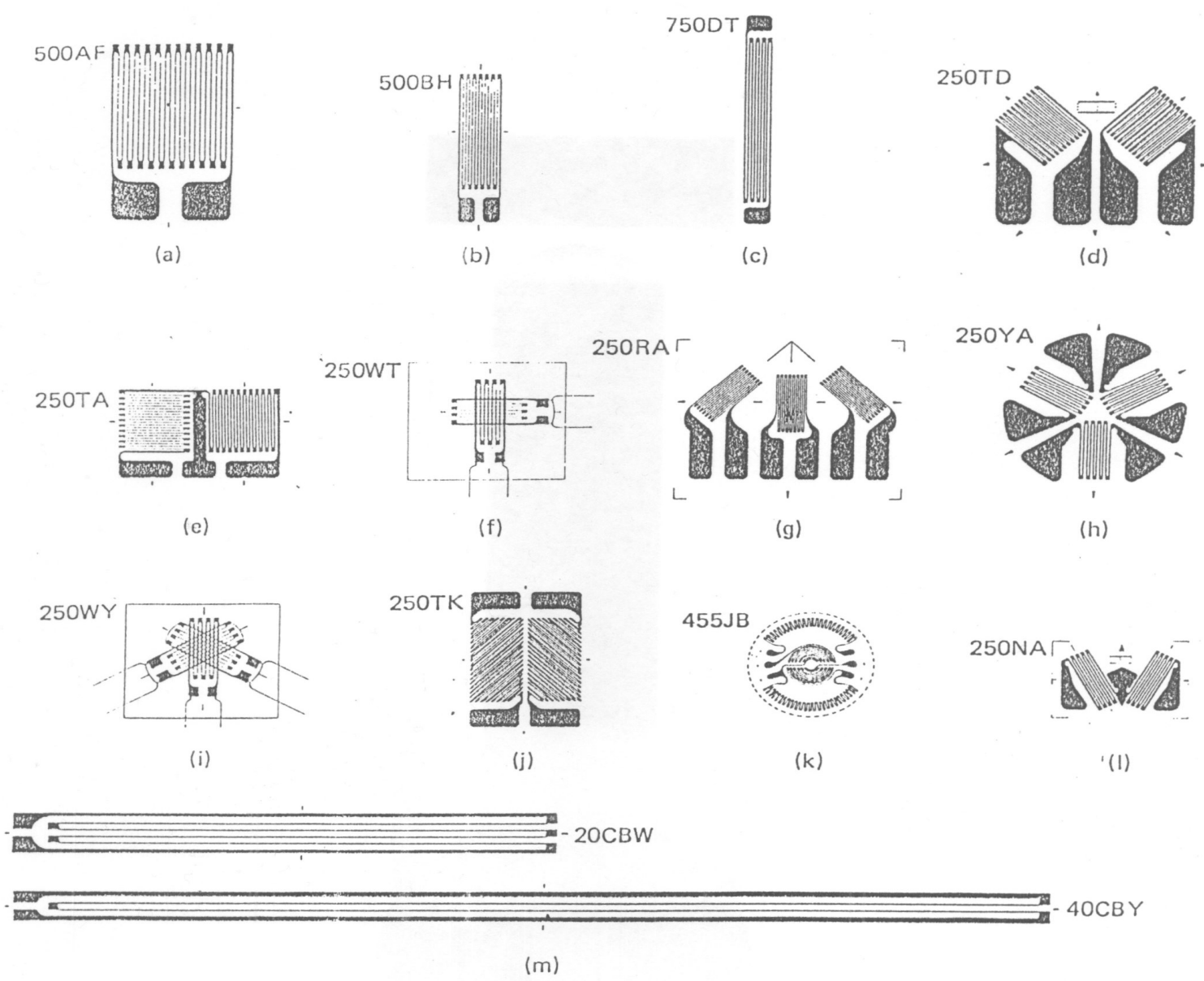
- 120 Ω uso generale
- 350 Ω trasduttori / misure di
precisione

- 600 Ω usi speciali / forniti
- 1000 Ω su richiesta

Supporto

Supporto	$\Delta(t)$ [°C]	
Carta	- 40 ÷ + 60	
Resina acrilica	-200 ÷ +100	
Resina epossidica	- 50 ÷ +100	
Resina poliammidica	-200 ÷ +200	uso generale
Resina epossidica + fibre vetro	-270 ÷ +230	
Resina fenolica	-200 ÷ +250	
Resina fenolica + fibre vetro	-200 ÷ +300	trasduttori - lunga durata
Resina epossifenolica	-270 ÷ +290	
Resina poliammidica + fibre vetro	-200 ÷ +330	
Cemento ceramico	-200 ÷ +750	alte temperature
Piastrina acciaio	-200 ÷ +800	alte temperature

Strain - gauge



Strain - gauge

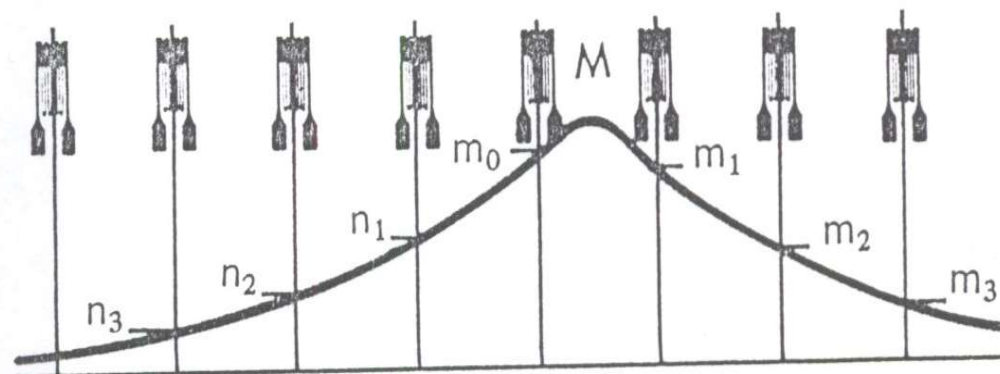
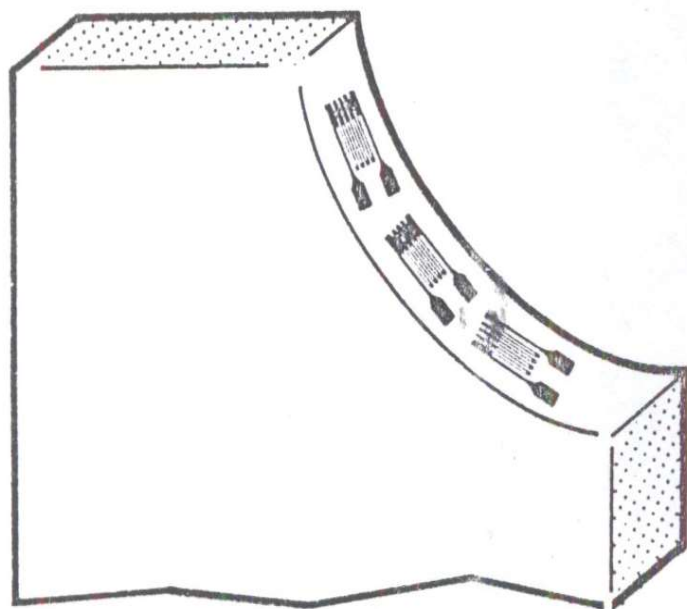
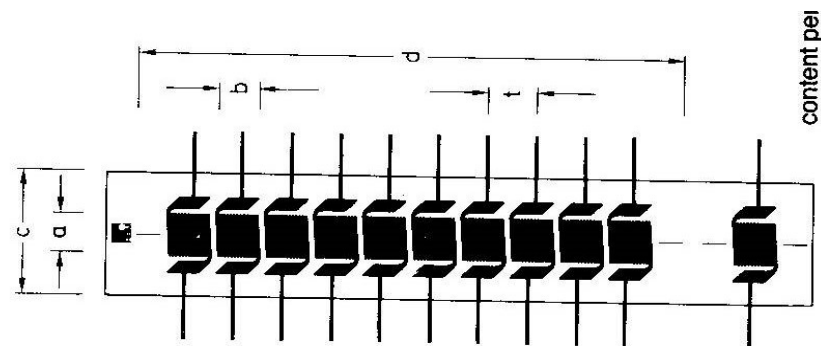
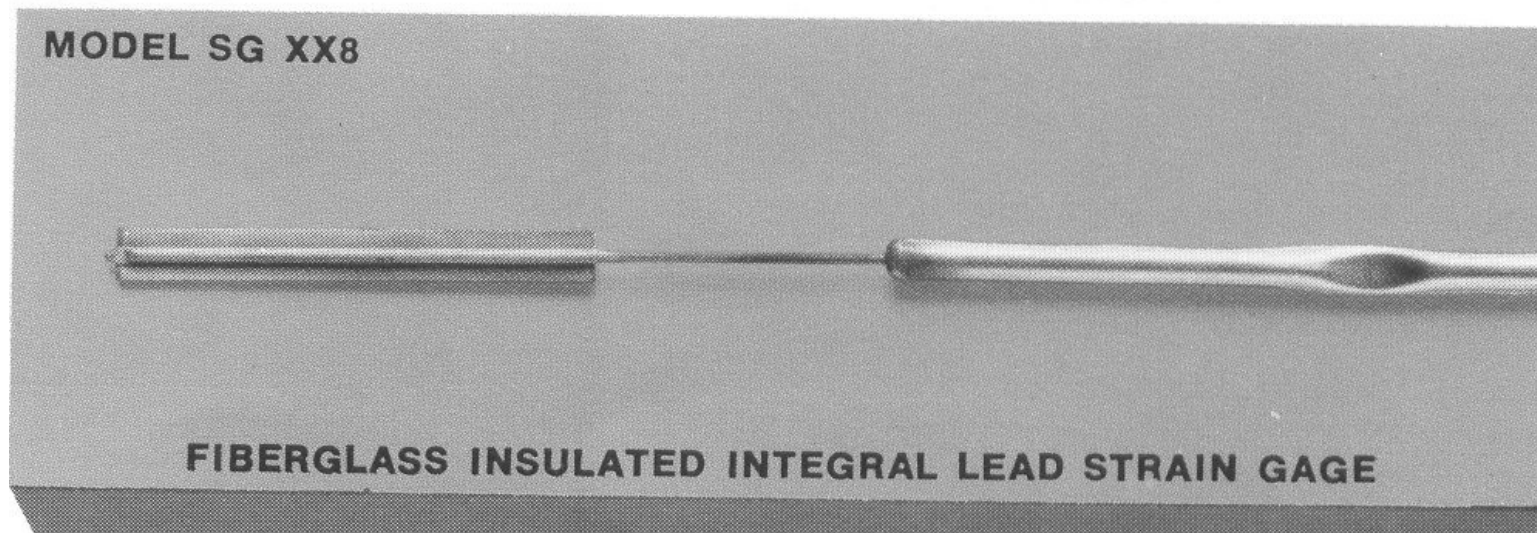
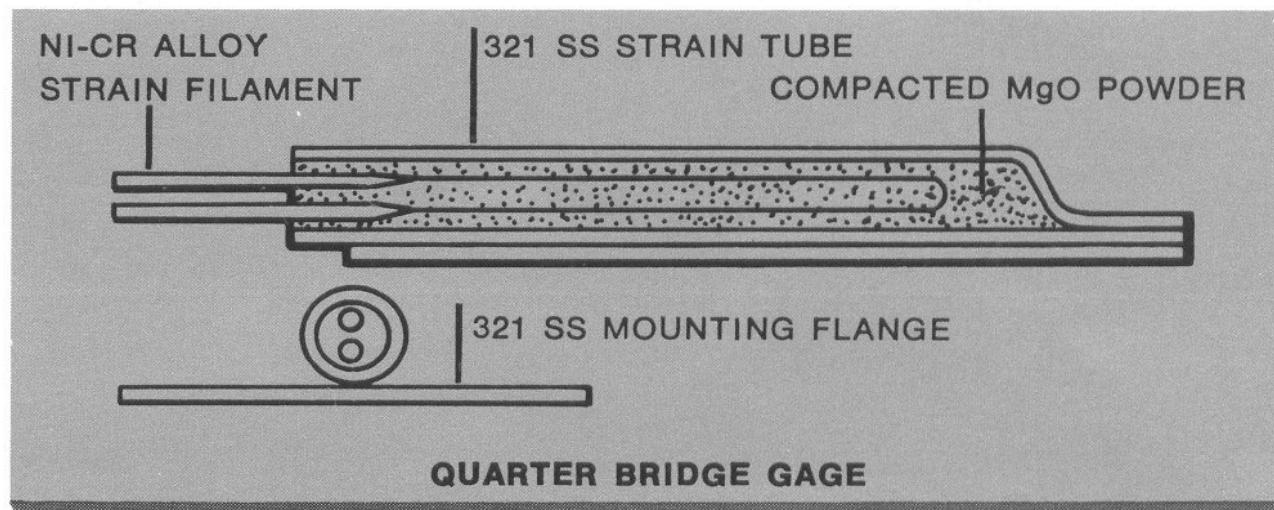

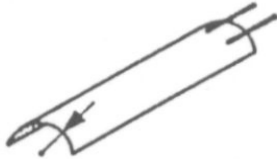


Fig. 25 - Parmi les différentes mesures des jauges d'une chaînette, il en existe une qui est maximale. Le maximum est calculé en grandeur et position par une interpolation tenant compte des valeurs voisines.

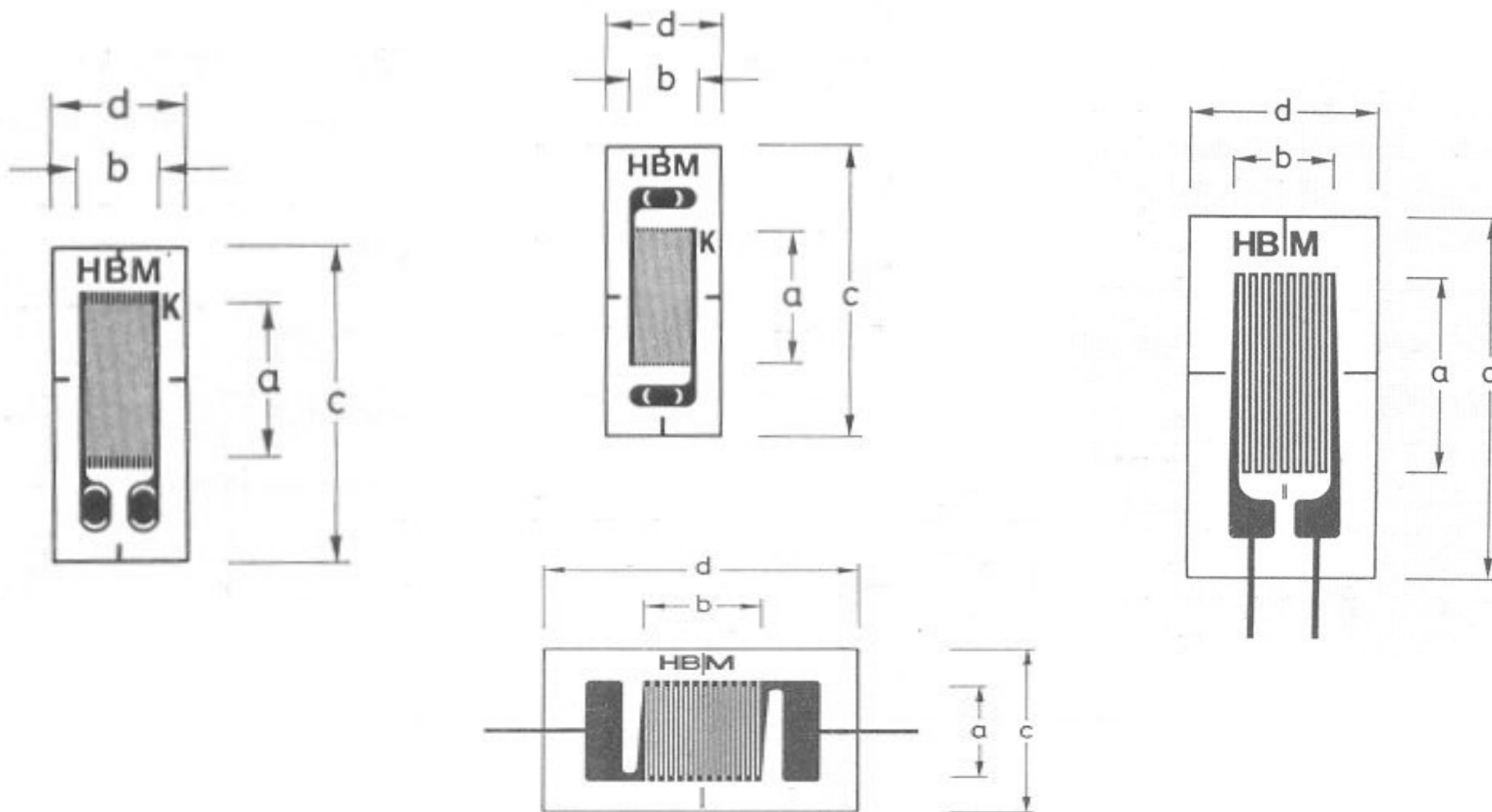
AilTech - strain gage alta temperatura



Strain - gauge

strain gauge		smallest bending radius	
carrier material	type name	 lengthwise mm	 across mm
foil gauges			
polyimide resin (Y-series)	LY 11, LY 21	< 1	< 1
	LY 61 near solder tags	< 1 2	< 1 2
phenolic resin glass fibre filled (G-series)	LG 11, LG 21	3	3
	XG 11, XG 21	3	3

Terminali



Adesivi

Tipo	Trattamento	Base	T [°C]	
organico	a freddo	nitrocellulosa	-50÷+80	
		cianomonoacrilato	-200÷+100	generale
		epossidica	-200÷+100	
organico	a caldo	epossidica	-270 ÷+250	T media
		epossifenolica	-270 ÷+300	T media
		poliammidica	-270 ÷+350	
inorganico	speciale	ceramica	-200 ÷+750	T alta
saldatura punti			-200 ÷+800	T alta

Protettivi

Protettivo	T [°C]	Protezione	
vernice uretanica	-50÷+120	umidità, olio, solventi	Protezione base
resina siliconica	+50÷+250	umidità, olio, solventi	
resina nitrilica	-250÷+250	umidità, olio, solventi	
mastice	-50÷+150	azioni meccaniche, umidità, acqua	
gomma siliconica	-70÷+250	azioni meccaniche, umidità, acqua	

Protezione

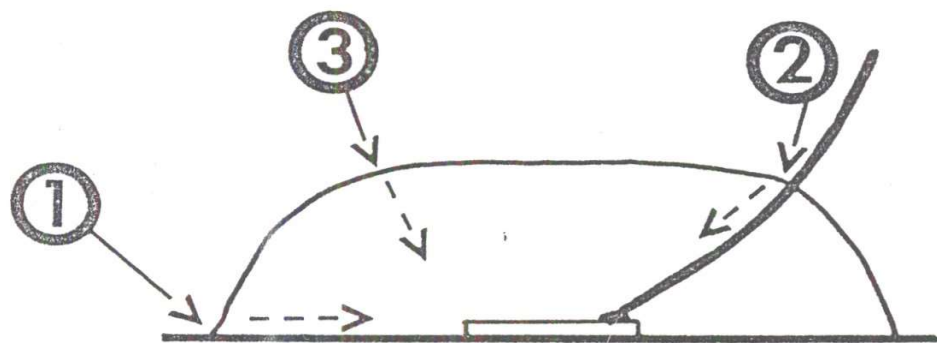


FIG. 10. Gauge installation breakdown paths.

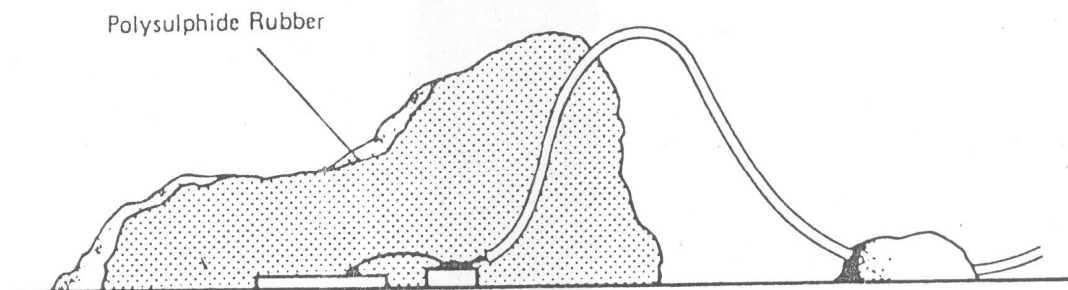


FIG. 11. Short-term protection technique.

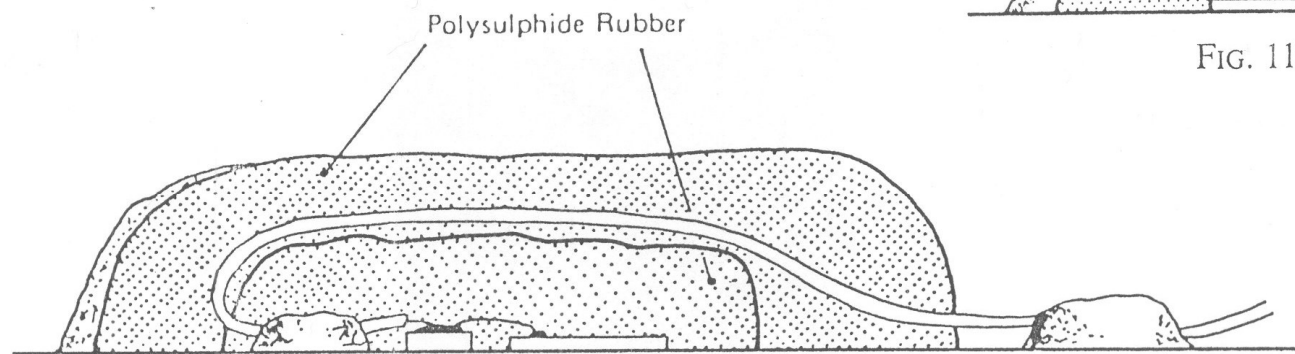
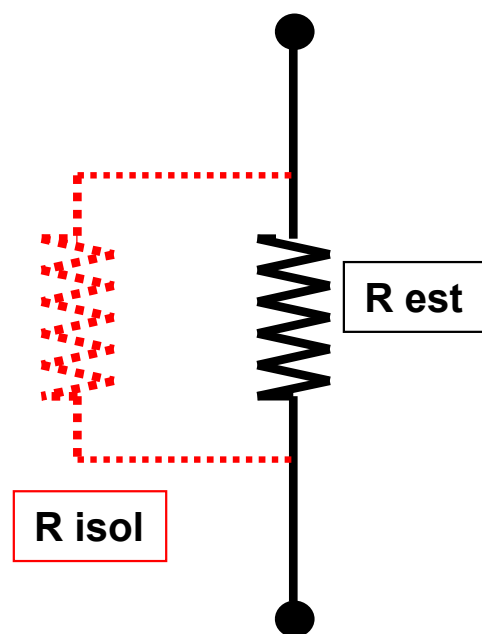


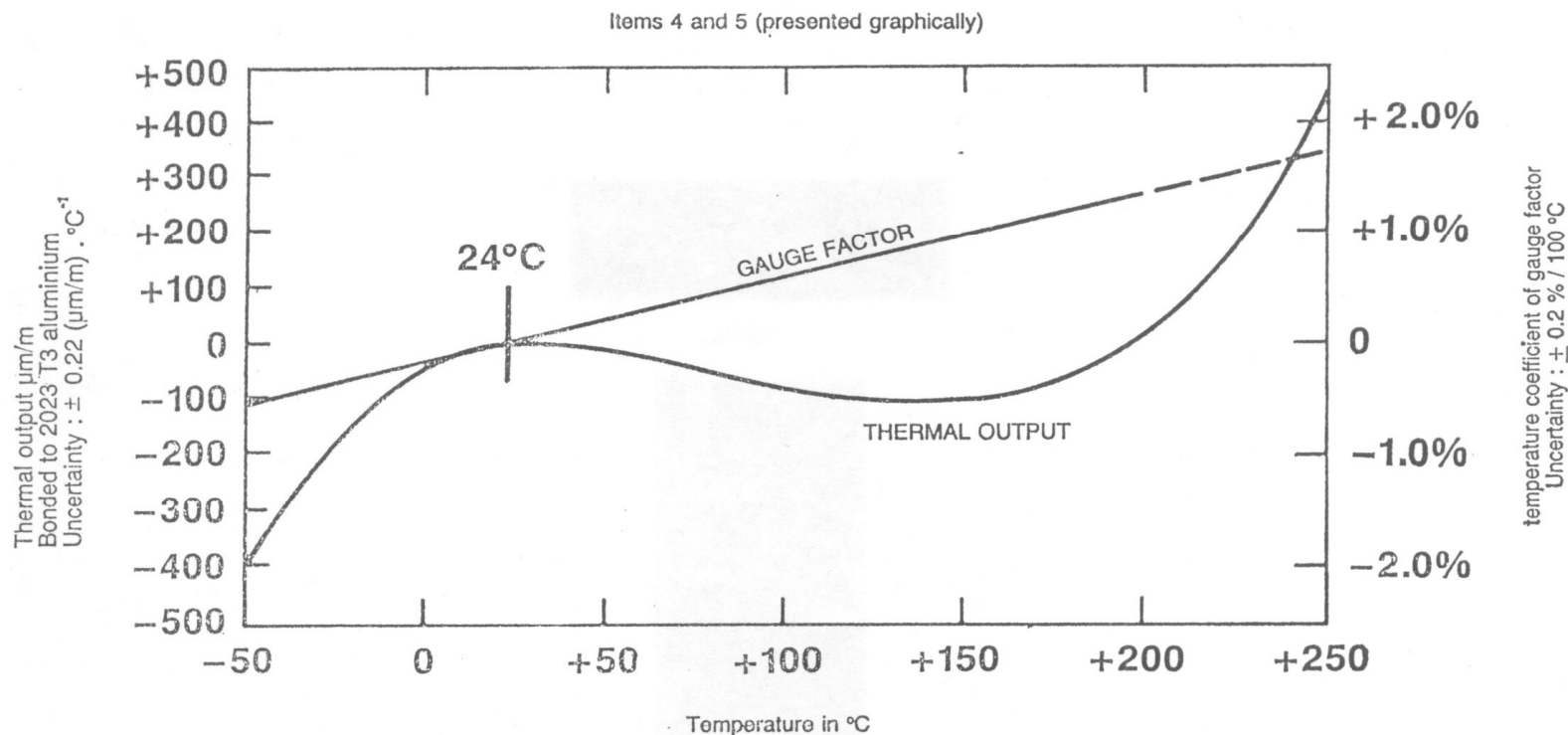
FIG. 12. Over-lap protection technique.

Ambiente & Umidità ⇔ Isolamento



- Ambiente & Umidità & Isolamento **variabile** e non predeterminabile
- Isolamento perfetto $R_{isol} = \infty$
Isolamento assente $R_{isol} = 0$
- Resistenza isolamento
 - in laboratorio (al chiuso) $> 2.000 \text{ M}\Omega$
 - in campo (all' aperto) $> 500 \text{ M}\Omega$

Temperatura



- Variazione del Gauge Factor
- Thermal Output (deformazione apparente)

Gauge Factor vs. temperatura

- **variazione lineare** $K_T = K_{rif} (1 + \beta \Delta T)$
- **K rif per T = 23 °C**

- **per $\Delta T = 100$ °C**
 - + 0,7 % Advance
 - + 1 % Cr Ni
 - - 1% Karma
- **$\Delta T = \pm 10$ °C $\Delta K \cong 1$ ‰ \Rightarrow trascurabile**

Thermal Output

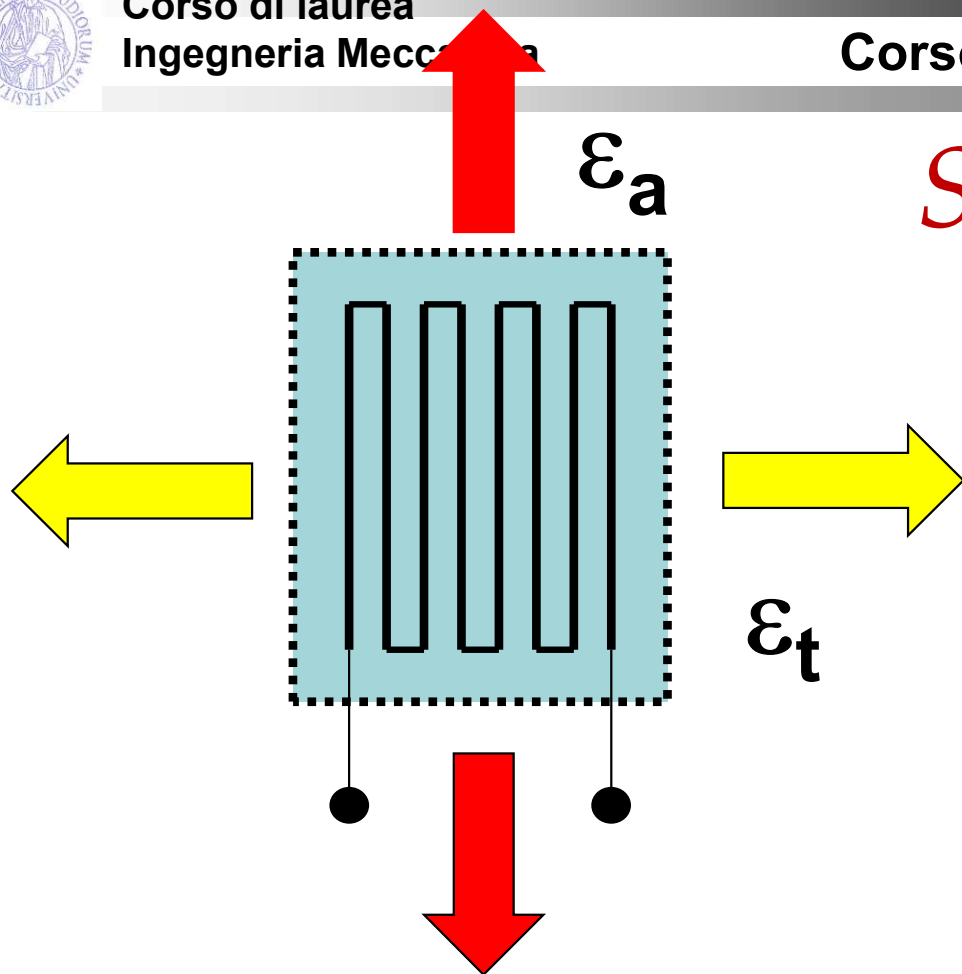
$$\left(\frac{\Delta R}{R} \right)_{\Delta T} = (\beta - \alpha) S_g \Delta T + \gamma \Delta T$$

- α = thermal coefficient of expansion of gage material
- β = thermal coefficient of expansion of base material
- γ = temperature coefficient of resistivity of gage material
- S_g = gage factor

- thermal output = gage factor * deformazione apparente

- $\varepsilon_a = 0$ per $T = 23$ °C estensimetro autocompensato

Sensibilità trasversale

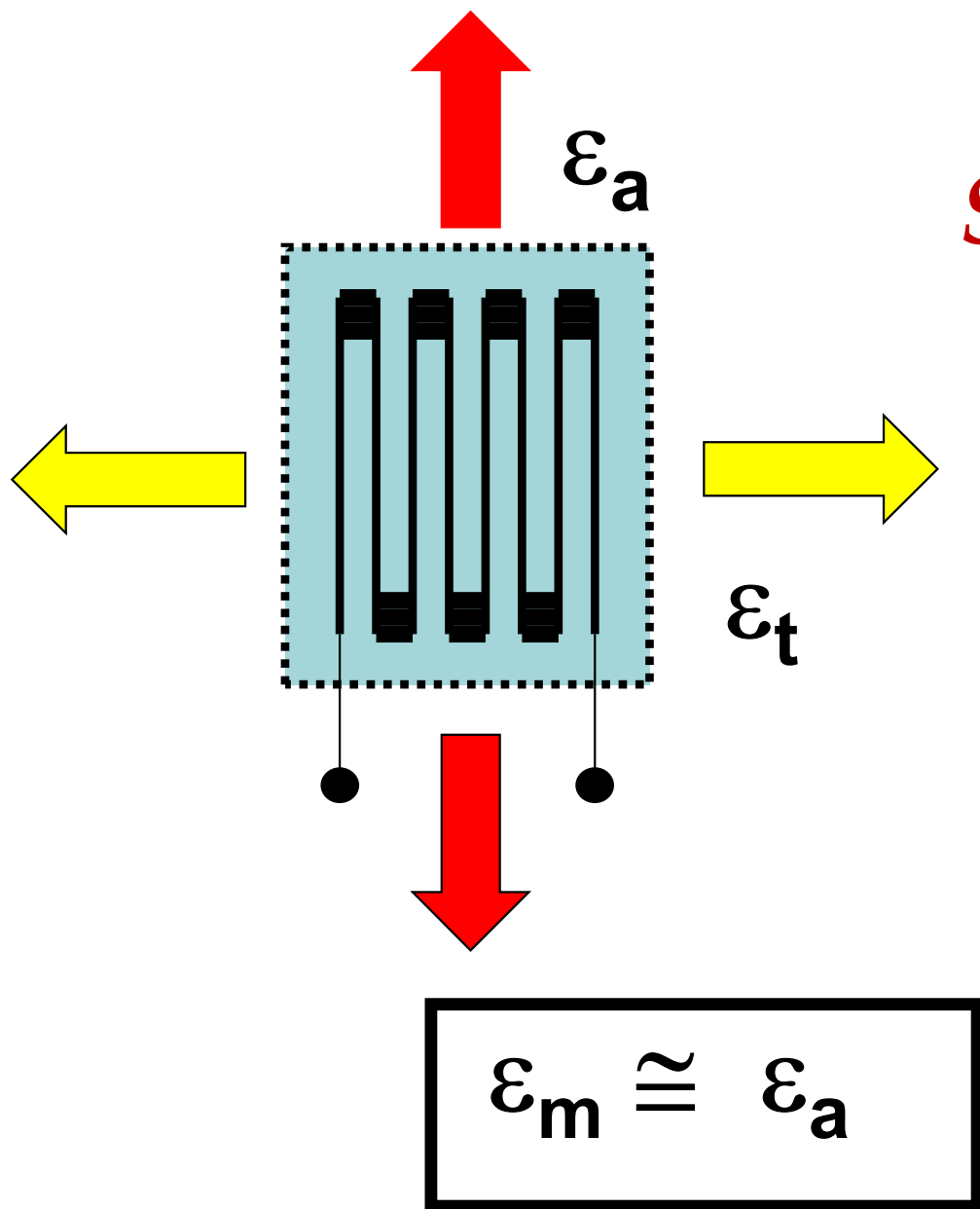


$$\frac{\Delta R}{R} = S_a \epsilon_a + S_t \epsilon_t + S_\gamma \gamma_{at}$$

$$\frac{\Delta R}{R} = S_g \epsilon_m$$

□ ϵ_m misurato $\Rightarrow \epsilon_a$ & ϵ_t

Riduzione Sensibilità trasversale



$$R = \frac{\rho l}{S}$$

$$l_t \ll l_a$$

$$A_t \gg A_a$$

Sensibilità trasversale $K_t = S_t/S_a$

$$\frac{\Delta R}{R} = S_a \varepsilon_a + S_t \varepsilon_t + S_\gamma \gamma_{at} \quad \Rightarrow \quad \frac{\Delta R}{R} = S_a (\varepsilon_a + K_t \varepsilon_t)$$

Taratura S_g $\frac{\Delta R}{R} = S_g \varepsilon_m$

□ carico imposto \Rightarrow stato di tensione σ_a

monoassiale $\Rightarrow \varepsilon_a$ & ε_t $\varepsilon_t = -\nu_0 \varepsilon_a$ $\nu_0 = 0,285$

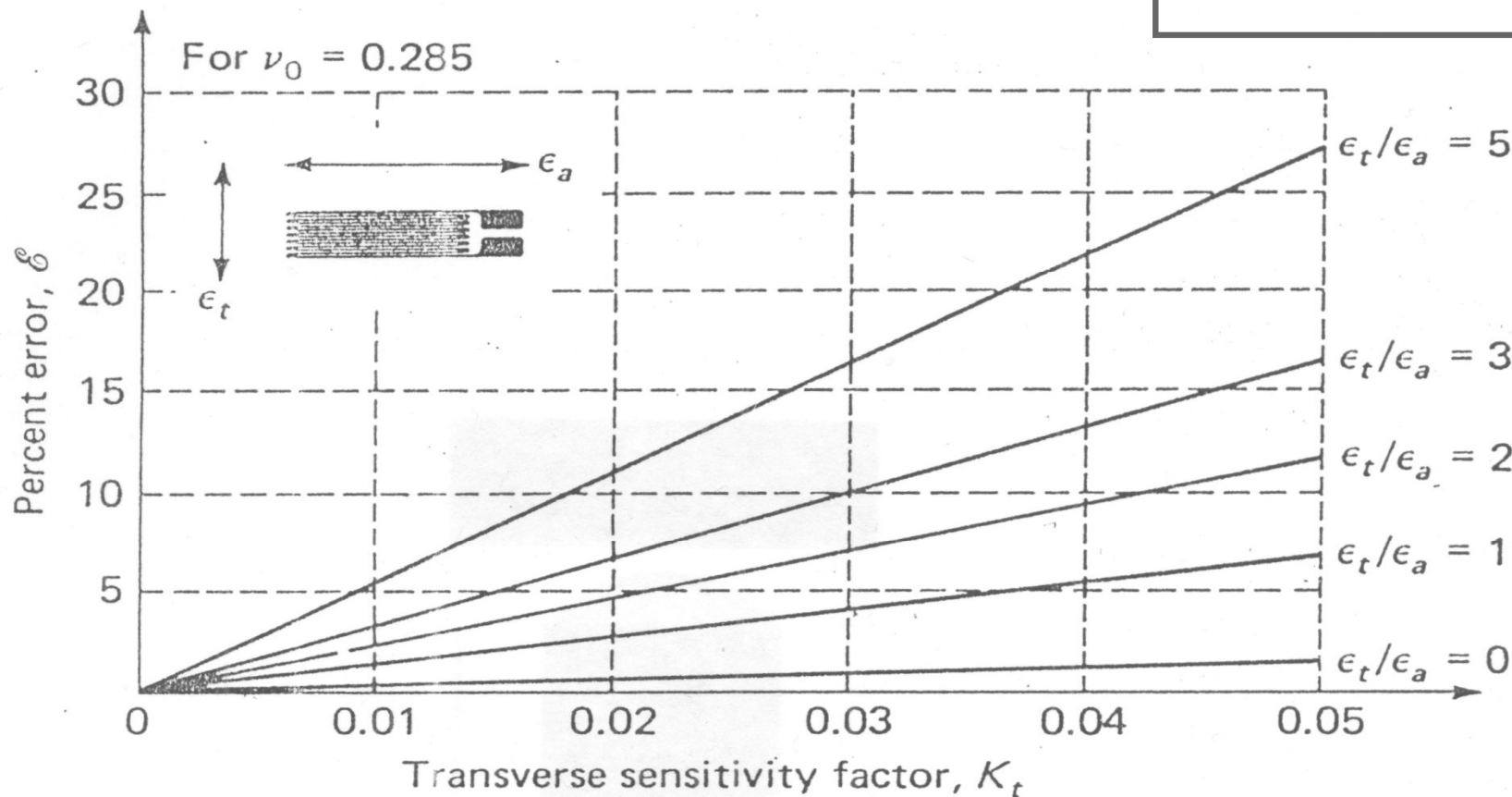
$\Rightarrow \varepsilon_m = \varepsilon_a$ $\frac{\Delta R}{R} = S_g \varepsilon_a = S_a \varepsilon_a (1 - \nu_0 K_t)$

\Rightarrow $S_g = S_a (1 - \nu_0 K_t)$

Sensibilità trasversale \Rightarrow misura ϵ \Rightarrow stima ϵ_a

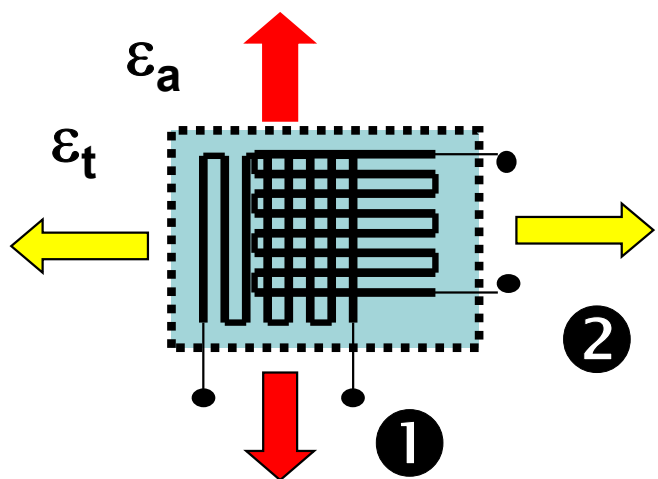
$$\frac{\Delta R}{R} = S_g \epsilon_m = S_a \epsilon_a \left(1 - K_t \frac{\epsilon_t}{\epsilon_a}\right)$$

$$\epsilon_a = \epsilon_m \frac{(1 - K_t \nu_0)}{\left(1 - K_t \frac{\epsilon_t}{\epsilon_a}\right)}$$



Sensibilità trasversale

misura $\varepsilon_1; \varepsilon_2 \Rightarrow$ valutazione $\varepsilon_a; \varepsilon_t$



ε_1

ε_2

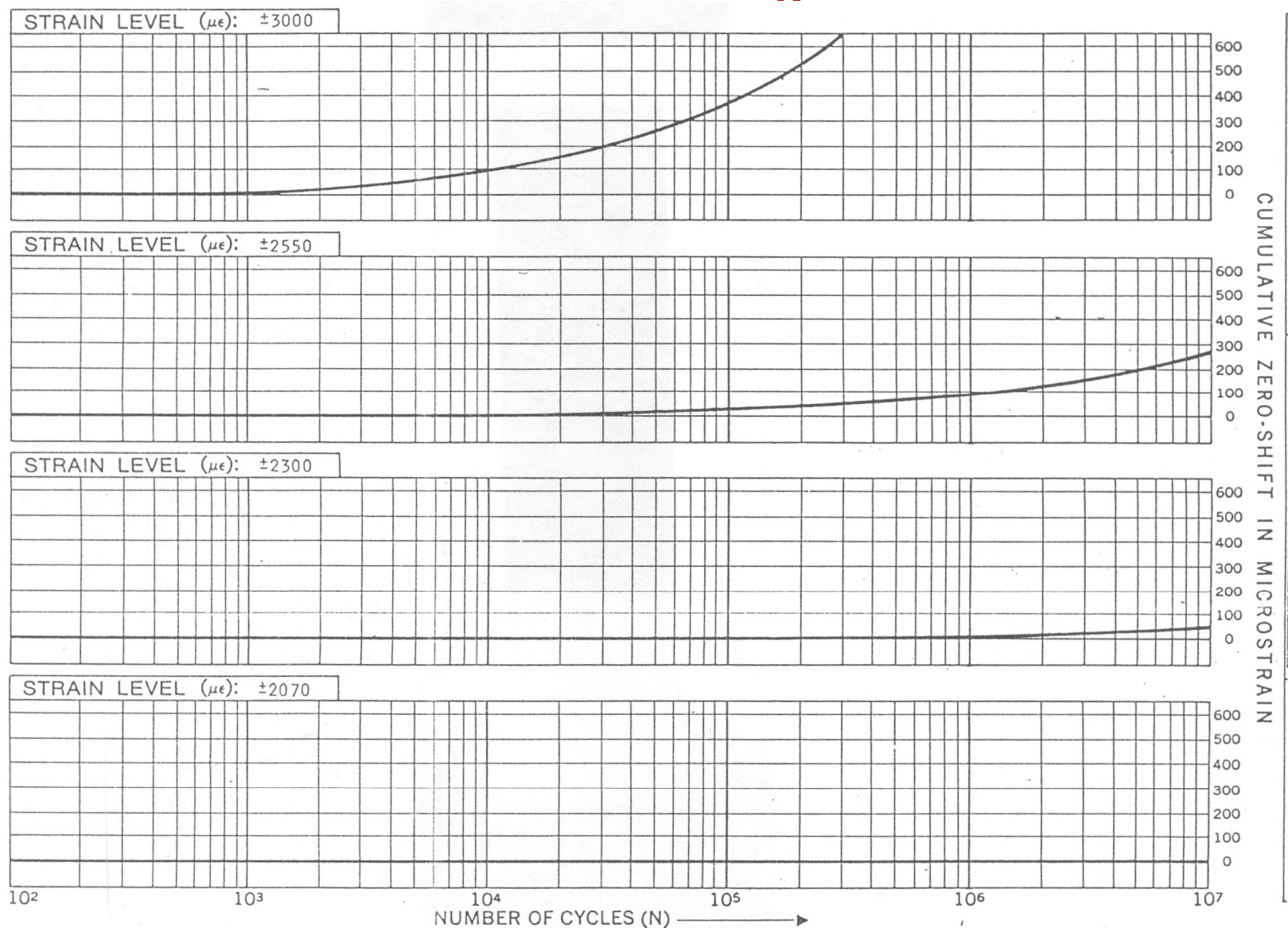
$$\frac{\Delta R}{R} = S_a (\varepsilon_a + K_t \varepsilon_t)$$

$$\frac{\Delta R}{R} = S_g \varepsilon_m$$

$$S_g = S_a (1 - \nu_0 K_t)$$

$$\left\{ \begin{array}{l} \varepsilon_1 = \frac{\varepsilon_a + K_t \varepsilon_t}{1 - \nu_0 K_t} \\ \varepsilon_2 = \frac{\varepsilon_t + K_t \varepsilon_a}{1 - \nu_0 K_t} \end{array} \right.$$

Fatica ϵ_n



9. Fatigue life of a 6 mm gauge (isoelastic alloy with reinforced epoxy-phenolic backin

Caratteristiche

- gage factor $K = 2 \pm 1\%$
- resistenza $R = 120; 350; 1000 \Omega \pm 0,25\%$
- linearità 0.1% fino a 5.000 $\mu\epsilon$
1% fino a 10.000 $\mu\epsilon$
- rottura 20.000 $\mu\epsilon$
- temperatura -70 ÷ +100 / 200 °C
- Thermal Output $\epsilon_a(T)$ - est. autocompensati
- sensibilità trasversale K_t
- risoluzione 0,1 $\mu\epsilon$ (sensore) →
2 - 5 $\mu\epsilon$ (catena di misura)



Caratteristiche

- | | |
|------------|--------------------|
| □ carichi | statici ; dinamici |
| □ fatica | buono |
| □ isteresi | assente |
| □ deriva | assente |
| □ soglia | assente |
| □ creep | assente (adesivo) |

Estensimetro

- converte grandezze meccaniche in elettriche
- consente letture remote, multiple - continue, discontinue
- carichi trazione, compressione - statici, variabili
- risoluzione e precisione idonei agli impieghi strutturali
- non risente eccessivamente dell'ambiente
- non invasivo, di semplice uso



Dehnungsmeßstreifen
Strain Gauges
Jauges d'extensométrie

Widerstand
Resistance
Résistance

120 Ω $\pm 0.35 \%$

k-Faktor
Gauge factor
Facteur k

2.02 $\pm 1 \%$ 

Querempfindlichkeit
Transverse Sensitivity
Sensibilité transverse

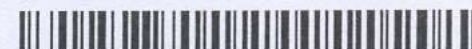
0.2 %

Temperaturkompensation: Angepaßt für
Temperature Compensation: Compensated for
Compensation de température: Compensation pour

Ferritischen Stahl mit
Steel with
Acier avec

Bestellnummer
Order No.
No. de référence

1-LY11-3/120



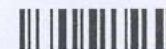
Typ
Type
Type

3/120LY11



Stückzahl
Contents
Quantité

10



Temperaturkoeffizient
des k-Faktors
Temperature coefficient
of gauge factor
Coefficient de température
du facteur k

93 ± 10 [$10^{-6} / ^\circ\text{C}$]
(-10...+45°C)

Folienlos
Lot
Lot de la feuille

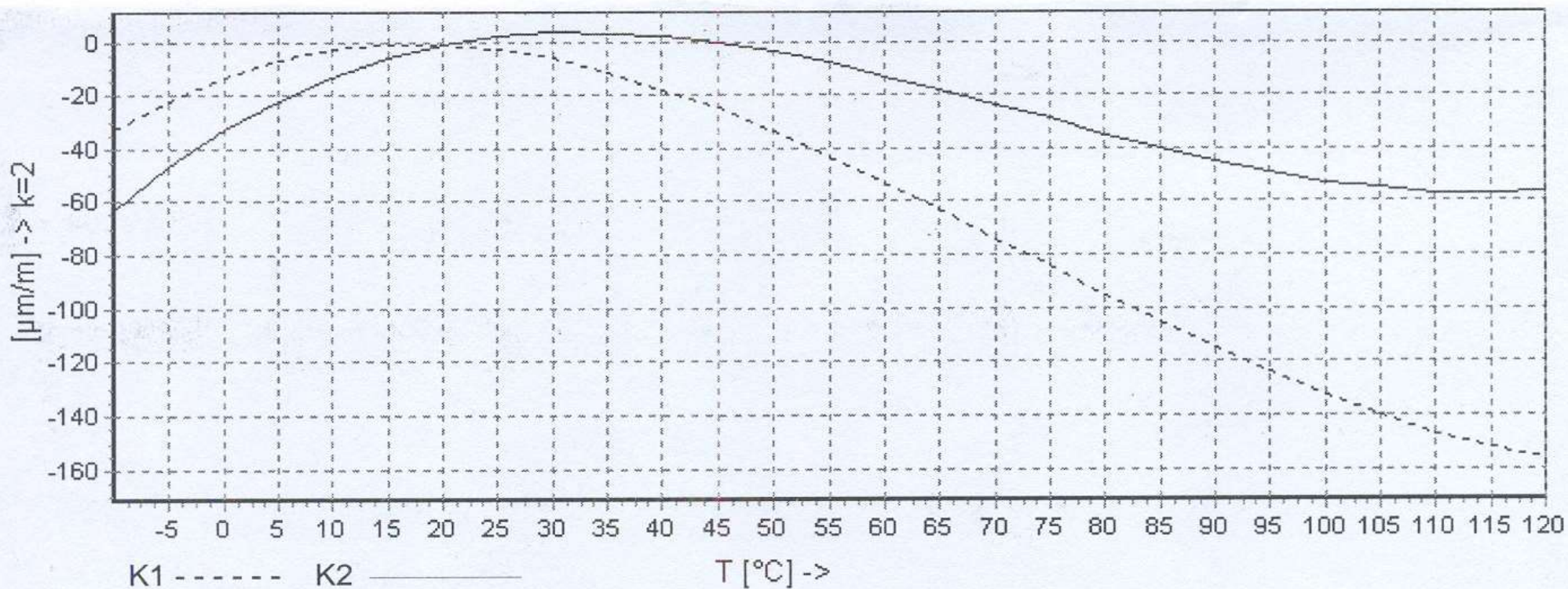
A401/06

Herstellungslos
Batch
Lot de fabrication

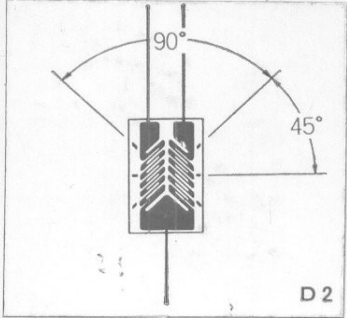
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$\alpha = 10.8$ [$10^{-6} / ^\circ\text{C}$]



$$\varepsilon_S(T) = -12.8 + 1.50 * T - 4.98 * 10^{-2} * T^2 + 2.28 * 10^{-4} * T^3 + 0.0333 * L * (T-20) \mu\text{m/m} \pm 0.3 (\mu\text{m/m}) \text{ } ^\circ\text{C}^{-1}$$

TEMPERATURE COMPENSATION FOR TEMPERATURKOMPENSATION FÜR COMPENSATION DE TEMPERATURE POUR COMPENSAÇÃO DE TEMPERATURA PARA		STEEL STAHL ACIER AÇO	STAINLESS STEEL ROSTFREIER STAHL ACIER INOX AÇO INOXIDÁVEL	ALUMINIUM ALUMINIUM ALUMINIUM ALUMINIO	MAGNESIUM MAGNESIUM MAGNÉSIUM MAGNÉSIO	GAGE RESISTANCE WIDERSTAND RESISTANCE RESISTÊNCIA	Ω 119.5	± 0.4
TYPE, TIPO KFC-2-D2-11	ADOPTABLE THERMAL EXPANSION ABGESTIMMT FÜR WÄRMEUSDEHNUNGS KÖEFFIZIE'NT COEFFICIENT DE DILATATION COEFICIENTE DE DILATAÇÃO TÉRMICA AFERIDO	10.8 PPM / °C			GAGE FACTOR K- FAKTOR FACTEUR DE JAUGE FATOR DA RESISTÊNCIA	2.08	± 1 %	
	GAGE LENGTH MESSGITTER LÄNGE LONGUEUR DE LA JAUGE COMPRIMENTO DA RESISTÊNCIA	2 m.m.			THERMAL OUT PUT WÄRMEABGABE DÉRIVE THERMIQUE RENDIMENTO TÉRMICO	± 1.8 $\mu\epsilon$ / °C		
	GAGE FACTOR CHANGE WITH TEMPERATURE TEMPERATURABHANGIGKEIT DES K- FAKTORS DÉRIVE THERMIQUE DU FACTEUR DE JAUGE MUDANCA DO FATOR DE CALIBRAÇÃO COM A TEMPERATURA	0.015 % / °C						
LOT NO. GRUNDSTÜCK NR.	LOT NO. LOTE NO.	Y392-062			QUANTITY QUANTITÉ MENGE QUANTIDADE	5		

STRAIN GAGES



ENGINEERING DATA SHEET

JF

057755

THE INFORMATION APPEARING ON THIS SHEET HAS BEEN COMPILED SPECIFICALLY FOR THE GAGES CONTAINED IN THIS PACKAGE. THIS FORM IS PRODUCED WITH ADVANCED EQUIPMENT & PROCEDURES WHICH PERMIT COMPREHENSIVE QUALITY ASSURANCE VERIFICATION OF ALL DATA SUPPLIED HEREIN. SHOULD ANY QUESTIONS ARISE RELATIVE TO THESE GAGES, PLEASE MENTION GAGE TYPE, BATCH NUMBER, AND LOT NUMBER.

H001

Micro-Measurements
Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F007

WA-06-030WT-120

TYPE

WA-06-030WT-120

QUANTITY

5

LOT NUMBER

A50BD03

RESISTANCE IN OHMS AT 20°C

120.0 ± 0.5%

GAGE FACTOR AT 20°C

2.10 nom

Kt

+1.3% nom

CODE

014111-311

GENERAL INFORMATION: WA-SERIES STACKED ROSETTE STRAIN GAGES

GENERAL DESCRIPTION: WA-Series stacked rosette strain gages are a family of superimposed constant-alloy strain gage elements oriented at 45°, 60°, or 90°; widely used in stress analysis applications. These gages have integral high-endurance lead-ribbons with a backing and encapsulation matrix consisting of a high-temperature epoxy phenolic resin system reinforced with glass fiber.

TEMPERATURE RANGE: -100° to +400° F (-75° to +205° C) for continuous use in static measurements; -320° to +500° F (-195° to +260° C) for special or short-term exposure.

SELF-TEMPERATURE COMPENSATION: See data curve below. The thermal output curve will be stable to at least +400° F (+205° C). Drift rate will be appreciable at +500° F (+260° C).

STRAIN LIMITS: ±1.5% at room temperature; ±1.0% at -320° F (-195° C); ±3% at +400° F (+205° C).

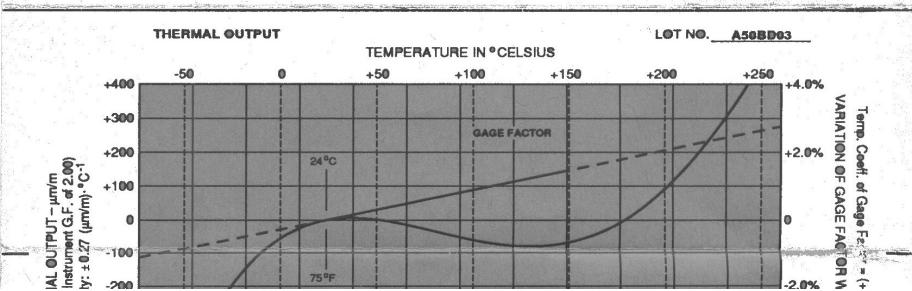
FATIGUE LIFE: 10⁷ cycles at ±1500µin/in (µm/m); 10⁸ cycles at ±1800µin/in (µm/m). Longer gage lengths and lower resistances result in greater endurance and less scatter in fatigue life.

BONDING AGENTS: High-temperature epoxy adhesives are recommended for best performance over the entire temperature range. Micro-Measurements M-Bond 610, 600 and M-Bond GA-60 are particularly compatible with WA-Series gages. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletin B-130 for installation procedures.

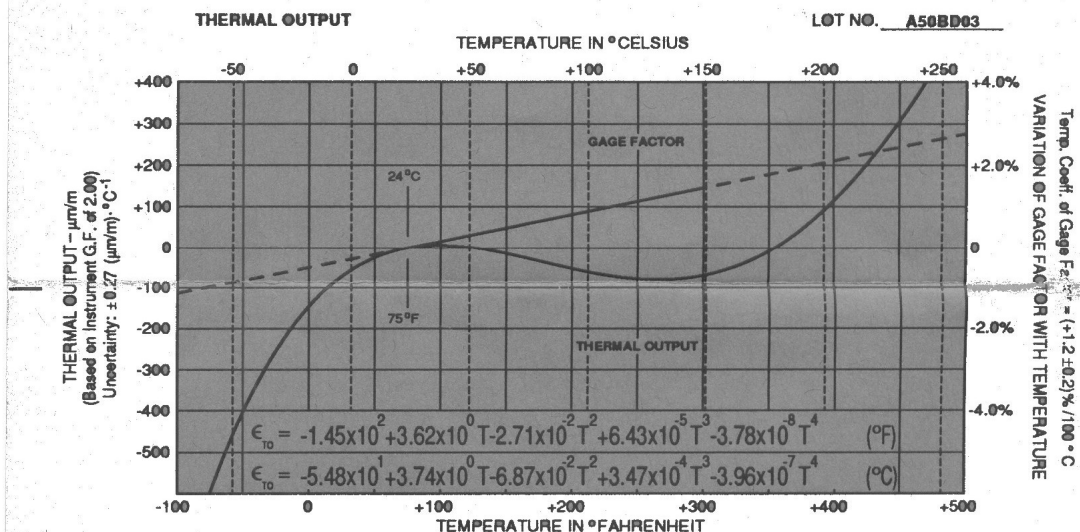
LEADWIRE SYSTEM: A single flat high-endurance lead is connected to each tab of each element. Internal tab connections on these gages are made with +570° F (+300° C) solder. Leadwires may be soft soldered, spot-welded, or silver soldered. Refer to M-M Bulletin B-132 for information on solders.

NOTE: The backing of WA-Series gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

G051



G051



TESTED ON: 1018 STEEL TEST PATTERN: 250BG CODE: 903219 ENG. GEW

TEST PROCEDURES USED BY MICRO-MEASUREMENTS

- OPTICAL DEFECT ANALYSIS M-M Procedure, Direct NBS Traceability on Resistance Standards
- GAGE RESISTANCE AT 24°C AND 50% RH M-M Procedure, Direct NBS Traceability on Resistance Standards
- GAGE FACTOR AT 24°C & 50% RH (UNIAXIAL STRESS FIELD - POISSON RATIO = 0.285) ASTM E-251 (Constant Stress Cantilever Method)
- TEMPERATURE COEFFICIENT OF GAGE FACTOR ASTM E-251 (Step Deflection Method)
- TEMPERATURE COEFFICIENT OF GAGE FACTOR ASTM E-251 (Slow Heating Rate, Continuously Recorded)
- TRANSVERSE SENSITIVITY AT 24°C AND 50% RH ASTM E-251
- FATIGUE LIFE NAS 942 (Modified)
- STRAIN LIMITS NAS 942 (Modified)
- GAGE THICKNESS M-M Procedure
- CREEP AND DRIFT M-M Procedure (Similar to NAS 942 Method)

NOTE: Gage resistance, gage factor, temperature coefficient of gage factor, thermal output, and transverse sensitivity testing and information presentation are in compliance with OIML International Recommendation NO. 62. *Performance characteristics of metallic resistance strain gages*. Other tests are not included in I.R. NO. 62.

T001

Norme tecniche

- UNI 10478 -1 ÷ 6 ; “Controllo mediante estensimetri elettrici a resistenza” (1996 - 1998)
- BS 6888:88 - British Standards
- ASTM E251, E837; E1237; E1319; E1561 - American Society of Testing Materials
- NAS 942 - National Standard Association - Aerospace industries
- NDIS 4001÷ 4002; 4101 ÷ 4106; 4301; 4401 (normativa giapponese)

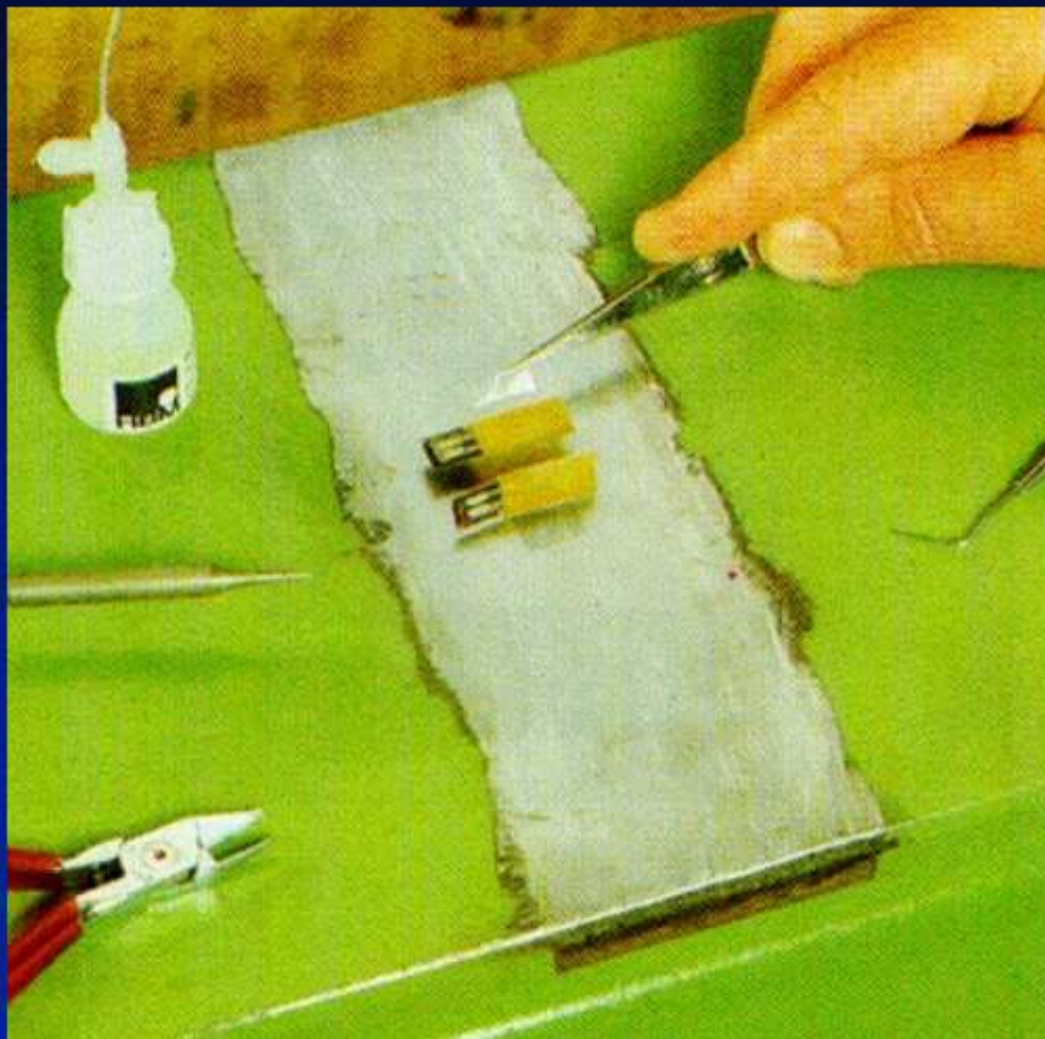
APPLICAZIONE ESTENSIMETRI



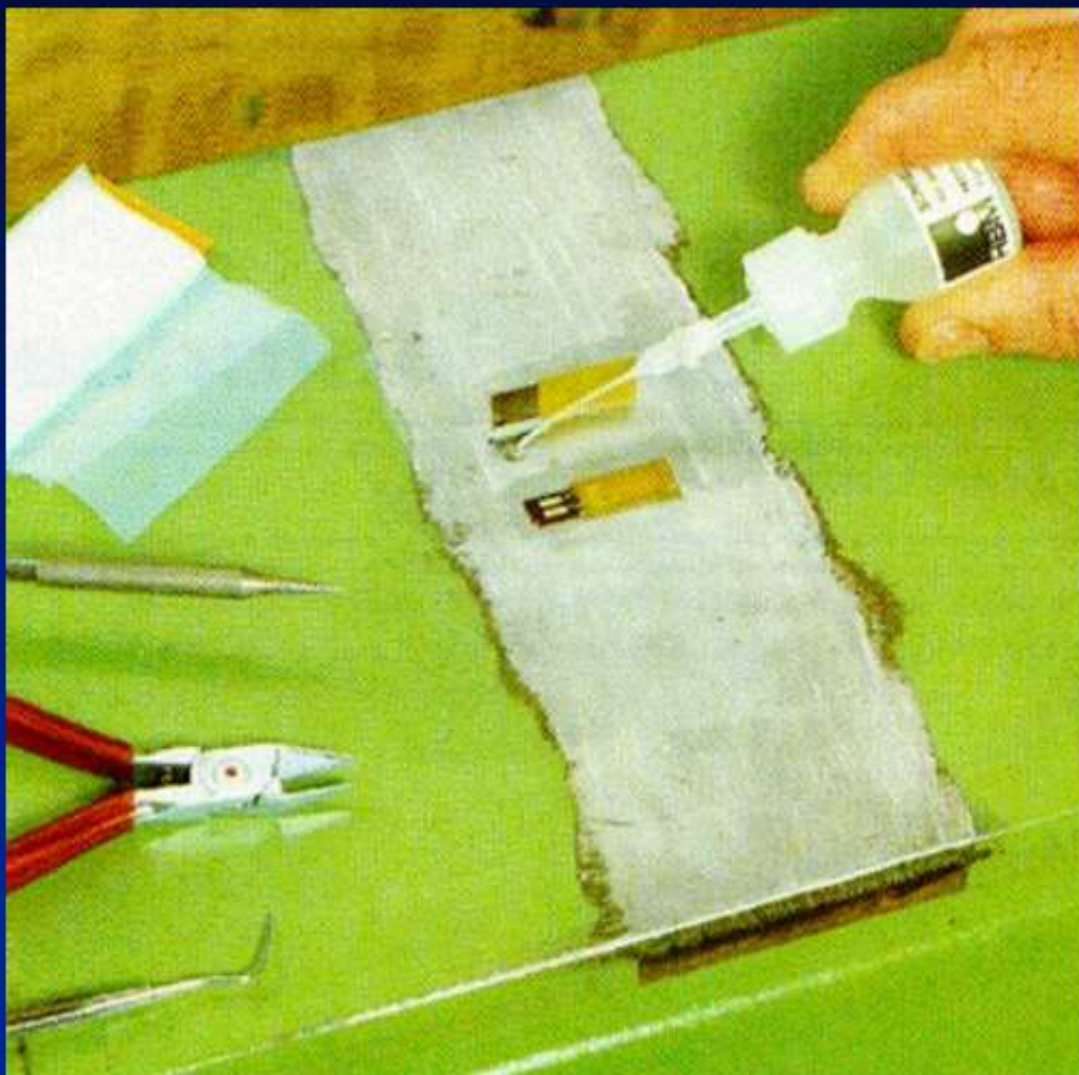
Abrasiono con carta vetrata della zona di applicazione



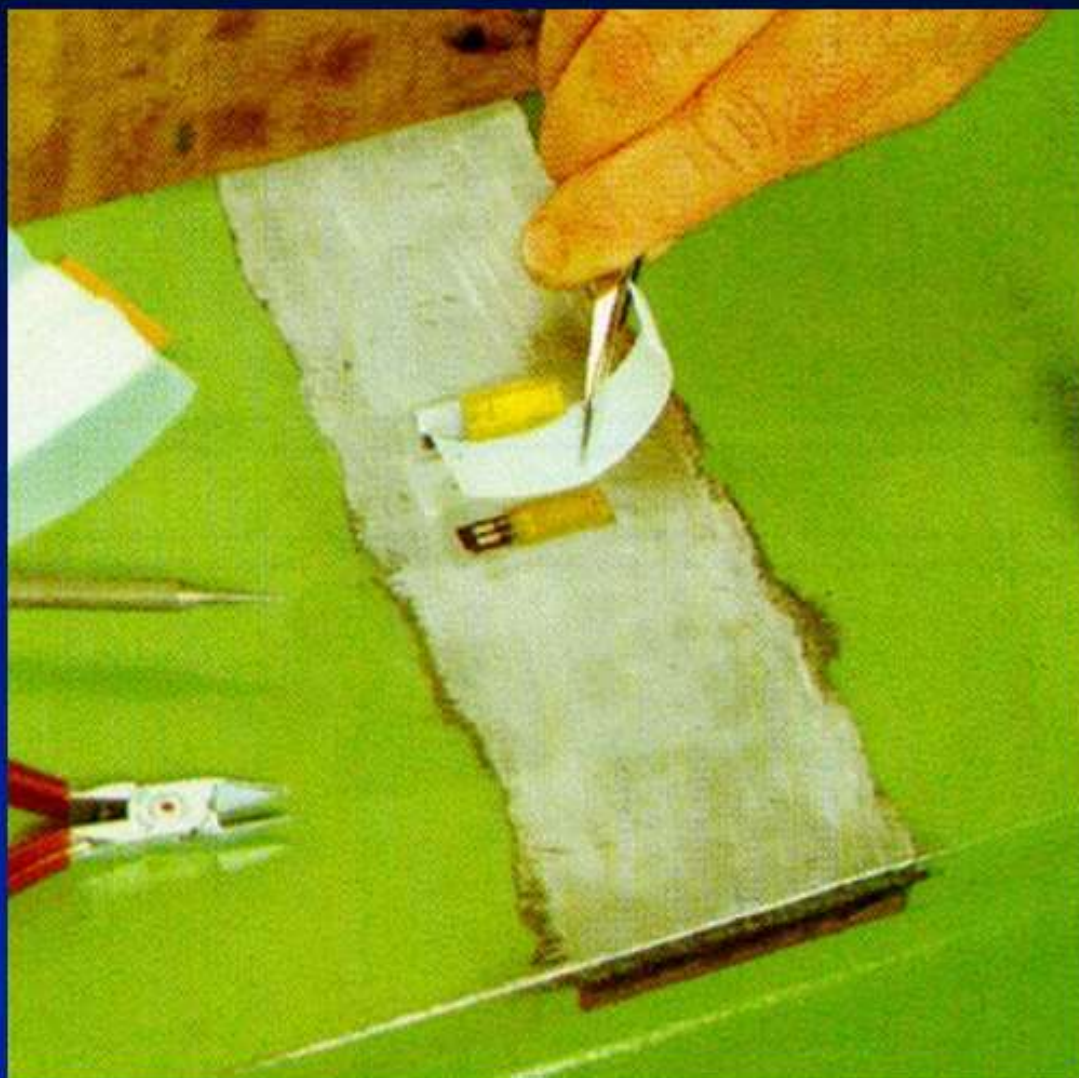
Pulizia della zona di applicazione



Posizionamento dell'estensimetro



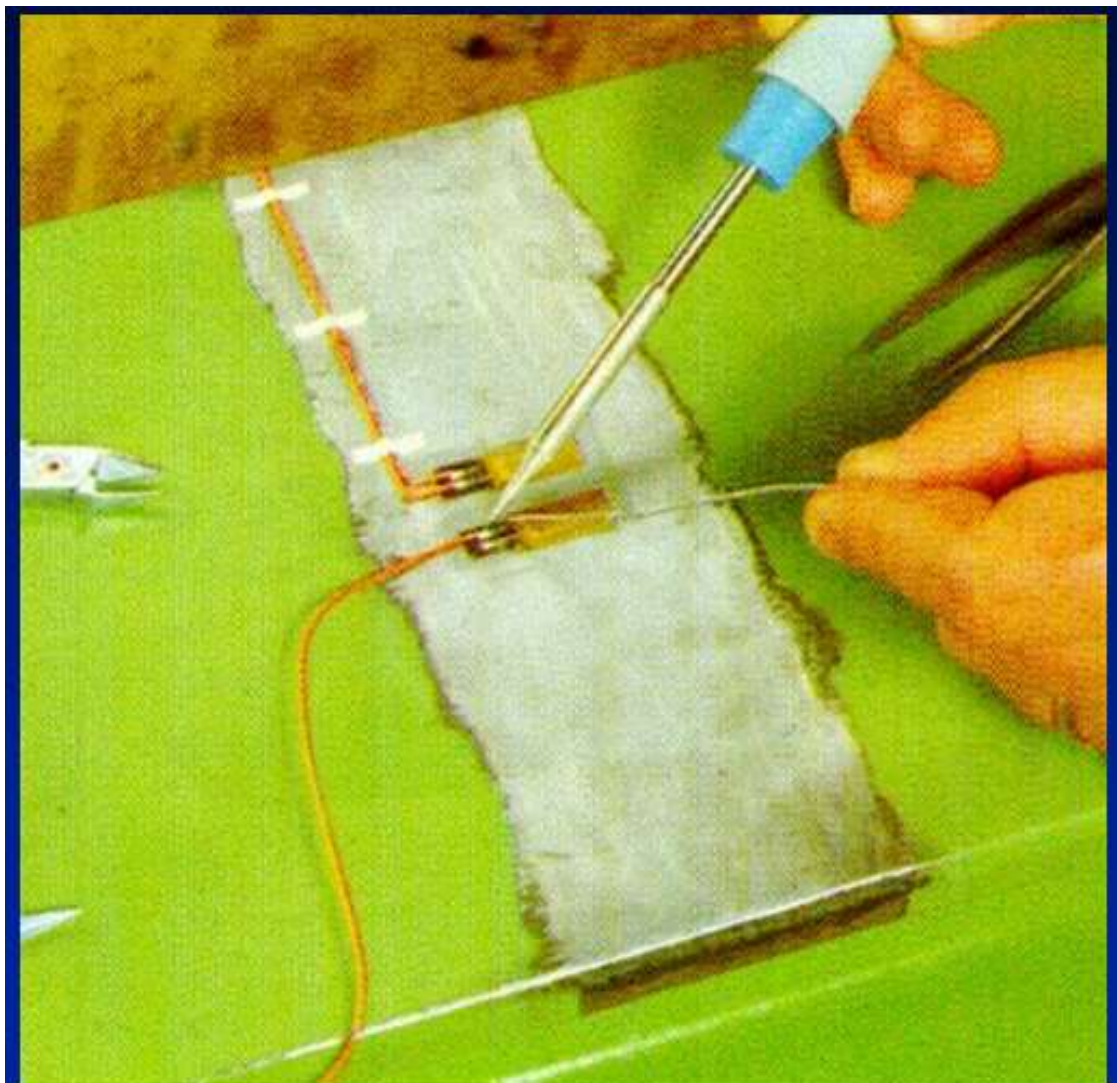
Applicazione dell'adesivo



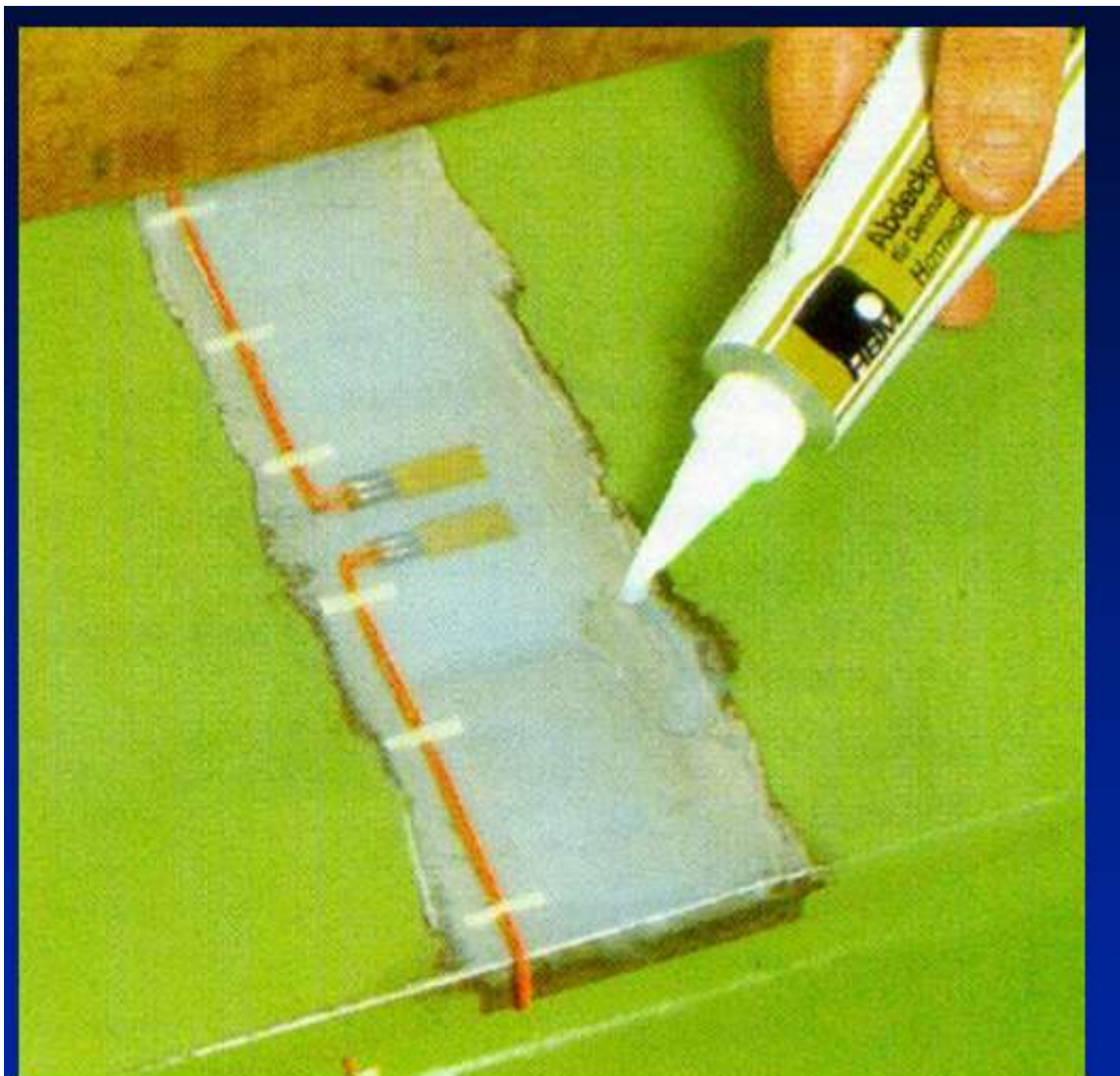
Applicazione dell'estensimetro



Pressione sull'estensimetro



Saldatura e fissaggio dei cavi



Applicazione del protettivo

Procedura

Preparazione superficie di incollaggio

- Preparazione iniziale
 - eliminare irregolarità, sgrassare, pulire
- Irruvidimento (carta abrasiva)
- Tracciatura
- Pulizia e decontaminazione finale con attacco chimico
- Neutralizzazione



Procedura

Applicazione dell'estensimetro

- posizionare estensimetro e basette su nastro adesivo posizionati su di un piano di vetro
- posizionare nastro,estensimetro e basetta sulla struttura
- applicare adesivo, incollare; togliere nastro
- ispezione visiva
- fissaggio dei terminali



Procedura

Applicazione dell'estensimetro

- **fissaggio dei cavi alla bassetta**
- **verifica estensimetri**
 - ispezione visiva
 - verifica continuità
 - verifica isolamento
 - verifica dell'adesione
- **protezione della installazione**



Estensimetria

Catena di misura

$$\frac{\Delta R}{R} = k \varepsilon$$

□ $R = 120 \Omega$

□ $k \cong 2$

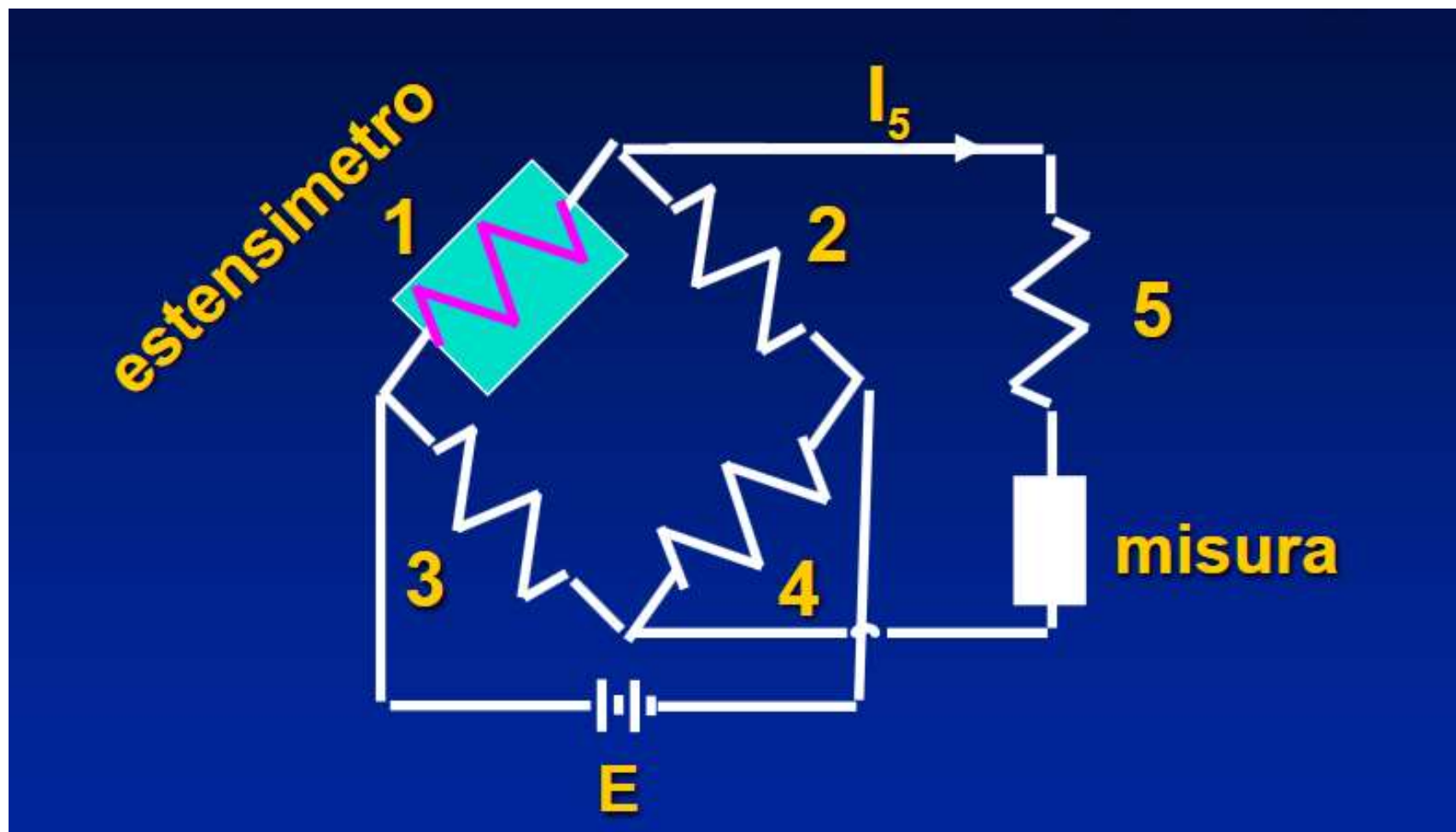
□ $\varepsilon = 1 \mu\varepsilon$

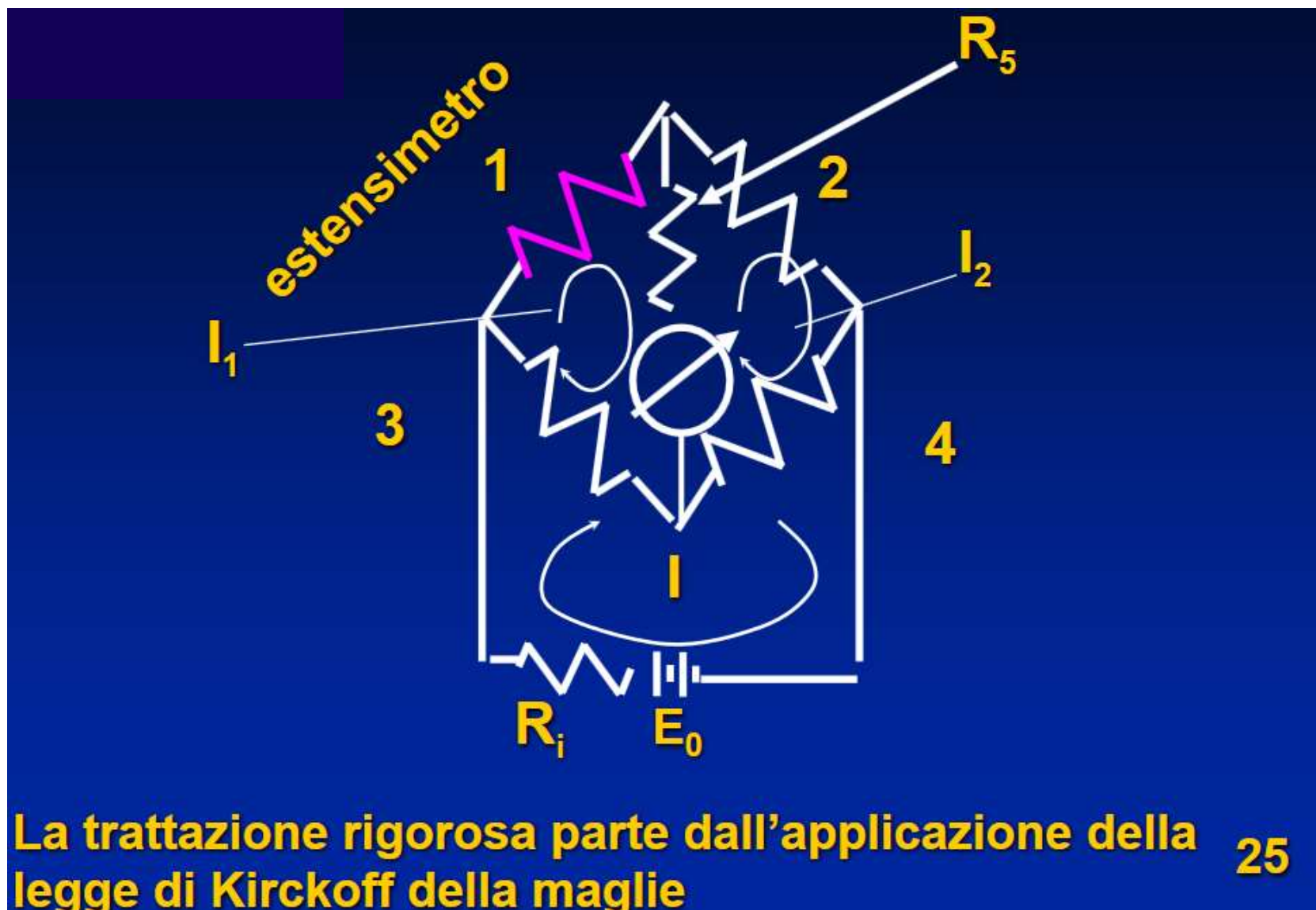
$\varepsilon = 10.000 \mu\varepsilon$

□ $\Delta R = 0,2 \text{ m } \Omega$

$\Delta R = 2 \Omega$

Ponte di Wheatstone





$$R_i I + R_3(I - I_1) + R_4(I - I_2) = E_0$$

$$R_3(I_1 - I) + R_1 I_1 + R_5(I_1 - I_2) = 0$$

$$R_4(I_2 - I) + R_2 I_2 + R_5(I_2 - I_1) = 0$$

Ordinando secondo le correnti e ricordando che $E_0 - R_i I = E$, si ha

$$(R_3 + R_4)I - R_3 I_1 - R_4 I_2 = E$$

$$-R_3 I + (R_1 + R_3 + R_5)I_1 - R_5 I_2 = 0$$

$$-R_4 I - R_5 I_1 + (R_2 + R_4 + R_5)I_2 = 0$$

E' un sistema lineare nelle 3 incognite I, I_1, I_2

Se si indica con $I_5 = I_2 - I_1$ la corrente che passa nel galvanometro G (cioè in R_5) e sostituendo $I_2 = I_1 + I_5$ si ha

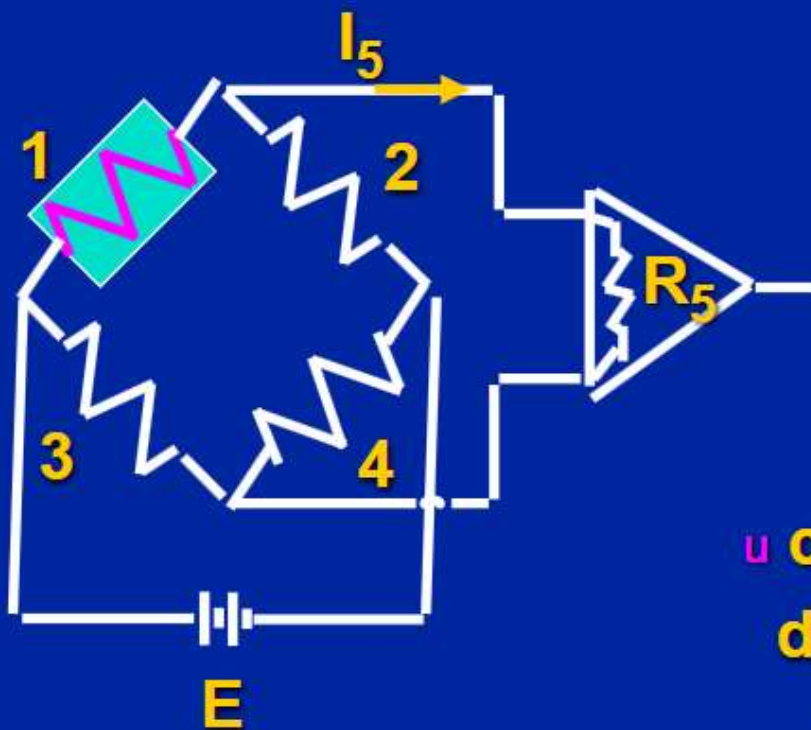
$$\begin{array}{rcll} (R_3 + R_4)I & - (R_3 + R_4)I_1 & - R_4I_5 & = E \\ -R_3I & (R_1 + R_3)I_1 & - R_5I_5 & = 0 \\ -R_4I & (R_2 + R_4)I_1 & (R_2 + R_4 + R_5) & = 0 \end{array}$$

$$I_5 = \frac{E(R_4R_1 - R_3R_2)}{R_1R_2R_3 + R_1R_3R_4 + R_1R_2R_4 + R_2R_3R_4 + R_5(R_1 + R_2)(R_3 + R_4)} \quad (1)$$

La relazione generale (1), ma anche quelle approssimate che saranno mostrate nel seguito sono lineari con la tensione di alimentazione del ponte, ma non sono lineari con I singole resistenze del ponte: se il ponte non è inizialmente bilanciato e una delle resistenze subisce una variazione, la tensione di uscita NON è proporzionale alla variazione di quella resistenza

SOLO partendo da condizioni di ponte bilanciato si ha linearità tra le variazioni di resistenza e la corrente (o

DEFLESSIONE



u Se R_5 è molto grande:

$$I_5 = \frac{E(R_1R_4 - R_2R_3)}{R_5(R_1 + R_2)(R_3 + R_4)}$$

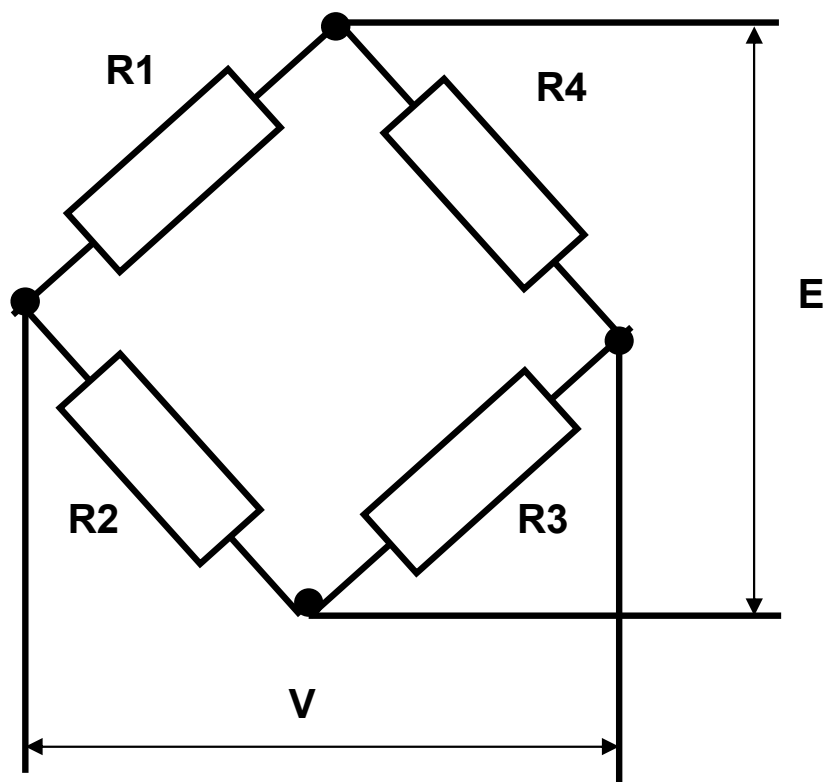
$$V = R_5 I_5 = \frac{E(R_1R_4 - R_2R_3)}{(R_1 + R_2)(R_3 + R_4)}$$

◆ azzero, carico $\rightarrow \Delta R$

u con 4 lati uguali e variazione di resistenza solo su un lato:

$$\frac{\Delta V}{E} = \frac{\Delta R / R}{4 + 2(\Delta R / R)} \approx \frac{\Delta R / R}{4} \quad 34$$

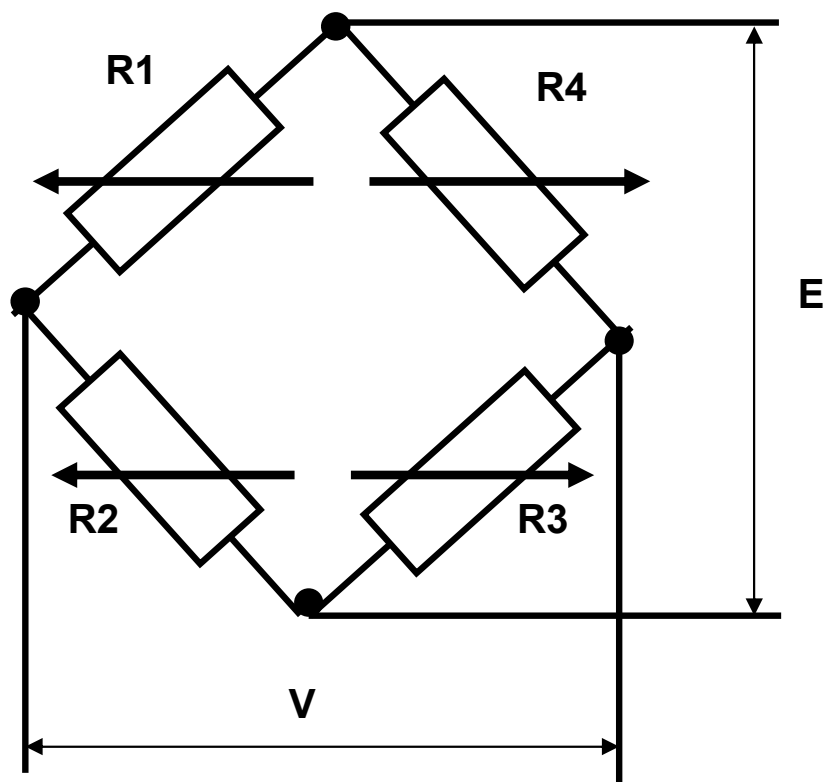
Ponte di Wheatstone



- E alimentazione
- V uscita
- Ponte equilibrato $V = 0$
 $R1 * R3 = R2 * R4$
- $R \rightarrow R + \Delta R$

$$V = \frac{E}{4} \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right)$$

Ponte di Wheatstone



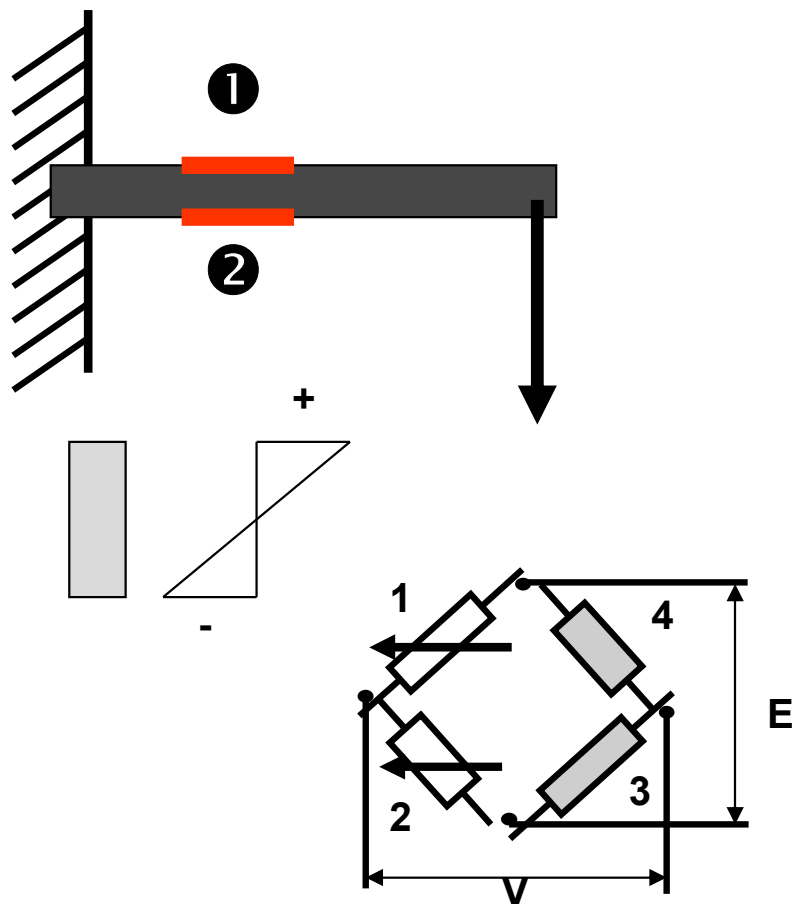
- Rami del ponte
⇒ estensimetri
- $\Delta R / R = k \varepsilon$

$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

	<p>$\frac{1}{4}$ di ponte</p>	$V = \frac{Ek}{4} \varepsilon_1$
	<p>$\frac{1}{2}$ ponte</p>	$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2)$
	<p>ponte intero</p>	$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$

Flessione

$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

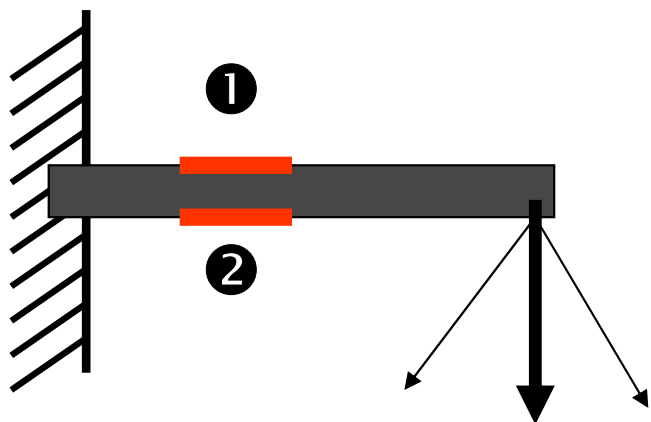


$$\square \textcircled{1} \quad \varepsilon_f \quad \textcircled{2} \quad -\varepsilon_f$$

$$\square \varepsilon_1 - \varepsilon_2 = 2 \varepsilon_f$$

Flessione

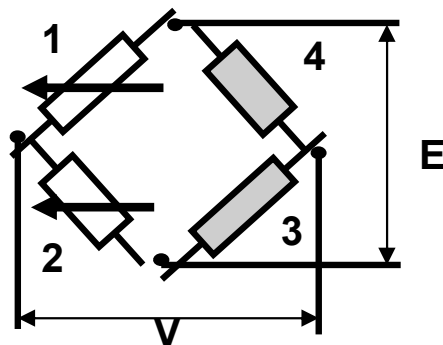
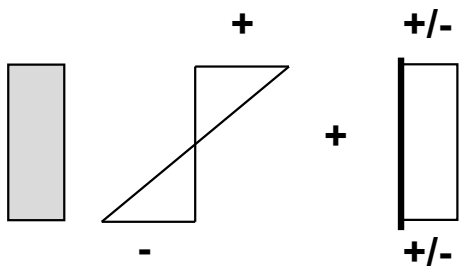
$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$



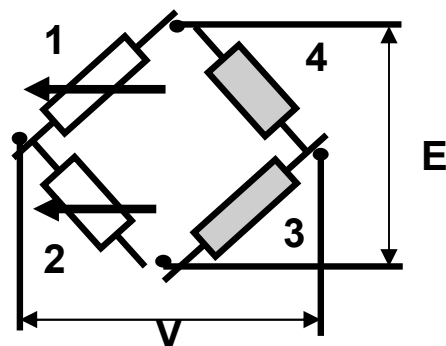
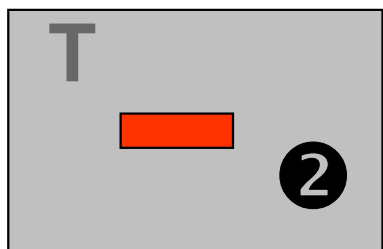
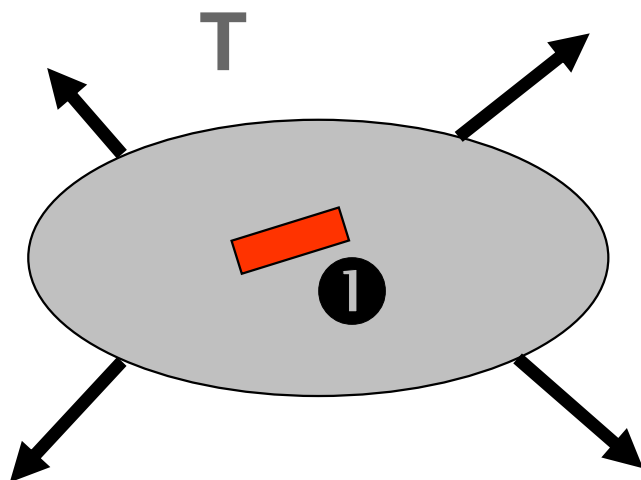
□ **1** $+\varepsilon_f + \varepsilon_n$

□ **2** $-\varepsilon_f + \varepsilon_n$

□ $\varepsilon_1 - \varepsilon_2 = 2\varepsilon_f$



Temperatura -



$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

□ ① $\varepsilon_F + \varepsilon_a$

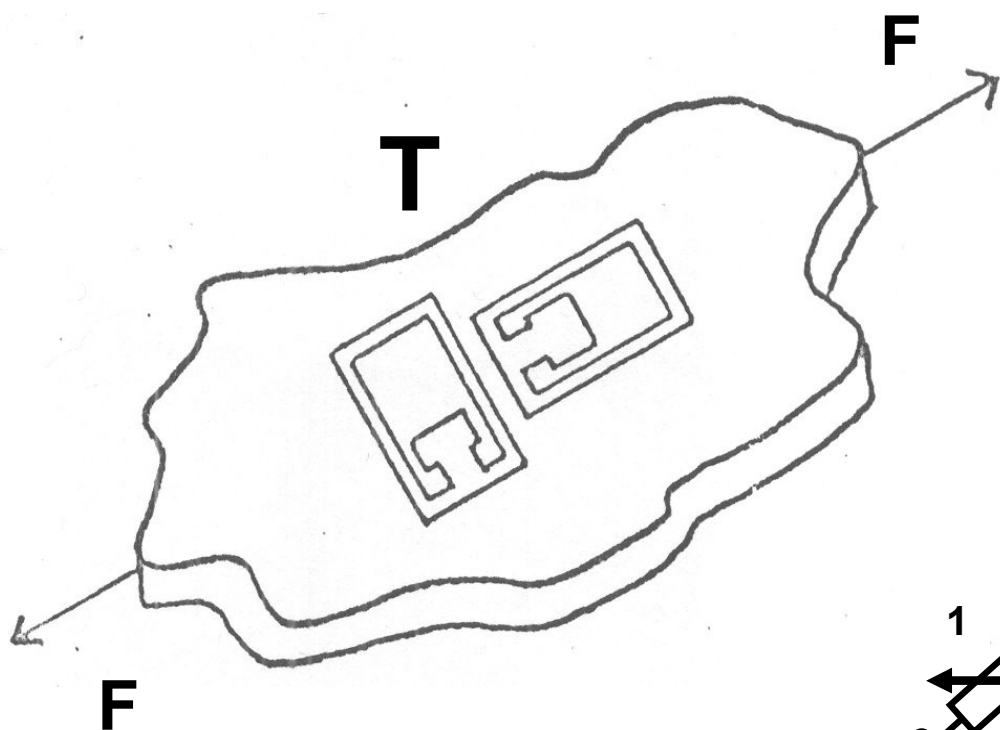
□ ② ε_a

□ $\varepsilon_1 - \varepsilon_2 = \varepsilon_F$

□ estensimetro
compensatore

Trazione -

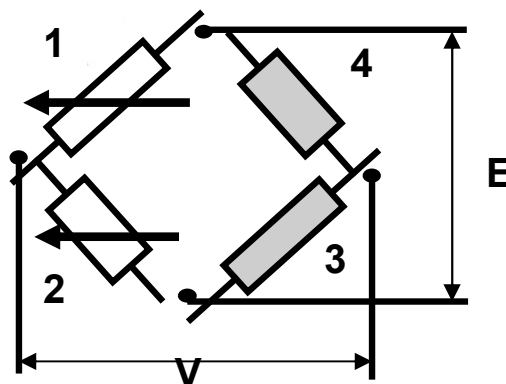
$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$



$$\square \textcircled{1} + \varepsilon_f + \varepsilon_a$$

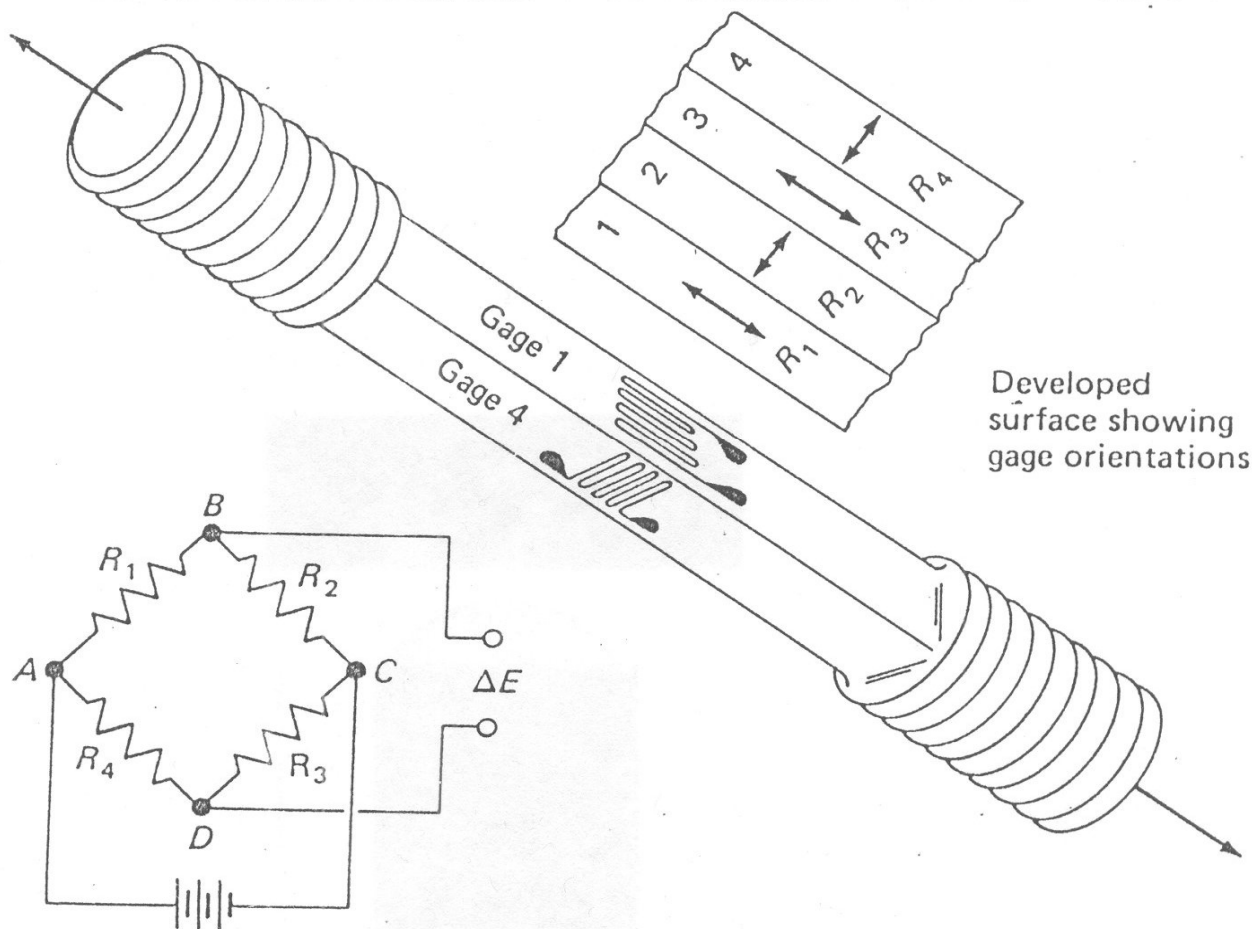
$$\square \textcircled{2} - \nu \varepsilon_f + \varepsilon_a$$

$$\square \varepsilon_1 - \varepsilon_2 = \varepsilon_f (1 + \nu)$$



Trazione -

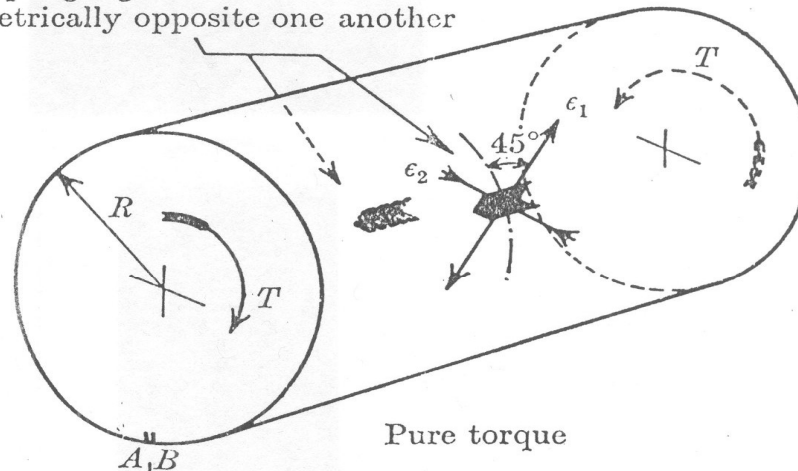
$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$



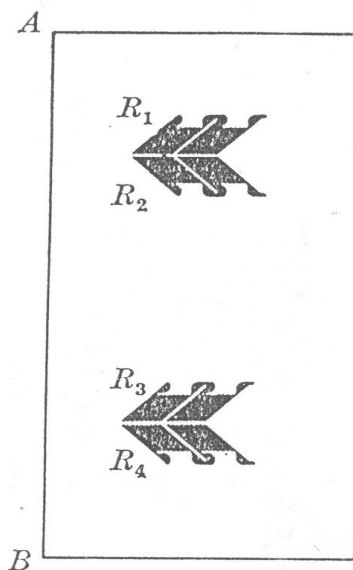
Torsione

$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

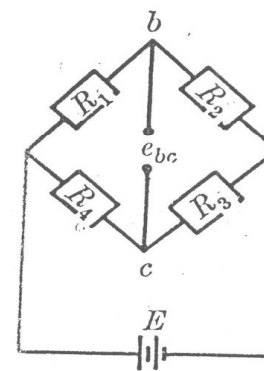
Torque gauges bonded diametrically opposite one another



Pure torque

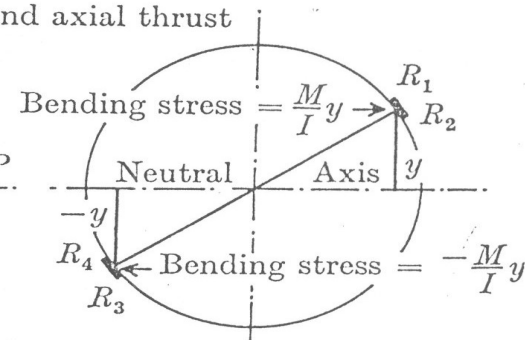
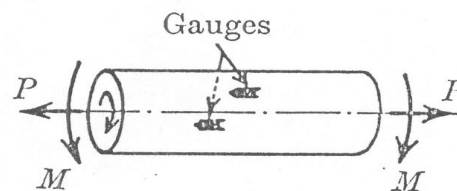


'Unwrapped' schematic of gauge positions



Full-bridge circuit

Torque with bending and axial thrust



=σ

1		$\epsilon = \epsilon_n + \epsilon_D = \frac{4}{k} \cdot \frac{UA}{UE} - \epsilon_s$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>1</td><td>1</td><td>1</td><td>0</td></tr></table>	t	P	M _b	M _d	1	1	1	0		
t	P	M _b	M _d										
1	1	1	0										
2		$\epsilon = \epsilon_n + \epsilon_D = \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>1</td><td>1</td><td>0</td></tr></table>	t	P	M _b	M _d	0	1	1	0		
t	P	M _b	M _d										
0	1	1	0										
3		$\epsilon = \epsilon_n + \epsilon_D = \frac{1}{(1+\mu)} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>1+μ</td><td>1+μ</td><td>0</td></tr></table>	t	P	M _b	M _d	0	1+μ	1+μ	0		
t	P	M _b	M _d										
0	1+μ	1+μ	0										
4		$\epsilon = \epsilon_D = \frac{1}{2} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>2</td><td>0</td></tr></table>	t	P	M _b	M _d	0	0	2	0		
t	P	M _b	M _d										
0	0	2	0										
5		$\epsilon = \epsilon_n = \frac{1}{2} \cdot \frac{4}{k} \cdot \frac{UA}{UE} - \epsilon_s$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>2</td><td>2</td><td>0</td><td>0</td></tr></table>	t	P	M _b	M _d	2	2	0	0		
t	P	M _b	M _d										
2	2	0	0										
6		$\epsilon = \epsilon_n + \epsilon_D = \frac{1}{2(1+\mu)} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>2(1+μ)</td><td>2(1+μ)</td><td>0</td></tr></table>	t	P	M _b	M _d	0	2(1+μ)	2(1+μ)	0		
t	P	M _b	M _d										
0	2(1+μ)	2(1+μ)	0										
7		$\epsilon = \epsilon_n = \frac{1}{2} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>2</td><td>0</td><td>0</td></tr></table>	t	P	M _b	M _d	0	2	0	0		
t	P	M _b	M _d										
0	2	0	0										
8		$\epsilon = \epsilon_D = \frac{1}{4} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>4</td><td>0</td></tr></table>	t	P	M _b	M _d	0	0	4	0		
t	P	M _b	M _d										
0	0	4	0										
9		$\epsilon = \epsilon_n = \frac{1}{2(1+\mu)} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>2(1+μ)</td><td>0</td><td>0</td></tr></table>	t	P	M _b	M _d	0	2(1+μ)	0	0		
t	P	M _b	M _d										
0	2(1+μ)	0	0										
10		$\epsilon = \epsilon_D = \frac{1}{2(1-\mu)} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>2(1-μ)</td><td>0</td></tr></table>	t	P	M _b	M _d	0	0	2(1-μ)	0		
t	P	M _b	M _d										
0	0	2(1-μ)	0										
11		$\epsilon = \epsilon_D = \frac{1}{2(1+\mu)} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>2(1+μ)</td><td>0</td></tr></table>	t	P	M _b	M _d	0	0	2(1+μ)	0		
t	P	M _b	M _d										
0	0	2(1+μ)	0										
12		$\epsilon = \epsilon_D = \frac{1}{2} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_b</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>2</td><td>0</td></tr></table>	t	P	M _b	M _d	0	0	2	0		
t	P	M _b	M _d										
0	0	2	0										
13		$\epsilon = \epsilon_D = \frac{1}{4} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_{bx}</th><th>M_{by}</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>0</td><td>0</td><td>4</td></tr></table>	t	P	M _{bx}	M _{by}	M _d	0	0	0	0	4
t	P	M _{bx}	M _{by}	M _d									
0	0	0	0	4									
14		$\epsilon = \epsilon_D = \frac{1}{4} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_{bx}</th><th>M_{by}</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>0</td><td>0</td><td>4</td></tr></table>	t	P	M _{bx}	M _{by}	M _d	0	0	0	0	4
t	P	M _{bx}	M _{by}	M _d									
0	0	0	0	4									
15		$\epsilon = \epsilon_D = \frac{1}{4} \cdot \frac{4}{k} \cdot \frac{UA}{UE}$	<table border="1"><tr><th>t</th><th>P</th><th>M_{bx}</th><th>M_{by}</th><th>M_d</th></tr><tr><td>0</td><td>0</td><td>0</td><td>0</td><td>4</td></tr></table>	t	P	M _{bx}	M _{by}	M _d	0	0	0	0	4
t	P	M _{bx}	M _{by}	M _d									
0	0	0	0	4									

Catena di misura

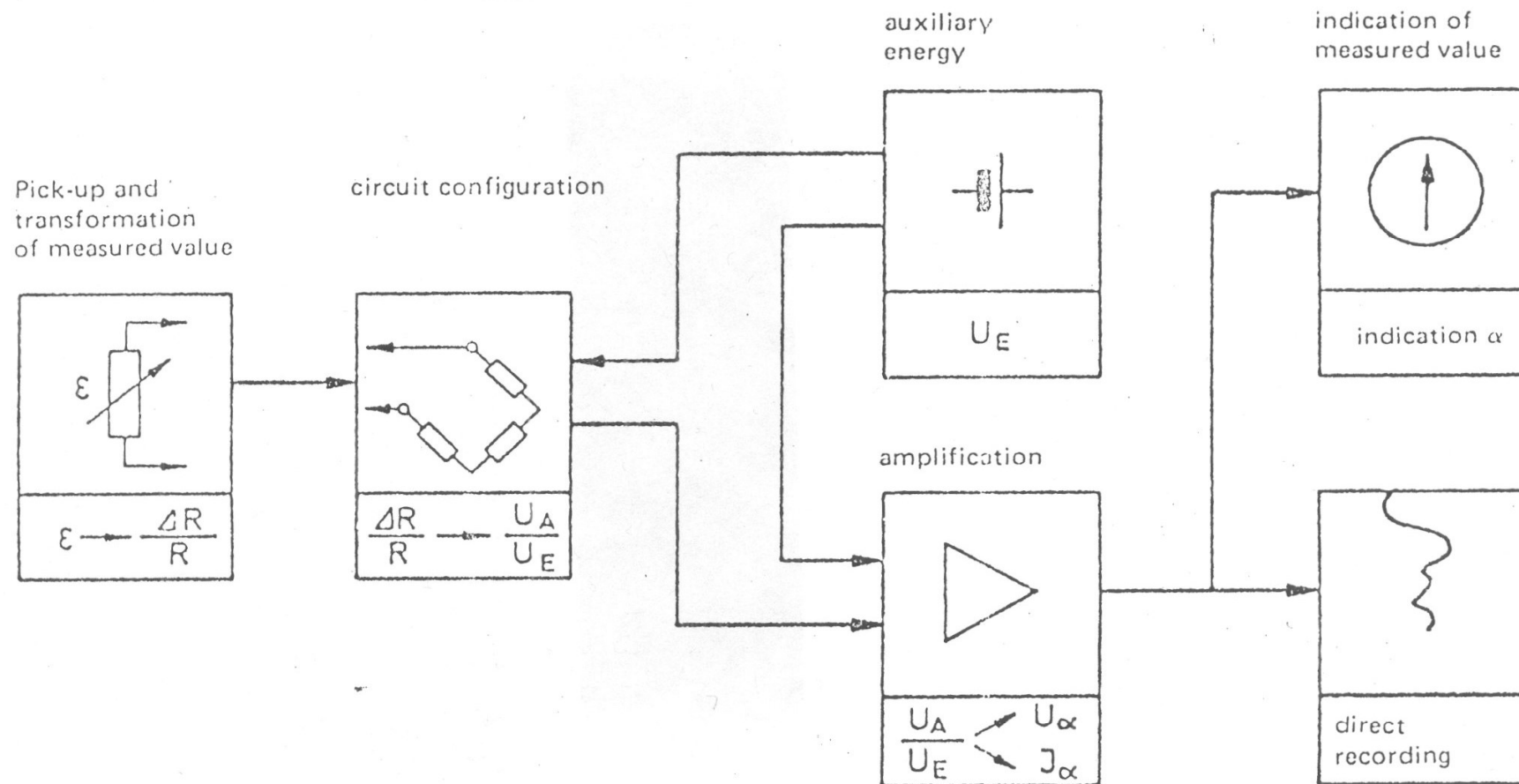


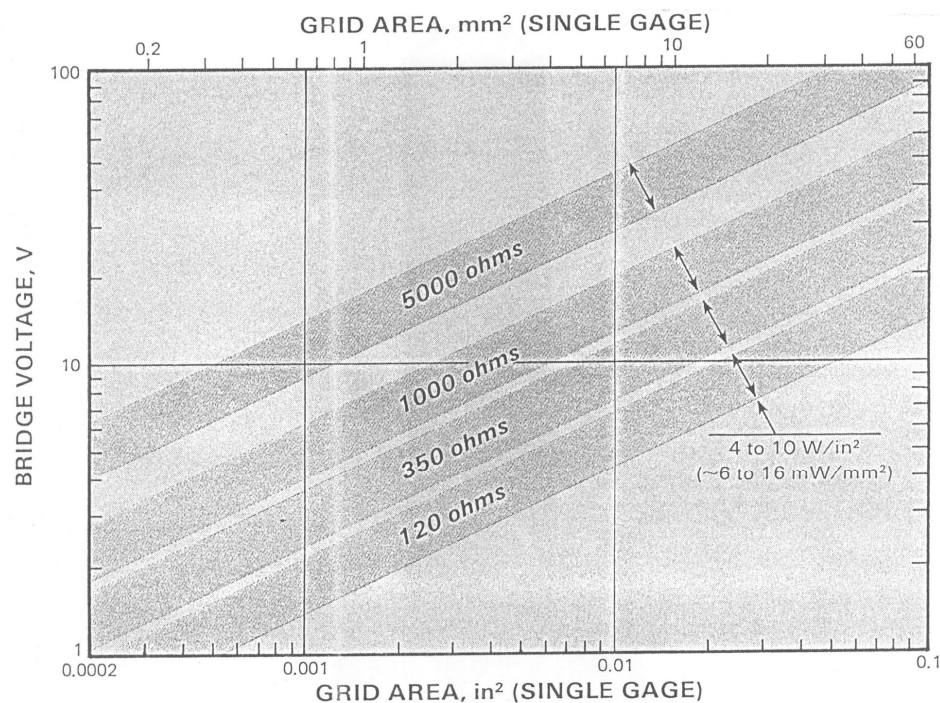
fig. 6: schematic structure of a measurement chain

Alimentazione

$$V = \frac{Ek}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

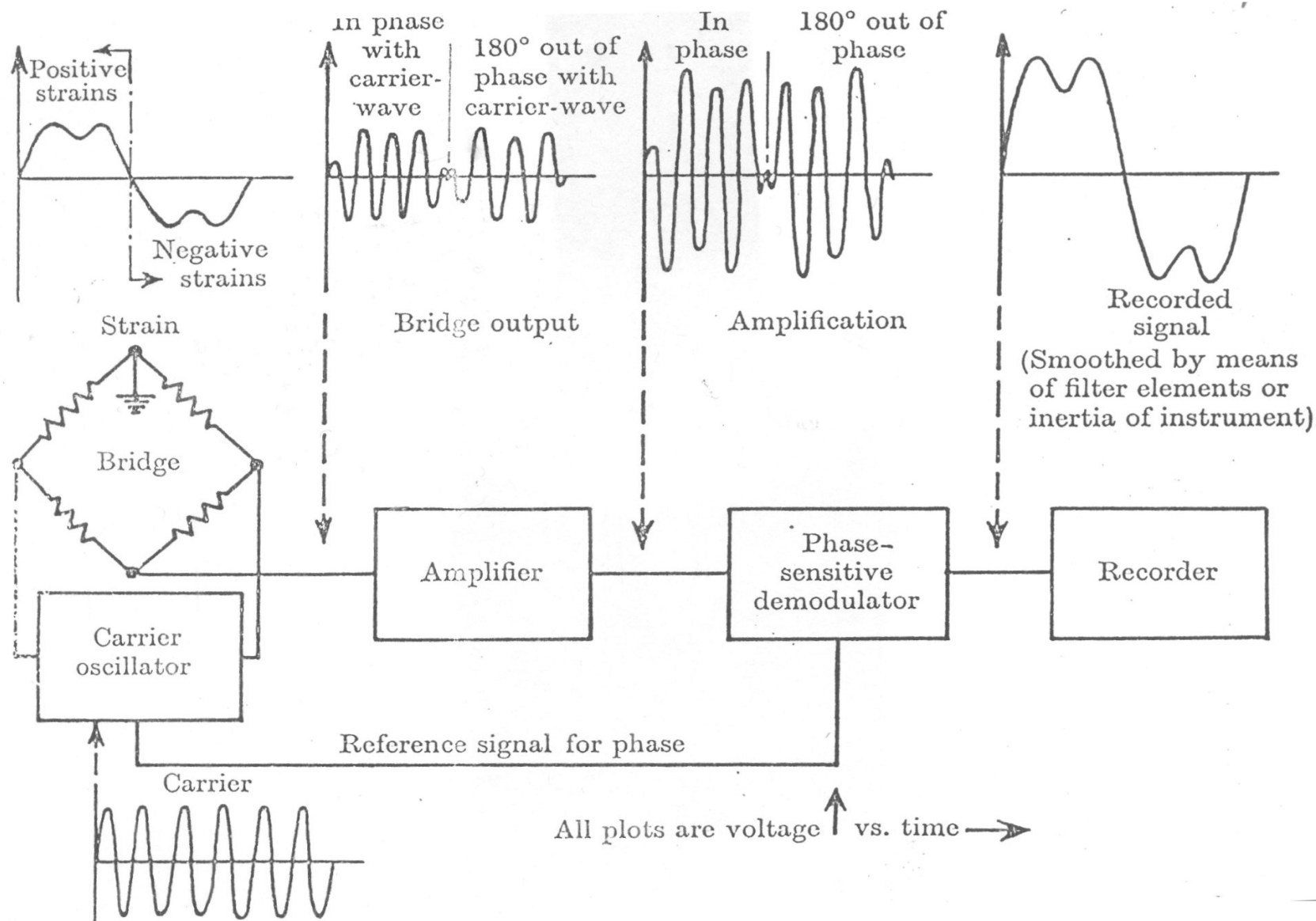
Potenza

$$W = V^2 / R$$



- V alimentazione = 0,5 - 10 V
- V continua / alternata - stabile

Alimentazione c.a.



Amplificazione

$$V = \frac{Ek}{4} \varepsilon_1$$

□ $E = 2 \text{ V} ; k = 2$

□ $\varepsilon = 1 \text{ } \mu\varepsilon$

$V = 0,001 \text{ mV}$

□ $\varepsilon = 10.000 \text{ } \mu\varepsilon$

$V = 0,01 \text{ V}$

□ Amplificatore \Rightarrow uscita $0 - \pm 1 / 10 \text{ V}$

Centralina estensimetrica

- alimentazione
- amplificazione
- completamento del ponte
- azzeramento (offset) del ponte
- calibrazione (sbilanciamento) del ponte

- I ▶ trasduttori resistivi (estensimetri), induttivi, capacitivi, termoresistenze, termocoppie, V
 ▶ monocanale ; multicanale

- O ▶ segnale V

Trasmissione dei segnali

□ **Cavi**

- resistenza (lunghezza)
- variazione di resistenza (temperatura)

□ **Connettori**

- » resistenza di contatto $\approx 0,3 \text{ m } \Omega \Rightarrow 1 \mu\epsilon$
- morsettiere
- commutatori
- contatti striscianti

□ **Telemetria**

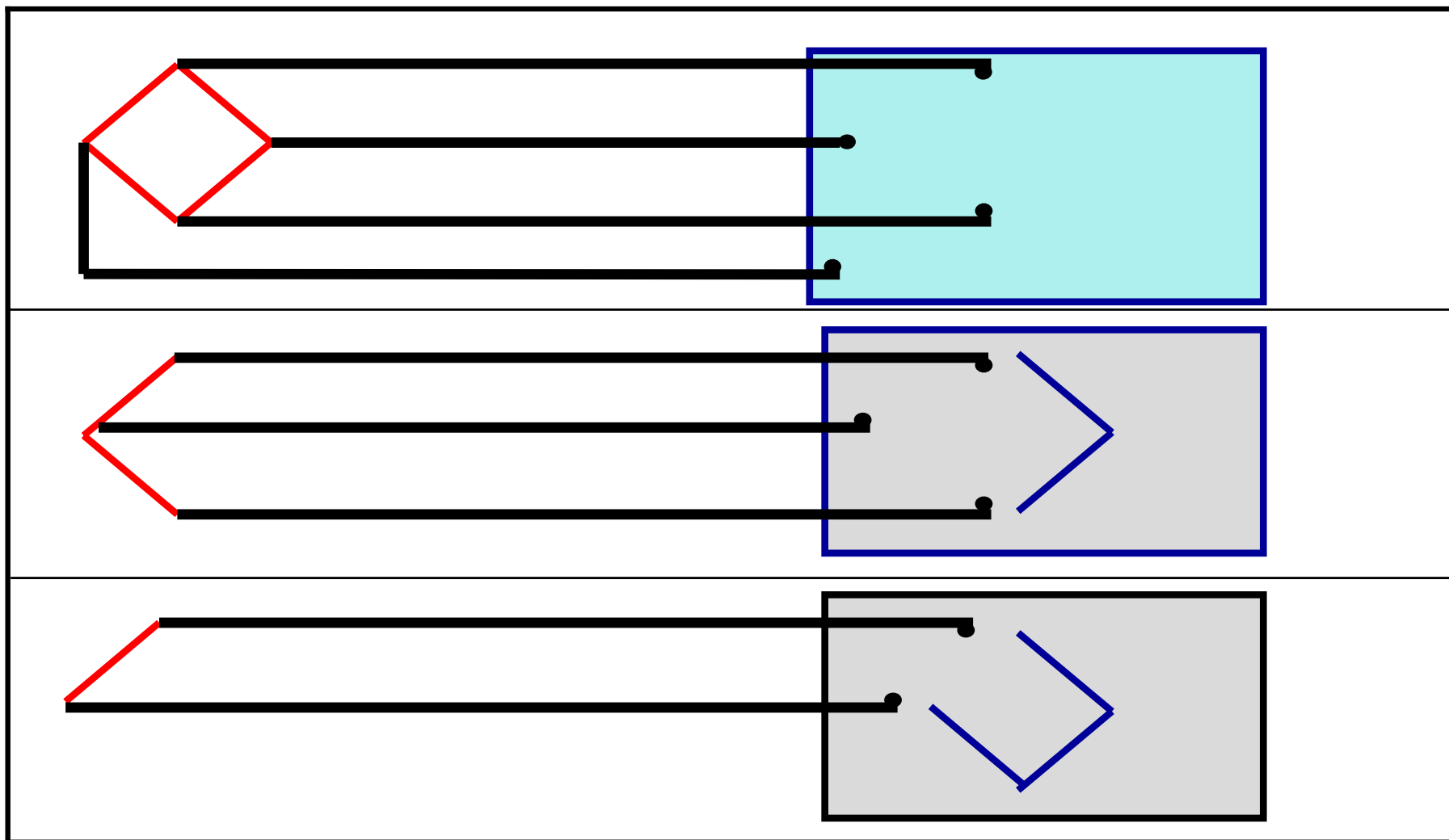
- wireless (breve distanza)
- telemetria (grande distanza)

Influenza dei cavi

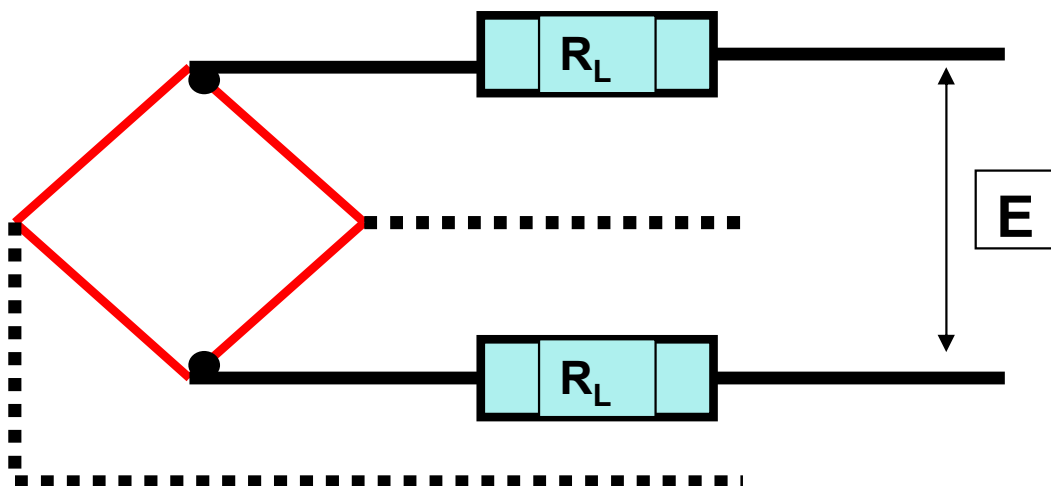
- resistenza (lunghezza)
- variazione di resistenza (temperatura)
- cavo rame $\varnothing 0,7 \text{ mm} \Rightarrow \text{Area } 0,38 \text{ mm}^2$
resistenza $0,017 \text{ } \Omega \text{ mm}^2 / \text{m} \Rightarrow 0.045 \text{ } \Omega / \text{m}$
 - 10 m di cavo $\Rightarrow 0,45 \text{ } \Omega \times 2 \cong 1 \text{ } \Omega$
- $\Delta R / R = 0,004 / ^\circ\text{C}$
 - 1 m di cavo $\Delta R 0,0004 \text{ } \Omega / ^\circ\text{C}$ equivalenti a

$$\frac{\Delta R_{temp}}{R_{est}} \frac{1}{k} = \varepsilon_{eq} \quad \frac{0,0004}{120} \frac{1}{2} \cong 1,5 \mu\varepsilon / ^\circ\text{C}$$

estensimetro - cavi - centralina



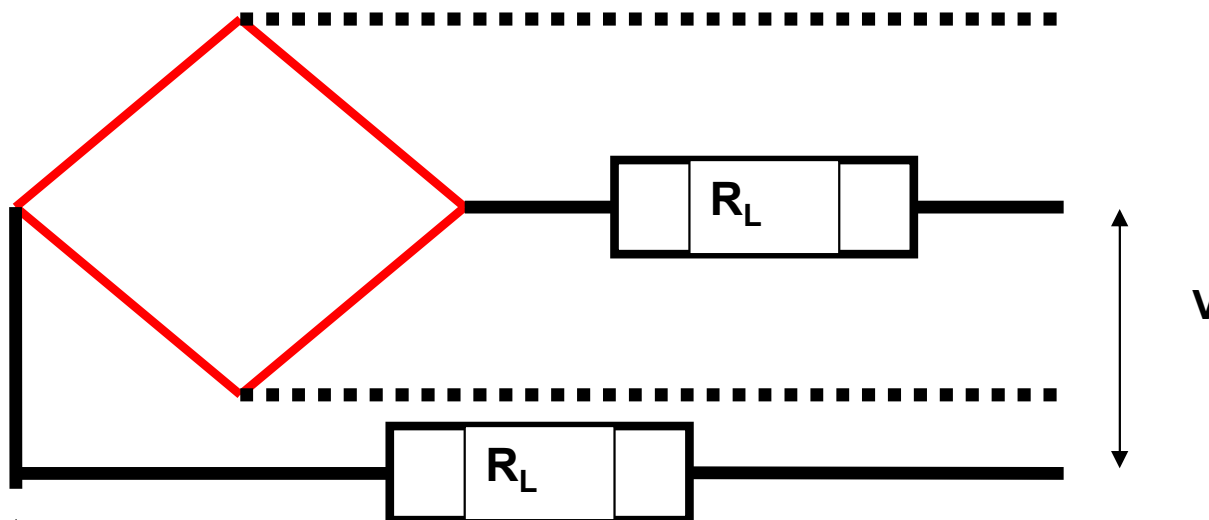
Ponte intero - alimentazione



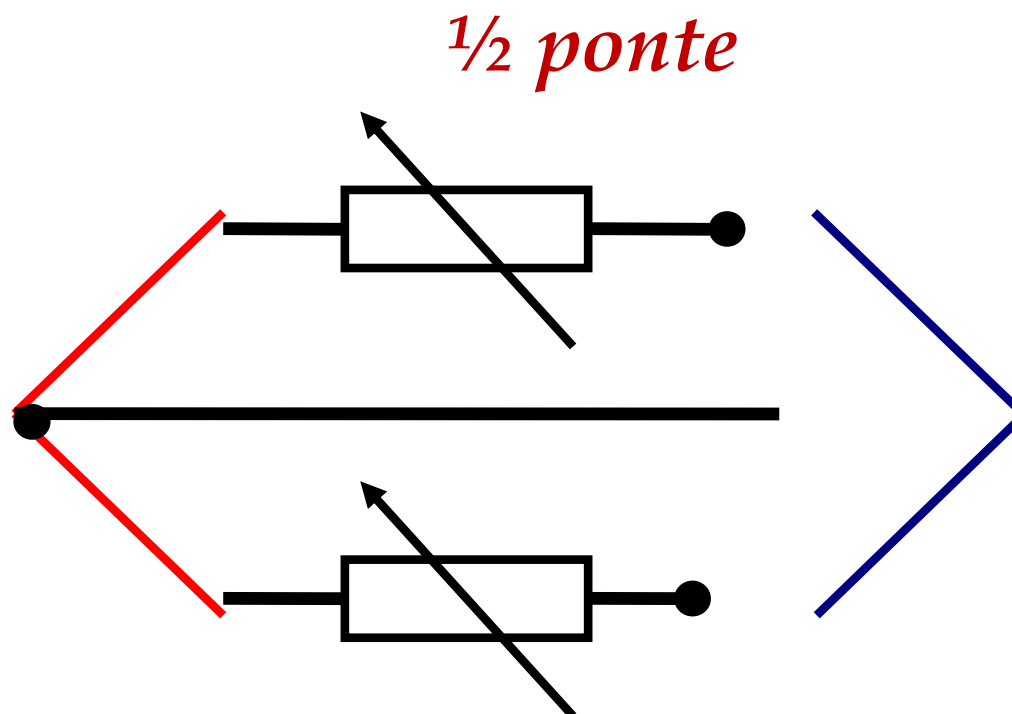
$$E_W = \frac{E}{R_W + 2R_L} R_W = E \frac{1}{1 + 2R_L / R_W}$$

□ **10 metri di cavo \approx 1% di attenuazione**

Ponte intero - segnale

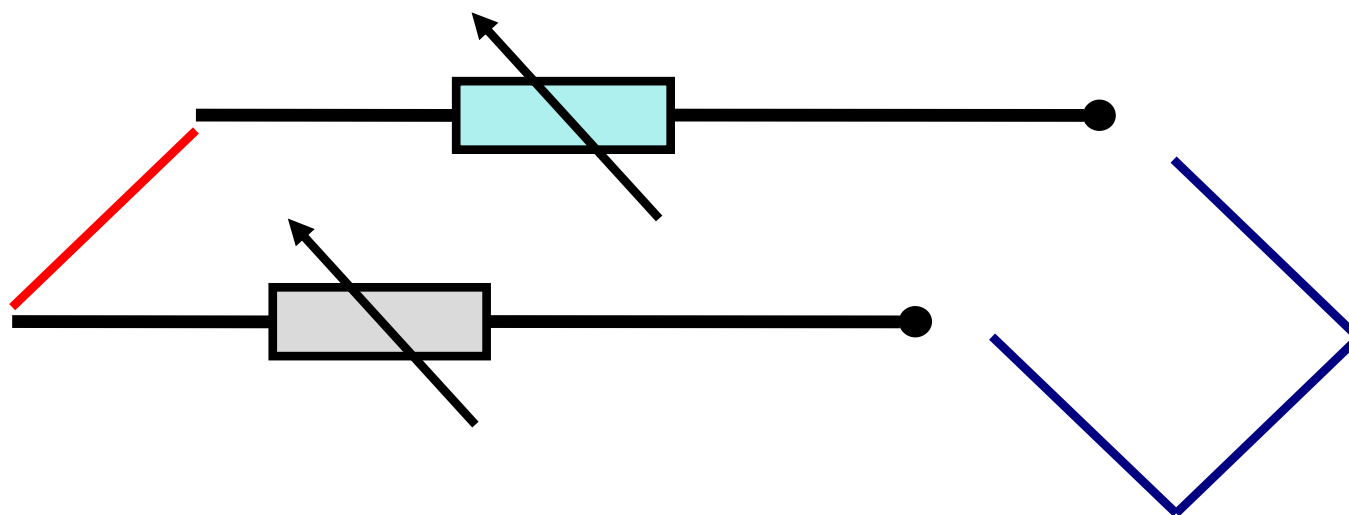


- Resistenza cavi influente - strumento misura con elevata impedenza di ingresso



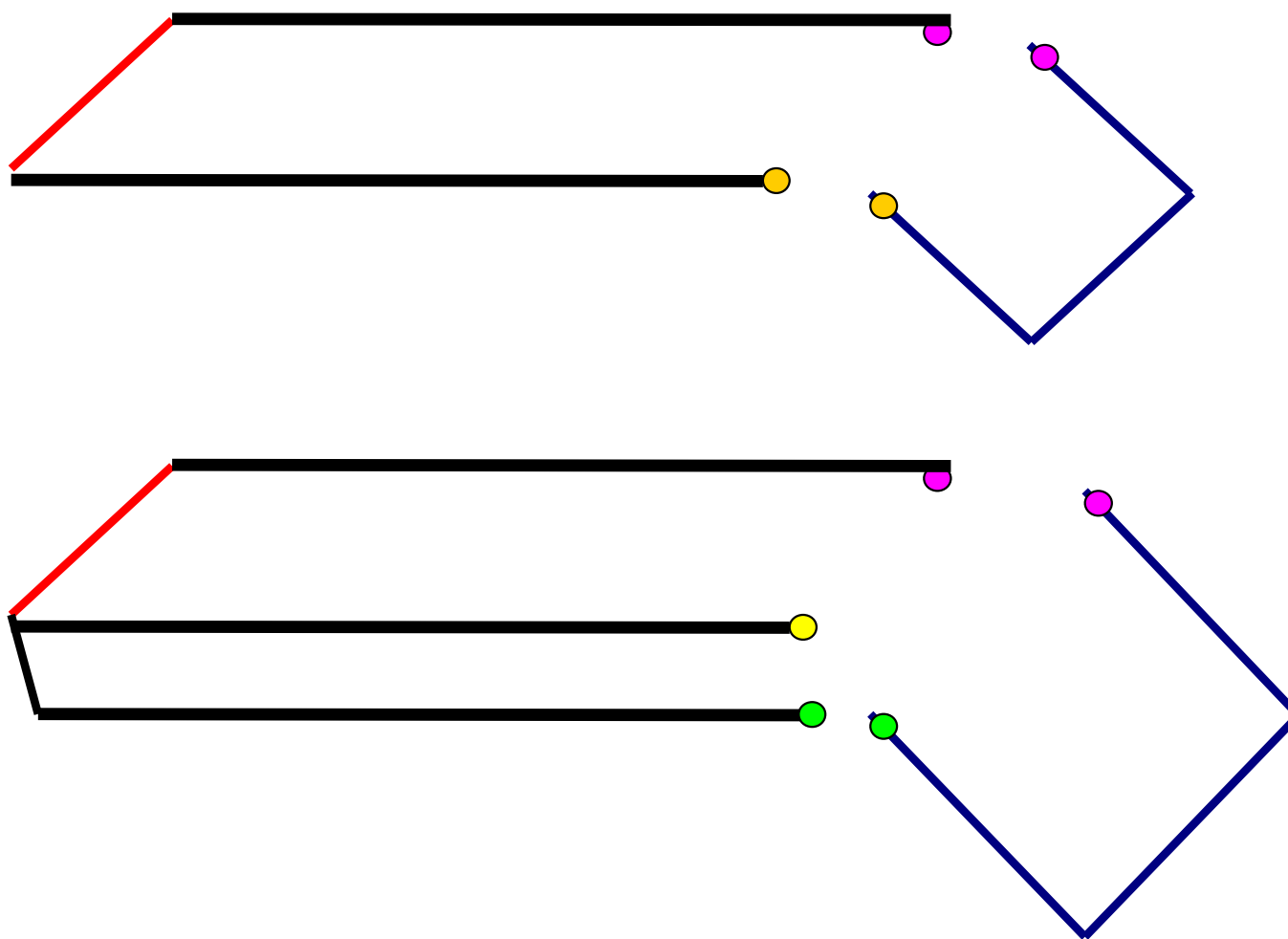
- R cavi “interni” al ponte poco influente
- ΔR cavi “interni” al ponte - influente ma compensabile (su rami adiacenti)
- R cavo esterno al ponte - ramo misura ininfluente

1/4 di ponte

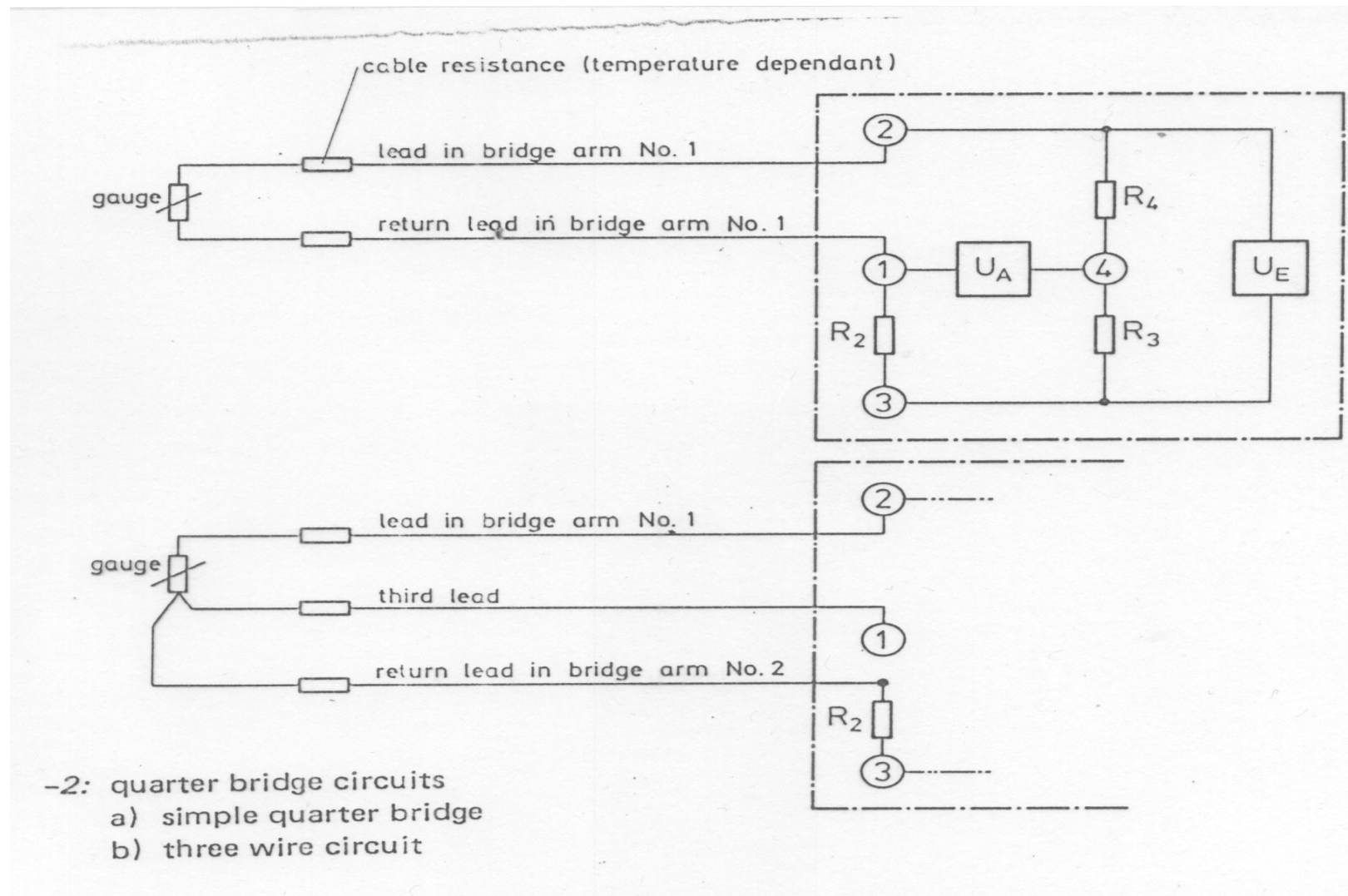


- Cavi interni ramo del ponte
- R poco influente
- ΔR influente - non valutabile né compensabile

1/4 di ponte - collegamento a tre fili



Collegamento a tre fili





Catena di misura

- segnale da acquisire (quasi-statico - variabile)
- durata della prova (breve / lunga - monitoraggio in continua / su richiesta)
- test controllati / non controllati
- numero estensimetri (letture in continua / in sequenza)
- precisioni richieste

Catena di misura

- processamento dei dati in tempo reale / in differita
- ambiente di prova (in laboratorio / sul campo)
- prove ripetibili / non ripetibili
- “protezione” dei risultati (dati duplicati / conservati / non alterabili)
- costo, disponibilità degli strumenti e delle competenze



Error Sources

- Gauge system and its environment
- Signal acquisition
- System readout
- Data processing

Gauge system and its environment

Signal acquisition

System readout

Data processing

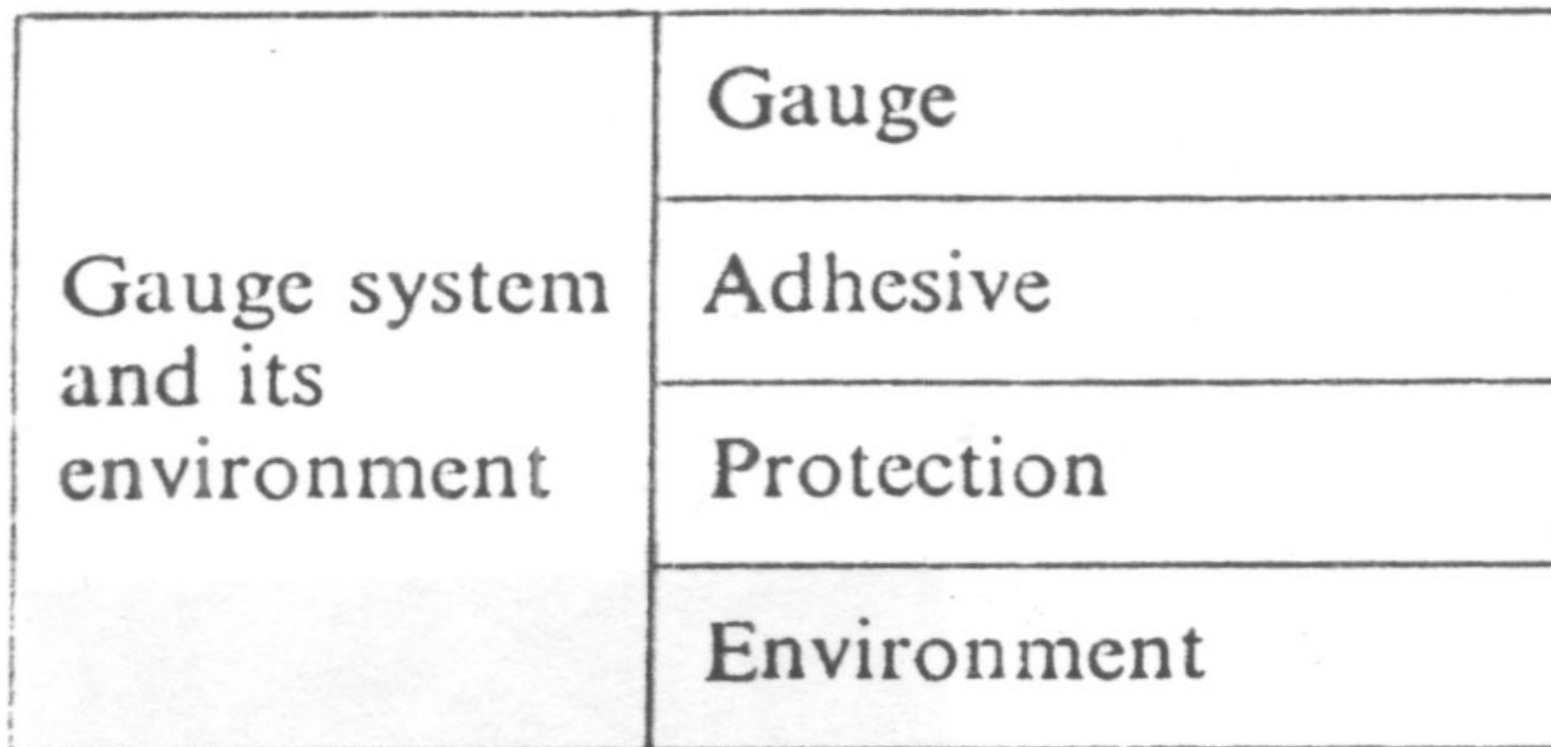


TABLE 1
ERROR SOURCES IN GAUGE SYSTEM AND ITS ENVIRONMENT

Gauge	<ul style="list-style-type: none">(a) Change in quoted gauge factor due to large strains.(b) Linearity.(c) Tolerance on quoted gauge factor.(d) Exceeding quoted fatigue life.(e) Transverse sensitivity.(f) Mismatch of gauge STC and structure.(g) Gauge length/strain gradient ratio.(h) Self-heating effect.(i) Ratio distances from structure neutral axis to structure surface and gauge axis.(j) Disturbance of strain field by gauge.(k) Magnetoresistance effect.(l) Resistance change repeatability (e.g. with cyclic strain).
Adhesive	<ul style="list-style-type: none">(a) Exceeding elongation capabilities.(b) Creep.(c) Hysteresis.(d) Insufficient cure; incorrect glue-line, inclusions and voids affecting strain transmission characteristics.
Protection	<ul style="list-style-type: none">(a) Coating attacking gauge grid and soldered joints.(b) Breakdown permitting grid etching and causing resistive and capacitive shunting paths.(c) Stiffening.
Environment	<ul style="list-style-type: none">(a) Effects of water, acid, corrosive substances, etc. on coating.(b) Effects of pressure, solar and nuclear radiation.(c) Effects of electromagnetic and electrostatic fields.(d) Effects of thermal shock.(e) Temperature-induced output (apparent strain).(f) Gauge factor variation with temperature.

Gauge system and its environment

Signal acquisition

System readout

Data processing

Signal acquisition	Joints
	Connections
	Leads

TABLE 2

ERROR SOURCES IN SIGNAL ACQUISITION

Joints	(a) Attack of soldered joints by active fluxes. (b) Ageing of solder. (c) Unsatisfactory joint, e.g. 'dry joint'. (d) 'Tin disease'. (e) Generation of thermal EMFs.
Connections	(a) Change in contact resistance causing change in gauge factor desensitisation. (b) Effect of contact resistance change within bridge circuit. (c) Generation of thermal EMFs.
Leads	(a) Lead resistance causing gauge factor desensitisation. (b) Change in lead resistance with temperature. (c) Generation of thermal EMFs. (d) 'Noise' pick-up.

Gauge system and its environment

Signal acquisition

System readout

Data processing

System readout	Bridge completion
	Bridge supply
	Signal conditioning
	Electrical noise

TABLE 3
ERROR SOURCES IN SYSTEM READOUT

Bridge completion	(a) Change in resistance values with temperature. (b) Effects of switching within the bridge circuit. (c) Linearity of bridge configuration.
Bridge supply	(a) Stability in out-of-balance mode of operation. (b) Resolution of adjustment for gauge factor. (c) Regulation in constant voltage or current modes.
Signal conditioning	(a) Shunting effect of amplifier input and readout device. (b) Resolution and linearity of readout. (c) Drift and linearity of amplifier.
Electrical noise	(a) Switching or transmission noise. (b) Series and common mode voltages and rejection ratio. (c) Pick-up in electromagnetic and electrostatic fields.

Gauge system and its environment

Signal acquisition

System readout

Data processing

Data processing	Gauge position
	Calibration
	Material constants
	Calculation

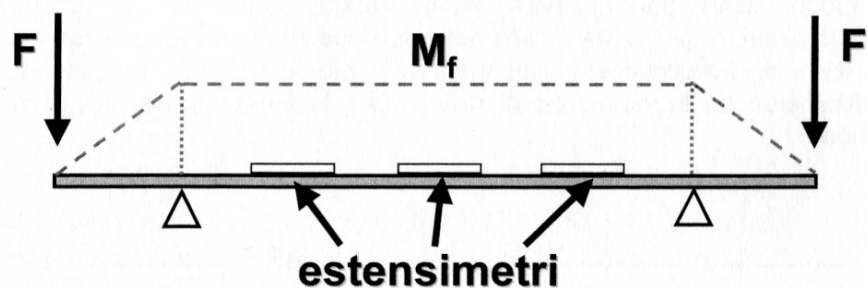
TABLE 4

ERROR SOURCES IN DATA PROCESSING

Gauge position	<ul style="list-style-type: none">(a) Reduction or increase of recorded strain because of gauge misalignment.(b) Incorrect data because of gauge mislocation.(c) Non-cancellation of unwanted signals (e.g. bending effects).(d) Grid relationship for two and three gauge rosettes.(e) Strain gradients parallel to the plane of the gauge.(f) Strain gradients normal to the test surface.
Calibration	<ul style="list-style-type: none">(a) Effect of using incorrect gauge factor to compute calibration resistor.(b) Effect on calibration resistor of assuming nominal gauge resistance.(c) Effects of lead length and single arm shunting for full bridge calibration.
Material constants	<ul style="list-style-type: none">(a) Difference between test material and structure constants affecting gauge factor.(b) Effect of material adiabatic temperature changes.(c) Effects of residual strain and work-hardening history.
Calculation	<ul style="list-style-type: none">(a) Use of single nominal gauge factor for two and three grid rosettes.(b) Assumption of homogeneous material for values of E, ν and ∞.(c) Assumption of measurement within elastic limit.

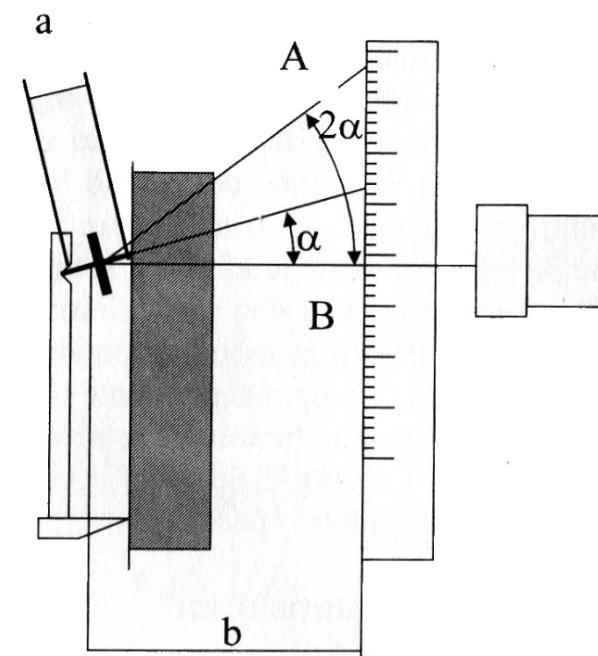
Taratura dell'estensimetro

Siccome un estensimetro dopo l'uso diventa inutilizzabile (a causa dell'incollaggio), la taratura deve essere fatta a campione (es. 2% di un lotto di produzione, da cui si ricavano media e scarto tipo).



Si usano travi a flessione (a 4 punti, per avere momento flettente costante).

Il campione di taratura è rappresentato da un estensimetro con precisione superiore (es. estensimetro ottico); non conviene passare dagli sforzi (si avrebbe una incertezza eccessiva).





Estensimetria

Applicazioni

- Misure di deformazione
- Costruzione di trasduttori

Misure di deformazione





Trasduttori

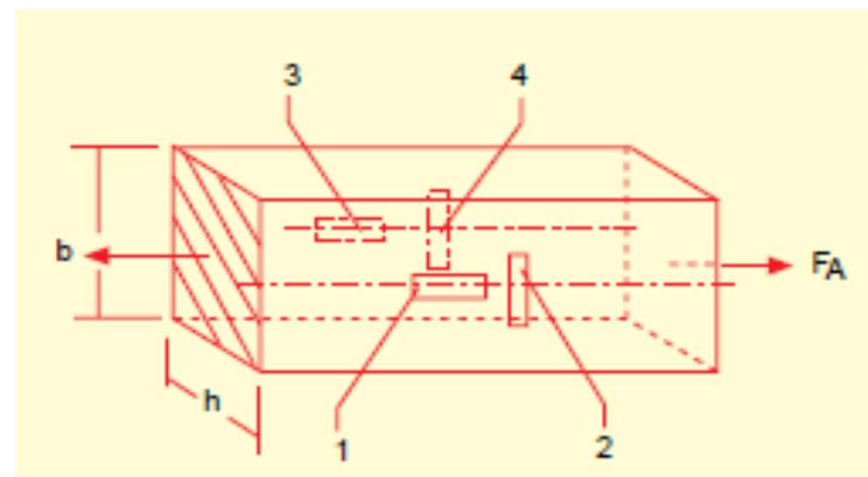
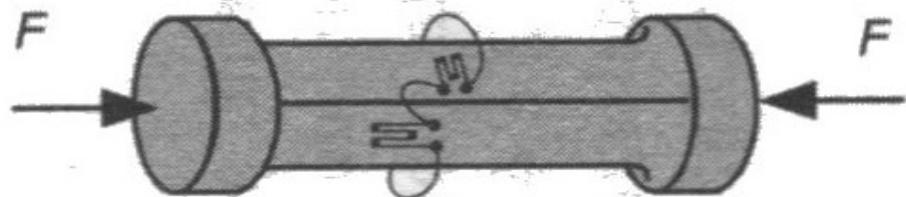
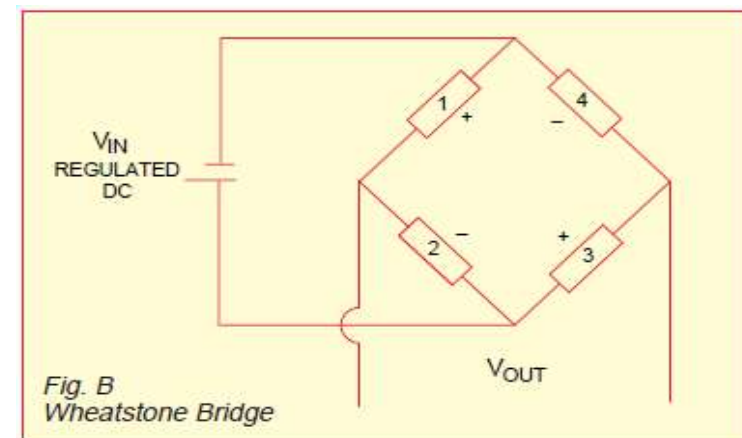
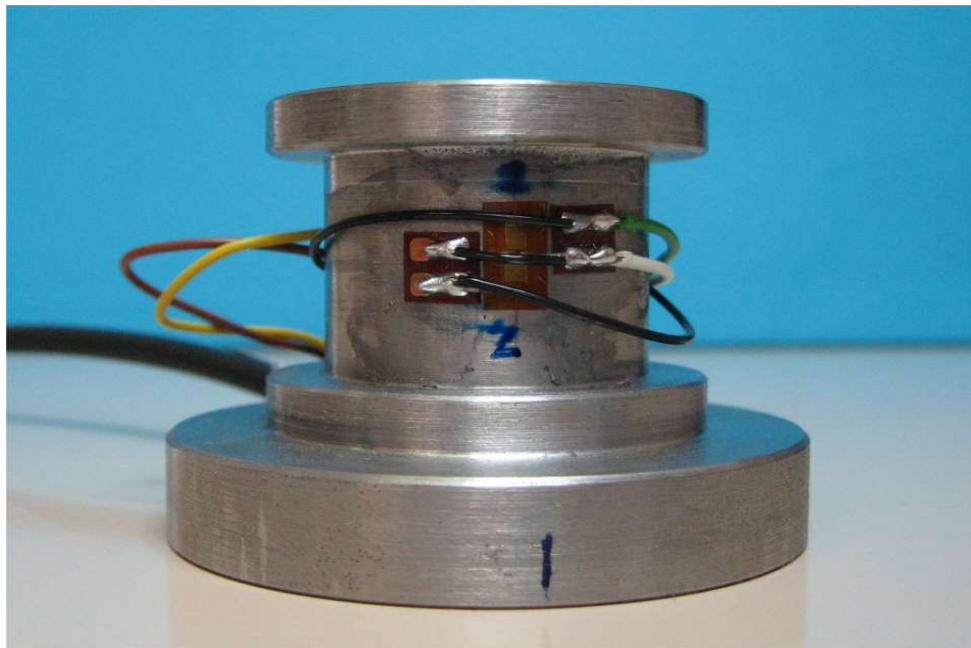
- Celle di carico (misura di forze, coppie, etc.)
- Accelerometri
- Sensori di deformazione/spostamento
- Sensori di pressione
- etc.



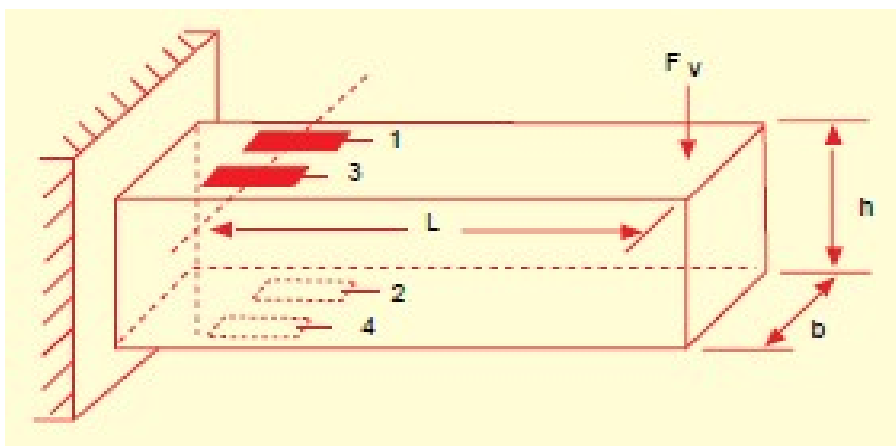
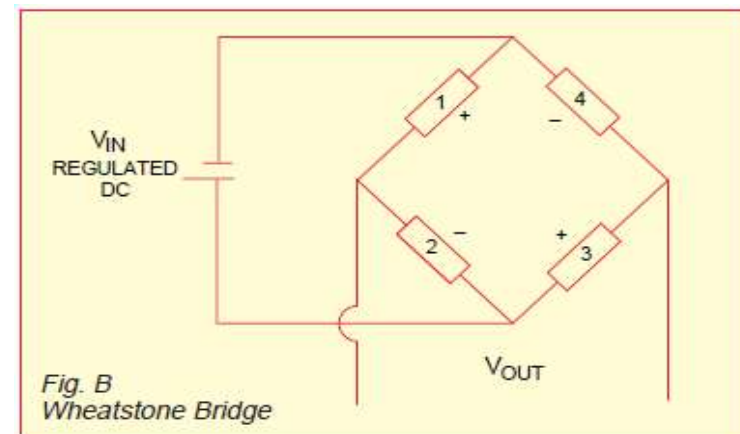
Celle di carico

- a trazione/compressione
- a flessione
- a taglio
- torsionometri

Celle di carico a trazione/compressione

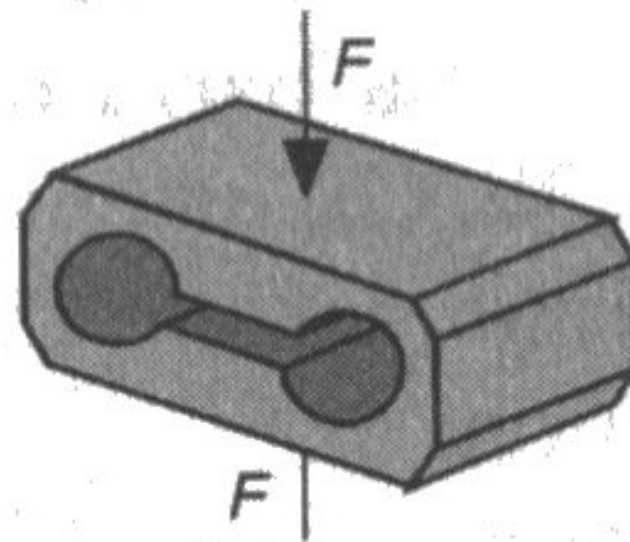
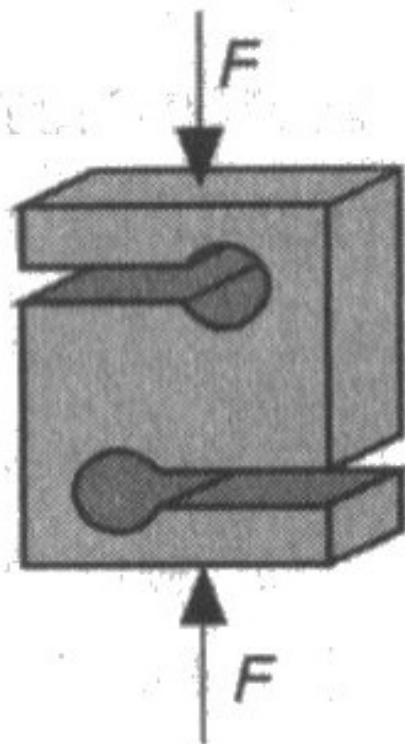
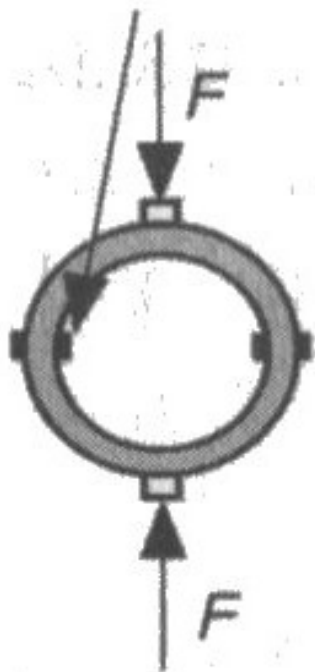


Celle di carico a flessione

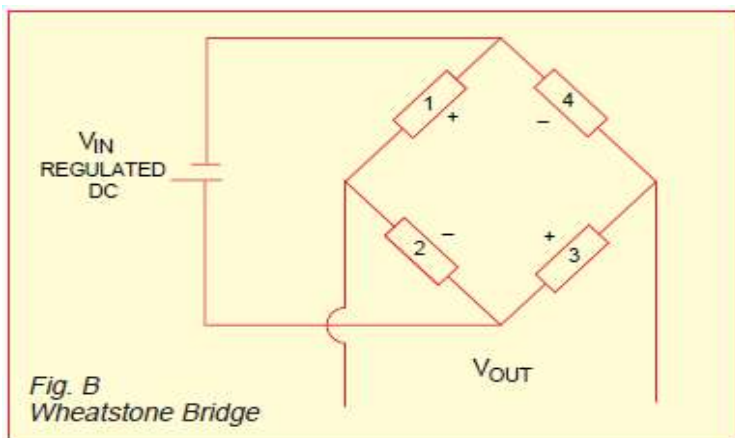
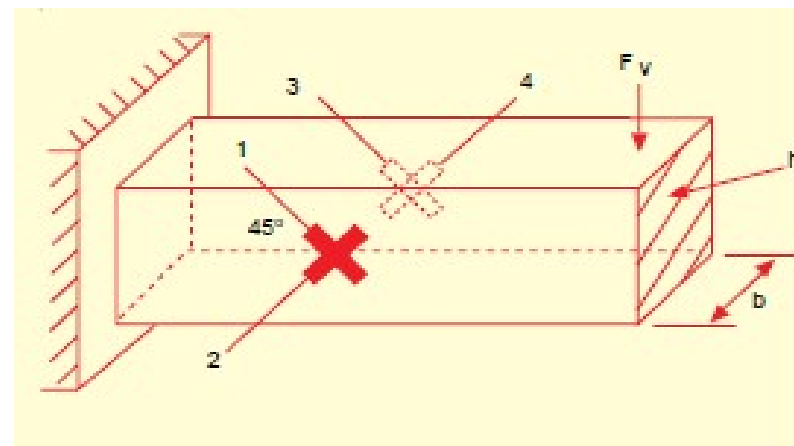


Celle di carico a flessione

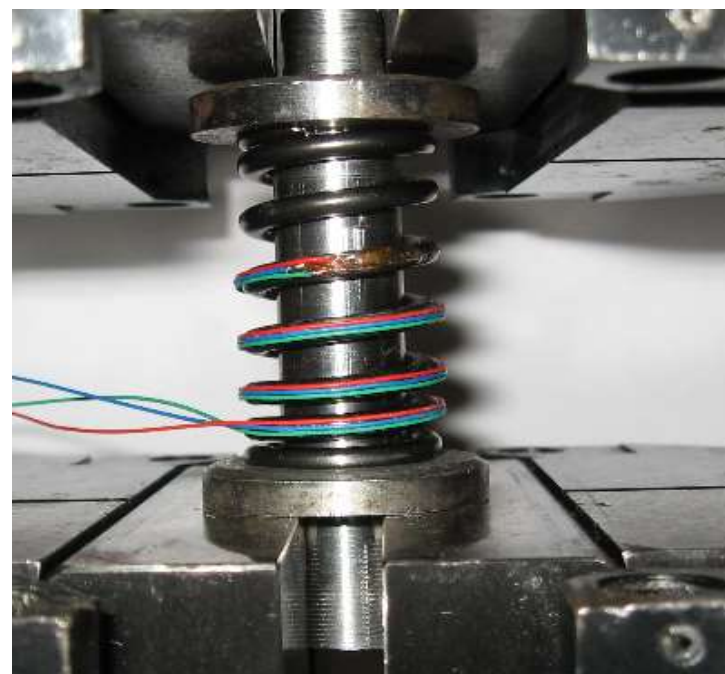
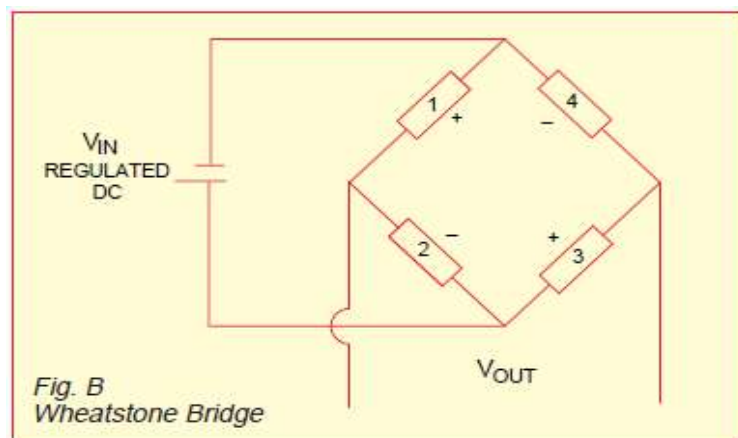
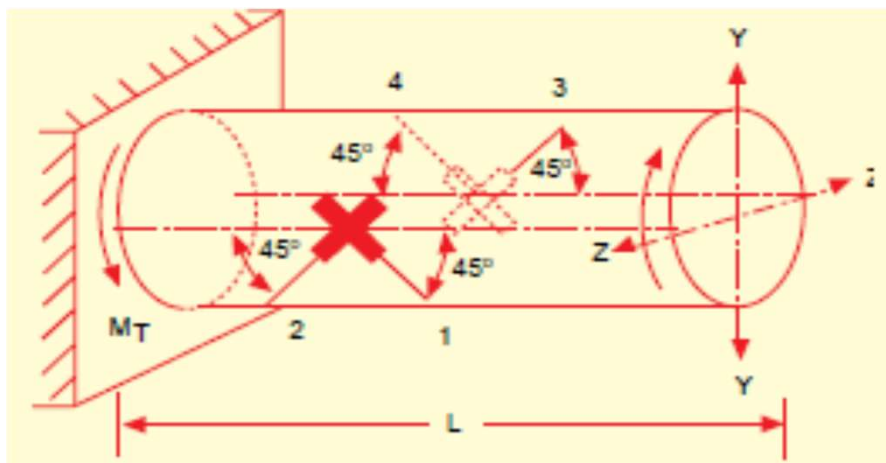
estensimetro



Celle di carico a taglio



Celle di carico a torsione

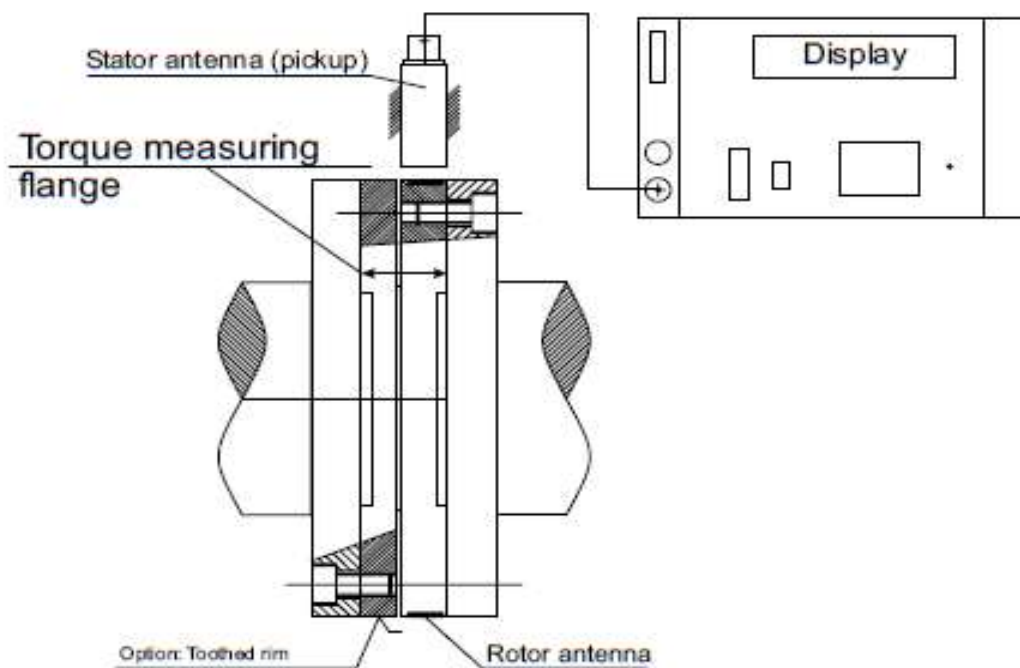


Effetto della configurazione

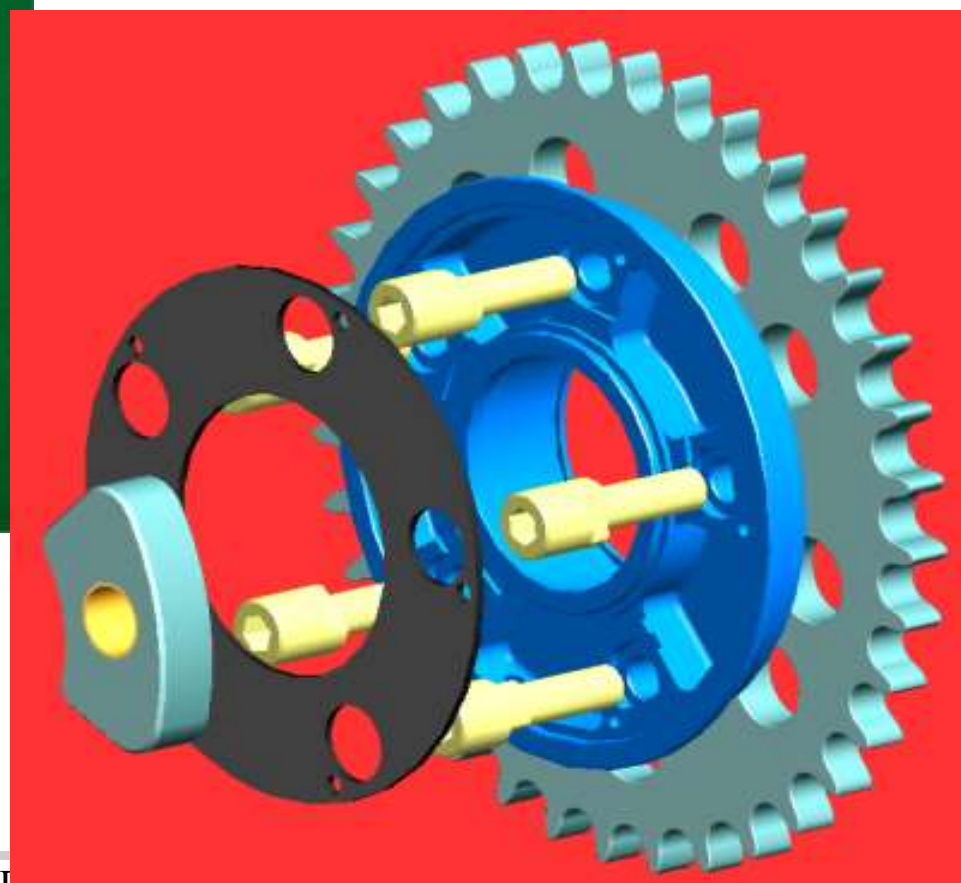
STRAIN	BRIDGE TYPE	POSITION OF GAGES Figs. C-F	SENSITIVITY MV/V @ 1000 $\mu\epsilon$	OUTPUT PER $\mu\epsilon$ @ 10 V EXCITATION	TEMP. COMP.	SUPERIMPOSED STRAIN COMPENSATED
BENDING	¼	1	0.5	5 $\mu\text{V}/\mu\epsilon$	No	None
	½	1, 2	1.0	10 $\mu\text{V}/\mu\epsilon$	Yes	Axial
	Full	All	2.0	20 $\mu\text{V}/\mu\epsilon$	Yes	Axial
AXIAL	¼	1	0.5	5 $\mu\text{V}/\mu\epsilon$	No	None
	½	1, 2	0.65	6.5 $\mu\text{V}/\mu\epsilon$	Yes	None
	½	1, 3	1.0	10 $\mu\text{V}/\mu\epsilon$	No	Bending
	Full	All	1.3	13 $\mu\text{V}/\mu\epsilon$	Yes	Bending
SHEAR & TORSIONAL	½	1, 2	1.0	10 $\mu\text{V}/\mu\epsilon$ @ 45°F	Yes	Axial and Bending
	Full	All	2.0	20 $\mu\text{V}/\mu\epsilon$ @ 45°F	Yes	Axial and Bending

Note: Shear and torsional strain = $2 \times \epsilon$ @ 45°

Torsiometri



Torsiometri



Torsiometri

Per misurare la potenza P trasmessa da un albero rotante è necessario conoscere il momento torcente M trasmesso e la velocità angolare ω :

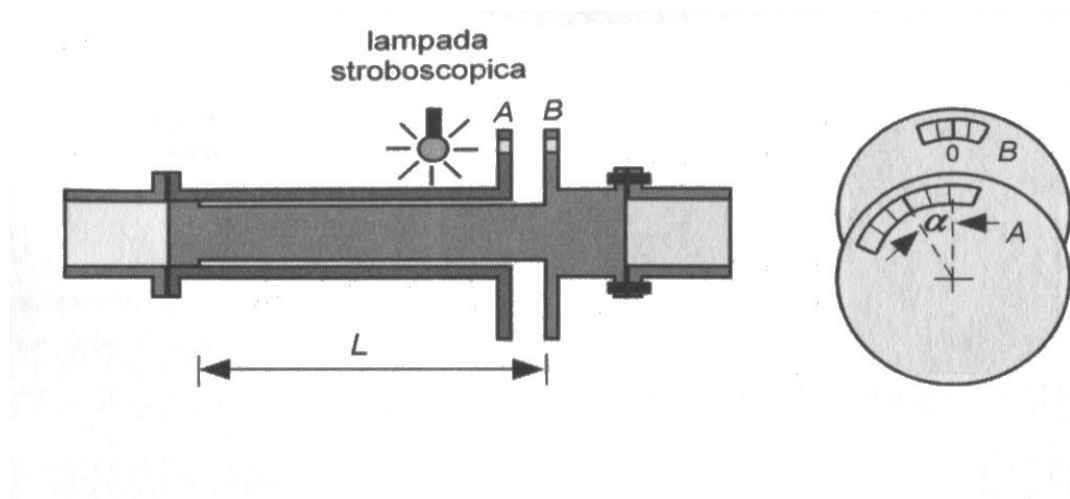
$$P = M \cdot \omega$$

Si usano strumenti detti *torsiometri* :

$$M = \alpha \cdot \frac{J_0 \cdot G}{L}$$

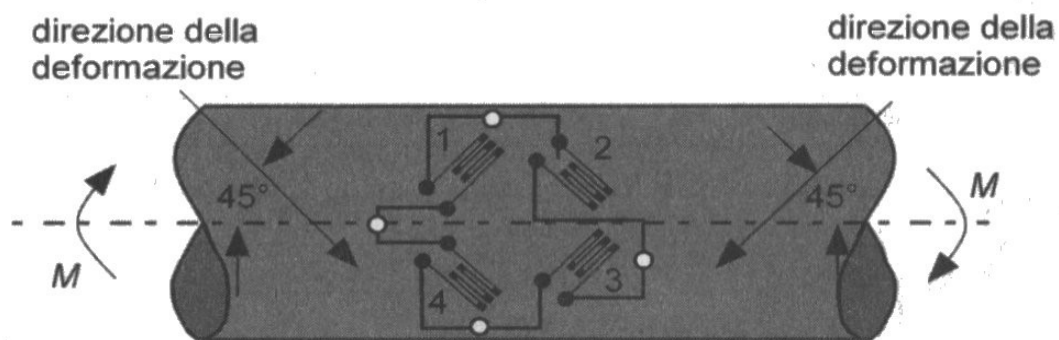
Torsiometri

Per misurare l'angolo α si può usare un metodo ottico:



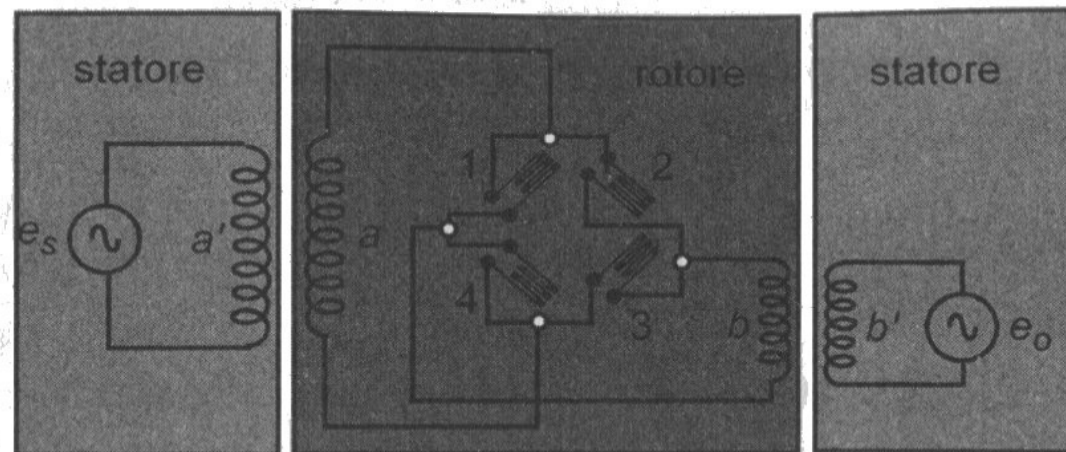
Torsiometri

Oppure si possono usare estensimetri elettrici a resistenza opportunamente disposti:



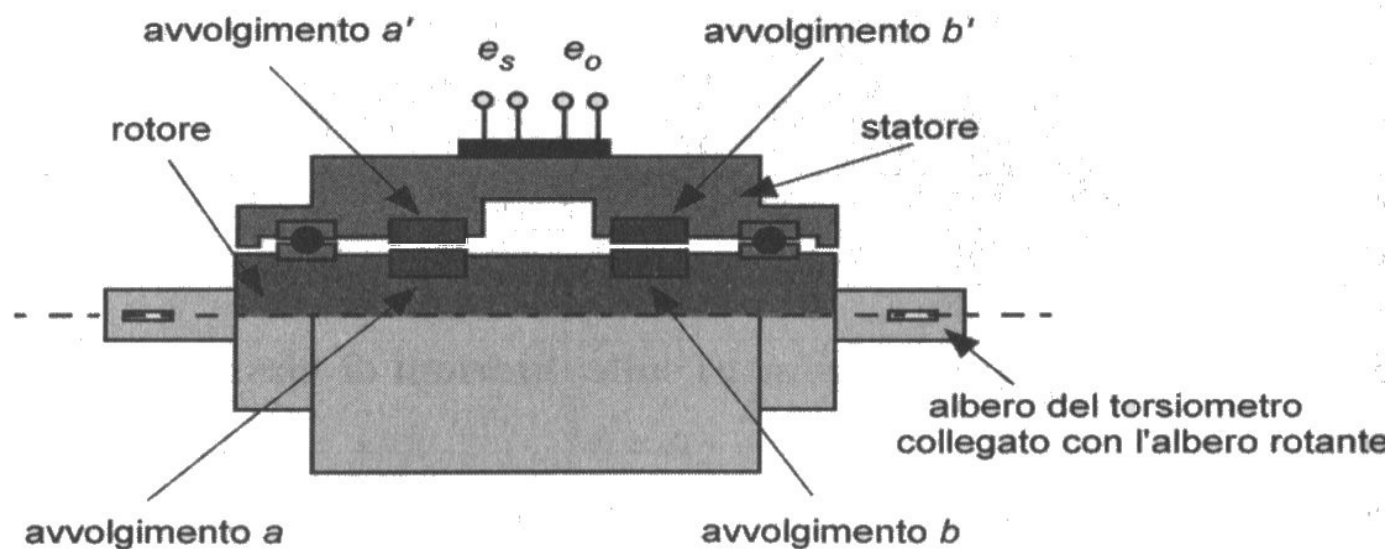
alimentazione ~

tensione di squilibrio ~



Torsiometri

$$e_o(t) = e_s(t) \cdot K \cdot \varepsilon$$

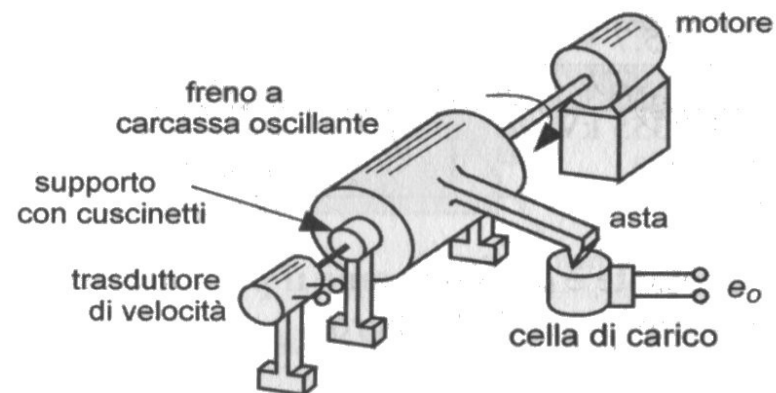
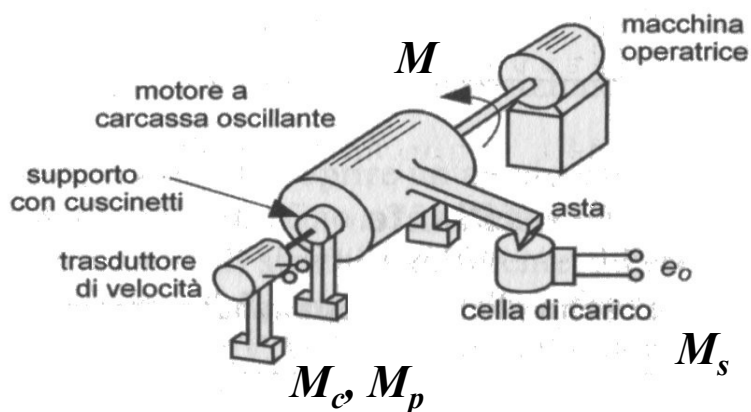


Torsiometri

Per misurare il momento torcente trasmesso da un albero rotante si possono usare macchine a carcassa oscillante:

$$M_s = M + M_c + M_p$$

$$M = F \cdot L$$



Accelerometri

Strain Gage Accelerometer



Applications

- Aircraft Flight Test
- Missile/Rocket Test
- Suspension Test
- Deceleration/Brake Test

Features

- Operates from ± 5 g to ± 500 g
- Wide temperature range
- Low cross axis sensitivity

Sensori di deformazione/spostamento

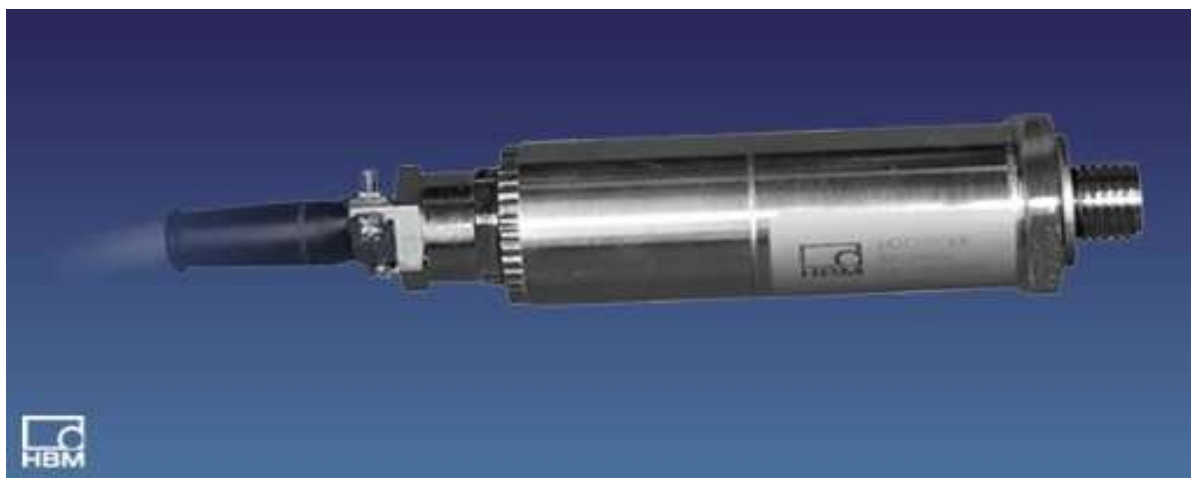


Clip-on Axial Extensometer



Clip-on Transverse Extensometer

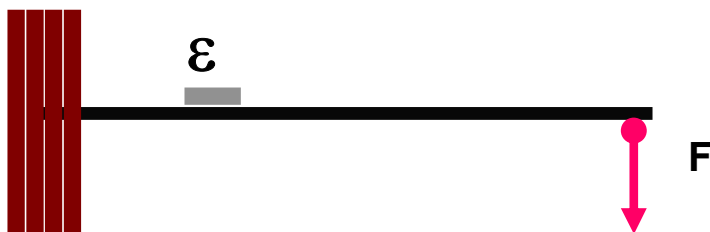
Trasduttori di pressione





strain - gauge

acquisizione - elaborazione
risultati



$$F^* \Leftrightarrow \varepsilon^*$$

□ $F^* \Leftrightarrow n$ misure $\varepsilon^* \Leftrightarrow$ media - scarto

□ **Comportamento lineare elastico**

– rampa di carico

» $0 \div F_{\max}$ ($F_{\max} \approx 1,2 F^*$) $\rightarrow 0 \div \varepsilon_{\max}$

– retta di best-fit

– sulla retta $F^* \rightarrow \varepsilon^*$

– ε^* - errore della stima

Mediante gli estensimetri possiamo misurare la deformazione; generalmente interessano gli sforzi.

Equazioni di legame lineare-elastico:
$$\varepsilon_{ij} = \frac{1}{2G} \left(\sigma_{ij} - \frac{\nu}{1+\nu} \delta_{ij} I_{\sigma} \right)$$

$$\begin{aligned} \varepsilon_x &= \frac{1}{E} [\sigma_x - \nu(\sigma_y + \sigma_z)] & \varepsilon_{xy} &= \frac{1}{2G} \tau_{xy} = \frac{\gamma_{xy}}{2} \\ \varepsilon_y &= \frac{1}{E} [\sigma_y - \nu(\sigma_z + \sigma_x)] & \varepsilon_{yz} &= \frac{1}{2G} \tau_{yz} = \frac{\gamma_{yz}}{2} \\ \varepsilon_z &= \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)] & \varepsilon_{zx} &= \frac{1}{2G} \tau_{zx} = \frac{\gamma_{zx}}{2} \end{aligned} \quad (1)$$

Se il sistema di riferimento è principale: $\gamma_{xy} = \gamma_{yz} = \gamma_{zx} = 0$



Caso a): $\sigma_x \neq 0; \sigma_y = \sigma_z = 0$

Se x è direzione principale, dalle (1):

$$\varepsilon_x = \frac{1}{E} \sigma_x$$

$$\varepsilon_y = -\frac{\nu}{E} \sigma_x$$

$$\varepsilon_z = -\frac{\nu}{E} \sigma_x$$

Se conosco la direzione principale, E e ν basta un solo estensimetro per conoscere completamente lo stato di sforzo e deformazione

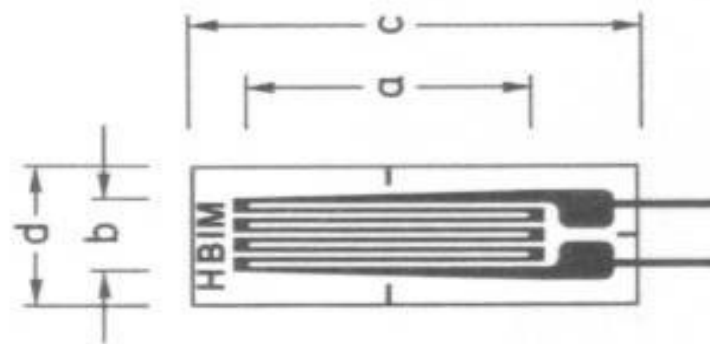
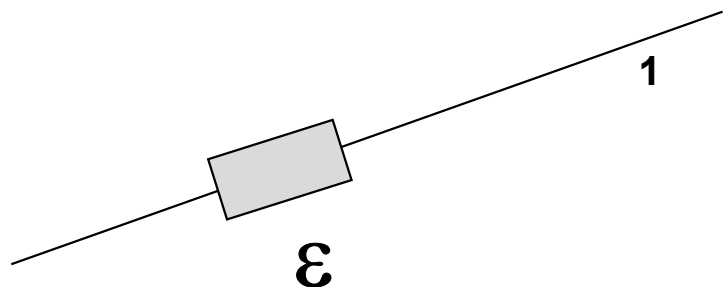
Meccanica dei Continui Lineari Elastici

$$\varepsilon \Rightarrow \sigma$$

□ stato tensione monoassiale - direzione nota

$$\square \sigma_1 = \sigma ; \sigma_2 = 0 ; \varphi = 0$$

$$\square \varepsilon_1 = \sigma / E ; \varepsilon_2 = -\nu \varepsilon_1 ; \varphi = 0$$



Caso b): $\sigma_x \neq 0; \sigma_y \neq 0; \sigma_z = 0$ x, y, z **direzioni principali;**

dalle (1):

$$\varepsilon_x = \frac{1}{E} (\sigma_x - \nu \sigma_y)$$

$$\varepsilon_y = \frac{1}{E} (\sigma_y - \nu \sigma_x)$$

$$\varepsilon_z = -\frac{\nu}{E} (\sigma_x + \sigma_y)$$

Posso ricavare gli sforzi:

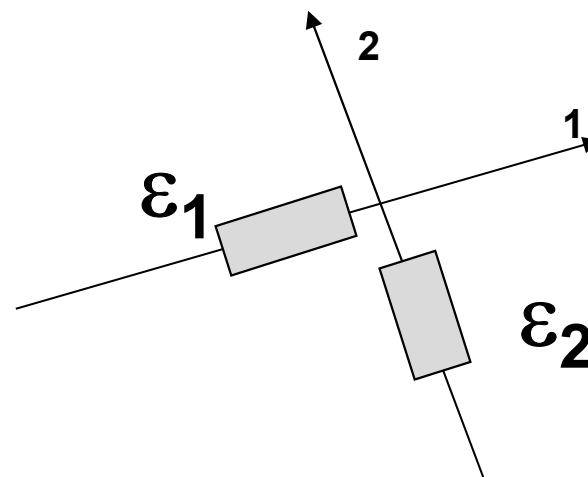
$$\sigma_x = \frac{E}{1-\nu^2} (\varepsilon_x + \nu \varepsilon_y)$$

$$\sigma_y = \frac{E}{1-\nu^2} (\varepsilon_y + \nu \varepsilon_x)$$

Meccanica dei Continui Lineari Elastici

$$\varepsilon \Rightarrow \sigma$$

- stato tensione biassiale
direzioni principali 1&2 note

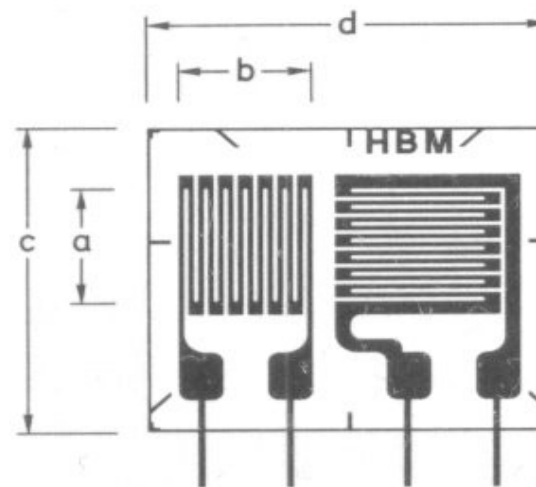


- $\sigma_1 ; \sigma_2 ; \varphi = 0$

- $\varepsilon_1 = 1 / E (\sigma_1 - \nu \sigma_2)$

- $\varepsilon_2 = 1 / E (\sigma_2 - \nu \sigma_1)$

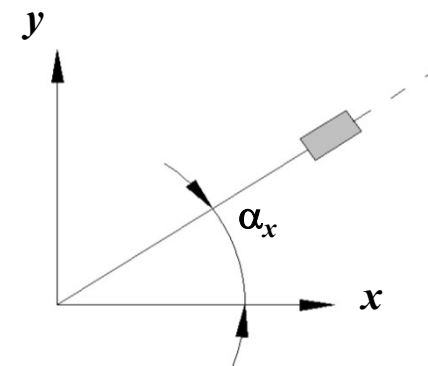
- $\varphi = 0$



Caso c): stato di sforzo monoassiale, estensimetro inclinato di α_x rispetto all'asse x principale;

$$\varepsilon_{\alpha_x} = \varepsilon_{ij} n_i n_j$$

$$\varepsilon_{\alpha_x} = \varepsilon_x \cos^2 \alpha_x + \varepsilon_y \sin^2 \alpha_x$$

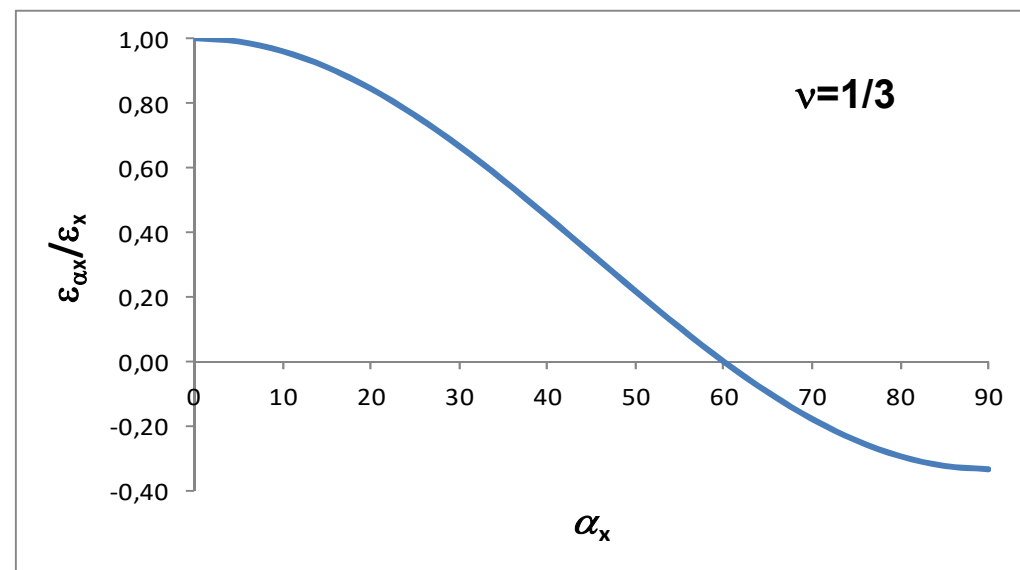


ed essendo:

$$\varepsilon_y = -\nu \varepsilon_x$$



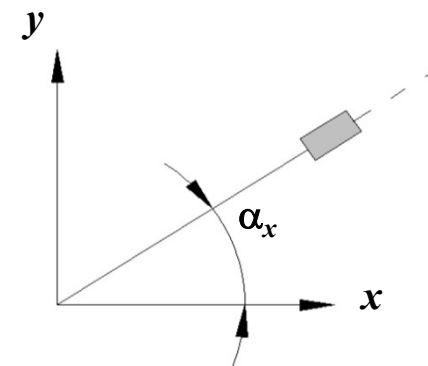
$$\varepsilon_{\alpha_x} = \varepsilon_x (\cos^2 \alpha_x - \nu \sin^2 \alpha_x)$$



Se invece l'asse x non è principale;

$$\varepsilon_{\alpha_x} = \varepsilon_{ij} n_i n_j$$

$$\varepsilon_{\alpha_x} = \varepsilon_x \cos^2 \alpha + \boxed{\gamma_{xy} \sin \alpha_x \cos \alpha_x} + \varepsilon_y \sin^2 \alpha$$



Con l'estensimetro non si possono misurare direttamente gli scorrimenti, però se ne possono valutare gli effetti sulla deformazione lineare lungo una certa direzione.

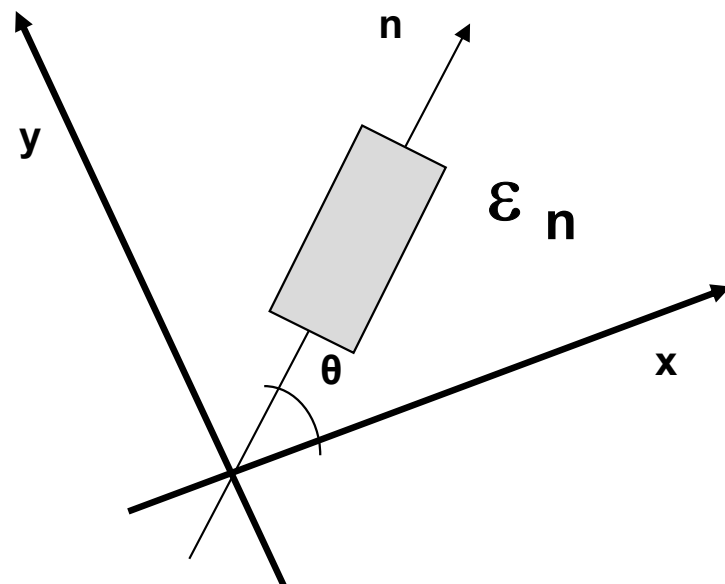
Meccanica dei Continui Lineari Elastici

$$\varepsilon \Rightarrow \sigma$$

□ stato di tensione biassiale

□ σ_1 ; σ_2 ; φ

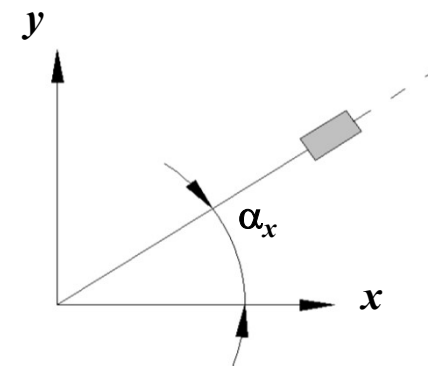
$$\square \varepsilon_n = \varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta + \gamma_{xy} \sin\theta \cos\theta$$



Se invece l'asse x non è principale;

$$\varepsilon_{\alpha_x} = \varepsilon_{ij} n_i n_j$$

$$\varepsilon_{\alpha_x} = \varepsilon_x \cos^2 \alpha + \boxed{\gamma_{xy} \sin \alpha_x \cos \alpha_x} + \varepsilon_y \sin^2 \alpha$$

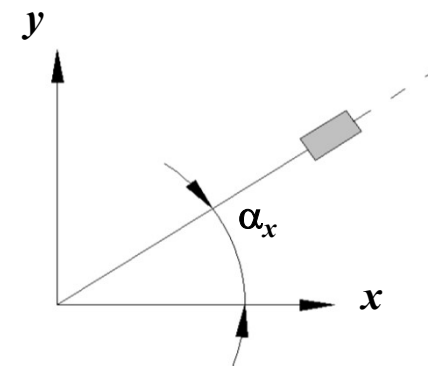


Con l'estensimetro non si possono misurare direttamente gli scorrimenti, però se ne possono valutare gli effetti sulla deformazione lineare lungo una certa direzione.

Caso d): stato di sforzo biassiale, con $\varepsilon_x = \varepsilon_y$

$$\varepsilon_{\alpha_x} = \varepsilon_x \cos^2 \alpha_x + \varepsilon_y \sin^2 \alpha_x$$

$$\varepsilon_{\alpha_x} = \varepsilon_x = \varepsilon_y$$



Tutte le direzioni sono principali.

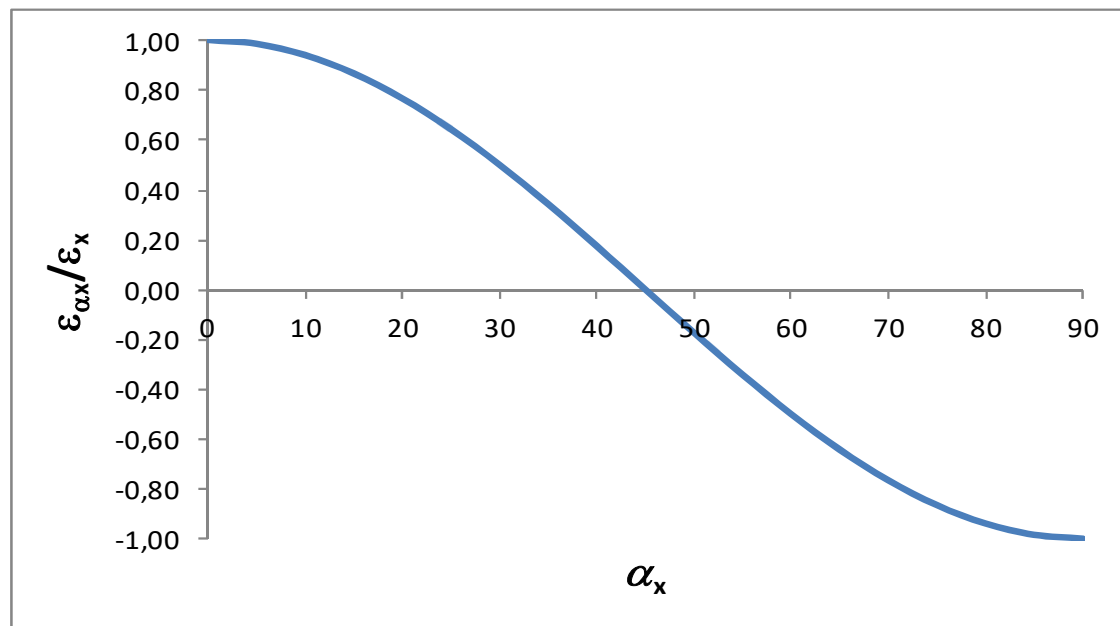
Misurando su due direzioni ortogonali ottengo sempre le stesse deformazioni.

Caso e): stato di sforzo biassiale, $\varepsilon_x = -\varepsilon_y$

$$\varepsilon_{\alpha_x} = \varepsilon_x \cos^2 \alpha_x + \varepsilon_y \sin^2 \alpha_x$$

$$\varepsilon_{\alpha_x} = \varepsilon_x (\cos^2 \alpha_x - \sin^2 \alpha_x)$$

**Misurando su due direzioni
ortogonali ottengo sempre le stesse
deformazioni in modulo (variabile)
ma di segno opposto.**



Rosetta estensimetrica

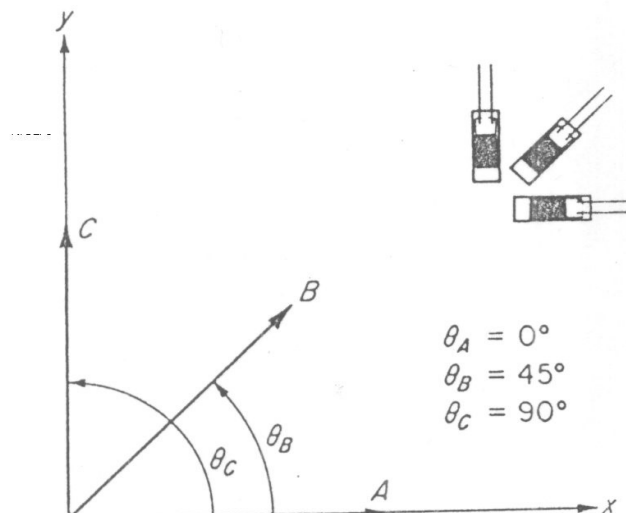
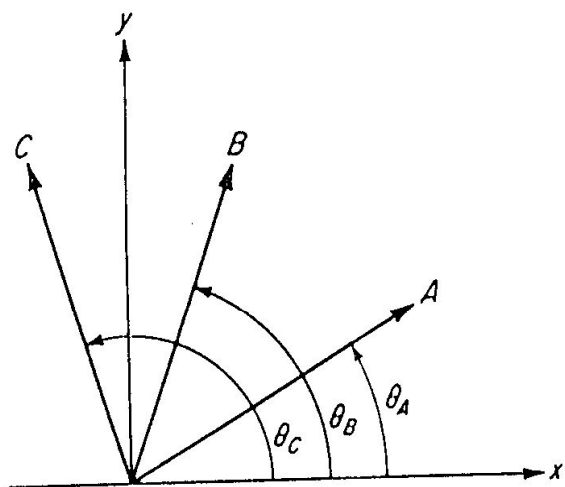


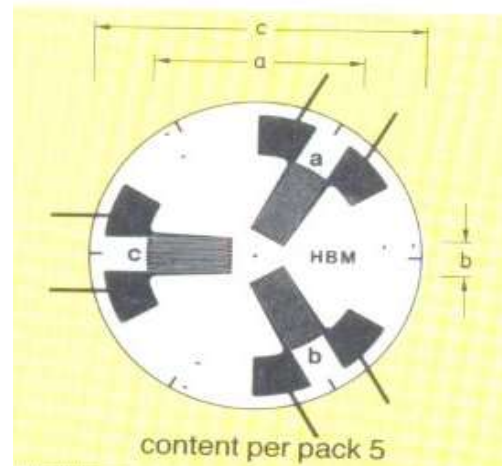
Figure 10.2 Three gage elements placed at arbitrary angles relative to the x and y axes.

$$\epsilon_A = \epsilon_{xx} \cos^2 \theta_A + \epsilon_{yy} \sin^2 \theta_A + \gamma_{xy} \sin \theta_A \cos \theta_A$$

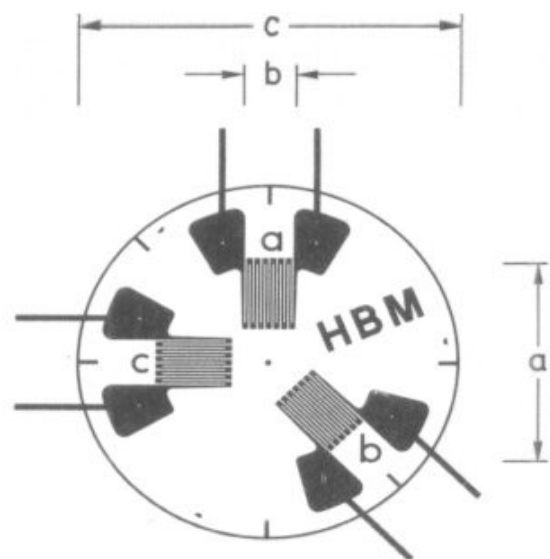
$$\epsilon_B = \epsilon_{xx} \cos^2 \theta_B + \epsilon_{yy} \sin^2 \theta_B + \gamma_{xy} \sin \theta_B \cos \theta_B$$

$$\epsilon_C = \epsilon_{xx} \cos^2 \theta_C + \epsilon_{yy} \sin^2 \theta_C + \gamma_{xy} \sin \theta_C \cos \theta_C$$

Rosetta estensimetrica

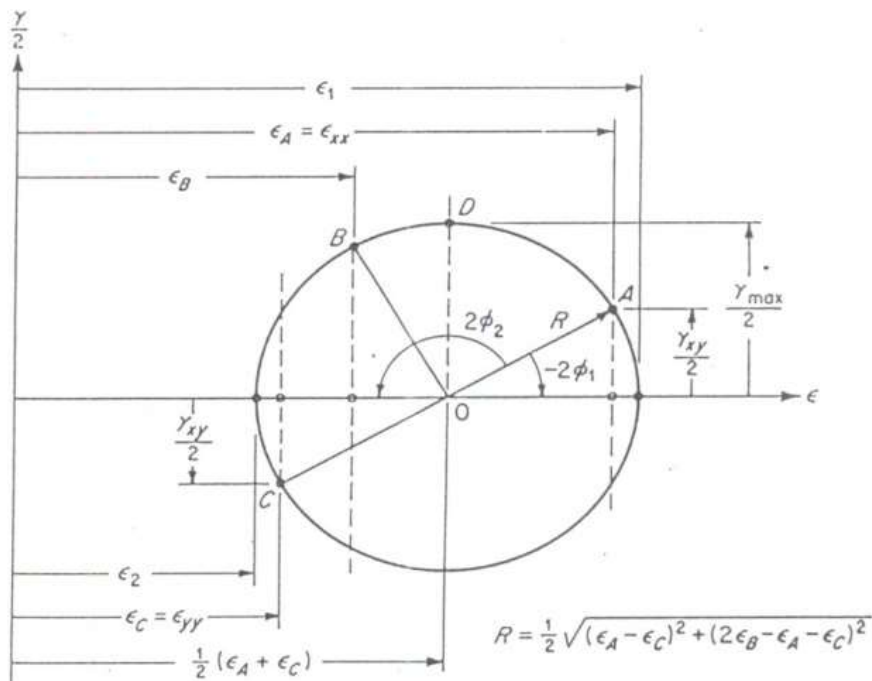


0, 120, 240



0, 45, 90

Rosetta estensimetrica



$$\epsilon_1 = \frac{1}{2}(\epsilon_{xx} + \epsilon_{yy}) + \frac{1}{2}\sqrt{(\epsilon_{xx} - \epsilon_{yy})^2 + \gamma_{xy}^2}$$

$$\epsilon_2 = \frac{1}{2}(\epsilon_{xx} + \epsilon_{yy}) - \frac{1}{2}\sqrt{(\epsilon_{xx} - \epsilon_{yy})^2 + \gamma_{xy}^2}$$

$$\tan 2\phi = \frac{\gamma_{xy}}{\epsilon_{xx} - \epsilon_{yy}}$$

Procedura di prova

- inserire (se possibile) punti di misura “di controllo”
- controllare “canale per canale” la identificazione dei punti di misura e la corretta configurazione della catena di misura
- effettuare una verifica “globale”, sia della strumentazione che degli apparati di prova, caricando (se possibile) la struttura a un livello di carico “basso”

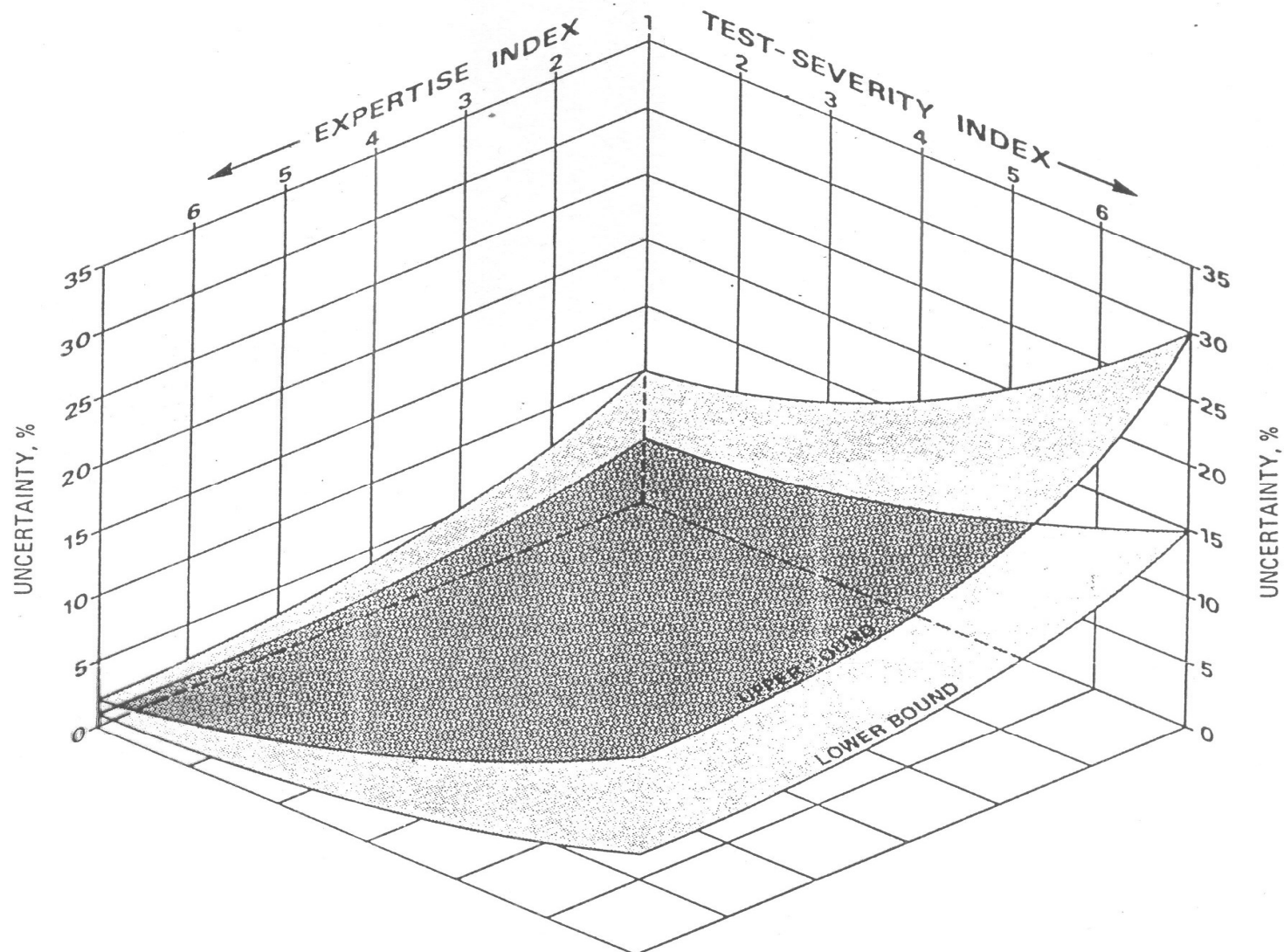


Procedura di prova

- Eseguire, (se possibile), alcuni cicli di “allenamento”, controllando gli zeri
- Usare procedure di prova ben collaudate, e personale qualificato (I, II, III livello)

misure “attendibili” \Rightarrow affidabilità dell’ operatore e del laboratorio

“Qualità” di una misura estensimetrica





Relazione tecnica

- Tipo di prova e descrizione dell'oggetto provato
- Attrezzatura utilizzata (disegni, collaudi, verifiche di funzionalità)
- Strumentazione e catena di misura
 - strumenti: tipo, classe di precisione, data di verifica
 - catena di misura: composizione, grado globale di precisione

Relazione tecnica

□ Estensimetri

- tipi di estensimetri utilizzati (criteri di scelta)
- collocazione (motivi della scelta)
- identificazione
- modalità di installazione (procedura)

□ Procedura di prova (sequenza dei carichi; livelli di esecuzione delle misure; procedura)

□ Condizioni di prova (temperatura, umidità)



Relazione tecnica

- Risultati (grafici, tabelle)
- Elaborazione dei risultati (motivi di rigetto, relazioni utilizzate, motivi di correzione, ecc)
- Analisi dei risultati (utilizzo dei risultati a fronte dello scopo della misura, relazioni utilizzate, caratteristiche del materiale, ecc)
- Commenti e Conclusioni