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THE SIGNIFICANCE OF THE MODULUS OF ELASTICITY FOR REFRACTORY MATERIALS AND ENGINEERING

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The development of refractory materials has been dominated for a long time by improvement of refractoriness and strength. Since the last twenty years interests and possibilities have increased to develope materials which have better elastic behaviour. This need was caused by more advanced steelmaking techniques like QBOP, vacuüm degassing and continuous casting. At vital spots in these production units refractory materials with good elastic behaviour are necessary. In this field the blast furnace wall is also of importance because of spalling phenomena.

To make progress in this area a correct description of the elastic behaviour is necessary.

Steel for instance has a simple elastic behaviour as can be seen in figure 1. As long as stresses are found in the elastic area Hooke's law is valid (the ratio of stress to strain is constant).

$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon} \qquad (1)$$

E is called Youngs-modulus or modulus of elasticity.

However ceramic materials do not follow Hooke's law due to lamination in the material.

The Youngs-modulus under tensile mode is markedly lower than the modulus under compressive mode, see figure 2. So:

$$\frac{E_c}{E_t} > 1 \qquad (2)$$

The methods to determine the Youngs-modulus of ceramic materials are tabulated in figure 3. The resonance method and the bend method are most familiar for refractory materials.

The ultrasonic method (figure 4) is based on the measurement of sound velocity. If dimensions and density are kwown the Youngs-modulus can be calculated.

The resonance method (figure 5) is based on the measurement of the specific frequency of a body.

The advantage compared to the previous method is that it can be used under different modes and gives us the possibility to determine not only Youngs-modulus but also the shear modulus (G) and the Poisson-ratio (ν). Besides the execution of the test is easier at elevated temperatures.
The most familiar static method is the bend test (figure 7). Tensile test and compressive test are used less because of execution problems at elevated temperatures. In fact this test is a extended modulus of rupture test. By measurement of the deflection and stress the Youngs-modulus of the bend test (E_B) can be calculated.
The stress distribution in the bend beam (figure 7) again differs from steel. When using the formulas which are usually applied for steel bend tests, the results deviate from the real situation.
In fact the tensile stress at the utmost under face is lower and the compressive stress at the upper face is markedly higher than the calculated value. Likewise the Youngs-modulus does not fit up with E_c as well as E_T

$$E_c > E_B > E_T \tag{3}$$

where: E_B is the calculated value.
Figure 8 quantifies this phenomenon.
In figure 9 some dynamic values are plotted as a function of the static values. Values for E_{reso}/E_B are:

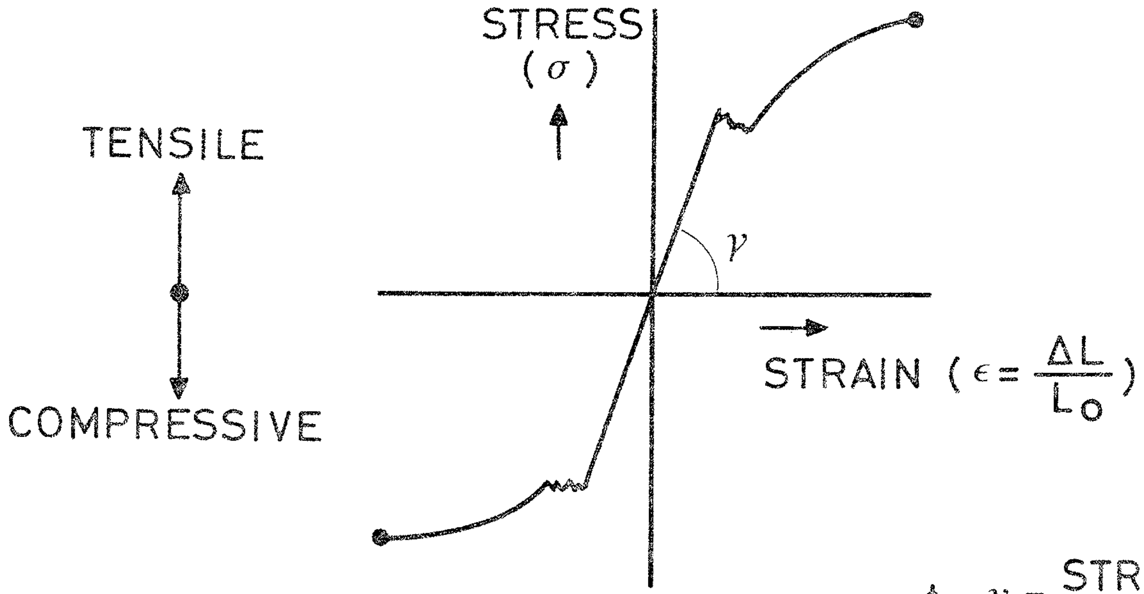
$$2 > E_{reso}/E_B > 8 \tag{4}$$

The reason why E_{reso} does not agree with E_B must be searched in the stress-strain diagram (figure 2). It can be expected that the static methods follow the closed lines and that the dynamic methods follow the dotted line in the tensile area. In that case static installation situations can not be brought in agreement with dynamic methods. Static methods must be applied for these situations. A survey of the methods and their application can be found in figure 10.
Figure 11 gives some examples of situations where the classical conception of refractory development (strength) is the governing item. In this area elastic behaviour of the materials is not of importance.
Figure 12 gives some examples of situations where strain is the governing item. Here elastic behaviour is very important. Both situations (the stationary and the thermal shock) are controlled by the ratio of maximum deformation and expansion.

$$\varepsilon_{max}/\alpha T \tag{5}$$

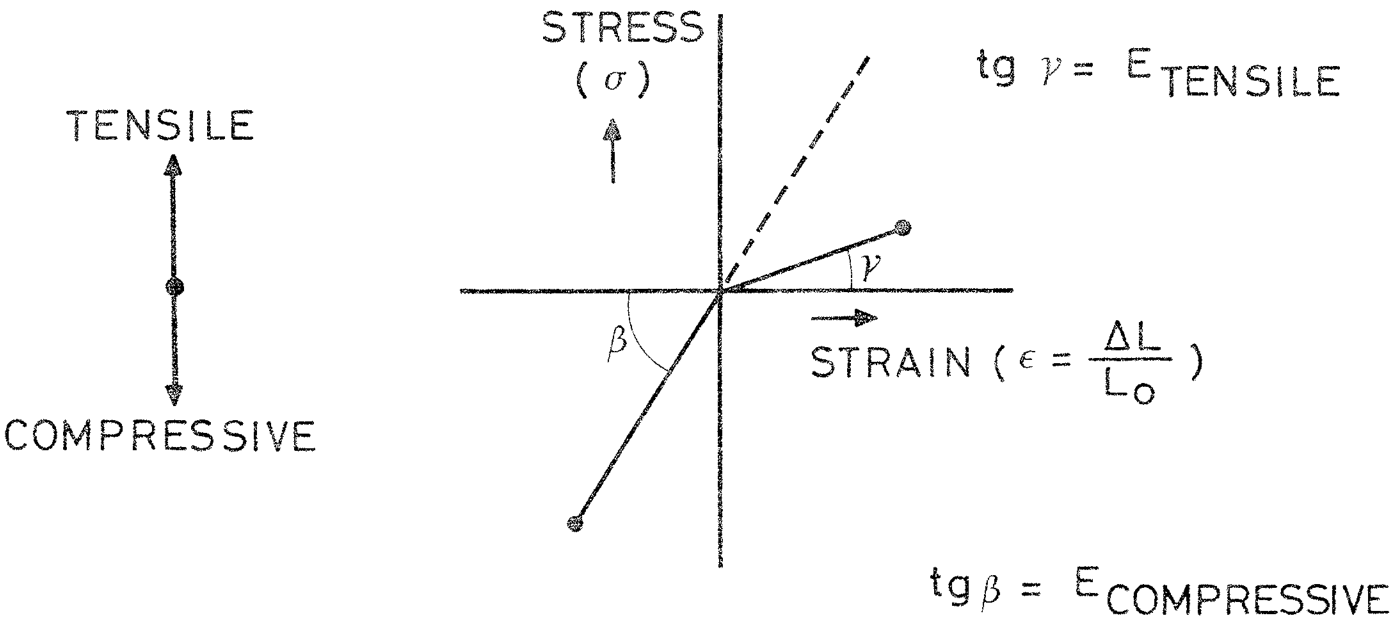
A high ratio prevents crack initiation. For some arbitraty materials this ratio is tabulated for temperature differences of 1500°C (figure 13).
As can be seen from these values all oxidceramic materials have relatively low ratios. An exception is fused silica because of the low value of the expansion (αT).
A good mterial is pure grafite with a ratio far above unity. In the last years the good elastic behaviour of grafite has been combined with other profitable properties of the oxidceramic materials like abrasion resistance, oxidation resistance, etc. Examples are alumina-grafite (ratio $\varepsilon_{max}/\alpha T = 0,56$) and mag-carbon bricks.
For these application elastic behaviour becomes more and more important.

1. STRESS-STRAIN DIAGRAM OF STEEL



$$\mathrm{tg}\,\nu = \frac{\text{STRESS}}{\text{STRAIN}} = E$$

2. STRESS-STRAIN DIAGRAM OF REFRACTORIES



$\text{tg}\ \gamma = E_{\text{TENSILE}}$

$\text{tg}\ \beta = E_{\text{COMPRESSIVE}}$

$E_C / E_T > 1$

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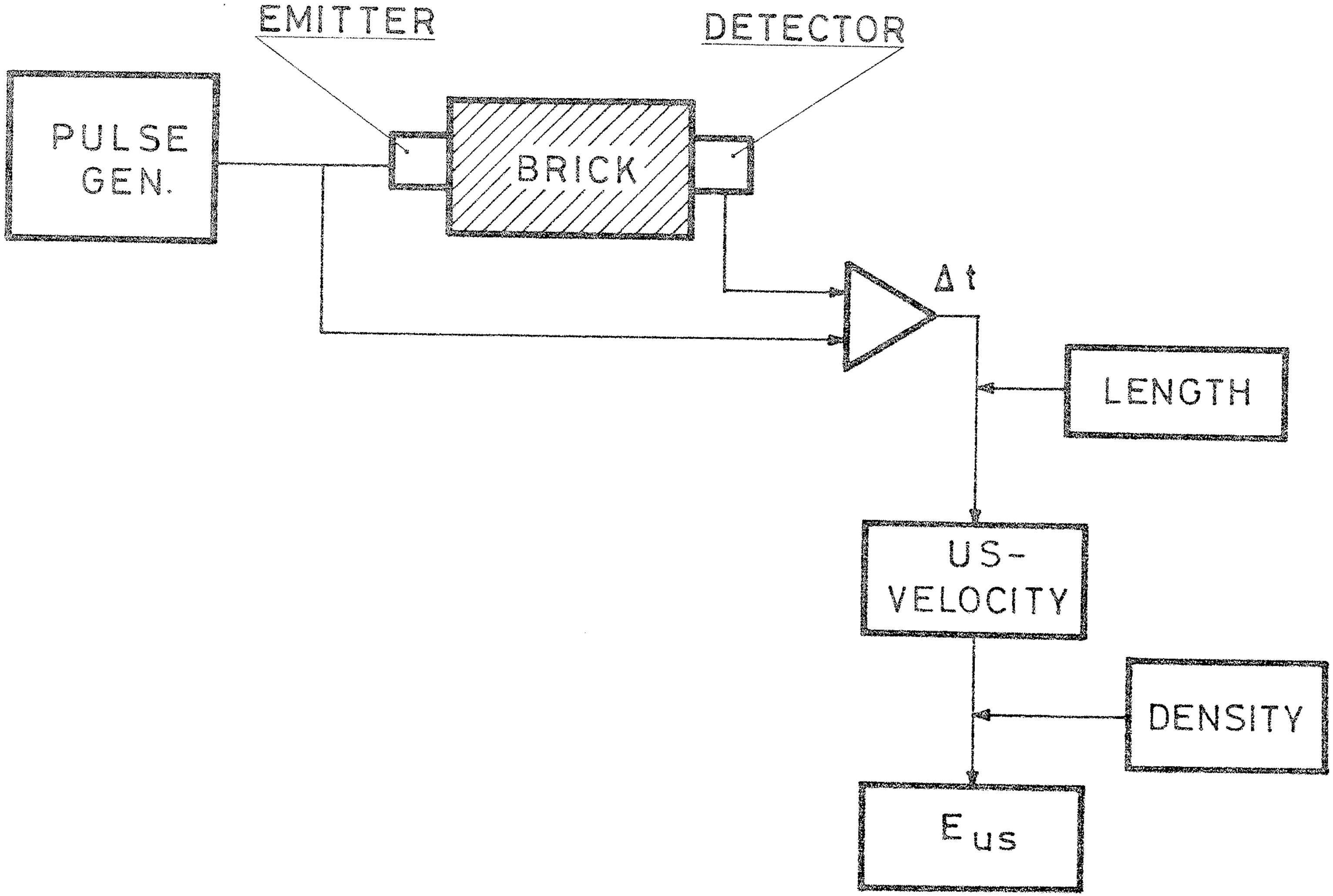
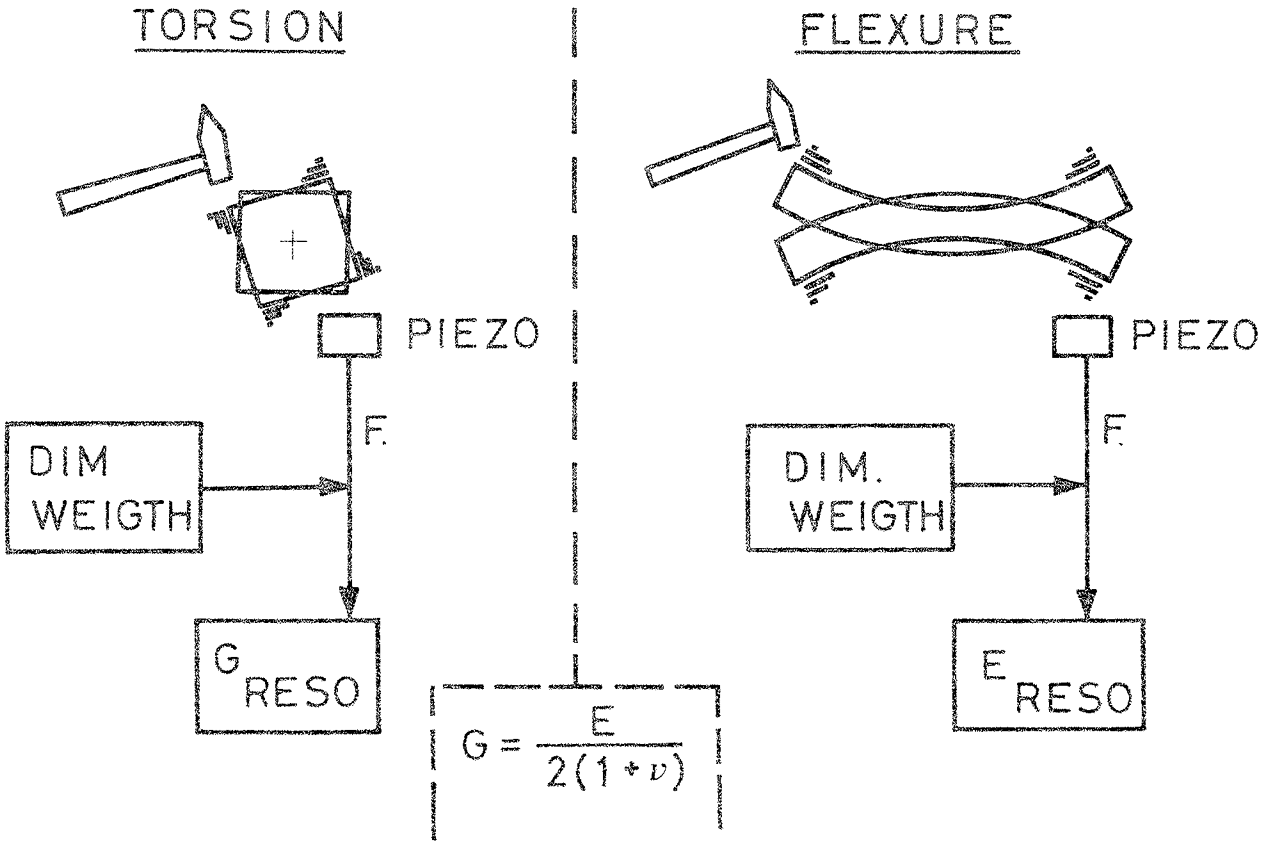
3. METHODS OF TESTING

- DYNAMIC
  - US-VELOCITY
  - RESONANCE
- STATIC
  - TENSION
  - COMPRESSION
  - BEND
  - TORSION

4. E BY (ULTRA)SONIC METHOD

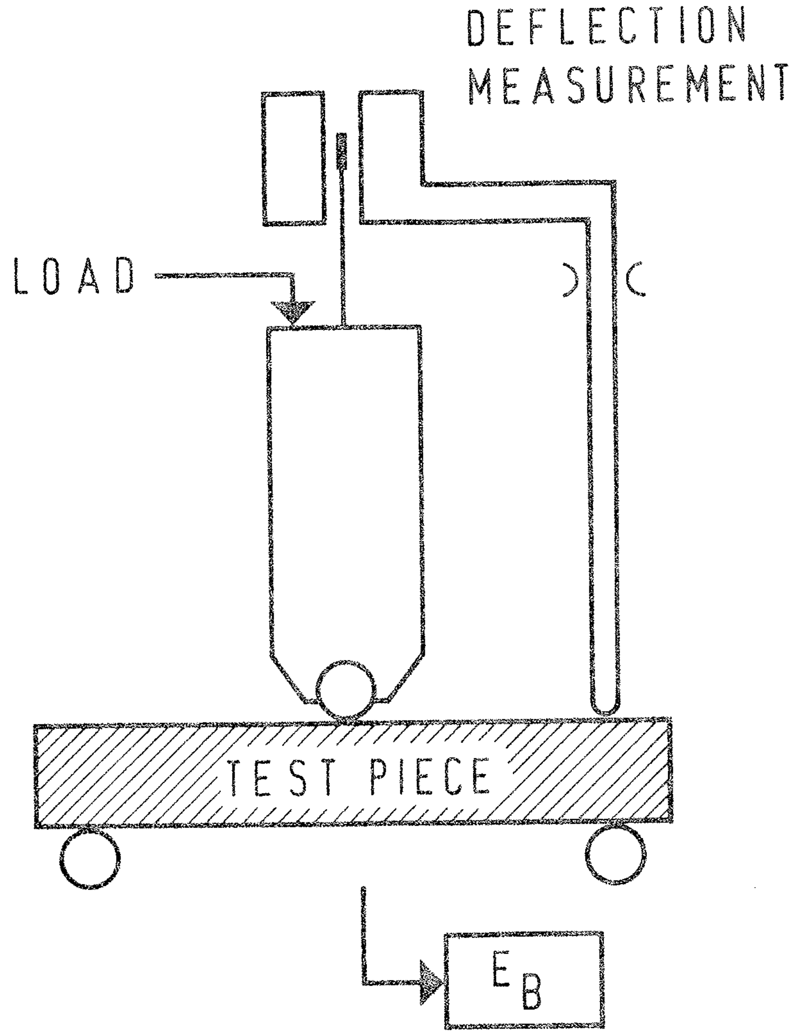


5. E BY RESONANCE METHOD



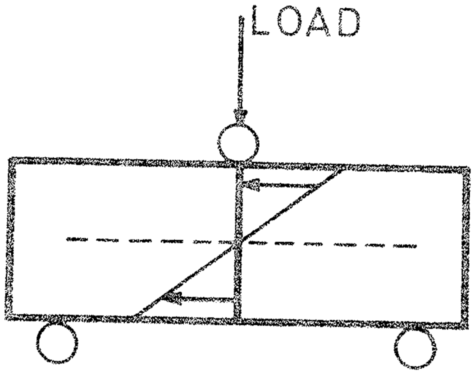
$$G = \frac{E}{2(1+\nu)}$$

6. HOT BEND TEST



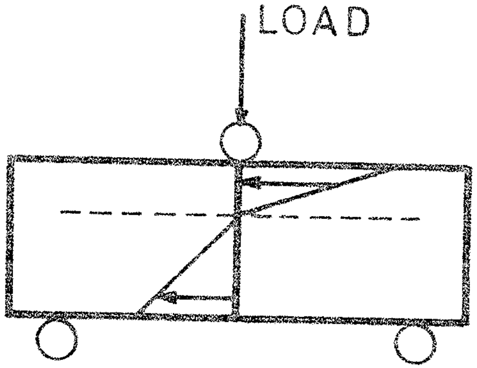
7 STRESS DISTRIBUTION IN BEND BEAM

STEEL



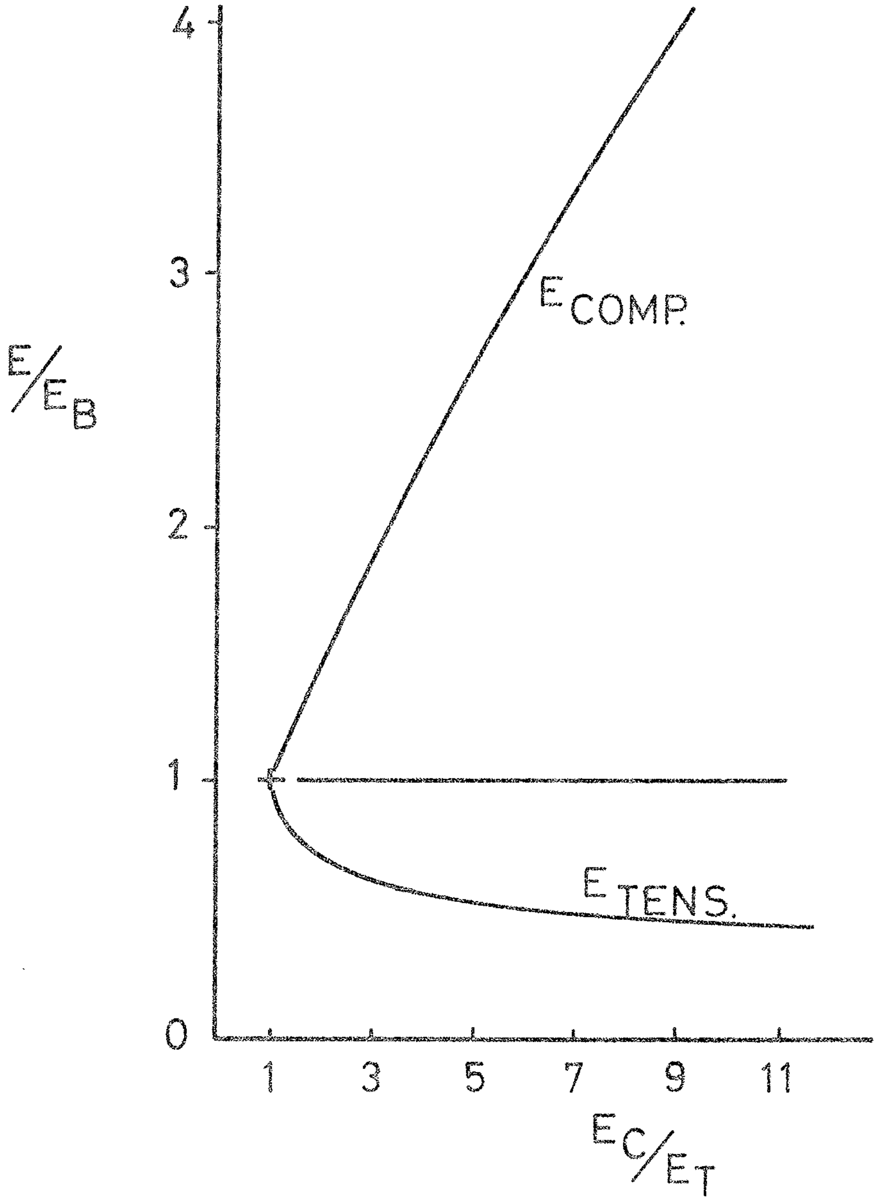
$E_C / E_T = 1$

REFRACTORIES

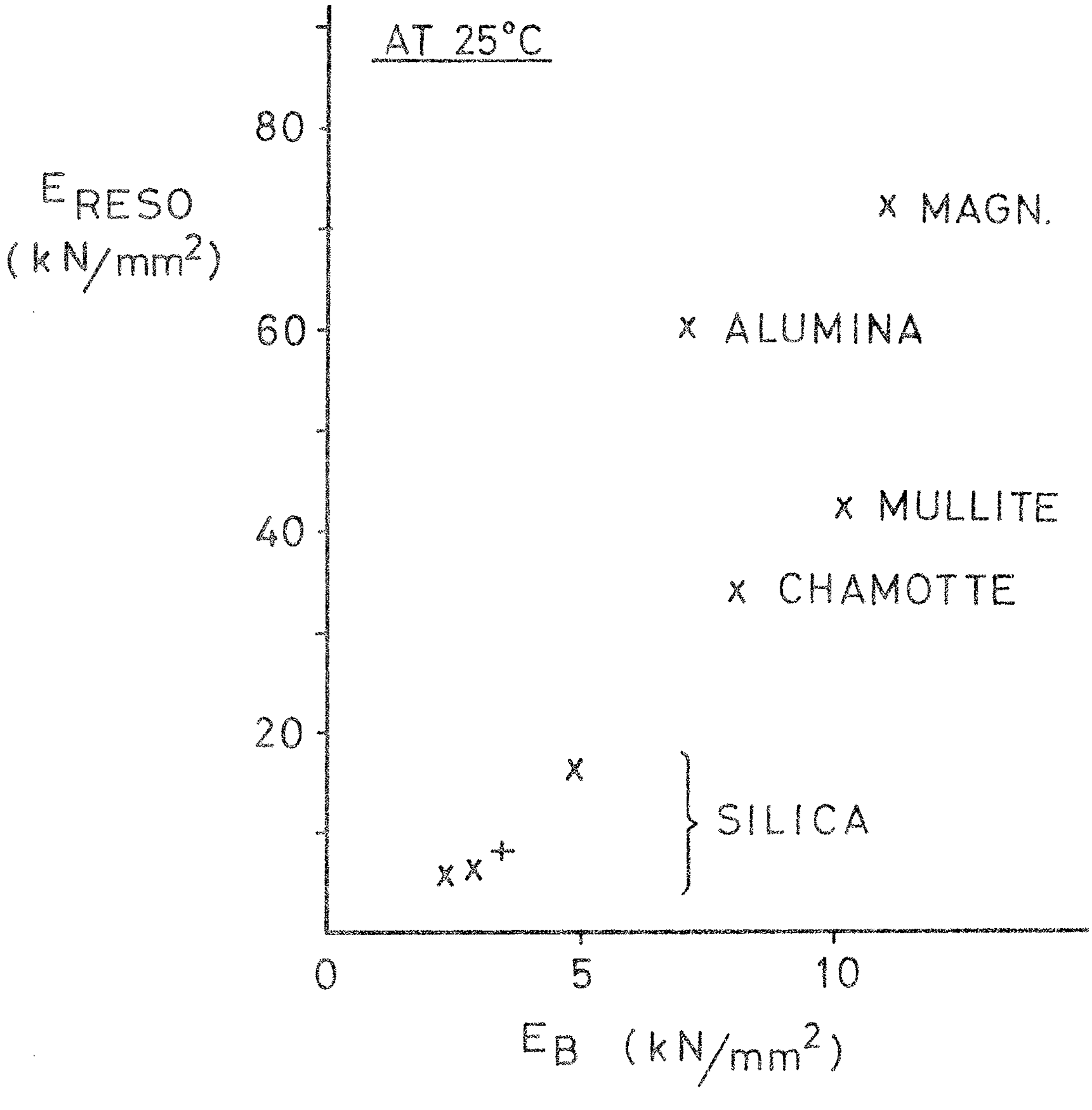


$E_C / E_T > 1$

8. NONLINEAR ELASTIC BEHAVIOUR IN BEND TEST



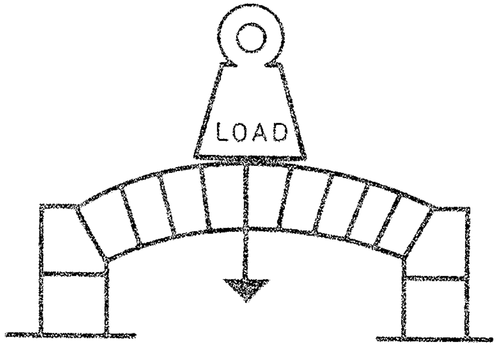
9. E_{RESO} AS A FUNCTION OF E_B

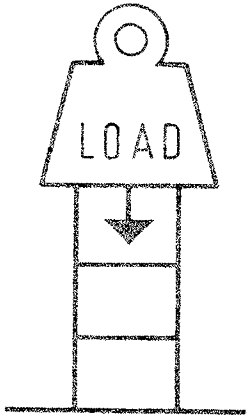


10. AREA OF APPLIABILITY OF RESULTS

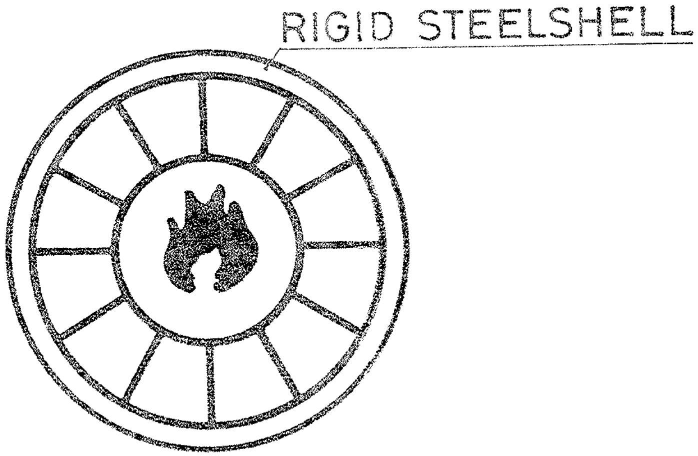
	E_{US}	E_{RESO}	E_{STAT}
QUALITY CONTROL	YES	YES	YES
ENGINEERING	STEEL (YES) CERAMICS (NO)		YES

11. EXAMPLES WHERE STRENGTH IS THE GOVERNING ITEM



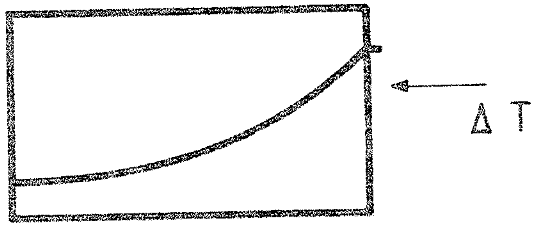


12. EXAMPLES WHERE STRAIN IS THE GOVERNING ITEM



WISH: HIGH $\varepsilon/\alpha T$

STATIONARY SITUATION



WISH: HIGH $\varepsilon/\alpha T$

THERMAL SHOCK

13.

DEFORMATION - EXPANSION RATIO

	MAX. DEFORM. (ε) %	EXPANSION 1500°C (αT) %	RATIO ($\varepsilon / \alpha T$)
SILICA (CRYST.)	0,25	1,2	0,21
(FUSED)	0,18	0,15	1,2
CHAMOTTE	0,16	0,55	0,29
ALUMINA	0,18	1,2	0,15
MAGNESIA	0,19	2,0	0,10
GRAFITE	0,7	0,1	7
ALUMINA - GRAFITE	0,48	0,85	0,56