GRAPHITE STRUCTURE AND ITS RELATION TO MECHANICAL ENGINEERING DESIGN

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SUMMARY

The inhomogeneous nature of polycrystalline graphite requires property measurements to be made over dimensions large enough to average the local variations in the structure. This is particularly true for mechanical integrity, and experimental data are presented which illustrate the importance of the real aggregate structure of graphite and the difficulties of interpreting strength data from different tests. The classical statistical treatments do not hold generally, and the problem of defining a failure criterion for graphite is discussed.

It is suggested that the stress conditions in graphite components might be classified in terms of the dimensions and stress gradients related to the characteristic flaw size of the material as determined experimentally.

1. INTRODUCTION

In any inhomogeneous material, the scale of the inhomogeneities must be considered, either when making property measurements on the material, or when the material is used in engineering components.

Measurements of the physical properties of a material for engineering design are generally made on specimens which are large enough to sample adequately the local inhomogeneities in the material structure and thus produce a good average value. Design calculations invariably treat the material as a continuum, whereas components in service often experience conditions in which the calculated temperature and stress based on the average properties vary rapidly over the dimensions of the inhomogeneities.

Polycrystalline graphite is a good example of a material in which the scale of the structural irregularities becomes important in practical situations, particularly when the strength of the structure is considered.

For nuclear reactor and other applications, graphite is made by grinding a coke derived from either petroleum or pitch to produce 'grist' particles, which are blended to achieve a chosen size distribution. These particles are mixed with a pitch binder, formed by extrusion or moulding into 'green' bricks, and then baked at about 1000°C to remove volatiles and produce a rigid body. Variations in the coke cource and/or grinding technique can produce particles of different shapes, resulting in different degrees of anisotropy in the materials after the forming process, or even near-isotropic bodies if the grist particles are isometric. The bricks are impregnated with pitch or other hydrocarbons to increase density and improve other properties, and they are finally graphitised at about 2800°C to produce a well-crystallised material.

Thus the final graphite product consists of aggregate particles of a range of sizes bound together in a structure which contains a substantial fraction of free pore space. The maximum particle size in typical nuclear grade graphite is ≈ 1 mm and the maximum linear dimensions of the pores are generally of similar magnitude to the maximum particle size. Examination reveals pores at all magnification levels from direct observation, through the optical microscope range, to the submicron size pores seen in the electronmicroscope. The pore spectrum may be studied quantitatively, for example by mercury penetration techniques.

There is no adequate statistical description of this material structure, hence when measuring physical properties of graphite the choice of minimum specimen dimensions sufficient to average the structure is rather arbitrary, although it is demonstrated experimentally that properties are not sensitive to specimen size around the typical dimensions used in laboratory tests. The problem is enhanced, however, in the measurement of graphite strength because under uniform stress this property is determined by the localised weak region of the sample, in contrast to properties such as Young's modulus which average all the structure within the specimen. Under non-uniform tensile stresses, fracture initiation is most probable in the restricted volume of material in which the stress field has high values. With this apparent concentration of high stresses within a volume which may be small compared to the scale of the inhomogeneities, it becomes very difficult to predict the failure condition for graphite components subjected to non-uniform stress fields in service.

This report presents specific examples of experimental data which show the influence of the real structure of graphite in limiting the success of failure criteria based on continuum mechanics, and also discusses alternative solutions to the problem.

2. PREVIOUS WORK

There are many factors to consider in defining a general engineering fracture criterion for graphite, and these have been discussed in detail in a recent review(1) of the subject.

Engineering design rules may be defined to allow for some of these aspects of graphite failure. For example, tests under uniform multi-axial stresses have shown that while graphite does not behave as a perfect Griffith solid, for a given material empirical equations may be established to define the fracture envelope. Graphite exhibits dynamic fatigue and curves have been established which show that failure can occur at alternating stress levels substantially below the normal static strength of the material. 'Static' fatigue has also been observed, but the influence of environmental effects on these fatigue phenomena has not been studied in detail, although internally absorbed moisture in as-received graphite has been shown to significantly reduce the room temperature strength. Changes imposed on the material either within the crystal lattice (e.g. fast neutron irradiation) or in the structure external to the graphitised coke grains (e.g. oxidation) modify the strength of graphite in a way which may generally be allowed for empirically in engineering design in terms of the fractional changes produced.

However, the outstanding difficulty in design applications is to recommend a method for treating stress gradients within graphite components. This problem was highlighted in a series of tests[2] on graphites of different geometry aimed at defining a common fracture criterion under conditions where the principal stress is tensile and non-uniform. These tests included bend tests, internal pressure tests on ring specimens, and diametral compression tests on rings, for comparison with results obtained in uniform tension. In all specimen geometries in which stress gradients were present it was observed that the calculated maximum elastic stress at failure exceeded that in uniform tension by an amount which increased with the severity of the stress gradient, i.e. components subjected to non-uniform stresses could survive much higher apparent localised tensile stresses than those tested in uniform tension.

Several possible approaches were explored in an attempt to inter-relate the different fracture tests. Calculations of the elastic energy stored in the specimens gave a reasonable correlation when the tensile stress varied in only one direction within the material, i.e. in bend and internal pressure tests (note particularly the corrigendum associated with reference 2). However an energy density fracture criterion could not be applied to more complex stress distributions (e.g. rings under diametral compression) because of the difficulty in defining the extent of the volume over which the averaging should be performed. Neither an empirical correlation between maximum stress at failure and stress gradient, nor a statistical approach based on a Weibull analysis, gave a satisfactory solution to the problem, and the latter is discussed further in this report.

The application of fracture mechanics to the problem has been explored[3,4] on the argument that the inherent cracks in the material are responsible for failure and a graphite might be characterised by a critical inherent defect size. The analysis could not explain the fracture data in terms of a unique crack length, but indicated that the inherent characteristic defect size decreased as the maximum stress gradient in the specimen increased.

These difficulties of defining an engineering failure criterion in terms of a characteristic defect are examined further in this Report with experimental fracture data for different stress distributions, and the relationship with the real crack structure is discussed.

3. EXPERIMENTAL DATA

3.1 NOTCH SENSITIVITY

Studies of the notch sensitivity of a nuclear graphite using a wide range of specimen types, sizes and shapes, showed[1] that the parameter of prime importance was the radius at the root of the stress-raising notch. The ratio of the observed to the theoretical stress concentration was a function of notch root radius independent of specimen geometry.

Comparison of the observed and theoretical effect of a stress raising notch is clearly illustrated in Fig. 1 which shows the results of four-point bend tests on edge-notched beams of 12.5 mm square cross-section. The 2.5 mm deep notches had root radii varying from 0.12 mm to 10 mm and, as an extreme condition, a sharp machined notch with a radius estimated from microscopic observations to be $\approx$ 0.02 mm. Six specimens were tested under each condition and the spread is indicated by the standard deviation.

Fig. 1a shows that the nominal strength (ignoring the notch and using the ligament thickness) is not significantly different from an unnotched beam when a large radius r = 10 mm is employed, but decreases rapidly at smaller root radii levelling out when $r \lessapprox 1$ mm so that sharper notches have little further stress-raising effect. Fig. 1b compares the observed and theoretical stress concentration factors expressed respectively by:

(i) the ratio of the unnotched bend strength to the observed nominal strength of the notched specimens,

and (ii) the ratio of the calculated maximum stress in the notched specimens to their nominal strength.

Fig. 1b shows that the theoretical magnitude of stress concentration is not observed in terms of failure at some critical maximum stress, indicating that either the theoretically high stress gradients are not real in the graphite structure when their scale is comparable to that of the actual flaw pattern, or with the very high localisation, the elastic energy stored is not sufficient to allow failure initiation and crack growth. In fact other tests on this type of graphite with different notched specimen geometries failed to raise the observed stress concentration by more than a factor 2.0.

For this material, Fig. 1a shows the critical value of r below which further stress raising effects are not significant is in the region of 0.5-1 mm. This must represent information on the scale of the important crack structure for failure initiation, possibly being a measure of the inherent crack separation, i.e. when the localised stress region near the crack tip limits the absorption of available energy to the minimum number of initiating cracks, so that further concentration at smaller radii has no additional effect. Bazaj and Cox[5] have reported a decrease in the observed stress concentration effect with increase in the grain size of the material, from about 1.6 at a grain size < 0.75 mm, $\approx$ 1.4 at < 2.5 mm, to $\approx$ 1.1 at < 8.5 mm. (The tests were on grooved specimens with no blend radius).

Thus there is a limit to the degree of notch sensitivity of the aggregate, set by the inherent crack structure, with larger grained material being less sensitive to notches. The important dimension is the notch tip radius, and its limiting value may be a measure of the scale of the inherent cracks.

3.2 SIZE EFFECTS AND GRAIN SIZE

The concept that failure arises from inherent flaws, which have a size distribution, leads to predictions of both an increasing strength with decreasing volume and the ability to sustain high maximum stresses under high stress gradients. Both these predictions arise from the low probability of sampling a large flaw when the volume under high stresses is small. Graphite certainly exhibits the stress gradient effect, but there are difficulties in producing a quantitative theory that describes both gradient and volume effects and is also consistent with the observed scatter in individual strength data. These difficulties appear to arise from the inability of the statistical theories, such as that of Weibull, to account for the real structure of the material.

For example, there have been several reported investigations[1,6 and 7] of size effects on strength which show a peak in the strength-volume curve. Strength increases with decreasing volume at high volumes as statistical flaw theories would predict, but then start to decrease as the specimen volume becomes smaller. The volume at the maximum strength increases with increasing maximum grain size,[7] (from 1 cm^3 to 7 cm^3 for 0.5 mm to 5 mm in one series of tests).

A simple indication of the effect of decreasing one linear dimension is shown in internal pressure tests on ring specimens of decreasing wall thickness in Ref.2. As the wall thickness decreases the circumferential tensile stress becomes more uniform and the maximum value tends towards the tensile strength of the graphite determined in direct tension tests on rods. However, at a wall thickness of 1 mm, the strength suddenly decreases towards zero. Hence at a linear dimension of about 1 mm, approximately the size of the maximum grains in this material, a significant portion of the specimen must already be regarded as having failed.

When two linear dimensions are reduced simultaneously, this effect is observed at larger dimensions. Thus tensile tests on rods of different length and diameter of a similar graphite show a decrease in strength with diameter when the diameter decreases below 10 mm, approximately 10 X grain size, Fig.2. At higher diameters (and volumes) the strength does not change significantly, indicating either no statistical size effect or a very broad peak in the strength-volume relationship. Increasing specimen length at constant diameter did not produce any significant changes in strength.

Fig. 2 also shows a more limited set of bend strength data for the same graphite on beams of square cross-section, indicating that the bend strength is apparently less sensitive to grain size effects. There is, however, a systematic decrease in bend strength in specimens of 12.7 mm square cross-section with increasing length between the inner supports. This effect is not observed in 12.7 mm dia. tensile specimens of differing length.

Four-point bend tests were performed as rectangular beam specimens of the same graphite with an extremely wide range of specimen sizes, but it is difficult to separate the influence of the different geometric variables on the bend strength. For the larger specimens, Fig. 3 shows a decrease in strength with increase in volume at constant thickness (or with increase in the elemental area under maximum stress) which is consistent with a Weibull type of size effect described by a high value for the homogeneity factor, m=16, but Fig. 4 shows there is also a small decrease in strength when the specimen thickness is increased (decreasing the stress gradient) at constant volume (by decreasing specimen breadth to compensate). Note, however, that it is not possible to extrapolate the bend strength data to zero gradient and obtain satisfactory agreement with the tensile data. For small specimens Table 1 shows that the bend strength is relatively insensitive to variations in specimen thickness and then, at the smaller dimensions, there is a decrease in strength. At these dimensions of a few millimetres in width and thickness, the effect of grain size is important.

Fig. 5 summarises an attempt to describe a set of bend and tensile strength data by Weibull statistics, which should consistently describe with the same parameters:

(i) the volume dependence

(ii) the bend/tensile strength ratio, and

(iii) the distribution of both bend and tensile strength at constant volume.

The tensile strength data is apparently independent of volume at the highest volumes and then decreases with decreasing volume, the diameter being the critical dimension as discussed earlier (Fig. 2). The bend specimens show a peak in the strength-volume curve at specimen volumes $\approx$ 1 cm^3, Fig. 5a. At higher volumes, the rate of decrease in bend strength with specimen volume is quantitatively consistent with Weibull analyses of the bend strength distribution of thirty specimens at a constant volume of 25 cm^3, Fig. 5b, and the strength distribution of a more limited set of tensile specimens is not inconsistent with the same Weibull parameters. At the highest volumes where grain size effects become less important in tension, the bend/tensile strength ratio is also tending towards values which could be described by the same set of Weibull parameters, but the decrease in tensile strength with volume was not observed at the specimen volumes tested. A tentative extrapolation of the experimental data in Fig. 5a shows how the Weibull analyses could give a consistent picture at very high sample volumes of both the volume effects and the tensile-bend strength difference. Alternatively, a limited maximum crack size would result in a constant strength at high volumes. The tensile strength data does not extend to high enough volumes to confirm either of these possibilities.

So the bend strength tends to fall at small specimen dimensions approaching the real crack size, there is a balance between the opposing effects at the maximum in the bend strength-volume plot, and an apparent Weibull effect dominates at higher volumes. In the uniform tension experiments referred to above, the maximum was not defined experimentally in that a decrease at high specimen volumes was not observed.

These observations can be interpreted as indicating that the size below which the sample becomes progressively less representative of the aggregate is considerably smaller in bend, i.e. when stress gradients are present, than under uniform stress.

3.3 EFFECTIVE FLAW SIZE AND FRACTURE MECHANICS

The fracture mechanics approach to graphite failure, in its simplest form, argues that the material has an effective inherent flaw size, and a characteristic fracture toughness parameter, often represented by the stress intensity factor $K_{Ic} = \sigma(\pi a)^{\frac{1}{2}} f(a/W)$, where $f(a/W)$ is a geometric factor. Thus in any geometry and stress distribution, failure is initiated when the stress intensity factor reaches the critical value, and $\sigma\sqrt{a}$ is a constant.

An experimental investigation of the effective flaw size concept applied to graphite was performed by establishing, in different tests, the size of artificial defect that just becomes distinguishable from the naturally occurring defects and flaws. These studies should give an experimental measure of the effective natural defect size in the material. This was done by testing:

(a) single edge-notched beams in four-point bend, with different notch depths,

and (b) similar edge-notched specimens under uniform tension.

Figs 6a and b show the applied load to failure as a function of notch depth for bend and tensile tests on edge-notched beams of four different graphites. The load to failure falls with increasing depth of artificial notch after an initial period of relatively small or insignificant effect at small notch depths. The effect is more pronounced for the fine grain material, and larger defects are required to produce significant effects in the coarser grained materials.

At small notch depths in these bend and tensile tests, the point of failure is not necessarily at the notch, although this 'ocation becomes more probable as the notch depth increases until all failures occur at the notch, and the load to failure then decreases rapidly with further increase in notch depth. It is more informative in these tests to consider the proportion of failures occurring at the notch as a function of artificial defect size.

Figs 7 and 8 show the fraction failing at the notch in the bend and the tensile tests respectively, and it is clear that the defect size giving 100% failure is significantly smaller for the fine-grained graphite than that for the coarse-grained PGA material. In both bend and tensile tests the materials order in approximately the same pattern, but there is a difference between the results from the two tests, which is discussed later.

Both these types of notched bend and tensile tests may be used to evaluate the stress intensity factors, by feeding in the artificial defect sizes into the equations:[8]

4-point bend, $$K_c^2 = EG = \sigma_b^2 \frac{W}{9}\left[34.7\frac{a}{W} - 55.2\left(\frac{a}{W}\right)^2 + 196\left(\frac{a}{W}\right)^3\right] \quad \cdots (1)$$

tension, $$K_c^2 = EG = \sigma_t^2 W\left[7.59\frac{a}{W} - 32\left(\frac{a}{W}\right)^2 + 117\left(\frac{a}{W}\right)^3\right] \quad \cdots (2)$$

where a is the artificial notch depth

W is the specimen thickness

σ_b and σ_t are the appropriate maximum stresses for a beam of thickness W.

These K_c values are low at small notch depths, but they increase with notch depth until the artificial defect dominates when they become constant values appropriate to the material for the test considered. These values are summarised in Table 2, both bend and tensile tests giving similar K_c values for a given graphite.

It is now possible to apply these K_c values for each material to the appropriate strength data for the unnotched beams, and to calculate an effective inherent flaw size for each material, using an iterative procedure on equations (1) and (2). These calculated values of effective flaw size are given in Table 2. They are illustrated by the arrows in Figs 7 and 8 where they show very good agreement with the independent and completely experimental determination of the artificial notch depth which significantly decreases the strength of the specimens and causes a high percentage failure at the notch. Table 2 also shows that observed maximum pore sizes are of similar magnitude.

It is important to note however, that while self-consistent in themselves, the bend and tensile data are different. The tensile tests give values for the effective flaw size which are greater than those obtained from the bend tests. Alternatively, a given artificial notch has a greater effect on bend specimens than it has on specimens tested in uniform tension.

These experiments support the conclusions obtained by Darby[3] via a different route that the application of fracture mechanics to graphite in situations where large artificial defects are not present requires the use of an effective inherent flaw size which depends not only on the material, but also on the particular test or stress distribution under consideration.

Hence these fracture mechanics tests show the effective defect size to be smaller in bend, where stress gradients exist, than in uniform tension, while the earlier size effect studies show grain size to be less important in bend than in uniform tension. These are different observations of the same problem which foils attempts to characterise the structure by a simple parameter independent of the applied stress distribution.

4. DISCUSSION

The experimental studies reported lead to two significant conclusions for the range of graphites studied:-

(a) The ability of a sample to withstand uniform tensile stresses decreases as its cross-section falls below ≈ 1 cm^2 or a linear dimension decreases below about 1 mm. These numbers would be expected to fall with grain size.

(b) The occurrence of high local stresses due to specimen geometry leads to apparent strengths well in excess of the highest uniform tensile stress values.

These two observations are apparently incompatible. The case (a) involves directly measured loads whereas (b) is an inferred situation using geometry and continuum properties. It is self-evident that stresses localised on a scale comparable with the granular structure of the material have no real existence, they are re-distributed by the structure to give the correct total force only. The employment of correct representations of the non-linear stress-strain curves does reduce the stresses compared to pure elastic calculations but this is not the source of the major part of the observed effects, which are also observed on neutron irradiated samples with more linear stress-strain curves. In the case of the notched samples machined cracks of length less than ≈ 1 mm are ineffective and notch root radii smaller than 1 mm do not increase the notch effect. Measurements of fracture mechanics parameters are only consistent for cracks long enough to sample the macroscopic properties.

There appear to be two important characteristic dimensions, an apparent inherent flaw size of about 1 mm and a dimension of about 1 cm, which is apparently the smallest length at which proper averaging of properties takes place to give bulk values. The maximum grain size of the materials is about 1 mm so that these numbers are consistent. If these two lengths are denoted by ℓ and L respectively then it is possible to classify the various stress conditions of graphite components in terms of the dimensions and the stress gradients $[\partial\sigma_{ij}(x, y, z)/\partial x$ etc$]$, by comparison with say σ_T/ℓ, where σ_T is the tensile strength maximum.

It is reasonable to suppose that for specimen dimensions much larger than L, and small stress gradients simple measures of strength apply and the effects of specimen volume can be taken into account by taking the products of failure probabilities for volumes of dimension ≈ L in which the stresses are averaged. This is important for finite element calculations. Identifiable notches larger than ℓ, or with notch root radii in the range 1 cm to 1 mm are readily assessed. This view has been particularly well expressed by CORDS et al.[9]

A second case, with specimens dimensions greater than L, but with high stress gradients compared to σ_T/ℓ, might be treated in several ways all designed to eliminate the apparent stress peaks. One scheme would be to replace conventional stress σ_{ij} by.

$$\bar{\sigma}_{ij} = \frac{1}{L^3}\int_0^L\int_0^L\int_0^L \sigma_{ij}\ (x, y, z)\ dx.dy.dz \qquad \text{... (3)}$$

where the L could be 'adjusted' values to give desired safety factors. This would be very convenient for finite element - finite difference work. The $\bar{\sigma}_{ij}$ would then be compared with uniform stress values on samples of dimension L. This has not been tested.

The third case of thin samples with near uniform stresses can be investigated experimentally e.g. thin walled tube burst tests, etc. The case of relatively thin specimens compared to L, and high stress gradients may be important in HTRs, and is the most difficult case. Experience is reassuring, but it appears that only careful simulation can adequately treat this condition.

The view presented here indicates that treatments such as that of Weibull[10] or more recent work such as Batdorf and Crose[11] cannot be applied generally. It is also to be expected that fine grain graphite will tend more closely to classical behaviour. An extended study of samples deliberately chosen with widely varying grain size and different degrees of stress localisation would be necessary to verify or reject these ideas.

There is evidence that these considerations are not well understood by designers or design assessors (see Svalbonas et al)[12] and an extensive effort to find a failure scheme for graphite would be well worth while. It is probable that similar considerations apply to both primary and secondary stresses.

5. REFERENCES

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TABLE 1

Some 4-point bend strength data at small specimen sizes for IM1-24 graphite

Width mm \ Thickness mm	6.3	3.2	1.6
	Strength MN/m^2 (with SEM for 6 specimens)		
12.7	37.0 ± 0.7	36.2 ± 0.6	36.8 ± 1.2
6.3	38.1 ± 0.9	36.0 ± 1.2	37.0 ± 0.7
3.2		34.9 ± 1.8	

Outer/inner span 38/19 mm

TABLE 2

Summary of 4-point bend and tensile tests on single edge-notched graphite beams

Graphite	Strength of unnotched beams MN/m^2		$\frac{\sigma_b}{\sigma_t}$	K_c* from deep notched beams MN/m$^{3/2}$		Calculated effective flaw size mm		Observed max size of pores mm
	4-pt bend σ_b	tension σ_t		4-pt bend	tension	4-pt bend	tension	
PGA(L27)	10.5 ± 1.7(8)	6.25 ± 0.7(10)	1.7	0.55	0.48	0.78	1.02	1-2.5
VNMC	18.9 ± 1.3(13)	10.6 ± 1.6(11)	1.8	0.96	0.91	0.67	1.33	1-2
SM2-24	18.9 ± 0.8(12)	12.0 ± 1.3(12)	1.6	0.80	0.85	0.49	0.79	1-2
IM1-24 (NI)	33.9 ± 2.3(10)	23.9 ± 2.6(10)	1.5	1.27	1.22	0.38	0.41	0.5-1
IM1-24 (NP)	32.0 ± 3.4(11)	22.4 ± 2.1 (9)	1.4	1.10	1.18	0.32	0.41	

* Tension $K_c^2 = \left(\frac{P}{WB}\right)^2 W\left[7.59\,\frac{a}{W} - 32\left(\frac{a}{W}\right)^2 + 117\left(\frac{a}{W}\right)^3\right]$

4-pt bend $K_c^2 = \left(\frac{P}{B}\right)^2 \frac{(L-\ell)}{W^3}\left[34.7\,\frac{a}{W} - 55.2\left(\frac{a}{W}\right)^2 + 196\left(\frac{a}{W}\right)^3\right]$

where width $B \approx 6.3$ mm
depth $W \approx 13$ mm
outer support distance $L \approx 10.2$ cm
inner support distance $\ell \approx 3.2$ cm
notch depth a is variable
notch width ≈ 0.17 mm

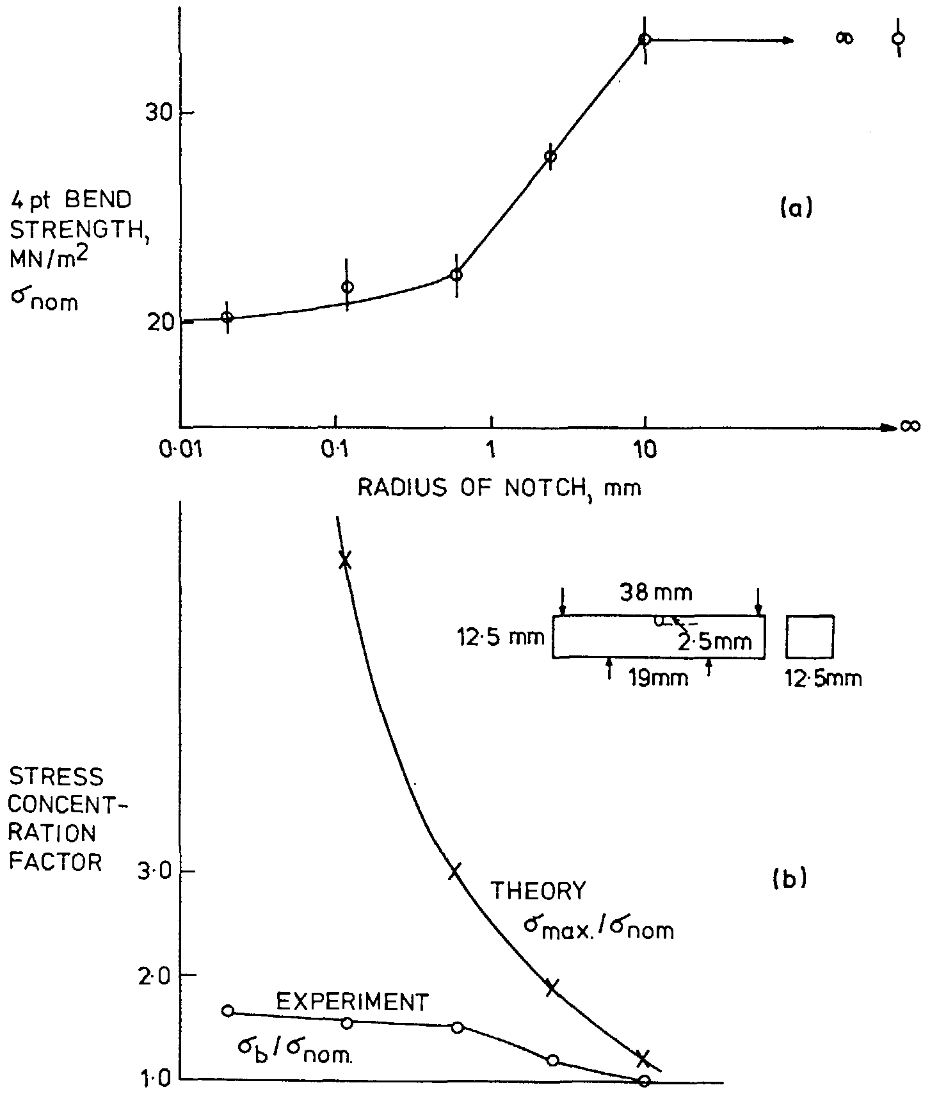

FIG.1.
4-pt BEND TESTS ON NOTCHED BEAMS OF IM1-24 GRAPHITE

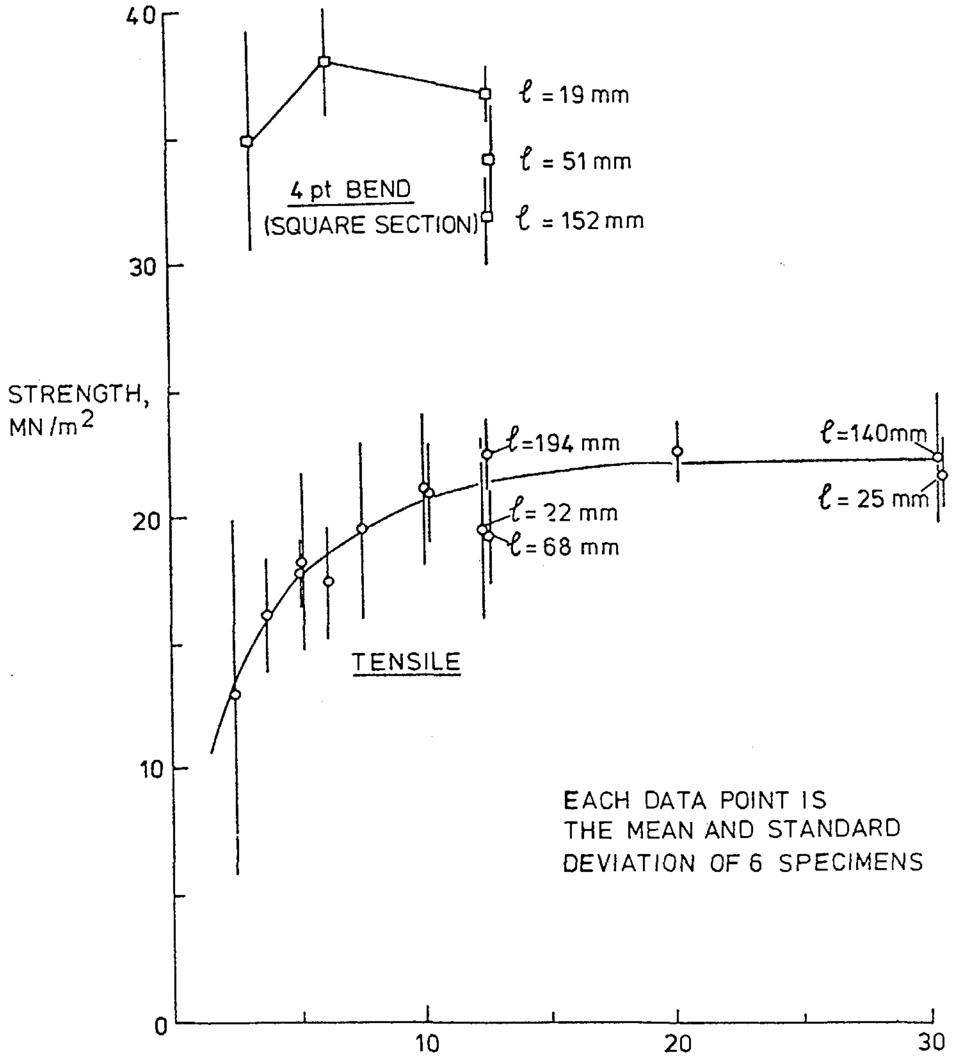

FIG.2.
EFFECT OF DIAMETER ON TENSILE STRENGTH OF RODS AND OF WIDTH ON 4-pt BEND STRENGTH OF SQUARE SECTION BEAMS

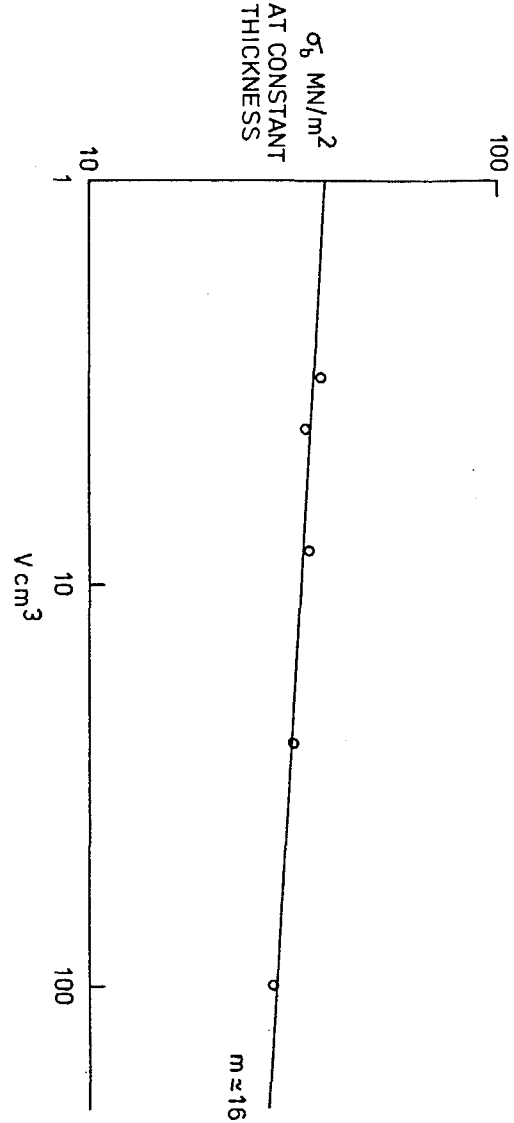

FIG.3. 4-pt BEND STRENGTH OF IMI 24 GRAPHITE BEAMS OF CONSTANT THICKNESS

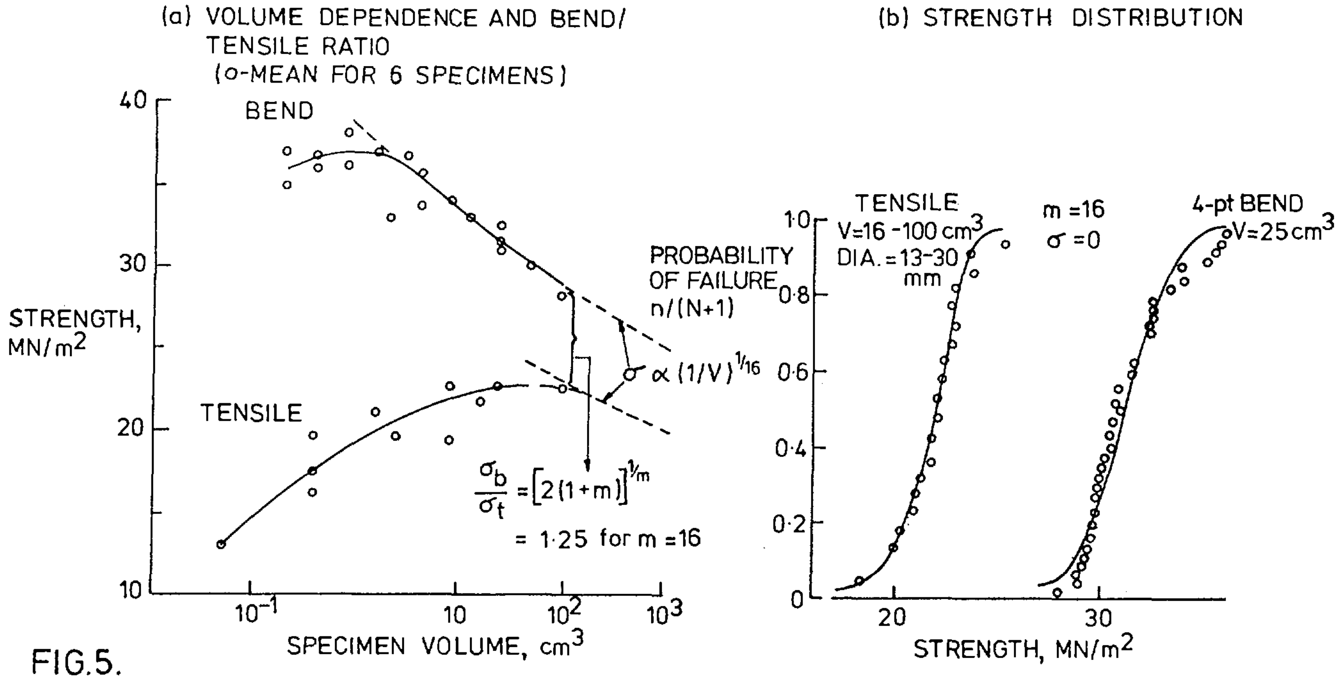

FIG.5.

ATTEMPT TO APPLY WEIBULL ANALYSIS TO 4-pt BEND AND TENSILE STRENGTH DATA FOR AN ISOTROPIC GRAPHITE

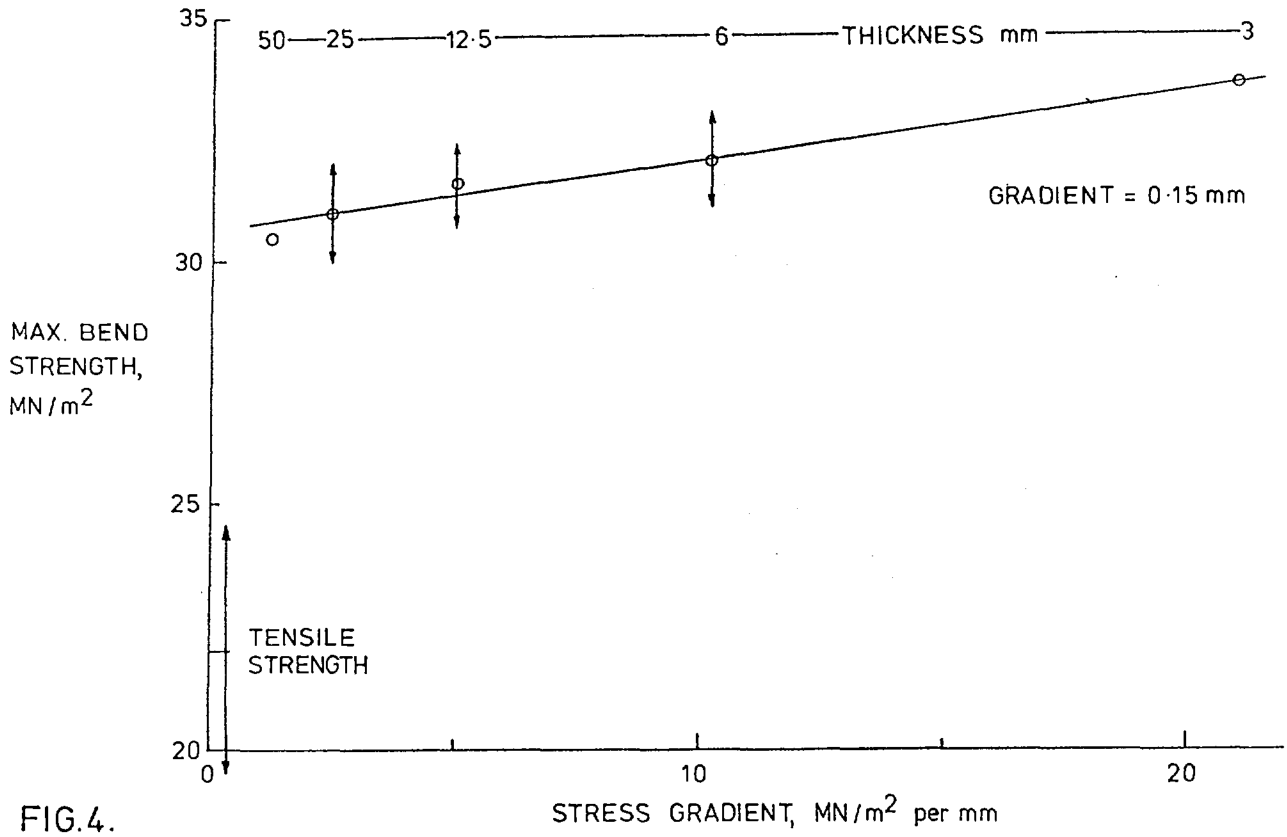

FIG.4.

4-pt BEND STRENGTH OF IM1-24 GRAPHITE BEAMS OF CONSTANT VOLUME ($25\,cm^3$) AND OF DIFFERENT THICKNESS

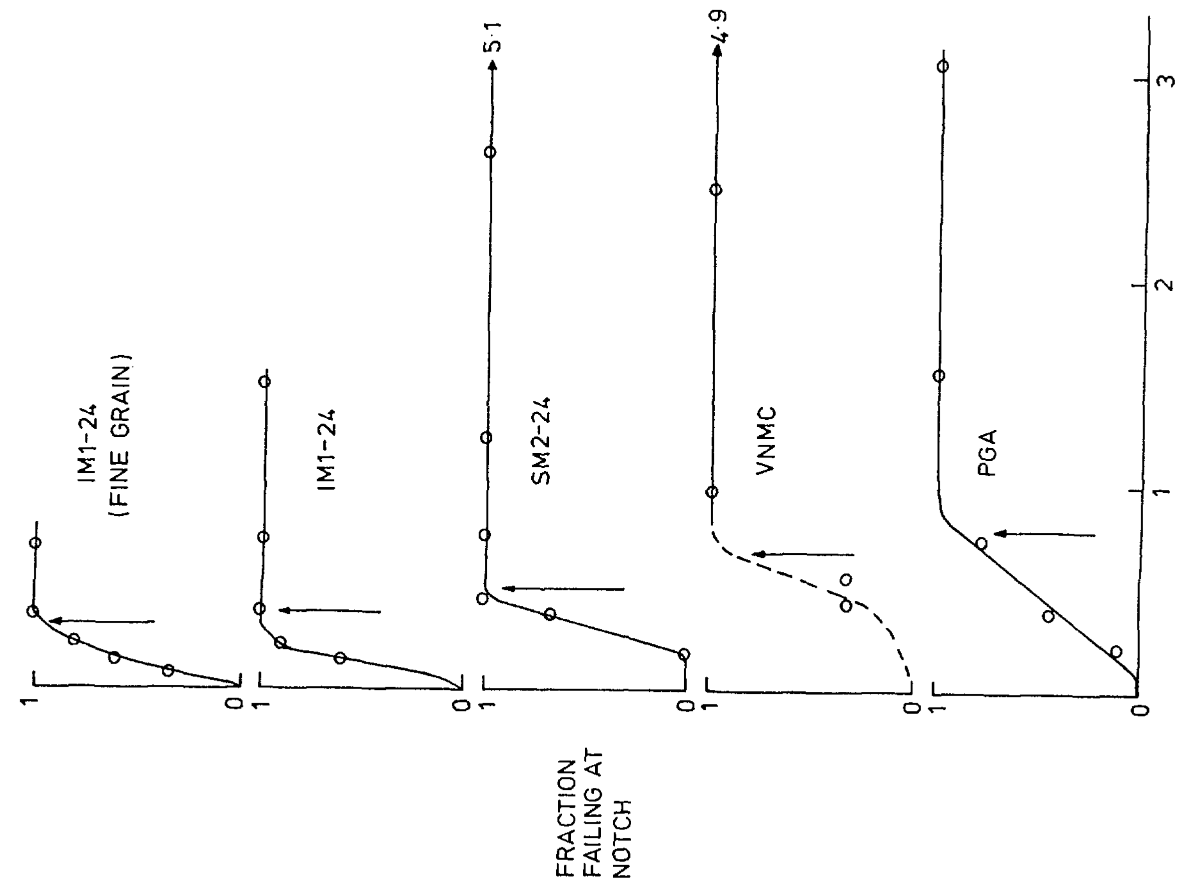

FIG. 7.
4-pt BEND TESTS ON SINGLE EDGE-NOTCHED GRAPHITE BEAMS

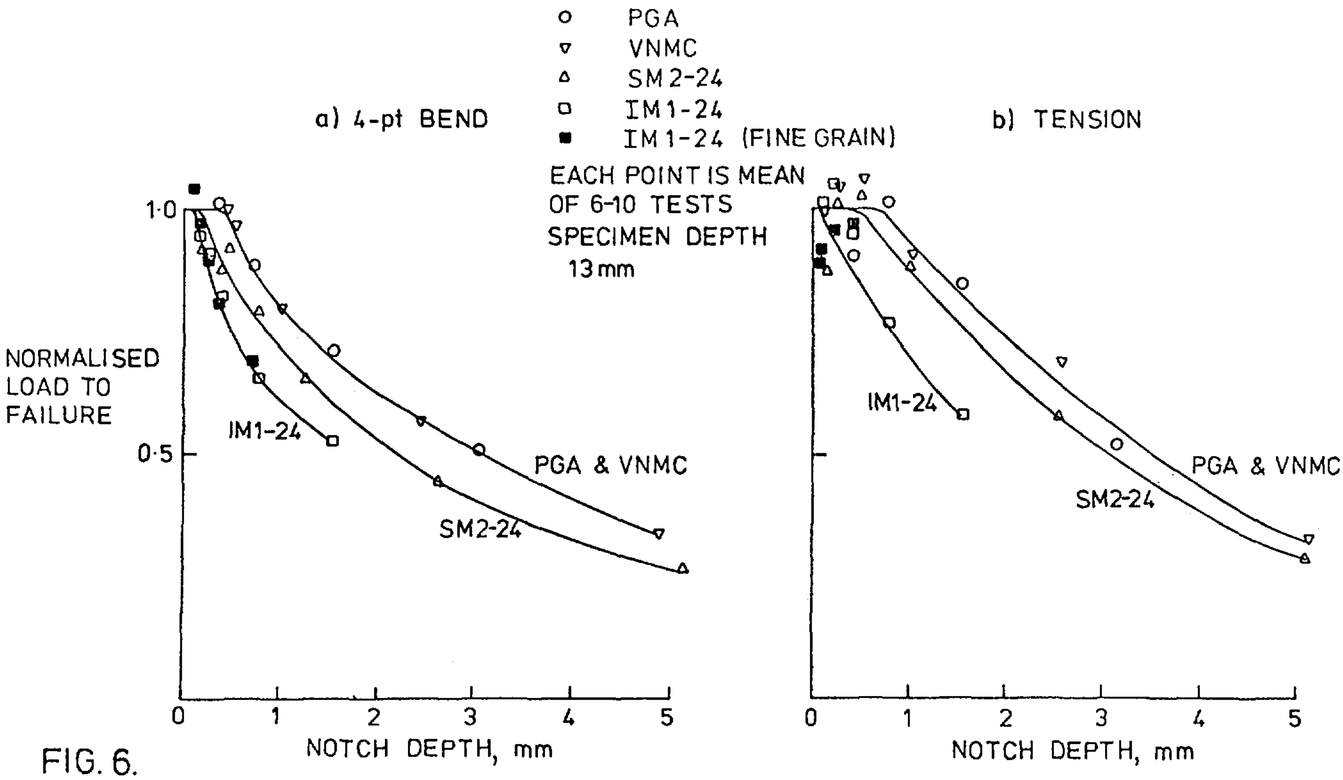

FIG. 6.
RELATIVE LOAD TO FAILURE IN BEND AND TENSILE TESTS ON EDGE-NOTCHED GRAPHITE BEAMS

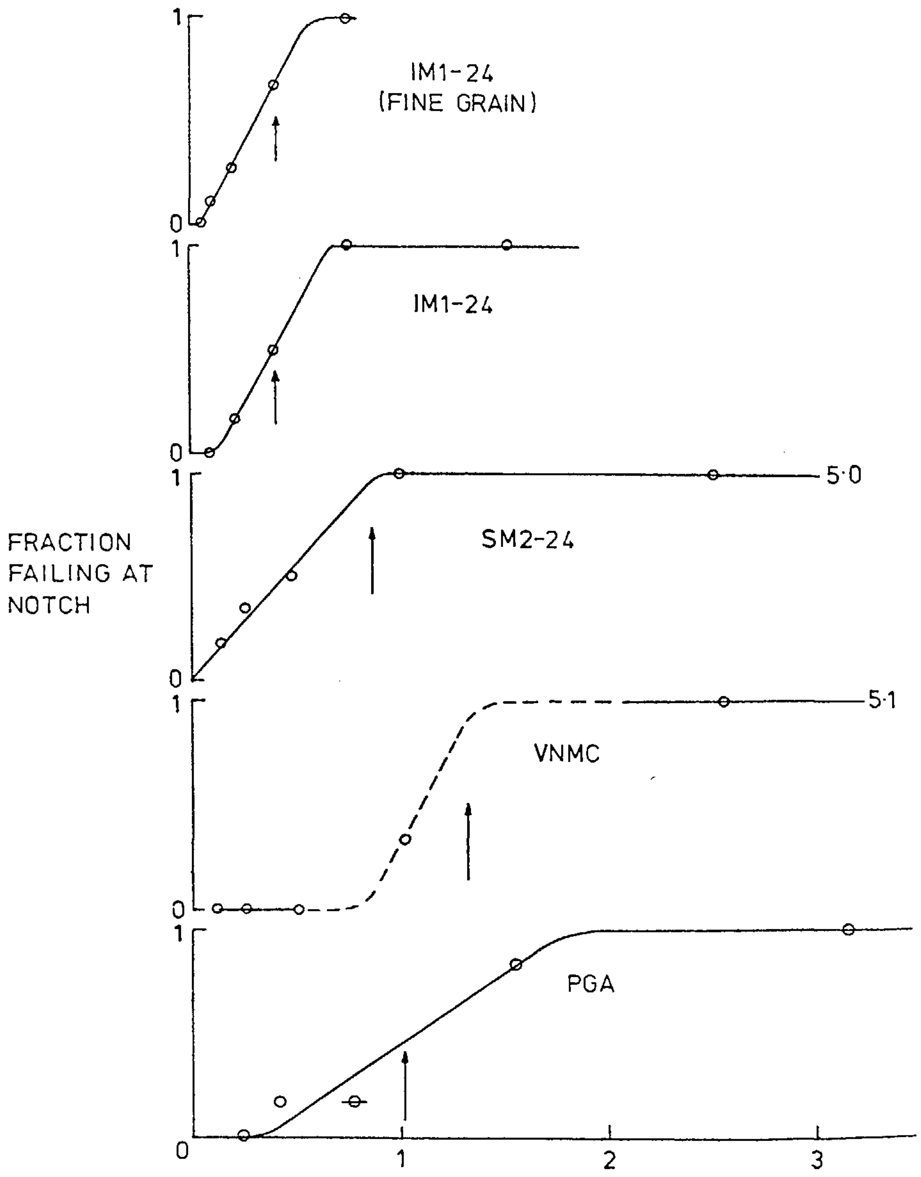

FIG. 8.
TENSILE TESTS ON SINGLE EDGE-NOTCHED GRAPHITE BEAMS

ANALYSIS OF THE STRESSES IN A SIDE REFLECTOR BLOCK OF THE PEBBLE BED REACTOR

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The side reflector of the pebble bed reactor is exposed to a high fast neutron dose during operation. At the end of its service life maximum doses of approx. 3 - 4 x 10^{22} n/cm^{-2} (EDN) are reached. The shrinkage induced in the graphite by the neutron flux results in internal stresses in the individual reflector blocks which may cause damage of the side reflector, e.g. chipping of major fragments. A further type of reflector block damage may be produced by the loss of strength. This loss of strength results from extremely high irradiation doses and is limited to the layers near the inner surface of the side reflector block since the neutron dose decreases almost exponentially with increasing distance from the core.

2. Calculation method

For calculating the internal stresses in graphite structures HRB developped the SIGMA code. This is a two-dimensional finite-element-program permitting the calculation of time-dependent stresses and deformations of graphite reactor components. The loads may be exerted by primary loads, temperatures, and shrinkage induced by irridiation doses. The SIGMA program permits to take into account the particular material properties of the graphite such as shrinkage and creep under the effect of fast neutrons as well as the anisotropy of the mechanical properties