Critical Stress Intensity Factors for Glass Reinforced Plastics

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INTRODUCTION. The possibility of failure of glass reinforced plastics (GRP) structural components in a manner similar to brittle fracture in metals is now receiving attention. The approach which has found the most favour in metal structures is based on the critical stress intensity factor K_c, and if it could be shown that this approach can be applied to composites then it may well be possible to further exploit the considerable volume of work which has been carried out on isotropic materials. The authors have carried out fracture toughness tests on a polyester resin containing various forms of glass reinforcement as part of a Ministry of Defence (PE) programme to investigate the effect of stress concentrators on the failure of reinforced plastics. The effect of crack length has been investigated and the results converted to K_c values. When values were not independent of crack length a method similar to the plastic zone correction factor proposed by Irwin (1) has been used to adjust the K_c values to be independent of crack length. Using the adjusted value of K_c the failure stress of a typical structural member in the form of a plate containing a circular hole was estimated and compared with that measured experimentally.

MATERIALS AND TEST METHODS. The materials selected for the experimental programme were chosen to produce laminates with a range of anisotropy ratios. Wet lay-up laminates were made with Beetle L2615 orthophthalic polyester resin. The types of reinforcement used were as follows; material A, chopped strand mat; material B, unidirectional fabric; material C, balanced plain weave fabric. Material B was tested in both major (B-0°) and minor (B-90°) principal directions. Standard double-edged notch specimens, crack length (a) to width (w) ratio 1:6, described by Srawley and Brown (2) were produced and the edge notches cut with a jeweller's saw. The effect of crack length was investigated by testing geometrically similar specimens 75, 100, and 150 mm wide. All testing was carried out in a modified 'E' type Tensometer universal testing machine of 110 KN capacity at a crosshead speed of 0.021 mm sec^{-1}.

DATA REDUCTION AND RESULTS. As there is no standard procedure for plane stress K_c testing the tentative ASTM standard method proposed by Brown and Srawley (3) for plane strain K_c testing has been implemented where possible to analyse the results obtained. The method specifies the use of a displacement clip gauge. Typical load v. crack opening displacement results are shown in Fig. 1. The load at which the slope of these curves first became zero corresponds to the load at which crack propagation first occurred and was used to calculate K_c from EQ.1. The effect of crack length on K_c for the various materials is shown in Fig.2.

For material B-90° the average K_c value, 4.6 MNm$^{-3/2}$, was taken as a measure of the fracture toughness. For materials A, B-0°, and C, K_c tends to increase with crack length. These materials exhibit progressive damage ahead of the crack tip. Constant values of K_c can be obtained by adding the radius of an apparent yield zone, r_y to the crack length after the manner of Irwin (1). The calculation of r_y (EQ.2) involves the equivalent yield stress, σ_{EY}. Suitable values of σ_{EY} which made K_c independent of crack length were obtained by trial calculations (Fig.3). A series of values of σ_{EY} were assumed, corresponding values of r_y calculated, and adjusted K_c values obtained from EQ.1. by iteration since r_y also depends on K_c.

Fig.3 shows that for material A a value of σ_{EY} equal to 70% of the ultimate tensile strength produces a K_c value independent of

crack length of 13.6 MNm$^{-3/2}$. σ_{EY} is very close to the value of yield stress used by Holdsworth et al also reported at this conference. It also corresponds closely to the stress at which resin cracking occurs. The corresponding values for material C are 54% and 26.2 MNm$^{-3/2}$ respectively. A suitable value of σ_{EY} could not be found for material B-0°. This was not surprising since the material failed by splitting parallel to the loading axis unless the crack was guided by side grooves.

FAILURE OF LARGE SPECIMENS WITH A CENTRAL HOLE. The authors have previously observed a substantial size effect for GRP specimens containing a central hole. When symmetrical specimens of materials A, B-90°, and C are loaded in tension transverse cracks are initiated which grow slowly prior to rupture. The nominal tensile strength of large specimens is lower than that for small specimens (4). Four specimens 254 mm wide x 458 mm long containing a plain circular hole 63.5 mm diameter were tested to failure and the crack length at which rapid crack propagation occurred was measured. Bowie's solution (5) for two cracks originating from the edge of a circular hole is of the form given in EQ.3., where σ = applied stress, L = crack length, r = hole radius, and $f(\frac{L}{r})$ is tabulated in (5). The failure stresses predicted from EQ.3 using the K_c values reported above and the crack length at failure are compared with the observed values in TABLE 1. Agreement is excellent. Failure of material B-90° occurred without measurable crack growth which is in accordance with the predicted crack length based on K_c.

CONCLUSIONS. (1) The applicability of linear elastic fracture mechanics to glass reinforced plastics depends on the type of reinforcement and the orientation of the crack. (2) K_c values independent of crack length can be obtained for unidirectionally reinforced materials with the crack positioned parallel to the fibres. For random mat and balanced weave fabric K_c values independent of crack length can be obtained using a correction factor based on an equivalent yield stress (3). K_c values can be used to predict the failure stress of a simple structural component.

EQUATIONS

$$K = \sigma\sqrt{\pi a}\left(\frac{w}{\pi a}\ \tan\frac{\pi a}{w} + 0.1\ \sin\frac{2\pi a}{w}\right)^{\frac{1}{2}} \quad \text{EQ.1.} \quad \text{(REF 2)}$$

$$r_y = \frac{1}{2\pi}\left(\frac{K_c}{\sigma_{EY}}\right)^2 \quad \text{EQ.2.}$$

$$K = \sigma\sqrt{\pi L}\ f\left(\frac{L}{r}\right) \quad \text{EQ.3.} \quad \text{(REF 5)}$$

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TABLE 1 FAILURE OF SPECIMENS CONTAINING A CENTRAL HOLE

Material	U.T.S. MNm^{-2}	Average Crack length at failure Lmm	$f(\frac{L}{r})$	K_c $MNm^{-3/2}$	Estimated Failure Stress MNm^{-2}	Measured Failure Stress MNm^{-2}
A	137	8.35	2.15	11.1**	32.0	31.2
B-90°	52.4	0.99*	3.12*	4.6	–	26.4
C	229	6.35	2.41	26.2	77.3	89.4

* values calculated from measured failure stress

** corrected value for this batch of specimens

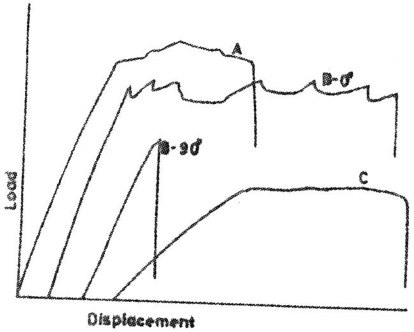
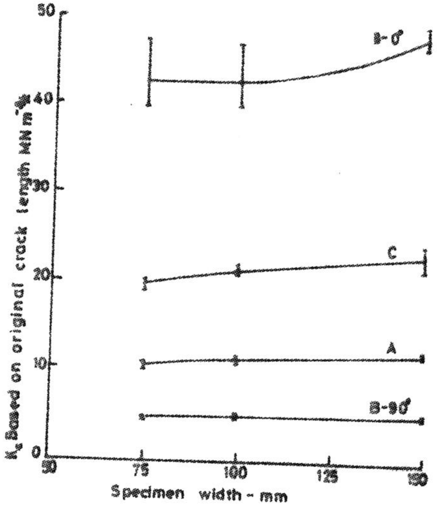


FIG. 1

Typical load vs displacement curves

FIG. 2

Variation of K_c based on the original crack length with specimen width



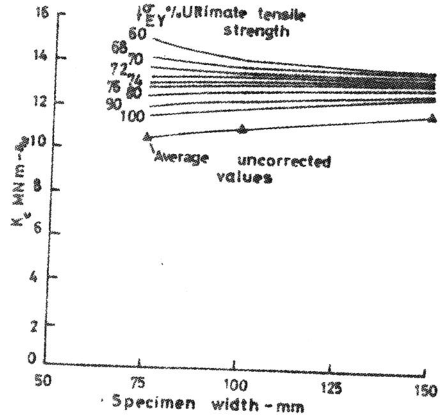


FIG. 3

The effect of the equivalent yield stress σ_{EY} on the correction to K_c for material A.