The Fracture Toughness of Glass Reinforced Plastics Containing Randomly Oriented Fibres

A. W. Holgsworth, S. Morris
ICI Ltd., Corp. Lab., Runcorn, Cheshire, England,
and M. J. Owen
Dept. of Mech. Eng., Univ. of Nottingham, England.

INTRODUCTION. The work described herein forms part of an investigation into the validity of conventional fracture toughness techniques when applied to glass reinforced plastics. An energy approach to fracture toughness which takes account of irrecoverable strain is compared with a stress-intensity approach; a modified stress intensity approach is then used to determine the effect of specimen size on fracture toughness.

EXPERIMENTS AND RESULTS. Specimens of the configuration shown in Fig.1 were cut from laminates prepared by hand lay-up from glass mat reinforcement consisting of 5 cm long 'E' glass strands held together with a PVA binder, and an orthophthalic polyester resin. Each specimen was loaded in tension at a constant displacement rate of 1.27 mm/min.

In the energy approach specimens were loaded to a level below the failure load and then unloaded. The material exhibited irrecoverable strain effects, and the recoverable elastic energy, U_R, was measured using a planimeter. The results were presented as U_R versus $(\text{load})^2$, P^2, for each initial crack length considered; specimens with initial cracks of length 2,3,4 and 5 cm were tested and a family of curves obtained. The recoverable elastic energy at catastrophic failure for each initial crack length was determined by extrapolating the straight line to a point corresponding to the failure load.

Balodis (1) has previously shown that for materials in which the amount of irrecoverable strain increases with increasing stress, that

$$G_c t = \left[\frac{dU_R}{d(2a_c)} - 2\frac{U_R}{P_c}\frac{dP_c}{d(2a_c)}\right] \qquad - 1$$

where c denotes the critical condition. Intense damage in the form of debonding and resin cracking occurred in the highly stressed crack tip regions during loading, thus increasing the effective crack length. The effective crack length at instability for each initial crack length was estimated from cine films taken during several tests and subsequently analysed frame by frame. Failure load and recoverable elastic energy at failure were plotted against critical crack length; the resulting values of crack extension force, G_c, calculated from equation 1 are shown in Table 1.

In the stress-intensity approach specimens were loaded up to failure and critical stress-intensity factor values, K_c, were calculated using Irwin's tangent formula (2), in which the initial crack length was substituted for a

$$K_c = \sigma_c \left(W \tan \frac{\pi a}{W}\right)^{\frac{1}{2}} \qquad - 2$$

where σ is the gross section stress. The average calculated K_c values shown in Table 2 illustrate the effect of initial crack length on fracture toughness. The K_c values shown in table 3 demonstrate the effect of specimen size on fracture toughness using similar specimens but with the width varied for a constant $2a_o$: W ratio of 0.3 and such that D:W ratio was always 2. In all tests taken to failure observations indicated that the nett remaining section at the onset of instability was not resin cracked.

<u>DISCUSSION</u>. It has been shown (2) that in linear elastic materials the crack extension force, G_c, can be related to the critical stress intensity factor, K_c, by the expression

$$K_c^2 = EG_c \text{ (plane stress)} \qquad - 3$$

where E is the initial Young's modulus. Equivalent values of K_c determined from the values of G_c using equation 3 are also shown in table 1. K_c values obtained in this way take into account irrecoverable work in the crack tip regions. Although the variation of K_c in table 2 is of the same form as the results shown in table 1 the former values are less than those calculated from energy considerations, because in calculating K_c in the stress intensity approach the irrecoverable damage in the highly stressed crack tip regions was not taken into account.

In the stress intensity approach the effect on fracture toughness of permanent damage at the crack tip may be estimated by adopting the approach used in metals, but using an equivalent yield stress, σ_{ys}. A plastic zone size can then be calculated from (3)

$$r_y = \frac{1}{2\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \qquad - 4$$

and a corrected value of fracture toughness, K'_c, calculated in an iteration procedure using equations 2 and 4 . The values of critical stress intensity factor K'_c shown in table 2 were calculated using the resin cracking stress as an equivalent yield stress and agree well with those shown in table 1, indicating that the resin cracking stress may be used to take into account irrecoverable damage at the crack tip. The resin cracking stress has been defined previously by Owen and Dukes (4).

Results showing the effect of specimen size are listed in table 3 and indicate that for these materials the fracture toughness decreases with increasing width to a constant value of 10 $MNm^{-3/2}$ at widths in excess of 20 cm. The results are consistent with visual observations of the volume of damaged material (irrecoverable energy) apparent on either side of the crack path which also decreases with increasing width. Catastrophic failure may therefore occur in wide plates at stress levels below those predicted from tests on small specimens.

CONCLUSIONS

1. Consistent values of K_c can be calculated by assuming an equivalent yield stress which accounts for irrecoverable damage at the crack tip.

2. Fracture toughness is dependent on design variables such as initial flaw size and specimen width.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of ICI Ltd.

REFERENCES

(1) BALODIS, V., Australian Jnl. Appl. Sci., 1963, 14, pp.284-304.

(2) IRWIN, G.R., Jnl. of Appl. Mechs., 1957, 24, pp.361-364.

(3) SRAWLEY, J.E. and BROWN, W.F., ASTM STP 381, p.152.

(4) OWEN, M.J. and DUKES, R., J. Strain Analysis 2, 272 (1967), pp.272-279.

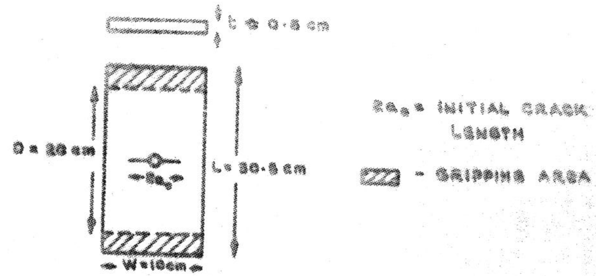

FIG.1. - TEST SPECIMEN CONFIGURATION

$2a_0$ cm	2	3	4	5
G_c 10^4 MNm^{-1}	1.746	1.946	2.278	1.488
K_c MNm$^{-3/2}$	12.03	12.70	13.74	10.89

TABLE I. - ENERGY MEASUREMENT RESULTS

$2a_0$ cm	2	3	4	5
K_c MNm$^{-3/2}$	8.81	9.49	9.78	8.91
K'_c MNm$^{-3/2}$	12.15	12.42	16.87	10.83

TABLE 2 - EFFECT OF INITIAL CRACK LENGTH ON K_c

W cm	10	15	20	25
K_c MNm$^{-3/2}$	9.49	9.02	8.62	9.18
K'_c MNm$^{-3/2}$	12.42	10.30	10.01	10.00

TABLE 3 - EFFECT OF SPECIMEN SIZE ON K_c