# Fracture toughness and crack - growth measurements in GRP

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Critical crack tip stress intensity factor ( $K_c$ ) measurements were made for polyester resin reinforced with glass chopped strand mat (CSM) and woven roving fabric (WRF). Specimen thickness and initial crack length were varied for centre notched (CN) 100 mm wide: specimens. Some specimens were saturated by immersion in water under pressure.  $K_{\rm c}$  was negligibly affected by specimen thickness and it was concluded that plane strain conditions are not achieved in laminates of normal thickness. Scatter can be reduced by adjusting results to a standard glass content and  $K_{\rm c}$  varies continuously with crack length. The CSM experiments were extended to 915 mm wide specimens which failed at very low nett section stresses but there may be a region in which  $K_{\rm e}$  is roughly constant relative to crack length. In WRF specimens, however, it is the nett section stress which is constant at a value substantially below the UTS. Fatigue crack-growth studies were carried out on CN specimens. The Paris law adequately describes crack growth in CSM specimens at low rates of growth but Forman's law is better at high rates of growth. Neither law is valid for WRF material when dry but the behaviour changes after saturation with water. The crackgrowth resistance of both materials is severely reduced by saturation with water.

## 1. Introduction

For both brittle and ductile materials, it is often possible to predict the failure of cracked components subjected to static or cyclic loads using the principles of fracture mechanics [1, 2]. In recent years there have been attempts to apply this growing body of work to glass-reinforced plastics (GRP). The aims of the work described here were to examine the problems associated with the application of linear elastic fracture mechanics to static and fatigue failure in GRP, both dry and after a period of immersion in water.

Table I summarizes the GRP fracture toughness results obtained by a number of investigators [3-15]. The parameters commonly measured are critical stress intensity factor,  $K_c$ , and critical strain energy release rate  $G_{\mathbf{c}}$ . It can be seen from Table I that these quantities are dependent on:

(1) glass content (glass content variation is indicated by different ultimate tensile strengths for similar materials);

(2) specimen type;

(3) specimen size;

(4) crack length;

(5) reinforcement type.

 $G_{\mathbf{c}}$  values determined by compliance methods differed from those calculated from  $K_c$  values unless they had been corrected to allow for crack tip damage [13] by adding a small amount to the crack length used to calculate  $K_{c}$ . This incremental crack length was either measured [3, 7], or Irwin's correction was applied [7, 9], i.e. by adding  $r_{\rm v}$  to the initial crack length, where

$$\mathbf{r}_{\mathbf{y}} = \frac{1}{c} \left( \frac{K}{\sigma_{\mathbf{y}}} \right)^2 \tag{1}$$

where  $c = \frac{1}{2}\pi$  for plane stress or  $\frac{1}{6}\pi$  for plane strain, and  $\sigma_{\mathbf{v}}$  is the yield stress. Since GRP do not yield, various stresses have been used for  $\sigma_{\rm v}$ , and attempts have been made to relate them to observed values, [9, 10, 13, 14]. Because corrections increased  $K_c$ values between 10 and 70%, for comparison purposes uncorrected values appear in Table I. Results taken from various sources [3, 5, 7, 9, 13] are plotted in Fig. 1.

Reductions in strength and stiffness of about \* Present address: National Coal Board, Mining Research and Development Establishment.

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Referential Matrix         U13         State         ESK         State	Randocontent         Matrix         UTS $S_{11}$ OR $S_{11}$ OR $S_{11}$ OR $S_{11}$									
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$ \begin{array}{  c   c   c   c   c   c   c   c   c   c$	[4] Unidirectional       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [1.26]       [1.27]       [1.27]       [1.26]       [1.27]       [1.26]       [1.27]       [1.26]       [1.27]       [1.26]       [1.27]       [1.26]       [1.27]       [1.26]       [1.27]       [1.26]       [1.26]       [1.26]       [1.26]       [1.26]       [1.26]       [1.26]       [1.27]       [1.26]       [1.26]       [1.26]       [1.27]       [1.26]       [1.27]       [1.26]       [1.27]       [1.27]       [1.27]       [1.27]       [1.27]       [									
	[4] Unidirectional     2.54     76.2     1.187     0.1751     2.54       FHTS     EPON 826/CL     2.54     76.2     1.187     0.1751     2.54       EHTS     ERL 2256/0820     2.54     76.2     1.209     0.2277     2.54       EHTS     ERL 2256/0820     2.54     76.2     1.209     0.0225     2.54       EHTS     ERL 2256/0820     2.54     76.2     0.9340     0.0252     2.54       FHTS     ERL 2256/0820     2.54     76.2     0.9340     0.0252     2.54       SHTS     EPON 826/CL     2.54     76.2     0.9340     0.0252     2.54       SHTS     ERV 826/CL     2.54     76.2     0.9340     0.0252     2.54       SHTS     EPON 826/CL     2.54     76.2     0.9340     0.0252     2.54       SHTS     EPON 826/CL     2.54     76.2     0.9340     0.0252     2.54       ShtTS     EPON 826/CL     2.54     76.2     0.9340     0.0252     2.54       ShtTS     EPON 826/CL     2.54     76.2     0.9340     0.0252     2.54       Chooped     PON 826/CL     2.54     76.2     0.935     1.36       Falas     Interes     0.1587     6.1.5 <td< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></td<>									
SHTS         EPON 826/CL         2.54         76.2         1.187         0.1751         2.54         38.1         1.70         0.2002           EHTS         ENL 226/0820         EHTS         ENL 226/0820         0.2277         254         38.1         1.67         0.2002           EHTS         ENL 226/0820         EHTS         ENL 226/0820         38.1         1.70         0.2002           EHTS         ENL 226/0820         2.54         76.2         1.0940         0.052         2.54         38.1         1.67         0.2002           EHTS         ENL 226/0820         2.54         76.2         0.9940         0.052         2.54         38.1         1.70         0.2002           SHT         EPON 82//MABA         7.6.2         1.74         0.524         38.1         1.67         0.894           Atage         0.1587         6.91         76.2         1.74         0.524         38.1         1.62         0.696           Atage         6.1         76.2         1.74         0.524         38.1         1.62         0.696           Atage         6.1         1.75         0.693         7.62         1.74         0.549         1.61         1.61           <	SHTS       EPON 826/CL       2.34       76.2       1.187       0.1751       2.54         EHTS       ERL 2256/0820       2.54       76.2       1.439       0.2277       2.54         EHTS       ERL 2256/0820       2.54       76.2       1.293       0.1926       2.54         EHTS       ERL 2556/0820       2.54       76.2       0.9340       0.0925       2.54         SHTS       ERL 2556/0820       2.54       76.2       0.9340       0.0325       2.54         SHTS       ERL 2556/0820       2.54       76.2       0.9340       0.0325       2.54         SHTS       EPON 826/L       2.54       76.2       0.9340       0.0325       2.54         SHTS       EPON 826/MAB       2.54       76.2       0.9340       0.0325       2.54         SHTS       EPON 826/MAB       2.54       76.2       1.374       0.529       2.54         Shitse       PON 826/MAB       2.54       76.2       1.374       0.520       0.593       2.54         Shitse       PON 826/MAB       0.1587       2.54       76.2       1.374       0.520       2.54         Grobed       Felast       I.125       2.50       2.50									[
EHTSERL 2256/002EHTSERL 2256/002EHTSERL 2256/002EHTSERL 2256/002EHTSERL 2256/0020EHTSERL 2256/002022772.930.01562.8438.11.4720.2802EHTSERU 2556/0020EHTSERU 2556/00200.05552.5438.11.4720.0205FHTSERU 2556/0020ERU 2556/00200.05552.5438.11.4720.0205FHTSERU 2556/0020ERU 2556/00200.05552.5438.11.6760.075FHTSERU 2556/0020ERU 2556/00200.05552.5438.11.6760.075FHTSERU 2556/0020ERU 25500.05552.5438.11.6760.075FHTSERU 2556/0020ERU 25500.05552.5438.11.6260.4904FHTSERU 25500.05552.5438.11.6260.49041.51.6FHTSERU 25500.15670.21752.6438.11.6260.49041.51.6FHTSERU 25500.15871.260.2571.6741.51.0010.010.016.0Felters0.15875.000.2175.001.6741.51.0010.016.0Felters0.15866.135.100.2771.6741.51.0010.016.0Felters0.15866.135.100.2771.6741.51.0010.016.0Felters0.	E-HTS       EN12256/0520       2.54       762       1.439       0.2277       2.54         E-HTS       EPON 88/CL       2.54       76.2       1.439       0.0217       2.54         E-HTS       EPON 88/CL       2.54       76.2       1.439       0.0217       2.54         FHTS       EPON 82/CL       2.54       76.2       1.209       0.1926       2.54         S-HTS       EPON 82/CL       2.54       76.2       0.9340       0.0525       2.54         S-HTS       EPON 82/MABA       2.54       76.2       1.39       0.0215       2.54         S-HTS       EPON 82/MABA       2.54       76.2       1.39       0.2277       2.54         S-HTS       EPON 82/MABA       2.54       76.2       1.34       0.5249       2.54         S-HTS       EPON 82/MABA       2.54       76.2       1.34       0.5249       2.54         S-HTS       EPON 82/MABA       0.1587       C.1.54       76.2       1.34       0.5249       2.54         S-HTS       EPON 82/MABA       0.1587       C.1.54       76.2       1.34       0.5249       2.54         S-HTS       EPON 82/MABA       0.1587       G.1.5       2.50	5.AT 76.3	1 1 8 7	01751 754	301 136	01576				
EHTS       EPON 826/CL         EHTS       EPON 826/CL         SHTS       FEU 2256/0820         SHTS       FEON 836/CL         SHT       ST         SHT	EHTS       EPON 826/CL $2.54$ $7.62$ $1.209$ $0.1926$ $2.54$ EHTS       ERL 255(0820) $2.54$ $76.2$ $1.209$ $0.0255$ $2.54$ FHTS       ERL 255(0820) $2.56$ $76.2$ $1.209$ $0.0255$ $2.54$ SHTS       EPON 826/CL $2.54$ $76.2$ $1.209$ $0.0255$ $2.54$ SHTS       EPON 826/MABA $2.54$ $76.2$ $1.374$ $0.2249$ $2.54$ SHTS       EPON 826/MABA $2.54$ $76.2$ $1.374$ $0.5249$ $2.54$ SH1S       EPON 826/MABA $2.54$ $76.2$ $1.374$ $0.5249$ $2.54$ (5)       Random       Polyester $0.1587$ $6.13$ $7.62$ $6.93$ $7.62$ (5)       Random       Polyester $0.1587$ $6.13$ $5.25$ $2.54$ (5)       Random       Polyester $0.1587$ $6.93$ $7.62$ $6.93$ $7.62$ (5)       Random       Polyester $0.1587$ $6.93$ $7.62$ $6.93$ $7.62$ $6.9$	10/ 10/ 10/ 10/ 10/ 10/ 10/ 10/ 10/ 10/	1 420	+C'7 IC/I'0	046.1 1.00	0/CI-0 0				
EHTS       ERL 2256/0820       2.54       76.2       0.2951       5.31       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       1.112       0.0225       2.54       38.1       0.112       1.0 <td>EHTS     ERL 2256/0820     2.54     76.2     0.9340     0.0225     2.54       SHTS     EPON 826/CL     0.1587     0.0254     0.0255     2.54       SHTS     EPON 826/CL     0.1587     0.0255     2.54     0.0255     2.54       SHTS     EPON 826/CL     0.1587     0.1587     0.0255     2.54     0.0255     2.54       SHTS     EPON 826/MABA     2.54     76.2     1.374     0.525     2.54       SHTS     EPON 826/MABA     0.1587     0.1587     0.550     9.68     14.86       Chopped     Felose     G1.5     2.50     250     9.58     14.86       Felose     G1.5     2.50     2.50     9.68     14.86       Totoped     Felose     G1.5     2.50     2.50     9.33       Totoped     S.5     2.50     2.50     9.33     3.06       Totes     S.5     2.50     2.50     9.33     3.06       Upress     G1.5     2.55     2.50     9.33     3.06       Upress     G1.5     2.55     2.50     9.39     3.06       Upress     S.5     2.50     2.50     5.88     3.06       Upress     S.50     2.50     6.93     3.06<td>54 76.7</td><td>1 200</td><td>0 1976 7 54</td><td>38.1 1.070</td><td>0.2017</td><td></td><td></td><td></td><td></td></td>	EHTS     ERL 2256/0820     2.54     76.2     0.9340     0.0225     2.54       SHTS     EPON 826/CL     0.1587     0.0254     0.0255     2.54       SHTS     EPON 826/CL     0.1587     0.0255     2.54     0.0255     2.54       SHTS     EPON 826/CL     0.1587     0.1587     0.0255     2.54     0.0255     2.54       SHTS     EPON 826/MABA     2.54     76.2     1.374     0.525     2.54       SHTS     EPON 826/MABA     0.1587     0.1587     0.550     9.68     14.86       Chopped     Felose     G1.5     2.50     250     9.58     14.86       Felose     G1.5     2.50     2.50     9.68     14.86       Totoped     Felose     G1.5     2.50     2.50     9.33       Totoped     S.5     2.50     2.50     9.33     3.06       Totes     S.5     2.50     2.50     9.33     3.06       Upress     G1.5     2.55     2.50     9.33     3.06       Upress     G1.5     2.55     2.50     9.39     3.06       Upress     S.5     2.50     2.50     5.88     3.06       Upress     S.50     2.50     6.93     3.06 <td>54 76.7</td> <td>1 200</td> <td>0 1976 7 54</td> <td>38.1 1.070</td> <td>0.2017</td> <td></td> <td></td> <td></td> <td></td>	54 76.7	1 200	0 1976 7 54	38.1 1.070	0.2017				
SHTS       EPON 826/CL       2.36       76.2       0.2367       3.81       0.3316       0.0376         SHTS       (B-suget)       2.4       76.2       1.74       0.5297       3.81       1.616       0.0976         SHTS       (B-suget)       3.81       1.616       0.4904       1.61       1.61       1.61         B-suget)       3.1       1.616       0.4904       3.81       1.610       0.01       1.1       1.61         B-suget)       3.1       1.616       0.729       2.54       3.81       1.616       1.61         B-suget)       3.1       1.616       0.724       3.81       1.616       0.4904       1.61         chopped       61       2.50       6.93       7.62       1.674       1.5       1.00       1.00       1.0         Felass       0.1587       0.1587       0.51       1.674       1.5       1.67       1.67         Berlon       Polyser       0.1587       0.127       16.74       1.5       1.6       1.00       1.00       1.01       1.61         fot       Berlon       Polyser       0.127       16.74       5.80       1.69       1.61       1.61       1.61	S-HTS         EPON 826/CL         2.3d         76.2         0.2367         0.0525         2.34           B-staged)         B-staged)         2.3d         76.2         0.2967         0.0525         2.34           S-HTS         EPON 826/MAIA         2.3d         76.2         0.374         2.54         2.54           S-HTS         EPON 826/MAIA         2.3d         76.2         1.74         0.3249         2.54           S-HTS         EPON 826/MAIA         0.1587         0.15         76.2         1.74         0.3249         2.54           Felas         Elass         G1.5         2.50         5.69         1.4.86         5.74           Ubbed         Polyester         0.1587         0.1587         0.127         16.74         5.74           Ubbed         Sis         2.50         25.0         9.38         1.386         5.64         3.36           Ubbes         Grifters         3.5         2.52         2.53         0.33         3.06         5.86         5.86           Felass         Grifters         3.55         2.50         9.33         3.06         5.88         5.86         5.86         5.86         5.86         5.86         5.86         5.	54 76.2	0.9340	0.0525 2.54	38.1 1.132	0.0575				
Betward         Betward <t< td=""><td>(B-11aget)         (B-11aget)           SHTS         EPON 826/MABA         2,34         76.2         1,374         0,3249         2,54           SHTS         EPON 826/MABA         0,1587         0,1587         6,93         7,62         1,374         0,3249         2,54           Isinom         Polyester         0,1587         0,1587         6,15         1,25         25.0         6,93         7,62           Explored         CIL:         2,37         2,56         10,37         16,74         16,74           Explass         GIL:         5,00         2,50         9,33         13,86         3,16           Creters         Greters         3,5         1,25         2,50         9,33         13,86           Operations         3,5         1,25         2,50         9,33         13,86         3,96           Operations         3,5         1,25         2,50         6,04         5,80         5,80         5,80         5,86         5,80         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86</td><td>54 76.2</td><td>0.2967</td><td>0.0525 2.54</td><td>38.1 0.351</td><td>6 0.0876</td><td></td><td></td><td></td><td></td></t<>	(B-11aget)         (B-11aget)           SHTS         EPON 826/MABA         2,34         76.2         1,374         0,3249         2,54           SHTS         EPON 826/MABA         0,1587         0,1587         6,93         7,62         1,374         0,3249         2,54           Isinom         Polyester         0,1587         0,1587         6,15         1,25         25.0         6,93         7,62           Explored         CIL:         2,37         2,56         10,37         16,74         16,74           Explass         GIL:         5,00         2,50         9,33         13,86         3,16           Creters         Greters         3,5         1,25         2,50         9,33         13,86           Operations         3,5         1,25         2,50         9,33         13,86         3,96           Operations         3,5         1,25         2,50         6,04         5,80         5,80         5,80         5,86         5,80         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86         5,86	54 76.2	0.2967	0.0525 2.54	38.1 0.351	6 0.0876				
SHTS         EPON 826/MABA         2.34         76.2         1.374         0.3249         2.54         38.1         1.6.26         0.4904           [5]         Random         Polvester         0.1587         G1.5         1.23         25.0         9.93         7.62         1.5         1.05         1.00         10.1         16.2           Random         Polvester         0.1587         G1.5         1.25         25.0         9.03         14.86         1.5         1.05         10.00         19.1         16.2           Replace         0.1587         G1.5         2.50         25.0         9.35         14.86         1.5         1.05         10.00         9.4         14.0           Felass         G1.5         5.50         6.33         7.65         9.35         13.66         9.5         15.6	SHTS         EPON 826/MABA         2.54         76.2         1.374         0.5249         2.54           [5]         Random         Polyester         0.1587         G.1.5         1.25         25.0         6.93         7.62         5.48           [5]         Random         Polyester         0.1587         G.1.5         1.75         25.0         6.93         7.62         5.48           [5]         Reales         G.1.5         3.75         2.50         9.35         9.36         1.486           [6]         G.1.5         3.75         2.50         9.35         13.66         9.35         13.66           [hbres         G.1.5         3.75         2.50         9.35         13.66         9.36           [hbres         G.1.5         3.75         2.50         9.35         13.66         9.36           [hbres         G.1.5         3.75         2.50         6.39         3.06         9.06         5.80         9.06         5.80           for effens         S.00         2.50         6.04         5.80         9.06         5.80         5.80         5.80         5.80         5.80         5.80         5.80         5.80         5.80         5.80									
$ \begin{bmatrix} 5 \end{bmatrix} \text{ Random Polyester} & 0.1587 & 0.1587 & 0.1587 & 0.1587 & 0.1587 & 0.010 & 101 & 16.2 \\ \text{topped} & \text{topped} & 1.5 & 1.05 & 10.00 & 100 & 100 & 16.0 \\ \text{Eglass} & 0.00 & 0.0127 & 16.74 & 1.5 & 1.3 & 1.30 & 10.00 & 100 & 16.0 \\ \text{Eglass} & 0.125 & 0.250 & 0.35 & 10.27 & 16.74 & 1.5 & 1.30 & 10.00 & 9.9 & 15.4 \\ \text{G1.5 } & 3.0 & 2.50 & 2.50 & 2.50 & 2.51 & 0.32 & 1.36 & 3.5 & 2.90 & 10.00 & 9.9 & 15.4 \\ \text{G1.5 } & 3.5 & 1.25 & 2.50 & 4.39 & 3.06 & 3.5 & 4.80 & 10.00 & 9.9 & 15.4 \\ \text{G1.5 } & 3.5 & 2.50 & 6.04 & 5.80 & 3.5 & 1.30 & 10.00 & 9.9 & 15.4 \\ \text{G1.6 } & 3.5 & 2.50 & 6.04 & 5.80 & 3.5 & 2.90 & 10.00 & 9.9 & 15.4 \\ \text{G1.6 } & 3.5 & 2.50 & 6.04 & 5.80 & 0.00 & 7.9 & 10.00 & 9.9 & 15.4 \\ \text{G1.6 } & 3.5 & 2.50 & 6.04 & 5.80 & 0.00 & 7.9 & 10.00 & 9.9 & 15.4 \\ \text{G1.6 } & 3.5 & 2.50 & 6.58 & 6.88 & 1.5 & 1.00 & 10.00 & 9.1 & 14.0 \\ \text{S1.6 } & 4.86 & 6.88 & 1.5 & 0.30 & 10.00 & 7.9 & 10.04 \\ \text{S1.6 } & 4.36 & 5.50 & 5.50 & 5.50 & 5.50 & 5.50 & 5.50 & 5.6 & 5.8 & 5.80 \\ \text{S1.6 } & 4.36 & 5.80 & 5.80 & 5.80 & 5.80 & 5.80 & 0.00 & 7.9 & 10.04 \\ \text{S1.6 } & 4.36 & 5.80 & 5.70 & 5.50 & 5$	[5] Random         Polyester         0.1587         0.1587         C         1.25         2.50         6.91         7.62           Expoped         Equas         61.5         2.50         25.0         6.93         7.62           Exposed         61.5         2.57         25.0         0.33         14.86           Explass         61.5         2.75         25.0         0.32         16.74           Ibres         61.5         2.75         25.0         0.32         15.86           Grefers         3.5         1.25         25.0         0.33         3.06           Crefers         3.5         2.75         25.0         6.93         3.06           orgrowed         3.5         2.75         25.0         6.88         88           specimens         3.5         3.75         25.0         6.41         6.52	54 76.2	1.374	0.5249 2.54	38.1 1.626	0.4904				
ClippedClips2.505.509.6814.861.53.0510.009.414.0EglassEglass1.53.752.5010.2716.741.53.51.009.915.4Erglass1.53.755.500.259.3510.2716.741.53.51.3010.009.915.4Erglass1.53.755.501.2716.743.52.9010.009.915.4Erglass3.51.272.504.933.063.52.9010.009.915.4S3.52.506.045.802.506.045.803.52.9010.009.915.4S3.52.506.045.805.805.805.805.905.709.915.4S3.52.506.045.805.805.805.805.901.51.009.915.4S3.52.506.045.805.805.805.905.701.51.009.91.11.04S3.52.506.045.805.705.905.705.905.701.51.009.91.11.04S3.55.002.505.506.045.805.905.701.51.009.91.11.04S5.505.505.505.505.505.505.905.705.901.00	Epiloped         G1.5         2.50         25.0         9.68         14.86           Epilos         G1.5         3.75         5.00         10.27         16.74           Ibres         G1.5         3.75         5.00         25.0         9.38           Ibres         G1.5         2.75         25.0         9.33         13.86           Ibres         G1.5         2.50         2.50         9.30         3.06           to growed         3.5         1.25         2.50         4.39         3.06           to growed         3.5         2.75         2.50         6.04         5.80           specimens         3.5         3.75         2.50         6.58         6.88	5 1.25 25.0	6.93	7.62		-	.5 1.05	10.00	10.1	16.2
	Eglas         G1.5         3.75         25.0         10.27         16.74           fibres         G1.5         5.00         25.0         3.5         13.86           fibres         G1.5         5.00         25.0         4.39         3.06           or refers         3.5         1.25         25.0         6.04         5.80           operimens         3.5         2.75         5.50         6.08         5.80           specimens         3.5         5.00         25.0         6.04         5.80	5 2.50 25.0	9.68	14.86		Г	.5 3.05	10.00	9.4	14.0
Tittes     G1.5     5.00     25.0     9.35     13.86     3.5     1.30     10.00     9.9     15.6       3.5     1.25     5.30     5.41     5.00     9.4     14.0       3.5     2.50     6.58     6.58     6.88     1.5     1.00     10.0     7.1     10.0       3.5     5.20     5.30     6.43     6.68     1.5     1.5     1.00     10.0     7.1     10.0       3.5     5.20     5.30     6.43     6.52     1.5     4.40     10.00     7.1     10.0       3.5     5.20     5.70     5.90     5.70     5.70     5.70     5.70     10.00     7.1     10.0       1.5     4.33     25.0     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70     5.70 </td <td>Tibres         G 1.5         5.00         2.50         9.35         13.86           G refers         3.5         1.25         25.0         6.04         5.80           to grooved         3.5         2.50         6.04         5.80           specimens         3.5         5.00         25.0         6.41         6.638           specimens         3.5         5.00         25.0         6.41         6.52</td> <td>5 3.75 25.0</td> <td>10.27</td> <td>16.74</td> <td></td> <td>1</td> <td>.5 4.80</td> <td>10.00</td> <td>10.0</td> <td>16.0</td>	Tibres         G 1.5         5.00         2.50         9.35         13.86           G refers         3.5         1.25         25.0         6.04         5.80           to grooved         3.5         2.50         6.04         5.80           specimens         3.5         5.00         25.0         6.41         6.638           specimens         3.5         5.00         25.0         6.41         6.52	5 3.75 25.0	10.27	16.74		1	.5 4.80	10.00	10.0	16.0
G refers     3.5     1.25     2.50     4.39     3.06     3.5     2.90     10.00     9.9     15.6       D oproved     3.5     2.50     6.04     5.80     5.80     3.5     4.85     10.00     9.4     14.0       D oproved     3.5     2.50     6.04     5.80     5.80     1.5     1.00     10.00     9.4     14.0       3.5     5.00     2.50     6.51     6.58     1.5     1.00     10.00     9.1     10.4       3.5     5.00     2.50     5.56     5.64     5.88     1.5     1.00     10.00     9.1     14.0       3.5     5.00     2.50     5.57     5.59     4.96     1.5     1.00     10.00     7.9     10.0       3.5     4.36     5.50     5.50     5.99     5.70     5.10     10.00     7.9     10.0       1.5     4.38     2.50     5.9     5.70     5.70     5.7     1.5     1.4.0       1.5     4.38     2.50     8.15     10.55     5.7     3.5     1.00     10.00     7.9     10.0       1.5     4.38     2.50     8.15     10.55     3.5     1.4.0     3.5     1.000     7.9     10.0	G refers         3.5         1.25         25.0         4.39         3.06           to grooved         3.5         2.50         2.50         6.04         5.80           specimens         3.5         3.75         2.50         6.58         6.88           specimens         3.5         3.06         5.41         6.52	5.00 25.0	9.35	13.86			5 1.30	10.00	6.6	15.4
to grooved     3.5     2.50     5.50     6.04     5.80     3.5     4.65     100     9.4     14.0       specimens     3.5     3.75     5.50     6.58     6.88     1.5     1.00     1000     8.1     10.4       3.5     5.70     5.50     6.54     6.58     6.88     1.5     1.00     1000     7.9     10.0       3.5     5.70     5.50     6.41     6.52     1.5     1.00     10.00     7.9     10.0       3.5     6.25     5.41     6.52     5.41     6.52     1.5     4.80     10.00     7.9     10.0       3.5     6.25     5.70     5.9     4.96     5.70     5.1     1.5     4.80     10.00     7.9     10.0       1.5     4.38     25.0     8.15     10.55     3.5     1.30     10.00     7.8     9.8       1.5     3.95     25.0     8.15     10.55     3.5     1.4.0     10.00     7.8     9.8       1.5     3.95     25.0     8.15     10.55     3.5     10.00     7.9     9.0       1.5     3.95     25.0     8.15     10.55     3.5     4.80     10.00     7.9     9.0       1.5	to grooved 3.5 2.50 5.04 5.80 3.5 3.75 25.0 6.04 5.80 3.5 specimens 3.5 5.00 6.58 6.88 3.5 5.00 25.0 6.41 6.52	1 25 25.0	4 30	3.06			5 2.90	10.00	0 0	15.6
specimens         3.5         3.75         2.50         6.28         6.88         1.5         1.00         100         8.1         10.4           3.5         5.00         25.0         6.41         6.52         1.5         0.30         10.00         8.1         10.4           3.5         5.00         25.0         6.41         6.52         1.5         0.30         10.00         9.1         14.0           3.5         6.22         25.0         8.15         10.55         3.5         10.00         7.9         10.0           1.5         4.38         25.0         8.15         10.55         3.5         10.00         7.9         14.0           1.5         3.95         25.0         8.15         10.55         3.5         10.00         7.9         9.8           1.5         3.95         25.0         8.15         10.55         3.5         10.00         7.9         9.8           1.5         3.95         25.0         8.15         10.55         3.5         10.00         7.9         9.8           1.5         3.95         25.0         8.15         10.55         3.5         4.00         10.00         7.9         9.0	specimens 3.5 3.75 25.0 6.58 6.88 3.5 5.00 25.0 6.41 6.52	5 2.50 25.0	6.04	5.80			5 4.85	10.00	94	14.0
3.5     5.00     2.50     6.10     5.00     1.5     0.30     1.00     0.00     7.9     1.00       3.5     5.00     2.50     5.59     4.96     1.5     1.60     7.9     10.0       1.5     4.38     25.0     8.15     10.55     3.5     1.00     7.9     10.0       1.5     4.38     25.0     8.15     10.55     3.5     1.00     7.9     10.0       1.5     4.38     25.0     8.15     10.55     3.5     1.00     7.9     10.0       1.5     3.98     25.0     8.15     10.55     3.5     10.00     7.9     10.0       1.5     3.98     25.0     8.15     10.55     3.5     4.80     10.00     7.9     10.0	3.5 5.00 25.0 6.41 6.52	1 1 75 250	6 5 8	88 4		. –	1 00	10.00	18	10.4
3.5     6.25     5.30     6.96     1.5     4.80     10.00     9.1     14.0       1.5     4.38     25.0     5.99     5.70     5.9     5.70     3.5     1.30     10.00     7.8     9.8       1.5     4.38     25.0     8.15     10.55     3.9     5.70     3.5     10.00     7.8     9.8       1.5     3.95     25.0     8.15     10.55     3.5     10.00     7.9     10.0       1.5     3.95     25.0     8.15     10.55     3.5     4.80     10.00     7.9     10.0		5 00 250	641	6.53				10.01	1.0	10.01
1.5 0.25 0.59 5.70 1.0.55 1.2 1.20 1.0.00 7.8 1.9.0 1.5 4.38 2.5.0 8.15 10.55 3.5 0.29 10.00 7.8 9.8 1.5 3.95 2.5.0 8.15 10.55 3.5 0.29 10.00 7.9 10.0 3.5 4.80 10.00 7.1 8.0		0.02 00.0		7 00			0.00	0001		
1.5 3.95 25.0 8.15 10.55 3.5 2.29 0.00 7.9 2.00 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0		0.22 0.20 050	00 4			- (*		10.00	1.1	
		3.95 25.0	8.15	10.55		<b>۲</b>	5 0.79	10.00	0.1	10.0
						1.60	5 4.80	10.00	7.1	8.0

$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	7.62       31.7       23.7.8         0.0363       3.17       27.07         6.35       3.81       43.29         6.73       3.81       44.17         9.52       3.81       44.17         9.53       3.81       44.17         9.53       3.81       44.17         9.53       3.81       44.17         9.53       3.81       44.32         9.53       3.81       44.32         9.53       3.81       43.29         9.53       3.81       43.29         9.65       3.81       43.29         9.65       3.81       43.29         9.65       3.81       43.29         9.65       3.60       8.1.32         6.55       3.61       49.89         6.55       3.66       8.1.32	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	1.78 2.29 254 6.96 1.78 2.79 254 8.06 1.78 3.56 254 8.42 1.78 3.56 254 8.42 1.78 3.56 254 8.48
0.0363			

	Reinforcemen	ıt Matrix	UTS	S <sub>11</sub>	CN				DEN				SEN			BEN	Q			
			(MPa)	(GPa <sup>-1</sup> )	t (mm)	a W (mm) (m	$K_c$ m) (MPam <sup><math>\nu</math></sup>	<sup>2</sup> ) (kJ m <sup>-2</sup> )	r (mm)	1) (mm)	/ K	$G_{c}^{e}$ $G_{c}^{e}$ (kJ m <sup>-2</sup> )	t a (mm) (mm)	W (mm)	K <sub>c</sub> G <sub>c</sub> (MPam <sup>1/2</sup> ) (KJ	п <sup>-2</sup> ) (тп	a () (mm)	M (um)	K <sub>e</sub> MPa m <sup>1/2</sup> )	G <sub>e</sub> (kJ m <sup>-2</sup> )
[6]	A Supremat E-glass CSM 3-plies	Polyester	137.0	0.101					3.2 3.2 4.54	12.50 16.67 1 25.00 1	75.0 10 00.0 11 50.0 11	0.47 1.08 1.80 1.80							-	
	Tyglass Y221 E-glass A1100 Silane finish 9-plies	Polycster							2											
	B - 0°		402.0	0.0354					2.79	12.50 16.67 1	75.0 42	2.44 2.44								
	B - 0°		52.4	0.0894					2.79 2.79 2.79	12.50 12.50 16.67 1 25.00 1	20.00 75.0 4 200.0 4 4 4 20.0 4 4 4 20.0 20 20 20 20 20 20 20 20 20 20 20 20 20	1,73 1,73 1,73								
	C Tyglass Y449 Silane finish 7-plies	Polyester	229.0	0.0487					3.09 3.09 3.09	100.00 0 12.50 16.67 1 25.00 1	75.0 19 75.0 19 50.0 22	1,51 2,60 2,70								
[10]	None	Polyester	52.9 52.9	0.2597	1.25	12.7 76	5.2 0.825 .2 0.699													
	CSM FGE 200 E-elass 1 nfv	Polyester	78.9		1.25	12.7 76	5.2 9.61													
	Tyglass Y227 E-glass 1 ply	Polyester	255.4		1.25	12.7 76	5.2 13.63													
[ <u></u> ]	CSM Supremat 6-plies	t Polyester	85.0	0.1205	5.8 5.8 5.8	10.0 10( 15.0 10( 20.0 10( 25.0 100	0.0	20.65 19.61 17.79 17.20												
[12]	M(CSM) + R(WRF 779- style) as M/R/M/R/M	Polyester		0.0545									5.49 Various	114.3	19.30					
[13]	CSM	Polyester	85.0	0.1205	5.8 5.8	10.0 100 15.0 100	0.0 8.81		5.8	10.0 1 15.0 1	00.0 8 00.0 8.	139				6.0 6.0	30.0 40.0	150.0 200.0	5.64 6.63	
					5.8 5.8	20.0 100 25.0 100	0.0 9.78 1.0 8.91		5.8 5.8	20.0 1 25.0 1	0.00 9.0	866 1.98				6.0	50.0	250.0	6.64	
					8.8.5 8.8.8	15.0 100 22.5 150 30.0 200	0.0 9.43 0.0 8.98 0 8.60		5.8 5.8	15.0 1	00.0 8	1.12								
					5.8	37.5 250 90.0 600	0 10.66		5.8	37.5 2	50.0 10	0.04								
	CSM	Urethane	67.7	0.0599												6.0 6.0	30.0 40.0 50.0	150.0 200.0 250.0	5.63 6.21 6.24	

Reinforcement Matrix         UTS         S1, (MPa)         CB         DEN         EBND         EBND         EBND         EBND         Component         MID         CBP-1         Component         MID         Cap         MID         Cap         MID         <	TABLE I (Continued)																		
	Reinforcement Matrix	UTS	S.,,	CN			DEN					SEN			BEN	ρ			
		(MPa)	(GPa <sup>-1</sup> )	r (mm)	a W (mm) (mm)	К <sub>е</sub> (МРа т <sup>и 2</sup> )	G <sub>c</sub> t (kJ m <sup>-2</sup> ) (mm)	a (mm)	M M	Ke (MPa m <sup>17</sup>	Ge (kJ m <sup>-2</sup> )	t a (mm) (mr	(mm) ()	$K_{c}$ $G_{c}$ $(MPam^{1/2})$ $(kJ_{1})$	n <sup>-2</sup> ) (mm	a (mm)	(mm)	γ <sub>e</sub> (MPa m <sup>1/2</sup> )	Ge (kJm <sup>-2</sup> )
V449 $3.6$ $1.000$ $11.720$ $3.6$ $2.00$ $10000$ $11.720$ $3.6$ $2.00$ $1000$ $17.20$ $3.6$ $2.00$ $1000$ $17.20$ $3.6$ $3.00$ $13.09$ $3.6$ $3.00$ $13.90$ $3.6$ $3.00$ $13.90$ $3.6$ $3.00$ $13.90$ $3.6$ $3.00$ $13.90$ $3.6$ $3.00$ $13.90$ $3.6$ $3.00$ $13.90$ $3.6$ $3.00$ $23.00$ $13.16$ $3.00$ $13.00$ $17.90$ $3.16$ $3.7.5$ $3.00$ $23.00$ $3.16$ $3.7.6$ $3.00$ $23.00$ $3.16$ $3.7.6$ $3.00$ $23.00$ $3.17.6$ $3.00$ $23.00$ $3.17.6$ $3.00$	Tyglass Polyester	202.3	0.1880	3.6	10.0 100.0	17.14	3.6	10.0	100.0	16.10									
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Y 44 Y			9.6 3.6	20.0 100.0	17.29	3.6 3.6	20.0	100.0	18.88									
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $				3.6	25.0 100.0	16.91	3.6	25.0	100.0	17.88									
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $				3.6	15.0 100.0	17.72	3.6	15.0	100.0	17.90									
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				3.6	22.5 150.0	19.86	3.6								3.6	30.0	150.0	13.99	
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				3.6	30.0 200.0	20.33	3.6								3.6	40.0	200.0	15.14	
				3.6	37.5 250.0	21.58	3.6	37.5	250.0	23.14					3.6	50.0	250.0	17.76	
[15] Unidirectional Epoxy     1295     3.10     12.7     25.4     14.4       Nomenclature     S1, Minimum normal material compliance     S1, Minimum normal material compliance     S1, Minimum normal material compliance       DEN Dubble edge-notes preciments     r     Speciment thickness     S1, Minimum normal material compliance       DEN Dubble edge-notes preciments     r     Speciment thickness     Concord speciments       DEN Dubble edge-notes preciments     r     Speciment thickness       Den So at a point band speciments     Wintimate tensile strength     Ke       Ultimate tensile strength     Ke     Uncorrected critical stress intensity factor (Mode I)	[14] CSM Epoxy 3 plies	160										3.18 5.0	8 25.4	13.42					
Nomenclature S <sub>11</sub> Minimum normal material compliance CN Centre notch specimens S <sub>11</sub> Minimum normal material compliance DEN Double dege-notch specimens a Catel length (nalf crack length in CN specimens) Bend 3 or 4-point bend specimens w Specimens with K <sub>c</sub> Uncorrected critical stress intensity factor (Mode I)	[15] Unidirectional Epoxy	1295										3.10 12.7	25.4	14.4					
	Nomenclature CN Centre notch specimens DEN Double edge-notch specimens SEN Single edge-notch specimens Bend 3 or 4-point bend specimens UTS Ultimate tensile strength	N. K. B. L. S.	Minimum n Specimen th Crack lengtl Specimen w Uncorrected	ormal mat hickness h (half cra idth	erial complianc ck length in CN ress intensity fi	e specimens) actor (Mode I)				- - -									

CSM Chopped strand mat  $G_{c}$  Critical strain energy release rate G Suffix in thickness column indicates grooved specimens  $K_{c}$  suffix in thickness column indicates grooved specimens  $K_{c}$  are uncorrected values, calculated by the author where not given in the reference. Corrected values are discussed in the text (Section 2.3).

10% have been recorded in GRP immersed for long periods in water at room temperature [16, 17]. The ability of filament-wound GRP to maintain its stiffness when subjected to cyclic loading under water has been shown to depend on the strength of the glass—resin bond [18].

The Paris crack-propagation law [19] has been applied to several types of composite materials [20-23]. Values of A and m in the equation

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A(\Delta K)^m \tag{2}$$

have been determined for some GRP up to 20000 cycles [23].

The main conclusions to be drawn from the survey are as follows:

(1) many of the published results have been derived from small specimens;

(2) the correlation between  $G_{c}$  and  $K_{c}$  results is poor;

(3) for some materials, e.g. chopped strand mat reinforced polyester resin, there seems to be a marked size effect which could suggest the relevance of fracture mechanics concepts;

(4) the conditions for valid fracture toughness testing of GRP have not yet been established.

## 2. Materials and test methods

The materials examined in the present work were (i) polyester resin reinforced with chopped strand mat (CSM/PR), and (ii) polyester resin reinforced with woven roving fabric (WRF/PR). The details are given in Table II. Laminates were laid up by hand, then left for 3 days at room temperature before post-curing for 3 days at  $40^{\circ}$  C, and then cut into specimens with a diamond-impregnated slitting wheel. The strength and stiffness properties of the materials were determined using the tensile and plate twist specimens shown in Fig. 2 and are summarised in Table III.

Glass content by weight was determined by burning the resin from weighed samples cut from test specimens in a muffle furnace, then weighing the remaining glass. Using the least squares method, straight lines were fitted to plots of strength, stiffness, and fracture toughness versus glass content. This adequately described the variation of these properties over the range of glass content encountered in the work.

To simulate the effect of several years immersion in water, specimens were conditioned in tap water at ambient temperature under a pressure of 6.9 MPa



Figure 1 Survey of reported fracture toughness results.

for 16 weeks. The water absorption was found to be independent of specimen type or size. For CSM/PR and WRF/PR the increase in weight due to water absorbed was 1.2 and 0.6%, respectively. Water damage took the form of patches of debonded fibres evenly distributed over the specimens. There were no resin cracks.

The centre-notched (CN) specimens shown in Fig. 2 were used in both fracture toughness testing and fatigue crack propagation studies. For this geometry, the stress intensity factor, K, is given in [1] as

$$K = \sigma_{\rm G} \sqrt{W} \left(\frac{a}{W}\right)^{\frac{1}{2}}$$
(3)  
$$\left[ \left( a \right)^2 \left( a \right)^2 \left( a \right)^{\frac{3}{2}} \right]^{\frac{3}{2}}$$

$$\times \left[ 1.77 + 0.454 \left( \frac{a}{W} \right) - 1.02 \left( \frac{a}{W} \right)^2 + 5.4 \left( \frac{a}{W} \right) \right]^5$$

where  $\sigma_{\rm G}$  is the gross stress applied to the ends of the specimen. To calculate  $K_{\rm c}$ , the peak value of  $\sigma_{\rm G}$  reached during a test,  $\sigma_{\rm cG}$ , was used in the above equation, with the half-length of the sawn crack,  $a_0$ .

The testing machines used for tensile and fracture toughness testing were either an Instron 1195, or a modified type "E" Tensometer, or a Denison T42(500 kN), according to availability, at crosshead speeds of about  $1 \text{ mm min}^{-1}$ . For 900 mm wide specimens, a 1000 kN machine was designed

TABLE II Description of materials

Abbreviation	Trade name	Description
CSM	Fibreglass Supremat	Chopped strand mat, E-glass, $450 \mathrm{g  m^{-2}}$
WRF	Turner Bros. ECK25	Woven roving fabric, E-glass, $830 \mathrm{g}\mathrm{m}^{-2}$ , 197 ends/m warp, 158 ends/m weft
PR	B.P. Cellobond A2785CV	Polyester resin, isophthalic type containing: isophthalic acid maleic anhydride 1:2 propylene glycol dissolved in styrene with added aerosil thixotrope and used with: catalyst: methyl ethyl ketone peroxide SD2 accelerator: 0.5% cobalt in styrene. NI 48/ST

and build [24] (Fig. 3) which was also capable of applying pulsating load. For fatigue crack propagation tests on small specimens the 35 kN machines described by Owen [25] were used.

## 3. Fracture toughness results

Fracture toughness tests were carried out on dry and wet CN specimens of both materials, having W = 50, 100 and 150 mm, and with a/W = 0.167. Dry specimens were cut from 3-, 6- and 9-ply material.  $K_c$  was found to depend on the glass content and where there was sufficient variation, it was possible [24] to apply a linear relation between  $K_{c}$  and glass content and hence establish  $K_{c}$  for a standard glass content (35 wt% for CSM/PR, 65 wt % for WRF/PR). Where this was impossible, mean values of results were used. From Tables IV and V, the increase in  $K_c$  with W is much greater in WRF/PR than CSM/PR, but the reduction in  $K_{c}$ due to water absorption is only between 5 and 14% in both materials. There is only a negligible change in  $K_{c}$  with specimen thickness, which indicates that plane strain conditions are unlikely to be achieved, even in many plied laminates. The highly strained material at the crack tip will be trying to contract along the crack front. The less strained material adjacent to the crack front pre-



Figure 2 Specimens (dimensions in mm): (a) tensile; (b) plate twist; (c) centre notched (CN), L/W = 2, and 2y is the gauge length for the compliance gauge.

TABLE I	II Summary	of ultimate	tensile stress	and compliances
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Property		CSM/PR at glass content 35%	% change due to water absorption	WRF/PR at glass content 65%	% change due to water absorption
UTS	(MPa)	124.8	- 2.5	385.2	- 17.5
S 11	(GPa <sup>-1</sup> )	0.1004	+ 10.4	0.040 37	+ 2.1
S 22	(GPa <sup>-1</sup> )	0.1004	+ 10.4	0.040 37	+ 2.1
S <sub>12</sub>	(GPa <sup>-1</sup> )	- 0.0399	6.9	- 0.008 23	+ 169.2
S 66	(GPa <sup>-1</sup> )	0.2805	+ 2.5	0.224 0	+ 16.3



Figure 3 1000 kN capacity loading frame.

vents this and in a homogeneous yielding material plane strain conditions may be established. In GRP, the interfacial and interply strength is probably too low to support tensile forces along the crack front.

If  $K_c$  is a constant material property, from Equation 3 as  $a_0/W \rightarrow 0$ ,  $\sigma_{cG} \rightarrow \infty$ . Clearly the failure stress of the material is an upper bound to  $\sigma_{cG}$ . Similarly, when  $a_0/W = 0.5$ , Equation 3 predicts a finite value for  $\sigma_{cG}$  when there is no material holding the specimen together.  $K_c$  cannot, therefore, be constant over the whole range of crack length. To see if a region existed between  $a_0/W = 0$  and 0.5, where  $K_c$  was constant, 100 mm wide CN specimens of both materials were tested containing various length cracks.  $K_c$ , together with gross failure stress  $\sigma_{cG}$ , and nett failure stress  $\sigma_{cN}$ , are shown in Figs. 4 and 6. Use of the dimensionless forms  $K_c/(\sigma_{UTS}\sqrt{W})$ ,  $\sigma_{cG}/\sigma_{UTS}$ , and  $\sigma_{cN}/\sigma_{UTS}$ , (where  $\sigma_{\text{UTS}}$  is that of the material around the crack, determined from the glass content of the material in this region), can be seen to reduce the scatter associated with glass content variation in the CSM/PR results (Figs. 4 and 5). In WRF/PR the glass content variation was smaller, so this procedure has little effect (Figs. 6 and 7).

In Figs. 4 to 7 it can be seen that  $K_c$  varies continuously with crack length. This behaviour was repeated in 915 mm wide specimens of CSM/PR (Fig. 8), but there appears to be a region where  $K_c$ may be reasonably constant with a/W. In Figs. 6 and 7, it can be seen that the nett section stress is constant in WRF/PR specimens, but not equal to the material ultimate tensile stress. Tests on a 100 mm wide specimen with no crack showed that this was caused by a stress concentration at the grips which proved more severe than the very short cracks. Failure of all WRF/PR specimens appeared to be by general simultaneous failure of the rovings, which tend to block crack propagation until their failure load is reached.

The failure of the 915 mm wide specimens of CSM/PR, occurred at very low stresses compared with the 100 mm specimens. The failure of all sizes of WRF/PR specimens occurred at about the same stress for a given crack length (Table VI). The load-displacement recording taken during the tests on the longest specimens was linear up to sudden failure. The failure of smaller specimens was less sharply defined.

Nominal width (mm)	Number of layers	Number of specimens	Mean K <sub>c</sub> (MPa m <sup>1/2</sup> )	35% glass content (MPa m <sup>1/2</sup> )
CN 50 Dry	3	4	10.35	9.97
100	3	4	10.90	10.57
150	3	3	11.52	11.53
CN 50 Wet	3	5	8.63	8.67
100	3	5	9.92	10.04
150	3	5	10.14	10.60
CN 50 Dry	6	5	10.24	9.79
100	6	5	10.89	10.77
150	6	6	11.62	11.40
CN 50 Dry	9	5	10.26	10.26
100	9	5	10.96	10.67
150	9	6	12.08	11.23
CN 50 Dry	3, 6, 9	14	10.27	9.89
100	3, 6, 9	14	10.92	10.63
150	3, 6, 9	15	11.78	11.41

TABLE IV Summary of mean  $K_c$  values and  $K_c$  values at 35% glass content, CSM/PR

Nominal width (mm)	Number of layers	Number of specimens	Mean K <sub>c</sub> (MPa m <sup>1/2</sup> )	65% glass content K <sub>c</sub> (MPa m <sup>1/2</sup> )
CN 50 Dry	3	4	35.89	35.84
100	3	4	46.13	43.83
150	3	4	55.31	50.63
CN 50 Wet	3	4	31.83	_
100	3	4	38.36	_
150	3	4	43.52	_
CN 50 Dry	6	3	28.42	_
100	6	2	39.87	_
50	9	3	31.40	
CN 100 Dry	9	3	45.66	
50	3, 6, 9	10	32.3	-
100	3, 6, 9	9	44.58	42.59

TABLE V Summary of mean K<sub>c</sub> values and K<sub>c</sub> values at 65% glass content, WRF/PR

## 4. Fatigue crack propagation studies

Fatigue crack propagation tests were carried out on 100 mm wide CN specimens of both materials at a constant stress intensity factor range. Crack length was estimated from changes in specimen compliance, since damage obscured the position of the crack tip. Holdsworth and co-workers [11, 13] measured the compliance of several specimens containing sawn cracks of different lengths, but found that small compliance changes due to crack length were masked by variations in glass content. To obtain consistent results in the work described here, compliance in the dimensionless form  $(Ct/S_{11})$  was related to crack length through the solution of a finite element model [24] similar to that described by Walters [27]. C is the specimen compliance measured between gauge points 2yapart (Fig. 2c), t the thickness, and  $S_{11}$  the normal



Figure 4 Change of fracture stress and fracture toughness with notch width, 100 mm wide CN specimens, CSM/PR material.



Figure 5 Results of Fig. 4 in dimensionless form.



Figure 6 Change of fracture stress and fracture toughness with notch width, 100 mm wide specimens, WRF/PR material.

material compliance (=  $S_{22}$  in both materials, see Table III), of the material around the crack estimated from its glass content. In this form, the compliance was shown to be independent of glass content for isotropic and transversely orthotropic materials provided 2y is small. Computed specimen compliances agreed well with experimental compliances when expressed as  $Ct/S_{11}$ .

Initially, a load-displacement curve for the test specimen (maximum load 3 kN), was recorded on an X-Y plotter and assigned a value of  $(Ct/S_{11})$ corresponding to the measured crack length, from the specimen compliance-crack length relation. The specimen was then cycled at a load to give the desired value of stress intensity factor range ( $\Delta K$ ) for a few hundred cycles. The compliance was measured again and the new crack length found from the calibration. The load was reduced to keep  $\Delta K$  constant and the cycling continued. This process was repeated until either the specimen broke, or a large number of cycles had been completed. The initial rate of crack growth was very high compared with the remainder of the test until just before failure.

Graphs of crack growth against cycles at various  $\Delta K$  values for wet and dry CSM/PR and WRF/PR are shown in Figs. 9 to 11 and 13. Rates of growth are given in Tables VII, VIII and IX. The variation in glass content of the dry CSM/PR specimens



Figure 7 Results of Fig. 6 in dimensionless form.

caused crack growth to occur at a lower rate in specimens tested at higher  $\Delta K$  than in specimens tested at an apparently lower  $\Delta K$ . Expressing  $\Delta K$  as  $\Delta K/(\sigma_{\rm UTS}\sqrt{W})$ , where  $\sigma_{\rm UTS}$  is found from the glass content, can be seen from Table VII to remove this anomaly.

In Fig. 9 it is difficult to distinguish regions



Figure 8 Change of failure stress and fracture toughness with notch width, 914 mm wide CN specimens, CSM/PR material.



Figure 9 Fatigue crack growth in 100 mm wide CN specimens, dry CSM/PR material.

where da/dN is constant. The Paris fatigue crack propagation law, equation 2, predicts a finite growth rate at  $\Delta K = K_c$ . In Forman's law [26],

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{A\Delta K^m}{(K_\mathrm{c} - \Delta K)} \tag{4}$$

 $da/dN \to \infty$  as  $\Delta K \to K_c$  but  $K_c$  is assumed constant with a. In the previous section it was shown that  $K_c$  varies with a/W so that it is possible for  $K_c$  to approach the value of  $\Delta K$  at which the specimen is being tested. A third-order polynomial was fitted to the  $K_c/(\sigma_{\rm UTS}\sqrt{W})$  against  $a_0/W$  curve in Fig. 5 to express Equation 4 in the form

$$\frac{\mathrm{d}a_{\mathrm{D}}}{\mathrm{d}N} = \frac{A\Delta K_{\mathrm{D}}^{m}}{[B_{0} - \Delta K_{\mathrm{D}}] + B_{1}a_{\mathrm{D}} + B_{2}a_{\mathrm{D}}^{2}} \quad (5)$$

where the  $B_0$ ,  $B_1$  and  $B_2$  are constants,  $a_D = a_0/W$ ,  $\Delta K_D = \Delta K/(\sigma_{\text{UTS}}\sqrt{W})$ , which in a constant  $\Delta K$  cycling test can be integrated to give [24]:

$$N - N_{i} = k \left[ (B_{0} - \Delta K_{D})(a_{D} - a_{Di}) + \frac{B_{i}}{2} (a_{D}^{2} - a_{Di}^{2}) + \frac{B_{2}}{3} (a_{D}^{3} - a_{Di}^{3}) \right]$$
(6)

where  $a_{Di}$ ,  $N_i$  are initial values and

$$k = 1/A\Delta K^m. \tag{7}$$

The least squares method was used to determine a value of 1/k that gives a best fit for Equation 6 to the curves in Fig. 9. The solid lines in Fig. 9 are Equation 6 and the dotted lines assume da/dN is constant. The Paris law is equivalent to Forman's law at low rates of growth where  $\Delta K$  is much less

than  $K_c$ . For wet CSM/PR and WRF/PR (Figs. 10 and 13), because crack growth took place at low  $\Delta K$  values relative to  $K_c$ , there were clearly defined regions where da/dN was constant.

The fatigue crack-growth resistance of WRF/PR is superior to CSM/PR and its mode of failure quite different. Horizontal crack growth is blocked by vertical rovings. There appear to be several distinct regions of growth rate in Fig. 11. The apparent horizontal crack growth which increases according to compliance measurements, is really growth of vertical cracks at the tips of the initial central crack (Fig. 12). When these have grown to a certain length, growth ceases until the horizontal rovings bridging the crack give way. This effectively divides the specimen into two separate ligaments. Failure follows in the next few thousand cycles. The growth rates in all regions were roughly independent of  $\Delta K$  (Table VII) but Fig. 11 shows that the duration of the central region of low growth rate decreased with increasing  $\Delta K$ . Application of either of the crack-growth laws mentioned above seems inappropriate.

Specimens that had undergone the waterabsorption treatment were kept in a water bath during testing. The rate of crack growth at equivalent  $\Delta K$  values increased by at least three orders of magnitude in CSM/PR specimens due to water absorption (Tables VII to IX). The mechanism in the WRF/PR specimens by which horizontal crack propagation is blocked and vertical cracks formed, is destroyed by prolonged water immersion and horizontal growth took place. Therefore, it was



Figure 10 Fatigue crack growth in 100 mm wide CN specimens, wet CSM/PR material.



Figure 11 Fatigue crack growth in 100 mm wide CN specimens, dry WRF/PR material.



Figure 12 Crack tips in WRF/PR.

possible to apply the Paris law to wet WRF/PR (Fig. 13). da/dN and 1/k are plotted logarithmically against  $\Delta K$  to obtain A and m in the crack growth laws, as in Fig. 14.

In summary, the crack growth in the various specimens could be represented by the following relationships.

For dry CSM/PR using the Paris law

$$\frac{\mathrm{d}a_{\mathrm{D}}}{\mathrm{d}N} = 3.37 \times 10^7 \Delta K_{\mathrm{D}}^{20.33} \tag{8}$$

or

$$\frac{\mathrm{d}a}{\mathrm{d}N} = 1.19 \times 10^{-26} \Delta K^{20.33}$$

(at 35% glass content). (9)

For dry CSM/PR using the Forman law

$$\frac{da_{\rm D}}{dN} = \frac{2.31 \times 10^3 \Delta K_{\rm D}^{15.97}}{K_{\rm Dc} - \Delta K_{\rm D}}$$
(10)

or

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{2.94 \times 10^{-26} \Delta K^{15.97}}{K_{\mathrm{c}} - \Delta K}$$
(at 35% glass content) (11)

where  $K_{c}$ ,  $K_{Dc}$  vary as shown in Figs. 7 and 8,

ΔK Glass content Cycles to failure  $\Delta K_{\mathbf{D}}$  $da_D/dN$ (MPa m1/2) by weight  $N_{\mathbf{c}}$ (%) 2 373 000 S\* Dry 7.75 39.48  $0.719 \times 10^{-8}$ 0.174 7.50 34.93 0.190  $0.206 \times 10^{-6}$ 397 640 8.25 34.95 0.209  $0.421 \times 10^{-6}$ 205630 9.00 34.92  $0.740 \times 10^{-6}$ 190 530 0.228 8.00 32.09 0.221  $0.234 \times 10^{-5}$ 37790 9.50  $0.257 \times 10^{-5}$ 56 300 37.15 0.227 8.50  $0.195 \times 10^{-4}$ 8 5 0 0 31.21 0.241 Wet 5.00 35.22  $0.301 \times 10^{-6}$ 614 050 0.126 6770 6.50 33.89 0.170  $0.249 \times 10^{-4}$ 8.25 35.44  $0.160 \times 10^{-3}$ 1 890 0.207

TABLE VII Fatigue crack propagation tests, CSM/PR

\* S indicates test stopped without failure occurring.

TA	BLE	VIII	Fatigue	crack pro	opagation	tests,	,WRF,	/PR,	dry
----	-----	------	---------	-----------	-----------	--------	-------	------	-----

Δ <i>K</i> (MPa m <sup>1/2</sup> )	Glass content by weight (%)	ΔK <sub>D</sub>	$da_{D}/dN$ phase 2	da <sub>D</sub> /dN phase 3	Cycles to failure N <sub>c</sub>
22	67.68	0.168	$0.215 \times 10^{-6}$	0.195 × 10 <sup>-8</sup>	4 904 000 S*
24	67.66	0.184	0.148 × 10 <sup>-6</sup>	$0.126 \times 10^{-8}$	4 268 179 S
26	64.71	0.215	$0.155 \times 10^{-6}$	$0.274 \times 10^{-8}$	2 287 000 S
30	66.95	0.234	$0.101 \times 10^{-6}$	$0.278 \times 10^{-8}$	2 503 260
34	65.52	0.275	$0.112 \times 10^{-6}$	$0.221 \times 10^{-8}$	1 493 400
		Mean value	$0.146 \times 10^{-6}$	0.219 × 10 <sup>-8</sup>	

respectively.

or

or

For wet CSM/PR using the Paris law

For wet WRF/PR using the Paris law

CN specimens, CSM/PR and WRF/PR

Half-crack length/

0.2187 CSM/PR

0.054 59 WRF/PR

width ratio

0.05519

0.010 93

0.219 90

a/W

)

 $\frac{da_{\rm D}}{dN} = 1.32 \times 10^5 \Delta K_{\rm D}^{12.86}$ 

 $\frac{da}{dN} = 3.92 \times 10^{-17} \Delta K^{12.86}$ 

(at 35% glass content).

 $\frac{da_{\rm D}}{dM} = 0.007\,94\Delta K_{\rm D}^{5.6}$ 

Gross stress

at failure

18.67

34.36

54.11

232.91

183.25

(MPa)

TABLE VI Fracture toughness tests on 915 mm wide

Nett stress

at failure

(MPa)

33.18

38.60

55.32

261.46

327.12

K<sub>c</sub>

(MPa m<sup>1/2</sup>)

16.49

13.88

93.68

161.98

9.60

(12)

(13)

(14)

\* S indicates test stopped without failure occurring.

$\frac{\Delta K}{(\text{MPa m}^{1/2})}$	Glass content by weight (%)	ΔK <sub>D</sub>	$da_{D}/dN$	Cycles to failure N <sub>c</sub>
14	65.46	0.114	$0.402 \times 10^{-7}$	1 970 000 S*
18	65.96	0.144	$0.166 \times 10^{-6}$	494 500
22	66.88	0.172	$0.410 \times 10^{-6}$	271680

TABLE IX Fatigue crack propagation tests, WRF/PR, wet

\* S indicates test stopped without failure occurring.



## 5. Conclusions

Clearly WRF/PR is the tougher of the two materials tested. The rovings prevent crack propagation, which causes the large increase in  $K_c$  with width. This size effect is much less in CSM/PR specimens. For the stress intensity approach to be applicable to GRP specimens they should be (i) of notchsensitive material, and (ii) large enough for rapid crack propagation to be the dominant failure mode. Such failures have been observed in large GRP structures. Results from thin specimens can be applied to thicker material, (provided transverse buckling is restrained in the thin specimens). The effect of water absorption on fracture toughness is small and comparable with the reduction in strength. The survey shows that most GRP are selected for testing at random. Further work should examine the effect on fracture toughness of varying fibre, strand or roving diameter of the reinforcing material, keeping glass content constant. The J



Figure 13 Fatigue crack growth in 100 mm wide CN specimens, wet

WRF/PR material.

Figure 14  $da_D/dN$  or 1/k against  $\Delta K_D$  for the determination of constants in the crack-growth laws.

integral approach has been shown [28] to give  $J_c$ values that are independent of crack length but increase with specimen thickness. The latter may be due to transverse buckling which is known to affect  $K_c$  values.  $J_c$  may be closer to being a material constant than  $K_c$ , but it is difficult to see how, practically, it can be used to describe fatigue crack propagation.

The use of dimensionless forms of  $\Delta K$  has been shown to eliminate scatter in fracture toughness results and explain apparently anomalous rates of growth observed in CSM/PR specimens. The use of Forman's law accounts for changing rates of growth at  $\Delta K$  close to  $K_c$ . The Paris fatigue crack-growth law adequately describes low rates of growth but higher rates of growth are better described by Forman's law, allowing for variation in  $K_c$  with crack length. Neither law is applicable to WRF/PR unless it has been in water for a long period of time. The most important finding is the severe reduction in crack-growth resistance in both materials caused by water absorption.

## Acknowledgement

This work has been carried out with the financial support of the Procurement Executive, Ministry of Defence.

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Received 28 November and accepted 18 December 1978.