Composites Part A 27A (1996) 1097–1105

1359-835X/96/$15.00
S1359-835X(96)00071-1

Interlaminar tensile strength (ILTS) measurement of woven glass/polyester laminates using four-point curved beam specimen

Weicheng Cui*, Tao Liu, Jianxin Len and Rongbiao Ruo
China Ship Scientific Research Center, PO Box 116, Wuxi, Jiangsu, 214082, People's Republic of China
(Received 10 October 1995; revised 22 April 1996)

Based on a review of the current methods for the measurement of interlaminar tensile strength (ILTS), a novel specimen of a four-point curved beam is evaluated for this purpose. Detailed finite element analysis is carried out to investigate the appropriateness of the data interpretation formula. A simple design method to choose the appropriate parameters in order to guarantee the delamination failure is provided. This specimen is used to measure the ILTS of woven glass/polyester laminates. The results are found to be comparable with other methods. The most attractive advantage of this test method is its simplicity and that it requires no special techniques in specimen preparation and test set-up. Copyright © 1996 Elsevier Science Limited

(Keywords: interlaminar tensile strength; woven glass/polyester; four-point curved beam; delamination; flatwise tension test specimen)

INTRODUCTION

Delamination failure caused by interlaminar (or through-thickness) stresses is the most prominent failure mode observed in composite structures. One reason for this is that the strength in this direction is typically very low and the other reason is that few reliable data on interlaminar tensile strength (ILTS) are available. Therefore, it is difficult for designers to design against delamination failure. A number of actual failures due to interlaminar tensile stresses have been reviewed by Kedward *et al.*[1]. Such problems have contributed significantly to the cancellation of several major composite hardware programmes. The problem of interlaminar tensile or shear stresses was also highlighted at the bonded joints and attachments of marine composite structures[2].

In order to design against delamination failure, interlaminar shear and tensile strengths must be measured. The Iosipescu specimen has often been recommended for use in measuring the interlaminar shear strength (ILSS)[3], while the most commonly used simple three- and four-point beam test can also be regarded as a valid means to measure the ILSS if the diameters of the loading and support rollers are carefully chosen or a piece of rubber is inserted between the specimen and the roller[4,5]. In contrast to the situation where much effort has been devoted to the measurement of ILSS, relatively little work has been done to measure the ILTS of composite laminates. The specimens recommended for measuring the ILTS in the literature can be divided into four types, as outlined below.

The first type of specimen is the delamination coupon specimen investigated by Harris and Orringer[6] and shown in *Figure 1*. Due to the coexistence of interlaminar tensile and shear stresses and the complexity of the stress determination, they concluded that this type of specimen was inadequate for the purpose of determining ILTS with acceptable confidence.

The second type of ILTS specimens are variations of the flatwise tension test specimen, bonded carefully to steel or aluminium end pieces, through which tensile load is applied, as shown in *Figure 2*. Kimpara and Takehana[7], and Bird and Allen[8] used this type of specimen to measure the ILTS of glass-reinforced thick laminates. A mean ILTS of 10.6 MPa with c.o.v. of 0.13 has been reported for E-glass woven roving/isophthalic polyester GRP of thickness 14–30 mm[8]. For CSM laminates, a mean ILTS of 8.8 MPa with c.o.v. of 0.12 has been found[9]. Lagace and Weems[10] have used this

*To whom correspondence should be addressed

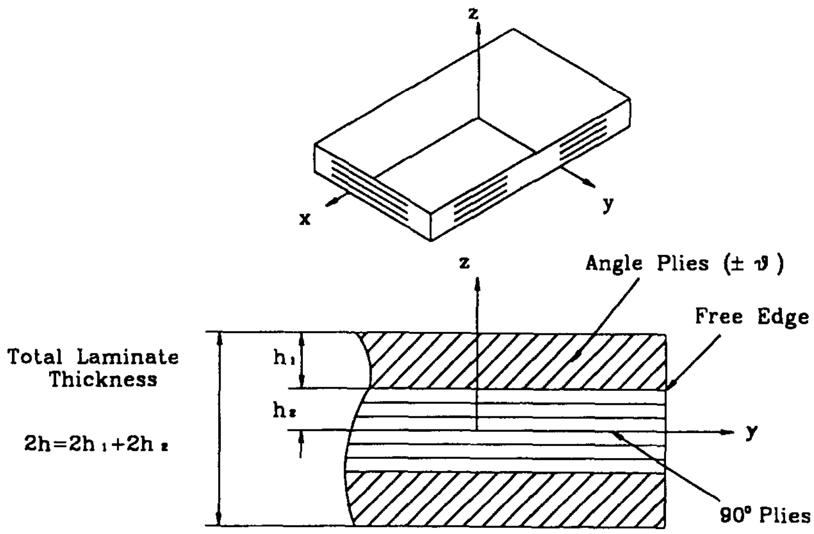

Figure 1 Delamination coupon[6]

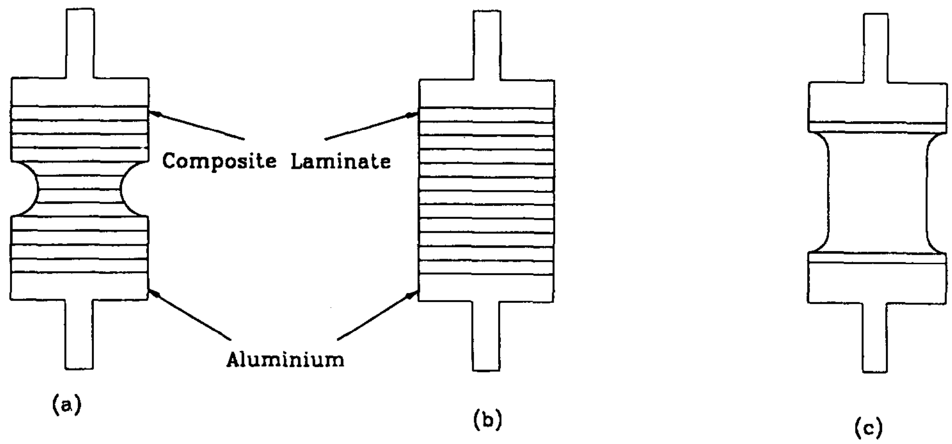

Figure 2 Variations of flatwise tension test specimen[3,7–10]

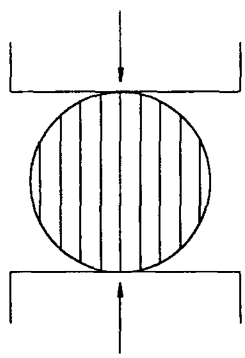

Figure 3 Diametrical compression disk specimen[11]

type of specimen to measure the ILTS of graphite/epoxy. The average value from three types of laminates is 43.0 MPa with c.o.v. of 0.156. Matthews *et al.*[3] have also used short, through-thickness parallel tensile specimens to measure the interlaminar tensile modulus and strength of thick woven glass/polyester laminates. Their measured results are in the range of 7.6–15.8 MPa, depending on fibre weight content.

Although some success has been achieved with the flatwise tension test specimen, this configuration has inherent limitations. Testing under extreme environmental conditions such as elevated temperature and moisture content is complicated by the presence of a failure-prone adhesive bond between the test specimen and the grips. Forcing the failure to occur within the laminate requires that the interlaminar tensile stress be concentrated by some means such as necking the specimen down at the test section. This requires relatively thick specimens, which may not be adequately representative of a particular composite structure.

The third type of specimen is a diametrical compression specimen, as shown in *Figure 3*[11]. In this specimen, a compressive load along one principal axis of a disk results in a tensile stress of about one-third the magnitude along the perpendicular, that is, the through-thickness axis. Similar results as with the first type of specimen[8,9] have been obtained for glass-reinforced plastics[11]. However, their results showed variations with specimen thickness and diameter, as well as significant scatter.

The fourth type of specimen involves variations of the curved beam test specimen[1,12–15], as shown in *Figures*

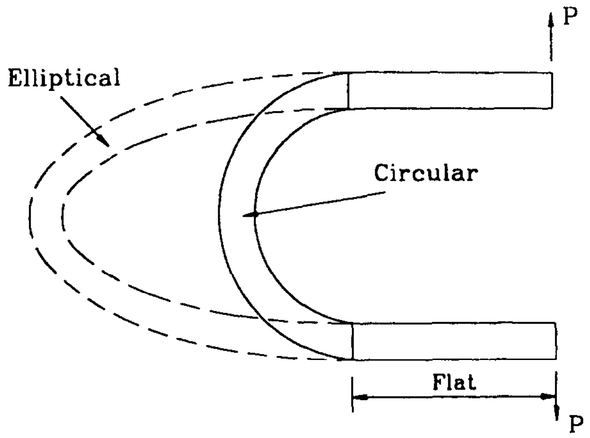

Figure 4 Semicircular or elliptical specimen[13]

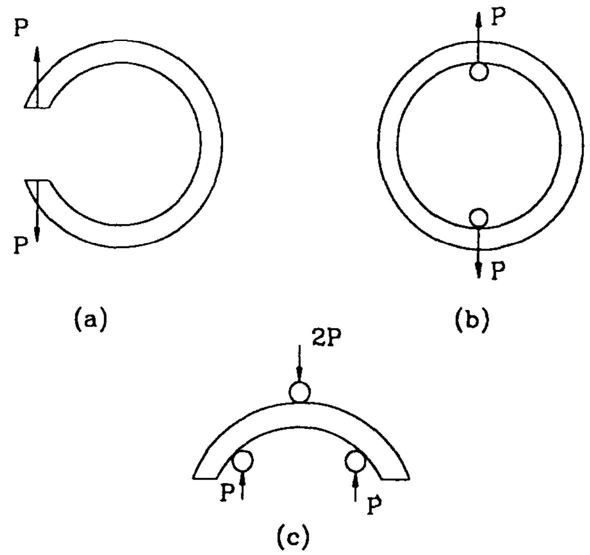

Figure 5 Ring or curved beam specimens[14]

4–8. Hiel *et al.*[13] suggested using the curved laminate specimen subjected to end tensile loads which open up the curvature and induce damage by delamination. Two variations of this configuration were tested and they include semicircular and elliptical specimens (*Figure 4*). The semicircular specimens were fabricated from carbon/epoxy (T300/934) prepreg. Ten semicircular specimens were tested. The data display a mean ILTS of 36.85 MPa which is only 63% of the in-plane transverse strength and the c.o.v. is 0.23. Static interlaminar tensile strength data obtained on 13 elliptical specimens showed that the mean strength of T300/934 is 107.06 MPa, which is 194% of the published in-plane transverse strength and the c.o.v. is 0.098. The extremely high interlaminar tensile strength obtained on these specimens was thought to be due to the size effect of ILTS. Wu *et al.*[14] have compared three different configurations (*Figure 5*) to measure the ILTS of E-glass/epoxy. Their results indicated that the average value of ILTS for $\pm 55°$ winding configuration was 9.10 MPa and for 90° winding configuration was 12.6 MPa. Shivakumar *et al.*[15] used an L-shaped curved beam specimen (*Figure 6*) to measure the ILTS

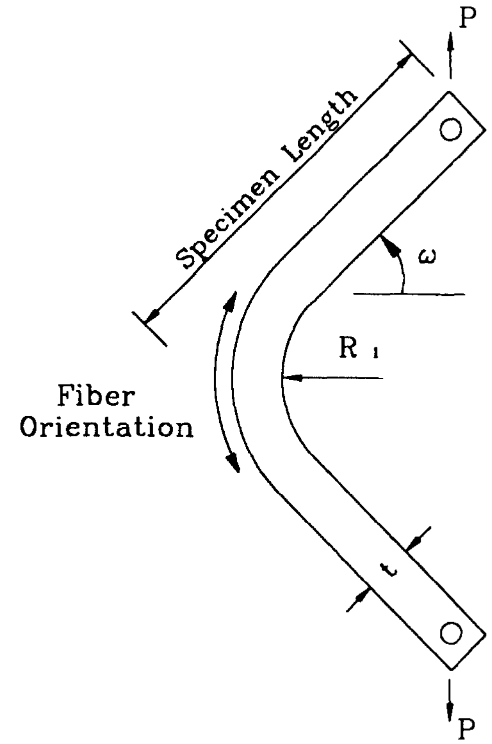

Figure 6 L-beam specimen[15]

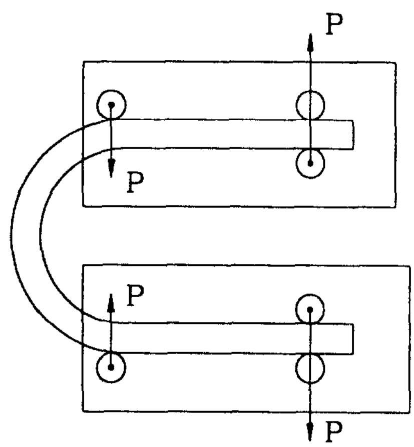

Figure 7 Pure moment on curved beam[12]

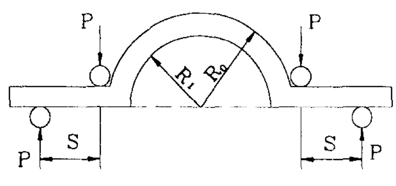

Figure 8 Four-point curved beam specimen

of AS4/3501-6 graphite/epoxy. Average ILTS of 16-, 24- and 32-ply laminates were 47.6, 40.9 and 23.4 MPa, respectively. ILTS decreased with increasing specimen thickness and width because of volumetric effects.

Since the application of an end load to a curved laminate induces both interlaminar tensile and shear stresses around the curvature, it is difficult to determine correctly the exact contribution of the ILTS to

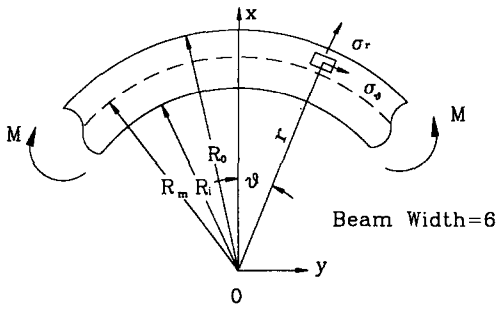

Figure 9 Uniform moment loading on curved beam

delamination failure which might have resulted from a combined effect of the two stresses. To overcome this problem, Ige and Sargent[12] have developed a curved testing apparatus which applies a pure bending moment to the generic curved specimen configuration (*Figure 7*). Under a pure bending moment, interlaminar shear stresses do not exist in a curved beam. Consequently, the specimen fails naturally by delamination resulting from high interlaminar tensile stresses alone. In addition, a pure moment loading induces an interlaminar tensile stress which is almost twice that induced by an equivalent end load on a semicircular curved specimen[12].

They used this configuration to measure the ILTS of a carbon/epoxy prepreg; the mean failure stress for the specimens was 23.63 MPa which is 60% of the in-plane transverse tensile strength and the c.o.v. is 12%. Although this test apparatus is a success, it requires relatively complicated manufacturing. A simpler test configuration which can also apply a pure bending moment to the curved beam is a four-point short beam bending test specimen (*Figure 8*). The purpose of this paper is to evaluate the validity of using the four-point curved beam specimen to measure the ILTS of woven glass/polyester laminates.

TEST SPECIMEN CONFIGURATION

Theory

The classical elasticity theory equations for stresses in a cylindrically anisotropic homogeneous curved beam under pure bending, M, (*Figure 9*) are given by Lekhnitskii[16] as:

$$\sigma_r = -\frac{M}{R_o^2 bg}\left[1 - \frac{c^{k+1}}{1-c^{2k}}\left(\frac{r}{R_o}\right)^{k-1} - \frac{1-c^{k-1}}{c^{2k}}c^{k+1}\left(\frac{R_o}{r}\right)^{k+1}\right] \tag{1}$$

$$\sigma_\theta = -\frac{M}{R_o^2 bg}\left[1 - \frac{1-c^{k+1}}{1-c^{2k}}k\left(\frac{r}{R_o}\right)^{k-1} + \frac{1-c^{k-1}}{1-c^{2k}}kc^{k+1}\left(\frac{R_o}{r}\right)^{k+1}\right] \tag{2}$$

$$\tau_{r\theta} = 0 \tag{3}$$

where R_i and R_o are the inner and outer radii of the curved beam, b is the width, r is the radius of the considered location, and c, k, g are defined by equations (5)–(7).

The radial location where the maximum radial stress occurs is given by:

$$r_m = \left[\frac{(k+1)(1-c^{k-1})c(R_iR_o)^k}{(k-1)(1-c^{k+1})}\right]^{1/2k} \tag{4}$$

where

$$c = R_i/R_o \tag{5}$$

$$k = (E_\theta/E_r)^{\frac{1}{2}} \tag{6}$$

$$g = \frac{1-c^2}{2} - \frac{k}{k+1}\frac{(1-c^{k+1})}{1-c^{2k}} + \frac{kc^2}{k-1}\cdot\frac{(1-c^{k-1})^2}{1-c^{2k}} \tag{7}$$

where E_r and E_θ are moduli in the radial and tangential directions.

By substituting equation (4) into equation (1), the maximum value of the radial stress $\sigma_{r\max}$ can be obtained. However, this will result in a very complicated expression. For a wide range of geometries and materials, a much simpler but quite accurate expression for $\sigma_{r\max}$ is given by Kedward[1]:

$$\sigma_{r\max} = \frac{3M}{2bt(R_iR_o)^{1/2}} \tag{8}$$

Equation (8) has been compared with Lekhnitskii's elasticity solution, equation (1), by Kedward[1]. It was found that for most practical applications in which $R_m/t \geq 2.5$ and $E_\theta/E_r \leq 6.0$, where R_m is the median radius of the curved beam, the maximum radial stress is almost independent of the degree of anisotropy and the maximum error resulting from the use of equation (8) is less than 1.0%.

However, the effect of large deflection on $\sigma_{r\max}$ values was not mentioned in ref. 1. This was observed in the tests and it might have some influence on the appropriateness of using equation (8) to interpret the test results. In order to investigate this, some finite element analyses were carried out in MSC/NASTRAN. The dimensions of the curved beam specimen are shown in *Figure 8*. The finite element model is shown in *Figure 10*. The elements used were QUAD4 with membrane properties. Altogether 2560 elements were used and the total number of nodes was 2737. The material properties used in the analysis were: $E_x = E_\theta = 13.7$ GPa, $E_y = E_r = 5.0$ GPa, $G_{xz} = G_{r\theta} = 2.6$ GPa, $\nu_{xz} = \nu_{r\theta} = 0.113$. These data were provided by Dongfang Fast Craft Company for E-glass woven roving/orthophthalic polyester laminates, based on their design data base. The material properties are not crucial here because the main concern for FE analyses is the geometric non-linearity. Therefore, only one set of

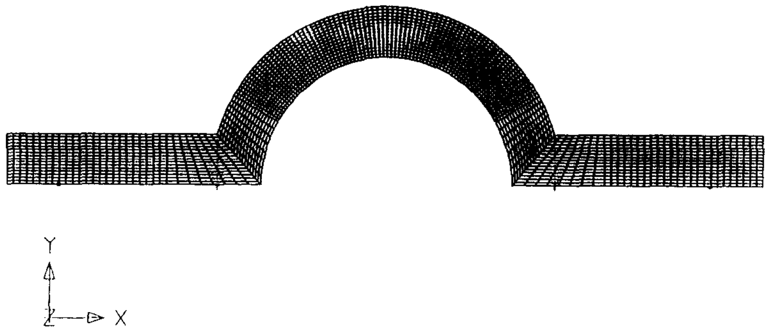

Figure 10 Curved beam finite element model

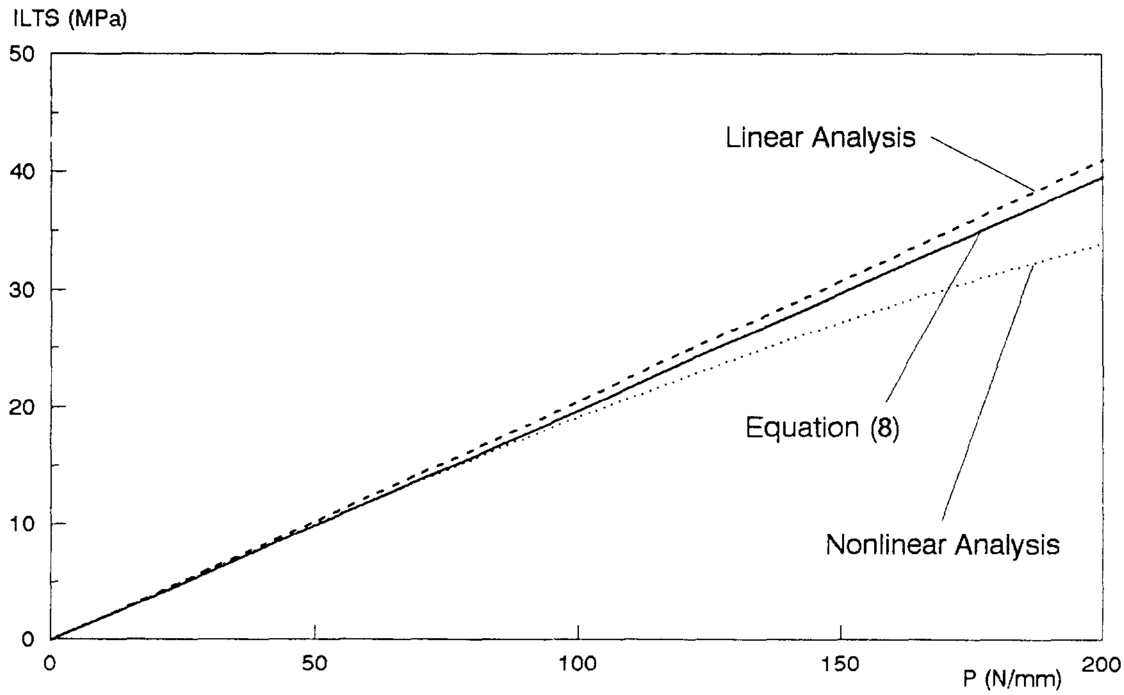

Figure 11 Effect of large deflection on maximum ILTS

material properties is used in the analyses. *Figure 11* shows the effect of large deflections on the load–maximum radial stress relation and *Figure 12* shows the effect of large deflections on the radial stress distribution along the thickness. It can be seen that for the practical E-glass/polyester laminates in which the ILTS is usually less than 20 MPa, the effect of large deflection on $\sigma_{r\max}$ is negligible, usually less than 3%. Therefore, equation (8) can be used to calculate the ILTS.

For a straight beam under pure bending moment M, the maximum bending stress σ_b is:

$$\sigma_b = 6M/bt^2 \tag{9}$$

where t is the specimen thickness and b is the width.

Within the curved region, the circumferential stresses decrease from the inner surface to the outer surface under the open-up bending moment. The circumferential stresses σ_θ within the curved region normalized by the maximum bending stress σ_b can be obtained from equation (2). It is found that the maximum value of the bending stress occurs at the inside surface of the curved specimen.

If we denote:

$$\sigma_{\theta\max} = \alpha\sigma_b = 6\alpha M/bt^2 \tag{10}$$

then α will depend on both k and R_m/t. It can be shown easily that the influence of k is negligible and, therefore, that R_m/t is the only parameter which influences α. When $R_m/t = 2.5$, $\alpha = 1.16$.

Specimen design

For the four-point curved beam specimen shown in *Figure 8*, three different failure modes are possible. The first one is the desired delamination failure within the curved region which is caused by the through-thickness tensile stress σ_r. The second one is the surface fibre fracture which is caused by σ_θ within the curved region. The third failure mode is the interlaminar shear crack within the straight region. The maximum interlaminar

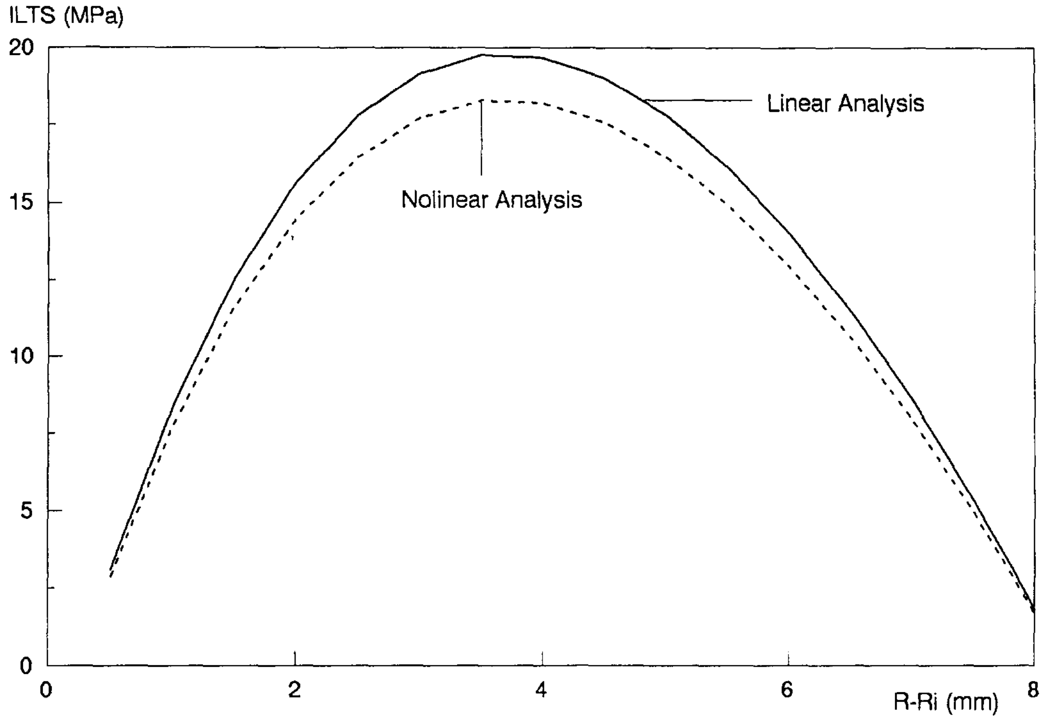

Figure 12 Effect of large deflection on ILTS distribution along the thickness

shear stress within the straight region is:

$$\tau_{\max} = 3P/2bt \tag{11}$$

where P is the applied load at the loading roller.

By carefully choosing the specimen thickness t, the inside radius R_i, and the distance between the support roller and the loading roller, it is possible to find a specimen configuration in which only the delamination failure will occur. The conditions for such a valid specimen are:

$$\sigma_{\theta\max} = 6\alpha PS/bt^2 < \sigma_B \tag{12}$$

$$\sigma_{r\max} = 3PS/2bt(R_iR_o)^{1/2} > \sigma_D \tag{13}$$

$$\tau_{\max} = 32P/bt < S_{13} \tag{14}$$

where σ_B, σ_D and S_{13} are the bending strength, delamination strength and the interlaminar shear strength of the composite, respectively.

Smith[17] has compiled the material data for ship-type laminates. For chopped strand mat (CSM), $\sigma_B = 177\,\text{MPa}$, $\sigma_D = 8.8\,\text{MPa}$, $S_{13} = 26.4\,\text{MPa}$; for woven roving (WR), $\sigma_B = 295\,\text{MPa}$, $\sigma_D = 10.6\,\text{MPa}$, $S_{13} = 23.5\,\text{MPa}$. Therefore, if S, x ($= R_m/t$) and t satisfy the following conditions:

$$\sigma_{\theta\max} = 6 \times 1.16 \times PS/t^2 < 177$$

$$\sigma_{r\max} = 1.5PS/t^2(x^2 - 0.25)^{1/2} > 10.6$$

$$\tau_{\max} = 1.5P/t < 23.5$$

then the delamination failure will be guaranteed. There are many solutions available and the following one is used in the current investigation:

$$R_m = 24, \quad t = 8\,\text{mm}, \quad S = 25\,\text{mm}$$

For this configuration, as long as $\sigma_D/\sigma_B < 0.073$, delamination failure can be ensured. From the data given by Smith[17], it is known that this condition is always satisfied for E-glass/polyester laminates.

Manufacture

The GRP laminates were made from either E-glass chopped strand mat ($200\,\text{g}\,\text{m}^{-2}$) or E-glass woven roving ($800\,\text{g}\,\text{m}^{-2}$) in either an orthophthalic or an isophthalic polyester resin in the workshop of the Dongfang Fast Craft Company. The reinforcements are provided by Chang Zhou No. 253 Factory. The orthophthalic polyester resin was provided by Chang Zhou No. 253 Factory, while the isophthalic polyester resin was provided by Jinlin BASF Company. These materials were used by Dongfang Fast Craft Company to manufacture small GRP crafts.

Before manufacturing the specimen, a semicircular hollow steel cylinder with an outer radius of 20 mm was machined. The surface of the steel cylinder was smoothed by emery cloth. Then this semicircular cylinder was fixed on the worktable and lamination started following the general procedure. Three different panels of 350 mm × 150 mm with the semicircular cylinder in the middle of the width were manufactured. The first panel, denoted E panel, was hand laid-up with 20 layers of CSM and orthophthalic polyester. The second panel, denoted F panel, was hand laid-up with eight layers of woven roving and orthophthalic polyester. The third panel, denoted G panel, was hand laid-up with eight layers of woven roving and isophthalic polyester. All the panels were cured at room conditions (24°C and 0.6 RH). Finally, the panels were cut into specimens with a

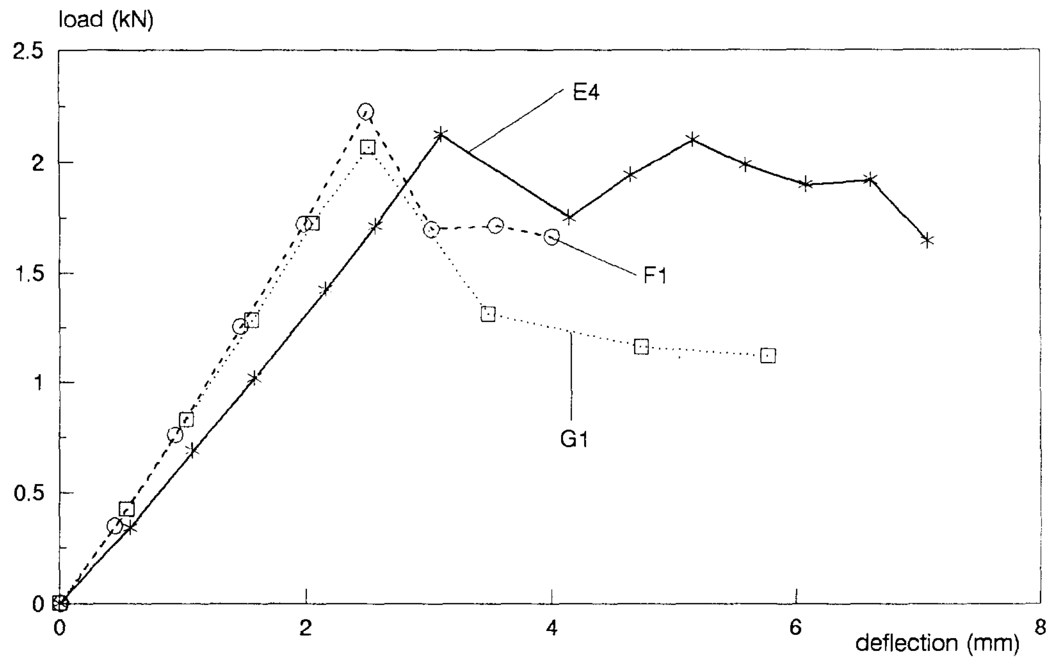

Figure 13 Typical load–deflection curves of the four-point curved beam

diamond saw. For each type, eight to nine good specimens were obtained.

Test set-up

The tests were carried out in the CSSRC structural strength laboratory, in a servohydraulically operated machine (ZDM 1-30) under load control. The load was increased continuously at a speed of $2\,\mathrm{N\,s^{-1}}$. *Figure 8* shows a schematic diagram of the test set-up. During the test, the load and the middle point deflection were recorded with an optical data collector (3530A).

EXPERIMENTAL RESULTS

All the specimens tested failed in a sudden manner and by delamination. The radial location of the delamination in these specimens was near the middle thickness, which coincided with the theoretical radial location of the maximum radial stress, thus confirming that failure occurred as a result of the ILTS reaching the interlaminar tensile strength of the laminate material. *Figure 13* shows some typical load–deflection curves for each type of panel. Using the least squares method, the average stiffness before failure can be obtained. *Table 1* summarizes the experimental results.

The ILTS measurements presented in *Table 1* show a scatter in the results larger than what was expected, with the c.o.v. varying between 0.06 and 0.22 for the three types of specimen. Two factors may be responsible for this. One is the quality of specimen manufacture. Due to the limited manufacturing conditions, all the panels had been manufactured by the rather primitive hand lay-up method. No special equipment such as a pressurized vacuum bag was used to remove the voids. Therefore, during the laminating process, defects were created in the laminates by small air bubbles being trapped in the polyester matrix. After curing, these bubbles form voids within the polyester and along the interface between the polymer and glass fibres. This can be seen quite clearly from the specimen surface. The size and distribution of the voids can vary between specimens. This is really a deficiency for further research because the true material behaviour may not be grasped at present. However, from a practical point of view, the material properties thus measured may be more appropriate for design calculations because the hand lay-up method is still the dominant one used in the manufacture of small GRP boats. It would be ideal to measure the void fraction and distribution, but for the same reason this was not done, even for the fibre volume fraction. ILTS is generally not very sensitive to the fibre volume fraction, as can be evidenced from various published results discussed earlier in this paper. The other factor is that the normal c.o.v. of ILTS would be generally higher than that of the other material properties such as tensile strength and bending strength, even for specimens having the same manufacturing quality. This is because the former is a void sensitive property, while the latter will not be so sensitive to the voids.

Although the manufacturing quality is not highly satisfactory for these specimens, the average value of ILTS for CSM and WR laminates measured here is still quite close to that provided by Smith[17] and Wu *et al.*[14]. This indicates that the current test method is quite appropriate for use in measuring the ILTS. Compared with other test methods proposed in the literature, the main advantage of this one is its simplicity in specimen preparation and test set-up.

Table 1 Experimental results

Specimen number	Thickness, t (mm)	Width, b (mm)	Failure load (N)	Stiffness (MPa)	Strength (MPa)
E1	7.9	24.7	945	24.0	7.77
E2	8.3	23.7	1050	26.4	8.15
E3	7.5	24.4	1415	22.9	13.07
E4	8.2	23.7	1155	27.9	9.19
E5	8.3	24.5	1092	27.5	8.20
E6	8.1	24.9	1107	29.2	8.59
E7	8.0	24.8	1381	27.1	11.03
E8	7.7	24.8	865	21.9	7.46
E9	7.8	25.0	1556	27.9	12.97
E10	8.2	24.9	1050	25.3	11.40
Mean	–	–	–	26.0	9.78
C.o.v.	–	–	–	0.09	0.22
F1	8.4	23.5	1200	37.3	9.17
F2	8.4	24.5	1150	35.9	8.43
F3	8.3	25.3	1250	39.1	9.09
F4	8.0	22.5	1020	28.4	8.98
F5	8.0	23.5	1043	34.9	8.79
F6	8.1	23.0	1050	30.0	8.82
F7	8.3	25.5	755*	16.1*	5.45*
F8	8.3	23.5	1220	35.9	9.55
F9	8.1	24.5	1300	39.3	10.25
F10	7.8	23.5	1055	35.5	9.35
Mean	–	–	–	35.1	9.16
C.o.v.	–	–	–	0.11	0.06
G1	6.9	25.0	1105	33.4	11.77
G2	7.1	21.7	755	30.7	8.75
G3	7.0	23.7	875	32.5	9.55
G4	7.0	23.5	915	24.9	10.07
G5	7.0	24.5	1165	34.6	12.30
G6	7.0	26.3	990	24.0	9.74
G7	7.3	27.0	665*	14.7*	5.86*
G8	7.0	24.0	1258	35.9	13.56
G9	7.0	24.5	1090	35.6	11.51
Mean	–	–	–	31.5	10.91
C.o.v.	–	–	–	0.15	0.15

*These data are not used in the average

SUMMARY AND CONCLUSIONS

In this paper a four-point curved beam specimen is evaluated for the validity of measuring the interlaminar tensile strength. Woven E-glass/polyester laminates were used. From the failure modes of the specimens, it can be concluded that the test specimen recommended in this paper is valid for measuring the ILTS. The measured ILTS values are also comparable with other test results reported in the literature. Furthermore, by detailed finite element analysis, it was further confirmed that the simple formula suggested by Kedward[1], equation (8), can be used for data reduction. The main advantage of this test configuration is its simplicity in specimen preparation and test set-up.

ACKNOWLEDGEMENTS

The first author is grateful to Professor Michael R. Wisnom, Department of Aerospace Engineering, University of Bristol for suggesting the use of a four-point curved beam specimen to measure the interlaminar tensile strength. The authors are also grateful to Ms Yu Lan for drawing all the figures.

REFERENCES

1 Kedward, K.T., Wilson, R.S. and McLean, S.K. Flexure of simply curved composite shapes. *Composites* 1989, **20**, 527–536

2 Dodkins, A.R., Shenoi, R.A. and Hawkins, G.L. Design of joints and attachments in FRP ship structures. *Marine Structures* 1994, **7**, 365–398

3 Matthews, F., Hodgkinson, J. and Ayache, S. In-plane and out-of-plane property measurements on thick woven glass/polyester laminates. In 'ECCM Composites Testing and Standardisation', European Association for Composite Materials, Amsterdam, 1992, pp. 277–286

4 Cui, W.C., Wisnom, M.R. and Jones, M. Failure mechanisms in three and four point short beam bending tests of unidirectional glass/epoxy. *J. Strain Analysis* 1992, **27**, 235–243

5 Cui, W.C., Wisnom, M.R. and Jones, M. Effect of specimen size on interlaminar shear strength of unidirectional carbon fibre-epoxy. *Compos. Eng.* 1994, **4**, 299–307

6 Harris, A. and Orringer, O. Investigation of angle-ply delamination specimen for interlaminar strength test. *J. Compos. Mater.* 1978, **12**, 285–299

7 Kimpara, I. and Takehana, M. Static and dynamic interlaminar strength of glass reinforced plastics thick laminates. In: 'Proc. Reinforced Plastics Congress', British Plastics Federation, Brighton, 1976

8 Bird, J. and Allen, R.C. The determination of the interlaminar tensile strength of ship type laminates. In 'Proc. 7th Int. Conf. on Experimental Stress Analysis', Haifa, Israel, 1982

9 Kitching, R., Tau, A.L. and Abu-Mansour, T.M.N. The influence of through thickness properties on glass reinforced plastic laminated structures. *Compos. Struct.* 1984, **2**, 105

10 Lagace, P.A. and Weems, D.B. A through-the-thickness

strength specimen for composites. In 'Test Methods for Design Allowables for Fibrous Composites', Vol. 2, ASTM STP 1003, (Ed. C.C. Chamis), American Society for Testing and Materials, Philadelphia, 1989, pp. 197–207

11 Mao, T.H. and Owen, M.J. Through-the-thickness tensile strength of fibre-reinforced plastics. In 'Composite Materials: Testing and Design (Sixth Conf.)', ASTM STP 787, American Society for Testing and Materials, Philadelphia, 1982, pp. 5–18

12 Ige, D. and Sargent, P. An apparatus for determining the interlaminar tensile strength of laminated composites using the curved specimen geometry. In 'ECCM Composites Testing and Standardisation', European Association for Composite Materials, Amsterdam, 1992, pp. 267–276

13 Hiel, C.C., Sumich, M. and Chappell, D.P. A curved beam test specimen for determining the interlaminar tensile strength of a laminated composite. *J. Compos. Mater.* 1991, **25**, 854–868

14 Wu, Y.S., Longmuir, A.J., Chandler, H.W. and Gibson, A.G. Through-thickness tensile stresses in curved composite shells. In 'Proceedings of Fibre Reinforced Composites '92', The Plastics and Rubber Institute, University of Newcastle upon Tyne, pp. 25/1–25/10

15 Shivakumar, K.N., Allen, H.G. and Avva, V.S. Interlaminar tension strength of graphite/epoxy composite laminates. *AIAA J.* 1994, **32**, 1478–1484

16 Lekhnitskii, S.G., Tsai, S.W. and Cheron, T. 'Anisotropic Plates', Gordon and Breach Science Publishers, New York, 1968

17 Smith, C.S. 'Design of Marine Structures in Composite Materials', Elsevier Applied Science, Amsterdam, 1990