

Through-Thickness Testing of Polymer Matrix Composites

Interlaminar or through-thickness (TT) stresses and strains occur in laminated structures; irrespective of loading mode or laminate thickness. Edge effects, holes, changes in thickness, curved edges, and bonded and bolted joints all result in TT stress and strain gradients. The presence of interlaminar tensile (peel) and shear stresses combined with inherently low TT strength properties may cause local microcracking and delaminations, and eventual failure. As a result, TT stiffness and strength properties are increasingly being required by structural engineers/designers for finite element analysis and other analysis methods in order to ensure efficient and safe use of composite materials in secondary and primary load bearing structures.

This Measurement Note describes test methods suitable for determining TT properties under tensile, compressive and shear loads. These methods can provide a full complement of TT elastic and strength property data, and stress-strain response to failure. The methods described in this Measurement Note have been successfully used with glass and carbon fibre-reinforced composite materials containing a wide range of different fibre formats, including continuous aligned, woven fabric and random mat. The use and limitations of these methods for characterising T-T properties under static and cyclic loads are discussed. The Measurement Note provides details on specimen fabrication, test apparatus and procedure, and failure mode.

The research reported in this Measurement Note, which has led to the drafting of standards for TT tension, compression and shear test methods, was undertaken as part of the 'Materials Measurement Programme' funded by the Engineering Industries Directorate of the UK Department of Trade and Industry. Future work will be directed towards validating the test methods by finite element analysis and interlaboratory comparative exercises.

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May 2001

Introduction

There is a tendency to associate interlaminar stresses or through-thickness (TT) stresses with "thick" sections, however interlaminar stresses and strains may be induced in "thin" laminates through the application of membrane (i.e. in-plane) loads. Features, such as free edges, holes, changes in thickness, curved edges, and bonded and bolted joints all act as stress concentrators (regions of high interlaminar tensile and shear stresses). The presence of interlaminar tensile (peel) and shear stresses combined with inherently low TT strength properties may cause local microcracking and delaminations. Delamination growth can cause severe reductions in stiffness and strength, and eventual failure under static or fatigue loading conditions.

TT stiffness and strength properties are increasingly being required by structural engineers/designers for finite element analysis (FEA) and other analysis methods to ensure efficient and safe use of composite materials in secondary and primary load bearing structures. Recent developments have seen the emergence of tensile, compressive and shear test methods suitable for generating TT elastic and strength property data [1-3].

This Measurement Note describes test methods suitable for determining TT properties under tensile, compressive and shear loads. These methods can provide a full complement of TT elastic and strength property data, and stress-strain response to failure (Table 1). The methods described in this Measurement Note have been successfully used with glass and carbon fibre-reinforced composite materials containing a wide range of different fibre formats, including continuous aligned, woven fabric and random mat. Details are provided on specimen fabrication, test apparatus and procedure, data analysis (or reduction) and failure mode. The use and limitations of these methods for characterising TT properties under static and cyclic loads are discussed.

Table 1: Short-Term Data for Orthotropic Materials

Load Type	Elastic Moduli	Poisson's Ratio	Strength	Failure Strains
Tension	E_{11}, E_{22}	ν_{12}, ν_{21}	S_{11}^T, S_{22}^T	$\epsilon_{11}, \epsilon_{22}$
	$[E_{33}]$	$[\nu_{13}, \nu_{23}]$	$[S_{33}^T]$	$[\epsilon_{33}]$
Compression	E_{11}, E_{22}	ν_{12}, ν_{21}	S_{11}^C, S_{22}^C	$\epsilon_{11}, \epsilon_{22}$
	$[E_{33}]$	$[\nu_{13}, \nu_{23}]$	$[S_{33}^C]$	$[\epsilon_{33}]$
Shear	G_{12}		S_{12}	ϵ_{12}
	$[G_{13}, G_{23}]$		$[S_{13}, S_{23}]$	$[\epsilon_{13}, \epsilon_{23}]$

Through-Thickness Testing

Many approaches have considered for determining TT properties of polymer matrix composites (PMCs) with varying degrees of success [1]. Ideally, the interaction between specimen geometry and loading configuration should aim to produce a region of pure, uniform, maximum stress in order to promote repeatable quantitative measurements. The test method should also be applicable to a wide range of materials and loading modes (i.e. static and fatigue).

Shear

The level of standardisation of TT shear test methods is well advanced when compared to TT tension and TT compression. Although there is a multitude of test configurations, most of these are unsuitable for measuring TT shear properties. Three test methods, the short beam shear (BS EN ISO 14,130 [4]), V-notched beam (ASTM D 5379 [5]) and double-notched shear (ASTM D 3846 [6]) have been evaluated as to their suitability for generating TT shear properties. The short beam and double notch shear methods are only suitable for determining interlaminar shear strength. The V-notched beam can be used to measure in-plane and TT shear properties for isotropic and anisotropic materials.

Short Beam Shear

Short beam shear specimen preparation is straightforward and only a small amount of material is required. Tests are carried out according to BS EN ISO 14,130, at a displacement rate of 1 mm/min. A schematic of the loading configuration is shown in Figure 1. The standard specimen thickness h is 2 mm (nominally) with a width and overall length of 10 and 20 , respectively. The recommended width is $5h$ and overall length is $10h$ for material sectioned from panels with a thickness in excess of 2 mm. In all cases, the loading span is $5h \pm 0.3$ mm.

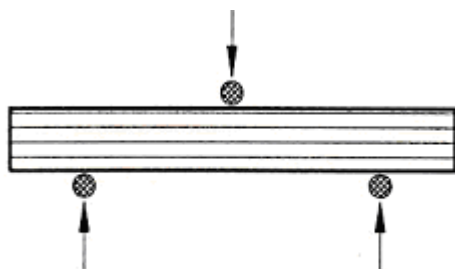


Figure 1: Short beam shear. unidirectional glass fibre-reinforced laminate.

The short beam shear test can be used for determining interlaminar shear strength of continuous aligned and 2-D woven fabric laminates. The shear stress distribution through the beam and along the beam length, is non-uniform. Failure frequently results from a combination of high shear and transverse compression gradients, present in the orthotropic beams near the central loading point. Occasionally, compressive buckling or yielding occurs in the upper portion of the beam. Testing and data analysis is relatively straightforward with the interlaminar shear

strength **S** given as:

$$S = \frac{3P_{\max}}{4bh}$$

where **P_{max}** is the maximum applied, **b** and **h** are the width and thickness, respectively.

There was reasonable agreement between interlaminar shear strength measurements obtained for aligned glass/epoxy and carbon/epoxy materials using the short beam shear and the V-notched beam methods ([Table 2](#)).

Double Notch Shear

The double notch shear test consists of loading a non-symmetrically notched composite specimen in either uniaxial tension (BS 4994 [\[7\]](#) and BS 6464 [\[8\]](#)) or compression (ASTM D 3846). The tension specimens are unsupported, whereas compression specimens (see [Figures 2](#) and [3](#)) are supported along the entire length of specimen to minimise out-of-plane deformation.



Figure 2: Double notch shear specimen. unidirectional glass fibre-reinforced laminate.

The experimental evaluation showed that the interlaminar shear strength data obtained using the compressive method ([Figure 3](#)) were generally consistent with those measured using the V-notched beam test ([Table 2](#)). Fractographic analysis indicated that shear stresses dominated failure when these materials were loaded in compression.

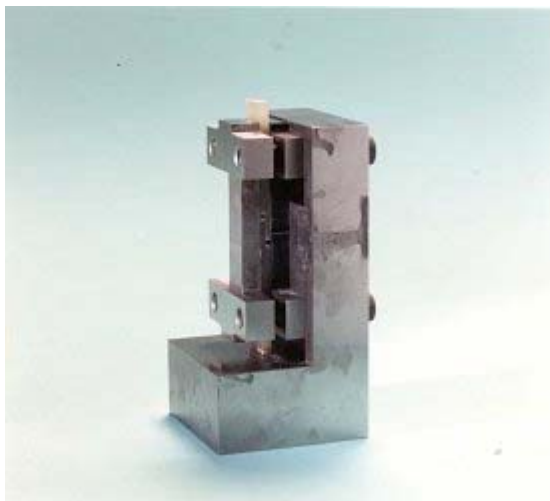


Figure 3: Compression fixture with double notch shear specimen.

The interlaminar shear strength measured using the compression test was consistently higher than corresponding tension tests. The lower strength values for the tension test can be attributed to peel stresses and shear stress concentrations at the notches. Large bending deformations were observed when double notch specimens were

loaded in tension.

The ASTM standard specifies a nominal length of 79.5 mm and a width of 12.7 mm. In the evaluation exercise, 10 mm wide specimens were used. This was to ensure equivalence with the short beam method. Specimen thickness varies from 2.5-10 mm. Two parallel notches, one on each opposite face of the specimen and 6.4 mm (0.25 in) apart, are cut across the entire width of the specimen and centrally located along its length. The notches can be machined using either a diamond slitting wheel (water lubricated) or a tungsten carbide end-mill cutter. The notch, which extends to the specimen mid-plane, is ~1.5 mm wide. The specimen is end-loaded in the supporting fixture (see ASTM D695 [9]) at a displacement rate of 1 mm/min. The securing screws are only finger tight. It is essential that the specimen is free to move along its longitudinal axis (free of friction).

Table 2: Through Thickness Shear Results

Test Method	Shear Modulus (GPa)		Shear Strength (MPa)	
	G _{xz}	G _{yz}	S _{xz}	S _{yz}
<u>Unidirectional Carbon/Epoxy</u>				
V-notched beam	5.3 ± 0.2	2.9 ± 0.3	111 ± 2	64 ± 9†
Double notch	n/a	n/a	75 ± 12	n/a
Short beam shear	n/a	n/a	108 ± 6	n/a
<u>Chopped Strand Mat</u>				
V-notched beam	1.64 ± 0.09	[1.64 ± 0.09]	40.7 ± 1.7	[40.7 ± 1.7]
Double notch	n/a	n/a	38.3 ± 4.7	[38.3 ± 4.7]
Short beam shear	n/a	n/a	13.4 ± 3.0†	[13.4 ± 3.0]†
<u>2 x 2 Twill Glass Fabric/Epoxy</u>				
V-notched beam	4.12 ± 0.14	[4.12 ± 0.14]	68.4 ± 0.9	[68.4 ± 0.9]
Double notch	n/a	n/a	64.9 ± 1.8	[64.9 ± 1.8]
Short beam shear	n/a	n/a	52.5 ± 0.6†	[52.5 ± 0.6]†
<u>Discontinuous Glass/Nylon 66</u>				
V-notched beam	1.68 ± 0.06	[1.68 ± 0.06]	56.9 ± 3.6†	[56.9 ± 3.6]†
Double notch	n/a	n/a	66.4 ± 4.8	[66.4 ± 4.8]
Short beam shear	n/a	n/a	18.6 ± 0.4†	[18.6 ± 0.4]†
<u>Random Mat/Polypropylene</u>				
V-notched beam	1.04 ± 0.04	[1.04 ± 0.04]	22.7 ± 0.8	[22.7 ± 0.8]
Double notch	n/a	n/a	38.3 ± 4.7	[18.1 ± 3.3]
Short beam shear	n/a	n/a	14.2 ± 1.5†	[14.2 ± 1.5]†

*n/a = not applicable; † non-shear value; [] denotes value assumed from material symmetry.

This method provides consistent strength data (low scatter) with interlaminar failure occurring along the mid-plane joining the notches. Notch depth must be accurately machined. Higher strength values are produced when the

notch depth is less than half the specimen thickness (i.e. $< h/2$). This is due to an increase in the cross-sectional area of the fracture path (i.e. not along the mid-plane). Conversely, notch depths exceeding a depth of $h/2$ will fail prematurely giving low strength values. Bending and peeling are frequently observed in over-cut specimens.

No allowances are made for non-uniformity of the stress distribution between notches or the effect of local stress concentrations at the fibre ends associated with the notch geometry. Failure surfaces indicate shear dominated mixed-mode failure.

The shear strength **S** is given by:

$$S = \frac{P_{\max}}{bl}$$

where **P_{max}** is the maximum applied, **b** and **l** are the width and notch separation, respectively.

V-Notched Beam Shear

This test employs a double edge-notched, flat, rectangular specimen (Figure 4). Tests are carried out according to ASTM D 5379 using the loading fixture shown in Figure 5. Standard specimens are 76 mm in length and 20 mm wide with a nominal thickness of 5 mm. Two 90° angle notches with a notch root radius of 1.3 mm are machined at the edge mid-length with faces oriented at $\pm 45^\circ$ to the longitudinal axis, to a depth of 20% of the specimen width (i.e. 4 mm). Notches are machined using a water lubricated, diamond grinding wheel. Shear strain is measured by bonding two biaxial strain gauges, one on each opposite face of the specimen at the specimen centre in the area between the notches. The strain gauges should have an active gauge-length of 1 or 2 mm and must be aligned $\pm 45^\circ$ to the longitudinal axis of the specimen (Figure 4).



Figure 4: V-notched beam specimen. unidirectional glass fibre-reinforced laminate.

Provided adequate material thickness is available (i.e. 20 mm thick), this method can be used to measure shear modulus and shear strength in all three material planes (**x-y**, **x-z** and **y-z**) for a diverse range of composite materials. Differences between shear moduli, due to out-of plane deformation, could be as high as 10% for a batch of nominally identical specimens. To ensure maximum accuracy, shear modulus is determined from the average response of back-to-back biaxial rosettes. At present the standard requires only one specimen from a batch to be tested in this manner provided the amount of twist for the test specimen is no greater than 3%.

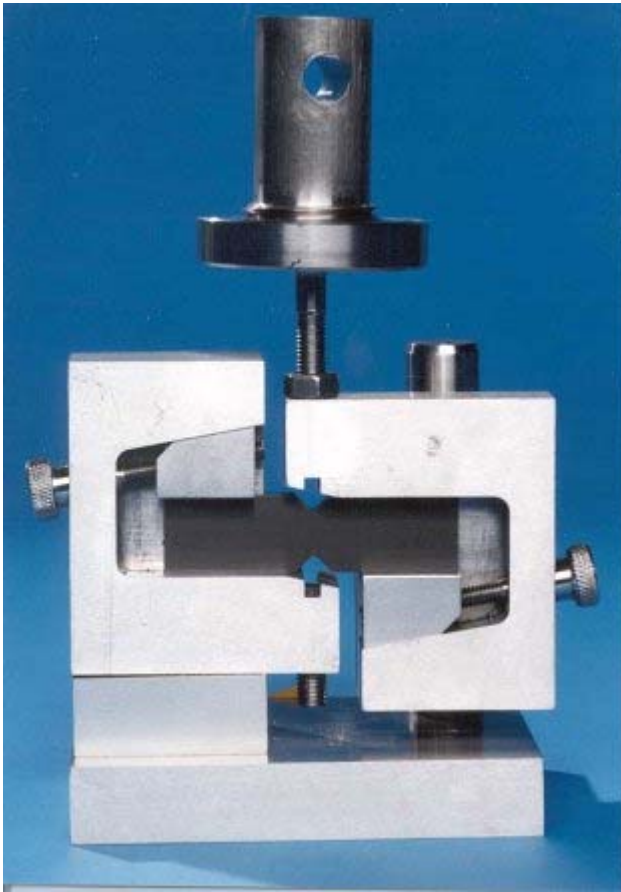


Figure 5: V-notched beam loading fixture and specimen.

The average shear strength **S** and shear modulus **G** can be determined using:

$$S = \frac{P_{\max}}{wh}; \quad G = \frac{\Delta\tau}{\Delta\gamma} = \frac{\Delta P}{wh\Delta(\varepsilon_{+45} - \varepsilon_{-45})}$$

where **P_{max}** is the maximum applied, **w** is the distance between the notches and **h** is the thickness. The variables **ΔP**, **Δε₊₄₅** and **Δε₋₄₅** are the change in applied load and +45° and -45° normal strains in the initial linear region of the stress-strain (τ-γ) curve.

The following improvements to the test fixture will reduce differences in shear moduli obtained from the two sides of specimen and possibly eliminate the need for two biaxial rosettes:

- Keying the bearing post or adding a second post to prevent twisting of the specimen due to the fixture rotating on the bearing post; and
- Lateral adjustment to minimise out-of-plane deformation. At present, the specimen is not centrally loaded through the specimen thickness.

In addition, the fixture needs to be modified to allow for large plastic deformations commonly encountered when testing fibre-reinforced thermoplastics, by allowing larger deformations to be reached.

Shear property data obtained for a range of PMCs are shown in Tables 2 and 3. It is reasonable to assume material property symmetry in the **x-z** and **y-z** planes for all the materials except the unidirectional carbon/epoxy laminate. Various failure modes were encountered with the failure process being highly dependent on the microstructure and orientation of the material. Most materials tended to fail in shear when tested in the **x-z** or **y-z** planes.

Table 3: V-Notch Beam Results for Carbon and Glass Woven Fabrics

Material	Shear Modulus (GPa)	Shear Strength (MPa)	Failure Strain (%)
	G_{xz} and G_{yz}	S_{xz} and S_{yz}	γ_{xz}^f and γ_{yz}^f
Carbon Fabric/Epoxy	3.88 ± 0.05	65.0 ± 2.4	20.9 ± 1.4
Glass Fabric/Epoxy	3.23 ± 0.35	66.2 ± 5.4	20.5

Shear Fatigue Testing

Constant amplitude (sinusoidal waveform) shear fatigue tests were conducted on carbon and glass woven fabric/epoxy materials using the V-notch beam method. The shear specimens were tested in load control using a servo-hydraulic test machine at a frequency of 5 Hz. The stress ratio R (τ_{min}/τ_{max}) was equal to 0.1. Tests were carried out at four different stress levels (90%, 80%, 70% and 55% S_{xz}). Fatigue strength data was normalised with respect to the corrected interlaminar shear strength S_{xz} for an equivalent loading rate to the fatigue test.

The woven carbon laminate was observed to have excellent shear fatigue resistance. The fatigue life N_f exceeded 5×10^6 cycles at a load of 90% of S_{xz} . The stress-life or S - N (S is the applied stress and N is the number of cycles to failure) response for these materials was almost flat. In comparison, the woven glass laminate was less resistant to fatigue loading (Figure 6). The normalised fatigue life (S - N data) for this material can be represented by the following relationship:

$$\tau_{max} / S_{xz} = 1 - k \log_{10} N_f$$

where τ_{max} is the maximum applied load, S_{xz} is interlaminar shear strength, k (the slope) is the fractional loss in interlaminar shear strength per decade of cycles and N_f is the number of cycles to failure. The value of k is approximately 0.078.

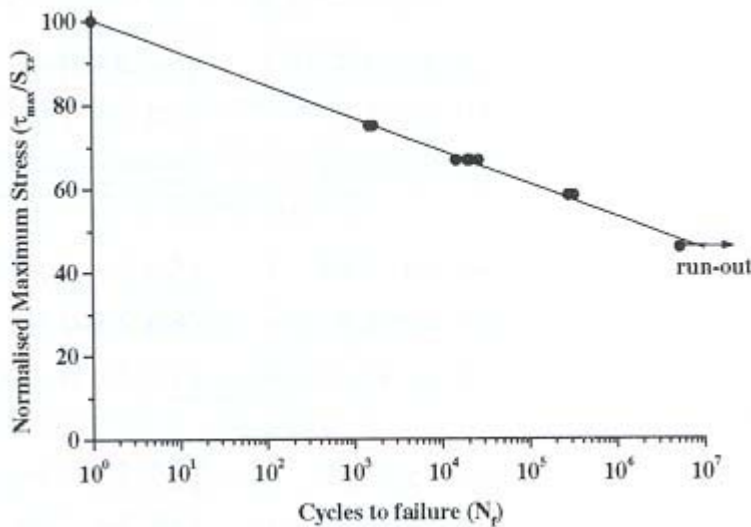


Figure 6: S-N shear fatigue data for woven glass/epoxy laminate.

The change in stiffness with loading cycles due to damage formation (notch-root cracks and shear cracking in the specimen mid-section) is shown in Figure 7. A failed glass fabric/epoxy specimen is shown in Figure 8.

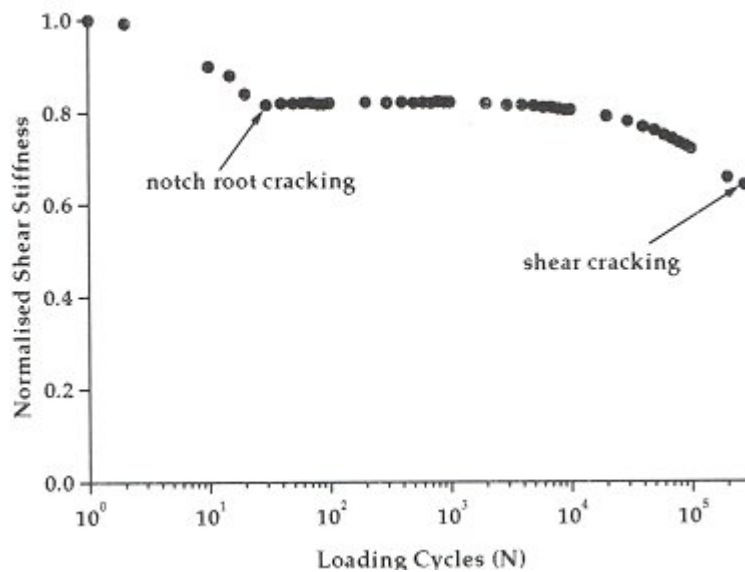


Figure 7: Stiffness vs cycles (70% S_{xz}) for woven glass/epoxy.



Figure 8: Failed woven glass/ epoxy specimen.

Tension

There are two contrasting methods and several associated geometries, which can be employed in the measurement of TT tension (i.e. direct and indirect tensile loading). The direct method introduces tensile load to parallel sided (square cross-section) or waisted short block specimens via adhesively bonded bars or through grips (Figures 9 and 10). The indirect method aims to induce TT tension, in significantly curved specimens by the application of bending moments. The load is introduced via the specimen lever arms, in either tension or flexure [1-3]. Indirect methods (e.g. C-section) tend to produce mixed mode failure, and not TT tension. In-plane tensile methods identified in ISO 527-5 [10] are unsuitable for adaptation to TT tensile testing due to manufacturing difficulties and costs associated with producing thick composite sections (i.e. 20 mm, or greater). ISO 527-5 specifies a specimen length of 250 mm.

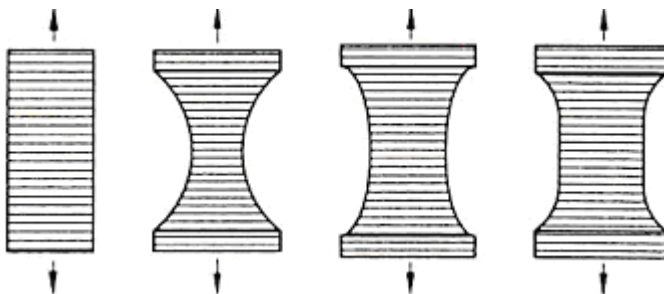


Figure 9: Schematic of direct T-T tensile test methods From left to right: Parallel sided, circular, elliptical and RARDE specimens.

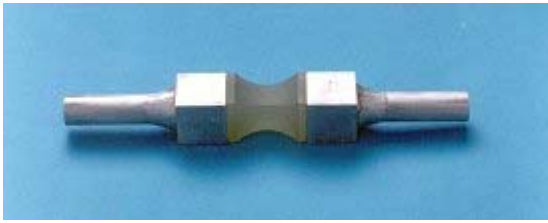


Figure 10: Circular waisted specimen with end loading grips.

This section describes three direct methods that can be used for generating TT tensile and compressive properties.

Short Parallel-Sided Block

Short parallel-sided blocks with a square cross-section can be used to measure TT tensile elastic properties. This geometry is unsuitable for measuring TT tensile strength. Biaxial strain gauges (2 or 3 mm gauge-length), measuring axial and transverse strains are bonded onto the mid-line of each of the four sides of the specimen. This enables average strains to be calculated, thus accounting for bending due to small deviations in specimen or load alignment.

Square cross-section specimens (15 mm square) with TT dimensions (i.e. thickness) ranging from 18 to 40 mm have proved satisfactory for measuring TT tensile elastic properties (see [Table 4](#)). It is essential that the top and bottom surfaces and faces are flat and parallel. This comment also applies to all surfaces. Specimens need to be ground to size with a tolerance of ± 0.1 mm. Reusable aluminium or hardened stainless steel (preferred option) loading bars are bonded to the specimen using a high strength epoxy adhesive. Specimens need to be held in a gluing fixture (e.g. V-blocks) to ensure good alignment between loading blocks and loading axis during the curing process, and to maintain pressure on the bonding surfaces. Specimens need to be left for at least 24 hours before testing.

Table 4: Through Thickness Tension Results

Test Method	Poisson's Ratio		Modulus, E_{zz}	Strength, S_{zz}
	ν_{zx}	ν_{zy}	(GPa)	(MPa)
UD Carbon/Epoxy				
Parallel-sided block	0.019 ± 0.002	0.55 ± 0.01	9.9 ± 0.1	n/a
RARDE waisted block	0.020 ± 0.001	0.47 ± 0.01	9.5 ± 0.1	78 ± 7
Plain waisted block	n/a	n/a	n/a	71 ± 6
Chopped Strand Mat				
Parallel-sided block	0.23	[0.23]	6.3	n/a
RARDE waisted block	0.25 ± 0.05	0.21 ± 0.05	5.3 ± 0.4	8.2 ± 12
Plain waisted block	n/a	n/a	n/a	9.1 ± 2.0
2 x 2 Twill Glass Fabric/Epoxy				
Parallel-sided block	0.19 ± 0.01	[0.19 ± 0.01]	11.0 ± 0.4	n/a
RARDE waisted block	0.18 ± 0.04	0.17 ± 0.01	11.2 ± 0.1	36 ± 1
Plain waisted block	n/a	n/a	n/a	41 ± 8
Discontinuous Glass/Nylon 66				

Parallel-sided block	0.27 ± 0.04	0.41 ± 0.02	4.4 ± 0.1	n/a
Plain waisted block	n/a	n/a	n/a	69 ± 7
Random Mat/Polypropylene				
Parallel-sided block	0.16 ± 0.04	$[0.16 \pm 0.04]$	3.5 ± 0.2	n/a
Plain waisted block	n/a	n/a	n/a	5.7 ± 1.6

* n/a = not applicable; [] denotes value assumed from material symmetry.

This is a relatively straightforward and economic specimen to test, requiring no special loading fixture. Although, care needs to be taken to ensure that misalignment, at both the fabrication and testing stages, is minimised. Failure consistently occurs at the adhesive joints between the specimen and the metallic loading bars for all but the weakest materials, and therefore this test geometry is unsuitable for measuring TT tensile strength. Difficulties will be encountered when trying to bond to thermoplastic materials.

RARDE Waisted Block

This test geometry (developed by the Defence Evaluation and Research Agency (DERA)), can be used to measure TT elastic and strength properties in both tension and compression. Specimens have 25 mm square ends and a nominal height (thickness) of 38 mm. The gauge-section is 12 mm long, with a rectangular cross-section of 10 mm (2-3 or y-z plane) x 16 mm (1-3 or x-z plane). Thinner material (19-20 mm thick) can be tested provided the linear dimensions of the specimen are scaled in proportion to the standard geometry shown in [Figure 11](#).

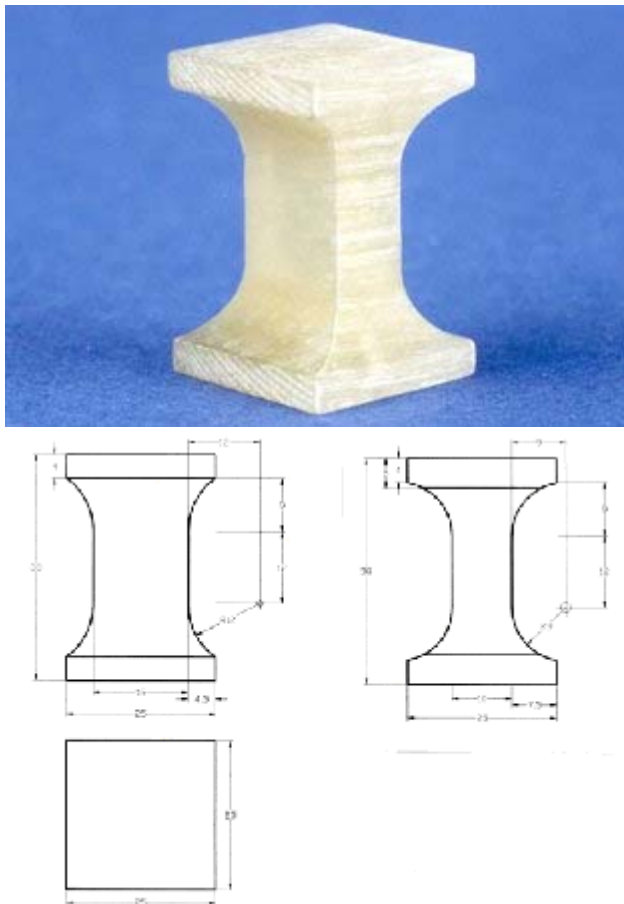


Figure 11: RARDE waisted block specimen.

Specimen preparation, testing ([Figure 12](#)), strain gauging and data analysis are similar to those employed for the

parallel-sided short block specimens. A profile grinding wheel is used to waist the specimen. TT tensile property data obtained using the standard RARDE geometry are shown in Tables 3 and 4. TT tensile strength S_{zz}^T is determined using the following relationship:



where P_{max} is the maximum applied and A is the cross-sectional area of the gauge-section.



Figure 12: RARDE tension test (courtesy of DERA)

RARDE specimens tend to fail in the gauge-section in the plane normal to the applied load. The presence of voids, either locally or globally, will contribute to premature failure under static or fatigue loading conditions. Again, care needs to be taken to ensure minimum misalignment, at both the fabrication and testing stages. Discounting the problem of misalignment, this test method is relatively straightforward to perform. However, machining and instrumentation is labour intensive and expensive. For the highest accuracy, the technique requires biaxial gauges on all four faces. Extensometers are not particularly suitable for this test geometry.

Plain or Circular Waisted Block

In an attempt to simplify machining requirements, reduce production costs and minimise stress concentrations, a plain/circular waisted specimen was developed for measuring TT tensile and compressive strengths. The specimen has a square cross-section (25 mm base), which is waisted on all side faces by a plain radius along the gauge-length (Figure 13). Specimen preparation and test procedure is identical to that employed for the other specimens. Failure occurs consistently within the gauge-section of well bonded specimens (Figure 14). The large (30 mm) radius ensures that the stress concentration at the mid-section is minimal (~ 1.10). Machining costs compared with the RARDE test are marginally lower.

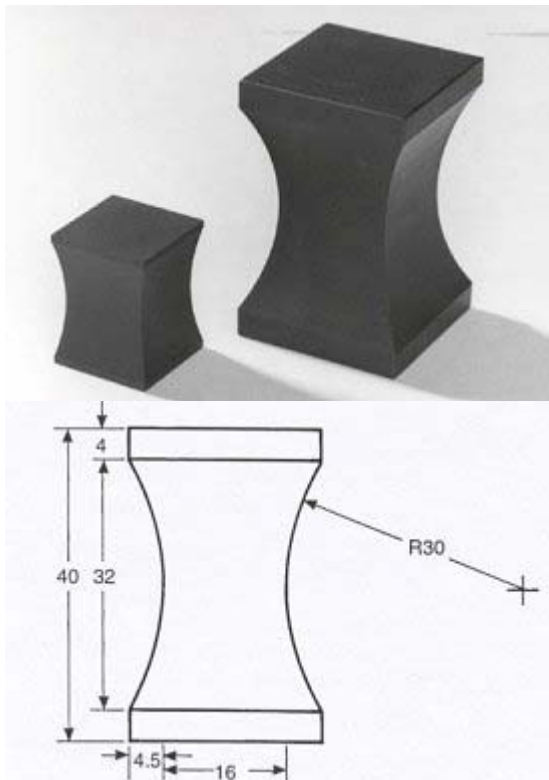


Figure 13: Plain waisted specimen.



Figure 14: Failed RARDE tension specimen.

Tensile Fatigue

Constant amplitude (sinusoidal waveform) tensile fatigue tests were conducted on carbon and glass woven fabric/epoxy materials using the RARDE test method (Figure 12). The specimens were tested in load control at a frequency of 5 Hz. The stress ratio R ($\sigma_{\min}/\sigma_{\max}$) was equal to 0.1. Tests were carried out at four different stress levels (90%, 80%, 70% and 55% σ_{UTS}). Fatigue strength data is normalised with respect to the ultimate tensile strength σ_{UTS} or in the case of TT tension S_{zz}^T (see Table 5 and Figure 15) for an equivalent loading rate to the fatigue test.

Table 5: RARDE Tension/ and Compression Results for Carbon and Glass Woven Fabrics

Test Method	Poisson's Ratio		Modulus, E_{zz}	Strength, S_{zz}
	ν_{zx}	ν_{zy}	(GPa)	(MPa)

Carbon Fabric/Epoxy				
Tension	0.08 ± 0.01	0.08 ± 0.01	9.8 ± 0.5	51.4 ± 2.2
Compression	0.09 ± 0.01	0.09 ± 0.01	12.4 ± 0.9	763 ± 25
Glass Fabric/Epoxy				
Tension	0.18 ± 0.01	0.17 ± 0.01	11.1 ± 0.6	48.5 ± 8.9
Compression	0.20 ± 0.01	0.20 ± 0.01	11.6 ± 0.9	526 ± 11

Provided the specimens are well aligned and the material is free of defects then the RARDE specimen can be used to produce TT tensile fatigue (**S-N**) data (Figure 15). However, small misalignments during testing and the presence of voids resulted in large uncertainties in the fatigue life of the woven fabric materials. The normalised fatigue life for woven glass laminate can be represented by the following relationship:

$$\sigma_{\max} / \sigma_{\text{UTS}} = 1 - k \log_{10} N_f$$

where $\sigma_{\max}$ is the maximum applied load and σ_{UTS} is ultimate TT tensile strength. The value of $k \approx 0.086$. The woven carbon laminate contained a high void content, which shortened the laminates fatigue life ($N_f > 10^6$ cycles for $\sigma_{\max} = 70\% \sigma_{\text{UTS}}$).

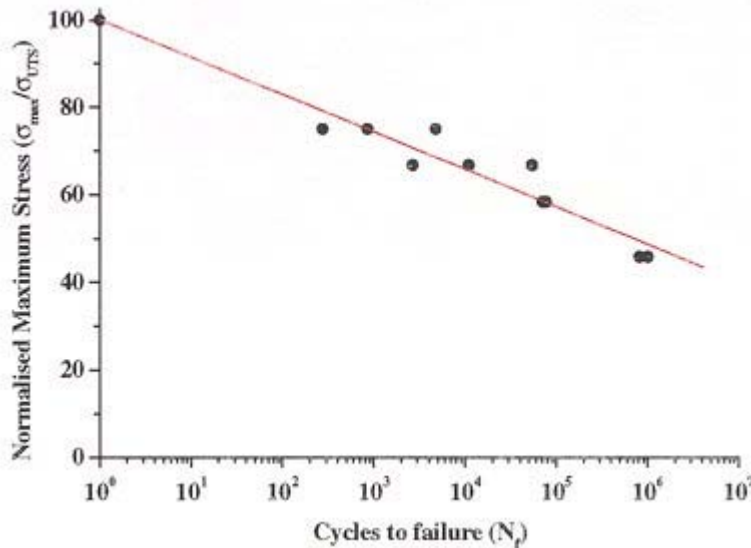


Figure 15: S-N tensile fatigue data for woven glass/epoxy laminate.

Compression

All three short block geometries described in the previous section have been evaluated in compression. The results obtained using the three geometries (Tables 5 and 6) parallel those for tension. Specimens are loaded in compression between flat, parallel hardened steel platens with recesses to reduce lateral movement of the specimen. It is recommended for static tests only that a four pillar die set be used to maintain uniform compression loading (Figure 16). Specimens 20-40 mm thick can be tested provided linear dimensions are scaled in proportion, and that the material does not buckle under compressive loads. Thermoplastic composites tend to buckle, and hence for these materials the plain waisted specimen is preferred method for measuring TT compressive strength. Stress concentrations at the fillet root of waisted specimens can be expected to reduce strength measurements. The effects of stress concentrations are less pronounced for the plain waisted blocks, and hence the generally higher strength values compared with the RARDE geometry.

Table 6: Through Thickness Compression Results

Test Method	Poisson's Ratio		Modulus, E_{xx} (GPa)	Strength, S_{xx} (MPa)
	ν_{xx}	ν_{xy}		
Unidirectional Carbon/Epoxy				
Parallel-sided block	0.022 ± 0.001	0.52 ± 0.01	10.0 ± 0.1	263 ± 3
RARDE waisted block	0.020 ± 0.005	0.56 ± 0.01	10.3 ± 0.2	297 ± 5
Plain waisted block	n/a	n/a	n/a	343 ± 7
Chopped Strand Mat				
Parallel-sided block	0.29 ± 0.01	$[0.29 \pm 0.01]$	6.3 ± 0.3	211 ± 6
RARDE waisted block	0.23 ± 0.04	0.23 ± 0.04	6.2 ± 0.3	202 ± 12
Plain waisted block	n/a	n/a	n/a	236 ± 10
2 x 2 Twill Glass Fabric/Epoxy				
Parallel-sided block	0.21	$[0.21]$	12.4	588 ± 29
RARDE waisted block	0.19 ± 0.01	0.18 ± 0.01	11.8 ± 0.2	545 ± 6
Plain waisted block	n/a	n/a	n/a	543 ± 5
Discontinuous Glass/Nylon 66				
Parallel-sided block	0.21	0.44	4.3	190 ± 8
Plain waisted block	n/a	n/a	n/a	195 ± 5
Random Mat/Polypolyene				
Parallel-sided block	0.27	$[0.27]$	4.2	181 ± 14
Plain waisted block	n/a	n/a	n/a	210 ± 9

* n/a = not applicable; [] denotes value assumed from material symmetry.

In-plane tests (i.e. IITRI, Celanese or end block methods [11]), are unsatisfactory due to the difficulty in obtaining material of the required thickness (110 mm) and the sensitivity of the specimens to premature failure during handling and testing. Parallel-sided blocks are only suitable for measuring TT elastic properties. Stress concentrations induced at the ends of specimens can result in premature failure. Shear is the predominant cause of failure in all cases; independent of material microstructure, loading configuration or specimen size [3].

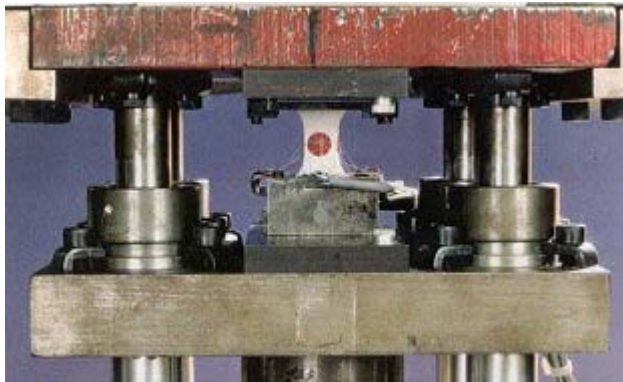


Figure 16: RARDE compression specimen and loading fixture (courtesy of DERA).

Compression Fatigue

Fatigue tests are normally carried out at the highest frequency possible in order to minimise test duration. Restrictions on test frequency can arise due to test equipment limitations, (response time), time-dependent processes and hysteretic heating. Hysteretic heating can precipitate a rise in temperature causing thermal degradation of the material. The increase in temperature is dependent on strain or frequency rate, stress amplitude, specimen geometry, loading mode and thermal conductivity of the material. Hysteretic heating, which increases with stress amplitude and frequency, was observed to adversely affect the compression fatigue performance of carbon and glass woven RARDE specimens. Test frequencies of the order of 1 to 5 Hz resulted in a substantial increase in the surface temperature ($> 170^{\circ}\text{C}$) and short fatigue life. Reducing the frequency to 0.1 Hz and stress amplitude to 25% ultimate compressive strength results in a fatigue life $N_f > 5 \times 10^6$ cycles. The maximum temperature rise of the material should be less than 10°C .

Concluding Remarks

The V-notched beam test has been shown to be suitable for measuring interlaminar shear properties under static

and fatigue loading conditions, although improvements to the ASTM test fixture are proposed. NPL has developed draft procedures that can be used to measure TT elastic and strength properties under tensile and compressive static loading conditions. The RARDE specimen has been shown to be suitable for use under tension-tension fatigue loading conditions, provided the material is free of voids and the specimen is well aligned. This geometry is also suitable for compression fatigue loading, providing hysteretic heating is avoided. The normalised **S-N** data for TT shear and tension fatigue for a glass woven/epoxy were similar, and can be represented by a simple empirical relationship.

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Acknowledgements

The research reported in this Measurement Note was carried out by NPL, in conjunction with DERA, as part of the 'Materials Measurement Programme' funded by the Engineering Industries Directorate of the UK Department of Trade and Industry. The authors acknowledge the contribution of their colleagues Dr G D Sims, Mr R Mera and Mr S Gnaniyah at the National Physical Laboratory, and Mr R Ferguson (now at BAE SYSTEMS), Dr C Messenger and Mr M Hiley at DERA.

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MATC(MN)06

Through-Thickness Testing of Polymer Matrix Composites

May 2001

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