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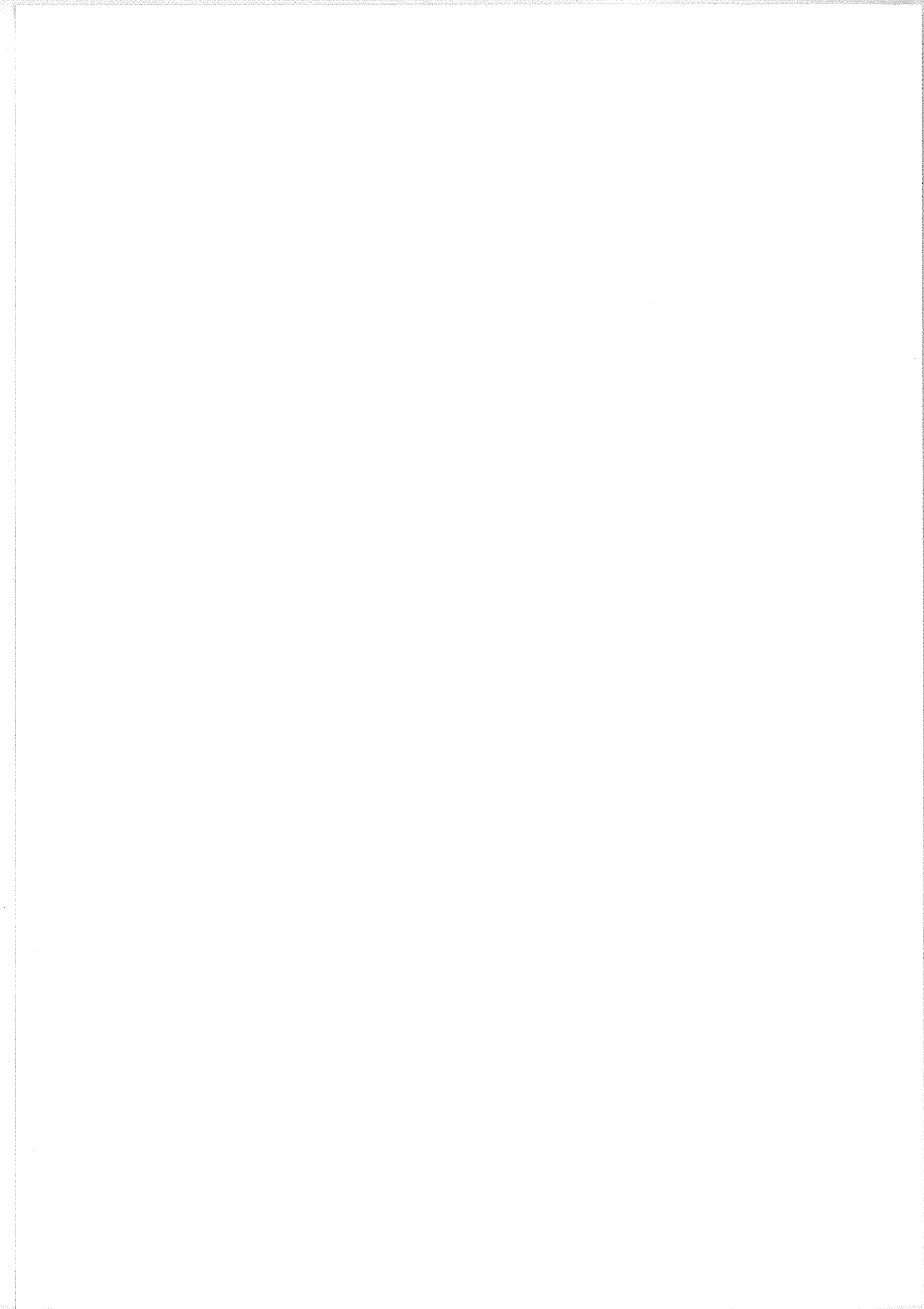


National Physical Laboratory

An Overview of Through-Thickness Test Methods for Polymer Matrix Composites

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ABSTRACT

One of the initial objectives of the project* is to evaluate critically the test methods available for the determination of all the out-of-plane or through-thickness (T-T) tensile, compressive and shear properties. A decision analysis technique was applied to quantitatively evaluate each method in terms of 14 criteria, encompassing a number of key issues. These included data producibility, cost of fabrication, cost of testing, availability of a standard test method, ease of data reduction and accuracy of test data. The relative importance of the criteria was based on an assessment by industry.

The results of the analysis were not unequivocal, there were no definite winners or losers. In fact, the evaluation clearly showed that all the tests were far from ideal, and often the difference between test methods was marginal.

Additional sections review ultrasonic techniques for the determination of in-plane and through-thickness elastic constants; and mode I, mode II, mixed mode I/II and mode III interlaminar fracture toughness test methods. Problems associated with material fabrication of thick sections are also considered.

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Approved on behalf of Chief Executive, NPL, by Dr M K Hossain,
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1. INTRODUCTION

Polymer matrix composite (PMC) materials are widely used throughout industry for applications ranging from automotive parts to civil engineering applications. To exploit European and global markets UK industry must be capable of improved and more consistent design and production, together with cheaper materials and processes. A pivotal factor for improving, or maintaining, competitiveness is through increasing the engineer's confidence in designing with PMC materials and thus encouraging the development of new applications. Improved product design will reduce cost, and improve the performance and reliability in service. To achieve this objective, requires reliable design procedures, relevant data and validated test methods, which are the aims of this current DTI funded research programme.

Extensive research has been undertaken worldwide into test methods and design procedures for in-plane properties of PMCs. As a result, a supporting infrastructure of test methods is beginning to be established on an international basis [1-2]. However, considerably less research and development of test methods for out-of-plane or through-thickness (T-T) properties has been undertaken.

T-T stresses occur in laminated structures; irrespective of laminate thickness. For example, laminated structures with local curvature (eg flanges) or other stress concentrating features are frequently encountered in engineering applications. Edge effects, holes, ply drop-off, and bolted and bonded joints all produce three-dimensional stress states. Consequently, the designer/user needs T-T engineering properties in tension, compression and shear to predict failure stresses resulting from the presence of these geometric features.

Whereas, since the 1960s work has been principally directed towards "thin" laminates (less than 6 mm), increasingly the applications involve larger thicknesses. There is concern that as thicker laminates are used, or a higher utilisation of properties is required for thin laminates, it is no longer satisfactory to design solely for in-plane loads. This concern already exists, as even for thin laminates there is low confidence in the assumption that a two-dimensional analysis is sufficient. To undertake more exact three-dimensional analysis requires a full three-dimensional set of strength and stiffness properties (see Table 1 below and Figure 1.1). In consequence, standard test methods applicable to material and applications encompassing both "thick" and "thin" sections are required.

TABLE 1 Short term data for orthotropic materials

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

[] T-T properties

The DTI funded project "Test Method Development and Prediction of Performance of Composite Components" aims to develop and validate test methods for measuring these T-T properties and to ensure their relevance and use in design. For example, the data will be used in the complementary part of the project on test methods and design methodology of structural elements and stress concentrating features.

2. SCOPE OF REVIEW

The main requirements of this critical review is to give more detailed consideration to T-T test methods and to extend the CRAG review [3] for PMCs with particular reference to:

- (i) Extending the review to non-aerospace/defence materials (eg chopped strand mat (CSM) and sheet moulding compounds (SMC)).
- (ii) Test methods applicable to thin laminates.

The T-T review provides:

- (i) A critical assessment of available tensile, compressive, shear, ultrasonic and fracture toughness test methods and their suitability for different PMCs.
- (ii) A ranking of alternative test methods for each category using a decision analysis technique. The assignment of quantitative ratings includes an assessment by the industrial panel associated with the work.
- (iii) Recommendations for modifying existing methods where deficiencies exist.
- (iv) An assessment of ultrasonic methods for determining in-plane and T-T elastic constants and interlaminar fracture toughness test methods.

Each test method is examined in terms of:

- (i) Suitability to various fibre formats or architecture, and matrices.
- (ii) Properties obtained.
- (iii) Test specimen geometry, size and alignment.
- (iv) Test specimen preparation (including machining and tabbing).
- (v) Fixture and testing equipment requirements.
- (vi) Strain measurement techniques.
- (vii) Problems associated with load introduction and free edges.
- (viii) Test data analysis, repeatability and reproducibility.
- (ix) Induced failure modes and associated problems.
- (x) Data reproducibility (limited information published to date).
- (xi) Level of standardisation.

Consideration is given to the practicality of using the test method in an industrial environment, in terms of ensuring "fitness for purpose". The importance of the different parameters has been developed by liaison with industry with the assignment of quantitative ratings based upon their evaluations.

Several additional issues have been considered when reviewing each test method: (i) residual stresses in thick laminates; (ii) non-linear response; (iii) degree of uniformity of stress distributions throughout the test geometry; and (iv) the applicability of the test method for fatigue and environmental testing;

The report is divided into ten sections (including the Introduction and Scope of Review (Section 2)). For each property: tension (Section 3); compression (Section 4); and shear (Section 5) the available mechanical test methods are assessed. Tables 2 to 4 contain a summary of each test method reviewed. Section 6 compares ultrasonic techniques, assessing their suitability for a wide range of materials. Mode I, mode II, mode III and mixed mode I/II interlaminar fracture toughness test methods are considered in Section 7. General issues on material fabrication are dealt with in Section 8.

The results of an industrial survey on the relative importance of a number of key issues related to T-T test methods is summarised in Section 9. This section also includes a quantitative assessment of tension, shear and compression T-T test methods. Conclusions are given in Section 10.

3. KEY ISSUES IN TENSION

The CRAG review [3] identified two basic configurations for T-T tension measurements: (i) direct tensile tests; and (ii) indirect tensile (or bending) tests. The latter involves bending of a curved specimen to induce T-T tensile stress. Direct tensile tests can be conducted on both thick and thin laminate specimen types. Thick laminate specimens are usually dog-bone shaped in the T-T direction and form the complete specimen. An example of this is the direct tensile long coupon specimen (Type A) shown in Figure 3.1.

Relatively thin laminates need to be loaded via bonded metal or composite blocks to produce T-T tension. The direct tensile short block (Type B) specimen shown in Figure 3.2 is a typical example. An example of a configuration which may be compatible with direct tensile loading is the waisted block or RARDE specimen (Figure 3.3). This configuration was designed using three-dimensional finite element analysis for the measurement of T-T compressive properties, with possibilities as a good candidate for T-T tensile testing. RARDE specimens under tensile loading would resemble the Type B configuration.

Applied bending moments in sections of significant curvature can also produce direct T-T tensile stresses. Bend test specimens include semi-circular and semi-elliptic plan curved beams. Typical examples of bend specimens are the C-section (Type C), hump-back or bridge specimen (Type D) loaded in four-point flexure and the closed ring specimen; as shown in Figures 3.4, 3.5 and 3.6, respectively.

This section will critically compare the two basic test configurations in order to identify suitable candidates for standardisation (see also Table 2).

3.1 LEVEL OF STANDARDISATION

The current status is that no method has been adopted or is in the process of being adopted as a standard for the measurement of T-T tensile properties (ie modulus, strength and strain). A transverse tensile test does exist for sandwich structures (ASTM C 297-61 [4]). In-plane tensile methods identified in the ISO/DIS 527 standard [5] are unsuitable. The prime factor restricting the use of the test configuration is the specimen dimension in the thickness-wise direction. The in-plane tensile specimens are 250 mm long, consisting of a gauge-length of 150 mm plus an additional 50 mm grip length at each end. In fact, thicknesses of 20 mm or greater can pose problems for certain fabrication routes.

A major driving force behind T-T test method research has been the aim to limit the thickness-wise dimension. This has inspired a number of atypical test configurations. It should be noted that no specific standard exists for specimen machining, which is likely to be particularly important for T-T tensile specimens. This subject is being studied by the CEN standards committee, TC249/SC2/WG5.

3.2 TENSILE PROPERTIES OBTAINABLE

Type A specimens are, in principle, suitable for measuring T-T modulus and T-T strength and are either rectangular or circular in cross-section. A rectangular cross-section facilitates the measurement of lateral strains, which are required for the determination of Poisson's ratios. A round cross-section, however, is incompatible with lateral strain measurements for anisotropic materials.

The RARDE specimen designed for T-T compression is also a suitable candidate for T-T tension measurements. This configuration has the capability of providing T-T tensile strength and a full set of elastic constants for the three material directions.

The remaining specimen designs are only suitable for measuring interlaminar tensile

strengths. It is not feasible to modify these test methods to obtain elastic constants (eg E_{33} and ν_{13}).

3.3 MATERIAL SUITABILITY

T-T testing has been restricted to the examination of continuous fibre, multilayered, laminated structures where constituent layer fibre orientations are clearly defined. Included in this classification are two-dimensional woven fabrics. The scope of materials tested reflects the requirements of the aerospace/defence industry where most of the ideas for T-T test methods originate. T-T test method requirements for discontinuous fibre-reinforced laminates and continuous random fibre arrays have been virtually ignored.

Indirect tensile or bending configurations (ie Type C, Type D and closed ring) are likely to be suitable for testing continuous fibre-reinforced laminates only; as defined above. These methods are probably unsuitable for measuring the T-T strength of random fibre arrays and discontinuous fibre-reinforced composite materials, as these tend to fail in transverse tension.

Direct tensile configurations (ie Type A, Type B and RARDE) are compatible with all isotropic and anisotropic materials. Obviously, caution should be used in the interpretation of failure; as the mode of failure can be expected to be dependent on fibre format.

3.4 SPECIMEN PREPARATION REQUIREMENTS

Indirect tensile or bending configurations (ie Type C, Type D and closed ring) are relatively easy to fabricate to a good standard using matched die moulding. This involves the use of matching tool, steel or aluminium, male and female dies which close to form a cavity of the shape of the component. Type C and closed ring specimens can be fabricated either by wrapping prepreg sheets onto a removable metal mandrel and curing under pressure or by filament winding about a mandrel.

Semi-circular Type C (normally with arms) and closed ring specimens are particularly suited for testing filament wound structures, and their geometry is also representative of a number of structural features, including bends and elbows, in other material systems. Specimens of both configurations can be sectioned from tubular structures. Machining individual specimens is relative simple and cheap to perform. Fabrication of the laminated sheet or structure is moderately expensive when accounting for the initial costs of producing mandrels and moulding dies.

Direct tensile configurations are usually machined from flat panels. These configurations can also be sectioned from tubular structures of sufficient wall thickness. The larger the diameter and the smaller the cross-section, the smaller the effects of ply curvature across the specimen width. Direct tensile configurations have considerable machining requirements, particularly Type B and RARDE specimens. The machining operation is labour intensive and expensive.

In the case of direct tensile specimens, symmetry is critical for low-failure strain systems; as bending stresses produced through eccentric loading can result in premature failure. Care should be taken during the machining operation to minimise/eliminate the possibility of specimen asymmetry.

The advantage of the indirect tensile configurations is that the test only requires materials of 10 mm thickness or less. Typically, Type B and RARDE specimens require thicknesses of 12 and 38 mm, respectively. Type A specimens need to be sectioned from laminated structures 150 mm to 190 mm thick. This is not cost effective when considering the expense involved in producing thick laminates. It is interesting to note that Type A specimens consume only a small amount of material, as the cross-sectional area for a standard set of five specimens is only 20 cm², while the cost of producing a laminate 150 mm thick or greater is

usually prohibitive. Tests need to be carried out to ascertain if Type A specimens with a length of 80 mm or less can be used.

3.5 SENSITIVITY TO IMPERFECTIONS

Interlaminar tensile strength can be expected to be degraded by the presence of voids, variations in fibre content, state of cure, fibre buckling and machine induced surface damage. Types of damage induced through cutting and milling are fibre pullout, fibre-matrix debonding, fibre breakage and delaminations. Indirect specimens C, D and closed ring can be expected to be relatively free of machine-induced edge damage because of limited machining requirements. However, cut edges are still being loaded. Conversely, the direct specimens require a considerable amount of machining which increases the chances of damage being induced during the machining operation. The RARDE specimen in particular requires considerable care during machining as the specimen geometry is relatively complex (Figure 3.6).

The application of external pressure to composite materials wrapped on a rigid mandrel can result in wrinkling of the laminate and thus poor quality tubular specimens. Type C and closed ring specimens, which are often produced in this manner, may suffer from wrinkling which is exacerbated with increasing thickness. This problem can be avoided through the use of high quality fabrication practices. Since Type C and closed ring specimens are usually less than 10 mm thick and relatively easy to fabricate, the possibility of process-induced damage should be minimal. Type D or humpback specimens which are 9 mm thick should also be relatively free of imperfections.

Specimens requiring a large thickness-wise dimension, for example the Type A configuration and to a lesser degree the Type B and RARDE specimens, are far more likely to contain process-induced damage than the indirect tensile specimens. The thickness-wise dimension of Type A specimens is usually greater than 150 mm, which means that process-induced stresses will have a significant effect on the residual strength properties of the laminated structure. From a fabrication point of view specimen thicknesses in excess of 80 mm can be regarded as impractical for most materials.

The assessment of process-induced damage on T-T properties of both flat and curved laminated structures has been concerned primarily with the effect of voids on the interlaminar shear strength of unidirectional laminates. A small amount of research has also been directed towards examining the effects of voids on matrix dominated properties of aligned materials. Interlaminar shear and transverse tensile strengths diminish dramatically for void contents in excess of 2%. Strength reduction is approximately 7% for every 1% increase in void content [6]. The inference is that interlaminar tensile strength will also be adversely affected in similar fashion.

3.6 LOADING AND FIXTURE REQUIREMENTS

Load introduction for all six configurations is reasonably straightforward using standard tensile/compression mechanical test equipment. The closed ring and Type C (Figure 3.7) specimens require specially designed loading fixtures. Fabrication costs for the Type C loading fixture can be expensive. It is recommended that the fixtures be manufactured from hardened stainless steel to reduce grip wear due to frictional effects and to enable the use of the fixture under hot/wet conditions. Before a specimen is mounted, its contact surfaces should be lubricated (eg graphite) or friction-reducing inserts (eg PTFE) used.

Hump-back (Type D) specimens are tested in four-point flexure. Four-point bend fixtures can be purchased from test machine manufacturers or produced in-house at a relatively low cost. Load spreading pads can be used, but the applied loads are reasonably low.

Type A specimens can be directly loaded in tension. These specimens can be either rectangular or circular in cross-section (Figure 3.1). The advantage of flat specimens is that the specimen geometry is compatible with standard grips, whereas special grips may need to be manufactured to suit circular cross-section specimens. Wedge grip inserts for testing circular cross-sections can be purchased off-the-shelf from a number of mechanical test machine manufacturers, for a small outlay. End tabs may be needed to avoid failures occurring within the grip section. Although this issue has been extensively investigated for in-plane longitudinal and transverse tensile testing, it has been virtually ignored in the experimental assessment of the Type A specimen.

Bonded metallic end blocks are used for Type B and RARDE specimens. The strength of the bonded joints needs to exceed the interlaminar tensile strength of the composite to avoid failure at the intersection between the composite and the loading block. Adhesively bonded loading blocks add to the cost, as well as introducing the problem of interlaminar stress concentrations in the material in the vicinity of the free edges. Interlaminar shear stress concentrations may be partially reduced by cutting off the edges of the end grips adjacent to the test specimen and filling the spacers with a polymer binder.

3.7 STRAIN MEASUREMENT REQUIREMENTS

For Type A and RARDE specimens, strain gauges rather than extensometers are typically used to measure strains. Strain gauges can be placed at the centre of the specimen gauge-length which is usually a region of uniform stress.

Only load and cross-head displacement need to be monitored during the testing of hump-back specimens. It is recommended that an extensometer be used to monitor the displacement between the upper and lower loading points for Type B, Type C and closed ring configurations. The use of an extensometer is preferred to that of directly monitoring cross-head displacement, as the former is far more accurate.

3.8 SIMPLICITY OF DATA REDUCTION

Data reduction procedures for the direct tensile configurations are straightforward. T-T tensile strength is simply the applied load at failure divided by the minimum cross-sectional area of the specimen, measured perpendicular to the direction of the load. Failure may initiate prematurely as a result of stress concentrations at the free edges or, in the case of the RARDE specimen, at the intersection between the gauge-length and the necking radius. Ultimately, it may be necessary to multiply the measured stress at failure by a stress concentration factor to obtain the actual strength.

In principle, data reduction for indirect tensile configurations is reasonably straightforward. However, these structures have a strong tendency to deform during loading and all three indirect tensile configurations tend to straighten under load. In straightening, tangential tensile stresses are introduced into the curved sections of these configurations. The influence of tangential stresses on interlaminar tensile strength needs to be accounted for in the calculations. The accuracy of the analysis depends on the degree of geometric change that takes place prior to failure. The use of thick specimens tends to reduce geometric deformation rather than eliminate this effect altogether. A suitable specimen thickness for elliptical Type C specimens has been found to be approximately 10 mm. Current analysis for the Type C specimens takes into account changes in specimen geometry. Further work is required to refine the error analysis for all three indirect tensile configurations.

3.9 STRESS UNIFORMITY AND FAILURE MODES

It is unlikely that an ideal uniaxial stress state will be present in the gauge-length of any of the three direct tensile configurations. Strain can be expected to vary over the gauge-length

cross-sectional area. Non-axial stresses can also be expected to occur, although these will probably be of secondary importance. High stresses and stress gradients can be expected at the intersection between the gauge-length and the necking radius. These stresses will almost certainly induce premature failure at these points. Stress concentrations in the vicinity of the grip regions could also lead to premature failure.

The uniformity of the stress field can be expected to be better for the longer Type A specimens in comparison with the Type B and RARDE specimens. This is because end effects become less significant with increasing specimen length. For T-T tension, the characteristic decay length over which the end effects are significant is far less than for in-plane longitudinal test geometries.

Two types of failure can occur in the indirect tensile configurations, flexural failure involving the outer layers of the section and delamination failure near the specimen mid-plane. Flexural failure involves either tensile fracture and/or compressive failure at the appropriate surfaces. Fibre fracture does not normally accompany the formation and propagation of delaminations at the centre of the specimen. Caution is required when differentiating between the two modes of failure as it is not unusual for flexural failure to be accompanied by a delamination failure in the outer layers.

For these specimens the resultant failure mode is dependent upon the thickness-to-mean radius ratio (t/R_m) of the curved section, the fibre/matrix system and the lay-up configuration. The specimen thickness is critical. Low t/R_m ratios will probably result in flexural failure and a large amount of elastic distortion prior to failure. A large structural deformation makes it difficult to measure the onset of failure and introduces unwanted tangential tensile and interlaminar shear stresses. An optimum geometry is one where flexural failure does not occur first. Effort is needed to optimise specimen geometry for each of these structures. Edge effects should also be considered in any evaluation exercise.

3.10 CONSISTENCY OF MEASURED DATA

Generally, there is insufficient T-T tensile data available in the literature for a comprehensive check on the reproducibility of results generated using the various T-T tension test methods. Specimen geometries and materials tested to-date are far too few and diverse to make a realistic statistical comparison.

3.11 SUITABILITY FOR LONG TERM AND ENVIRONMENTAL TESTING

Type A specimens should pose no additional problems when subjected to long term testing such as creep or fatigue loading. Type B and RARDE specimens should also be suitable for creep and fatigue testing, provided the integrity of the composite loading-block adhesive joint is not compromised during testing.

Semicircular and elliptical Type C, and the hump-back (Type D) specimens are particularly suited to fatigue testing. The problem of fretting at the loading points may be a problem. Frictional effects are minimal when graphite lubricant or friction-reducing inserts (eg PTFE) are used. This particular problem is also pertinent to fatigue testing of closed ring specimens. All the indirect loading configurations should be compatible with creep testing.

All six loading configurations are suitable for environmental testing. However, difficulties can be expected in trying to reproduce actual environmental conditions experienced by in-service components and structures. The relatively large surface area to volume for these specimens is unrepresentative of actual applications. In addition, environmental degradation of adhesively bonded joints (eg end loading blocks for Type B and RARDE specimens) may occur. Thus, care should be taken to ensure bond integrity for the entire duration of the test.

3.12 SUMMARY

LONG COUPON (TYPE A)

ADVANTAGES	DISADVANTAGES
• Generates all T-T tensile properties • Compatible with most PMCs • Testing is straightforward • Data reduction is simple • Fatigue/creep/environmental use	• Very thick laminates required • Stress concentrations present • Free-edge effects present • Sensitive to specimen misalignment

SHORT BLOCK (TYPE B)

ADVANTAGES	DISADVANTAGES
• Low specimen fabrication cost • Testing is straightforward • Data reduction is simple • Suitable for fatigue (care needed) • Suitable for creep testing • Suitable for environmental testing	• Interlaminar strength only • Non-uniaxial stress state • Stress concentrations present • Free-edge effects present • End load attachments necessary

C-SECTION (TYPE C)

ADVANTAGES	DISADVANTAGES
• Thin laminates (< 10 mm) • Compatible with curved structures • Testing is straightforward • Suitable for fatigue/creep testing • Suitable for environmental testing	• Interlaminar strength only • Moulded/filament wound • Special loading fixture necessary • Complex data reduction • Complex failure analysis

HUMPBACK (TYPE D)

ADVANTAGES	DISADVANTAGES
• Thin laminates (< 10 mm) • Testing is straightforward • Suitable for fatigue/creep testing • Suitable for environmental testing	• Interlaminar strength only • Moulded/filament wound • Four-point loading fixture required • Complex data reduction • Complex failure analysis

WAISTED BLOCK RARDE

ADVANTAGES	DISADVANTAGES
• Generates all T-T tensile properties • Compatible with most PMCs • Testing is straightforward • Data reduction is simple • FEA validation available • Fatigue/creep/environmental use	• Extensive machining required • Non-uniaxial stress state • Stress concentrations present • Free-edge effects present • End load attachments required

CLOSED RING

ADVANTAGES	DISADVANTAGES
• Thin laminates (< 10 mm) • Compatible with tubular structures • Testing is straightforward • Suitable for fatigue/creep testing • Suitable for environmental testing	• Interlaminar strength only • Moulded/filament wound • Special loading fixture • Complex data reduction • Complex failure analysis

4. KEY ISSUES IN COMPRESSION

The determination of in-plane and T-T compressive properties of PMCs is particularly difficult. The problems associated with compression are rather complex, with failure being dependent upon the specimen geometry, material microstructure and loading configuration/apparatus [3, 7]. Ambiguities and uncertainties in the interpretation of fracture can be expected as a result of competition between several failure mechanisms prior to final fracture (eg interfacial failure, fibre microbuckling and plastic deformation in continuous aligned PMCs). These mechanisms are most likely interactive, with progressive damage leading to local stress-redistribution. As a result, the overall stress-strain state within a structure will change continuously with progressive failure.

This section will critically compare the RARDE (Figure 4.1) and short block or Type B (Figure 4.2) end-loaded T-T compressive test methods [3] and in-plane test methods undertaken using the Celanese (Figure 4.3), IITRI (Figure 4.4) and end-block (Figure 4.5) test fixtures. The in-plane methods may be suitable for measuring T-T compressive properties, however there is no data available for verification (see Table 3).

4.1 LEVEL OF STANDARDISATION

No standard exists or is being prepared. The in-plane configurations are covered for glass-fibre systems in ISO 8515 [8]. Method A is for shear loading via end tabs, as undertaken in the Celanese or IITRI test fixtures. Method B is for combined end and shear loading employed by the end-block fixture (EBF) [9, 10]. The revised draft of ISO 8515 [8] has standardised on a rectangular test specimen geometry (Figure 4.6) that can be used in Method A or B test fixtures.

The Celanese type loading configuration is included in ASTM D 3410 [11], prEN 2850, JIS 7076, DIN 65380 and CRAG 400. The IITRI loading configuration was added to ASTM D 3410 in 1987 [11] and is also included in the JIS 7076 and DIN 65380 standards. The prEN 2850 standard now includes a machined integral tab specimen, as well as a tabbed specimen.

4.2 COMPRESSIVE PROPERTIES OBTAINABLE

In principle, all compression test methods could be used to obtain a complete three-dimensional set of elastic constants and T-T compressive strength.

The stress state within the short block compression specimen is far from being uniaxial and so is not particularly reliable for determining elastic properties. This test method, which was developed for testing metals, is only suitable for testing relatively low strength composite materials. It is used for measuring the transverse compressive strength of an aligned composite or the T-T compressive strength of a composite laminate.

4.3 MATERIAL SUITABILITY

All compression test methods, except the short block compression test, should be compatible with all isotropic and anisotropic materials. Obviously, caution should be used in the interpretation of failure; as the mode of failure is dependent on fibre format.

Although the short block compression test method has been used to measure the in-plane and T-T compressive properties of a multitude of PMCs, it is only suitable for testing relatively low strength PMCs.

4.4 SPECIMEN PREPARATION REQUIREMENTS

Short block and RARDE compression tests have been performed on materials with a thickness of 13 and 38 mm, respectively. These two configurations are usually machined from flat panels, but can also be sectioned from tubular structures of sufficient wall thickness. The larger the diameter and the smaller the cross-section, the smaller the effects of ply curvature across the specimen width. Although the RARDE specimen does not require end tabs, the machining operation is labour intensive and expensive.

An overall specimen length of 110 mm, a width of 10 mm and a gauge-length of 10 mm is recommended for use with the Celanese, IITRI and EBF loading configurations (ISO 8515 [8]). These specimen dimensions are recommended for all PMCs. The required thickness is 2 mm for continuous unidirectional materials and between 2 and 10 mm for multidirectional laminates and non-unidirectional fibre reinforcements (eg CSM, woven rovings and hybrids).

The specimens are end tabbed to prevent failure at the loaded ends of the specimen, although for random array reinforcements they are not always necessary. End tabs should be between 0.5 mm and 2 mm thick, non-tapered (ie 90° tab angle) and made from either a glass-fibre/resin cross-ply or fabric laminate with the fibre axes of the fabric set at 45° to the specimen axis.

The use of a T-T dimension of 110 mm is neither feasible nor cost effective when considering the expense involved in producing thick laminates. It may be possible to test thinner laminates using end spacers bonded to each end of the specimen. In this configuration, the specimen butts onto the spacer to form a double-strap joint. The spacer material and thickness is identical to the specimen. The overlap length-to-thickness ratio is ~ 10:1 [12].

4.5 SENSITIVITY TO IMPERFECTIONS

Slender specimens used for the Celanese, IITRI and end-block fixtures are liable to fail as a result of column buckling, whereas short thick block and RARDE specimens are relatively stable under axial compression with compressive behaviour being dominated by the end constraints. Specimen dimensions should be tailored so that Euler buckling is avoided.

The Celanese specimen must be of precise thickness in the tabbed regions. In addition, the thickness of the tabbed specimen continuously changes with increasing load. The combined effect of these errors results in non-symmetric loading (ie non-circular split cone assembly), which allows the gripped ends of the specimen to rotate within the grips. As a consequence, it is easier for the specimen to bend and/or buckle which could result in premature failure.

The RARDE specimen geometry is complex and warrants considerable care when machining to avoid undercuts and to provide parallel load-bearing surfaces. The high degree of machining required exposes this specimen geometry to a high risk of machine-induced damage (eg fibre pullout and delaminations).

4.6 LOADING AND FIXTURE REQUIREMENTS

The RARDE and block compression specimens are subjected to direct compressive loading between two flat, parallel, hardened steel platens with the specimens located at the centre of the platens. A shallow inset in both platens minimises lateral displacement which may occur during the test.

The Celanese, IITRI and end-block compression test methods require special test fixtures. Fixture loading is straightforward using standard mechanical test equipment. Test fixtures need to be accurately machined and are relatively expensive. The end-block test method has an additional cost in the form of a high precision die set.

The Celanese fixture loads a specimen by friction, imposed by split conical collet grips that fit into a matching holder which in turn fits into a close fitting cylindrical sleeve (Figure 4.3). The wedge action of the grips applies side loading to the specimen. The Celanese assembly requires perfect cone to cone contact which is virtually impossible to achieve. Non-symmetric loading will result in premature failure through buckling, unless the test fixture is precision machined. High frictional forces can arise between the inner and outer sleeves of the cylindrical assembly leading to erroneously high stiffness and strength values.

The IITRI method uses flat rather than conical wedges. This provides greater lateral stability than conical collet grips. The wedge grips have broad, flat surfaces which make full contact with the mating flat surfaces in the end-block cavities (Figure 4.4). Two hardened steel rods provide alignment of the upper and lower halves of the fixture. Linear bearings are inserted into the upper block to minimise frictional effects.

The end-block fixture consists of two steel blocks into which either end of the specimen is inserted (Figure 4.5). The specimen is gripped over the length of the end tabs by the side face clamps. All surfaces in contact with the specimen are smooth to prevent damage to the specimen by gripping (end tabs may not be required). The loading blocks are placed within a high precision die set to ensure axial loading. The upper block is bolted to the die set, while the lower block is free to move. Frictional effects are minimal. The end-block fixture can accommodate much thicker specimens than either the Celanese or IITRI test fixtures.

4.7 STRAIN MEASUREMENT REQUIREMENTS

Celanese, IITRI, end-block and RARDE compression test methods can in principle be used to measure all T-T elastic constants; including Poisson's ratios. Strain gauges adhesively bonded to the mid-section of the gauge-length are used in preference to extensometers because of the short gauge-length. Poisson's ratio can be determined from axial and lateral strain measurements. Although short block specimens are not particularly suited to measuring elastic constants, the specimen has suitable length to accommodate strain gauges or an extensometer. As with any compression test, whenever there is concern about specimen bending or buckling, it is necessary to monitor axial strain on both faces of the test specimen.

4.8 SIMPLICITY OF DATA REDUCTION

For all five test geometries, the compressive strength is simply the applied load at failure divided by the cross-sectional area of the specimen measured perpendicular to the direction of the load (ie $\sigma = P/A$). Provided the specimen does not bend and/or buckle under compressive loads the failure analysis is relatively straightforward. There is no experimental or numerical evidence to suggest that a narrow specimen width induces anomalous failure modes.

4.9 STRESS UNIFORMITY AND FAILURE MODES

It is unlikely that an ideal uniaxial stress state will be present in the gauge-length of any of the direct loading configurations. Strain variation and non-axial stresses can be expected, although the latter are likely to be of secondary importance. For the RARDE specimen, high stresses and stress gradients can be expected at the intersection between the gauge-length and the necking radius. These stresses will almost certainly initiate premature failure (Figure 4.1).

The major problem with the short block compression test method is that failure usually initiates at the specimen ends due to stress concentrations. This is true for all materials, with or without fibre reinforcement. In principle, this can be minimised/eliminated by bonding end blocks to the test specimen or by waisting the specimen in the gauge-section. However, failure commonly occurs at the intersection between the gauge-length and the necking radius.

The discontinuities at the ends of the tabs in the in-plane test specimens, combined with the large lateral forces induced by the clamping action of the grips, induce stress concentrations at the intersection between the gauge-length and the tabbed-section. Stress concentrations can be expected to result in lower strength measurements. The use of weakly bonded end tab edges (PTFE inserts between specimen and tabs) reduces these stress concentrations and has been shown to result in a 13% increase in longitudinal compressive strength of unidirectional carbon-fibre reinforced plastics (CFRPs) [10]

4.10 CONSISTENCY OF MEASURED DATA

Generally, there is insufficient T-T data available in the literature for a comprehensive check on the reproducibility of results generated using the various compression test methods. Short block compression strength data are usually widely scattered. This reflects the difficulty encountered when trying to control the end conditions, which can vary from specimen to specimen within the same batch of material. There is insufficient data from RARDE tests to pass comment.

4.11 SUITABILITY FOR LONG TERM AND ENVIRONMENTAL TESTING

High frictional forces, which can arise between the inner and outer sleeves of the Celanese cylindrical assembly, could cause particular problems when using this test fixture for creep and fatigue testing. Friction between the grips and the specimen will probably result in fretting of the grips. The IITRI compression test method has limited creep and fatigue capabilities. The presence of frictional forces between the grips and specimen will probably result in fretting. Frictional effects within the die set can also be expected to limit the use of the end-block fixture for creep and cyclic loading.

The RARDE and short block compression specimens should be suitable for creep and fatigue testing. For fatigue tests, there may be a problem of wear at the specimen/loading platen interfaces.

The Celanese, IITRI and end-block fixtures are suitable for environmental testing. The problem of ice forming within the moving parts of the fixtures could cause problems at sub-zero temperatures. No particular problem is expected for the use of the direct loading configurations for environmental testing.

4.12 SUMMARY

LONG COUPONS

ADVANTAGES	DISADVANTAGES
• All T-T compressive properties • Compatible with most PMCs • Simple data reduction • ISO 8515	• Very thick laminates required • Precise specimen dimensions • Sensitive to misalignment • Numerous test fixtures available

TEST FIXTURES	
ADVANTAGES	DISADVANTAGES
<u>Celanese (shear loaded)</u> • Extensive in-plane database • Suitable for environmental testing	<u>Celanese (shear loaded)</u> • High precision machining • End tabbed specimens required • Limited creep/fatigue capability
<u>ITTRI (shear loaded)</u> • Improved lateral stability • Extensive in-plane database • Suitable for environmental testing	<u>ITTRI (shear loaded)</u> • End tabbed specimens required • Limited creep/fatigue capability
<u>End-Block (end or end/shear loaded)</u> • Specimen end tabs optional • Highest strength measurements • Suitable for environmental testing	<u>End-Block (end or end/shear loaded)</u> • High precision machining • End tabbed specimens required • Limited creep/fatigue capability

WAISTED BLOCK (RARDE)

ADVANTAGES	DISADVANTAGES
• All T-T compressive properties • Compatible with most PMCs • Testing is straightforward • Simple data reduction • FEA validation available • Fatigue/environmental testing	• Extensive machining • Non-uniaxial stress state • Stress concentrations present • Free-edge effects present

SHORT BLOCK (TYPE B)

ADVANTAGES	DISADVANTAGES
• Simple/economic fabrication • Simple/economic test • Simple data reduction • Fatigue/environmental testing	• T-T compressive strength only • Non-uniaxial stress state • Stress concentrations present • Free-edge effects present • Low strength materials • Large scatter in strength data

5. KEY ISSUES IN SHEAR

There are a multitude of shear test methods for the determination of intralaminar (in-plane) elastic properties of laminated composites [13, 14]. In contrast, the number of test methods available for T-T shear characterisation is limited, with most of the techniques demonstrating deficiencies. Ideally, the shear method should provide a region of pure, uniform shear stress for the entire stress-strain response. This section critically compares five test configurations listed below:

- (i) Short beam shear (Figure 5.1).
- (ii) Double-notched laminate shear (Figure 5.2).
- (iii) Torsion of solid rod (Figure 5.3).
- (iv) V-notched beam shear or Iosipescu (Figure 5.4).
- (v) Torsion of circular disc (Figure 5.5).

There are at least five other test methods which could provide T-T shear modulus and/or shear strength data. A significant proportion of these methods have common features or are unsuitable for standardisation.

5.1 LEVEL OF STANDARDISATION

Standards exist for the short beam shear and double-notched laminate shear test methods for determining interlaminar shear strength. In 1993, the V-notched beam (or Iosipescu) method was standardised by ASTM, as ASTM D 5379 [15]. This method is used for determining shear properties of PMCs reinforced by high-modulus fibres.

The short beam shear or interlaminar shear strength (ILSS) test is widely used for measuring the "apparent" interlaminar shear strength of unidirectional or fabric fibre-reinforced composites. This test method was standardised by ASTM, as ASTM D 2344 [16] and can be applied to all fibre types. The ILSS test is available in several forms, including ISO 4585 - glass fibres (currently being revised) [17], EN (Aerospace Series) 2377 - glass fibres [18], prEN (Aerospace Series) 2563 - carbon fibres [19] and BSI 2782/Method 341a - glass fibres [20]. The original CRAG reports on test methods [12] also listed the short shear beam test.

The double-notched shear test, which consists of loading a non-symmetrically notched composite plate in uniaxial tension or compression, is available as ASTM D 3846 [21], BS 4994 [22] and BS 6464 [23]. The double-notched test is simple to perform and as such is often used to measure the "apparent" interlaminar shear strengths of aligned and angle-ply laminates. A thin region of almost uniform shear stress exists in the centre of the test area, which indicates that in principle interlaminar shear strength can be measured using this method. Shear failure is expected in continuous fibre systems provided there are no fibres crossing the mid-plane [14]. This technique is also used to measure shear strengths of adhesive bonds (ASTM D 3165).

5.2 SHEAR PROPERTIES OBTAINABLE

The ILSS and double-notched shear test methods are only suitable for determining "apparent" interlaminar shear strength (S_{13}). Torsion of a circular disc will only provide T-T shear strength. In principle, it should be possible to measure shear strength and shear modulus along the three principal material axes by twisting an axially aligned-fibre circular rod in torsion, with one end free to move axially.

The V-notched beam method can be used to measure in-plane and T-T shear moduli (G_{12} , G_{13} and G_{23}) for all isotropic and anisotropic materials. The technique can be used to measure in-plane and T-T shear strengths (S_{12} , S_{13} and S_{23}) for a wide range of PMCs (see Section 5.3).

5.3 MATERIAL SUITABILITY

The ILSS test can be used for determining "apparent" interlaminar shear strength of continuous aligned and two-dimensional woven fabric laminates. There has been limited success with the double-notched shear test method when applied to continuous aligned, cross-ply laminates and CSM [14]. Specimens tend not to fail in shear, but undergo a complex fracture consisting of bending, peeling and fibre tearing.

It is possible to determine the in-plane and T-T shear moduli for anisotropic materials by twisting a long circular or rectangular rod. This loading configuration can be used to measure interlaminar shear strength of continuous aligned and multidirectional laminates. Care needs to be taken, as often specimens do not fail in shear. In fact, the failure mode can be expected to be rather complex for most types of PMCs. Torsion of circular discs is probably only suited to the measurement of interlaminar shear strength of continuous aligned and multidirectional laminates.

The V-notched beam appears to be suitable for measuring the in-plane and T-T shear strengths for aligned and woven fabric composites. This test method is unsuitable for measuring shear strength properties of continuous multidirectional laminates. Discontinuous fibre-reinforced PMCs and brittle unreinforced polymers fail in a tensile mode rather than yielding in shear.

5.4 SPECIMEN PREPARATION REQUIREMENTS

The ILSS specimen preparation is simple and only a small amount of material is required. Specimen thickness is normally 2 mm for advanced composites. For this specimen the recommended span-to-depth ratio (L/h) and width-to-depth ratio (b/h) is 5. The width and length of a 2 mm thick specimen should be 10 and 20 mm, respectively. Materials with thicknesses other than 2 mm can be tested provided both (L/h) and (b/h) are 5 [17].

The main advantage of using the double-notched shear test is that thin laminates can be tested. This advantage is counteracted by the fact that it is very difficult to machine notches to the required depth of half the specimen thickness (ie mid-plane). The BS 4994 [22] uses a specimen with a minimum thickness of 3 mm, a width of 25 mm and length of 200 mm. Two parallel cuts, one on each of the upper and lower faces of the specimen are machined across the entire specimen width. The notches are 12.5 mm apart and equidistant from the specimen mid-length. No particular details are available on the notch width.

Circular torsion rod specimens may be fabricated from very thick laminates or directly from rods. It has been recommended that the rods have a minimum diameter of 6.25 mm (0.25") [14]. These specimens need to be machined to size using a lathe. A minimum gauge-length-to-diameter ratio (L/D) of 16 is required to minimise gripping effects in longitudinally aligned CFRPs. The gripped end should be approximately 45 mm in length. No end tabs or other attachments are required. Slippage may occur when using larger diameter rods. This effect can be minimised by grinding small flats at the specimen ends.

Due to economic and technical difficulties in producing thick sections, the gauge-length for the circular torsion specimen would need to be greatly reduced. The use of end tabs would also reduce the thickness requirements for T-T testing. These tabs could possibly be adhesively bonded to the specimen provided the bond strength is greater than the T-T shear strength.

It would be simpler and preferable to use rectangular cross-section rods of aligned PMCs. This would minimise machining requirements. Flat surfaces are also more suitable for bonding strain gauges. A minimum width of 12.5 mm is probably required when testing longitudinal specimens. To reduce the stiffening effect due to axial stresses, occurring at high

shear strain levels, the width-to-thickness ratio w/h should be ≤ 2 . The ratio of gauge length-to-width L/w should be ≥ 20 [14].

V-notched beam shear tests employ a double edge-notched, flat rectangular specimen with notches machined at the top and bottom edges (Figure 5.4). Two 90° angle notches are cut at the mid-length, with faces oriented at 45° to the longitudinal axis, to a depth of 20% of the specimen width. ASTM D 5379 [15] specifies a 76 mm specimen length and 20 mm width. The width dimension corresponds to the thickness-wise dimension for T-T shear tests. Thickness dimension is as received. It is recommended that a notch root radius of 1.3 mm be used to minimise the shear stress concentration at the notch roots.

This technique is only suitable for materials with a thickness of 3.5 mm or greater. Specimens with a thickness less than 3.5 mm require adhesively bonded tabs to prevent out-of-plane bending or twisting which could lead to premature failure [24]. Local crushing which can occur near the inner loading regions can be avoided by the use of tabs. The use of tabs could be expected to have a stiffening effect.

Two waisted specimen geometries based on the circular disc loading configuration have been used to determine interlaminar shear strength (Figure 5.6). Both specimens are suitable for testing laminates with thicknesses ranging from 2 to 25 mm. The circular cross-sections need to be machined on a lathe. The first specimen type consists of a circular specimen with a relatively narrow circular groove at the specimen mid-length. The critical dimensions for this specimen are the gauge-length, L , and the diameter, D [25]. A length-to-diameter ratio (L/D) of 0.2 to 1.0 results in constant S_{13} values.

The second type of waisted specimen is actually in the form of a short tube, which is more labour intensive and expensive to produce. This specimen geometry has the advantage that the stress state in the gauge length is more uniform. A 2 mm wall thickness has been shown to produce the most acceptable values of interlaminar shear strength for glass-fibre reinforced epoxy and polyester laminates [24].

5.5 SENSITIVITY TO IMPERFECTIONS

The waisted circular disc specimen geometries are complex and thus warrant considerable care when machining to avoid undercuts and to provide parallel load bearing surfaces. The high degree of machining required exposes this specimen geometry to a high risk of machine-induced damage (eg fibre pullout and delaminations). The use of unwaisted circular discs avoid this problem. Circular and rectangular solid rod specimens, which also need to be machined by lathe, are prone to machine-induced damage.

The apparent shear strength measured using the double-notched laminate specimen is highly sensitive to the accuracy of the notch machining. This is due in part to the inability to cut the grooves exactly to the mid-plane. Higher strength values are produced when the notch is less than half the specimen thickness (ie $< h/2$). This is due to an increase in the cross-sectional area of the fracture path (ie 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 overcut specimens [14].

Shear strength measurements using the V-notched beam test are highly sensitive to defects within the material, such as voids, and to specimen misalignment due to poor specimen preparation. The longitudinal edges need to be flat and parallel in order to avoid out-of-plane deformation.

5.6 LOADING AND FIXTURE REQUIREMENTS

Load introduction for the ILSS test configuration is reasonably straightforward using standard tensile/compression mechanical test equipment. A three-point flexure fixture with support and loading rollers 6 mm in diameter are required for testing ILSS specimens. Flexure fixtures can be purchased from test machine manufacturers or produced in-house at a relatively low cost. Simplicity and economy of the test method has led to the wide acceptance of the ILSS as a quality control screening tool.

Double-notched specimens can be directly loaded in tension or compression. These specimens are preferably loaded in tension to avoid possible buckling of the laminated structure. The advantage of using flat specimens is that the specimen geometry is compatible with standard grips.

The disadvantage of torsion rod and disc specimens is that a torsion facility is required to test these configurations. Many laboratories do not possess or have access to this facility. This equipment is relatively complex and requires that no axial loads are applied to the specimen during the test. Servo-hydraulic torsion + tension/compression test machines are more costly than servo-hydraulic tension/compression machines. Costs can be reduced by using a torsion gear box attached to a screw-driven test frame.

A working document drafted by the ASTM requires that V-notched beam shear tests be performed using a specially designed test fixture (Figure 5.6). This test fixture can be purchased from a test machine manufacturer or produced in-house, but they are relatively expensive.

5.7 STRAIN MEASUREMENT REQUIREMENTS

Only load and cross-head displacement need to be monitored during the testing of ILSS specimens. In the case of double-notched shear tests, the displacement can be measured from the cross-head movement or by an extensometer.

Torsion testing of solid circular and rectangular rods is relatively easy to perform, provided suitable mechanical test equipment is available. Surface shear strain is measured using two strain gauges oriented at 45° to the longitudinal axis of the test specimen. The gauges are adhesively bonded to the specimen surface at the centre of the gauge-section. An additional axially aligned strain gauge is recommended to monitor longitudinal strain. Tensile or compressive axial strains must not be present throughout the test duration. Strain gauges oriented at 45° to the longitudinal axis of the test specimen can also be used to monitor surface strain of circular discs under torsional load. Angular displacement can be obtained directly from the test frame; as these specimens were designed to measure shear modulus.

The V-notched beam shear test is suitable for measuring T-T shear modulus. The surface shear strain is measured by adhesively bonding two strain gauges to the centre of the specimen in the area between the notches. Strain gauges have a gauge-length of 1 mm or 2 mm and are aligned at 45° to the longitudinal axis of the specimen. A 90° biaxial rosette bonded at 45° to the specimen axis can also be used.

5.8 SIMPLICITY OF DATA REDUCTION

Data reduction is straightforward for the ILSS test, with the shear strength given as:

$$\tau = \frac{3P}{4bh} \quad (5.1)$$

where P is the maximum load, and b and h are beam width and thickness, respectively.

The average applied stress for both the double-notched and V-notched beam shear test methods is the total force applied to the specimen divided by the cross-sectional area between the notches. In both cases, the effect of shear stress concentrations present at the notches is assumed to be negligible.

Simple data reduction procedures are available for both the linear and non-linear stress-strain response of circular rods in torsion. Only linear analysis is available for rectangular cross-sections. The analysis is able to account for non-uniform cross-sectional shear stress distribution and large shear strains. Confidence in the analysis is far greater for circular cross-sections compared with rectangular cross-sections. This is understandable considering the fact that the stress state within rectangular sections is far more complicated.

5.9 STRESS UNIFORMITY AND FAILURE MODES

According to classical beam theory, the shear stress in beams is distributed parabolically through the specimen thickness. The stress is a maximum at the mid-plane and zero at the upper and lower surfaces. In fact, the shear distribution through the beam depth of ILSS specimens is severely skewed and varies along the beam length, with shear stress maxima positioned between the mid-plane and the upper surface and close to the loading zones. Failure frequently results from a combination of high shear and transverse compression gradients, present in the upper portion of orthotropic beams near the concentrated central load. Occasionally, compressive buckling or yielding in the upper portion of the beam will occur.

The stress state in double-notched specimens is highly complex with the shear stress distribution between the notches being non-uniform and dependent on the ratio of thickness to the distance between the notches [14]. Shear stress concentrations exist at the notches. Failure is usually quite complex with bending, peeling and fibre tearing occurring in addition to shear. Large bending deformations and significant T-T normal stresses are induced when a uniaxial tension or compression load is applied. The presence of large stress concentrations at the notch corners initiate fibre/matrix cracks at these locations.

A non-uniform shear state exists along the gauge-length and through the thickness of circular rods under torsional load. Shear strain increases from a value of zero at the centre to a maximum value at the surface [14]. In the inelastic range, the stress distribution is non-linear. The stress state near the end grips is very complex with stresses peaking at the grip boundary. Twisting a solid rod with a fixed length induces axial tensile stresses, in addition to shear stresses in the material away from the central axis. The longitudinal strain is a maximum at the rod surface resulting in a net longitudinal tensile force acting on the rod. If the specimen has freedom of movement in the axial direction then the rod can change length and as a result the net force reduces to zero. The net effect is that the core of the rod is in compression and the surface in tension.

In brittle matrix composite rods with fibres aligned parallel to the longitudinal axis, fracture initiates in the vicinity of the end grips. Axial cracks develop within the gripped section and propagate inward along the radial axis. Cracks can also extend into the gauge section. For larger diameter specimens (ie $D > 6.25$ mm) where flats are ground to facilitate gripping, fracture never occurs in the gauge section. A possible solution would be to waiste the specimen within the gauge-section. Alternatively, a shallow circumferential notch at the specimen mid-length would promote fracture in the region of uniform shear stress.

The stress state is far more complicated in rectangular sections as compared to circular rods. Non-circular sections, when twisted, will warp rather than remain plane. Warping is prevented if one or both ends of a bar are fixed (or clamped). The axial stresses, due to warping restraint, assist the torsional shear stresses in carrying the applied torque and result in an increase in the torsional rigidity of the section.

The shear stress distribution in the test section of V-notched specimens is not uniform [13, 14]. Furthermore, shear and normal stress distributions are highly dependent on the orthotropy ratio E_{11}/E_{22} , fibre orientation, notch geometry and loading boundary conditions. The surface shear strain is also sensitive to the surface layer architecture (eg woven fabrics).

For continuous unidirectional specimens with fibres parallel to the longitudinal axis (0°), the shear stress concentration is a maximum at the notch root and increases with orthotropy ratio. Only a small region ($\sim 2 \text{ mm} \times 2 \text{ mm}$) in the specimen centre can possibly be considered to be in pure shear. Although the shear stress concentration is reduced by using a radius of 1.3 mm, failure still initiates at the notch roots via axial splitting.

These axial splits, one at each of the notch roots, extend on the opposite side to the inner loading points and are caused mainly by the high shear stresses present at the notch roots. Axial splitting provides stress relief at the notch roots, which tends to promote a more uniform shear stress distribution in the region between the notches. Further loading results in the arrest of the axial splitting and in the formation of numerous short cracks along the fibre-matrix interfaces in the test-section. This last event leads to structural failure with the ultimate stress being associated with shear strength.

Conversely, for transverse (90°) V-notched specimens, the shear stress is at a minimum at the notch root and increases progressively along the notch root axis to a maximum value at the specimen centre. A uniform, almost pure shear stress exists at the centre of 90° material with a high orthotropy ratio. These specimens fail prematurely as a result of a combination of shear and transverse tensile stresses at the notch roots. Cracks propagate in an unstable manner along the notch-root axis, which is the path of least resistance. These specimens invariably fail at lower stress levels than those measured for the corresponding longitudinal specimens. This failure mode does not represent shear failure and thus transverse fibre oriented specimens are unsuitable for measuring shear strength.

The critical dimensions for a torsion disc specimen with a relatively narrow circular groove at the specimen mid-length are the gauge-length, L , and the diameter, D . A length-to-diameter ratio (L/D) of 0.2 to 1.0 results in constant interlaminar shear strength values. Increasing the gauge-section diameter from 5 mm to 10 mm has no effect on the interlaminar shear strength measurement, but a further increase in D results in a sharp reduction in the measured strength. The strength reduction is associated with an increase in the inhomogeneity of the stress state within the gauge-section [24].

A waisted disc specimen, in the form of a short tube, has the advantage that the state of stress in the gauge length is more uniform. The principal variable of this specimen type is the gauge-length wall thickness, h . A 2 mm wall thickness has been shown to produce the most acceptable values of interlaminar shear strength for glass-fibre reinforced epoxy and polyester laminates [24].

5.10 CONSISTENCY OF MEASURED DATA

Although an interlaminar shear failure is not always obtained, ILSS test data is relatively consistent within test batches and between different test sites. This consistency coupled with low fabrication, preparation and testing costs, supports its popular use as a quality assessment test. There is substantial ILSS data available from different sources for data comparison.

In contrast, there is little T-T data available in the literature on the reproducibility of results generated using the double-notched, torsion rod, V-notched beam and torsion disc shear test methods. The scatter of strength data within test batches is usually 10% or higher.

5.11 SUITABILITY FOR FATIGUE AND ENVIRONMENTAL TESTING

ILSS test method is unsuitable for fatigue testing. This comment may also apply to both the double-notched and circular disc specimens. There is insufficient information to pass a qualified comment. The V-notched shear test has limited fatigue testing capabilities. The loading fixture may need to be modified in order to minimise frictional effects. The possibility of fretting at the loading points may cause an additional problem.

Torsion fatigue behaviour of unidirectional CFRP has been examined under both constant shear stress and shear strain amplitude [25]. The fatigue life was clearly definable. The relationship between fatigue life and the stress or strain amplitude was found to be approximately logarithmic.

All five shear test methods are suitable for creep and environmental testing. The problem of ice forming within the moving parts of the V-notched beam test fixture could cause problems at sub-zero temperatures. However, this test method has been used successfully to test unidirectional CFRP's over the range -40°C to 100°C . No particular problem is expected for the use of the direct loading configurations for environmental testing.

5.12 SUMMARY

SHORT BEAM SHEAR (ILSS)

ADVANTAGES	DISADVANTAGES
• Simple/economic fabrication • Simple/economic testing • Simple data reduction • Consistent strength data • ISO standard 4585 • Suitable for creep testing • Suitable for environmental testing	• Interlaminar strength only • Loading point stress concentrations • Complex failure analysis • Unsuitable for fatigue

DOUBLE-NOTCHED LAMINATE

ADVANTAGES	DISADVANTAGES
• Moderate specimen fabrication cost • Testing is straightforward • Data reduction is simple • ASTM standard D 3846 • Suitable for creep testing • Suitable for environmental testing	• Interlaminar strength only • Difficult to machine notches • Non-uniform shear stress state • Stress concentrations present • Complex failure modes • Unsuitable for fatigue

TORSION OF SOLID CIRCULAR ROD

ADVANTAGES	DISADVANTAGES
• All T-T shear properties • Data analysis straightforward • Insensitive to imperfections • Suitable for creep/fatigue testing • Suitable for environmental testing	• Very thick laminates required • Specimens machined on lathe • Torsion facility required • Stress concentrations (end grips) • Complex failure analysis

V-NOTCHED BEAM

ADVANTAGES	DISADVANTAGES
• All T-T shear properties • Compatible with most PMCs • Low material requirements • Simple data reduction • Suitable for environmental testing • ASTM standard D 3579 • Substantial in-plane database	• Accurate specimen machining • Special test fixture necessary • Non-uniform shear stress state • Limited creep/fatigue capability

TORSION OF CIRCULAR DISC

ADVANTAGES	DISADVANTAGES
• Suitable for thin laminates • Simple data reduction • Suitable for environmental testing	• Interlaminar shear strength only • Specimens machined on lathe • Torsion facility is required • Stress concentrations (end grips) • Complex stress state • Limited creep/fatigue capability

6. ULTRASONIC METHODS

The elastic constants of isotropic and anisotropic solids can be determined from the propagation velocity of a pulsed ultrasonic signal. For anisotropic materials, the density and wave velocity are directly related to the components of the stiffness matrix. Anisotropic elasticity theory can be used to derive the necessary in-plane and T-T elastic constants from the matrix stiffness components.

The main advantage of ultrasonics compared to mechanical testing is that the technique for measurement of elastic property data is non-destructive and uses small amounts of material. Testing is relatively fast, and requires little specimen preparation [26]. However, the use of ultrasonic techniques is still at the research stage, since although data has been available for 20 years, the industrial need and capacity to use this information has not been present until more recent times [26 - 28].

Two ultrasonic methods used for the determination of in-plane and T-T elastic constants will be reviewed in this section.

(a) Immersion Method

The test facility consists of two high frequency transducers, a transmitter and receiver mounted in a thermally controlled immersion tank with the test specimen mounted on a turntable. To produce a full set of elastic constants the velocity of an ultrasonic pulse, along a range of directions, in the test specimen is measured. Pulses of approximately 1 s duration are transmitted in the frequency range 0.5 to 5 MHz with a repetition rate of 1 kHz. Transducer diameter is 6.25 mm. The transmitted pulse is captured on a digital oscilloscope and data analyses performed by computer (Figure 6.1).

The ultrasonic facility at NPL has recently been updated with user-friendly software, allowing operation by any technically competent person. Testing and analysis is relatively fast.

(b) Contact Probes Method

This method uses several small specimens cut so that the ultrasonic wave can be propagated in known directions. The transmitter and receiver transducers are directly attached by a coupling medium (eg grease) to opposite faces of the specimen and the transit time measured (Figure 6.1). The transducer separation can be varied to accommodate specimens of different thickness. It is not necessary to place the specimen in a water bath.

For both methods, the receiver may be replaced by a reflecting surface, such as a metal block, positioned normal to the axis of the transmitter. The transmitter is now used to detect the beam of pulses reflected back through the specimen and couplant (ie pulse-echo mode) [29]. The reflected signal is captured using transit-time measuring equipment.

6.1 LEVEL OF STANDARDISATION

Neither technique is standardised. However, Part 9 of ISO 6721 [29] covering the determination of dynamic mechanical properties of plastics, under compression, using an ultrasonic wave propagation method is being prepared by NPL project leader Dr G Dean. ISO 6721-9 describes a method for the measurement of longitudinal modulus of unreinforced polymers. There is the possibility that the scope of the standard will be expanded to include the measurement of shear modulus of polymers, allowing Poisson's ratio to be calculated. Also, it is hoped to generalise this method in a further part of the standard to cover its use for anisotropic materials.

6.2 PROPERTIES OBTAINABLE

The immersion method allows a full set of elastic constants of a composite material to be determined by measuring, in an immersion tank, the velocities of ultrasonic waves propagated in various directions in the specimen [26]. However, the measurements are made at very small effective strains and therefore do not relate to the reduced modulus found at high strains in the non-linear region of the shear stress-strain response. As the measurements are made at a high frequency (0.5 to 5 MHz) there may be some small degree of difference for more matrix dependent properties, such as transverse shear and tensile (including T-T) properties [26], compared to moduli measured in a conventional mechanically loaded test. The effect is considered to be small [27], especially when compared to the benefits arising from the accuracy and repeatability of the test and the completeness of the data. As the test is non-destructive it can be repeated. There is no guarantee that the contact method could be used to obtain the complete set of elastic constants.

6.3 MATERIAL SUITABILITY

The immersion method is most accurate for low porosity, fine structure material (ie not porous, heavy-weight woven fabric material) and is potentially suitable for the newer material with three-dimensional reinforcement. This technique has been successfully applied to transversely aligned laminates [27, 28]. Although the contact method is suitable for use with unreinforced polymers, difficulties have been experienced when applying this technique to PMCs.

6.4 SPECIMEN PREPARATION REQUIREMENTS

The main advantage of the immersion technique compared to mechanical testing is that only one or two simple beams need to be tested to obtain a complete set of elastic properties. For transversely isotropic laminates, longitudinal (0°) and transverse (90°) specimens are tested. Specimens are typically 100 mm long, 20 mm wide and 10 mm thick, but thicknesses as low as 2 mm can be used.

The contact method also requires only two specimens for elastic stiffness measurements. Specimens are cut in the longitudinal and transverse directions. This method allows measurements to be made on small specimens, typically 20 mm x 20 mm x 5 mm [29]. Specimen geometries similar to the immersion method specimen can also be used.

In both cases, the surfaces normal to the wave direction must be smooth, plane and parallel over an area comparable with the area of the faces of the transmitter and receiver transducers. The specimen dimension in the wave direction must be accurate to within 0.5% over this area [29].

6.5 SENSITIVITY TO IMPERFECTIONS

In principle, the elastic constants of completely anisotropic materials can be determined using ultrasonic techniques. However, the material must behave in a homogeneous manner for the technique to work successfully. If the material is too thick or too porous then the wave may not transmit through the specimen without excessive attenuation. Wave attenuation occurs through dissipation or dispersion in heterogeneous materials. For the material to behave as a homogeneous elastic solid, it is essential that the pulse wavelength is larger than the structural inhomogeneities. Transversely isotropic laminates free of defects, such as delaminations and voids, satisfy this condition. The wave velocity associated with propagation through an inhomogeneous area can only be used to determine a mean elastic modulus; it is not considered to be a fundamental elastic property.

In practice, the accuracy in elastic stiffness measurements is limited usually by the quality of the specimen. Localised variations in fibre alignment, fibre volume fraction and packing arrangement will result in variations in velocity measurements with the position of the wave path in the specimen [27].

6.6 SIMPLICITY OF DATA REDUCTION

Data analysis is based on an optimisation procedure and is usually performed by a microcomputer. NPL has developed software for this purpose.

6.7 CONSISTENCY OF MEASURED DATA

The immersion method does provide a complete set of elastic constants, using a physical test that can be repeated on the same specimen to assess sources of error, levels of precision and the effect of applied conditions (eg ultrasonic wave frequency).

The accuracy of the contact method and the relationship of generated data to that obtained by the immersion technique has not been studied in any detail. If acceptable results are obtained it could prove to be a cheaper method for routine use. Unlike the immersion method it may not be feasible to obtain a complete set of elastic constants.

6.8 SUITABILITY FOR ENVIRONMENTAL TESTING

The immersion method is suitable for testing in a liquid medium over a wide range of temperatures, providing the transducers are able to operate at the designated temperatures. It should be noted, that wave propagation velocity in both the specimen and coupling agent is temperature dependent.

The contact method should be suitable for use under low and high temperature test conditions. High temperature couplants are available for direct contact measurements.

7. INTERLAMINAR FRACTURE TOUGHNESS TEST METHODS

Delaminations are probably the most life-limiting defects that occur in laminated composite structures, and may arise during processing or subsequent service. Common structural elements (eg edge effects, notches, ply drop-off and bolted/bonded joints) generate interlaminar stress concentrations, which may initiate delaminations under static or fatigue loading conditions. Barely visible to the human eye, these insidious entities can cause severe reductions in stiffness and strength, and possibly result in catastrophic structural failure.

Delaminations are often subjected to a combination of mode I (crack-opening), mode II (forward shear) and mode III (scissor shear) loading. As a result, fracture toughness test methods have been developed to quantify interlaminar critical strain energy release rate (G_c) for the various loading modes [30, 31].

The double cantilever beam (DCB) test has been used extensively to measure the initiation and propagation values of G_{Ic} . A tensile load is applied to a specimen with an embedded through-width delamination at the laminate mid-plane (Figure 7.1). Specimens are typically 20 to 25 mm wide and 150 mm long. A minimum thickness of 3 mm is generally preferred [30].

The end notched flexure (ENF) test, which was first used for characterising mode II interlaminar fracture of cracked wood beams, has emerged as the most commonly used test method for quantifying G_{IIc} for laminated polymer composites. The ENF test is essentially a DCB specimen loaded in three-point flexure (Figure 7.2). The end-loaded split (ELS) laminate is an alternative approach for measuring G_{IIc} (Figure 7.3). This particular loading configuration has been favoured by ESIS (European Structural Integrity Society - formerly EGF, European Group on Fracture) as it promotes more stable delamination growth [32].

A number of test methods have been proposed for characterising mixed-mode I/II behaviour. The simplest of these is the asymmetric DCB specimen which allows a single mode I/mode II ratio of 4/3 to be obtained (Figure 7.4) [32]. The ASTM group is now examining the mixed-mode bend (MMB) specimen which allows the ratio of the modes to be varied.

The split cantilever beam (SCB) specimen was developed and used to measure mode III fracture toughness values. However, the SCB is not a pure mode III test, there is a large mode II component at the free edge. As a result, DRA Farnborough in conjunction with Imperial College have developed a modified version of the SCB test, which eliminates the mode II component (Figure 7.5) [33].

In this project, it is not intended to develop fracture toughness tests, as several other initiatives exist and the data is not normally considered as primary design data. For completeness and because data may be needed for the structural element side of the project, the fracture toughness methods are briefly reviewed.

7.1 LEVEL OF STANDARDISATION

There are several strong standard-type initiatives and a strong academic interest in this area. Organisations currently involved include ISO, ASTM, JIS (Japanese Industrial Standards), VAMAS (Versailles Project on Advanced Materials and Standards - international pre-standards collaborative research) and ESIS.

A new work item on "Plastics - determination of critical stress intensity factor (K_{Ic}) and the energy per unit area of crack (G_c) at fracture initiation (linear elastic fracture mechanics)" has recently been proposed by ISO (work item proposal 572) based on a ESIS protocol. The method is claimed to be suitable for "plastics, including composites", but as the geometries are similar to those for metals using compact tension and notched flexure mode I specimens,

they will not always be applicable to high performance composites. The method may be suitable for dough moulded compounds and injection moulded PMCs where a crack can propagate transverse to the lamination.

Test methods for determining the mode I and mode II delamination resistance of fibre-reinforced composites are well developed. A version of the DCB test method has been published by ASTM, as ASTM D5528-94a [34]. This has been accepted by ISO as a new work item. JIS have recently published versions of these methods. EN Aerospace 6000 series developed from Airbus will also include versions of the DCB and ENF test methods for CFRPs.

Protocols have been prepared by ESIS for characterising interlaminar fracture behaviour under mode I, mode II and mixed-mode I/II loading [32]. Work is at the research stage for more than one design of fixture to give mixed mode testing. ASTM are examining the MMB test and ESIS has run a round-robin which included the asymmetric DCB test. Standards work on mode III delamination is at an embryonic stage. ASTM, VAMAS and ESIS have run round-robins on static and fatigue delamination tests, for modes I and II.

7.2 PROPERTIES OBTAINABLE

All the test methods mentioned above can be used to determine initiation G_c values. The DCB specimen can be used to measure the resistance to crack initiation and crack propagation. In principle, the same should be possible using the ELS mode II and asymmetric DCB mixed-mode I/II test methods.

7.3 MATERIAL SUITABILITY

Interlaminar test methods have been used successfully for testing fully aligned laminates and two-dimensional woven fabrics. Fracture toughness has been determined for both thermoset and thermoplastic based fibre/polymer systems. Difficulties have been encountered when testing multidirectional laminates, as crack propagation is not confined to the mid-plane of the laminate (ie cracks jump between layers).

7.4 SPECIMEN PREPARATION REQUIREMENTS

For each method there is common agreement on the general aspects of specimen size, load application, etc. Differences to be resolved include whether propagation or initiation energies are measured and the method of crack initiation (ie mode I pre-cracking or growing the delamination from the end of an insert). G_c values for a specimen without pre-cracking are artificially higher than specimens with natural crack-tip morphologies. During processing, a resin-rich pocket is created at the end of the insert. This blunts the crack tip and increases the energy required to initiate delamination growth. Without pre-cracking, fracture toughness increases with increasing thickness of the insert [31].

7.5 SENSITIVITY TO IMPERFECTIONS

Intrinsic defects (eg voids) and the presence of residual stresses can be expected to have an adverse effect on the interlaminar fracture toughness (see Section 8).

7.6 LOADING AND FIXTURE REQUIREMENTS

The DCB specimen is the only directly loaded specimen. The remainder of the interlaminar test methods require specially built fixtures which are often fairly expensive. The test fixture for the modified split cantilever beam (SCB) specimen, used to measure mode III fracture toughness, is fairly elaborate and requires a precision die set to ensure accurate alignment. All testing can be carried out using a universal mechanical test machine.

7.7 CRACK MEASUREMENT REQUIREMENTS

In general, the delamination onset and subsequent propagation is monitored by eye using a travelling microscope, video camera or crack gauge. Incorrect crack measurement is a major source of error in data reduction. A load-displacement curve is recorded for all loading configurations.

7.8 SIMPLICITY OF DATA REDUCTION

Data reduction is not always straightforward. If the specimens are too thin, large displacements cause non-linear behaviour and corrections to the beam theory used for data reduction. Tough materials also show extensive non-linearity on the load-displacement curve. For tests involving mode II loading, the contribution of shear deformation to the overall beam deflection increases with increasing specimen thickness. This needs to be considered when calculating G_c .

A serious cause for concern with mode I tests is related to the effects of fibre bridging and multiple cracking. For many unidirectional laminates an increase in G_{Ic} is observed after initiation. This is partially attributed to fibre bridging of the crack. Multiple cracking also occurs under mode II and mixed-mode I/II loading conditions and has been observed to increase with a reduction in specimen thickness. The result is that G_c values are lower for thin laminates.

Empirical compliance calibration methods have been used successfully for determining G_c values. Compliance is measured at several crack lengths and a polynomial expression is fitted to the data.

7.9 CONSISTENCY OF MEASURED DATA

Published results show considerable scatter in data. The magnitude of data variability can be seen in a summary of the UK results for a VAMAS round robin project on delamination of composite materials [35].

7.10 SUITABILITY FOR FATIGUE AND ENVIRONMENTAL TESTING

The most commonly used interlaminar fracture toughness tests are suitable for creep, fatigue and environmental testing. Problems such as fretting and ice formation on the fixture need to be addressed. From the limited fatigue data that is available, it is evident that significant delamination growth can occur, even at low energies (ie $\Delta G/G_c$), in so called tough composites [31, 36]. More fatigue data is required.

8. GENERAL ISSUES ON MATERIAL FABRICATION

8.1 PROCESSING

A problem with many T-T test methods is the need to fabricate thick samples in order to machine specimens in the T-T direction. Fabrication of specimens with thicknesses greater than 20 mm is expensive and often difficult, with process-induced stresses becoming increasingly important as the thickness is increased. Residual stresses, which are strongly influenced by processing history, can have a significant effect on the engineering properties of laminated structures by inducing warpage, fibre buckling, matrix microcracking and delaminations. Residual stresses arise from resin chemical shrinkage, as a result of curing and differences in thermal contraction between adjacent plies on cooling the laminate from the cure temperature. The net effect is that the residual strength properties of a laminate are diminished.

The most familiar problem associated with processing thermoset based PMCs is material degradation, induced through exothermic chemical reaction of the matrix. The risk of material degradation exists when the dissipation of liberated heat through thermal conduction is slow. In this case, the internal temperature may be elevated to levels that induce irreversible thermal damage. A second concern relates to the complex temperature and degree of cure gradients that develop in thick-sections during the curing process. These gradients may induce a non-uniform state of cure through the laminate thickness. Non-uniform curing can produce poor consolidation, leading to undesirable volume fraction gradients and entrapped volatiles or voids.

Defects such as voids can significantly degrade matrix dominated properties. Interlaminar shear strength diminishes by approximately 7% for each 1% increase in void content, for void contents in excess of 2% [6]. Increasing the thickness of a test piece will lower the "apparent" shear strength, as the number of critical flaws can be expected to increase with the additional material. Thus, the detrimental affect of voids on interlaminar shear strength can be expected to be more evident when testing long solid rods.

8.2 THREE-DIMENSIONAL REINFORCEMENTS

A number of the test methods are likely to be unsatisfactory for use with materials with 3-D reinforcements as they rely on a large ratio between the in-plane and T-T strengths (eg C-section tension). This ratio will be lower for 3-D reinforced systems. For example, curved test geometries where a bending load is applied in order to generate a T-T stress may fail in the in-plane direction (eg arms of C-section tension) rather than in the transverse direction. This also applies to the mode I and II fracture toughness test methods. Difficulties are envisaged for test geometries where the load is introduced through bonded end loading attachments. Failures can be frequently expected to occur at the interface between the adherends or within the adhesive.

9. RESULTS OF INDUSTRIAL SURVEY AND EVALUATION OF T-T TEST METHODS

9.1 INDUSTRIAL SURVEY

The survey was fairly clear in identifying the needs in this area. All the elastic and strength properties for the three loading cases of tension, compression and shear were mentioned in most returns. The majority of replies stated design related use of data, rather than quality assurance (except the short beam shear test method). Perhaps the latter will develop once the properties are shown to be important in design and can be measured reliably. There was no mention of the use of the data for materials development.

The survey suggested that data was required for all classes of PMC, with thicknesses in the range 1 to 20 mm. There were no tests in regular use except ILSS, and in this case the available standards were not referenced, although they are likely to be used. The accuracy required for these data was in good agreement, being encompassed within the range 5 to 10 %, with one request for better than 5%.

9.2 EVALUATION OF T-T TEST METHODS

An assessment form was sent to the steering committee and correspondent members of the Composite Design Advisory Group, and to any other interested organisation within the UK. Recipients were requested to assign a weight of 1 to 10 for each of the 14 criteria in terms of design and quality assessment (QA) requirements. A value of 1 designates a low priority and conversely a value of 10 indicates a high priority. The weighting was dependent upon the relative importance the responding organisation placed on each criterion with respect to the other criteria. The average and range of the weightings (W) supplied by industry for each criterion are presented in Table 5. Table 6 shows the order of importance industry places on each separate criteria. (NB. Criteria not given weightings were excluded from the assessment).

Each test method was numerically rated (R) from 0 to 10 for each of the 14 criteria (see Tables 7, 8 and 9, and Section 9.4). The product of the numerical rating (R) and the average weight (W) for each criterion was summated to give an overall evaluation (E) for the test method. That is $E = \sum(R_i W_i)$ for $i = 1$ to 14. The total score for each of the test methods has been compared for tension, compression and shear test methods (see Table 10).

9.3 INDUSTRIAL WEIGHTING EVALUATION (W)

Weightings provided by UK industry have been summarised in Table 5. Seventeen (17) forms were returned from 14 organisations, including three returns from one organisation and two from another. The relative importance industry placed on each criterion with respect to the other criteria is given in Table 6, considering separately the use of the tests for "design" and "QA" purposes. The data in columns 2 and 3 show the detailed differences between the two uses. The position in the list reflects the overall ranking industry placed on the criteria; with the criterion at the top of the list considered the most important. A ranking number for each criterion is also included for design and QA requirements.

The availability of the test method as a "standard" was considered overall to be the most important factor when selecting a test method for either design or QA requirements. The next most important factors were that test methods should produce a consistent failure mode, provide strength data and be applicable to a wide range of PMCs. Although stiffness data were rated as relatively important for design purposes, it was considered of least importance in terms of QA requirements. The low overall importance implied by the results suggests that for current materials, designers may be satisfied to approximate or calculate the stiffness value, but not the strength value.

The cost of specimen fabrication, testing and instrumentation were naturally considered to be more important when selecting a test method for QA purposes. This reflects industrial concern for minimising the cost of QA for checking production. Obviously, less emphasis was placed on the cost factor when selecting a test method to produce engineering data.

The need for a special test fixture or the cost involved in procuring specimen preparation equipment was regarded to be of low importance for both categories. However, it was surprising to find that a "small amount of material" was considered to be of least importance for producing T-T specimens; independent of design or QA requirements. This is contrary to the usual assumption that the preference is for thin specimens to minimise processing problems and material costs. Further discussion on this item may be needed.

9.4 CRITERION RATING (R)

This section describes the basis upon which each criterion was numerically rated (see Tables 7, 8 and 9).

"Stiffness Data available". If in principle, a test method can be used to determine a full set of either tensile, compressive or shear T-T elastic constants, then a numerical rating of 10 was assigned. Conversely, a value of 0 indicates that the test method cannot be used for measuring T-T elastic constants.

"Strength Data available". A numerical rating of 10 was assigned to a test method which can in principle be used to determine a full set of either tensile, compressive or shear strengths. A score of 5 was assigned to those methods where strength data is only available in one direction. For example, the short beam shear and double notched shear tests can only be used to determine interlaminar shear strength S_{13} and thus warrant a 5 rating. Whereas, the V-notched beam shear test can in principle be used to measure in-plane and T-T shear strengths (ie S_{12} , S_{13} , S_{23}).

"Small amount of material needed". A specimen was assigned a value of 10 when only small quantities of relatively thin material (ie 2 to 6 mm thick) were required to produce a test specimen. This decision was independent of the specimen geometry. Large specimens with a thickness between 2 and 10 mm were assigned values of either 8 or 9 depending on the in-plane cross-sectional area. Values of 9 and 8 were also assigned to small specimens with thicknesses of 10 and 20 mm, respectively. For thicker specimens, an additional point was deducted for every 20 mm increase in thickness required. Obviously, the normally available/used thickness varies with material system to a certain degree.

"Low cost of specimen preparation equipment". Test methods using flat rectangular specimens and circular specimens were numerically rated at 10 and 1, respectively. Circular specimens are usually filament wound, which requires special processing equipment. A rating of 5 was assigned to those test methods requiring a dedicated mould (eg humpback or Type D tensile specimens).

"Low cost of specimen preparation". A rating of 10 was assigned to those methods which used either flat rectangular or made-to-measure specimens (eg humpback tension). The need to notch or waist a specimen reduced the rating by 3. Three points were deducted for the use of either end tabs or end loading blocks, or when machining was required to produce rectangular or circular profiles. A rating of 1 was assigned to the RARDE tension test; as this method requires specimens to be profiled, waisted and have adhesively attached end-blocks.

"Low cost of specimen instrumentation". Test methods were rated at 10 when no auxiliary instrumentation was required to measure strain (eg strain gauges and extensometers). A rating of 5 was assigned to test methods using extensometers. The need to use strain gauges resulted in a rating of 1.

"Low cost of test equipment". Torsional loading requires specialised test equipment, which is not always (NB. May depend on industry) available in industrial laboratories. Hence, torsion loading of both a solid rod or disc was rated at 5. A rating of 10 has been given to the remainder of the test methods as these require only a universal tension/compression test machine.

"Avoids special test fixture". Most of the test methods require additional test fixtures with each method rated on the complexity of the testing fixture. A method was rated at 10 when no test fixture was required (ie directly loaded). Hence, the long coupon tension and torsion rod methods were rated at 10. Test methods requiring relatively simple test fixtures (eg closed ring tension) were assigned a rating of 8. The need for a flexure loading fixture resulted in a rating of 6. The RARDE and short block compression test methods were also given a rating of 6. A high precision die set is used to load the specimens in compression.

Although the C-section tension test requires a special test fixture, the design can be regarded as relatively straightforward. In this case, only 4 points were deducted. Test methods requiring a complex test fixture (eg Celanese, IITRI and End-block compression tests and the V-notched beam shear test) were assigned a rating of 1.

"Low cost of testing per specimen". A number of tests were simple to perform and required minimal set-up time to insert and align the test specimen (ie less than 10 minutes). These tests were rated at 10. Tests requiring a moderate amount of time (ie 10 to 20 minutes) for specimen alignment were de-rated by 3 points to a value of 7. Tests requiring additional time were given a rating of 4. Two points were deducted if difficulties were encountered in removing failed specimens from a fixture (eg Celanese compression). The actual set-up time varies from operator to operator and thus ratings for this criterion is fairly subjective.

"Standard test method available". Evaluation for this criterion was based on the level of standardisation. An ISO standard applicable to T-T measurements was rated at 10, a CEN standard at 9 and national standards (eg BSI and ASTM) at 8. Six points were deducted from each of these ratings when there was only an in-plane equivalent available. When a recommended method was available, a rating of 6 was given. A rating of 4 was applied to those methods where there was detailed analysis in the published literature and work was currently in progress towards possible standardisation. This was derated by 2 when no work was in progress towards standardisation. A rating of 0 applied when no detailed analysis was available in published literature.

"Simple data reduction". Data analysis was relatively straightforward for many of the test methods with the values of elastic and strength properties being approximated through the use of simple algebraic expressions. The analysis used to estimate these quantities assumes that a uniform stress distribution exists throughout the actual specimen gauge-section and is free of extraneous stress components. In these cases, the method was rated at 10.

Three points were deducted for those test geometries where the cross-sectional stress distribution in the test section was non-uniform. A rating of 4 was assigned to those test methods where the specimen can experience significant non-linear deformation or geometric deformation. The occurrence of either phenomenon will often require complex failure analysis resulting in a high degree of uncertainty in strength data. There was no validated analysis available for the humpback tensile specimen and thus the method was rated at 2.

"Consistent failure mode". In general, irrespective of the testing mode and materials tested, a consistent failure mode is difficult to achieve for T-T test methods. This uncertainty originates from the difficulty of producing a uniform stress state. No test method warranted a rating in excess of 8 as all test geometries have uncertainties associated with their use. In addition, a number of tests are either untried or are not commonly used. This made subjective assessment unavoidable.

Failures frequently occur as a result of stress concentrations in the region of load introduction (eg short block compression). A rating of 6 was assigned to those methods using either end tabs or end loading blocks for load introduction (eg short block tension and torsion rod). Test geometries with stress concentrations in the form of a notch (eg V-notched beam shear) or where the stress distribution was highly non-uniform were given a rating of 6. Waisted specimens without end attachments (eg RARDE compression) rated an 8.

A rating of 2 was assigned to those methods where failure often occurs at the specimen ends (eg short block compression). Test methods that were not used for T-T measurements, but produced acceptable failure modes for in-plane testing (eg IITRI compression), were rated at 5. An additional point was deducted from the Celanese test method as lower compression strengths have been reported for this test in comparison to data measured using the IITRI test method. Methods for which there was no published test data were rated at 2.

"Applies to a wide range of materials". A rating of 10 was assigned to those test methods which were compatible with all 6 classes of PMCs (ie 100%) listed in Tables 7, 8 and 9. Lower ratings were assigned to those test methods which were only suited to testing 5 or less of the PMCs. For example, if a test method could only be used with 4 of the six materials (ie 66%) then the method was rated at 7.

"High accuracy of results". The accuracy of data generated by a test method depends on the exactness of the stress analysis and on the repeatability of test results. In all cases, the stress state is only an approximation to a uniform distribution and therefore there is a significant degree of uncertainty in the test data. Tests were de-rated if the available analysis was regarded as unsatisfactory and/or there were difficulties in maintaining specimen alignment for the entire duration of a test. Frequently, the rating assigned to a test method tended to mirror that given for the **"consistent failure mode"** criterion.

The in-plane compression test methods (eg IITRI) were rated at 5. The Celanese compression test was rated at 4, as the strength data is less consistent than the other in-plane methods. Waisted specimens without end attachments (eg RARDE compression) were penalised 3 points. Test geometries with stress concentrations in the form of a notch (eg V-notched beam shear) or where the stress distribution was highly non-uniform were rated at 6.

A number of test geometries have the potential to undergo significant geometric deformation prior to failure (eg C-section tension) and were therefore rated at 4. These methods require complex failure analysis in order to determine strength. In addition, the failure analysis has not been independently corroborated. A rating of 2 was assigned to those methods where failure often occurs at the specimen ends (eg short block compression), since the analysis reported in published literature casts considerable doubt on the validity of the strength data. Methods where there was no published test data were also given a 2 (eg humpback tension).

10. CONCLUSIONS

The overall evaluation (see Table 10) obtained from the decision analysis technique clearly showed that all the test methods were far from ideal. In many cases the differences were marginal and dependent upon the material, etc. being studied. The comparative experimental and round-robin programmes will provide information on ease of use, reliability, etc. An overall score of 2800 was possible, but none of the test methods managed to obtain a value that exceeded 50% of this maximum. The range of evaluated scores for each testing mode is as follows:

- (a) Tension - 1014 (36%) to 1311 (47%).
- (b) Compression - 1137 (41%) to 1365 (49%).
- (c) Shear - 915 (33%) to 1396 (50%).

The range of scores is relatively narrow for tensile and compressive test methods, and marginally wider for the shear test methods. The relatively low scores indicate that all the test methods are far from ideal and may need improvements to satisfy design and QA requirements. Also, as in other cases, compromises may be necessary depending on material thickness and availability of different composite systems, so that it may be necessary to prepare the standard for any test mode in multiple parts.

With the exception of the humpback tensile test, the results from the analysis suggest that all the tensile and compressive tests should be evaluated in the experimental stage of the programme. In the case of shear, the lowest scoring tests were the two torsion loading configurations (ie torsion of a solid rod or disc). The low scores obtained by these tests can partially be attributed to the need for a torsion facility, which is not always available.

Although, the analysis suggested that it is acceptable to use specimens with T-T dimensions greater than 100 mm (eg IITRI and Celanese compression and long coupon tension), subsequent discussion with the Industrial Advisory Group suggested that the use of these loading fixtures was not supported. Tests could be performed using end pieces bonded to each end of the specimen such that these end attachments would be outside the gauge-section, but this may not have any benefits over directly loading the same specimen. As material is available at NPL in the form of 2 mm, 5 mm, 10 mm, 20 mm, 40 mm and 100 mm thick glass-fibre/epoxy fabric laminates (Tufnol 10g/40), some limited comparisons are possible.

As previously mentioned, the two most important criteria were the availability of a standard test method and the ability of a test method to produce a consistent failure mode. An improvement in the corresponding ratings through the development of a standard procedure and improved specimen design would result in a marked increase in the overall evaluation of a test method.

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TABLE 2 Test Methods for Determining Through-Thickness Tensile Properties

Test Method	Long Coupon (Type A)	Short Block (Type B)	C-Section (Type C)	Humpback (Type D)	Waisted Block (RARDE)	Closed Ring
Tensile Properties Obtained	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(T)$	$S_{33}(T)$	$S_{33}(T)$	$S_{33}(T)$	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(T)$	$S_{33}(T)$
Material Quantity Requirements per Specimen	High (very thick laminate)	Low	Moderate	Moderate	Low - thick laminate	Moderate
Typical Specimen Dimensions (mm)	44.5 wide 9.5 thick 150 long ^{T-T}	25 x 25 13 thick ^{T-T}	10 wide 10 thick ^{T-T} 50 inner radius	270 long 36 wide 9 thick ^{T-T}	25 x 25 waisted 16 x 10 38 thick ^{T-T}	10 wide 10 thick ^{T-T} 25 inner radius
Materials Suitable for Testing	1 to 6	1 to 6	1, 5 and 6	1, 5 and 6	1 to 6	1, 5 and 6
Cost of Specimen Fabrication and Preparation	Very high	Moderate	Moderate	Moderate	High	Moderate
Cost of Testing per Specimen	Moderate	Moderate	Low	Low	Moderate	Low
Specimen Fabrication Equipment Requirements	None	None	Match moulding dies or filament winding facility	Match moulding dies	None	Match moulding dies or filament winding facility
Specimen Instrumentation Requirements	Strain gauges	Extensometer	Extensometer	None	Strain gauges	Extensometer
Test Equipment and Fixture Requirements	Universal Test Machine + End Grips	Universal Test Machine	Universal Test Machine + Loading Fixture	Universal Test Machine + 4-Point Bend Fixture	Universal Test Machine	Universal Test Machine + Loading Fixture
Data Reduction	Straightforward	Straightforward	Complicated for thin laminates	Complicated for thin laminates	Straightforward	Complicated for thin laminates
Accuracy (Estimated)	To be determined	To be determined	To be determined	To be determined	To be determined	To be determined
Standard Test Methods Available	None	None	None	None	None	None

1 = continuous aligned; 2 = continuous random; 3 = discontinuous aligned; 4 = discontinuous random; 5 = continuous multidirectional; and 6 = two-dimensional fabrics.

TABLE 3 Test Methods for Determining Through-Thickness Compressive Properties

Test Methods	Celanese	IITRI	RARDE	Short Block	End-Block
Compressive Properties Obtained	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(C)$	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(C)$	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(C)$	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(C)$	$E_{33}, \nu_{13}, \nu_{23}$ $S_{33}(C)$
Material Quantity Requirements per Specimen	High - very thick laminate	High - very thick laminate	Moderate - thick laminate	Low	High - very thick laminate
Typical Specimen Dimensions (mm)	110 long ^{T-T} 10 wide 2-10 thick	110 long ^{T-T} 10 wide 2-10 thick	25 x 25 waisted to 16 x 10 38 thick ^{T-T}	13 x 13 12.7-25 thick ^{T-T}	110 long ^{T-T} 10 wide 2-10 thick
Materials Suitable for Testing	1 to 6	1 to 6	1 to 6	1, 5 and 6	1 to 6
Cost of Specimen Fabrication and Preparation	Moderate	Moderate	Moderate	Moderate	Moderate
Cost of Testing per Specimen	Low/Moderate	Low/Moderate	Moderate	Low	Low/Moderate
Specimen Fabrication Equipment Requirements	None	None	None	None	None
Specimen Instrumentation Requirements	Strain gauges	Strain gauges	Strain gauges	Strain gauges	Strain gauges
Test Equipment and Fixture Requirements	Universal Test Machine + Test Fixture	Universal Test Machine + Test Fixture	Universal Test Machine	Universal Test Machine	Universal Test Machine + Test Fixture + Die Set
Data Reduction	Straightforward	Straightforward	Straightforward	Straightforward	Straightforward
Accuracy (Estimated)	To be determined	To be determined	To be determined	To be determined	To be determined
Standard Test Method Available	ISO 8515/R ASTM D 3410 PrEN 1850 JIS 7076 DIN 65380 CRAG 400	ISO 8515/R ASTM D 3410 JIS 7076 DIN 65380	NONE	NONE	ISO 8515/R
NB. Celanese, IITRI & EBF are in-plane tests					

1 = continuous aligned; 2 = continuous random; 3 = discontinuous aligned; 4 = discontinuous random; 5 = continuous multidirectional and 6 = two-dimensional fabrics.

TABLE 4 Test Methods for Determining Through-Thickness Shear Properties

Test Method	Short Beam Shear	Double Notched	Torsion of Solid Rod	V-Notched Beam	Torsion Disc
Shear Properties Obtained	S_{13}	S_{13}	G_{13}, G_{23} S_{13}, S_{23}	G_{13}, G_{23} S_{13}, S_{23}	S_{13}
Material Quantity Requirements per Specimen	Very low	Low	Moderate	Low	Low
Typical Specimen Dimensions (mm)	20 long 10 wide 2 thick ^{T-T}	200 long 25 wide 3 thick ^{T-T}	10 diameter 115 long ^{T-T}	76 long 20 wide ^{T-T} 5 thick	25 diameter 2 to 25 thick ^{T-T}
Materials Suitable for Testing	1, 5 and 6	1, 2, 5, 6	1 - 6	1 - 4, 6	1 - 6
Cost of Specimen Fabrication and Preparation	Very low	Moderate	Moderate	Moderate	Moderate
Cost of Testing per Specimen	Very low	Low	Low/Moderate	Low	Low/Moderate
Specimen Fabrication Equipment Requirements	None	Machine notches	End attachments	Machine notches	End attachments
Specimen Instrumentation Requirements	None	None	Strain gauges	Strain gauges	None
Test Equipment and Fixture Requirements	Universal Test Machine + 3-Point Flexure Fixture	Universal Test Machine	Torsion Facility + End Grips	Universal Test Machine + Test Fixture	Torsion Facility + End Grips
Data Reduction	Straightforward	Straightforward	Straightforward	Straightforward	Straightforward
Accuracy (Estimated)	To be determined	To be determined	To be determined	To be determined	To be determined
Standard Test Methods Available	ISO 4585/R ASTM D 2344 EN 2377 prEN 2563 BSI 2782	ASTM D 3846 BS 4994 BS 6464	None	ASTM D 5379	None

1 = continuous aligned; 2 = continuous random; 3 = discontinuous aligned; 4 = discontinuous random; 5 = continuous multidirectional and 6 = two-dimensional fabrics.

TABLE 5 Evaluation of the Weightings for Through-Thickness Test Methods

NUMBER OF ASSESSMENT FORMS RECEIVED: 17
NUMBER OF ORGANISATIONS: 14

CRITERION	Design			QA		
	Responses	Range	Mean	Responses	Range	Mean
Stiffness Data available	17	2-10	7.9	15	1-8	4.1
Strength Data available	17	8-10	9.4	15	3-10	7.1
Small amount of material needed	15	1-9	4.2	14	1-10	5.1
Low cost specimen preparation equipment	16	1-9	4.7	15	1-10	6.1
Low cost specimen preparation	16	1-9	5.0	15	1-10	7.6
Low cost specimen instrumentation	16	1-9	4.8	15	4-10	7.4
Low cost test equipment	16	1-9	5.0	15	2-10	6.8
Avoids special test fixtures	16	1-9	4.6	15	1-10	6.4
Low cost of testing per specimen	16	1-9	4.6	16	1-10	8.4
Standard test method available	16	7-10	8.9	15	8-10	9.0
Simple data reduction	16	1-10	6.7	14	3-10	6.6
Consistent failure mode	15	5-10	8.5	14	5-10	7.9
Applies to a wide range of materials	17	1-10	7.2	15	3-10	7.1
High accuracy results	16	2-10	7.6	15	2-10	6.5

TABLE 6 Industrial Ranking of Criteria

CRITERION	Use in Design	Use for QA
1. Standard test method available	2	1
2. Consistent failure mode	3	3
3. Strength Data available	1	6
4. Applies to a wide range of materials	6	7
5. Low cost of specimen preparation	9	4
6. High accuracy of results	5	9
7. Low cost of testing per specimen	13	2
8. Low cost of specimen instrumentation	10	5
9. Low cost of test equipment	8	8
10. Simple data reduction	7	10
11. Stiffness data	4	14
12. Avoids special test fixtures	12	11
13. Low cost of specimen preparation equipment	11	12
14. Small amount of material needed	14	13

TABLE 7 Through-Thickness Tensile Test Method Criteria Rating

CRITERION	Long Coupon	Short Block	C-Section	Humpback	Waisted Block	Closed Ring
Stiffness Data available	10	10	0	0	10	0
Strength Data available	10	10	10	10	10	10
Small amount of material needed	1	9	10	8	8	9
Low cost specimen preparation equipment	10	10	1	5	10	1
Low cost specimen preparation	4	7	10	10	1	10
Low cost specimen instrumentation	1	1	10	10	1	10
Low cost test equipment	10	10	10	10	10	10
Avoids special test fixtures	10	6	6	6	10	8
Low cost of testing per specimen	7	7	10	10	7	10
Standard test method available	0	0	4	0	0	2
Simple data reduction	10	10	5	2	7	5
Consistent failure mode	8	6	6	2	6	6
Applies to a wide range of materials	10	10	5	5	10	5
High accuracy results	7	2	4	2	7	4

TABLE 8 Through-Thickness Compressive Test Method Criteria Rating

CRITERION	RARDE	Short Block	Celanese	IITRI	End-Block
Stiffness Data available	10	10	10	10	10
Strength Data available	10	10	10	10	10
Small amount of material needed	8	9	2	2	2
Low cost specimen preparation equipment	10	10	10	10	10
Low cost specimen preparation	4	7	7	7	7
Low cost specimen instrumentation	1	1	1	1	1
Low cost test equipment	10	10	10	10	10
Avoids special test fixtures	6	6	1	1	1
low cost of testing per specimen	10	10	2	4	7
Standard test method available	4	4	4	4	4
Simple data reduction	7	7	10	10	10
Consistent failure mode	7	2	4	5	5
Applies to a wide range of materials	10	5	10	10	10
High accuracy results	7	2	4	5	5

TABLE 9 Through-Thickness Shear Test Method Criteria Rating

CRITERION	Short Beam Shear	Double Notched	V-Notched Beam	Torsion of Solid Rod	Torsion Disc
Stiffness Data available	0	0	10	10	0
Strength Data available	5	5	10	10	5
Small amount of material needed	10	8	8	2	8
Low cost specimen preparation equipment	10	10	10	10	10
Low cost specimen preparation	10	4	4	1	4
Low cost specimen instrumentation	10	10	1	1	10
Low cost test equipment	10	10	10	5	5
Avoids special test fixtures	6	10	1	10	10
low cost of testing per specimen	10	7	7	4	4
Standard test method available	10	6	8	2	0
Simple data reduction	10	7	7	4	4
Consistent failure mode	5	5	5	6	2
Applies to a wide range of materials	5	7	8	10	10
High accuracy results	6	2	6	6	2

TABLE 10 Overall Evaluation for T-T Test Methods
(Maximum possible score = 2800)

Tension

METHOD	DESIGN	QA	TOTAL
Short Block (Type B)	643	668	1311
Long Coupon (Type A)	637	652	1289
Waisted Block (RARDE)	615	630	1245
C-Section (Type C)	549	646	1195
Closed Ring	536	636	1172
Humpback (Type D)	454	560	1014

Compression

METHOD	DESIGN	QA	TOTAL
Waisted Block (RARDE)	669	696	1365
End-Block	610	622	1232
IITRI	596	597	1193
Short Block (Type B)	572	616	1188
Celanese	571	566	1137

Shear

METHOD	DESIGN	QA	TOTAL
Short Beam Shear	638	758	1396
V-Notched Beam	629	638	1267
Double Notched	532	635	1167
Torsion of Solid Rod	541	532	1073
Torsion Disc	416	500	915

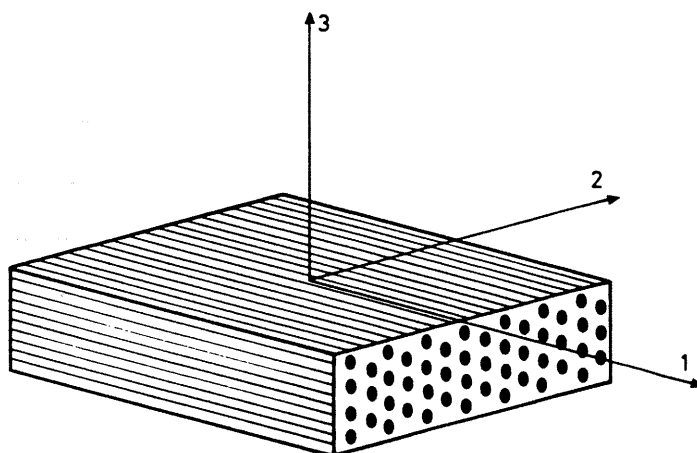


Figure 1.1 Three-dimensional system.

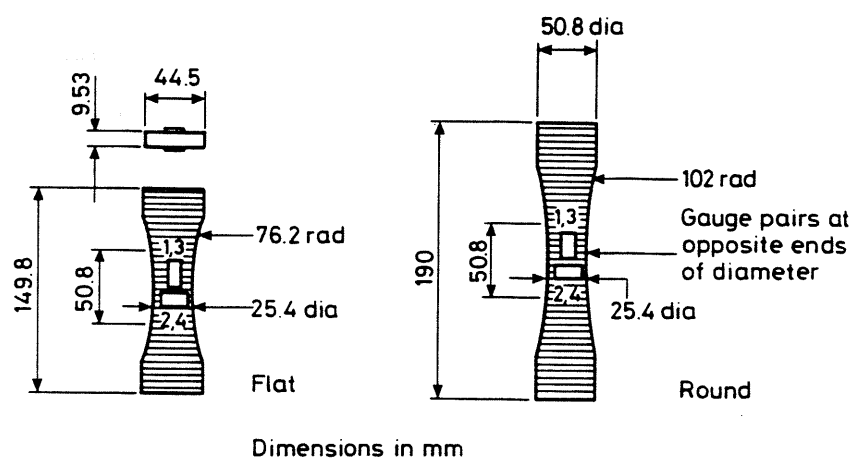


Figure 3.1 Long coupon (Type A) specimens: (a) rectangular; (b) circular [3].

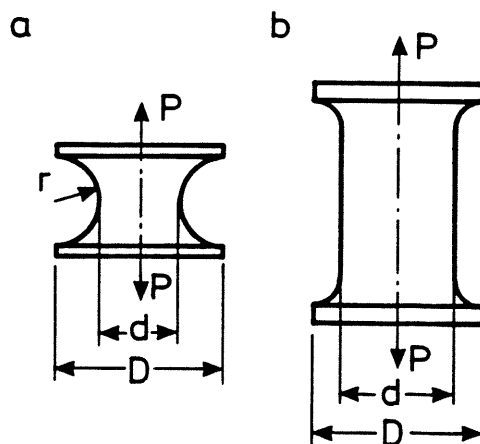


Figure 3.2 Short block (Type B) specimen [3].

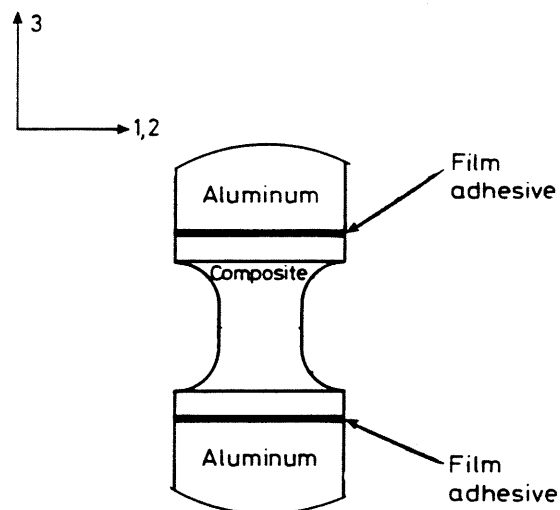


Figure 3.3 Waisted block (RARDE) tensile specimen with end tabs.

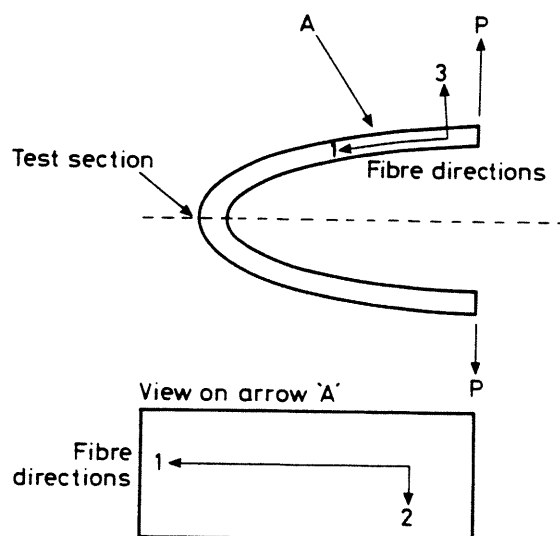


Figure 3.4 C-section (Type C) specimen [3].

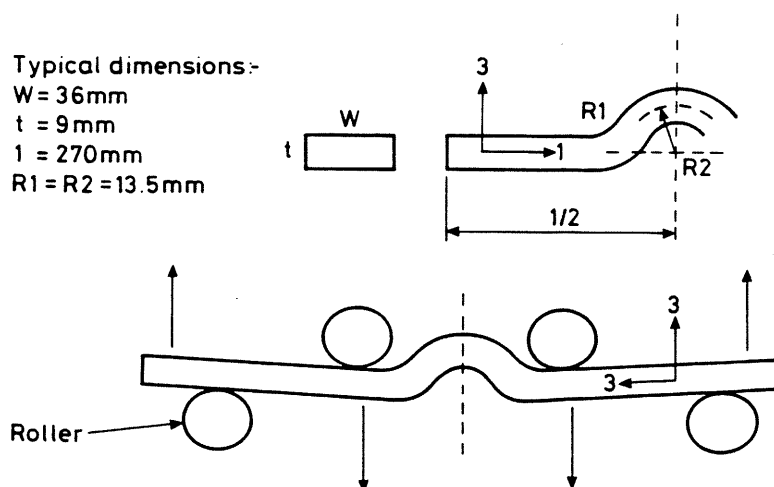


Figure 3.5 Hump-back (Type D) specimen [3].

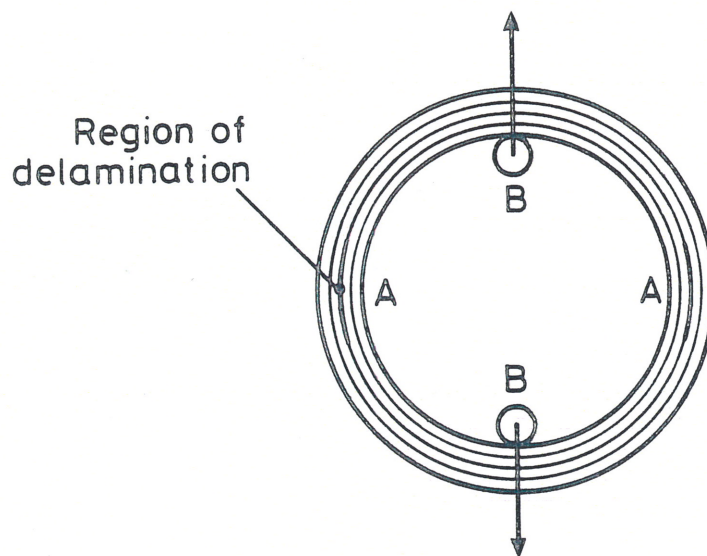


Figure 3.6 Closed ring tensile specimen.

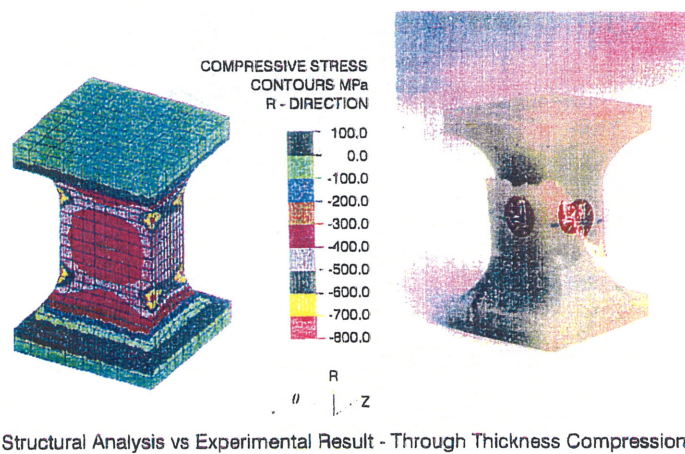


Figure 4.1 Waisted block (RARDE) compression specimen [3].

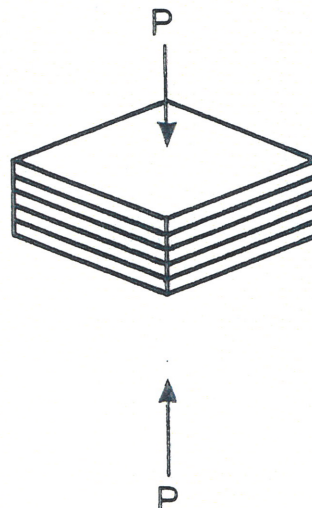


Figure 4.2 Short block compression specimen.

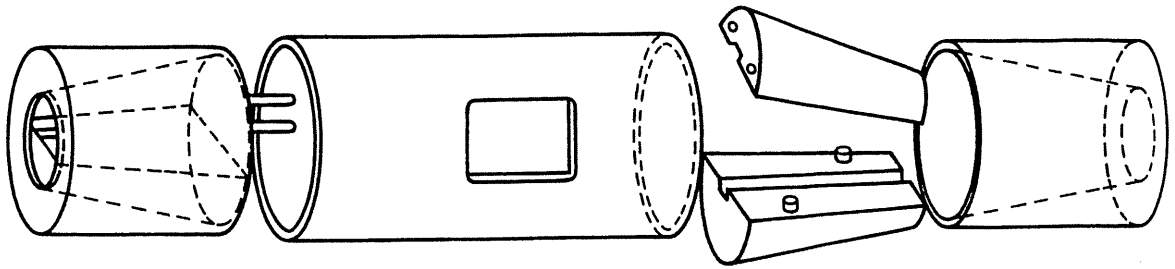


Figure 4.3 Exploded view of Celanese compression test fixture.

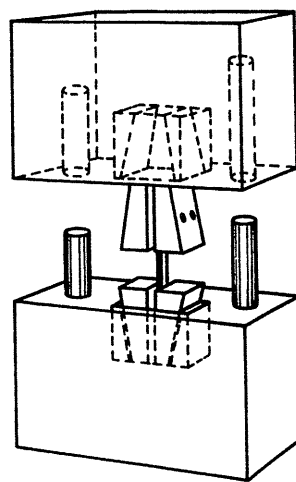


Figure 4.4 IITRI compression test fixture.

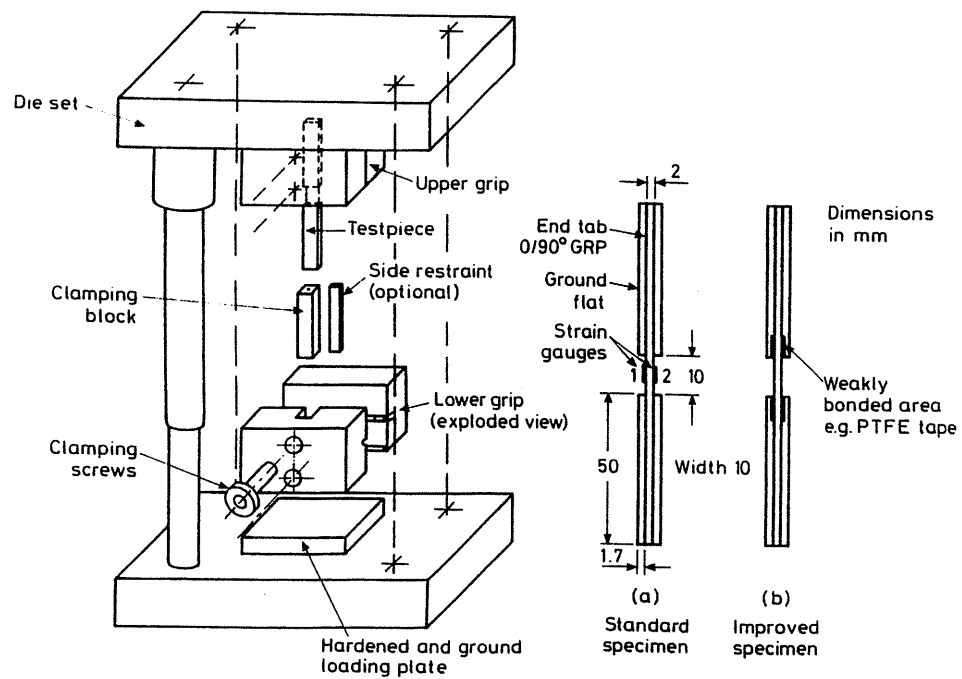


Figure 4.5 End-block loading assembly and specimen [9].

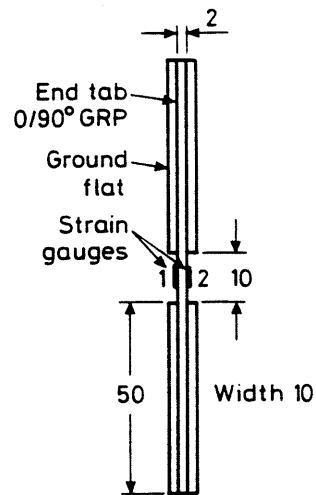


Figure 4.6 Standard compression coupon specimen.

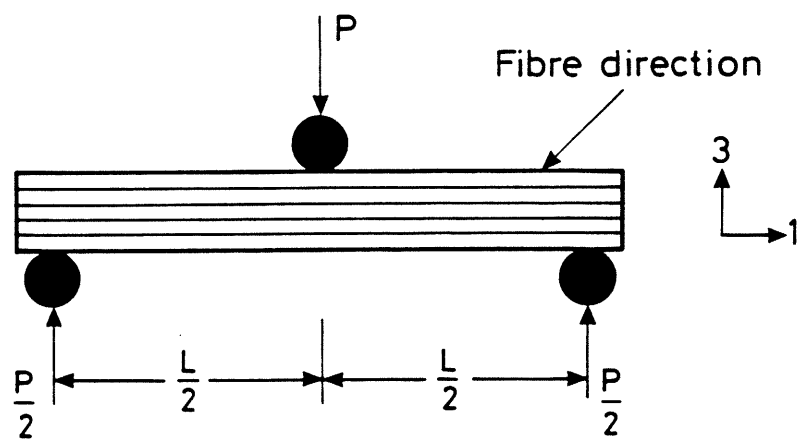


Figure 5.1 Short beam shear test.

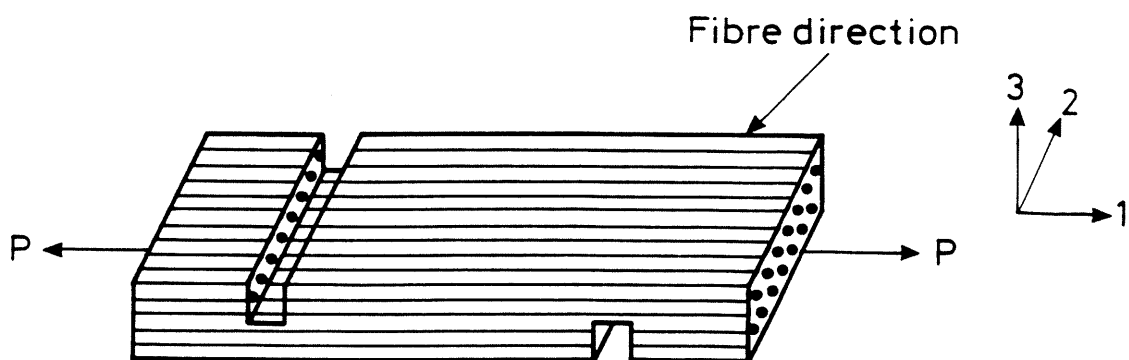


Figure 5.2 Double-notched laminate shear specimen.

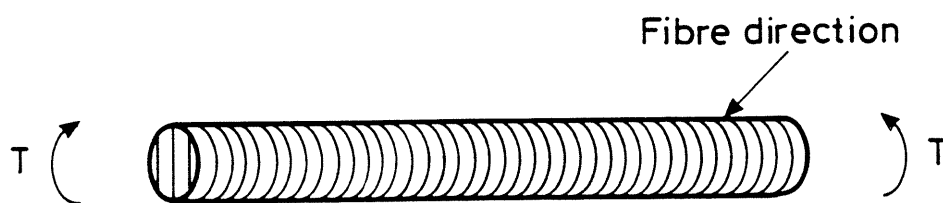


Figure 5.3 Torsion of solid circular rod.

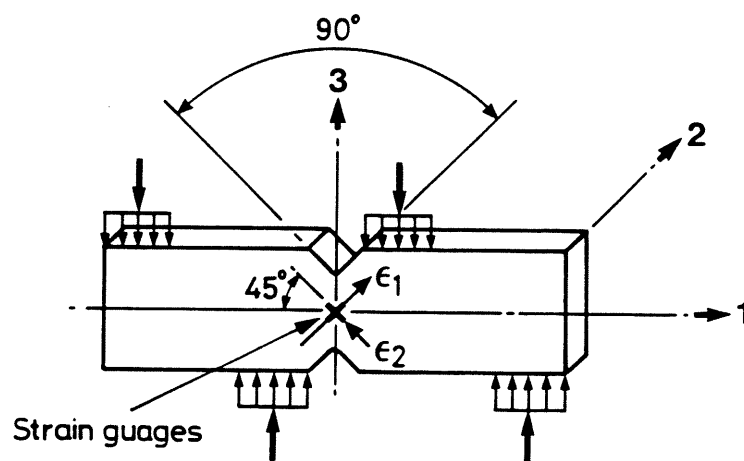


Figure 5.4 V-notched beam shear loading configuration.

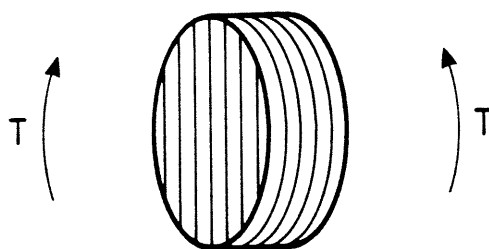


Figure 5.5 Torsion of circular discs.

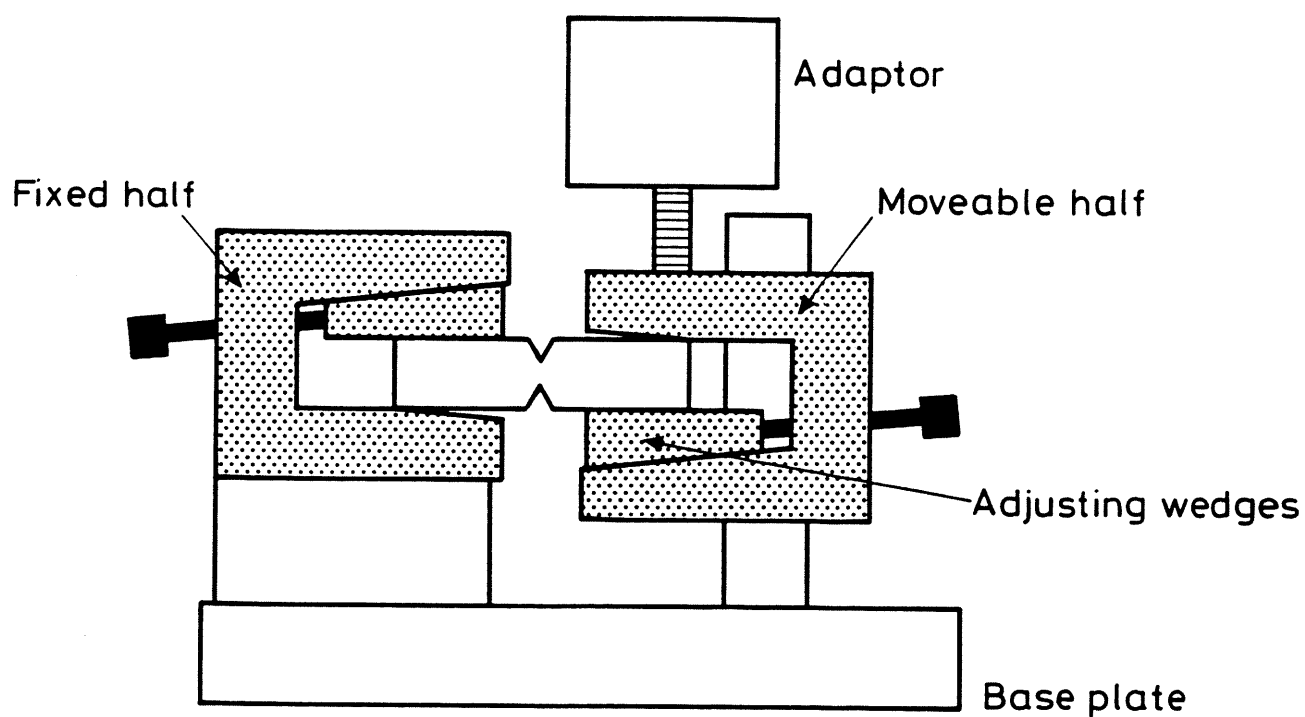


Figure 5.6 V-notched beam test fixture and specimen.

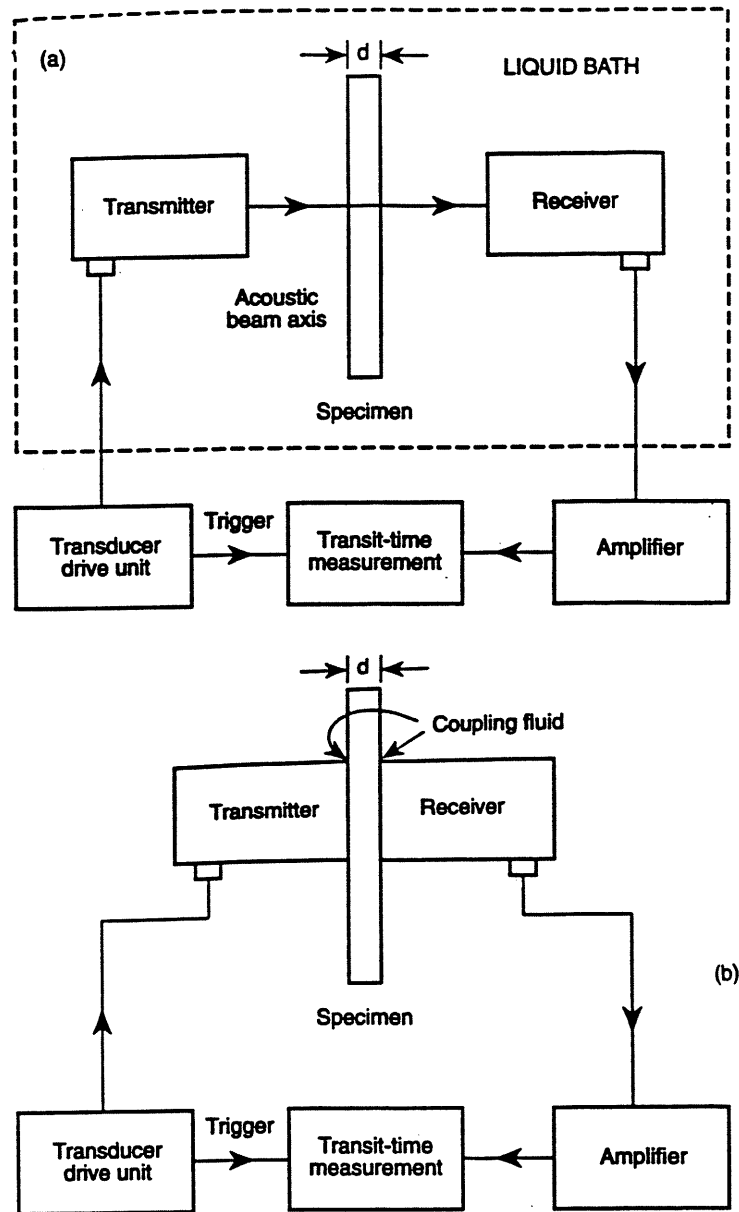


Figure 6.1 Ultrasonic methods: (a) immersion method; (b) contact method [29].

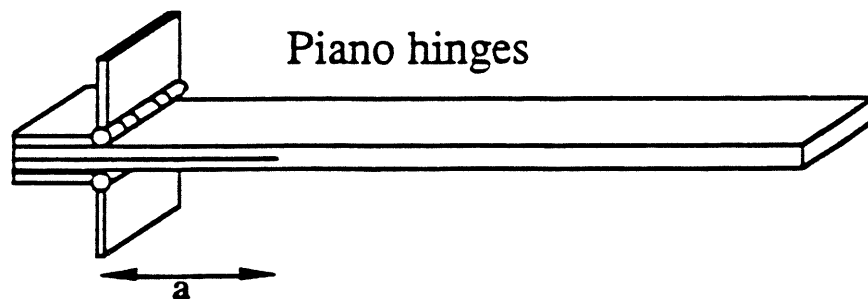


Figure 7.1 Mode I double cantilever beam specimen (DCB) geometry [32].

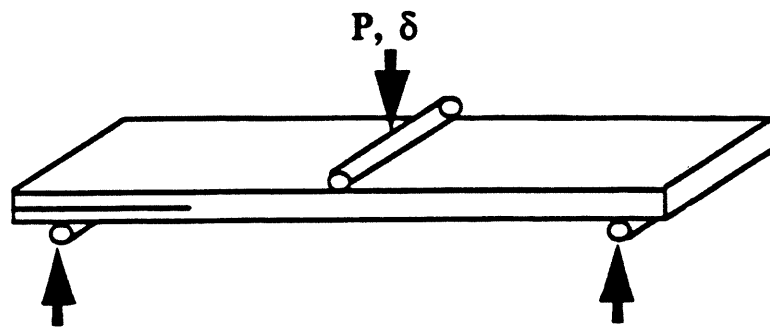


Figure 7.2 Mode II end notched flexure (ENF) specimen geometry [32].

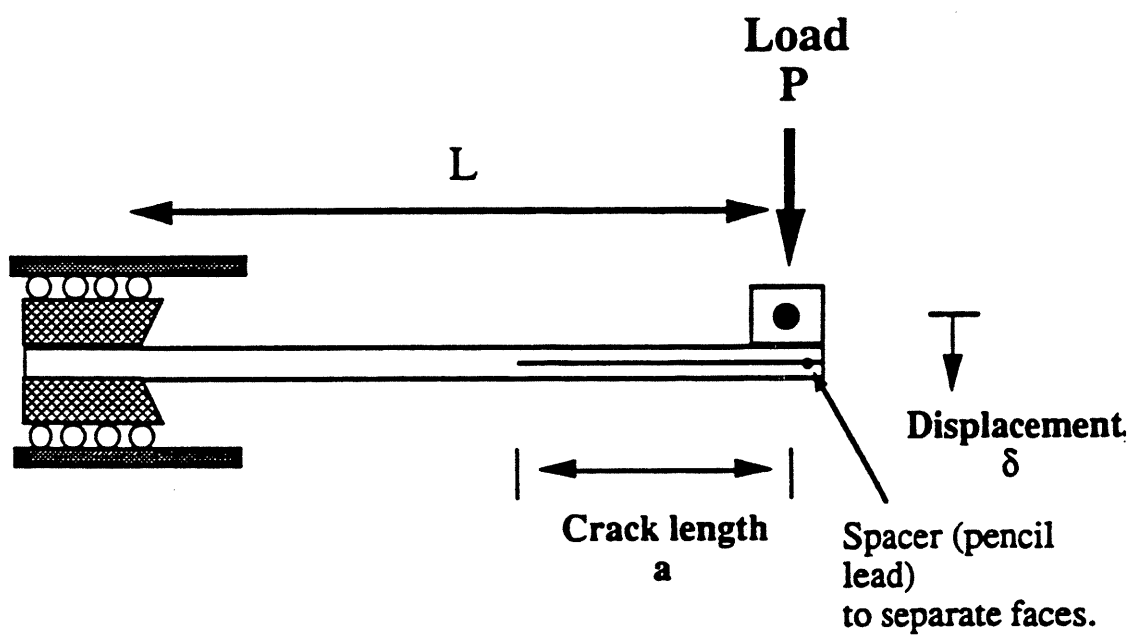


Figure 7.3 Mode II end loaded split (ELS) specimen geometry [32].

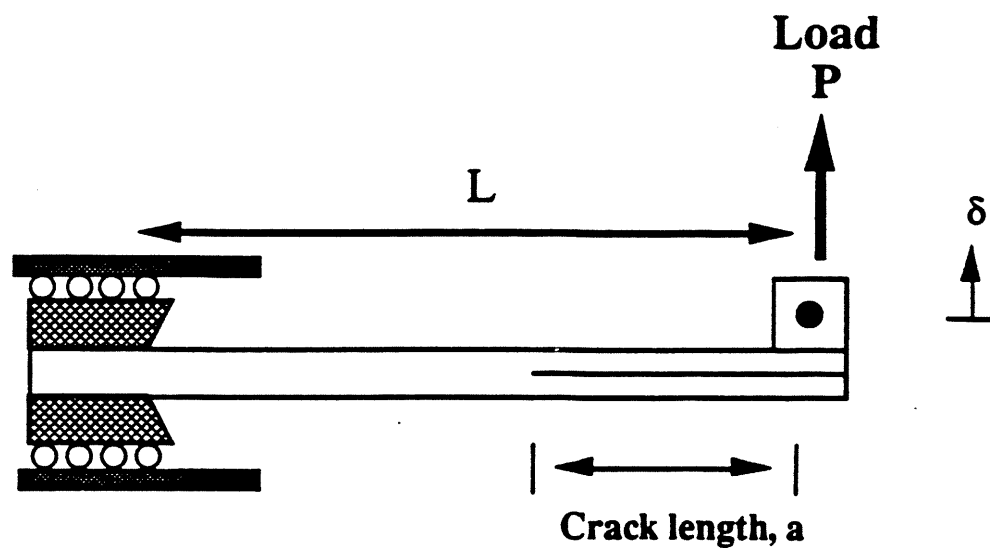


Figure 7.4 Mixed-mode I/II asymmetric DCB specimen geometry [32].

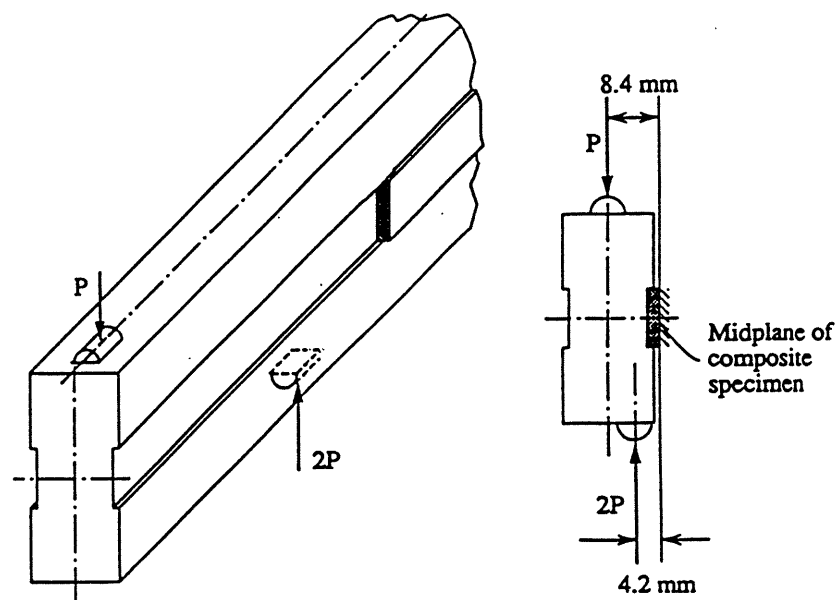


Figure 7.5 Mode III Modified split cantilever beam (SCB) specimen geometry [32].