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Material Data Requirements and Recommended Test Methods for the Predictive Modelling of Defect Criticality in Composite Material Systems

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ABSTRACT

Prior work within the MMS13 project had proposed an approach for the modelling of delamination and matrix micro-cracking defect criticality based on three assessment levels; ranging from the relatively straightforward and simplistic Level 1 analysis, up to a more complex, accurate and time consuming Level 3 investigation. This report documents the material property requirements and associated recommended test methods/experimental guidance for generating material data for the predictive modelling of the criticality of such defects according to the three level approach.

In-plane and through-thickness properties are required for tension, compression and shear, as well as the measurement of fracture toughness data for Mode I and II loading. Details on the most appropriate test standards, specimen sizes and testing good practice are provided.

For the highest degree of accuracy when undertaking a Level 1, 2 or 3 assessment of defect criticality, measured data should ideally be used, however it is acceptable at Levels 1 and 2 to use assumed data provided that any assumptions made are valid and justifiable. For a Level 3 analysis it is strongly recommended that only first hand measured or validated predicted data are used.

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GLOSSARY OF SYMBOLS

E_{11}	Young's modulus in 1-direction
E_{22}	Young's modulus in 2-direction
E_{33}	Young's modulus in 3-direction
G_{12}	In-plane shear modulus (1-2 plane)
G_{13}	Shear modulus in the 1-3 plane
G_{23}	Shear modulus in the 2-3 plane
ν_{12}	In-plane (major) Poisson's ratio
$\varepsilon_{matcrack}$	Strain at onset of matrix micro-cracking
E_{xx}	Young's modulus in x-direction
E_{yy}	Young's modulus in y-direction
G_{xy}	Young's modulus in z-direction
ν_{xy}	In-plane (major) Poisson's ratio
S_{xxt}	Tensile strength in x-direction
S_{yyt}	Tensile strength in y-direction
S_{xxc}	Compressive strength in x-direction
S_{yyc}	Compressive strength in y-direction
S_{xy}	In-plane shear strength (1-2 plane)
S_{xz}	Shear strength in the 1-3 plane
S_{yz}	Shear strength in the 2-3 plane
ΔG_{Ith}	Mode I crack growth threshold strain energy release rate
ΔG_{IIth}	Mode II crack growth threshold strain energy release rate
G_{IC}	Mode I critical strain energy release rate
G_{IIC}	Mode II critical strain energy release rate

N.B. Ply (or fully unidirectional laminate) properties are denoted using numeric suffixes, whilst laminate properties are denoted using alphabetic suffixes

1. INTRODUCTION

This report documents the material property requirements and associated recommended test methods/ experimental guidance for generating material data for the predictive modelling assessment of defect criticality in composite material systems. Prior work within the MMS13 project [1,2] proposed an assessment procedure for the modelling of defect criticality based on three levels, ranging from the relatively straightforward and simplistic Level 1 analysis, up to a more complex, accurate and time consuming Level 3 investigation. In this report the term 'defect' includes manufacturing flaws and in-service damage.

Although in practice there are over one hundred individual defect types, most defects, whilst perhaps differing in detail, retain broadly similar morphology and effect on material behaviour. These defects can be categorised into generic defect classifications, e.g. delamination, matrix micro-cracking, laminate through-thickness cracking, material thinning and voids. In order to simplify the modelling approaches for the three levels of assessment, it has been further assumed that most defects fit into either the delamination or matrix micro-cracking classifications. Therefore, the material data requirements and associated test methodology described in this report only consider the material data required by the theoretical models detailed in [2] for delaminations and matrix micro-cracking.

The report is split into two main sections: (i) Section 2 details the material properties that are required for the modelling assessment of delaminations and matrix micro-cracking defects, and (ii) Section 3 provides recommendations and guidance on the test methods that should be used for the accurate measurement of those properties. Conclusions are given in Section 4.

2. MATERIAL DATA REQUIREMENTS FOR A 3 LEVEL ASSESSMENT

The approach proposed in this project is based on a 3 level assessment. The Level 1 assessment has been defined so as to require the operator to undertake only a relatively simple analysis involving basic calculations and retaining a high degree of conservatism. The Level 2 approach allows for a reduction in some of the conservatism employed at Level 1, but is based on more detailed analysis reliant on fewer simplifying assumptions. A Level 3 assessment is the most complex and involved, with fewer simplifying equations and will typically involve a finite element analysis (FEA).

Table 1 - Material Data Requirements at Each Assessment Level

Assessment level	Defect category		Degree of accuracy required
	Delamination	Matrix microcracking	
1	E_{min} ΔG_{Ith}	E_{xx}, E_{yy}, G_{xy}, ν_{xy} S_{xxt}, S_{yyt}, S_{xxc}, S_{yyc}, S_{xy} $\varepsilon_{matcrack}$ (glass ~ 2500 $\mu\varepsilon$ carbon ~ 4000 $\mu\varepsilon$)	If material data is not available, conservative assumptions can be made to estimate values
2	E_{11}, E_{22}, G_{12}, ν_{12} ΔG_{Ith}, ΔG_{IIth}	E_{11}, E_{22}, G_{12}, ν_{12} S_{xxt}, S_{yyt}, S_{xxc}, S_{yyc}, S_{xy} $\varepsilon_{matcrack}$ (glass ~ 2500 $\mu\varepsilon$ carbon ~ 4000 $\mu\varepsilon$)	Ideally test data should be used, but estimated values are allowed if data not available
3	E_{11}, E_{22}, G_{12}, ν_{12} ΔG_{Ith}, ΔG_{IIth} G_{IC}, G_{IIC}	E_{11}, E_{22}, E_{33}, G_{12}, G_{13}, G_{23}, ν_{12} S_{xxt}, S_{yyt}, S_{xxc}, S_{yyc}, S_{zzt}, S_{zzc}, S_{xy}, S_{xz}, S_{yz} $\varepsilon_{matcrack}$	For full benefits of level 3 investigation to be achieved, accurate test data should always be used

Although each assessment level requires a number of material properties, it is essential that for all levels, the assessor has a full knowledge of material type/format and ply stacking sequence for laminates. (N.B. Ply and laminate properties are designated using numeric and alphabetic suffixes respectively (Figure 1)).

In general ply 'material' properties will not be equivalent to 'structural' laminate properties as laminates consist of a number of differently oriented plies, the exception being when the laminate is fully unidirectional i.e. for this case $E_{xx} = E_{11}$, $E_{yy} = E_{22}$, $G_{xy} = G_{12}$ and $\nu_{xy} = \nu_{12}$. At the laminate level, the reference axes usually align with the dominant fibre direction, any natural structural reference or primary loading axes.

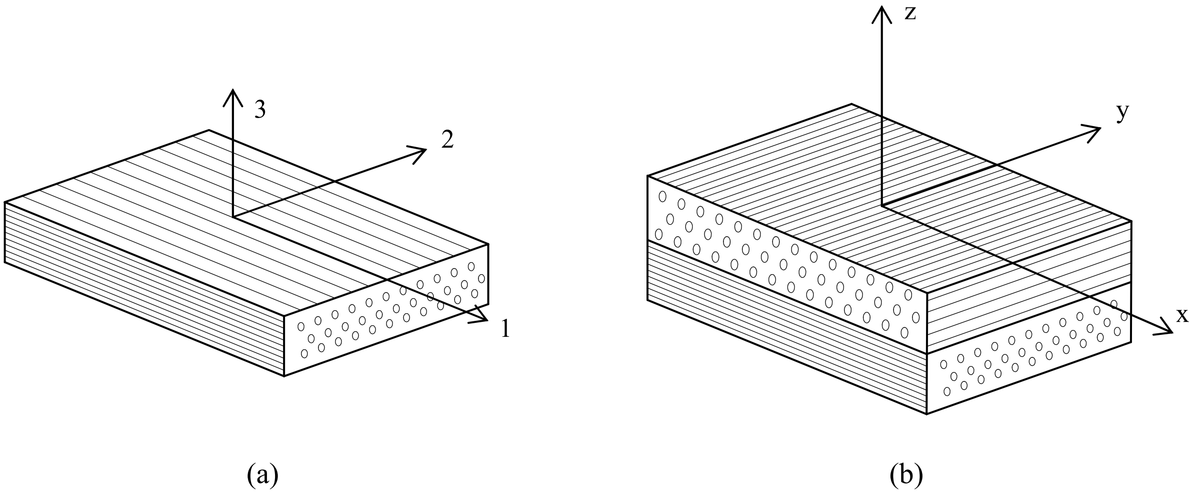


Figure 1 - Fibre-reinforced plastic composite axes definitions for (a) ply and (b) laminate levels

2.1 LEVEL 1

The material properties required at this level are listed in Table 1. For the assessment of delamination type defects, a minimum value of Young's modulus (this value corresponds to the laminate's minor principal axis) and the Mode I threshold strain energy release rate (ΔG_{Ith}) are required. Assessment of matrix micro-cracking defect types requires basic in-plane elastic and strength data at the laminate level plus an estimate of the strain limit for the onset of micro-cracking. For a Level 1 assessment, if measured material data is not available, conservative assumptions are permitted to be made in order to estimate values, e.g. strain limits for the onset of micro-cracking can be assumed to be ~2500 $\mu\varepsilon$ and ~4000 $\mu\varepsilon$ for glass and carbon laminates, respectively.

2.2 LEVEL 2

Details of the material properties required for a Level 2 assessment are given in Table 1. In contrast to a Level 1 assessment, the analysis of delamination type defects at Level 2 requires the in-plane elastic properties at the ply level in addition to the Mode I and II threshold strain energy release rates. For matrix micro-cracking; in-plane elastic ply and laminate strength data, and an estimate of the strain limit for the onset of micro-cracking (see Section 2.1) are required.

2.3 LEVEL 3

The material properties required at this level are listed in Table 1. In addition to the properties needed at Level 2, a Level 3 assessment requires the critical strain energy release rates for Mode I and Mode II, plus through-thickness elastic ply and laminate strength properties. The strain limit for the onset of matrix micro-cracking should also be measured and not assumed as for the previous levels.

3. RECOMMENDED TEST METHODS

Although estimated material data can be used for Level 1 and 2 assessments, accurate test data should be used at all 3 levels of assessment and always for a Level 3 assessment. The complexity and accuracy of a Level 3 assessment could be compromised if estimated material data are used. Synthesised data can be used as long as validation evidence is available.

The following sub-sections provide brief details on test standards that are recommended for use in generating the data listed in Section 2. The reader is advised to study the individual standards for full details on testing procedures.

The use of accurate load and displacement monitoring equipment is essential for precision measurements. For measurement of displacement, at the very least the test machine crosshead should only be used in conjunction with a machine compliance correction, which may be non-linear. However, this is really only satisfactory for flexure tests. For tension and compression testing; clip gauge extensometers, strain gauges, non-contact video extensometers or LVDTs with a low spring stiffness are recommended for displacement/strain measurement. Specimen dimensions should always be measured to the level of accuracy required in the test standard as small errors in the measurement of dimensions can make large differences to the results.

3.1 IN-PLANE PROPERTIES

This section details those test methods recommended for use in measuring in-plane properties, i.e. in the 1-2 or x-y plane (see Figure 1). Test methods for measuring properties in the through-thickness direction (3 direction) are discussed in Section 3.2.

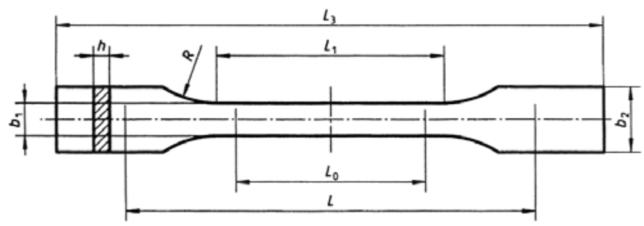
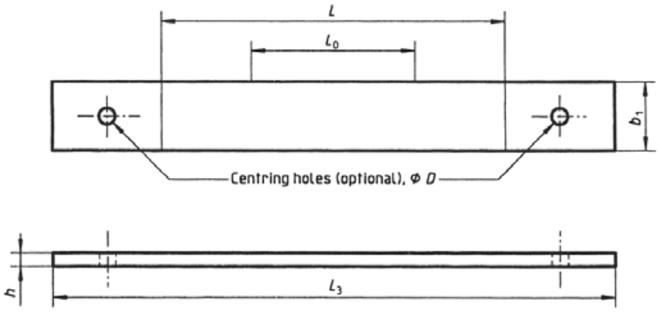
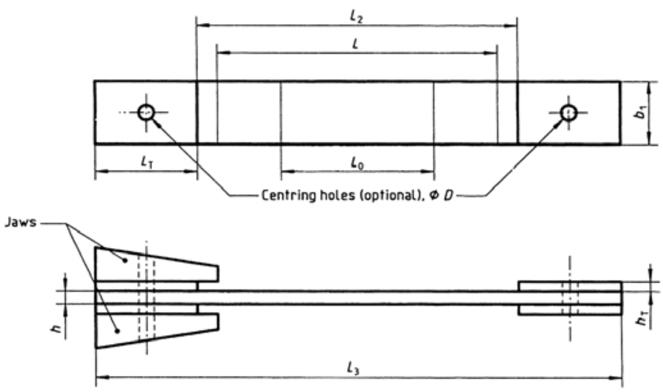
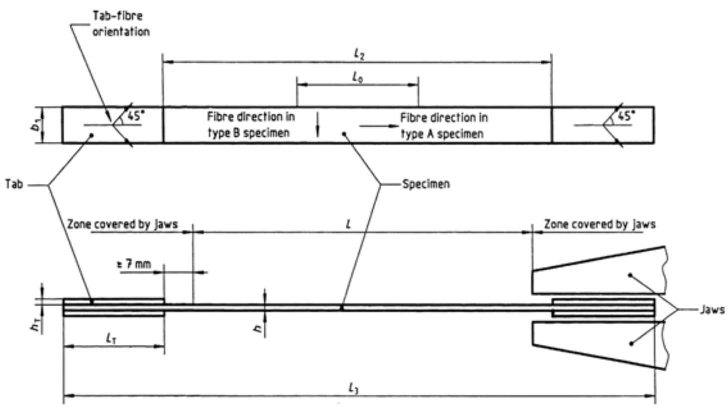
3.1.1 Tension - BS EN ISO 527 Parts 1, 4 and 5 [3,4,5]

The recommended test standard for generating tensile material property data for isotropic and orthotropic, and unidirectional fibre-reinforced plastic composites is BS EN ISO 527 (Parts 4 and 5

Table 2 - In-Plane Tensile Test Specimen Dimensions

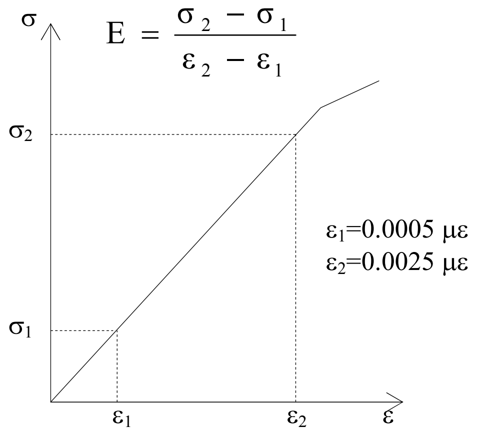
Dimension		Standard specimen sizes (mm)				
		ISO 527-4			ISO 527-5	
Symbol	**Definition**	**Type 1B**	**Type 2**	**Type 3**	**Type A**	**Type B**
L	Initial distance between grips	115 ± 1	150 ± 1	136	136	136
L_0	Gauge length for extensometers	50 ± 0.5	50 ± 1	50 ± 1	50 ± 1	50 ± 1
L_1	Length of narrow parallel section	60 ± 0.5	-	-	-	-
L_2	Distance between end tabs	-	-	150 ± 1	150 ± 1	150 ± 1
L_3	Overall length	≥ 150	≥ 250	≥ 250	250	250
L_T	Length of end tabs	-	-	≥ 50	≥ 50	≥ 50
b_1	Width	10 ± 0.2	25 ± 0.5 50 ± 0.5	25 ± 0.5 50 ± 0.5	15 ± 0.5	25 ± 0.5
b_2	Width at ends	20 ± 0.2	-	-	-	-
h	Thickness	2 to 10	2 to 10	2 to 10	1 ± 0.2	2 ± 0.2
h_T	Thickness of end tabs	-	-	1 to 3	0.5 to 2	0.5 to 2
R	Radius	≥ 60	-	-	-	-
D	Diameter of centring holes	-	3 ± 0.25	3 ± 0.25	-	-

Table 3 - In-Plane Tensile Test Specimens for BS EN ISO 527 Parts 4 and 5

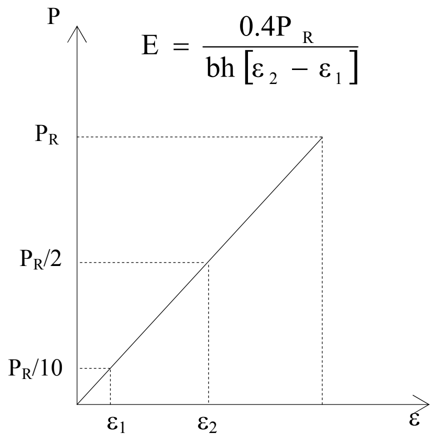
<table>
<tr><th>Specimen</th><th>Geometry</th><th>Use</th></tr>
<tr><td>BS EN ISO 527-4
Type 1B</td><td>
</td><td>• fibre-reinforced thermoplastics
• fibre-reinforced thermosets that fail in the gauge length
• not for multidirectional, continuous fibre-reinforced materials</td></tr>
<tr><td>BS EN ISO 527-4
Type 2</td><td>
</td><td rowspan="2">• for fibre-reinforced thermosets and thermoplastics
• suitable for orthotropic (multidirectional) laminates
• N.B. type 2 specimens are untabbed and type 3 are tabbed
• to decide whether end tabbed specimens are needed tests should be carried out on Type 2 specimens first</td></tr>
<tr><td>BS EN ISO 527-4
Type 3</td><td>
</td></tr>
<tr><td>BS EN ISO 527-5
Type A and B</td><td>
</td><td>• for testing of fibre reinforced thermosets or thermoplastics
• only suitable for unidirectional fibres, rovings, fabrics and tapes</td></tr>
</table>

respectively). These two parts of BS EN ISO 527 detail standard specimen geometries for different formats of composite material - see Tables 2 and 3. The standard is suitable for polymer matrix composites consisting of thermosetting or thermoplastic matrices and a wide range of fibre formats, e.g. unidirectional, cross ply, mats, woven fabrics, woven rovings, chopped strands, hybrids, rovings and short or milled fibres. The standard covers glass, carbon, aramid and other similar fibre reinforcements.

BS EN ISO 527 can be used to determine tensile strength, Young's modulus, Poisson's ratio, strain to failure and strain to onset of matrix cracking. For accurate measurement of displacement or strain it is essential that clip gauge extensometers (using a suitable gauge length of ~50 mm), strain gauges or LVDTs be used. The test machine crosshead displacement without a compliance correction will give erroneous results.



(a)



(b)

Figure 2 - Calculation of Young's modulus

The tensile Young's modulus is calculated from the initial linear portion of the stress-strain response between the strain limits of 0.05 and 0.25% strain (Figure 2(a)). Alternative tensile standards use the same specimen geometry and sizes, but calculate the Young's modulus slightly differently; ASTM D3039 [6] takes the modulus between 0.1 and 0.3% strain limits (i.e. the same strain range of 0.2%) and BS EN 2561 [7] between strain levels corresponding to $P_R/10$ and $P_R/2$ (where P_R is the specimen failure load - see Figure 2(b)). The advantage of calculating the modulus between set strain limits is that results are obtained over the same range of the stress-strain curve for different materials/specimens, whereas for BS EN 2561 the strain range used will vary depending on the failure load. However, BS EN 2561 has the advantage that it will always give a modulus value for materials such as ultra high modulus (UHM) carbon fibre-reinforced plastics (CFRP) that may fail at strain limits below 0.25%. For these types of materials it is not always possible to calculate a modulus of elasticity according to the BS EN ISO and ASTM specifications, although in these cases the maximum strain achieved should be used as the top strain limit and noted in the test report.

Calculation of tensile strain to failure can be difficult as strain gauges can become un-bonded from the specimen and clip gauge extensometers can be damaged near to or at failure. For materials where the load-deflection response to failure is almost linear (i.e. not suitable for 0°/90° laminates), it is recommended that measurement of deflection be made up to 0.5% strain using a clip gauge extensometer or strain gauges, and for the remainder of the test the machine crosshead be used. To estimate the future strain project a best fit line through the data recorded by the extensometer, and then calculate the strain corresponding to the failure load using the equation for the best-fit line (N.B. the procedure used should be noted in the test report). A strain to failure value can then be calculated using the gauge length of the extensometer, as illustrated in Figure 3.

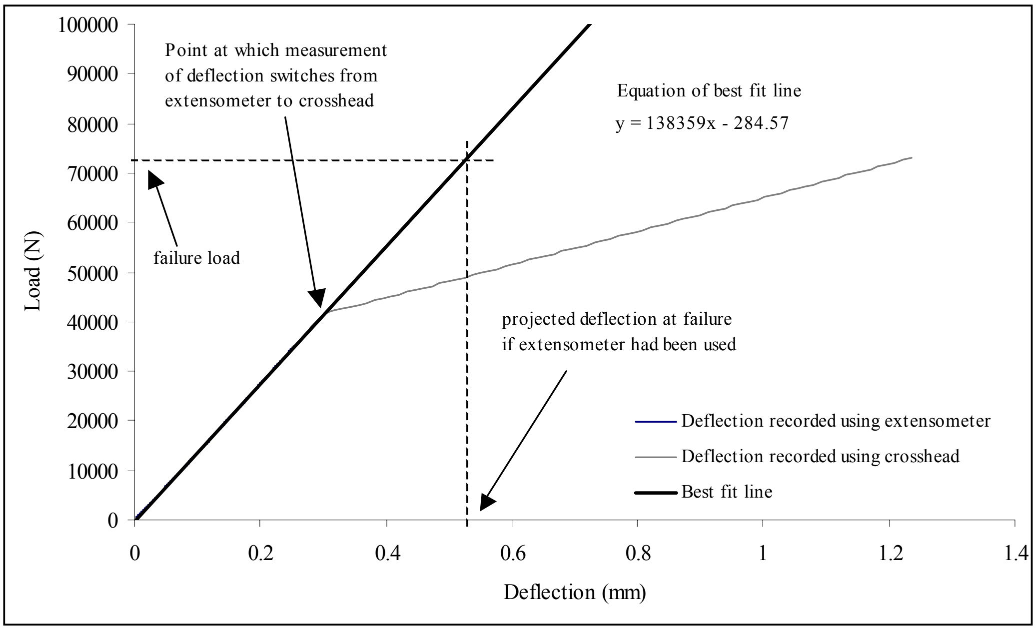
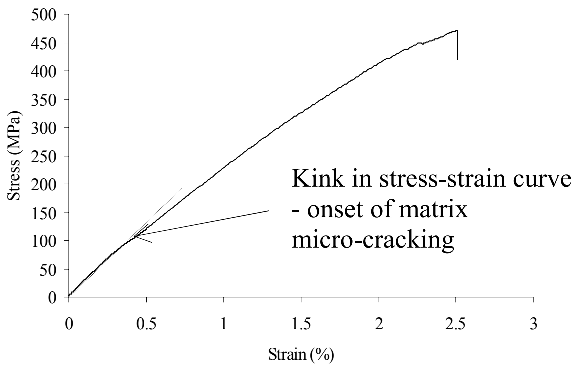


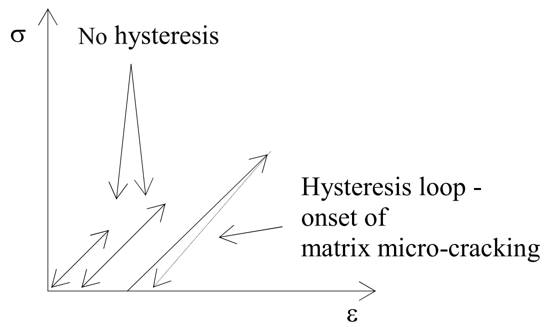
Figure 3 - Calculation of tensile deflection/strain to failure for plain tensile specimens

The major Poisson's ratio (ν_{12} or ν_{xy}) is the negative ratio of the measured strain in the longitudinal direction (1- or x- direction) to the strain in the transverse direction (2- or y- direction). The ratio should be calculated using strain readings from the same region of the stress-strain curve as used for the modulus determination and longitudinal and transverse strain gauges or extensometers should be used.

The strain level corresponding to the onset of matrix micro-cracking can be determined in a number of ways. For some materials, such as 0°/90° cross-ply laminates, the stress-strain curve has a distinctive kink where matrix micro-cracking in the 90° plies has initiated - see Figure 4(a). For other formats of material, such a kink or "knee" will not be so obvious and it may be necessary to load and unload the specimen at increasing load levels until hysteresis in the stress-strain response is observed (Figure 4(b)). Acoustic emission monitoring can also be employed to detect the onset of micro-cracking and the corresponding strain level. For all these approaches, fractographic analysis of the specimens after being loaded to just above the onset point is recommended to verify the presence of micro-cracks.



(a)



(b)

Figure 4 - Determining the strain limit for onset of matrix micro-cracking

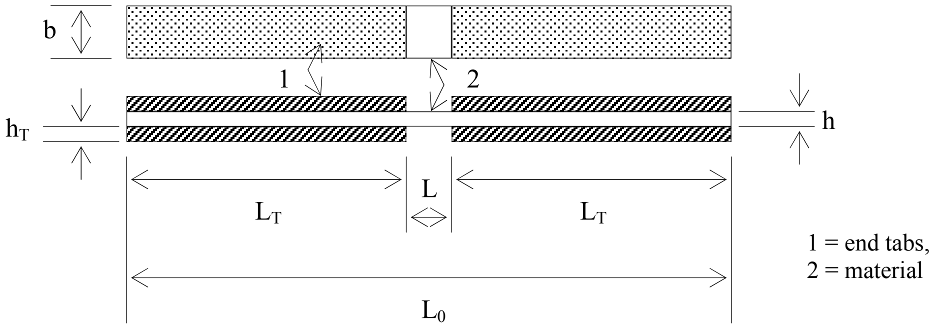


Figure 5 - Schematic of in-plane compression test specimen for BS EN ISO 14126

3.1.2 Compression - BS EN ISO 14126 [8]

The recommended test standard for generating in-plane compressive material property data for fibre-reinforced thermoplastic and thermoset composites is BS EN ISO 14126. The standard can be used to determine compressive strength, Young's modulus and strain to failure.

BS EN ISO 14126 allows the use of two loading methods; shear loading and end loading. For both loading methods the gauge length is unsupported. Two specimen types are detailed (see Figure 5 and Table 4); Type A (thickness of material is fixed) and Type B where the material thickness can be over a range. For Type B specimens, end tabs are optional. Type A specimens are typically used for unidirectional material (ply data) tested in the fibre direction, whereas for multidirectional composites (multidirectional laminates, fabrics, mats etc.) the Type B2 specimen geometry is recommended.

Alignment fixtures appropriate to the loading method should be employed to ensure good alignment of the specimen during testing. The standard requires that two longitudinal strain measurements be made, via a strain gauge on each face of the specimen, in order to ascertain whether Euler buckling has taken place during loading. If the difference between the strain gauge readings is 10% or less then the alignment is considered satisfactory and the test is acceptable.

Compressive Young's modulus is calculated in a similar way and between the same strain limits (0.05 to 0.25%) as for tensile testing (to BS EN ISO 527 Parts 4 and 5). Strain values are taken as the average readings of the two faces. If transverse strain gauges are also used, the Poisson's ratio can also be determined in compression and generally gives good agreement to values determined in tension.

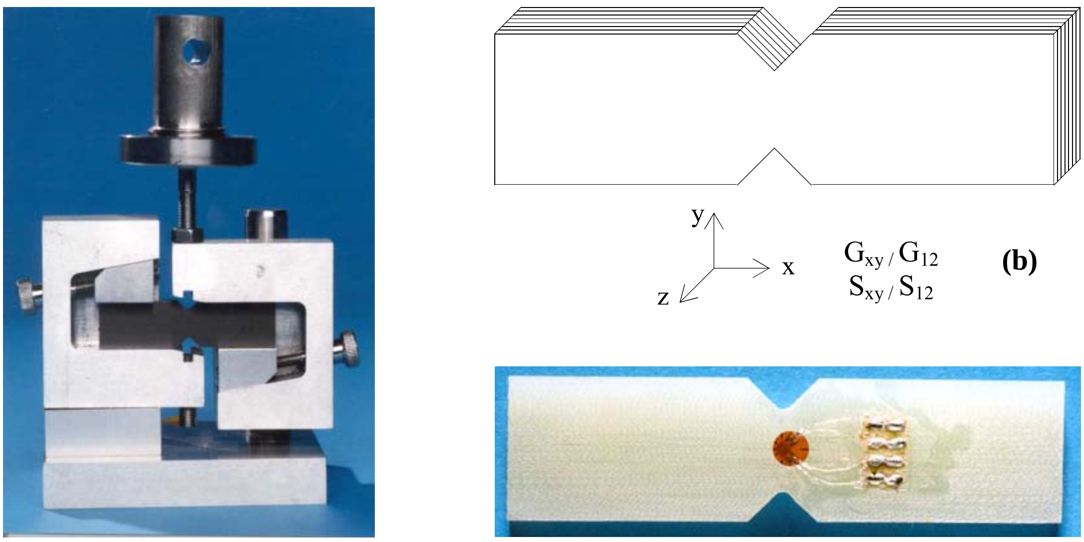
Table 4 - In-Plane Compression Test Specimen Dimensions for BS EN ISO 14126

Dimension		**Specimen sizes (mm)**		
Symbol	**Definition**	**Type A**	**Type B1**	**Type B2**
L	Distance between end tabs/grips	10	10	25
L_0	Overall length	110 ± 1	110 ± 1	125 ± 1
L_T	Length of end tabs (minimum)	50	50 (if required)	50 (if required)
b	Width	10 ± 0.5	10 ± 0.5	25 ± 0.5
h	Thickness	2 ± 0.2	2 ± 0.2 to 10 ± 0.2	≥ 4
h_T	Thickness of end tabs	1	0.5 to 2	0.5 to 2

3.1.3 Shear - ASTM D5379 (Double V-notch beam (Iosipescu)) [9, 10]

The large number of test methods that can be used to measure shear properties can cause confusion when selecting the most appropriate procedure for the required properties. Some shear test methods produce data at the ply level, while others produce data at the laminate level. Consequently, the choice of test method directly relates to the stress analysis approach being used, i.e. ply or laminate level.

The recommended test standard for generating in-plane shear data (and through-thickness shear data - see Section 3.2.2) for fibre-reinforced thermoplastic and thermoset composites is ASTM D5379 [9]. The double V-notch shear test method (Iosipescu) uses a fixture of the type shown in Figure 6(a). The test specimen is a double edge-notched, flat, rectangular geometry (Figure 6(b)). Standard specimens are 76 mm in length and 20 mm wide with a nominal thickness of 5 mm. The two 90° notches have a root radius of 1.3 mm and are cut at ±45° to the longitudinal axis of the specimen to a depth of 20% of the specimen width (i.e. ~4 mm). The quality of the machined notch; in particular the radius, cut surface smoothness, and alignment can all have an effect on the quality of measured shear properties. Specimens of insufficient thickness can fail prematurely in compression at the edges in contact with the test rig, or through buckling. Therefore, a specimen thickness of ≥ 5 mm is used to avoid these occurrences. The loading fixture applies an in-plane shear stress between the notches. For calculation of shear modulus, a biaxial rosette strain gauge is attached at the specimen center at ±45° orientation to the loading direction (Figure 6(c)). Back to back strain gauges are required for calculation of shear modulus, G_{12}. A check for twisting of the specimen is performed at the shear strain mid-point between the shear modulus calculation points. Differences between shear moduli, due to out-of plane deformation, can be as high as 10% for a batch of nominally identical specimens. To ensure maximum accuracy, the shear modulus is determined from the average response of back-to-back biaxial rosettes. At present the standard requires only one specimen from a batch to be tested in this manner provided the amount of twist for the test specimen is no greater than 3%. Improvements to the test fixture to reduce the differences in shear moduli obtained from the two sides of specimen and possibly eliminate the need for two biaxial rosettes have been proposed,



(a) (c)

Figure 6 - (a) Iosipescu V-notch beam test rig, (b) fibre axes system for measuring in-plane properties G_{xy}/G_{12} and S_{xy}/S_{12}, and (c) specimen with biaxial rosette strain gauge

namely; (i) keying the bearing post or adding a second post to prevent twisting of the specimen due to the fixture rotating on the bearing post, and (ii) lateral adjustment to minimise out-of-plane deformation. At present, the specimen is not centrally loaded through the specimen thickness. The displacement of each half of the Iosipescu specimen cannot be used for measurement of shear strain due to the compressive deformation that often occurs at the contact surfaces.

The shear strength can be calculated from:

$$S_{12} = \frac{P_{max}}{wh}$$

Where P_{max} = Maximum load
w = distance between the notches
h = thickness

And the shear modulus using:

$$G_{12} = \frac{\Delta\tau}{\Delta\gamma} = \frac{\Delta P}{wh\Delta(\varepsilon_{45} - \varepsilon_{-45})}$$

Where the variables ΔP, $\Delta\varepsilon_{45}$ and $\Delta\varepsilon_{-45}$ are the change in applied load and +45° and –45° normal strains in the initial linear region of the stress-strain curve.

3.2 THROUGH-THICKNESS PROPERTIES

3.2.1 Tension and compression - RARDE waisted block [10]

The recommended test geometry for generating through-thickness (TT) data in both tension and compression is the RARDE waisted block (developed by the Defence Evaluation and Research

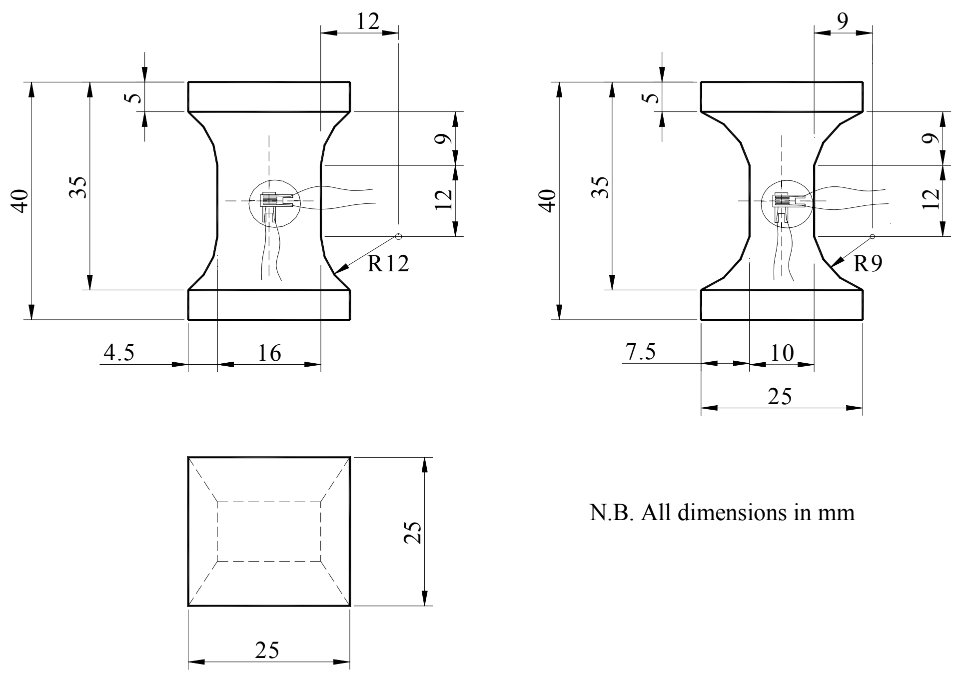


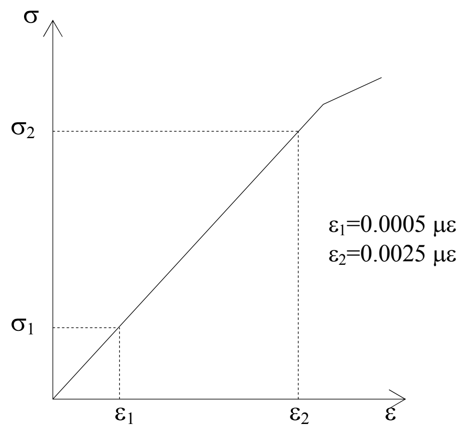
Figure 7 - RARDE waisted block specimen for through-thickness tension and compression

Agency (DERA) - now Qinetiq). The gauge-section is 12 mm long, with a rectangular cross-section of 10 mm (y-z plane or 2-3) x 16 mm (x-z plane or 1-3). Specimens are 40 mm thick, but thinner material (19-20 mm thick) can be tested provided the linear dimensions of the specimen are scaled in proportion to the standard geometry shown in Figure 7. However, it is difficult to apply strain gauges in this case. Tensile load is introduced to specimens via adhesively bonded bars which are then gripped in mechanical or hydraulic wedge action grips on the test machine. Care should be taken in selecting an adhesive that has a cure temperature lower than that of the material being tested. In compression, specimens are loaded between flat, parallel hardened steel platens and a four pillar die set is recommended to ensure uniform loading.

The TT tensile and compressive strengths, S_{zzt} and S_{zzc} respectively, can be calculated using the following expressions:

$$S_{zzt} = \frac{P_{maxt}}{a \times b} \qquad S_{zzc} = \frac{P_{maxc}}{a \times b}$$

Where P_{maxt} and P_{maxc} are the maximum tensile and compressive load respectively, 'a' is the specimen width and 'b' is the specimen depth.



$$E_{zzt} = \frac{\sigma_{2t} - \sigma_{1t}}{\varepsilon_{2t} - \varepsilon_{1t}}$$

$$E_{zzc} = \frac{\sigma_{2c} - \sigma_{1c}}{\varepsilon_{2c} - \varepsilon_{1c}}$$

Figure 8 - Calculation of modulus for through-thickness tension and compression

The technique requires biaxial (longitudinal and transverse) gauges bonded on all four specimen faces. The use of gauges on all four faces enables average strains between opposite faces to be calculated, hence small deviations in specimen/load alignment can be taken into account. The strain readings are used to assess the uniformity of loading. Tests are deemed acceptable if the difference between strains on opposing faces is ≤3%. The through-thickness tensile and compressive moduli, E_{zzt} and E_{zzc} respectively, are calculated between the same strain limits (0.05 to 0.25%) as for in-plane tension and compression tests - see Figure 8.

3.2.2 Shear - ASTM D5379 (Iosipescu V-notch Beam) [9, 10]

As for in-plane shear properties the recommended test method for through-thickness shear is ASTM D5379. Provided adequate material thickness is available (i.e. 20 mm for UD materials, 76 mm otherwise), the shear modulus and strength in the x-z (or 1-3) and y-z (or 2-3) planes can be

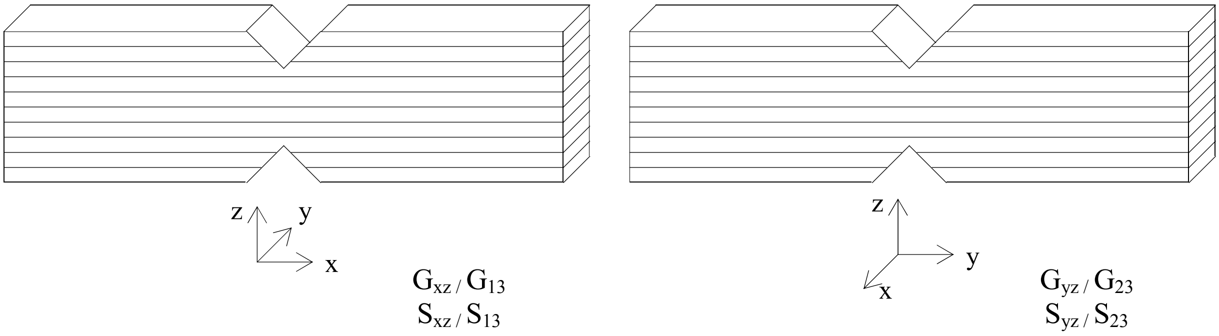


Figure 9 - Ply orientations of specimens for measurement of through-thickness shear properties

measured for a range of composite materials. Figure 9 shows the orientation in which specimens should be machined for measurement of shear properties in these planes. Modulus and strength values can be calculated using similar expressions as for the in-plane V-notch beam tests detailed in Section 3.1.3.

3.3 FRACTURE ENERGY PROPERTIES

3.3.1 Mode I

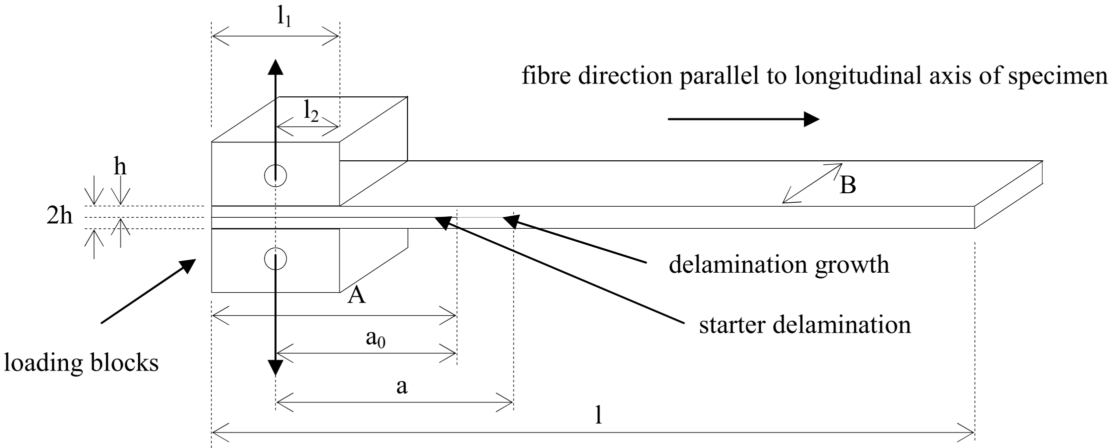


Figure 10 - Double cantilever beam specimen for measurement of Mode I properties

The recommended test method for measuring the critical strain energy release rate for Mode I loading (G_{IC}) is ISO 15024 [11] which is equivalent to ASTM D5528 [12]. The method is suitable for unidirectional carbon and glass fibre-reinforced thermoset and thermoplastic materials. The standard recommends the use of a double cantilever beam (DCB) specimen which is loaded in tension through loading blocks (as shown in Figure 10 - dimensions in Table 5) or piano hinges. Specimens contain a thin (≤ 13 μm) layer of PTFE at mid-thickness to act as an initial delamination. The specimens are quasi-statically loaded until delamination growth from the tip of the starter crack is observed at which point the load is removed. The specimens are then re-loaded and the onset of stable delamination growth is monitored. During loading the delamination length is measured by observing the crack growing through a series of lines marked at set intervals (1 and 5 mm) on the side of the specimen. The points at which the delamination front passes through the marked intervals are marked on the load-deflection trace. Data reduction is then performed to determine the strain energy release rates for crack delamination initiation and propagation.

Table 5 - Dimensions for Mode I DCB Specimen

Dimension		Value (mm)
Symbol	**Definition**	
B	Width	20 (but can use 15-30)
2h	Thickness	~3 for CFRP ~ 5for GFRP
l	Length	≥125
l_1	Loading block width	≤15
l_2	Loading block hole centre	$l_1/2$
h	Mid-plane depth	half thickness
A	Insert length	60
a	Delamination crack length	a_0 + measured delamination length
a_0	Initial delamination crack length	60-l_2

The Mode I growth threshold strain energy release rate (ΔG_{Ith}) can be determined using ASTM D6115 [13]. DCB specimens are cycled between a minimum and maximum displacement in tension-tension fatigue at a specified frequency. The number of cycles (N) to the onset of delamination growth is recorded and a corresponding Mode I cyclic strain rate can be calculated using corrected beam theory (CBT) or the modified compliance calibration (MCC) method as set out in [10]. ΔG_{Ith} can be calculated in a similar way but for an acceptable (specified by the end-user or designer) value of delamination growth rate da/dN instead of a number of cycles.

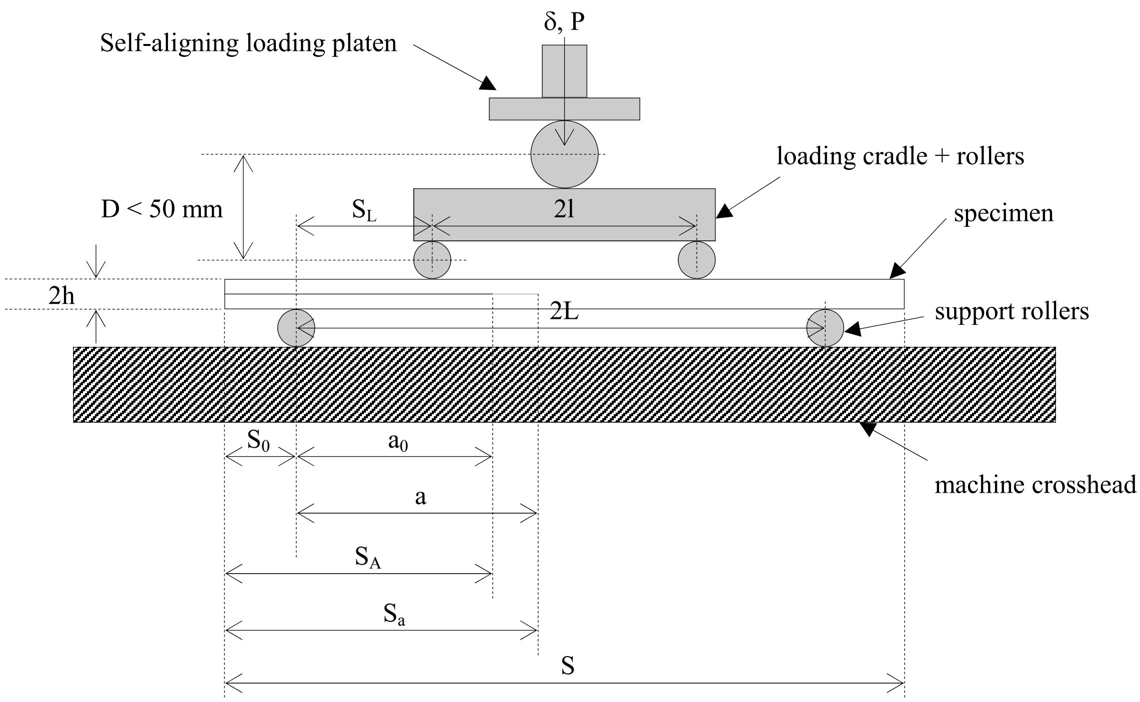


Figure 11 - 4-point end notch flexure (4ENF) specimen for measurement of Mode II properties

3.3.2 Mode II

The recommended test method for measuring the critical strain energy release rate for Mode II loading (G_{IIC}) is the four-point bend end notch flexure (4ENF) test [14]. The specimen and test geometry are illustrated in Figure 11. The specimen is typically ~3 and 5 mm thick for carbon and glass fibre-reinforced materials respectively. The specimen width is the same as for the DCB test (20 mm) and a PTFE film ≤ 13 μm thick should be used to provide a starter delamination. Specimens are loaded quasi-statically in the jig shown in Figure 11 and a delamination is initiated and grown from the PTFE insert. In the same way as for Mode I testing, the crack growth is monitored throughout the test and related to the load displacement response. Data reduction is then performed to give a value for the strain energy release rate.

A standardised method for determination of the Mode II growth threshold strain energy release rate (ΔG_{IIth}) does not currently exist. The current procedure is to adopt the approach for Mode I. The 4ENF test is suitable for static work but in fatigue the small deflections make it difficult to control at low values of G. A specimen configuration that has been used with more success in fatigue is the end-loaded shear (ELS) specimen [15]. The ELS specimen dimensions are the same as for the DCB specimens. In a similar manner for measurement of ΔG_{Ith} in Mode I loading, ΔG_{IIth} can be determined at an acceptable value of delamination growth rate da/dN.

4. CONCLUSIONS

Test standards and procedures are recommended for the generation of in-plane and through thickness tension, compression and shear data, as well as Mode I and II fracture toughness properties. For the highest degree of accuracy when undertaking a Level 1, 2 or 3 assessment of defect criticality, measured data should ideally be used, however it is acceptable at Levels 1 and 2 to use assumed data provided that any assumptions made are valid and justifiable. Certainly for a Level 3 analysis it is recommended that only known, measured data be used.

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