

Size Effects in Composite Materials

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ABSTRACT

The majority of property design data are obtained on small specimens for reasons of material availability and cost, fabrication cost and test machine capacity. Consequently, for design of relatively thick or large products, testing has to be carried out either on full-scale prototypes, or, in order to save both time and expense on small-scale models using the principles of dimensional analysis, or, the cheaper option, the data obtained on small coupon specimens must to be used. Therefore, any discrepancies encountered whilst variations from small coupon to large product (i.e. any scale or size effects) needs to be both identified and understood. There is evidence from several researchers of size effects but these are based often on bending tests that have both complex and non-uniform stress distributions. In addition, there are multiple loading points that cause local variations in the stress field at these contact points. The opposing view is also present, when the coupon data is taken as a minimum value and higher results are expected for thicker components built using 160 mm thick material.

Hence, the work described here concentrates on axial compression and tension testing. The report describes several aspects of testing that are related to determining the properties of composites over arrange of sizes. It is clear that there exist many artefacts that can suggest size effects but when carefully analysed, there is little evidence of a Weibull weakest-link type size effect. several steps are identified to minimise testing artefacts, such as:-

- to ensure that the same strain rate is used for all tests,
- to use “distributed” ply stacking sequences,
- to use the optimised tab design described in this work,
- to use 90° and 45° as outer plies to reduce the tab stress concentration.

The report was prepared as part of the research undertaken at NPL for the Department of Trade and Industry funded project on “Composites Performance and Design”.

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ISSN 1473-2734

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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INTRODUCTION

The relatively recent introduction of fibre reinforced composites (FRP) compared to metal structures, together with the large range of materials used from aerospace grade carbon-fibre/epoxy systems to the more common glass-fibre/polyester chopped strand mat systems used for small boat production, means that a broad single design methodology has not been satisfactory compiled for FRP materials. This has been compounded by the fact that there is insufficient confidence in designing structures purely theoretically without experimental testing. Consequently, testing of composite components has to be carried out either on full-scale prototypes, or, in order to save both time and expense on small-scale models using the principles of dimensional analysis. Material property data is normally obtained from specimens that are relatively small and/or thin compared to the final products. Therefore, any discrepancies encountered whilst scaling from coupon data or model to full size (i.e. any scale or size effects) needs to be both identified and understood.

Several papers have reported on the effect of size in composites, which is usually (but not exclusively) detrimental with increasing size. This is thought to be due to the increased probability of a larger specimen containing a flaw large enough to lead to failure following the “Weibull” weakest link approach. However, an accurate quantitative description of such effects, or even concrete evidence of their existence has proved elusive. These problems may be compounded by the fact that a separately manufactured specimen may not necessarily have the same properties (due to factors such as volume fraction, thermal history, etc.) as a comparable specimen cut from the full-scale structure. This latter effect is due more to the scale of production than to the actual size of the composite laminate considered. Hence, it may be helpful to think of this as a ‘scale effect’ rather than a ‘size effect’. The scaling problem is especially complex for composites due to the intricate and heterogeneous nature of their microstructure. It becomes either very difficult, or impossible to scale, for example, elements such as fibre diameter, fibre/matrix interface or ply layer.

In this report, Section 2 reviews common aspects mainly developed in later Sections. Experimental data obtained in tension and compression for a wide range of specimen volumes is reported in Sections 3 and 4, respectively. Conclusions are drawn in Section 4.

2 COMMON ASPECTS AFFECTING STRENGTH MEASUREMENTS

When tests are undertaken for different specimen sizes, there are several other aspects of the test that are difficult to scale exactly. These include:-

- loading rate or time of loading
- tab design (for higher load transfer requirements)
- ply stacking/blocking and interfacial stresses

2.1 RATE EFFECTS.

When specimens are scaled, it is not always possible to maintain the same strain rate, particularly for flexure loading where the dependences on test span, and therefore displacement rate, is different for strength and modulus properties. The tensile properties of glass-fibre/polyester and carbon-fibre/vinylester pultruded rods were determined for a range of displacement rates (i.e. 0.1, 1, 5, 10 and 100 mm/min). Testing was conducted according to BS ISO 9163 with five specimens tested per condition. Displacement was determined directly from cross-head movement. The tensile strengths are shown in Figures 1 and 2, for the two material tested. The glass-fibre system shows a significant effect and the carbon-fibre system a small or insignificant effect. No effect observed on the moduli.

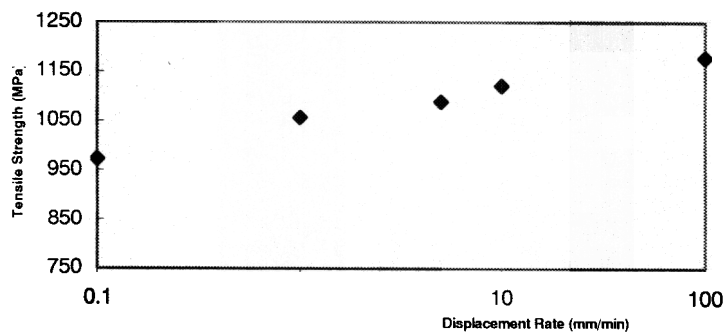


Figure 1 *Effect of displacement rate on tensile strength for glass-fibre/polyester rod*

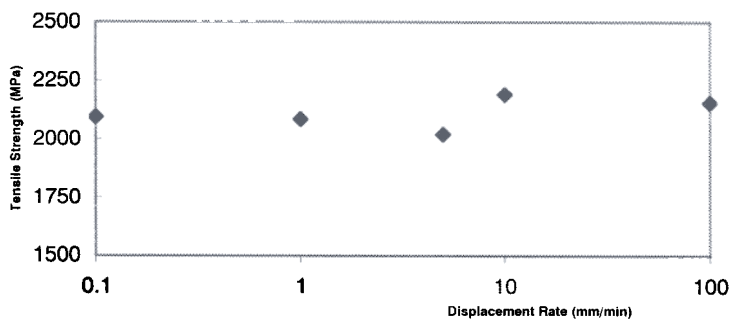


Figure 2 *Effect of displacement rate on tensile strength for carbon-fibre/vinylester rod*

Further tests carried out on quasi-isotropic glass-fibre/epoxy prepreg specimens tested in tension to EN ISO 527-4 showed that while the modulus was not significantly effected by test rate, the strength had increased by 12% between 0.25 to 15 mm/min. as shown in Figure 3. Tests were previously conducted on a glass-fibre fabric/epoxy over a range of loading rates equivalent to different fatigue test frequencies from 0.002 to 80Hz. [1]. The data, shown in Figure 4 was then used to successfully normalise a series of different fatigue curves undertaken at decade steps in frequencies to give a

single normalised curve and providing a rational explanation for the frequency dependence. Other effects in this case can be due to autogenous heating.

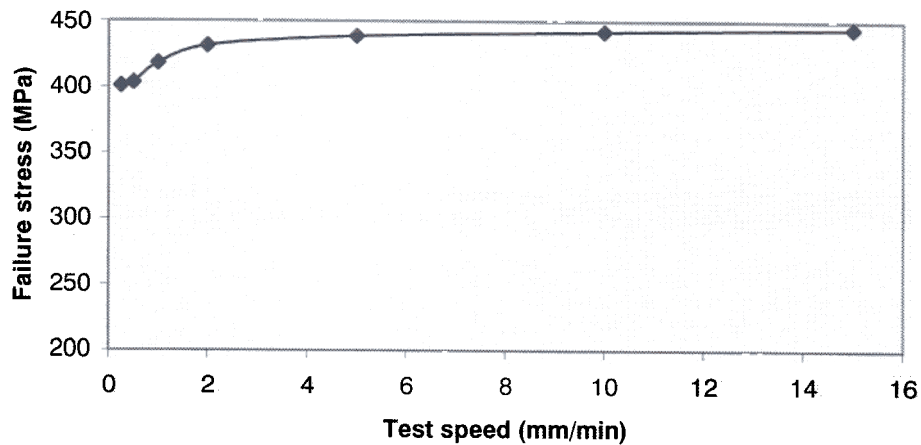


Figure 3 *Effect of test speed on tensile strength for QI glass-fibre/epoxy specimen*

These results show that the tensile properties of glass-fibre based systems are significantly rate sensitive, with a possible small rate dependence for the carbon-fibre systems even for fibre dominated properties. Shear, compression and flexure (if not tension initiated) will be likely to show a greater dependence on test rate. Hence, changes of 10% in strength can be obtained for glass-fibre based systems by a decade change in strain rate that may appear as an artefact in the test programme, in the same manner as the frequency does in the fatigue tests.

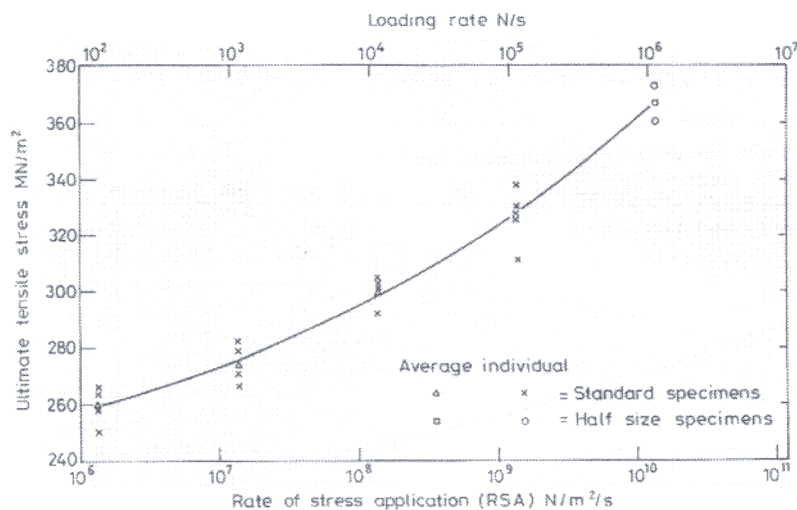


Figure 4 *Effect of test rate on the strength of a glass-fibre fabric/epoxy[1]*

2.2 TAB DESIGN

As the specimen size increase, re-design of the tab may be considered in order to transfer the larger load through the specimen/tab/grip interfaces (i.e. stress transfer related to surface area and not volume of specimen in the clamps). Investigations undertaken for both tension and compression strength tests are reported in Sections 3.1 and 4.1, respectively.

2.3 PLY BLOCKING AND INTERACIAL STRESSES

One aspect that is very different for composites, compared to isotropic materials, is that in manufacturing thicker material often the same thin layers will be needed but instead of a few layers, there will be tens of layers. This can have processing implications as it may not be possible to achieve the same compaction, removal of voids or cure uniformity for thick material compared with the thin material. The need to avoid over-heating due to the exothermic cure is well recognised.

In addition, the layer stacking sequence or lay-up can also be important. For example, in order to manufacture a 40 mm thick quasi-isotropic laminate, the stacking sequence for a quasi-isotropic lay-up 4 mm thick specimen could be repeated as a unit 10 times, or each layer in the original stack could be ten plies rather than one. The former arrangement is known as “distributed” and the latter as “blocked”. A series of test were undertaken to assess the impact of these options as described in Sections 3 and 4.

3 TENSION TEST DATA

3.1 TAB DESIGN

As noted above, as the specimen size increase it may be beneficial to consider optimisation of the tab design. Finite element analyses (FEA) have been carried out to assess the effect of tab length on the measured tensile strength. Non-linear properties were obtained for the adhesive and the CoDA [2] composites analysis software was used to predict the properties of the tab material, which consisted of a $\pm 45^\circ$ glass-fibre/epoxy. The test specimen was 2 mm thick, unidirectional carbon-fibre/epoxy. The standard length and thickness of each tab was 50 mm and 1.5 mm, respectively. The adhesive bond line thickness was 0.25 mm. Quarter models were run in plane stress with the element size kept at a constant size throughout all the runs to minimise element result discrepancy.

Figure 5 shows that the maximum principal stress in the specimen at the edge of the tab over a certain length (i.e. > 30 mm) does not decrease; therefore scaling the length of the bonded tabs will not necessarily reduce the stress concentration at the end of the tabs.

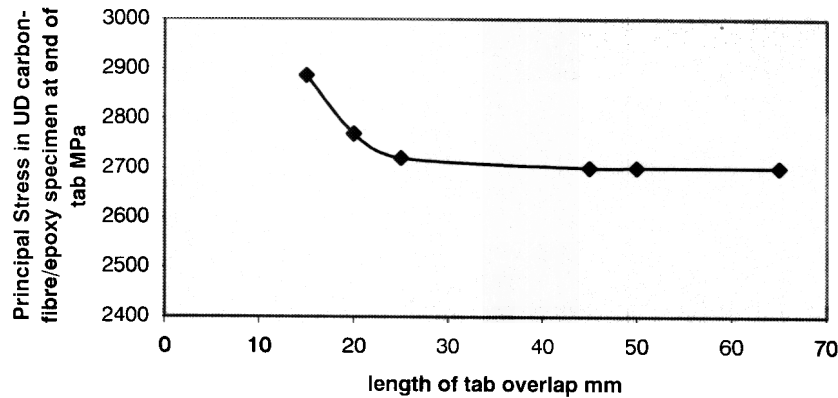


Figure 5 Maximum principal stress in the UD carbon-fibre specimen at the edge of the tab subjected to a far field stress of 1700 MPa

Further FEA was carried to determine the effect of increasing the tab thickness. For a 4 mm thick carbon-fibre epoxy specimen with tab length of 100 mm, the maximum principle stress in the specimen decreases linearly with respect to increasing tab thickness. However, this stress concentration relief is minimal, with a difference of 2.8 % between a tab of 1.5 mm and 3 mm. A similar effect was found for different specimen thickness.

FEA was used to predict the failure in the scaled specimens and compared to test results for the unidirectional specimens previously described. Figure 6 is an example of the finite element mesh used around the area of greatest stress concentration, element size was kept constant for all of the specimen thicknesses as this was found to have an effect on the results. Tab and adhesive thickness were kept the same as in the experiment at 1.5 mm and 0.25 mm, respectively.

Failure of the specimen was set to when the maximum principle stress in the composite at the edge of the tab reached the experimental failure stress of the 1 mm specimen. It was observed that the ultimate strength of the laminate σ_{uts} was described by the following relationship:

$$\sigma_{uts} = 1681t^{-0.21} \quad (1)$$

where t is the thickness of the specimen in mm

Table 1 Weibull and FEA prediction of failure stress (MPa) compared to experimental results

Dimensions, mm Width × Thickness)	Experimental Maximum Stress,	Weibull Prediction Maximum Stress,	FEA Prediction Maximum Stress,
10 × 1	1681	(1681)	(1681)
20 × 2	1735	1458	1453
30 × 3	1340	1341	1335
40 × 4	1264	1263	1256

Table 1 shows that the specimen size effect for the UD material tests are explained by the effect of tab induced stress concentrations. Even though the Weibull theory [3] can be used to obtain similar strength values, the mode of failure is not a weakest link, but that of an artefact caused by the stress concentrations induced by the tabs.

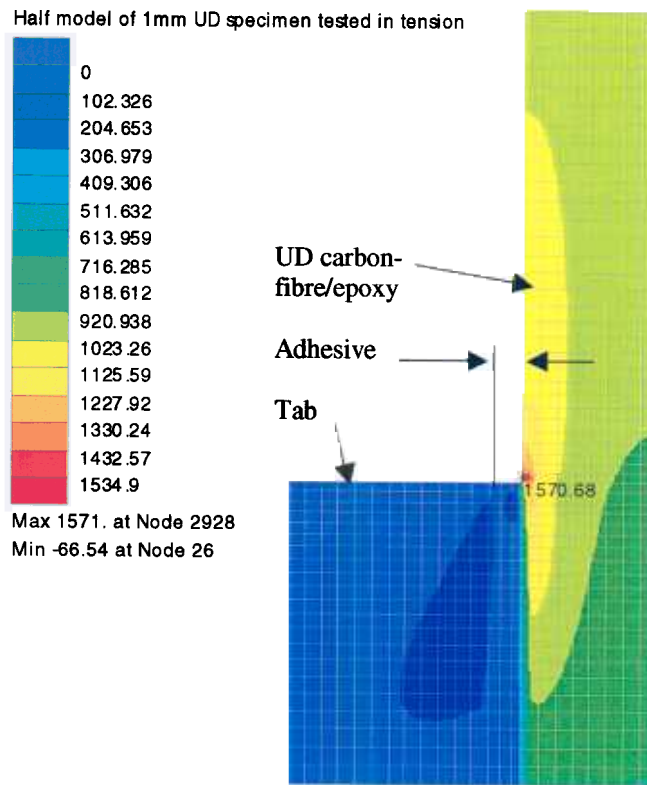


Figure 6 Example of the finite element mesh around the area of greatest stress concentration

Figure 8 shows that the standard tab would produce a stress concentration in the specimen of approximately 1.7. However most specimens in production have an adhesive spew fillet between the tab and the specimen that reduces the stress concentration to around 1.35, which agrees closely with work by O'Brien [4], which predicts a stress concentration of 1.3. The square ended specimen with 45° fillet reduced this further to just over 1.2. The reverse tapered specimen with 45° fillet reduced the stress concentration in the specimen at the edge of the tab 1.18, indicating that while the reverse taper has an effect on the reduction of stress concentrations this is minimal; in practice it would be sufficient to grind the sharp corners off the tabs. Increasing the fillet taper to 30° can be expected to reduce the stress concentration further, however, this angle is more difficult to achieve in practice and would need to be especially formed. Due to the findings, above all further experimental tests were carried out using the reverse taper geometry.

Four different types of end tabs were compared as shown in Figure 7.

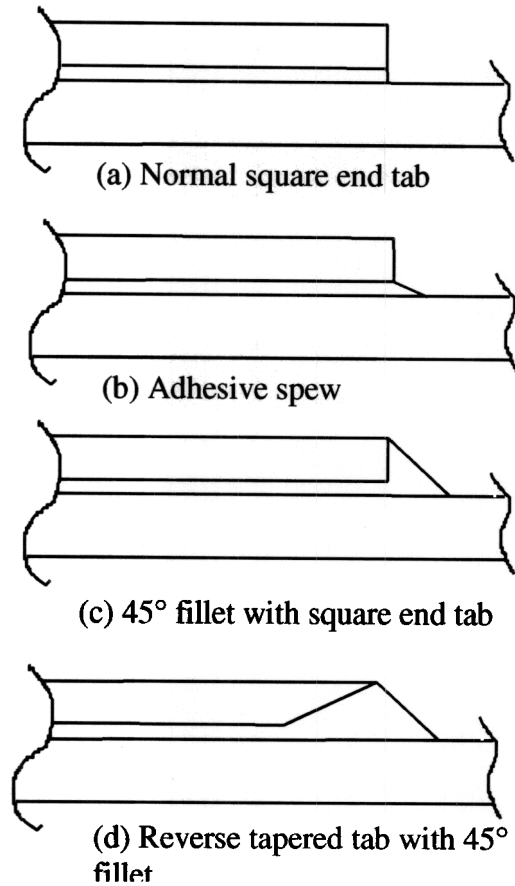


Figure 7 Different end designs of tabs

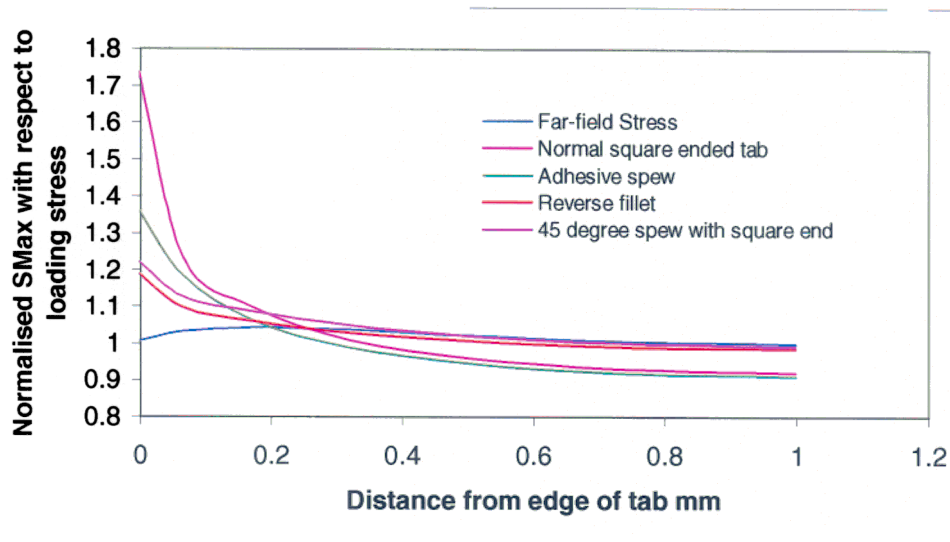


Figure 8 Stress concentrations at edge of tab

3.2 CROSS-PLY [0/90]

As noted in Section 2.3, there are two options when preparing thick laminates; “distributed” reinforcement and “blocked” reinforcement. In principle, this applies to all fibre formats and processes; and not just to aerospace prepregs. For example, the new heavyweight, non-crimp fabrics (NCFs) are using thicker layers equivalent to a blocked stacking geometry. A series of experiments have been conducted using different generic lay-ups to compare the effect of the alternative stacking sequences.

Three differing sets of experimental tests were carried out on cross-ply specimens. Initial tests were conducted on $[90/0]_{4s}$ and $[0/90]_{4s}$ specimens tested to ISO 527-4 with the addition of using the reverse taper with 45° fillet tab for both lay-ups. Table 2 shows that the strength and strain to failure results were similar for both lay-ups. However, all the $[90/0]_{4s}$ specimens failed with gauge section failures with a low coefficient of failure, while the $[0/90]_{4s}$ specimens showed more scatter with specimens failing both at the end of the tab and within the gauge section. A possible explanation is that the 90° fibres protect the load carrying 0° fibres from the stress concentrations at the tabs.

Table 2 Experimental tensile test results for the $[90/0]_{4s}$ and $[0/90]_{4s}$ lay-ups

Specimen type	Laminate Strength, MPa	Laminate Strength Coefficient of Variation	Failure strain %	Calculated 0° Failure Stress, MPa
$[90/0]_{4s}$	971	4.3	1.3	1754
$[0/90]_{4s}$	964	7.0	1.3	1726

The ultimate stress in the 0° plies in the multidirectional laminates σ_{uts}^0 , at the ultimate tensile failure of the laminate, has been obtained by multiplying the laminate strain at failure ϵ_{lam} by the modulus of the 0° plies E^0 ,

$$\sigma_{uts}^0 = E^0 \epsilon_{lam} \quad (2)$$

A value of E equal to 137 GPa from tests on unidirectional material was used to calculate the values for the 0° fibre strength shown in Table 2. The assumption was made that the strain in the 0° plies was the same as the laminate strain.

A second set of tests was carried out on a carbon-fibre/epoxy laminate with the ply-level scaled and using the following lay-up $[90_n/0_n/90_n/0_n]_s$ for $n = 1$ to 4. Table 3 shows a 12% drop in strength between the $n = 1$ and $n = 4$ specimens, however, all of the $n = 1$ specimens failed within the gauge section. The $n = 2$ specimens predominately failed within the gauge section with some end tab failures, while the $n = 3$ and $n = 4$ specimens all failed at the end tab region. No significant size effect was found for the specimens that failed in the tab region ($n = 3$ and $n = 4$), while the $n = 2$ specimens that failed within the gauge length gave similar results to the $n = 1$ specimens.

Table 3 Experimental tensile test results for the $[90_n/0_n/90_n/0_n]_s$ lay-ups

n	Dimensions, mm (Width × Thickness)	Gauge Length, mm	Laminate Strength, MPa	Failure Strain, %	0° Failure Stress, MPa
1	10 × 1	75	835	1.3	1767
2	20 × 2	150	802	1.2	1699
3	30 × 3	225	739	1.2	1576
4	40 × 4	300	734	1.1	1562

A third set of test were carried out on cross ply $[90/0/90/0]_{ns}$ specimens using the same material as that used in the second set of tests. All specimens failed within the gauge length with no volume related strength scaling in evidence as shown in Table 4.

Table 4 Experimental tensile test results for the $[90/0/90/0]_{ns}$ lay-ups

n	Dimensions, mm (Width × Thickness)	Gauge Length, mm	Laminate Strength, MPa	Failure Strain, %	0° Failure Stress, MPa
1	10 × 1	75	835	1.3	1767
2	20 × 2	150	847	1.3	1795
3	30 × 3	225	824	1.3	1740
4	40 × 4	300	829	1.3	1754

The three sets of experiments show that there was no discernable strength scaling effect for the cross- ply type specimens. Any difference observed was due to the lay-up sequences used rather than a true scale effect.

3.3 ANGLE-PLY $[+45/-45]$

Two generic $\pm 45^\circ$ lay-up laminates were studied, one with blocked plies $[+45_n/-45_n/+45_n/-45_n]_s$ and the other with distributed plies $[+45/-45/+45/-45]_{ns}$ with $n = 1, 2, 3, 4$. The material and dimensions were identical to the cross-ply specimens, with tabs having the reverse taper and 45° adhesive fillet geometry. All tests were subjected to a constant strain rate, with ten specimens tested per condition. Displacement was determined directly from cross-head movement. Extensometers or strain gauges were not used to monitor the strain due to their limited large strains measuring capability.

Table 5 Experimental tensile test results for the $[+45/-45/+45/-45]_{ns}$ lay-ups

n	Dimensions, mm (Width × Thickness)	Gauge Length mm	Tensile Strength MPa	Tensile Strain %
1	10×1	75	194	1.7
2	20×2	150	222	8.0
3	30×3	225	253	11.5
4	40×4	300	271	11.9

Table 6 Experimental tensile test results for the $[+45_n/-45_n/+45_n/-45_n]_s$ lay-ups

n	Dimensions, mm (Width × Thickness)	Gauge Length, mm	Tensile Strength, MPa	Tensile Strain, %
1	10 × 1	75	194	1.7
2	20 × 2	150	146	1.2
3	30 × 3	225	122	1.1
4	40 × 4	300	108	0.9

Table 5 shows that for distributed plies $[+45/-45/+45/-45]_{ns}$ there was an increase in tensile strength with increasing specimen size, while for the blocked specimens $[+45_n/-45_n/+45_n/-45_n]_s$ in Table 6 the opposite was observed. Also the distributed specimens exhibited a ductile stress-strain behaviour, while the blocked exhibited a brittle, low strain behaviour. For the $n = 4$ specimens, the strain to failure of the blocked plies was around 1%, while for the distributed plies this was around 12% with the strength differing by a factor of 2.5. The experiments showed failure initiation in the surface plies followed by cracking in the mid plane where the plies are blocked due to symmetry. This was found to be true for all specimen sizes and laminate thickness. Classic laminate theory assumes that all the plies are at the same strain level, however the top (free) surface of the outermost ply in an angle ply laminate is not as constrained as the inner surface, which is bonded to an adjacent 45° ply. As a result, in-plane shear strains, develop on the surface, close to the free edge of the laminate when an axial load is applied.

Pipes and Daniel [5] showed, using a simple strain transformation approach, that shear strains can be transformed into significant normal strains, which act transverse to the fibre direction. Since the free surface material is unconstrained in the direction transverse to the fibres, cracking occurs. Therefore, the first ply failure on the surface was a normal tensile fracture and not a shear mode fracture. The mid region of the laminate where a -45° ply is blocked with another -45° ply the laminate is subjected to a reduced constraint when compared to the inter-ply region, where the constraint of the neighbouring $+45^\circ$ ply is at a maximum.

3.4 QUASI-ISOTROPIC $[+45/-45/0/90]$

Two generic quasi-isotropic lay-ups were studied, one with blocked plies $[+45_n/-45_n/0_n/90_n]_s$ and the other with distributed plies specimens $[+45/-45/0/90]_{ns}$ with $n = 1, 2, 3, 4$. The material used and test conditions were identical to the cross-ply specimens. The lay-up was chosen with $\pm 45^\circ$ plies on the outside as they are a necessary constituent element in most structural laminates where damage tolerance is a requirement.

Table 7 shows that there is no evidence of a size effect for the distributed plies, the predominant mode of failure was within the gauge section. As failure strain was taken from the cross-head displacement of the testing machine the predicted failure stress of the 0° plies is a rough estimate, however the values correlate closely to that found in the distributed lay-up for the cross-ply specimens as shown in Table 2. Table 8 indicates a reduction in tensile strength with increase in n . A similar initial mode of failure to the angle-ply specimens occurred, with the noticeable cracking of the outside $\pm 45^\circ$ plies before final failure. There was a tendency for failures to occur near the grip

for the $n \geq 2$ specimens, with the predominant failure initiated at the grip, indicating that blocking the plies reduces the damage tolerance of the lay-up making it more susceptible to stress concentrations initiated by the tabs.

Table 7 Experimental results for the $[+45/-45/0/90]_{ns}$ lay-ups

n	Dimensions, mm (Width × Thickness)	Gauge Length, mm	Laminate Strength, MPa	Failure Strain, %	0° Failure Stress, MPa
1	10 × 1	75	552	1.3	1740
2	20 × 2	150	571	1.3	1822
3	30 × 3	225	564	1.3	1767
4	40 × 4	300	548	1.3	1713

Table 8 Experimental results for the $[+45_n/-45_n/0_n/90_n]_s$ lay-ups

n	Dimensions, mm (Width × Thickness)	Gauge Length, mm	Laminate Strength, MPa	Failure Strain, %	0° Failure Stress, MPa
1	10 × 1	75	552	1.3	1740
2	20 × 2	150	499	1.2	1576
3	30 × 3	225	496	1.1	1548
4	40 × 4	300	474	1.1	1493

4. COMPRESSION TEST DATA

Compression data is more difficult to generate than tensile data for composite specimens, with a variety of test methods and modifications of test pieces proposed over the past two decades. Due to the different types of specimens and loading rigs used; the new BS EN ISO 14126 compression standard drafted by NPL allows any loading fixture to be used, provided the bending strain is less than 10%, making the use of strain gauges on both faces a necessity.

NPL have manufactured an end-loaded test rig, that complies with BS EN ISO 14126 for these tests. For tabbed specimens, a portion of the load is transmitted by shear via the end tabs, thus lowering stresses at the end of the test piece. Two further compression rigs based on same concept were built to accept specimens 25 mm and 36 mm wide, and both up to 10 mm thick. The rationale for these sizes were that the 25 mm wide set-up conforms to Specimen B2 in BS EN ISO 14126 and the 36 mm wide specimens conforms to the new open hole compression test method ISO NWI 713, drafted at NPL.

4. TAB DESIGN

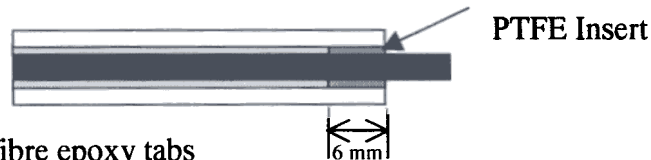
Initial tests were carried out on various types of specimens to determine the influence of the tab, and taper, on the axial compressive strength of unidirectional carbon-fibre/epoxy. Specimen dimensions followed BS EN ISO 14126 Type B1 with all of the specimens having a thickness of 2 mm, gauge length and width of 10 mm, tab thickness of 1.5 mm and length of 50 mm. All specimen tab surfaces were ground flat and parallel. The flatness of these surfaces is important for achieving specimen alignment so that bending effects of the specimens are minimised.

The different specimens tested are shown in Figure 9.

Standard specimen to ISO14126



b. Standard tabs with PTFE inserts as recommended by Imperial College [6]



c. Co-cured glass-fibre epoxy tabs



d. Co-cured carbon-fibre epoxy tabs



e. Co-cured glass-fibre epoxy tabs with 45° resin fillet



f. Co-cured carbon-fibre epoxy tabs with 45° resin fillet



g. Secondary bonded glass-fibre tabs with reverse taper and 45° resin fillet



Figure 9 Design of end tabs for compression specimens.

Seven specimens were tested of each type at a displacement rate of 1 mm/min. Through-thickness stresses are suspected of promoting compressive failure at the tab tip. Using the above jig, these stresses are controlled by the torque applied to the clamping bolts of the end blocks. Work at Imperial College [6] found that the ideal torque for most consistent results was 10 Nm for the bolts nearest the end of the blocks with 5 Nm for the ones nearest the gauge section.

Table 9 Compressive failure stress for different types of specimens

Specimen type	Failure Stress MPa	Coefficient of Variation %	Failure Mode
Standard specimen	1365	7.2	Through-thickness shear / In-plane shear
Tabs with PTFE inserts	1475	3.2	Through-thickness shear / In-plane shear
Co-cured glass-fibre epoxy tabs	1095	17.2	Through-thickness shear / Compressive in tab/Shear initiated in tab
Co-cured carbon-fibre epoxy tabs	705	30.6	Compressive in tab / Shear initiated in tab / Through-thickness shear
Co-cured glass-fibre epoxy tabs with 45° resin fillet	1236	10.7	Through-thickness shear
Co-cured carbon-fibre epoxy tabs with 45° resin fillet	733	10.3	Compressive in tab / Shear initiated in tab / Through-thickness shear
Secondary bonded glass-fibre tabs with reverse taper and 45° resin fillet	1515	2.9	In-plane shear/Complex

Table 9 shows that the secondary bonded glass-fibre tabs with reverse taper and 45° resin fillet and the standard tabs with PTFE inserts had both the highest stress at failure and the highest consistence, which improved on the results obtained with the standard tab design. All the co-cured specimens had much lower strength values, with a large range of failure modes. These data would support the addition of the tab design using PTFE to the ISO standard, which was not accepted previously due to an absence of collaborating data [6].

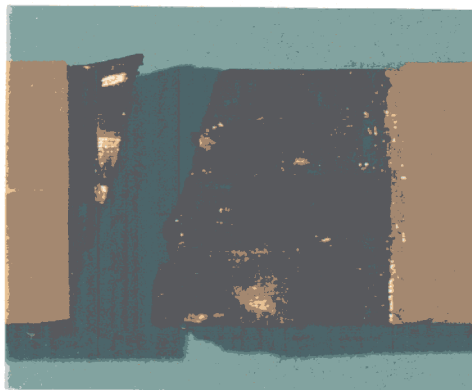


Figure 10. In plane shear failure of secondary bonded glass-fibre tabs with reverse taper and 45° resin fillet



Figure 11 Complex failure of secondary bonded glass-fibre tabs with reverse taper and 45° resin fillet

Figures 10 and 11 illustrate the different types of failure obtained with the secondary bonded glass-fibre tabs with reverse taper and 45° resin fillet specimens. As these specimens consistently failed within the tab region with the highest results they were subsequently used for all further tests

4.2 UNIDIRECTIONAL LAY-UP

Scaling specimens in compression is more complicated than for tension as it is not possible to scale the gauge length due to buckling constraints. Also, due to the cost of manufacturing test fixtures, tab length and thickness was not scaled, however as showed above these do not have a significant effect on the results.

Table 10 shows the tensile strengths of carbon-fibre/epoxy specimens for a range of different sized specimens. For the 2mm thick specimens fractures were either in-plane shear or complex. There was little scatter in the results and little difference between the various widths indicating no width effect. The unidirectional modulus was found to be 134 GPa.

The 6 mm thick samples were tested for two gauge lengths of 10 mm and 25 mm, with widths kept to 10 mm and 25 mm. The 36 mm wide samples were not tested as the predicted failure load exceeded that of the available test machine. The scatter of the strength results significantly increased with increasing thickness due to the fact that over half the samples failed within the tab with a “compression in tab” type failure. However, as Table 11 shows when only using the results of the specimens that failed within the gauge length there is no apparent size effect.

Table 10 *Compressive strength of UD carbon-fibre/epoxy specimens*

Dimensions, mm (Width × Thickness)	Gauge Length mm	Stress at Maximum load, MPa	Coefficient of Variation, %
10 × 2	10	1515	2.9
25 × 2	10	1546	2.2
36 × 2	10	1523	3.6
10 × 6	10	1392	11.1
25 × 6	10	1406	9.0
10 × 6	25	1423	5.7
25 × 6	25	1468	6.0

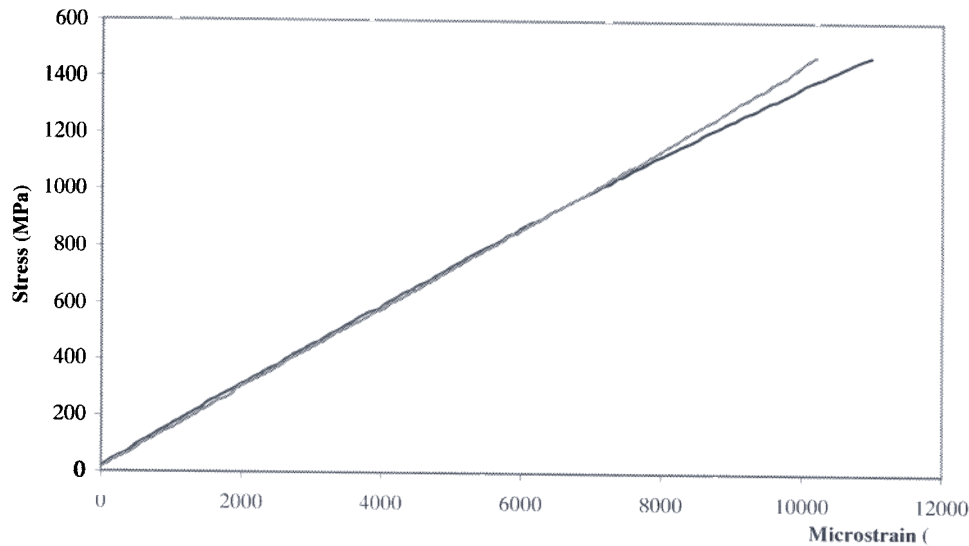


Figure 12 Example of stress strain curve for a unidirectional carbon-fibre epoxy specimen loaded in compression

Table 11 Compressive strength of 6 mm UD carbon-fibre/epoxy specimens that failed in the gauge length

Dimensions, mm (Width × Thickness)	Gauge Length mm	Ultimate Stress at Maximum Load, MPa	Number of Specimens Averaged	Failure Mode
10 × 6	10	1483	3	In-plane shear
25 × 6	10	1499	3	In-plane shear
10 × 6	25	1481	2	In-plane shear
25 × 6	25	1514	4	In-plane shear

4.3 CROSS-PLY [0/90]

Initial tests were conducted on 2 mm wide [0/90]_s specimens, with differing widths, using tabs with reverse taper and 45° fillet. Table 10 showed that the strength and strain to failure results were similar for all the specimens that failed in the in-plane shear mode, however, the 10 mm wide specimens had slightly higher scatter. Therefore, all further tests were carried using 25 mm wide specimens. The ultimate stress in the 0° plies in the multidirectional laminates $\sigma_{ucs}^{0^\circ}$ at ultimate compression failure of the laminate was calculated by multiplying the laminate strain at failure ϵ_{lam} by the modulus of the 0° plies, ie 134 GPa (Equation. 2). Table 12 shows that by using the [0/90]_s lay-up, the compression strength to failure was similar to that of the unidirectional tension strength (see Section 3). This agreement was not shown by the tests on UD material, suggesting that the [0/90] – distributed ply specimen gives more relevant UD ply properties for multidirectional use.

Table 12 Compressive strength of 2 mm [0/90]_s carbon-fibre/epoxy specimens

Dimensions, mm (Width × Thickness)	Gauge Length, mm	Average Stress at Maximum Load, MPa	Coefficient of Variation, %	Strain to Failure, %	0° Failure Stress MPa
10 × 2	10	809	5.02	1.28	1715
25 × 2	10	843	3.39	1.33	1782
36 × 2	10	827	3.64	1.30	1742

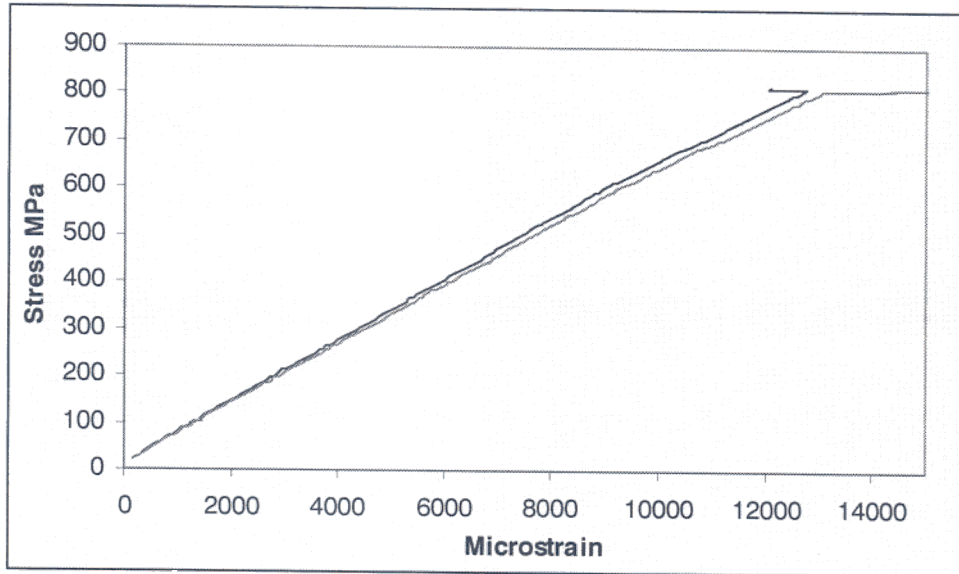


Figure 13 Example of stress strain curve for a 10 mm wide, 2 mm thick $[0/90]_s$ carbon-fibre/epoxy specimen loaded in compression

A further series of tests was carried out on 25 mm wide, 6mm thick carbon-fibre epoxy specimens with the following lay-ups:

- $[90/0/90/0]_{12s}$.
- $[90_2/0_2/90_2/0_2]_{6s}$.
- $[90_{12}/0_{12}]_s$

Table 13 Compressive strength of 6 mm cross-ply carbon-fibre/epoxy specimens

Specimen Lay-up	Gauge Length mm	Maximum Stress at Maximum Load, MPa	Strain to Failure, %	0° Failure Stress MPa
$[90/0/90/0]_{12s}$	25	799	1.3	1729
$[90_2/0_2/90_2/0_2]_{6s}$	25	748	1.2	1621
$[90_{12}/0_{12}]_s$	25	761	1.2	1648
$[0_{12}/90_{12}]_s$	25	557	0.9	1233

Table 13 shows that there is no evidence of a size effect when the specimens are scaled up as sub-laminate when compared to the 2 mm specimens, although there is a 9.5% reduction in strength between the $[90/0/90/0]_{12s}$ and $[90_{12}/0_{12}]_s$ specimens. However the blocked specimens all failed within the tab. All the results with the 90° fibres on the outside gave higher unidirectional fibre strength than for the fully unidirectional tests.

Specimens with blocked plies, $[0_{12}/90_{12}]_s$, with 0° fibres are on the outside were also tested. It was found that all the specimens failed at the edge of the tab, with a considerably lower stress and strain to failure than the $[90_{12}/0_{12}]_s$ specimens. The calculated unidirectional failure stress is 28% lower for the $[0_{12}/90_{12}]_s$ lay-up. When this latter result is compared in isolation to the 2 mm thick specimens results in table 12, it could be concluded that it is a scale effect, however, Table 13 shows that it is purely an artefact of the specimen stacking sequence.

4.4 QUASI-ISOTROPIC [+45/-45/0/90]

Two generic quasi-isotropic lay-ups were studied, one with blocked plies $[+45_n/-45_n/0_n/90_n]_s$ and the other with distributed plies specimens $[+45/-45/0/90]_{ns}$ with $n = 2$ and 4. The material used and dimensions were identical to that of the cross-ply specimens, with all tabs using the reverse taper and 45° fillet of adhesive. All tests were subjected to a constant compression strain rate, with ten specimens tested per condition. The lay-up was chosen with $\pm 45^\circ$ plies on the outside, as they are a necessary constituent element in most structural laminates where damage tolerance is a requirement.

Initial test were carried out on $[+45/-45/0/90]_{2s}$ specimens of differing widths, of 10, 25 and 36 mm to establish any width effects. Table 14 shows no evidence of a specimen width effect.

Table 14 Compressive strength of 2 mm thick $[+45/-45/0/90]_{2s}$ carbon-fibre/epoxy specimen

Dimensions, mm (Width × Thickness)	Gauge Length, mm	Average Stress at Maximum Load, MPa	Coefficient of Variation, %	Strain to Failure, %	0° Failure Stress, MPa
10 × 2	10	637	1.8	1.3	1729
25 × 2	10	646	1.3	1.3	1742
36 × 2	10	634	4.9	1.3	1715

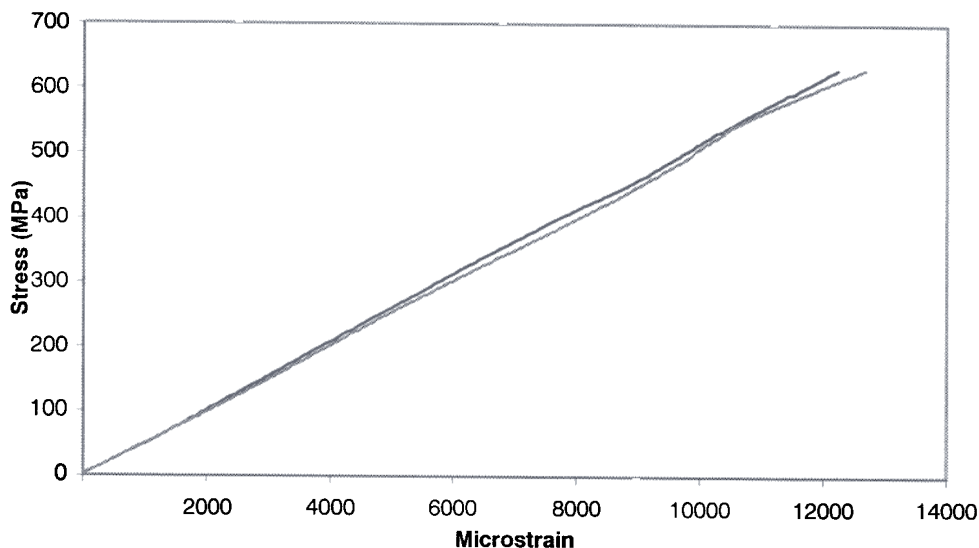


Figure 14 Example of stress strain curve for a 36 mm wide 2mm thick $[+45/-45/0/90]_{2s}$ carbon-fibre epoxy specimen loaded in compression

Further tests were carried out comparing the $[+45_n/-45_n/0_n/90_n]_s$ lay-ups with the $[+45/-45/0/90]_{ns}$ with $n = 2$ and 4, for 25 mm wide specimens. Table 15 shows no evidence of a size effect when the specimens are scaled up using distributed plies when compared to the 2 mm specimens. In fact, there was an increase in strength for the larger sub-laminate scaled quasi-isotropic specimens. Similar results were found by Soutis et al [7]. The 2 mm blocked specimens had reduced compression strength of around 10% compared to the sub-laminate specimens, with no noticeable additional strength reduction for the 4 mm samples.

Table 15 Compressive strength $[+45/-45/0/90]_{ns}$ and $[+45_n/-45_n/0_n/90_n]_s$ carbon-fibre/epoxy specimen

Specimen Type	Dimensions, mm (Width × Thickness)	Gauge Length, mm	Average Stress at Maximum Load, MPa	Strain to Failure, %	0° Failure Stress, MPa
$[+45/-45/0/90]_{2s}$	25 × 2	10	646	1.3	1742
$[+45_2/-45_2/0_2/90_2]_s$	25 × 2	10	581	1.2	1595
$[+45/-45/0/90]_{4s}$	25 × 4	25	695	1.4	1876
$[+45_4/-45_4/0_4/90_4]_s$	25 × 4	25	571	1.2	1541

Figures 12-14 show the experimental traces for load vs strain for the two strain gauges on opposite faces of the specimens. For all three types of laminates, good axial loading is achieved with satisfactory (c.f. BS EN ISO 14126) maximum bending strains. These results support the approach adopted by NPL in drafting this standard based on the quality of the actual test, in preference for using particular designs of fixtures, which can be misused and cannot compensate a poorly prepared specimen.

5 FLEXURE

Experiments were undertaken using these same materials in flexure at three thicknesses, but as noted earlier due to the complex stress distribution, it is difficult to distinguish the controlling failure modes, etc. Although the detailed work is not reported here, it is worth considering the deflection based on the axial data obtained in tension and compression. A non-linear geometrical FEA was carried out on the four point bending test in order to provide some accurate results when tackling the effects due to large deflections. Continuum 8 noded plain stress elements were used, with contact elements between the rollers and specimens. This allowed for correct representation of the varying point of contact and direction of reaction at the rollers.

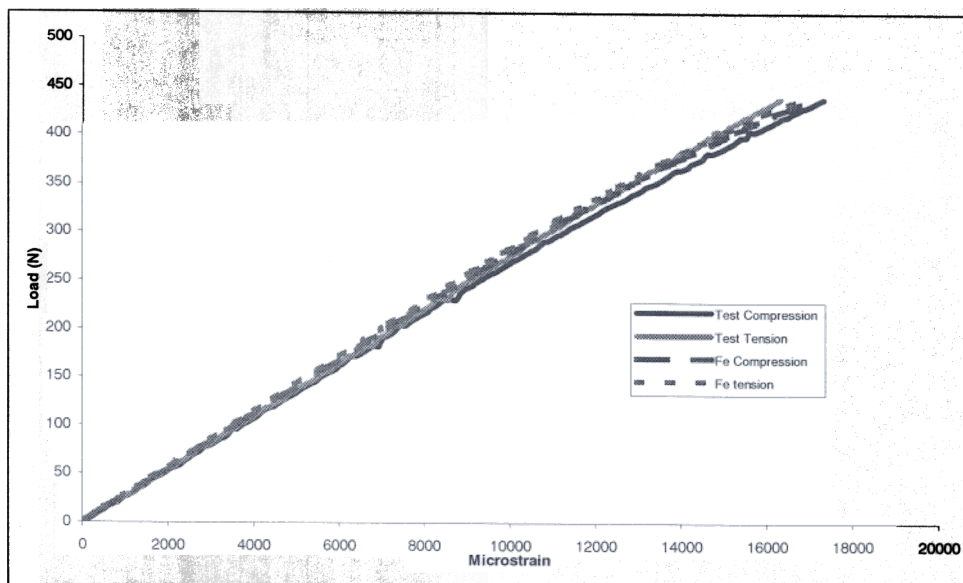


Figure 15 Comparison of test results and FEA predictions of load v strain for 1 mm thick 4 point bend specimen

Linear material properties were used with differing moduli for tension and compression (Tensile Modulus = 137 GPa and Compression Modulus = 134 GPa). Figure 15 shows that FEA can predict the strain to failure to 3 % in compression and 1% in tension. It was also noted that in bending, the tension response was linear while the compression response of the material became slightly non-linear at higher loads. The experimental data was obtained from strain gauges on each face positioned between the two central loading points where the axial surface strains are uniform.

6. SUMMARY

This report focuses on the ultimate strength in tension and compression of carbon-fibre/epoxy specimens with differing lay-ups and orientation, when their volume is increased. The report develops a case against strength scaling from detailed observation of actual modes of failure of fractured test coupons backed by investigations using FEA.

The source of the apparent strength scaling in tension was found to be related to how efficiently load could be introduced into the gauge-section of specimens with different composite lay-ups and specimen test volumes. Compression strength was also found to be limited by the stress concentration developed at the tabs.

The report has found that using Weibull strength-scaling can predict the strength of tensile specimens, however it is not recommended as the specimens fail due to stress concentrations at the tab rather than by the weakest-link theory that is assumed. It is clear that detailed consideration of the test conditions is needed before any apparent size effect is accepted.

The report describes several aspects of testing that are related to determining the properties of composites over a range of sizes. It is clear that there exist many artefacts that can suggest size effects but when carefully analysed, there is little evidence of a Weibull weakest-link type size effect. There are procedures that can be adopted to minimise the testing artefact, such as:-

- to ensure that the same strain rate is used for all tests,
- to use “distributed” ply stacking sequences,
- to use the optimised tab design described in this work,
- to use 90° and 45° as outer plies to reduce the tab stress concentration.

The NPL compression test fixture, used in the work, allows testing in accordance with ISO 14126 type A, B1 and B2 specimens, as well as ISO NWI 713 for open-hole compression specimens. The test fixtures, along with good specimen preparation, showed that specimens could be loaded axially within the allowed bending strains.

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STANDARDS

EN ISO 527 Part 4, - "Determination of tensile properties - Test conditions for isotropic and orthotropic fibre-reinforced plastic composites".

BS ISO 9163:1996 "Textile glass – rovings – manufacture of test specimens and determination of tensile strength of impregnated rovings"

EN ISO 14126 "Fibre-reinforced plastic composites - Determination of the in-plane compression strength".

ISO NWI 713, Fibre reinforced plastic composites - Determination of the open-hole (notched) compression strength (UK proposed new work item).

ACKNOWLEDGEMENTS

This work forms part of the programme "Composites Performance and Design" funded by the Department of Trade and Industry, as part of the technological competitiveness of the UK industry. Thanks are due to Dr Bill Broughton of NPL and Professor Frank Matthews of Imperial College London for their advice and encouragement, and Mr Richard Shaw of NPL for help with some of the test work.