

Understanding Compression Testing of Thick Polymer Matrix Composites

Summary

As engineers rely more heavily on finite element analysis for the design and evaluation of high performance structures manufactured from polymer composite, there are real concerns regarding the material property data used in these simulations. Particular concerns have been expressed with regard to the ability to generate representative, repeatable and reproducible measurements of compressive properties, especially for thick sections, where fracture is more likely than the previously encountered buckling failures. This is further confused by the large number of different test rigs and specimen geometry/preparation methods.

This Measurement Note details work undertaken towards improving the current test method by understanding the factors which affect the measured properties and failure modes, and suggests modifications to enable extending the methods to thick sections.

The principal conclusions of the work are:

- a novel fillet geometry and clamping surface developed for the end-loading compression rig was observed to produce consistently higher strengths,
- waisted specimens were found to produce good strength data, but artificially increased modulus values,
- representative thick section data can be obtained from material machined down to a suitable thickness,
- the clamping loads were found to be critical in determining the failure mode of the samples.



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INTRODUCTION

The validity of measured compression properties is of particular concern in high strength polymer composites where demanding applications, such as Formula One cars, primary aircraft structure and minesweepers, are constantly pushing component parts to their design limits. Along with the advances and innovations in manufacturing processes in recent years, it has become easier to make cost effective, high quality, thick section composites for high loading applications without the need to resort to high cost, labour-intensive production techniques such as autoclaving. This means that thicker section components are now commonly being produced (often up to 50 mm), but whilst the compressive behaviour is critical to understand in this case, it is more difficult to measure using standard test methods which were designed for use with thin materials (i.e. less than 4 mm). Accurate material compression properties must be obtained experimentally for these thicker structures, in order to enable safe and functional designs to be realised.

An improved understanding of the importance of compression in many component failures has initiated renewed interest and further test method developments over recent decades, aimed at establishing “true” compressive data. However, the composite community has not universally agreed the adoption of any one specific test rig, associated loading method or preferred specimen preparation, thus encouraging the development of ever more test methods and modifications to eliminate problems or make improvements. While some of these innovations appear promising, most have not been adequately tested ^[1].

The BS EN ISO 14126 Standard ^[2] exists for the determination of compressive properties, but there is scant supporting evidence regarding the effectiveness or suitability of the recommended loading conditions/rigs or for the strain-based specimen alignment criterion (i.e. less than 10% bending). In order to accommodate the multitude of different test rigs available, a variety of

specimen geometries are covered by this standard, however it does not cater for thick section materials.

BACKGROUND

Previous work conducted by NPL and other organisations has highlighted several important issues.

Load Introduction

There are three main methods for loading a standard test specimen, as shown in Figure 1:

- Pure shear loading – the compressive load is applied to the specimen by shear through the end-tabs,
- Pure end loading – the compressive load is applied directly and solely to the ends of the specimen, and
- Combination of both shear and end loading.

As yet there is no consensus on the best loading method for generating compression within a specimen due to the lack of supporting experimental evidence.

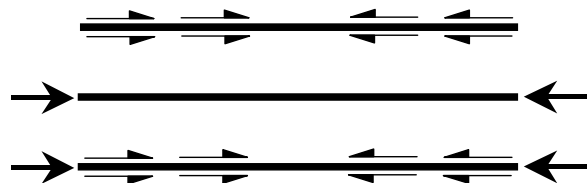


Figure 1 - Methods for inducing compression loading: pure shear loading (upper), pure end loading (centre) and mixed (lower).

Test Rigs

At present, there are four commonly used rigs for compression testing. Little work has been done to extend applicability of any of these rigs beyond thin samples and their suitability for thicker samples (where these can be accommodated) has not been investigated experimentally.

Celanese Rig

A well-publicised, popular rig in widespread use due to the open availability of the detailed rig design. One of the first developed, but now losing popularity due to its practical limitations.

It employs conical wedges as a means of shear loading the specimen in compression, shown in Figure 2 (a). Due to the detailed nature of the gripping mechanism, the specimen thickness is extremely important. Specimens must be machined to a tolerance of 0.025 mm otherwise a non-circular split cone is formed when the test rig is assembled, which no longer fits precisely into the conical cup. This causes wedging within the cone grips leading to premature specimen buckling failure or artificially higher results due to the increased frictional contribution to the apparent load.

The Celanese rig gave the lowest strength results in a comparative evaluation with the IITRI ^[3] and is also quoted as having a large amount of scatter in test results due to the sensitivity to exact specimen dimensions.

End-Loading Rig

Developed at both Birmingham University and Imperial College, modifications to the rig have been implemented by NPL to simplify both rig manufacture and use, enabling it to cater for several sample thicknesses, as shown in Figure 2 (b).

Originally developed for use with waisted and then debonded end-tab specimens.

It is important when end-loading specimens that the end surfaces of the specimen are ground flat and square to avoid inducing out-of-plane loading. Pressure must be applied to the faces of the specimen in order to maintain alignment and avoid buckling during testing. Recommended torques are 5 Nm and 10 Nm on the inner and outer screws, respectively ^[4].

Strength results obtained using this rig are quoted with a coefficient of variation of 4.8% and up to 13% higher average strengths when using the debonded end-tab specimen ^[5].

IITRI Rig

Based on the Celanese rig with the use of trapezoidal wedge grips instead of conical ones, as shown in Figure 2 (c). This results in considerable advantages:

- tolerances on the specimen thickness are not as critical,
- frictional effects are minimised by the use of flat wedges instead of conical ones, and larger than standard compressive specimens can be tested (up to 15 mm thick and 38 mm wide) to allow open hole compression and other compression test variants to be performed.

No detailed information is available on typical data scatter using this rig.

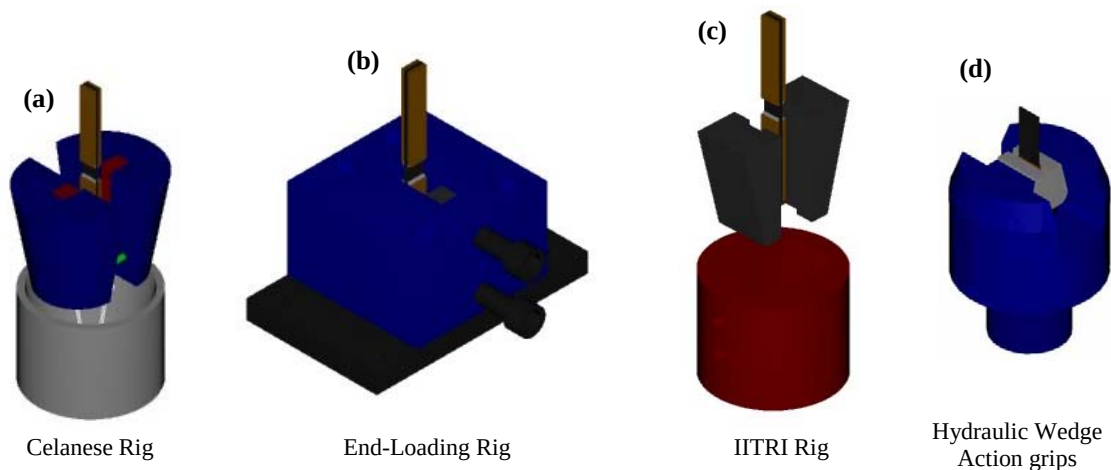


Figure 2 - Different compression test rigs, lower halves shown.

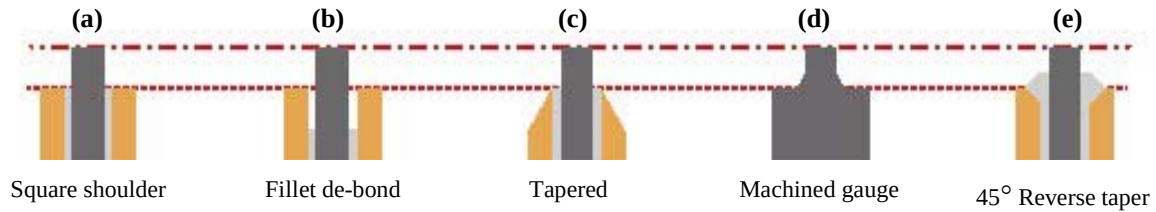


Figure 3 - Close-up schematics of detailed end-tab and fillet types.

Hydraulic Wedge Action Grips

Manual wedge action grips have been used in tensile testing for many years. The introduction of hydraulics to provide higher clamping pressures has widened their applicability to include compression testing, shown in Figure 2 (d), inducing compression loading through pure shear. Specimens can range in size from 1-12 mm in thickness with a width of up to 50 mm. Pressures applied to the specimen can be up to 300 bar.

No real information on the grip pressures required, or scatter of results is available for this method of load application in compression, but limited studies at NPL suggest lower strengths are generally realised.

Specimen Tabs and Fillet Geometry

The BS EN ISO 14126 standard ^[2] recommends the use of a square-shoulder end-tab geometry, shown in Figure 3 (a). These are bonded to the ends of the specimen in order to reduce local clamping damage, which can otherwise give rise to premature failure. Due to the high stress concentration in this area, there is considerable debate as to whether changing this geometry will make it possible to achieve more consistent test results and improve the measured material properties. Investigations have been conducted on a range of end-tab materials (glass fabric epoxy, titanium and steel), different end-tab and adhesive fillet geometries and clamping conditions, shown in Figure 3 (b) – (d) ^[6, 7, 8].

Deliberate debonding of the lower edge of the end-tab, as a means of reducing stress concentrations, has been proven to produce

higher strengths than those obtained using a standard specimen, but is difficult to manufacture consistently. Preliminary finite element analysis studies at NPL suggested a 45° reverse taper tab could reduce stress concentrations significantly and would be worth investigating further, shown in Figure 3 (e).

Specimen Geometry

For thicker sections, ensuring failure occurs within the gauge-length and within machine related load limits can be a problem. Possible solutions may include waisting a thick sample or testing a 2 mm sample cut from a thicker section.

Material Lay-up

Since the highest compressive strength values are obtained from unidirectional materials, structural components intended to withstand compressive forces are generally

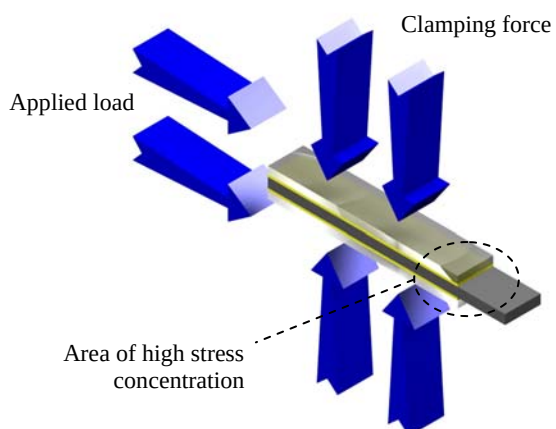


Figure 4 - Typical location of stress concentration in specimen.

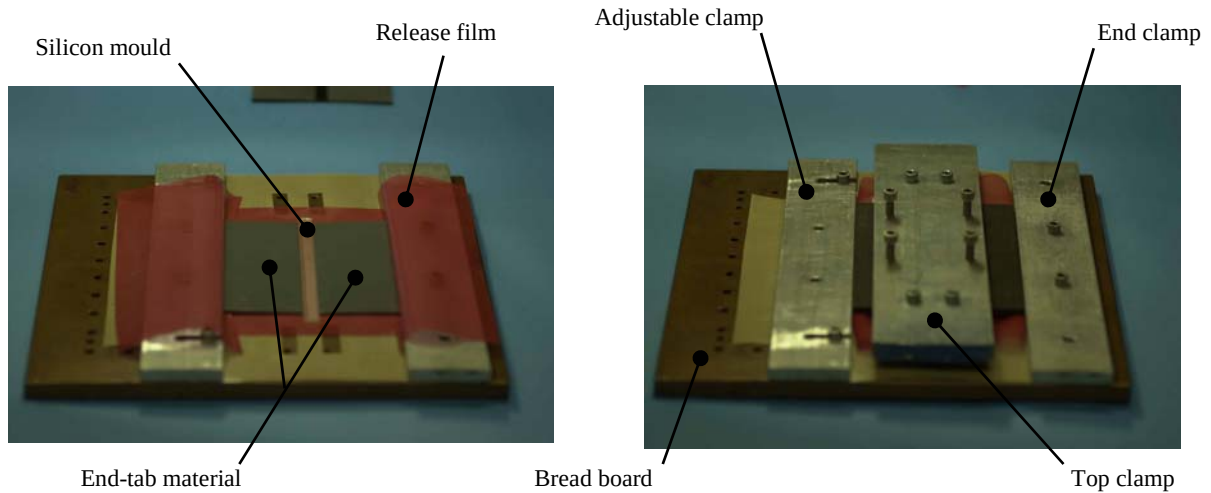


Figure 5 - Specimen bonding rig: partially assembled (left) and fully assembled (right).

designed with the majority of fibres along the principle load path. As a result, premature failure within the gripped region during testing may occur. This is associated with the correspondingly higher clamping stress levels induced by the different rigs^[5].

Similarly, high strength unidirectional composites are susceptible to local stress concentrations due to their extreme anisotropy, shown in Figure 4. These occur at the edge of the end-tab and are caused by the combination of applied clamping forces and the local discontinuity associated with the change in section of the test specimen.

EXPERIMENTAL WORK

Specimen Preparation

In order to produce specimens of consistent quality, a repeatable manufacturing procedure was developed to accommodate different geometries and thicknesses. This ensured comparative studies were independent of any variation in batch-to-batch specimen manufacture.

Prior to bonding, the faces of both the specimen bond area and end-tab were grit-blasted using a fine grain blasting media (at 5 bar pressure). This removed the epoxy surface layer, any surface contamination and provided mechanical keying. All specimens were bonded using a Redux 312 film

adhesive, with a cure schedule of 45 minutes at 120°C.

A rig was designed and built to apply pressure (improving adhesive flow), to form accurate fillet geometries and to prevent slipping of the end-tabs during cure. This rig is shown in Figure 5.

Specimen fillets were controlled using silicon moulds pre-shaped to the required geometry. These are shown in Figure 6.

End-tabs were bonded onto full-size composite coupon panels and were subsequently cut into multiple specimens of the required dimensions using a water cooled diamond slitting wheel. This guaranteed the side and end faces of the specimen were perpendicular to the specimen surface, which is particularly important in the case of the end-loading test rig.

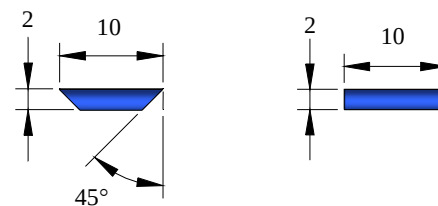


Figure 6 - Silicon mould dimensions in mm: 45° reverse taper (left) and square shoulder (right).

Test Details

Tests were conducted using a calibrated Instron 1196 screw driven mechanical test machine with 5500 series controller, in accordance with BS EN ISO 14126 compression standard. Batches of between three and five specimens were tested. The specimens were loaded axially in compression at a displacement rate of 1 mm/min, using either:

- IITRI, or
- end-loading rig.

Specimens were manufactured from two materials:

- Material 1: Unidirectional glass fibre/epoxy, autoclaved, (GFRP)
- Material 2: Unidirectional carbon fibre/epoxy, autoclaved. (CFRP)

Two fillet geometries were used with the GFRP material to investigate the effects of stress concentrations:

- standard ISO recommended square shoulder (SQ), and
- NPL proposed 45° reverse taper (RT).

Typical specimen dimensions are shown in Figure 7. Tests were conducted with GFRP and CFRP materials using both the end-loading and the IITRI rigs, to establish the effect of the compression loading mode.

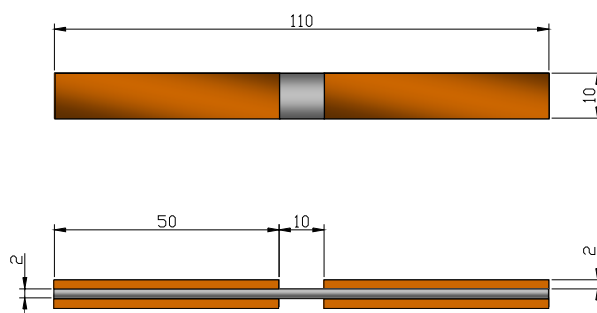


Figure 7 - Compression specimen dimensions in mm, BS EN ISO 14126 Type A.

The end-loading rig was studied in greater detail, as it is versatile enough to accommodate a wide variety of specimen thicknesses without the need for expensive modifications. These included:

- Width constraints: the effect of Poisson's expansions were studied using a 25 mm wide slot rather than the usual close-fitting 10 mm wide slot (designed to exactly match the specimen dimensions) with 45° reverse taper specimens, made from both materials.
- Standard specimens from thick sections: to establish whether it is possible to generate equivalent data using specimens machined down to standard dimensions from a thick panel, as opposed to testing thick sections directly. Both 2 and 5 mm thick panels were machined from a 160 ply (20 mm) thick panel of GFRP. Coupon panels were then manufactured specifically to those same thicknesses, using 16 ply (2 mm) and 40 ply (5 mm) laminate lay-ups. Specimens were then prepared from all of these panels using the 45° reverse taper.
- Waisted specimens: to assess whether it is possible to obtain comparable data between parallel-sided and radiussed specimens, often useful for thicker sections to assist in staying within test machine load limits and forcing failure within the gauge length. A 40 ply, 5 mm thick panel of GFRP was used to produce specimens 25 mm wide with a 25 mm gauge length, but with the width of the specimen in the central region reduced to a minimum section 10 mm wide using radii of 75, 15 and 7.5 mm, as shown in Figure 8. These results were compared to a parallel-sided 10 mm width specimen with gauge lengths of both 10 and 25 mm, made from the same material.

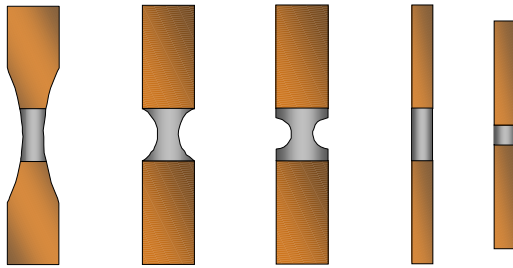


Figure 8 - Waisted and oversized specimens: 75 mm, 15 mm, and 7.5 mm radius; 25 mm and 10 mm gauge-lengths, respectively (left to right).

- Additional side loads: to determine the magnitude of the clamping loads applied to the specimen during torque application on the inner and outer bolts of the clamping blocks, which hold the specimen in place and maintain alignment, as well as those induced by Poisson's expansion during testing. In order to do this, instrumentation was designed to enable continuous monitoring. Initially, attempts were made to instrument the actual clamping bolts by using specially designed bolt strain gauges^[9] bonded into holes drilled through the centre of each bolt, but these proved unsuccessful (gauges sensitive to quality of bond and misalignment). The final solution used small, strain-gauged cylinders that were positioned between the face of the clamping block and each individual bolt,

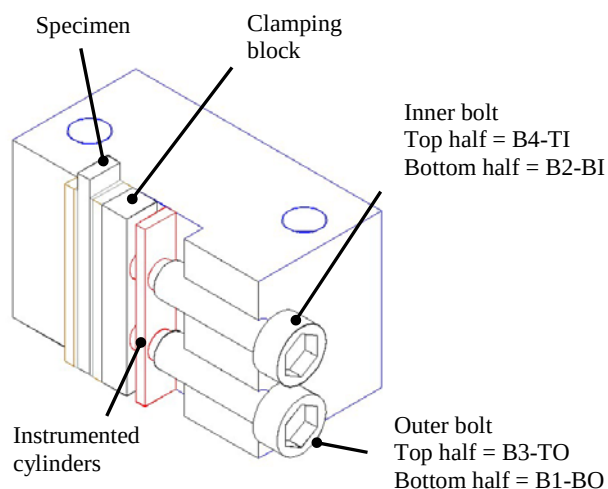


Figure 9 - Position of instrumented cylinder in lower half of end-loading rig, with bolt notations.

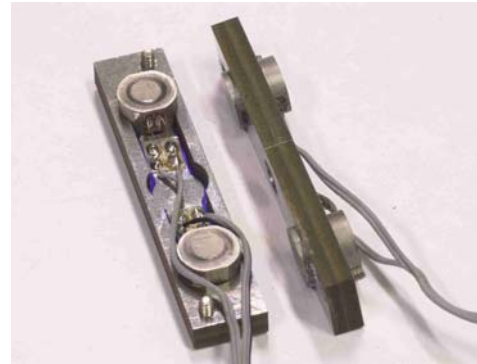


Figure 10 - Instrumented cylinders and holding device.

as shown in Figures 9 and 10. Stress/strain calibration curves were generated for each cylinder before use, so that the measured strain could be correlated to the load applied on the cylinder and hence the bolt or clamping loads.

- Torque levels: to determine the effect on specimen failure mode and strength of different bolt torque levels, tests were carried out using the recommended values of 5 and 10 Nm for the inner and outer bolts which were then compared to all the bolts torqued to 10 Nm using standard specimens for both materials with 45° reverse taper.
- Clamping surfaces: the effect of serrated clamping block gripping surfaces (instead of the usual smooth, flat surfaces) was also investigated using the standard specimen geometry in CFRP with 45° reverse taper.

Data Capture and Analysis

Strain gauges with an active gauge length of 2 mm were applied axially to the mid-plane on both sides of each specimen, using manufacturer's recommended adhesive.

Strain gauge conditioning and test data acquisition were conducted using an ELE MM700 Autonomous Data Acquisition Unit (ADU) recording at a rate of 5 Hz. Data were subsequently analyzed using a macro program created in Microsoft® Excel to speed and simplify initial analysis of the large amount of data created.

The compressive strength, σ_{CM} (MPa), was calculated using the equation:

$$\sigma_{CM} = \frac{F}{ab}$$

where:

F is the maximum load, (N);

a is the specimen width, (mm);

b is the specimen thickness, (mm).

The compressive modulus, E_c (MPa), was calculated using the equation:

$$E_c = \frac{\sigma_c'' - \sigma_c'}{\epsilon_c'' - \epsilon_c'}$$

where:

σ_c' is the compressive stress at $\epsilon' = 0.0005$, (MPa);

σ_c'' is the compressive stress at $\epsilon'' = 0.0025$, (MPa).

Acceptable specimen bending was then calculated using the equations:

$$\left[\frac{\epsilon_b - \epsilon_a}{\epsilon_b + \epsilon_a} \right] \leq 0.10$$

where ϵ_a and ϵ_b represent each of the axial strains measured using strain-gauges on opposite faces of the specimen.

RESULTS AND DISCUSSION

The results of the compression studies carried out are described below. In all cases, coefficients of variation (CoV) were better than 10% and modulus measurements showed no significant differences, unless otherwise stated.

Loading Rig and Fillet Geometry Comparisons

The comparison between the two different loading methods, summarised in Table 1,

shows that the end-loading rig gives approximately 15% higher strengths for both the materials tested. It should be noted, however, that it proved difficult to consistently achieve the correct compressive failures for the CFRP material.

Table 1 – Comparison of average compression strengths obtained using IITRI and end-loading rigs for standard specimens.

Material	Fillet Type	IITRI (MPa)	End-loading (MPa)
GFRP	RT	1104.7	1308.1
CFRP	RT	1349.7	1539.4

When results from the two fillet geometries using GFRP are compared, as presented in Table 2, a further increase in the measured strength is seen of up to 35% for the 45° reverse taper. Combining the effects of both fillet geometry and test rigs, it is evident that large differences in material strengths can be achieved even for identical material, as much as 45% was seen in this study.

Table 2 – Comparison of average compression strengths obtained for different fillet geometries using standard specimens of GFRP.

Fillet Type	IITRI (MPa)	End-loading (MPa)
SQ	911.3	1238.6
RT	1104.7	1308.1

This effect has been similarly confirmed for carbon fibre reinforced materials in previous unpublished work conducted at NPL.

It is worth noting that the 45° reverse taper has an adverse effect in tension, as shown by the results in Table 3 for unidirectional carbon reinforced 913 epoxy. This is probably due to the different constraints imposed by the different loading conditions; short gauge-length and lateral expansion in compression compared to long gauge-length and lateral contraction in tension.

Table 3 – Comparison of average tensile strengths and moduli obtained using different fillet geometries for standard tensile specimens.

Property Specimen type	σ_{TM} (MPa)	E_T (GPa)
Square shoulder	1621 ± 73	125.9 ± 2.8
Reverse taper	1317 ± 166	124.5 ± 0.7

Although the ultimate compression strength values are different depending on the loading rig and fillet geometry used, it can be seen from Figure 11 that the specimen behaviour in all cases is consistent and linear, resulting in comparable stiffness properties.

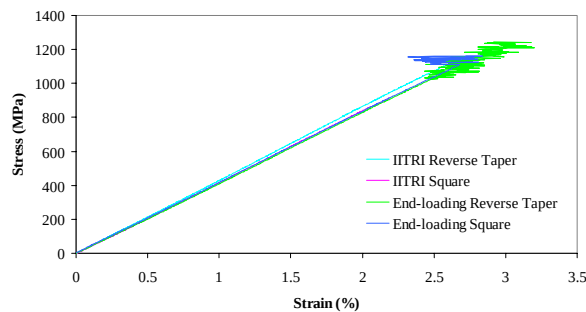


Figure 11 - Typical stress/strain responses for the end-loading and IITRI rigs, with square and 45° reverse taper fillet geometries.

Analysing the axial strain data from the strain gauges on opposing faces of the test specimen, shown in Figure 12, the end-loading rig shows the best average bending results. The IITRI rig may exhibit higher bending because of unequal frictional effects on the mating faces and the continually increasing clamping induced during loading.

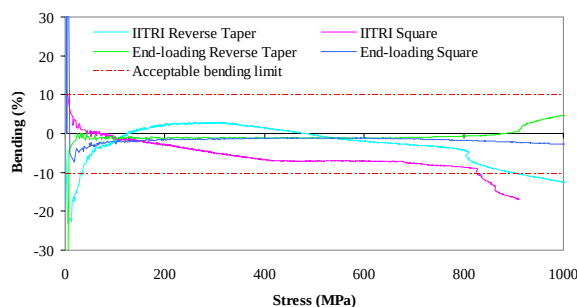


Figure 12 - Typical bending responses for the end-loading and IITRI rigs, with square and 45° reverse taper fillet geometries.

During the strain analysis, it was found to be impossible to keep bending below the recommended acceptance level throughout the entire duration of the test. Bending is invariably outside recommended limits at the start of the test, while the specimen and load train settle; and again near the end of the test when gauges may fail before the specimen, producing inconsistent readings. This is not an uncommon scenario in materials achieving high failure strains.

Width Constraints

Results, shown in Table 4, for tests on constrained and unconstrained specimen widths showed little difference in failure strengths. However, very different modes of failure were obtained, as shown in Figure 13. Constrained specimens showed uniform brushing failures close to the end-tabs, whereas unconstrained specimens showed fibre splitting and lateral splaying within the tabbed region.

Table 4 – Comparison of average compression strengths obtained using 10 mm and 25 mm slot widths for standard specimens of material 1.

Material	Fillet Type	10 mm slot (MPa)	25 mm slot (MPa)
GFRP	RT	1308.1	1305.6
CFRP	RT	1539.4	1471.5

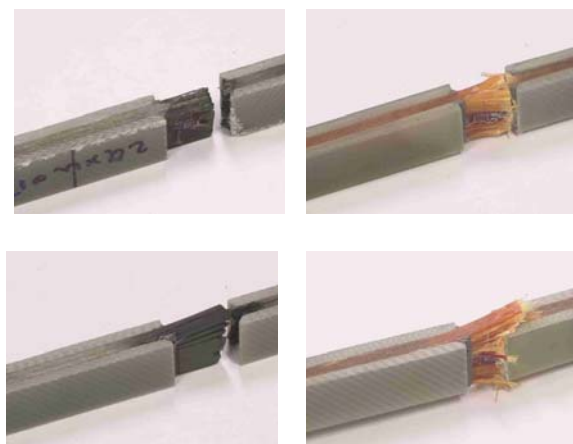


Figure 13 - Photographs of different failure modes for constrained (upper) and unconstrained specimens (lower) for both materials.

Standard Specimens Machined from Thick Sections

The results, given in Table 5, for thin specimens machined from a thick section panel as compared to specimens manufactured directly to thickness showed no significant difference. It is interesting to note, however, that the CoV for the machined 5 mm specimens is far greater than that obtained for the other samples. This may be due to the difficulty associated with achieving correct alignment of the fibres and possible machining damage (cutting of undulating fibres) in the case of machined thicknesses. This could be a problem particularly for pultrusion and fabrics where fibre waviness is common.

Table 5 – Average compression strengths and standard deviations obtained using machined and manufactured 2 and 5 mm thick GFRP specimens .

As manufactured thickness (MPa)		Machined thickness (MPa)	
2 mm	5 mm	2 mm	5 mm
1308.1 ± 61.4	1144.5 ± 47.5	1200.6 ± 43.4	1166.2 ± 174.6

Waisted Specimens

It can be seen in Table 6 that the results obtained by waisting the specimen width give equivalent failure strengths to a standard 2 mm panel. Unfortunately, the change in gauge section results in a non-uniform strain distribution within the gauge-length producing artificially high modulus measurements (most apparent for smaller radius waisting).

Table 6 – Comparison of average compression moduli and strengths obtained using various radiussed GFRP specimens.

Property Specimen type	σ_{CM} (MPa)	E_C (GPa)
R 75	1077.3	44.0
R 15	1126.8	53.4
R 7.5	1193.7	58.1

This effect is clearly shown in Figure 14, where the error bar shows the typical standard deviation for a batch of five standard geometry GFRP specimens. The stress/strain response of the waisted specimens in Figure 15 highlights how the longitudinal cracks propagate from the edge of the radius during loading. Waisting the specimen forces failure at the minimum section, unless the longitudinal cracks travel the full length of the specimen, which effectively leaves a narrower parallel-sided specimen (and detached side sections) which can fail anywhere within the gauge-length (or within the end-zone in some cases).

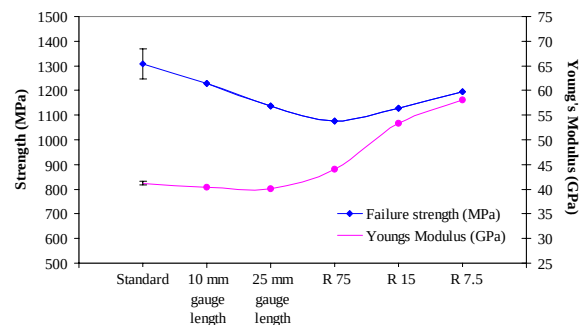


Figure 14 - Trends in strength and modulus for radiussed and parallel sided specimens.

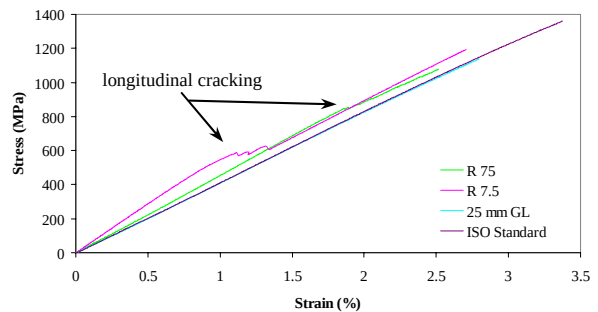


Figure 15 - Typical stress/strain response for radiussed and parallel sided specimens.

Table 7 shows data for different thickness and gauge-length GFRP specimens. These show no significant differences for modulus, although there is some indication that the greater test volume for thicker specimens and longer gauge-lengths increases the probability of encountering a failure promoting defect and ultimately leading to lower strengths.

Table 7 – Comparison of average compression moduli and strengths obtained using various parallel-sided specimens.

Property Specimen type	σ_{CM} (MPa)	E_c (GPa)
25 gauge-length, 5 mm	1138.5	40.1
10 gauge-length, 5 mm	1227.2	40.4
10 gauge-length, 2 mm (standard)	1308.1	41.2

Torque Levels

Previously, the specimen failure mode has been shown to vary when using the end-loading rig. It is designed to apply the load through pure end-loading, with the alignment of the specimen achieved by means of a clamping block held in place by inner (B2-BI and B4-TI) and outer bolts (B1-BO and B3-TO) torqued to 5 and 10 Nm respectively. This keeps the specimen aligned and prevents bending during the test. Applying specific torque levels does not guarantee reliable or repeatable clamping loads, due to simple factors, such as the material used for the bolt and the thread, whether it is clean or has grease on it, etc. This is confirmed in Figure 16, where the same bolt is loaded to both 5 and 10 Nm using different bolt conditions. If the torque applied to the bolts does not produce correct and consistent clamping loads, it could explain this observed discrepancy in specimen failures.

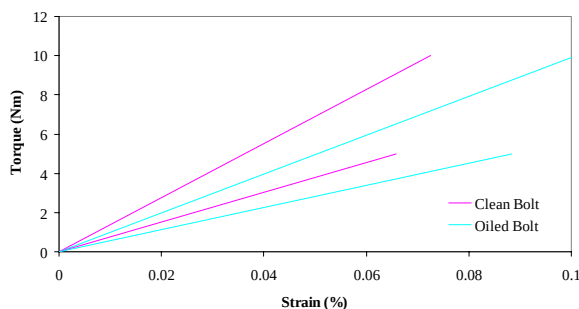


Figure 16 - Measured bolt strains under different lubricated conditions for set torque levels.

This is highlighted further in Figure 17 where it can be seen that without careful consideration of the condition of the bolts, incorrect clamping loads can be applied to the specimen. In this case, although bolt B3-TO is tightened to a torque of 10 Nm, the same as bolt B1-BO, it has in fact applied a side load to the specimen of less than bolt B4-TI which was tightened to only 5 Nm.

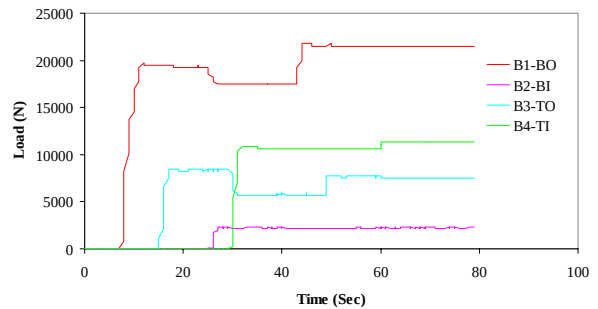


Figure 17 - Clamping torques of 5 and 10 Nm applied to end-loading rig bolts.

Figure 18 illustrates the order in which torque is applied to the bolts and how they react when clamping the specimen. The bottom outer bolt B1-BO is first torqued to its required level, but when the next top outer bolt B3-TO is then tightened, a drop in the load present on the first bolt is noted. This occurs due to the realignment of the specimen and the redistribution of load between the bolts. This happens for each consecutive bolt tightening in turn. As a result of these changes in the bolt loads with successive tightening, it is necessary to adjust the torques applied to all the other bolts once the final bolt is tightened, in order to achieve the recommended 5 and 10 Nm torque setting. Otherwise, the torque on the first bolt could be as much as 50% lower than expected.

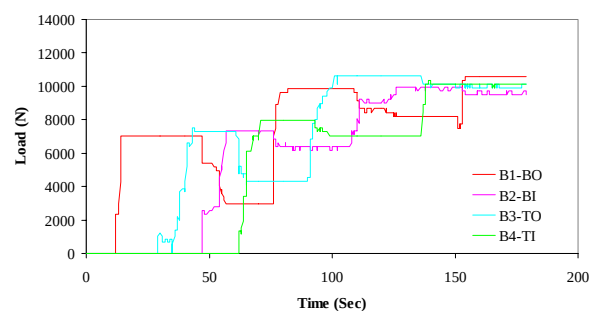


Figure 18 - Clamping torques of 10 Nm applied to successive adjacent end-loading rig bolts.

This work suggests an improvement to the procedure for achieving the recommended bolt torques in the test rig of 5 and 10 Nm, as given in Table 8.

Table 8 – Suggested procedure for the application of correct standard torque levels.

Step	Bolt	Torque (Nm)
1	B1-BO	8
2	B3-TO	8
3	B2-BI	5
4	B3-TI	5
5	B1-BO	10
6	B3-TO	10
7	B2-BI	5
8	B3-TI	5

During compression loading, the specimen expands laterally causing additional pressure to be applied against the clamping block. By using the instrumented cylinders, with the correct clamping forces applied initially, this expansion data can then be analysed. Table 9 presents these results for both materials under different initial clamping conditions.

It can be seen in Table 9 and Figure 19 for the GFRP material that despite the different initial clamping loads for the 5/10 kN and 10/10 kN torque combinations, the Poisson's expansions produced are roughly the same with the outer bolts experiencing a far greater load increase during the test than the inner bolts. This effect is also seen in the CFRP material, Figure 20. In the latter case, the lower load increases on the inner bolts are presumably due to the lower lateral Poisson's ratio for carbon reinforced materials, but the outer bolts show

disproportionately high load increases. This may in part explain the high incidence of specimen end zone failures in the CFRP material.

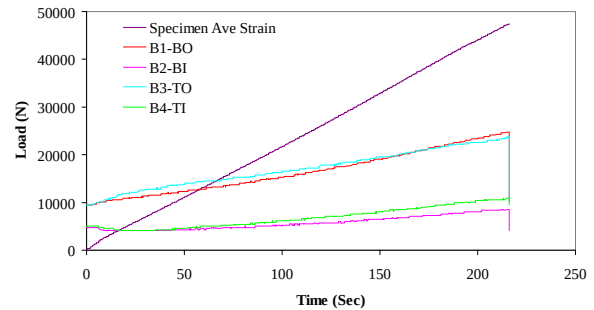


Figure 19 – Clamping load against time for 5/10 kN combination in the GFRP material during compression testing.

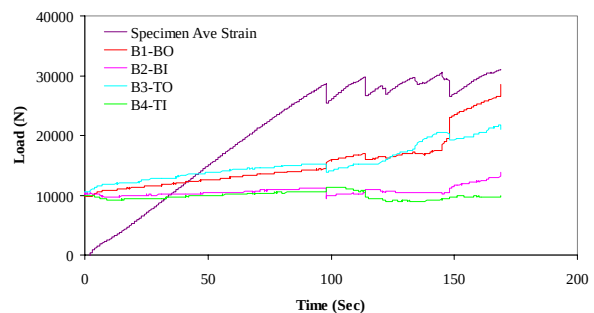


Figure 20 – Clamping load against time for 10/10 kN combination in the CFRP material during compression testing, showing cracking and failure within the gripped region.

Serrated Clamping Surfaces

Due to the high number of end zone failures seen with the end-loading rig for the CFRP material, it was suspected that the method of applying load to the specimen was encouraging this failure mode to dominate (carbon material less tough than glass). In order to improve this situation, serrations were machined onto the clamping block

Table 9 – Comparison of average clamping loads before and after testing for standard size specimens.

	Material 1 5/10kN		Material 1 10/10kN		Material 2 10/10kN	
	Inner	Outer	Inner	Outer	Inner	Outer
Load after torque (N)	4880	9404	9805	10360	10047	10249
Load at specimen failure (N)	9686	24304	14104	22656	11892	24795
Load increase during test (N)	4806	14900	4300	12286	1844	14546

faces, as shown in Figure 21. This limited the extent of the lateral Poisson's expansions within the gripped region by restricting the slipping and relative motion within this area, the compression within the gripped region was effectively reduced. This is suggested by the data shown in Figure 22. The torque levels, in this instance, were limited to 5 Nm/5 Nm due to the local indentation of the end-tabs by the serrations which made higher loads difficult to achieve without causing excessive damage.

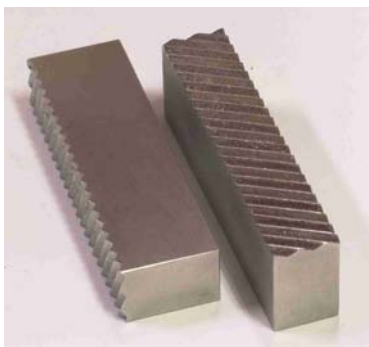


Figure 21 – Detail of serrated clamping block faces.

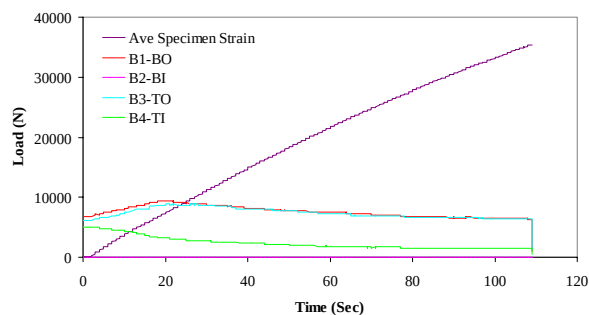


Figure 22 – Clamping load against time for 5/5 kN combination in the CFRP material during compression testing, using serrated clamp faces.

The results shown in Table 10 indicate yet further improvements in the measured compression strength.

However, although the specimens successfully failed more consistently within the gauge section, some end zone failures still occurred so further optimisation of this rig modification is required. Photos of the different failure modes are shown in Figure 23.

Table 10 – Comparison of average compression strengths for different specimen clamping faces.

Surface Type	Compression strength (MPa)
Smooth	1475
Serrated	1723

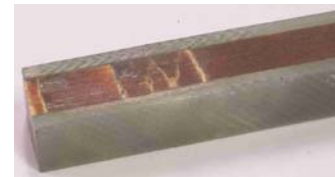
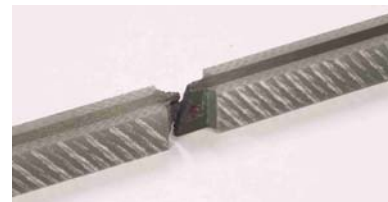
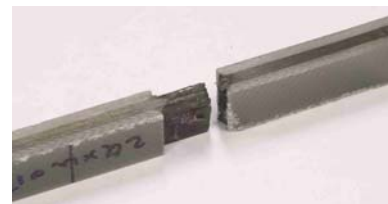


Figure 23– Failure modes obtained using different clamp surfaces: smooth (upper), serrated (centre) and typical end-zone failure (lower).

CONCLUSIONS

The investigations carried out and the data presented here suggest the following facts and recommendations:

- The end-loading rig gave consistently higher strength results when compared to the IITRI rig, however stiffness results for the two rigs were not significantly different.
- The end-loading rig easily accommodates a broad range of specimen thicknesses, making it more suitable for thick section compression testing than the IITRI rig, which requires specifically made wedges to adapt to each different thickness.
- The novel 45° reverse taper has been shown to produce repeatably higher compression strengths when compared to the ISO standard recommended square shoulder. This does not transfer directly to tension where the opposite constraints are encountered.
- Waisted specimens gave similar strength results to those obtained using standard parallel-sided specimens, but the stiffness properties were artificially increased by the non-uniform strain field produced as a result of waisting the specimen.
- It is possible to obtain approximate thick section compression data by machining 2 mm standard test specimens from a thicker panel, provided care is taken to keep the correct fibre alignment and minimise damage.
- Instrumentation of the clamping bolts in the end-loading rig has shown the inherent variability in the applied torques. Care must be taken to keep all bolts in the same condition for each test conducted, either fully clean or fully greased to minimise frictional contributions to the measured torque, with each bolt being tightened progressively. It is not recommended that instrumentation be employed as standard, as it is complicated and time-consuming, but is a useful addition in helping to investigate particular problems/issues in detail.

- Serrating the clamping faces in the end-loading rig seems to limit damage occurring within the gripped region, effectively minimising the number of premature failures in this zone.
- It is clear to see where the poor reproducibility frequently reported between test laboratories can arise, when different test rigs, specimen geometries and end-tab constructions can produce results from a single operator on the same material to vary by as much as 45%.

Further work is required to:

- Investigate the suitability of waisted specimens for different ply orientations, laminate lay-ups, fibre formats (e.g. fabrics) and manufacturing routes (e.g. pultrusions).
- Optimise the serrated grips modification to the end-loading rig, by evaluating different types of serrations, in order to improve the incidence of acceptable failures for all materials and minimise the CoV for this method.
- Investigate alternative methods of applying a consistent clamping force to the specimen in the end-loading rig, by means other than multiple bolts.
- Finite element analyses to evaluate the effect of serrations, radiussed widths (reason for higher measured modulus) and clamping loads on the stress distribution within a specimen.

As greater focus is placed on establishing the lifetime performance of materials, it is necessary to solve the issues related to static compressive methods in order to permit suitable developments to be made for compressive fatigue test methods and full cycle tension/compression testing. The further work discussed here would assist in this aim, enabling a new rig to be developed and evaluated to satisfy these needs.

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