TESTING OF THICK CARBON FIBRE LAMINATE COMPOSITES: COMPARISON OF THICK WITH THIN COUPONS, CURRENT STANDARDS AND PRODUCT CASE STUDY

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SUMMARY

Within many industrial sectors there is a trend towards the utilization of carbon fibre laminates for primary structural applications. This trend includes a change from thin to thick laminate cross sections for many components. Much of the technical information supplied by the vendors relates to traditional thin sections. The use of thick laminates requires a re-evaluation of the data, testing approaches, design and fabrication techniques. This paper seeks to highlight the technical issues and the difficulties relating to the testing of thick section carbon fibre laminates and compares results of thin and thick coupons. The shortfalls of the current testing standards and manufacturing considerations for thick components are also discussed. A case study is presented to demonstrate product derived testing for thick monolithic curved panels.

1. COMPRESSION TESTING OF COMPOSITE MATERIALS

Composite materials require more property data to characterize their properties due to their anisotropy, than typical competing isotropic materials such as metals. Hence, normally there are three directions in orthogonal planes (i.e. x, y and z) that require unique characterisation. For some fibre formats these properties may be approximately equal, such as the z and y directions in a fully unidirectionally reinforced material. However, due to the manufacturing process even in this case the values are unlikely to be identical. In addition, there may be significant differences between measurements made in the tensile and compressive directions, particularly for strength properties. These differences are due to differences in the failure modes. In tension the failure of fully unidirectionally reinforced material is related to the tensile strength of a bundle of fibres influenced by the degree of bonding of the matrix to give varying brittle to tough response.

Compressive failure for fully unidirectionally reinforced material is related to the buckling of fibres, acting as supported columns, in a gross shearing/compression failure. In other directions for unidirectional material or other fibre formats a clearer shear failure may be apparent in compression and macro-crack growth in tension (e.g. mat reinforcements).

The form of the material tested also affects the conduct of the test. Most high performance materials are produced as thin plates that can be easily machined into straight or dumbbell shaped coupons for tensile testing, although there are difficulties associated with the transfer of load into the specimen without the creation of stress concentrations (1).

In compression, as well as this latter difficulty, the thin specimens are unstable when loaded. Hence, testing is based on either a fully stabilised thin coupon or short un-supported gauge lengths of thin coupons, which has resulted in many variations of the compression test method being produced over the past four decades. These variations have mainly centered on the design of the end loading jigs for unsupported specimens (i.e. short spans/gauge length), with some resultant variation in the aspect ratio of the test gauge length. Unsupported specimens have been preferred, as the proportion of load carried by the jig itself in fully supported specimens is not known. Some form of rigid end support/load transfer mechanism is used in most designs to apply load and to avoid end failure by a “brooming” or “brushing” failure.

No standard has been published for the through-thickness or “z” direction in the material. It is not usually possible to use the conventional specimen, as the “z” direction is not large enough (i.e. 110 mm required). NPL had reviewed the options for measuring the stiffness and strength properties in the “z” direction (2), and developed some of the methods to give procedures for future standardization covering both tension and compression properties (3,4).

2. CASE STUDY - TEST PROCEDURES

This case study looks at the manufacture and testing of thick unidirectional (UD) carbon fibre monolithic panels. The purpose of the study was to compare the compressive results of thick UD laminate with the thin coupon material traditionally used for determining mechanical properties using a filament wound approach. The filament winding process was chosen because the product that the testing was supporting was filament wound thick tubes and the effects of manufacturing were also paramount to the investigation. The results were compared with conventional UD coupons manufactured using the same materials. Testing was conducted in the Material Centre of the National Physical Laboratory in the UK.

2.1 Thick Plate Compression Testing The test plates were wet wound using Toray T700 24k and a proprietary epoxy matrix on a flat paddle. The dimensions were 300 mm by 400 mm by 25 mm thick. An 89.5^{o} wind angle was selected, which was considered to be unidirectional. They were pressed during the cure to a temperature of 100^{o}C.

Three sets of compressive tests to determine strength, modulus and Poisson’s ratio were carried out in each of the three planes; through thickness, transverse and longitudinal direction.

2.1.1 Longitudinal In the longitudinal direction (parallel to the fibres) the specimens were 125 mm long and nominally 20 x 10 mm in cross-sectional area. End tabs were fixed onto the two narrower faces of each specimen, 50 x 10 mm in area, leaving a 25 mm gauge length in the centre of the specimen. To check the axiality of the loading arrangement and to calculate the compressive modulus, two 10 mm strain gauges, one in the fibre direction and one perpendicular to it, were bonded onto the opposite faces of each specimen, in the gauge length region.

2.1.2 Transverse and Though Thickness For the transverse and through thickness directions a base area of 25 x 25 mm and a waisted central area of 15 x 15 mm was tested in the two directions orthogonal to the fibre direction. Two sets of specimens were manufactured for each test orientation: parallel-sided blocks, 12.5 x 12.5 mm in cross-section and 20 mm high, to allow strain gauges to be attached to all four faces; and waisted blocks, 15 x 15 mm at the base and 20 mm high, with a 30 mm radius on all four faces, so the cross-section at the centre of the specimen tapers down to approximately 12.8 x 12.8 mm. The parallel-sided blocks were used to take modulus measurements, and the waisted specimens to measure the ultimate compressive strength.

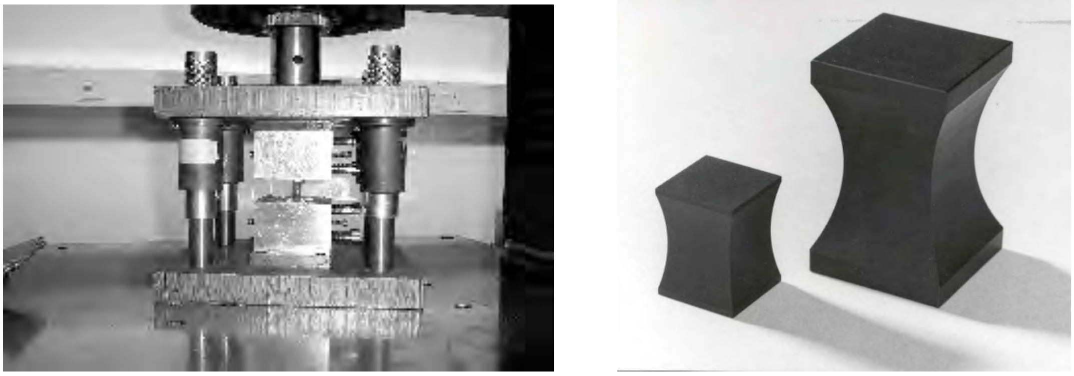


Figure 1 left, Test rig in strain-gauge test position for "x" direction, Right, Shaped through-thickness test specimen designs

The compressive modulus was determined using a KFG-1-120-D16-11 biaxial strain gauge rosette bonded onto each specimen in the centre of each of its four faces. The strain outputs and the load were monitored and recorded.

2.2 Thin Coupon Compression Testing The testing of the thin coupons was undertaken using the established EN ISO 14126 (5). The material used was Toray T700 12 k using the same proprietary epoxy resin system as the thick panel. Five samples for each test were carried out.

2.3 Fibre and Void Volume Fractions The volume fraction measurements were carried out according to ISO/FDIS 14127 (6) using the nitric acid digestion method. The initial density of the composite was determined by the zeroed pan immersion method as described in ISO 1183 (7). Three specimens were taken from each sample. The analysis procedure in ISO/FDIS 14127 was used to determine overall fibre and void fractions. The calculations initially used assumed values of densities as below.

Carbon fibre	- 1.80 g/cm^3
Resin	- 1.099 g/cm^3

3. CASE STUDY – EXPERIMENTAL RESULTS

3.1 Microscopic Evaluation Figure 2 illustrates typical wet filament wound quality for the thick plate. Fibre alignment is a function of the machine control and the winding head can easily be controlled to within 0.5^{o} of the desired wind angle. However, in wet filament winding processes there can be measurable difference between the as built wind angle and the programme requirements and any misalignment would be expected to affect the measured data.

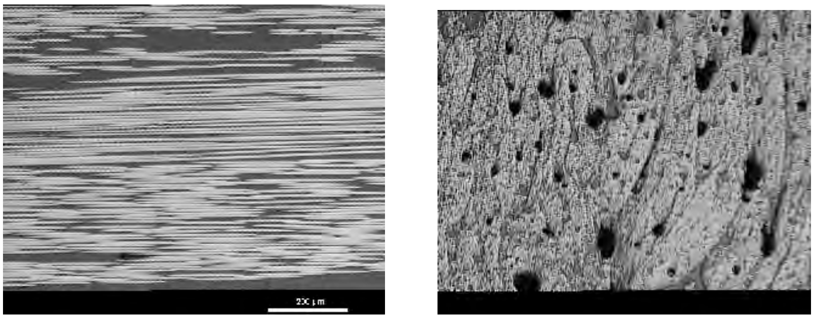


Figure 2. Left, Example of Panel Micrographs showing Fibre Alignment, Right, Micrographs showing voiding

3.2 Fibre and Void Volume Fractions The values obtained according to ISO/DIS 14127 using nitric acid digestion method for the thin and thick plate material are given in table 1. Values of less than 1%, as obtained for the thin plate, are typical of autoclaved produced material.

Table 1 Fibre volume and void content

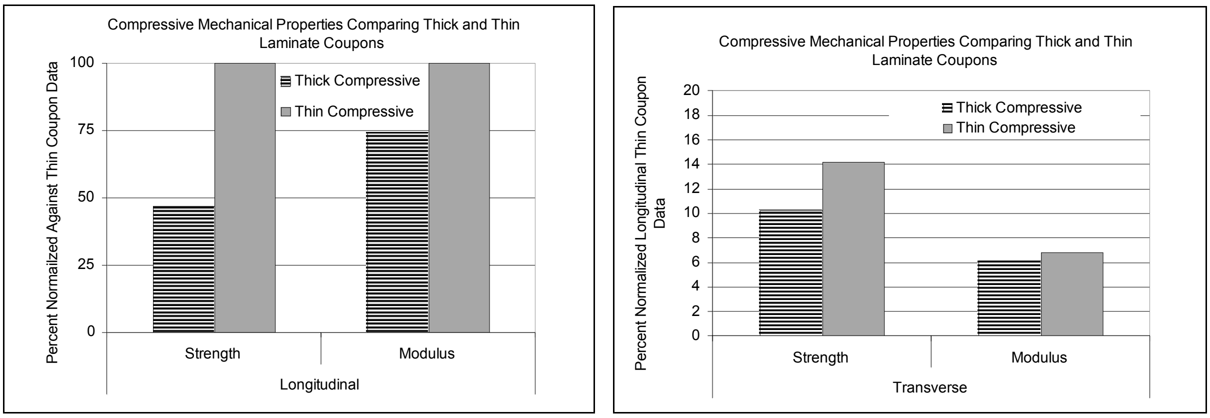
	Thick Coupons	Thin Coupons
Mean Fibre Volume Fraction, %	58.3	65.3
Mean Void Content, %	2.5	0.9

It is noted that the thick plate material has a higher void fraction and a lower fibre volume fraction. These values might be expected to produce a least a linearly proportional response in the measured values, but possibly a larger effect.

3.3 Mechanical Test Results The mechanical test results are given in Figure 3 in terms of the thin specimen data, without any normalization for fibre content. In all cases the measured value has been expressed with respect to the thin plate “x” direction compressive strength or modulus as appropriate. This presentation highlights the anisotropy between the “x” direction properties and the “y” directions, as well as the differences between thin and thick material.

For the “x” direction the thick plate showed a 25% reduction for modulus and a 52% reduction in strength. The “y” direction for the thin plate was 14% of the “x” value for strength and 7% for stiffness, so highlighting the marked anisotropy present. The “y” and “z” values for the thick plate were 10% and 6% of the “x” values for thin plates for strength and modulus, respectively. Because of the reduced “x” direction properties in the thick plate, the anisotropy in the thick plate is lower.

It is noted that considerable difficulties were encountered in testing material in the “x” direction that was thicker than the current standard. This is especially relevant for compression test, which are acknowledged as the most difficult of the composite tests to undertake. Difficulties were associated with end failures and within tab failures.



(a) “x” direction

(b) “y” direction

Figure 3. Properties expressed as a function of thin plate data - “x” direction.

4. CONCLUDING DISCUSSION

The data obtained in this case study suggests a fall-off in properties for the thick plate but also a lower quality as seen through a higher void fraction and a lower fibre fraction. The effect of the fibre volume fraction if linearly applied would result in a 10% fall. However, it has not been proven that the compression strength can be normalized in this manner and NPL’s Component and Composite Design Analysis (CoDA) personal computer (PC) based software micro-mechanics prediction for unidirectionally composites does not depend directly on fibre volume fraction.

It is possible to estimate the effect of misalignment on the modulus using the CoDA material synthesis and design software supplied and validated by NPL. If half the fibre content is misaligned by ±5° in a nominally fully aligned material with 60% fibre content, the predicted modulus falls by 2.4%. For the compression strength, a 20% reduction is obtained, although the micro-mechanics within CoDA does not include any additional effect of the misalignment on triggering a local compression crippling failure. The fibre misalignment may be in the through-thickness direction due to “pull-through” in thick sections, rather than from inaccuracies in the path laid-down on the surface of the wound part (i.e. in the x-z plane).

For a ±10° misalignment of half the fibre content, the effects are a 9.5% and 40% reduction for modulus and strength, respectively. Interestingly if all the misalignment is in the same direction, such as, -10°, the effects are larger at 15% and 53% reduction for modulus and strength, respectively. Misalignment in one direction, inwards towards the mandrel, could occur in a thick filament-wound component.

The CoDA[a] software can also be used to study the effect of the resin properties on the compression strength. Reducing the resin moduli by half has little influence, but reducing the shear strength by 33% reduces the compression strength by 23% with no effect on the modulus. Again, the shear strength would be expected to be sensitive to void content, although no measurements were made in this study.

These comments do suggest that the fall-off in properties measured is connected to the quality differences between the thin and thick plate.

5. ACKNOWLEDGEMENTS

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[a] CoDA is a product developed by and available from the National Physical Laboratory www.npl.co.uk/cog/index.html