두꺼운 일방향 탄소섬유-에폭시 적층판의 정적 압축 강도 연구

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Static Compressive Strength of Thick Unidirectional Carbon Fiber - Epoxy Laminate

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Abstract

Existing test methods for thick-section specimens (4mm) have not provided precise compressive properties to date for the analysis and design of thick structure. A survey of the failure behaviour of such thick specimens revealed that the failure initiated at the top corner of the specimen and propagated down and across the width of the specimen as premature failure, not typically reported for thin compression specimens. In the current study, the premature failure was successfully avoided during compressive testing and the failure mode was quite similar regardless of increasing specimen thickness and specimen volume. Failure mode was similar regardless of increasing specimen thickness and specimen volume, i.e. brooming failure mode combined with longitudinal splitting, interlaminar cracking, fibre breakage and kinkband formation (fibre microbuckling). Nevertheless, average failure strengths of the specimens decreased with increasing specimen thicnkiness from 2mm to 8mm with the T800/924C system (36% strength reduction) and specimen volumes from scaling factor 1 to scaling factor 4 with the IM7/8552 system (46% strength reduction). It wasrevealed from the literature[11] that the thickness effect and scaling effect are caused by manufacturing defects such as void content and fibre waviness..

Key Words: compressive strength, unidirectional composite laminate, thickness effect

1. Introduction

Considerable effort has been expended to understand the compressive deformations and the mechanisms of compressive failure with thin unidirectional composite laminates (2mm - 3mm). As s result, numerous theoretical models predicting the compressive strength and test methods have been developed. The models could be classified under two categories, i.e. microbuckling theories and kinking theories. The test methods for thin specimens (2mm 3mm)ave been categorized according to the way the load is applied, i.e. direct end-loading (ASTM 695, CRAG and Wyoming End-loaded method), shear loading (Celanese, IITRI, Cambridge fixture and Herculas fixture) and mixed shear/direct-end laoding (RAE method, Birmingham method, Aerospatiale Test fixture and ICSTM method). have been categorized according to the way the load is applied, i.e. direct end-loading (ASTM 695, CRAG and Wyoming End-loaded method), shear loading (Celanese, IITRI, Cambridge fixture and Herculas fixture) and mixed shear/direct-end laoding (RAE method, Birmingham method, Aerospatiale Test fixture and ICSTM method).

Much less attention, however, has been paid to understand the compressive behaviour for thick unidirectional composite laminates even though requirement for advanced composite materials in thick structural sections has significantly increased. This is caused by notorious difficulty of obtaining reliable test results. In fact, all problems related with compression testing become more serious and complicated with thicker composites, because of the tendency for premature failure due to global buckling or end crushing. In order to prevent the premature failure of the specimen, compression test specimens as well as test fixtures should be manufactured to provide a uniform one-dimensional stress field, carefully considering following factors: properties of the tabbing materials, tab bond characteristics, tab thickness and constant specimen

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production procedures. Nevertheless, these factors are often and mistakenly dismissed by many workers as being of no importance. For example, Componeschi[1], Hsiao2, Daniel3 and Lee4 performed experimental works to develop a new compression test method for thick composites or investigate thickness effects on the compressive strength. In their studies, the thicker specimens failed at the end of the specimens at the load introduction (end crushing) even though the test results revealed the tendency that the failure strength decreases with increasing thickness of unidirectional composite laminates. The researchers might only consider typical factors influencing the compressive test results such as specimen geometry, Euler buckling, test fixture and specimen misalignment in the fixture, ignoring the end-tab thickness effects. Existing test methods have not provided precise compressive properties to date for the analysis and design of thick structure. Therefore, it is important to develop a reliable compression test method to prevent premature failure of the thick specimens.

In terms of scaling of unidirectional laminates, the tendency of the thickness effects was revealed in the literature even though the thick specimens failed prematurely1-5. No one, however, has performed 3-D scaling effects on the compressive strength. In trying to explain the unexpected low failure strength of thick composites, possible explanations could fall into the categories of material or manufacturing related issues1. Questions can be raised on these issues. In terms of material issues, the elastic constants or strength determined for thin laminates may not be applicable to thick composites. What are the trends for the compressive properties of composite materials with increasing thickness? In terms of manufacturing aspects, does thickness change have an influence on fibre volume fraction, void content, fibre waviness etc.? If manufacturing quality is affected directly by the thickness change of the composite, a thickness effect would be expected since the compressive strength is governed by and is sensitive to the defects.

In the present study, premature failure is successfully avoided through the careful design of thick compressive test specimens. The failure of all size specimens is similar regardless of increasing specimen thickness and specimen volume. 1-D thickness effects with T800/924C unidirectional laminates and 3-D scaling effects with IM7/8552 unidirectional laminates are carefully examined. Finally failure strengths for both materials are predicted through Budiansky model5as a function of fibre waviness.

2. Experimental

2.1 Materials

Two material systems, T800/924C and IM7/8552 were used in this study. The material was in the form of pre-impregnated tapes, which are 0.125mm thick and commercially available by Hexcel Composites Ltd. The tapes were made of unidirectional Toray 800 carbon fibres and intermediate modulus unidirectional carbon fibre (IM7), which are pre-impregnated with Hexcel 924C epoxy resin and 8552 epoxy resin, respectively. The standard cure cycle recommended by Hexcel Composite Ltd was used for the thin laminates less than 4mmthick. As the laminate thickness increases, the laminate has to dwell in an autoclave for a while to allow even heat distribution throughout the panel and to diminish possibility of exotherm (heat energy, which causes uncontrollable temperature rise within thick laminates). The in-plane stiffness and strength properties of the T800/924C and IM7/8552 unidirectional laminates are given in Table 1. These parameters were obtained by Hexcel Composite Ltd. In this study, 2mm, 3mm, 4mm and 8mm thick unidirectional laminates $[0_4]_{ns}$ (n = 2, 3, 4, and 8) were fabricated.

Table 1 Elastic Properties of the T800/824C and IM7/8552 system

Property	E_{11} Gpa	E_{22} Gpa	G_{12} Gpa	ν_{12}	σ_{11c} Mpa	σ_{22c} Mpa	$\tau_{12\#}$ Mpa
T800/924C	168	9.25	6.0	0.35	1615	250	105
IM7/8552	150	11.0	4.6	0.30	1690	250	120

(σ_{11c}=logitudinal compressivw strength and σ_{22c} =transverce compressive strength)

2.2 Test programme

The specimen dimensions were determined on the basis of the above calculation to avoid Euler buckling and to introduce failure at the gauge section with waisted specimens. For the investigation of thickness change from 2mm to 8mm, the gauge sections of 10mm 10mm were used using the T800/924C system.

Table 2 Compression test programme for the T88/924C and IM7/8552 systems

Material	1-D thickness effect				
T800/924C	Thickness	2	3	4	8
	Specimen width × gauge length	10×10	10×10	10×10	10×10
Material	3-D scaling effect				
IM7/8552	Thickness	2	4	8	
	Specimen width × gauge length	10×10	20×20	40×40	

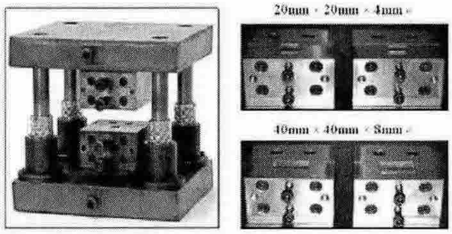
3-D scaling effects were also examined with the IM7/8552 system. The baseline specimen sizes of 10mm x 10mm x 2mm in gauge width x gauge length x thickness are increased by a scaling factor of 2 and 4. All the specimens were bonded with woven glass fibre-epoxy reinforced tabs (tab length

= 50mm). At least five specimens for each configuration were tested. Table 2 shows the systematic test matrix for the thickness effects and scaling effects with unidirectional laminates.

2.3. Compressive testing

No universally accepted test standards are available for such thick specimens. Existing test methods for characterising the compressive response of a unidirectional composite laminate recommend 2 3mm thick specimens.

In the present study, compression tests on the unidirectional specimens were performed using the ICSTM test jig at a constant compression rate of 1 mm / min on a servohydraulic machine of load capacity 1000 kN, see Figure 1. The ICSTM method applied the load directly at the ends of the specimen. However, a small amount (in the region of 10%) is applied by shear loading via tabs.



(a) (b)

Figure 1 ICSTM compression test fixture (a) and grip blocks for large specimens (b)

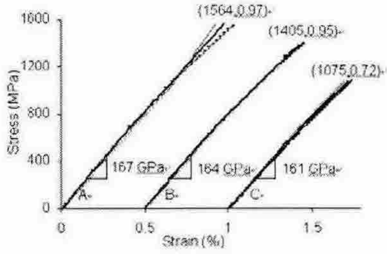
Since 90% of the load is applied directly, the ends of the specimen must be carefully machined in order to achieve uniform contact between the end faces and the surfaces of the platens of the test fixture. On loading, premature failure of the specimen can occur before the entire end face of the test piece comes into contact with the platen. Usually the specimen starts to split in the region near the loaded edge of its end face, and the crack tends to propagate along the length of the specimen (brooming effect) causing premature failure. After tabbing, individual specimens were machined to final tolerance by grinding the specimen ends and tab surfaces parallel within 0.025 mm (0.001 in).

Foil strain gauges were used on both faces of all specimens to be tested in order to measure axial modulus, axial strain and monitor the degree of Euler bending. The location and nature of damage in the UD laminates was obtained by scanning electron microscopy (SEM).

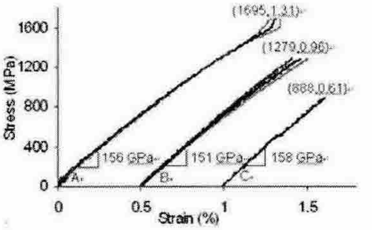
3. Uniaxial Compressive Test Results

Representative stress-strain curves of 2mm (Plot A), 4mm (Plot B) and 8mm (Plot C) thick unidirectional specimens for T800/924C and IM7/8552 material systems obtained at the centre of each specimen from back-to-back strain gauges are shown in Figure 2. Plots B for the 4 mm thick specimen and C for the 8 mm thick specimen are offset by 0.5% and 1.0% strain, respectively, so results can appear on the same graph.

The consistency of the two strain gauge readings up to failure in each curve indicates that bending due to misalignment has been successfully minimized. These three curves show similar stress-strain behaviour, which is essentially linear up to a strain level of approximately 0.5 %. Thereafter, the material behaves nonlinearly with a softening which increases with increasing strain. The compressive modulus was determined by averaging the initial slopes of the stress-strain curves from readings of back-to-back strain gauges at 0.25 % strain. The plots show the moduli are independent of specimen thickness (Figure 2 (a)) and volumes (Figure 2 (b)).



(a) T800/824C unidirectional specimens

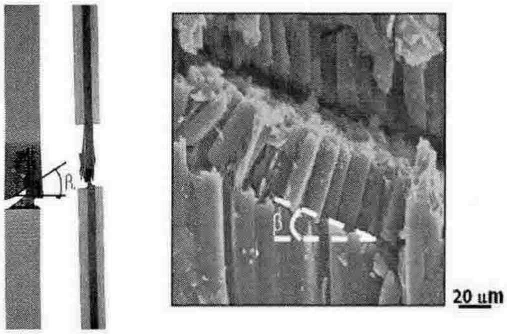


(b) IM7/8552 unidirectional specimens

Figure 2 Typical stress-strain curves of the unidirectional laminates obtained from back-to-back strain gauge - (a) T800/824C unidirectional specimens (A: 10mm 10mm 2mm, B: 10mm 10mm 4mm and C: 10mm 10mm 8mm) and (b) IM7/8552 unidirectional specimens (A: 10mm 10mm 2mm, B: 20mm 20mm 4mm and C: 40mm 40mm 8mm)

Compressive failure of the unidirectional T800/924C and IM7/8552 carbon-epoxy composite for all sizes was instantaneous and catastrophic and was accompanied by an audible acoustic event but no cracking sound prior to the catastrophic failure. When failure occurred, the test piece parted into two pieces with fracture surfaces inclined at typical anglesof between = 5 30 (: kinkband inclination angle) in the width direction or thickness direction in both material, see Figure 3 (a).

After compression tests, some of the broken T800/924C specimens were selected and examined in the SEM. Figure 3 (b) depicts the microscopic feature of a typical fracture surface, in which the characteristic step features associated with microbuckling of the fibre forming a kink band are clearly evident as described in most publications. There is also little reason to doubt that failure in general is by microbuckling and kinking of fibres because the characteristic kink band angle is similar to the fracture surface angle of test piece fragments (see Figure 3 (a)), though usually slightly larger. It is observed that the fibres break at two points, which create a band inclined at = 23 to the horizontal axis, where is defined in Figure 3 (b). Kink band starts at the free edge or locations of stress concentration such as a pre-existing material defect and load introduction, i.e. at the end of end tabs where the specimen emerges from the clamps. Then the band is propagated, keeping its direction.



(a) (b)

Figure 3 Typical failure mode (a) and SEM micrograph of fibre kinking (b) of unidirectional specimen (10mm 10mm 2mm - T800/924C)

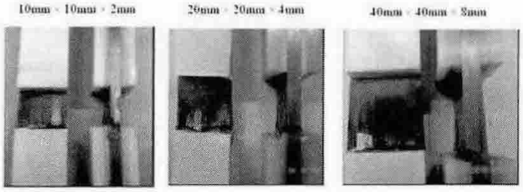


Figure 4 Typical failure mode of the unidirectional specimens with increasing specimen volumes(IM7/8552 system). Front view and side view are shown for different thicknesses

Table 3 average compressive strength of T800/924C and IM7/8552 unidirectional laminates

<table>
<tr><td>Material</td><td colspan="12">1-D tickness effect</td></tr>
<tr><td rowspan="3">T800/924C</td><td>Dimensions (mm)</td><td colspan="3">10×10×2</td><td colspan="3">10×10×3</td><td colspan="3">10×10×4</td><td colspan="3">10×10×8</td></tr>
<tr><td>Failure strength (MPa)</td><td colspan="3">1625</td><td colspan="3">1602</td><td colspan="3">1419</td><td colspan="3">1069</td></tr>
<tr><td>C.V.</td><td colspan="3">4.79</td><td colspan="3">7.08</td><td colspan="3">1.07</td><td colspan="3">2.32</td></tr>
<tr><td>Material</td><td colspan="13">3-D scaling effect</td></tr>
<tr><td rowspan="3">IM7/8552</td><td>Dimensions (mm)</td><td colspan="4">10×10×1</td><td colspan="4">20×20×4</td><td colspan="4">30×30×8</td></tr>
<tr><td>Failure strength (MPa)</td><td colspan="4">1570</td><td colspan="4">1253</td><td colspan="4">869</td></tr>
<tr><td>C.V.(%)</td><td colspan="4">4.51</td><td colspan="4">6.60</td><td colspan="4">6.03</td></tr>
</table>

From the post failure examination, failure combined with longitudinal splitting, fibre breakage and kinkband formation was observed in all size specimens of both materials (T800/924C and IM7/8552). The failure was located near the tab ends with part of the material ejected. This suggests that stress concentration may be partly responsible for the failure, Figure 4.

Table 3 presents the ultimate compressive failure strength according to the specimen thickness (T800/924C) and volumes (IM7/8552). The results show a sharp decrease in compression strength with increasing thickness and volumes for the unidirectional specimens. The strength of the T800/924C and IM7/8552 unidirectional laminates dropped by 36% and 45 % in going from 2mm to 8mm, respectively.

4. Prediction of Compressive Strength

The most frequently considered compressive failure modes in unidirectional laminates are fibre microbuckling and fibre kinking. On this basis, theoretical models analyse compressive failure using two major models, namely, the microbuckling model and the kink model. In the present study the fibre kink model (Budiansky model$^{6)}$ for compressive strength prediction based on an assumed initial fibre waviness and the in-plane shear characteristics of the composite was adopted. The predicted compressive strength is matrix dominated and intimately related to the in-plane shear stress-strain behaviour of the lamina and the initial fibre waviness. The longitudinal compressive strength is predicted as

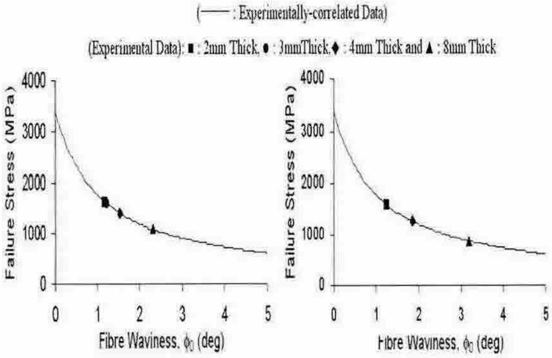
$$\sigma = \frac{\tau_y^*}{\phi_0 + \gamma_y} \tag{1}$$

where $_0$ is the initial fibre waviness angle in the kinkband, y is the yield shear strain and

$$\tau_y^* = \tau_y \left[1 + \left(\frac{\sigma_{T_y}}{\tau_y} \right)^2 tan^2 \beta \right]^{\frac{1}{2}} \tag{2}$$

Here y,Ty and are the in-plane shear yield strength, transverse yield strength and kinkband inclination angle of the composite, respectively. Using this relationship, one can predict the variation of compressive strength as a function of fibre waviness for the T800/924C and IM7/8552 materials investigated (see Figure 5).

The experimentally - correlated compressive strengths are compared with the measured experimental values in Figure 5. The measured 2mm thick compressive strength of 1625 MPa for T800/924C laminates and 1570 MPa for IM7/8552 laminates corresponds to an initial fibre waviness of 0 1.17 and 0 1.27, respectively. For the 8mm thick specimens, the measured compressive strengths of 1087 MPa for T800/924C system and 869 MPa for IM7/8552 system are in accord with an initial fibre waviness of 0 2.31 and 0 3.19, respectively. The average fibre misalignment measured in accordance with Yurgartis method varied from 0.90 to 1.90 with increasing specimen thickness of T800/924C (2mm to 8mm thick)[11].



(a) T800/924C unidirectioal laminests

(b) IM7/8552 unidirectioal laminests

Figure 5 Variation of longitudinal compressive strength with initial fibre waviness for a T800/924C unidirectional laminates (a) and IM7/8552 unidirectional laminates (b)

4. Concluding Remark

Existing test methods for compression data are designed for thin composite laminates (2m-3mm). The composite materials have a high ratio of compressive strength in the direction of the fibres to shear strength in the planes parallel to the fibres. For pure compressive loading transverse stresses are induced in the ends of the specimens due to Poisson deformation. Instability is also a problem and is exacerbated by the low out-of-plane shear modulus of the composite. All these problems with thicker composites become more serious and complicated. As the specimen gets thicker,a higher percentage of the load must be transmitted at the end, thus increasing the chances of premature failure such as end crushing.

In the present study, all the specimens failed at the gauge section, especially around the junction of end tab and gaugesection. Premature failure was successfully avoided during compression testing. Failure mode was similar regardless of increasing specimen thickness and specimen volume, i.e. brooming failure mode combined with longitudinal splitting, interlaminar cracking, fibre breakage and kinkband formation (fibre microbuckling).

Nevertheless, average failure strengths of the specimens decreased with increasing specimen thicnkiness from 2mm to 8mm with the T800/924C system (36% strength reduction) and specimen volumes from scaling factor 1 to scaling factor 4 with the IM7/8552 system (46% strength reduction). It was revealed from the extensive experimental study that the thickness effect and scaling effect are caused by manufacturing defects such as void content and fibre waviness[11].

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