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STRETCHING THE ENDURANCE BOUNDARY OF COMPOSITE MATERIALS: PUSHING THE PERFORMANCE LIMIT OF COMPOSITE STRUCTURES

Scaling effects in notched carbon fibre/epoxy composites loaded in compression

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Abstract The aim of the work was to develop an understanding of the failure mechanisms controlling the strength of composites of different dimensions and hence to be able to predict size effects in composite structures without resorting to empirical laws. Adequate models do not currently exist, and extensive testing is necessary, which is very costly. The ability to predict the effect of size on strength would be a major step forward, which would reduce costs and encourage the more widespread usage of these materials in the aerospace and other industries. In this article the effects of scaling (specimen size) on the strength of notched laminates are presented. The most important variables have been identified as hole (notch) size, ply and laminate thickness. Manufacturing defects and specimen design can also lead to premature failures, especially in unnotched laminates, but in laminates with an open hole are of less significance, since the notch dominates the fracture. The compressive strength results are compared to data obtained for the same composite system and laminate stacking sequences loaded in uniaxial tension.

Background

Large composite structures can give much lower strengths than small coupons, and so a proper understanding of scaling is vital for their safe and efficient use [1–3]. Small scale tests are commonly used to justify allowable stresses, but could be dangerous if results are extrapolated without accounting for scaling effects. On the other hand large factors are sometimes applied to compensate for uncertainties, resulting in overweight designs. A substantial amount of full size component and structural testing is currently required, which is very expensive (>£10 M for a typical aircraft, excluding the full scale test). Airworthiness authorities would be prepared to waive much testing if the analysis and prediction of failure was more reliable. This would result in lower cost, more reliable composite structures and encourage the more widespread usage of composite materials across the aerospace industry. Despite much research worldwide on failure, there are no methods capable of accurately predicting scaling effects in notched composites, and so a substantial amount of full size component and structural testing is currently required, which is very expensive. The present work has been performed in collaboration with Airbus, Dowty Propellers, Hexcel and the University of Bristol where the tensile properties of notched and unnotched laminates were investigated. The project focused on determining the effects of specimen dimensions on the unnotched and notched tensile and compressive strength of the IM7/8552 carbon fibre/epoxy composite system through a carefully designed experimental programme, identifying and understanding the different factors influencing strength as a function of specimen size and modelling the behaviour by analytical and finite element analyses [4–9]. Also, the stacking sequence effects on failure strength were examined using two different scaling techniques: sublaminate-level ($[45/90/-45/0]_{ns}$) and ply-level scaling ($[45_n/90_n/-45_n/0_n]_s$). The research has led to major advances in understanding of notched failure. Models developed at Bristol can successfully predict tensile scaling effects from fundamental, independently measured material properties and several conference and journal papers have been published or in progress [4–6]. In this article the

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compression results in the form of damage mechanisms and strength data are presented and discussed.

Experimental procedure

The specimens were fabricated from commercially available (Hexcel Composites Ltd.) carbon/epoxy pre-impregnated tapes 0.125 mm thick. The tapes were made of continuous intermediate modulus IM7 carbon fibres pre-impregnated with Hexcel 8552 epoxy resin (34 vol % resin content). The material was laid up by hand in 0.25 m × 0.3 m unidirectional plates $[0_4]_{ns}$ with $n = 2$, 3, 4 and 8 (i.e. 2, 3, 4 and 8 mm thick) and two generic quasi-isotropic lay-ups, one fabricated with blocked plies $[45_n/90_n/–45_n/0_n]_s$ and the other with distributed plies $[45/90/–45/0]_{ns}$ with $n = 2$, 4 and 8. This helped to gain an insight into the efficiency of 0° plies when employed in multidirectional laminates under uniaxial compression and investigate the effect of open holes on strength. The basic in-plane stiffness and strength of the IM7/8552 unidirectional laminate under tensile and compressive loading provided by the materials manufacturer, Hexel Composites Ltd., are presented in Table 1. For the unnotched multidirectional laminates the baseline specimen dimensions are based on those recommended by Airbus Industry Test method (AITM) [10], i.e. 30 mm × 30 mm × 2 mm in gauge width × gauge length × thickness. The specimen dimensions were increased by a scaling factor of 2 and 4. For open hole multidirectional specimens, a hole with the same diameter (a) to width (W) ratio, a/W = 0.2, was drilled at the centre of each specimen using tungsten carbide for a 6.35-mm hole diameter and hollow diamond drill bits for a 12.7-mm and 25.4-mm hole diameter to minimise fibre damage and delamination at the hole boundary. Three different types of scaling were used for open hole specimens, see Table 2: one-dimensional (1-D), where only the thickness is scaled from 2 mm to 4 mm and from 4 mm to 8 mm, two-dimensional (2-D), where the in-plane dimensions (hole diameter and gauge length and width) are scaled keeping the same a/W ratio (=0.2) and three-dimensional (3-D), where all dimensions of the baseline specimen are increased by a scaling factor of 2 and 4.

All specimens (notched and unnotched) were tested on a 1,000 kN servo-hydraulic machine at a constant compression rate of 1 mm/min. An anti-buckling device was used for the thinner or longer specimens to prevent Euler buckling failure [9].

Compressive strength results

In order to meet the overall objectives, obtaining reliable experimental results is vital. Careful experimental work with various specimen sizes was carried out using a specially designed fixture [8, 9] for the unidirectional and multidirectional specimens. Based on these experimental results, the scaling effects on compressive strength of unnotched and notched composites are presented. The factors causing the scaling effects are explained through closed form analysis, appropriate fracture models and the comparison of measured experimental data.

Unnotched unidirectional (UD) strength

The stress–strain curves obtained for all unidirectional IM7/8552 specimens showed similar behaviour, which was essentially linear up to a strain level of ≈0.5%. Thereafter, the material exhibited some non-linearity with a softening that increased with increasing applied load (failure strain ≈1%). The axial modulus, determined at 0.25% applied strain, was little influenced by specimen size. Optical

Table 1 Stiffness and strength properties for the IM7/8552 composite system

	E_{11}, GPa	E_{22}, GPa	G_{12}, GPa	ν_{12}	$\sigma_{11T}/\sigma_{11C}$ MPa	$\sigma_{22T}/\sigma_{22C}$ MPa	τ_{12}, MPa
Value	150	11	4.6	0.3	2,400/1,690	111/250	120

($\sigma_{11T}/\sigma_{11C}$ are longitudinal tensile and compressive strength, $\sigma_{22T}/\sigma_{22C}$ are transverse tensile and compressive strength and τ_{12} is in-plane shear strength)

Table 2 Compression test programme for the notched MD specimens

Material	Lay-up (QI)	Specimen thickness/mm	Hole diameter (a)/mm		
IM7/8552 Ply thickness: 0.125 mm	$[45/90/–45/0]_{ns}$/ $[45_n/90_n/–45_n/0_n]_s$	2	6.35	–	–
		4	6.35	12.7	25.4
		8	–	–	25.4
Specimen gauge length × Width (W)/mm			32 × 32	64 × 64	128 × 128
a/W			0.2	0.2	0.2
Tab length/mm			50	50	50

Notes: Number of tested specimens = 6, End-tab material: Woven glass fibre-epoxy reinforcement

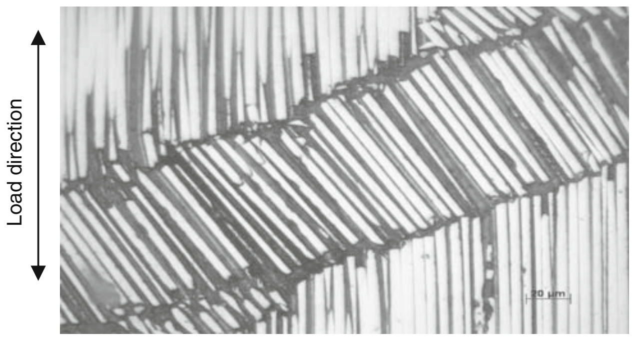

Fig. 1 Optical micrograph showing fibre microbuckling observed in the 0° plies (5.6-μm fibre diameter)

microscopy studies revealed that ultimate failure of the UD specimens was due to fibre microbuckling, Fig. 1, which is considered as a fibre instability failure mode [11–13]. In most specimens and especially the thicker ones, final fracture was located near the line where the end tab terminates and the gauge section begins, suggesting that the high-local stresses developed due to geometric discontinuity can contribute to premature failure, resulting into lower compressive strengths [9]. The results showed a sharp decrease in compressive strength with increasing thickness and volume. The average strength of the IM7/8552 unidirectional laminate dropped by 45% in going from a 2 mm (1,570 MPa) to 8 mm (869 MPa) thick specimen. Previous published work by the authors [7–9] demonstrated that the 4-mm (32-ply) and 8-mm thick (64-ply) specimens failed prematurely, due to end-tab-induced stress concentrations in addition to reduced fibre volume fraction, increased ply waviness, fibre misalignment and increased void content that may occur with increasing specimen thickness. It may not be possible to achieve the same compaction, removal of voids or cure uniformity for the thicker laminates (≥8 mm). The unidirectional tensile strength of the IM7/8552 carbon/epoxy system was reduced from 2,806 MPa for 30 mm × 5 mm × 0.5 mm specimens to 2,410 MPa for 240 mm × 40 mm × 4 mm [5, 6].

Unnotched multidirectional strength

The strength results for all volumes as presented in Table 3 were valid and reproducible. All specimens regardless of specimen volume and scaling technique failed within the gauge length. Table 3 shows the ultimate compressive strength according to the different specimen volumes for the multidirectional specimens of both stacking sequences. The average failure strength values of the specimens using the sublaminate-level scaling technique ($[45/90/–45/0]_{ns}$) are very similar regardless of the specimen size, indicating that no significant scaling effect exists, Fig. 2a. The strengths of the multidirectional specimens using the ply-level scaling technique ($[45_n/90_n/–45_n/0_n]_s$) differ very little up to 4 mm, considering the scatter in the results. However the 8-mm thick specimen's average strength is significantly lower than that of thinner specimens (drops about 29% in going from 2 mm to 8 mm) due to matrix cracking introduced by thermal stresses during the specimen cutting process, Fig. 2b. It was identified from X-ray radiography that cracks parallel to fibres at 45° and 90° plies emerged in the specimens after cutting the plates to specimen size, Fig. 3. The overall failure mode was that of edge delamination rather than fibre microbuckling. Finite element results demonstrated that in the 8-mm thick specimens edge delamination is expected at around 440 MPa, which is close to the measured strength [4].

Table 3 Unnotched average compressive strength of IM7/8552 quasi-isotropic scaled specimens

Unnotched compressive strength/MPa		
Dimensions/mm	$[45/90/–45/0]_{ns}$	$[45_n/90_n/–45_n/0_n]_s$
30 × 30 × 2	658 (3.15)	666 (19.6)
60 × 60 × 4	675 (6.6)	642 (19.0)
120 × 120 × 8	644 (14.0)	472 (13.4)

(): Coefficient of variation, %

The tensile strength of IM7/8552 unnotched quasi-isotropic laminates showed either a 46% decrease or 10% increase depending on whether the plies were blocked together or interleaved when changing the thickness, Fig. 2a and b. This highlights the crucial effect of ply block thickness. The strength of the ply-level scaled specimens dropped

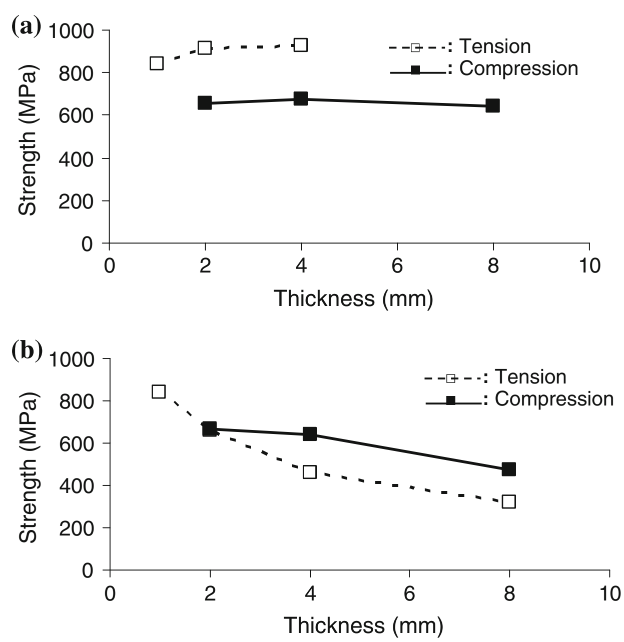

Fig. 2 (**a**) Average unnotched compressive and tensile strengths of the sublaminate-level scaled $[45/90/-45/0]_{ns}$ specimens. (**b**) Average unnotched compressive and tensile strengths of the ply-level scaled $[45_n/90_n/-45_n/0_n]_s$ specimens

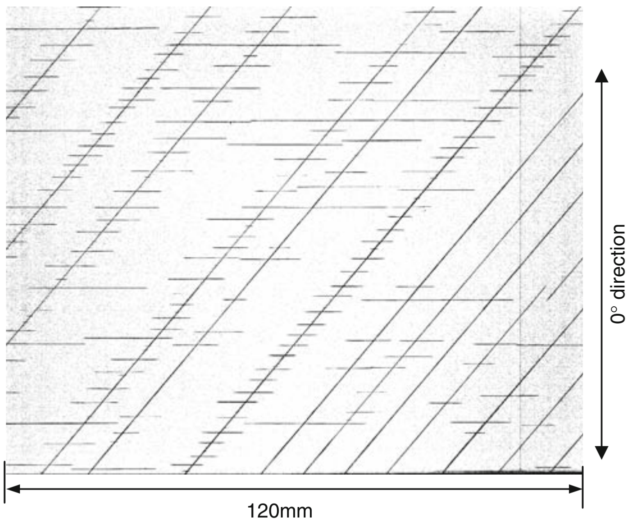

Fig. 3 X-ray radiograph of an 8-mm thick IM7/8552 $[45_8/90_8/\text{-}45_8/0_8]_s$ specimen before compressive testing. Extensive matrix cracking due to thermal stresses is shown

from 842 MPa for 30 × 8 × 1 mm to 458 MPa for 240 × 64 × 8 mm specimens (a 46% reduction), Fig. 2b. The 2 mm and thicker ones all failed by delamination, with the large drop in strength as a result of the greater energy available due to the thicker ply blocks [5, 6]. The strength of the sublaminate-scaled specimens increased in strength from 842 MPa for the baseline 30 × 8 × 1 mm up to 929 MPa for 120 × 32 × 4 mm specimens (a 10% increase), Fig. 2a. This was due to earlier failure initiation in the surface layers having a greater effect in the thinner specimens. None of the specimens attained the strength that would be predicted from existing theories based on the unidirectional tests because of failure initiating due to free edge effects [5, 6].

Notched multidirectional strength

Effect of thickness on open hole specimens

The average compressive strengths of the 32 mm × 32 mm specimens obtained from both scaling techniques (sublaminate-level $[45/90/–45/0]_{ns}$ and ply-level scaled technique $[45_n/90_n/–45_n/0_n]_s$) increase with increasing specimen thickness, Table 4. This can be explained by considering the specimen stability and the damage development at the hole edge. The stability issue in the 32 mm × 32 mm specimens was examined by studying the local stress–strain behaviour of the 2-mm and 4-mm thick specimens. Back-to-back strain gauges were attached near the hole boundary and revealed that although an anti-buckling device was employed, the strain gauge readings indicated out-of-plane bending that increased with increasing applied load, in the window area of the anti-buckling device [8, 9]. This bending of the 2-mm thick specimen also significantly influences initial failure

Table 4 Notched average compressive strength results for IM7/8552 quasi-isotropic scaled specimens

Notched compressive strength/MPa (a/W = 0.2)			
Dimensions (mm)	Hole size (mm)	$[45/90/–45/0]_{ns}$	$[45_n/90_n/–45_n/0_n]_s$
32 × 32 × 2	6.35	338	373
32 × 32 × 4	6.35	351	424
64 × 64 × 4	12.7	300	348
128 × 128 × 4	25.4	285	288
128 × 128 × 8	25.4	284	263

Notes: Coefficient of variation = 5–8%

that occurs at the hole edge and hence ultimate fracture. The back-to-back strain gauge readings for the 4-mm thick specimen were almost the same until initial failure such as matrix cracking, delamination and fibre breakage at the hole edge occurred; final failure of the specimen was not influenced by Euler bending. In the ply-level scaled specimens the increased notched strength observed in the 32 mm × 32 mm × 4 mm specimens is due to axial splitting (local damage) that occurs near the edge of the hole prior to fibre microbuckling. This causes stress redistribution that leads to an increased failure load. For the larger size specimens presented in Table 4 the fracture and ultimate strength is influenced by the hole size rather than laminate thickness, see section "Effect of in-plane size on open hole specimens".

In tension large sublaminate-scaled specimens showed a brittle failure across the width, whereas small ones failed with significant pullout between the plies; there was little influence of thickness except for the 1-mm thick specimens, which were stronger. Most of the ply-level scaled specimens failed by delamination, with a significant strength reduction with thickness, as for the unnotched case [5, 6].

Effect of in-plane size on open hole specimens

The in-plane dimensions (hole diameter and gauge section length and width) were scaled keeping the same thickness (4 mm) and a/W ratio (hole diameter/width, a/W = 0.2). The average strengths obtained from both stacking sequences decreased with increasing hole size or specimen width, i.e. 19% reduction (ply thickness = 0.125 mm) in unblocked specimens and 32% reduction in blocked specimens, Fig. 4. This strength reduction could be attributed to hole-size effect in a finite width specimen. The values predicted by the cohesive zone model [13–15] were in good agreement with the measured failure strengths (less than 10% difference). The presence of the hole rather than fibre or other imperfections dominates the fracture process [16]. Under tensile loading in-plane scaling with dispersed plies showed the expected hole-size effect, Fig. 5a, whilst

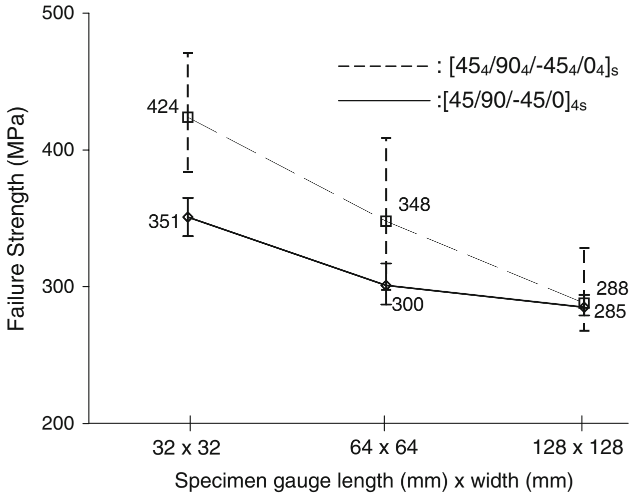

Fig. 4 Average compressive strength of 4-mm thick open hole specimens (a/w = 0.2) as a function of gauge section size for IM7/8552 $[45/90/-45/0]_{4s}$ and $[45_4/90_4/-45_4/0_4]_s$ laminates

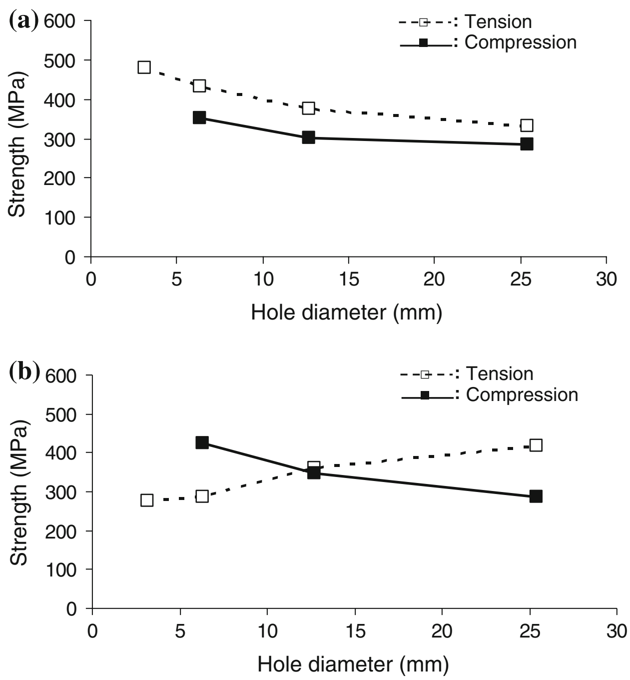

Fig. 5 (**a**) Hole-size effect: average notched compressive and tensile strengths of the sublaminate-level scaled $[45/90/-45/0]_{4s}$ specimens (laminate thickness 4 mm) (**b**) Hole-size effect: average notched compressive and tensile strengths of the ply-level scaled $[45_4/90_4/-45_4/0_4]_s$ specimens (laminate thickness 4 mm)

scaling of specimens with blocked plies showed a surprising increase in strength with hole size that has not previously been reported, Fig. 5b. In Fig. 5a and b the notched compression and tension results are presented for comparison; it can be seen that the IM7/8552 quasi-isotropic laminates with an open hole are stronger in tension than when loaded in compression and the notch has a lesser effect when the plies in the laminate are blocked.

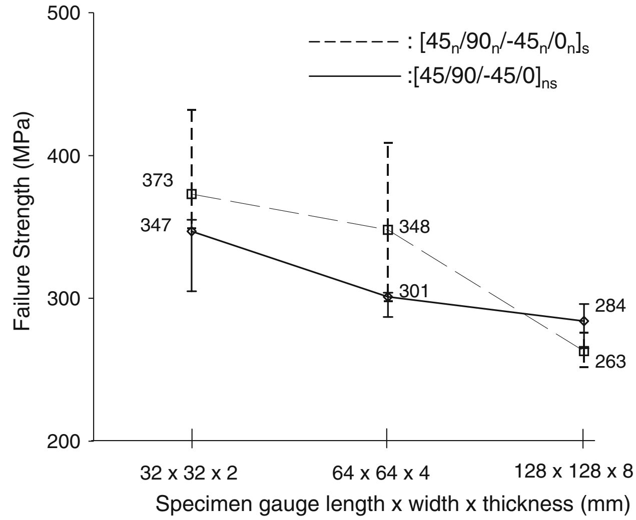

Fig. 6 Average open hole compressive strength as a function of specimen volume for IM7/8552 $[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$ laminates (a/w = 0.2)

Three-dimensional scaling effects

The 3-D scaling effects were investigated, where all specimen dimensions are increased by a scaling factor of 1, 2 and 4. The average strengths decrease with increasing specimen volume up to 16% in the sublaminate-level scaled specimens ($[45/90/–45/0]_{ns}$) and up to 30% in the ply-level scaled specimens ($[45_n/90_n/–45_n/0_n]_s$), Fig. 6. The reduction rate in the failure strength, however, is very similar to the rate of the 2-D in-plane size effects. It could, therefore, be considered that the notched strength reduction with increasing specimen volume is caused by 2-D in-plane size effects (hole-size effect) rather than 3-D scaling effects.

Stacking sequence effects

Figure 6 shows that the open hole compressive strength values obtained from the ply-level scaled specimens are higher than those obtained for the sublaminate-level scaled specimens. This result is attributed to stress redistribution that occurs due to local damage around the hole. The ply-level scaled specimens developed local damage around the open hole at a lower applied compressive load than the sublaminate-level scaled specimens [16]. Fibre/matrix splitting was observed in the ply-level scaled specimens at an applied load of 42.8kN (75% of failure load) whilst in the sublaminate-level scaled specimens no damage was present. This local damage delays the final failure to a higher applied load since the stress concentration factor at the edge of the hole is reduced and stress is redistributed. For the 4-mm thick open hole specimen with a 12.8-mm hole diameter, Fig. 6, the predicted fracture toughness by the Soutis et al. fracture model [13, 14] for ply-level scaled and sublaminate-level scaled specimens was 55 MPa $m^{1/2}$ and 42 MPa $m^{1/2}$, respectively. This implies that the blocked lay-up is less notch sensitive (i.e. more damage tolerant) than the sublaminate-level scaled one.

Concluding remarks

An apparent scaling effect existed in the UD specimens ($[0_4]_{ns}$) with a 46% strength reduction in going from small to large size (scaling factor 1–4). This is explained by the effect of tab-induced stress concentrations in addition to reduced fibre volume fraction, increased ply waviness, fibre misalignment and increased void content that may occur with increasing specimen thickness. In the ply-level scaled MD specimens ($[45_n/90_n/–45_n/0_n]_{s}$), a trend, which is the unnotched strength reduction with increasing specimen volume was shown. This is attributed to the blocked 0° ply thickness (increase of fibre waviness and void content), free edge effect and residual thermal stresses. Also, in the 8-mm thick laminate the failure mode changed from fibre microbuckling to edge delamination. However, the compressive strength of the sublaminate-level scaled specimens ($[45/90/–45/0]_{ns}$) was unaffected regardless of the specimen thickness and volume (0° plies evenly distributed in the laminate) and the parameters such as fibre volume fraction, void content and fibre waviness, were not influenced by the specimen size. In the open hole specimens, it was identified that there were not 1-D thickness effects in both stacking sequences but local buckling in thinner specimens that may occur inside the anti-buckling device can lead to premature failure. For 2-D in-plane size effects, the average strengths obtained from both stacking sequences decreased with increasing hole size, i.e. 19% reduction in sublaminate-level scaled specimens and 32% reduction in ply-level scaled specimens. However, there was no 3-D scaling effect in open hole specimens. The actual open hole compressive strength values of the ply-level scaled specimens were higher than those measured for the sublaminate-level scaled specimens. This result was caused by stress redistribution due to local damage in the form of axial splitting around the hole leading to a higher failure load. Finally the measured strengths for both stacking sequences agreed well with the results predicted by the cohesive zone model [13, 14]; the predicted fracture toughness of ply-level scaled laminate was 55 MPa $m^{1/2}$, whilst the sublaminate-level scaled specimens showed a lower value of 42 MPa $m^{1/2}$ [16]. The notched and unnotched compressive strengths of the IM7/8552 laminates are lower than those under tensile loading due to fibre microbuckling that occurs in the 0° plies, which is considered as a fibre instability failure mode. Only the unnotched tensile strength of the 4 mm and 8 mm ply-level scaled specimens are lower due to edge delamination that is triggered at a lower applied load [5, 6]. Further work is required to study the effect of residual thermal stresses especially in the thick (≥8 mm) multidirectional blocked lay-up.

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