SPECIMEN SIZE EFFECTS ON THE NOTCH SENSITIVITY OF COMPOSITE LAMINATES LOADED IN COMPRESSION

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Abstract

The most important variables for scaling effects on the strength of notched composites from the experimental tests have been identified as notch size, and ply and laminate thickness. These have been scaled both independently and simultaneously over as large a range as possible. The specimens are fabricated from commercially available (Hexcel Composites Ltd.) carbon/epoxy pre-impregnated tapes 0.125mm thick (IM7/8552). The material is laid up by hand in 0.25 m x 0.3 m unidirectional plates $[0_4]_{ns}$ with n = 2, 3, 4, and 8 (i.e., 2, 3, 4 and 8mm thick) and two quasi-isotropic lay-ups, one fabricated with blocked plies $[45_n/90_n/\text{-}45_n/0_n]_s$ and the other with distributed plies $[45/90/\text{-}45/0]_{ns}$ with n=2, 4 and 8. It is shown that the critical failure mechanism is in the form of fibre microbuckling or kinking and that the unidirectional compressive strength in thicker specimens (>2 mm) is found to be limited by the stress concentration developed at the end tabs and manufacturing induced defects in the form of ply waviness, fibre misalignment and voids. An scaling effect existed in the unidirectional specimens ($[0_4]_{ns}$ - scaling factor 1 to 4) and 2-dimensionally (in-plane size) scaled multidirectional open hole specimen. The notched compressive strength results obtained are compared to a simple cohesive zone fracture model for the prediction of notched strength to assess its applicability.

1 Introduction

Large fibre reinforced composite structures can give much lower strengths than small test specimens, and so a proper understanding of scaling is vital for their safe and efficient use. Small size (scale) specimens are commonly tested 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 (>£10M 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.

The aim of current research work is to develop an understanding of the failure mechanisms (that occur at microscopic level) 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, that would reduce costs and increase the reliability of composite structures and encourage the more widespread usage of these materials in the aerospace and other industries.

2 Materials and Lay-ups

The specimens were fabricated from commercially available (Hexcel Composites Ltd.) carbon/epoxy pre-impregnated tapes 0.125mm 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 x 0.3 m unidirectional (UD) plates $[0_4]_{ns}$ with n = 2, 3, 4, and 8 (i.e., 2, 3, 4 and 8mm thick). In addition, two quasi-isotropic lay-ups (MD) were fabricated, one with blocked plies $[45_n/90_n/\text{-}45_n/0_n]_s$ and the other with distributed plies $[45/90/\text{-}45/0]_{ns}$ with n=2, 4 and 8 in order to gain an insight into the efficiency of 0° plies when employed in multidirectional laminates under uniaxial compression. The standard cure cycle recommended by Hexcel Composites Ltd was used for the thinner laminates, less than 4mm thick. The thicker laminates had to dwell in the autoclave for a longer period of time to allow even heat distribution throughout the panel and diminish the possibility of an exothermic reaction (heat energy that causes uncontrollable temperature rise within thick laminates). Thicker prepreg (0.25mm) were also manufactured by pressing two thinner pre-pregs (0.125mm) of the IM7/8552 system. Laminates 2mm, 4mm, 8mm and 16mm thick with the ply-level scaled stacking sequence $[45/90/-45/0]_{ns}$ (n = 1, 2, 4 and 8) were fabricated.

3 Test Programme

i) *Unnotched UD specimens* The baseline specimen dimensions are based on those recommended by Imperial College Standard Test method (ICSTM)[1], i.e. 10mm x 10mm x 2mm in gauge length x width x thickness. The size was increased by a factor of 2 and 4.

ii) *Unnotched MD specimens* The baseline specimen dimensions are based on those recommended by Airbus Industry Test method (AITM)[2], i.e. 30mm x 30mm x 2mm in gauge width x gauge length x thickness. The specimen dimensions were increased by a scaling factor of 2 and 4. For thicker ply specimens (ply thickness = 0.25mm), two baseline specimen dimensions were used with 16mm x 16mm x 2mm and 30mm x 30mm x 2mm in gauge length x width x thickness and increased by a scaling factor of 2 and 4.

iii) *Notched MD specimens* For open hole 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 6.35mm hole diameter and hollow diamond drill bits for a 12.7mm and 25.4mm hole diameter to minimise fibre damage and delamination at the hole boundary. Penetrant enhanced X-ray radiography was used to inspect the quality of drilling. No damage around the hole edge were found due to drilling process. Three different types of scaling are used for open hole specimens for thinner ply specimens and thicker ply specimens, see Table 1: one-dimensional, where only the thickness is scaled from 2mm to 4mm & from 4mm to 8mm,two-dimensional, where the in-plane dimensions (hole diameter and gauge length and width) are scaled keeping the same a/W ratio (hole diameter/width, a/W=0.2) and three-dimensional, where all specimen dimensions are increased by a scaling factor of 1, 2 and 4.

4 Experimental Results and Discussion

Carefully thought experimental work with various specimen sizes as described in Section 3 was carried out using the ICSTM fixture[1] for the unidirectional and multidirectional specimens. Based on these experimental results, the scaling effects on compressive strength of unnotched and notched composites are first presented. The factors causing the scaling effects are explained through closed form analysis, finite element analysis, appropriate fracture models and the comparison of published experimental data.

4.1 Unnotched UD Specimens

Initial compression tests on unidirectional specimens with relatively thin end tabs showed that failure occurred within the tabbed region, resulting in relatively lower compressive strengths (20-30% lower than expected). It appears that damage initiated on the end of the specimen at the load introduction point and propagated down the length

Table 1 Compression test programme for the notched MD specimens (ply thickness: 0.125mm and 0.25mm)

Material	Lay-up (QI)	Specimen Thickness/mm	Hole Diameter (a)/mm		
IM7/8552 Ply thickness: 0.125mm/0.25mm	$[45/90/-45/0]_{ns}$/ $[45_n/90_n/-45_n/0_n]_s$	2	6.35 $^{*\,1,2}$	-	-
		4	6.35 ^{1,2}	12.7 $^{*\,1,2}$	25.4 $^{*\,1,2}$
		8	-	12.7 $^{*\,2}$	25.4 $^{*\,1}$
		16	6.35 ^{2}	12.7 $^{*\,2}$	25.4 $^{*\,2}$
Specimen Width (W) × Gauge Length/mm			31.8 × 31.8	63.5 × 63.5	127 × 127
a/W			0.2	0.2	0.2
Tab Length*/mm			50	50	50

(Number of tested specimens = 6, End-tab material: Woven glass fibre-epoxy reinforcement, *: Anti-buckling device, ^{1}: thinner ply specimens (0.125mm), ^{2}: thicker pre-preg specimens (0.25mm)) and across the width of the specimen. As a result of these findings, 'compression in tab' type failure, the tab thickness was increased substantially (at least end tab thickness ≥ specimen thickness); the following results reported here are for such specimens. Representative stress-strain curves of 2mm (plot A), 4mm (plot B) and 8mm (plot C) thick unidirectional IM7/8552 specimens obtained at the centre of each specimen from back-to-back strain gauges are shown in Figure 1. Plots B for the 4 mm thick (32-ply) specimen and C for the 8 mm thick (64-ply) 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 exhibits some non-linearity with a softening that increases with increasing applied load. The axial compressive modulus was determined at 0.25 % applied strain. The stress-strain curves illustrate that the axial modulus is little influenced by specimen size.

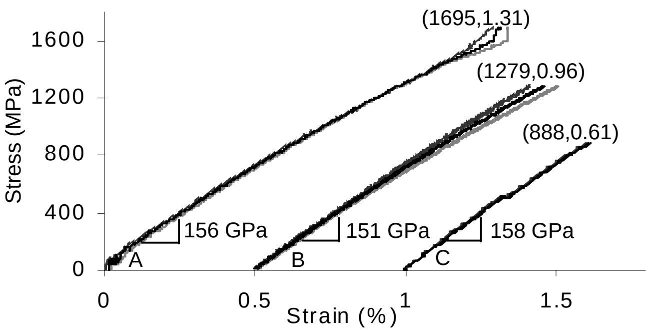

Fig.1. Typical stress-strain curves of the IM7/8552 unidirectional specimens obtained from back-to-back strain gauges (A: 10mm × 10mm × 2mm, B: 20mm × 20mm × 4mm and C: 40mm × 40mm × 8mm.)

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 contribute to premature failure and hence reduced compressive strength. A three-dimensional finite element stress analysis shows that a 4 mm thick end tab would produce a stress concentration of approximately 1.7, explaining partly the premature failure of the thicker specimens. Using a thinner tab would cause a less sever discontinuity and reduced stress concentration factor (SCF) but wouldn't be stiff enough to transfer the compressive load effectively on thick specimens leading to compression failure under the tab. The results show 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 (1570 MPa) to 8 mm (869 MPa) thick specimen see Figure 2. It should be noted that the 4 mm and 8 mm thick specimens still failed prematurely, but this is explained by the effect of 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[1]. In the effort to quantify the tab effect and avoid near grip failures, three 8 mm thick unidirectional specimens with a waisted gauge section were tested. They had a gauge section of 20 mm x 40 mm and a reduced thickness of 5.5 mm. Overall fracture occurred almost in the middle of the gauge section in the form of fibre breakage and axial splitting. Although this can be considered as a successful test with a valid failure mode (away from the end tabs) the average compressive strength of 1118 MPa (22% higher than the value reported for the plain 8 mm thick test piece) is at least 30% lower than the average strength measured for the standard 10 mm x 10 mm x 2 mm specimen (1570 MPa), suggesting that the thickness and other related factors are affecting its ultimate strength. It may not be possible to achieve the same compaction, removal of voids or cure uniformity for the thick laminates compared with the thinner ones. The need to avoid overheating due to the exothermic cure is well recognized and documented.

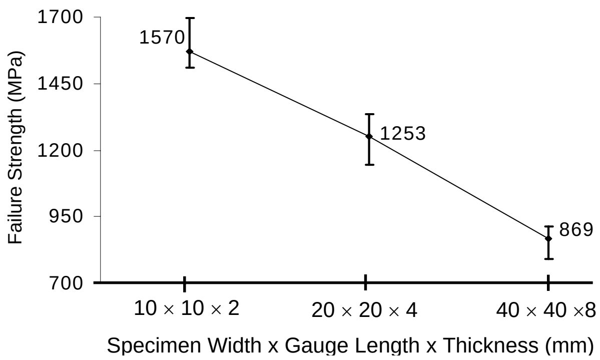

Fig.2. Average UD compressive strength as a function of specimen volume (IM7/8552).

4.2 Unnotched MD Specimens

The strength results for all volumes as presented in Table 2 were valid and reproducible. All specimens regardless of specimen volume and scaling technique failed within the gauge length. Table 2 shows the ultimate compressive strength according to the different specimen volumes for the multidirectional thinner ply 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. 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 4mm, considering the scatter in the results. However the 8mm thick specimen's average strength is significantly lower than that of thinner specimens (drops about 29 % in going from 2mm to 8mm) due to matrix cracking introduced by thermal stress during the specimen cutting process. 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. 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.

(i) _1-D Thickness effect:_ The average strengths 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 except for the 8mm thick ply-level scaled specimens, $[45_8/90_8/-45_8/0_8]_s$, where matrix cracks exist in the specimens before testing, see Figure 3. This can be explained by considering the specimen stability and the damage development at the hole edge. The stability issue in the 32 mm x 32 mm specimens was examined by studying the local stress-strain behaviour of the 2mm and 4mm 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. This bending of the 2mm thick specimen also significantly influences initial failure 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;

Table 2 Unnotched average compressive strength obtained from the sublaminate level scaled specimens ($[45/90/-45/0]_{ns}$) and ply level scaled specimens ($[45_n/90_n/-45_n/0_n]_s$) (ply thickness: 0.125mm and 0.25mm)

Ply thickness: 0.125mm			Ply thickness: 0.25mm		
Specimen dimensions	$[45/90/-45/0]_{ns}$	$[45_n/90_n/-45_n/0_n]_s$	$[45/90/-45/0]_{ns}$	Specimen dimensions	$[45/90/-45/0]_{ns}$
30 x 30 x 2	658 MPa (3.15)	666 MPa (19.6)	655 MPa (2.03)	16 x 16 x 2	588 MPa (8.71)
60 x 60 x 4	675 MPa (6.6)	642 MPa (19.0)	588 MPa (4.36)	32 x 32 x 4	603 MPa (1.73)
120 x 120 x 8	644 MPa (14.0)	472 MPa (13.4)	-	64 x 64 x 8	541 MPa (4.9)

(Specimen dimensions: specimen width x gauge length x thickness (mm), ( ): Coefficient variation, %)

For specimens fabricated with the thicker pre-preg (0.25mm), the average failure strengths (Table 2) are unexpectedly lower than the strengths of specimens made from thinner pre-preg (ply thickness: 0.125mm). Through optical microscopy it was confirmed that this was caused due to manufacturing defects. The thicker prepreg (0.25mm) was manufactured by squeezing two thinner plies (0.125mm) and during this process the fibres and layers were seriously misaligned/undulated. Such defects are less evident in the thinner prepreg specimens.

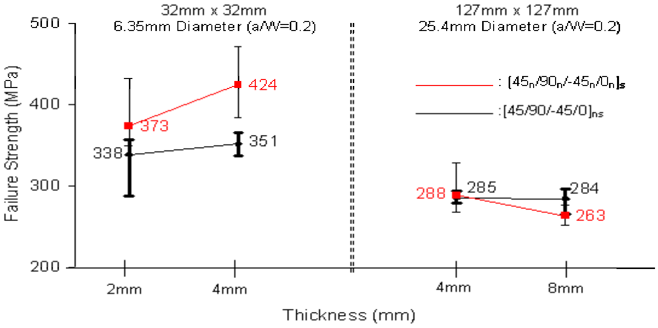

Figure 3. Average strength of open hole specimens as a function of thickness for IM7/8552 multidirectional laminates ($[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$).

4.3 Notched MD Specimens

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 x 32 mm x 4 mm specimens is due to axial splitting (local damage) that occurs near the edge of the hole. This causes stress redistribution and increased failure load.

(ii) *2-D in-plane size effect of IM7/8552 open hole specimens:* The in-plane dimensions (hole diameter and gauge section length and width) were scaled keeping the same thickness (4mm) and a/W ratio (hole diameter/width, a/W=0.2), see Table 1. The average strengths obtained from both stacking sequences decreased with increasing hole size or specimen width, i.e. 19% reduction (ply thickness: 0.125mm) and 22% reduction (ply thickness: 0.25mm) in unblocked specimens and 32% reduction in blocked specimens, Figure 4.

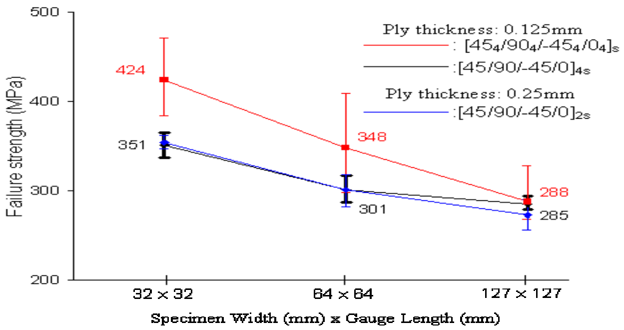

Figure 4. Average strength of 4mm thick open hole specimens as a function of gauge section size for IM7/8552 laminates ($[45/90/-45/0]_{4s}$, $[45/90/-45/0]_{2s}$ and $[45_4/90_4/-45_4/0_4]_s$).

This strength reduction could be attributed to hole size effect in a finite width specimen. Even though stress concentration factors are the same at the hole edge due to the same a/w ratio, the overall stress distribution across the specimen width is dependent on the hole size, i.e. specimens with a larger hole experience higher stress that may cause failure at lower applied loads. The values predicted by the cohesive zone model[12] were in good agreement with the measured failure strengths (675 MPa) and predicted fracture toughness[3] (42 MPa $m^{1/2}$) of 4mm thick sublaminate-level scaled specimens, showing width effects in the same a/W ratio, Figure 5. The presence of the hole rather than fibre or other imperfections dominates the fracture process.

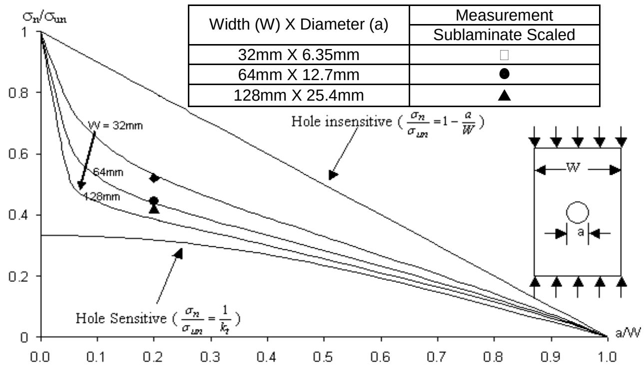

Figure 5. Hole size and width effects on the compressive strength of an IM7/8552 – $[45/90/-45/0]_{ns}$ laminate.

(iii) *3-D scaling effects:* 3-D scaling effects were investigated, where all specimen dimensions are increased by a scaling factor of 1, 2 and 4, see Table 1. 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 ($[45_n/90_n/-45_n/0_n]_s$), see Figure 6.

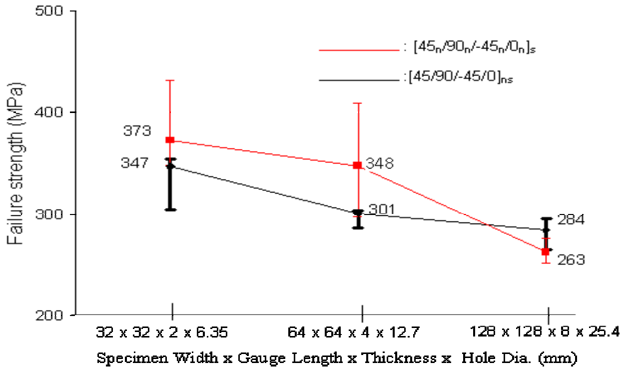

Figure 6. Average open hole strength as a function of specimen volume for $[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$ IM7/8552 laminates.

The reduction rate in the failure strength, however, is very similar to the rate of the 2-D in-plane size effects (up to 19% reduction in the sublaminate level scaled specimens and up to 32% reduction in the ply level scaled specimen). In addition, it was identified that there is no thickness effect. It could, therefore, be considered that the strength reduction with increasing specimen volume is caused by 2-D in-plane size effects rather than 3-D scaling effects.

(iv) *Stacking sequence effects ($[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$):* Figures 4 and 6 show 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 could be attributed to stress redistribution that

85% of failure load 98% of failure load

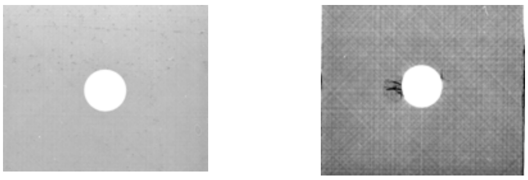

Fig. 7 (a) Average failure load: 47.5kN, Hole diameter = 6.35mm - $[45/90/-45/0]_{4s}$

75% of failure load 98% of failure load

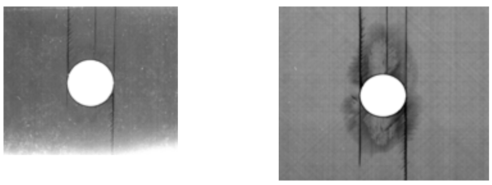

Fig. 7(b) Average failure load: 54.3kN a = 6.35mm - $[45_4/90_4/-45_4/0_4]_s$

occurs due to local damage near the hole, Fig.7.

The ply-level scaled specimens developed local damage around the open hole at a lower applied compressive load than the sublaminate-level scaled specimens. In Figure 7 (b), fibre/matrix splitting developed in the ply-level scaled specimens at an applied load of 42.8kN (75% of failure load) while in the sublaminate-level scaled specimens (Figure 7 (a)) no damage is present. This local damage delays the final failure to a higher applied load since the stress concentration factor at the edge of hole is reduced and stress is redistributed in the specimen. If the local damage does not occur or occur just prior to the catastrophic failure, the composite material behaviour is closer to ideal brittle behaviour, resulting in a lower failure load. Furthermore, the local damage enhances the fracture toughness of the laminate. For the 4mm thick open hole specimen with a 6.35mm hole diameter, the predicted fracture toughness[3] for ply level scaled and sublaminate level scaled specimens was 63 MPa $m^{1/2}$ and 42 MPa $m^{1/2}$, respectively. This implies that the blocked lay-up is less notch sensitive than the sublaminate-level scaled laminate.

5. Concluding Remarks

In the unnotched specimens, the scaling effects observed are due to the laminate stacking sequence, i.e. the thickness of the blocked 0° plies in the composite laminates affect the initiation, propagation and ultimate failure. An apparent scaling effect existed in the unidirectional specimens ($[0_4]_{ns}$) with 46% strength reduction in going from small to large size specimen (scaling factor 1 to 4) . This could be 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 multidirectional specimens ($[45_n/90_n/-45_n/0_n]_s$), a trend, which is the unnotched strength reduction with increasing specimen volume was shown. The trend could be attributed to the blocked 0° ply thickness (small 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 (that can be influenced by the presence of matrix cracking). 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 that may occur inside the anti-buckling device could lead to premature failure and hence reduced strengths. For 2-D in-plane size effects, the average strengths obtained from both stacking sequences decreased with increasing hole size or specimen width due to open hole size in a finite specimen width, i.e. 19% reduction in sublaminate level scaled (unblocked) specimens and 32% reduction in ply-level scaled (blocked) specimens. However, there was no 3-D scaling effect in open hole specimens. Even though there is strength reduction with increasing specimen volume, the strength reduction rate was almost the same as the reduction rate in the 2-D in-plane size change. In addition, the open hole compressive strength values obtained from the ply-level scaled specimens were higher than those obtained from 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[3,4]; the predicted average fracture toughness (based on measured notched strength) of ply-level scaled laminate was 55 MPa $m^{1/2}$ while the sublaminate-level scaled specimens showed a lower value of 41 MPa $m^{1/2}$.

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