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Abstract: Large fibre reinforced composite structures can give much lower strengths than small test specimens, 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. The most important variables of scaling effects on the strength of composites with open holes have been identified from experimental tests as notch size, ply and laminate thickness. In this study, these have been scaled both independently and simultaneously over a large range of combinations. 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 unidirectional [04]ns with n = 2, 3, 4, and 8 (i.e., 2, 3, 4 and 8mm thick) and multidirectional laminates; two generic quasi-isotropic lay-ups, one fabricated with blocked plies [45n/90n/-

45n/0n]s and the other with distributed layers [45/90/-45/0]ns with n=2, 4 and 8 are examined. It is shown that the critical failure mechanism in these laminates is in the form of fibre microbuckling or kinking. The unnotched compressive strength in unidirectional specimens thicker than 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 rather than specimen size (scaling). In the open hole specimens, for both lay-ups, the strength reduction observed is due to hole size effect rather than specimen thickness or volume increase. The open hole (notched) compressive strength results obtained compare favourably to predictions by a linear softening cohesive zone fracture model developed in earlier work by the second author.

Measuring the notched compressive strength of composite laminates: Specimen size effects

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Abstract

Large fibre reinforced composite structures can give much lower strengths than small test specimens, 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. The most important variables of scaling effects on the strength of composites with open holes have been identified from experimental tests as notch size, ply and laminate thickness. In this study, these have been scaled both independently and simultaneously over a large range of combinations. 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 unidirectional $[0_4]_{ns}$ with n = 2, 3, 4, and 8 (i.e., 2, 3, 4 and 8mm thick) and multidirectional laminates; 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 layers $[45/90/-45/0]_{ns}$ with n=2, 4 and 8 are examined. It is shown that the critical failure mechanism in these laminates is in the form of fibre microbuckling or kinking. The unnotched compressive strength in

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unidirectional specimens thicker than 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 rather than specimen size (scaling). In the open hole specimens, for both lay-ups, the strength reduction observed is due to hole size effect rather than specimen thickness or volume increase. The open hole (notched) compressive strength results obtained compare favourably to predictions by a linear softening cohesive zone fracture model developed in earlier work by the second author.

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1. Introduction

The design of composite structures frequently includes discontinuities such as cut-outs for access and fastener holes for joining and they become critical regions under compressive loading. It is, therefore, important to understand the compressive behaviour of composite laminates. Although it is possible to perform laboratory tests on composite specimens and measure certain response data for a controlled set of loading, specimen size and material conditions, the question of how these data relate to the compressive strength of the laminate is, as yet, unresolved. Especially the specimen size effect (or scaling effect), has become an important issue in composites design over recent years. A substantial amount of full size component and structural testing is currently required to qualify a new aerospace composite system, which is a very expensive exercise (more than £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.

Continuous fibre reinforced plastics (FRP) have a number of characteristics that are typical of brittle materials. They lack plasticity to reduce the influence of stress concentrations arising from discontinuities introduced either intentionally as cut-outs and fastener holes, or unintentionally due to in-service damage (impact damage) and defects induced during the manufacturing process. They have an almost linear stress-strain response when loaded along the fibre direction in tension or compression and display a significantly larger scatter in strength than metallic materials [1]. Also, it has been well known that the strength of brittle materials depends on the size or volume of stressed material.

In light of these facts, it is natural to ask whether the strength of composites depends on material volume. Although there is a significant, but inconclusive, amount of evidence that there is a size effect in composites under tensile and flexural load [2-7], scaling of composite strength is not well documented or understood. Most of the research to date has looked at the size effect on the unnotched rather than notched strength under unidirectional tensile [4-7] or compressive loading [8-10]. The results show the importance of ply thickness and the interactions between delamination and matrix cracking with the fibre direction failure modes. Size effects are generally more evident in laminates scaled at ply-level (increasing ply thickness) rather than sub-laminate level scaled (increasing the number of repeated ply sequence) plates.

For plates with an open hole where failure commonly originates from the stress concentration, less research related to specimen size or volume has been done. The increase in notched tensile and compressive strength with decreasing notch size has been observed previously in several studies [9, 10]. However, very few scaled tests have been reported, and the effects of thickness and ply blocking have received less attention. The results of plates with circular holes [9] have shown that the decrease in strength with hole size can be explained using a fracture mechanics analysis [11]. This approach seems to work because the compressive failure mechanism is an unstable micro-buckle ("kink-band" failure) of the 0° fibres in a fairly sharp crack-like manner, which does not happen in tension where several blunting mechanisms are present. However the effects of thickness variations have not been analysed in this work and it is likely that edge effects may be significant, causing through-thickness peeling which will depend on the stacking sequence as well as the absolute thickness [12].

The aim of the current research work is to develop an understanding of the failure mechanisms (that occur at microscopic level) controlling the strength of composite specimens of different dimensions and hence to be able to predict size effects if they exist without resorting to empirical laws. Unnotched and notched specimens using the stacking sequences, $[0_4]_{ns}$, $[45/90/\text{-}45/0]_{ns}$ and $[45_n/90_n/\text{-}45_n/0_n]_s$ (n = 2, 4 and 8, ply thickness: 0.125mm) are tested statically in uniaxial compression; the hole size effect and stacking sequence effect are also examined experimentally and analytically. In addition, unnotched and notched specimens fabricated with thicker prepreg (0.25mm) and stacking sequence, $[45/90/\text{-}45/0]_{ns}$ (n = 1, 2, 4 and 8) are tested. A cohesive zone model [11] is employed to estimate the strength of open hole specimens. The results are compared to experimental measurements.

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 roll was 1200mm wide and about 0.125mm thick. The prepreg was cut into 600mm wide by 600mm long sheets using a metal template and laid up in the unidirectional plates, $[0_4]_{ns}$ with n = 2, 3, 4, and 8 (i.e., 2, 3, 4 and 8mm thick) and quasi-isotropic ($[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$) stacking sequence giving a total thickness of about 2mm, 4mm and 8mm thickness (n = 2, 4, and 8). The in-plane stiffness and strength of the IM7/8552 unidirectional laminate are given in Table 1. The material's manufacturer, Hexel Composite Ltd., performing standard strength tests, obtained these parameters.

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 (hold at 110°C for 60 min) 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). In consultation with colleagues from Hexcel Composites it was decided that a higher autoclave pressure (7+ bar) together with slow heating (0.5 to 1°C/min) and cooling rate (2°C/min) would reduce thermal stresses and void content in the 8 mm thick plates. 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 and specimen geometry

3.1. Unnotched unidirectional (UD) specimens

The baseline specimen dimensions are based on those recommended by Imperial College Standard Test method (ICSTM) [13], i.e. 10mm x 10mm x 2mm in gauge width x gauge length x thickness. The specimens are increased by a scaling factor of 2 and 4 and tested on a 1000 kN servo-hydraulic machine at a constant compression rate of 1 mm / min using an enlarged test fixture based on the ICSTM design, Fig1a.

3.2. Unnotched multidirectional (MD) specimens

The baseline specimen dimensions are based on those recommended by Airbus Industry Test method (AITM) [14], 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. All specimens were tested in compression using the test jig shown in Fig.1a.

3.3. Notched multidirectional (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, Fig. 1b. Three different types of scaling are used for open hole specimens for thinner ply specimens and thicker ply specimens, see Table 2: one-dimensional (1-D), where only the thickness is scaled from 2mm to 4mm and from 4mm to 8mm,two-dimensional (2-D), 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 (3-D), where all dimensions of the baseline specimen are increased by a scaling factor of 2 and 4.

4. Experimental Results and Discussion

Experimental work with various specimen sizes as described in Section 3 was carried out using the ICSTM fixture [14, 15] for the unidirectional and multidirectional (notched and unnotched) specimens. Based on these results, the scaling effects on the compressive strength 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 and current experimental data.

4.1. Unnotched Unidirectional Specimens

Initial compression tests on unidirectional specimens with relatively thin end tabs showed that failure occurred within the tabbed region, resulting in relatively low 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 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 Fig. 2.

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.

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 by the authors [15] shows that a 4 mm thick end tab would produce a stress concentration of approximately 1.7, explaining partly the premature failure of the 4 mm thick specimen. Using a thinner tab would cause a less severe 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, Fig. 3. 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 [10, 15]. 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 20 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 28.8% 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 appears that 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.

4.2. Unnotched Multidirectional Specimens

The strength results for all volumes as presented in Table 3 were valid and reproducible. All specimens regardless of specimen size (or volume) and scaling technique failed within the gauge length. 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 method ($[45_n/90_n/-45_n/0_n]_s$) 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 stresses during the specimen cutting process [15]. 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.4. 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. For specimens fabricated with the thicker pre-preg (0.25mm), the average failure strengths (Table 3) are 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, in the form of resin rich regions and ply undulation (waviness). The thicker prepreg (0.25mm) was manufactured by compacting two thinner plies (0.125mm) together, which resulted in larger fibre and ply waviness. Such defects are less evident in the thinner prepreg specimens.

4.3. Notched Multidirectional Specimens

4.3.1. One-dimensional thickness effect

The average strengths obtained from both scaling techniques (sublaminate-level $[45/90/-45/0]_{ns}$ and ply-level scaled laminate $[45_n/90_n/-45_n/0_n]_s$) 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, Fig. 5. 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; 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, see section 4.3.4.

4.3.2. Two-dimensional in-plane size effect

The in-plane dimensions (hole diameter and gauge section, length x width) were scaled keeping the same thickness (4mm) and a/W ratio (hole diameter/width, a/W=0.2), see Table 2. 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, Fig. 6.

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 of the notched compressive strength predicted by the cohesive zone model [11] are in good agreement with the measured failure strengths, Fig.7. Fig.7 illustrates the notched (residual) strength of the 4mm thick sublaminate-level scaled composite laminate as a function of a/W for different specimen widths (W=32, 64 and 128 mm). This is lower than that predicted by the ideally ductile behaviour (1-a/W) but definitely higher than the value estimated by the maximum stress failure criterion (ideally brittle fracture, $1/k_t$). The cohesive zone model is a two-parameter model, requiring the knowledge of the unnotched compressive strength (675 MPa) and the fracture energy associated with fibre microbuckling in the 0° layers or fracture toughness (K_C= 42 MPa $m^{1/2}$) that can be measured or predicted [16]. It can be said that the presence of the hole rather than fibre or other imperfections dominates the fracture process in the 2-D scaled specimens.

4.3.3. Three- dimensional scaling effect

Three-dimensional scaling effects were investigated, where all dimensions of the baseline specimen were increased by a scaling factor of 2 and 4, see Table 2. 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. 8.

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 (due to hole size) rather than 3-D scaling effects.

4.3.4. Stacking sequence effects

Figures 6 and 8 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 occurs due to local damage around the hole, Fig. 9. 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 Fig. 9a, 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 (Fig. 9b) 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 occurs just prior to the catastrophic failure, the composite laminate behaviour is closer to 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 [16] 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 (due to splitting) 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 ($[45_n/90_n/\text{-}45_n/0_n]_s$), 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 (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 strength for the 2 mm thick specimen. 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 up to 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 [11,16]; 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 average value of 41 MPa $m^{1/2}$.

6. Acknowledgments

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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	2400/1690	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 (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 Gauge Length x Width (W) /mm			32 × 32	64 × 64	128 × 128
a/W			0.2	0.2	0.2
Tab Length*/mm			50	50	50

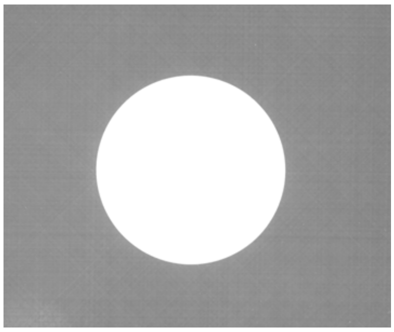
(Number of tested specimens = 6, End-tab material: Woven glass fibre-epoxy reinforcement, *: Anti-buckling device, 1: thinner pre-preg specimens (0.125mm), 2: thicker pre-preg specimens (0.25mm))

Table 3 Unnotched average compressive strength obtained for the sublaminate-level ($[45/90/-45/0]_{ns}$) and ply-level ($[45_n/90_n/-45_n/0_n]_s$) scaled specimens (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 gauge length x width x thickness (mm), ( ): Coefficient variation, %)

a) ICSTM test fixture



b) X-ray radiograph, d = 25.4mm

Fig. 1. a) Compression test fixture. b) Typical X-ray radiograph illustrating hole quality of specimens used in this study; no drilling damage is visible.

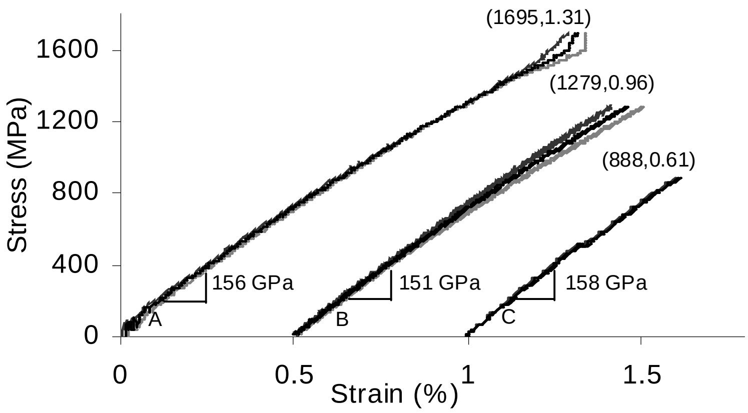


Fig. 2. Typical stress-strain curves of the IM7/8552 unidirectional specimens obtained from back-to-back strain gauges (A: 10mm × 10mm × 2mm, B: 20mm × 20mm × 4mm and C: 40mm × 40mm × 8mm.)

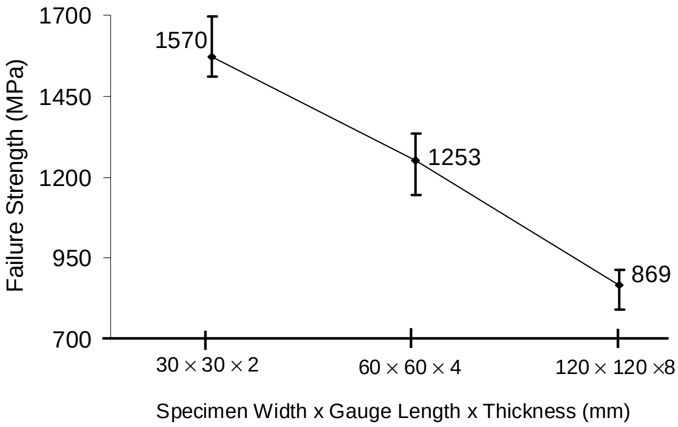


Fig. 3. Average UD compressive strength as a function of specimen volume (IM7/8552)

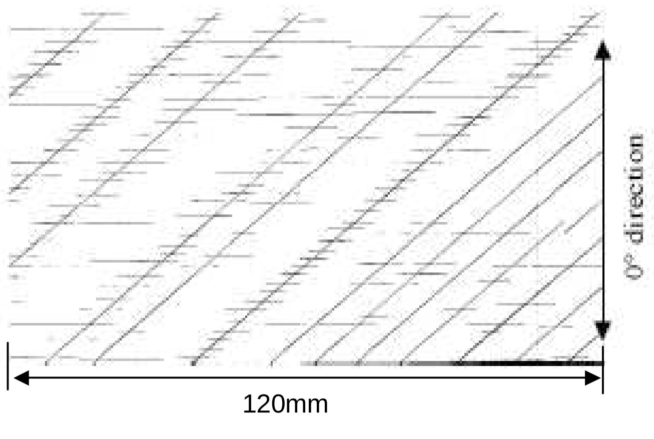


Fig. 4. X-ray radiograph of an 8mm thick IM7/8552 $[45_8/90_8/\text{-}45_8/0_8]_s$ specimen before compressive testing. Extensive matrix cracking due to thermal stresses is shown.

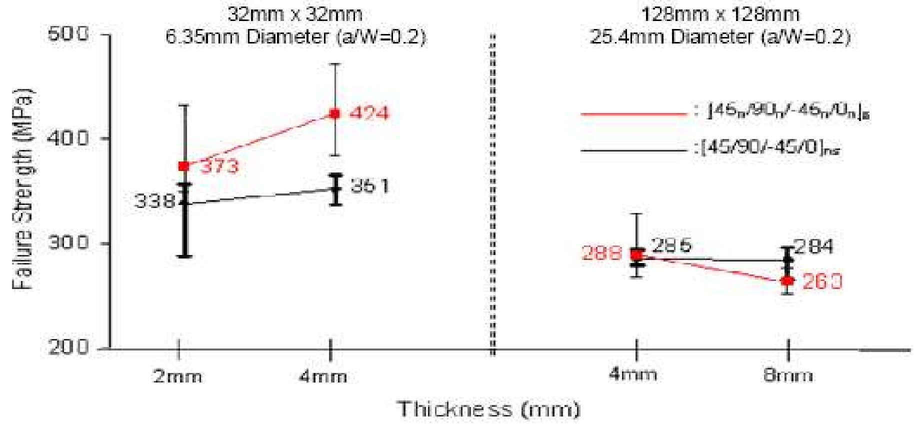


Fig. 5. Average strength of open hole specimens as a function of thickness for IM7/8552 multidirectional laminates ($[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$)

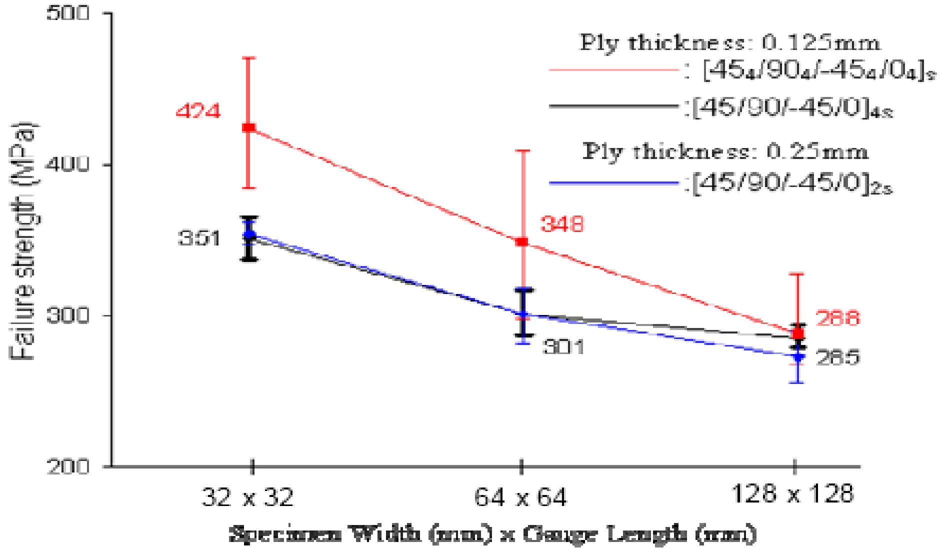


Fig. 6. Average strength of 4mm thick open hole specimens as a function of gauge section size for IM7/8552 laminates ($[45/90/-45/0]_{4s}$, $[45/90/-45/0]_{2s}$ and $[45_4/90_4/-45_4/0_4]_s$)

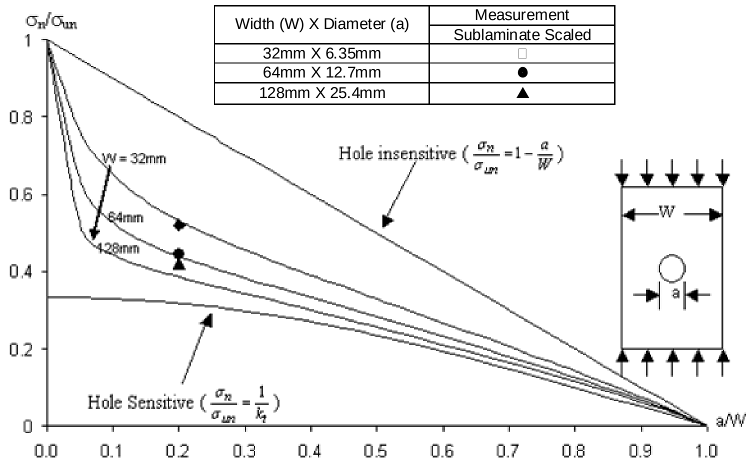


Fig. 7. Hole size and width effects on the compressive strength of an IM7/8552 – [45/90/-45/0]$_{ns}$ laminate

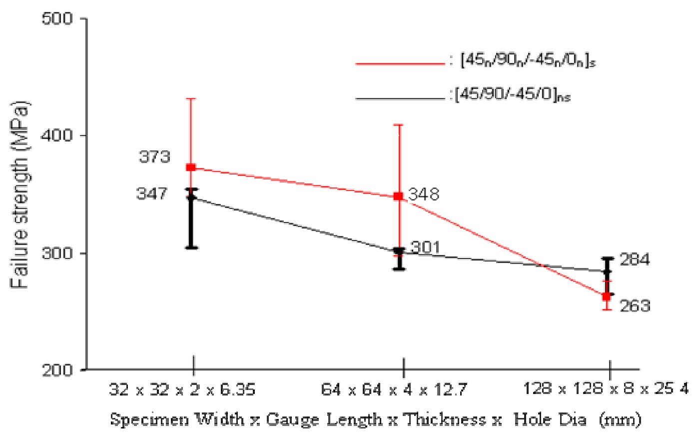


Fig. 8. Average open hole strength as a function of specimen volume for IM7/8552 [45/90/-45/0]$_{ns}$ and [45$_n$/90$_n$/-45$_n$/0$_n$]$_s$ laminates

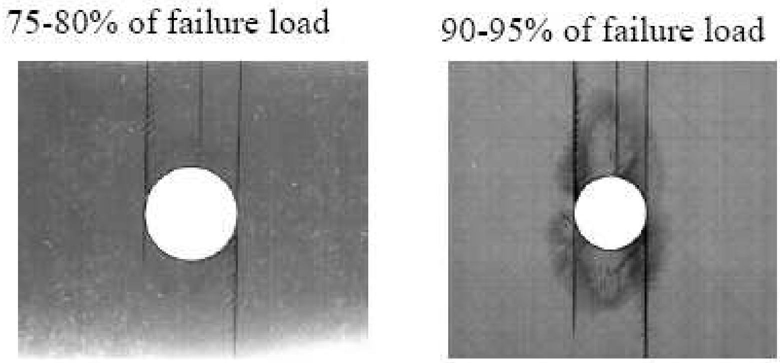


Fig. 9a) Damage development in a ply-level scaled laminate $[45_4/90_4/-45_4/0_4]_s$. Average failure load: 54.3 kN, hole diameter = 6.35mm. 47.5kN, Hole diameter = 6.35mm - $[45/90/-45/0]_{4s}$

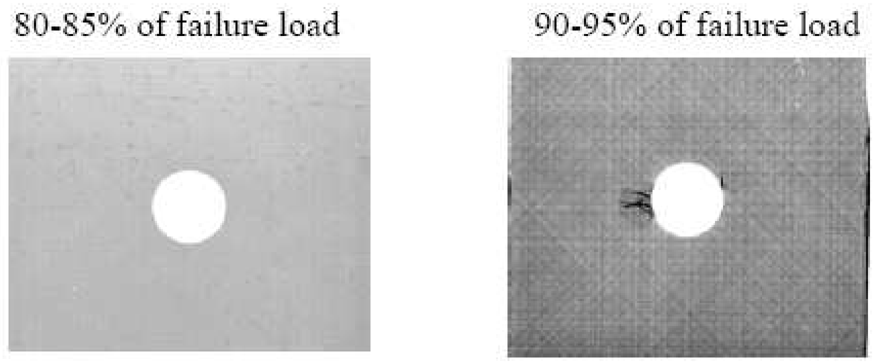


Fig. 9b) Damage development in a sublaminate-level scaled laminate $[45/90/-45/0]_{4s}$. Average failure load: 47.5 kN, hole diameter = 6.35mm.

Response to the referees' comments

Ref. No. CSTE-D-07-00418: "Measuring the notched compressive strength of composite laminates: Specimen size effects", by Lee and Soutis

The authors are grateful to all referees for the much-appreciated comments and useful suggestions, which contributed to the improvement of the paper. In the following paragraphs we'll respond in more detail to some of their comments:

Referee #1

1. Fig.1 has been changed to illustrate the specimen, the ICSTM test fixture and the test frame during the compression loading. The specimen geometry is described in the text as rectangular flat specimens and their dimensions are presented in Table 2.

2. In the 3D scaling all three dimensions (length, width, thickness) of the specimen are varied, while in the 2D configuration the thickness is kept constant, see text description.

3. The text on Page 8, lines 18-19 were left unchanged, while the % has been changed as suggested.

4. In section 4.3, there are more that two data points, for each test at least 5-6 specimens were tested.

5. Two notched specimens with the same a/w can have the same stress concentration factor but in the one with the largest hole (actual size) a larger volume of material experiences high stresses which prevents stable growth of local damage (stress redistribution) and leads to a more brittle failure, resulting to a lower notched (residual) strength. This hole size effect is well documented in the composites literature and here is illustrated quite well by Figure 7.

6. Section 4.3.4, in Fig.8, the 8mm thick specimen with the blocked plies fails below the strength of the equivalent one with the distributed layers because the matrix cracking damage is not restricted just near the hole but extends across the width and along the specimen length, which makes it weaker. It is true that a composite part showing the damage of that of Fig.9a would be removed from service, but here it is demonstrated that the part is damage tolerant and won't fail catastrophically. When we design with composites we care that the designed part to be damage resistant, but also damage tolerant.

7. In Fig.7 the results correspond to the current system and the plotted data is the one that is presented in Fig.6 for the 4 mm thick laminate with the distributed plies. The predictions are made by using the fracture model presenting in [11], see section 4.3.2 of revised text.

8. The specimen dimensions are very important when measuring the unnotched strength and results are affected by end effects (if specimen is too short), edge effects (if specimen is too narrow), or disproportionately thick that could lead to an invalid failure mode. Results in table 3 demonstrate that the specimens of the same lay-up and thickness but different in-plane dimensions (length x width) have different strength values, they are further explained in [15].

9. All minor issues/corrections presented in the 2nd part of the report have been implemented as suggested by the reviewer.

Reviewer #2

1. The resin content is given as 34%. In the thick specimens the void content can vary from 0.9 to 1.9%, further information can be found in ref.[10] where more detailed fractographic studies were performed.

2. Additional information has been inserted in the revised manuscript as requested.

3. More detailed study that examined the behaviour of the unnotched UD and MD specimens of the same composite system has appeared in [15].

4. Mistype has been corrected and scale is giving in Fig.4.

5. The FE results are presented in more detail in [15]. We agree with the referee that the cohesive zone model is more suitable to describe damage initiation and development in specimens that fail as the one shown in fig. 9b, while in order to model the progressive failure illustrated in Fig.9a both stress and energy based criteria are needed, but this is not the aim of the present work.

6. The out-of-plane stiffness could have an effect but a bigger one when the specimen is loaded in flexure (out-of-plane) rather than in-plane uniaxial compression, which is the case in this study.

Reviewer #2

We thank the reviewer that read the paper and found it of a high quality.