SCALING EFFECTS IN NOTCHED COMPOSITES

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ABSTRACT

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. This research project was established, with tension to be investigated at Bristol University, and compression at the University of Sheffield. The work has been performed in collaboration with Airbus, Dowty Propellers and Hexcel Composites Ltd. The work focused on determining the effects of specimen dimensions on the unnotched and notched tensile and compressive strength of the IM7/8552 carbon fibre/epoxy 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. Finally, examining the stacking sequence effects on failure strength using two different scaling techniques: sub-laminate-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 and Sheffield can successfully predict tensile and compressive scaling effects from fundamental, independently measured material properties.

1. Introduction

The design of composite structures frequently includes discontinuities such as cut-outs and holes for joints and they become critical regions under tensile or compressive loading. It is, therefore, important to understand their behaviour on 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 sizes and material conditions, the question of how these data relate to the tensile or compressive response of structural laminates is, as yet, unresolved. In addition continuous fibre reinforced composites have a number of characteristics of typical brittle materials, and it is well known that the strength of brittle materials depends on the 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 amount of evidence that there is a size effect in composites under tensile and flexural load [1-3], scaling of composite strength is not well understood. Most of the research to date has looked at un-notched strength under unidirectional tensile [1, 3] and compressive loading system [4, 5]. For notched composites where failure commonly originates from the stress concentration, less research has been done on the scaling implications. The increase in notched tensile and compressive strength with decreasing notch size has been observed [5, 6]. However, very few scaled tests have been reported, and the effects of thickness and ply blocking have generally received little attention. The overall aim of this project, jointly performed between the Universities of Sheffield and Bristol was to develop an understanding of the mechanisms controlling the strength of notched composites of different dimensions and hence to be able to predict scaling effects in composite structures without resorting to empirical laws.

2. Tensile Strength Results

2.1 Unnotched Unidirectional (UD) Tensile Strength

A novel ply chamfering technique was used to create coupons tapered through the thickness, which failed in the gauge section with no damage in the tapers. This is important - few convincing results for true gauge section tensile failure of unidirectional carbon-epoxy have been published. Tests scaled in all three dimensions successfully avoided premature failures, enabling the size effect to be established. Unidirectional tensile strength of IM7/8552 carbon/epoxy pre-preg with 0.125 mm ply thickness reduced from 2806 MPa for 30 x 5 x 0.5 mm specimens to 2410 MPa for 240 x 40 x 4 mm [7]. This reduction of 14% over a volume increase of 512 times corresponds to a Weibull modulus of 40.

2.2 Unnotched Quasi-Isotropic Laminate Tensile Strength

3D scaled tests were carried out on constant section specimens of layup $(45_m/90_m/-45_m/0_m)_s$ and $(45/90/-45/0)_{ns}$ [7]. In the first series the thickness was changed by blocking plies of the same orientation together, referred to as ply-level scaling, and in the second series, referred to as sublaminate scaling, the whole block of plies was repeated through the thickness. The ply-level specimens showed a 46% drop in strength from 842 MPa for 30 x 8 x 1 mm to 458 MPa for 240 x 64 x 8 mm specimens. 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. The sublaminate scaled specimens showed a 10% increase in strength from 842 MPa for the baseline 30 x 8 x 1 mm up to 929 MPa for 120 x 32 x 4 mm specimens. 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.

2.3 Notched Quasi-Isotropic Tensile Strength

Scaled open hole tension tests were carried out with thickness, in-plane and full three dimensional scaling for both ply level and sublaminate level scaled specimens [8]. A constant width to hole diameter ratio of 5 and length to diameter of 20 was used. Large changes in strength of nearly a factor of 3 were found, and also change in the failure mechanisms, Table 1. Large sublaminate scaled specimens showed a brittle failure across the width, whereas small ones failed with significant pull-out between the plies. In-plane scaling with dispersed plies showed the expected hole-size effect, but there was little

Table 1: Summary of results for quasi-isotropic scaled specimens

	Hole sizes (mm) Sublaminate level scaling				Ply level scaling				
t(mm)	**3.175**	**6.35**	**12.7**	**25.4**	**3.175**	**6.35**	**12.7**	**25.4**	**Un-notched**
1	570				570				842
2	500	438			396	498			660
4	478	433	374	331	275	285	362	417	458
8	476			332	202			232	321

Brittle Pull-out Delamination

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. In-plane scaling of specimens with blocked plies showed a surprising increase in strength with hole size that has not previously been reported.

2.4 Damage Development in Tension

Failure mechanisms were investigated by video, interrupted tests, C-scans and X-rays [8]. The damage sequence was found to be similar for all specimens, but the extent of damage before final failure varied with size. It started with transverse cracking at the hole in the surface 45º ply, followed by delamination at the hole edge. This then started to spread towards the specimen free edge, and also stepped down through matrix cracks and associated delamination until reaching the 0º ply interface. At this point on some specimens complete separation occurred between the -45º and 0º plies, producing the delamination failure mechanism. On others fibre failure occurred first, producing a pull-out failure. In some cases fibre failure occurred much earlier, before significant delamination had occurred, leading to the brittle failure. Progressive failure was also studied with compact tension tests carried out at the University of British Columbia in Vancouver in Prof. Anoush Poursartip's lab. Full-field strain measurements were carried out in collaboration with Prof. Fabrice Pierron from ENSAM in France using a grid attached to the surface of the specimens [9]. This showed the high strain concentrations at the hole, how they developed and were affected by damage.

2.5 Effect of Lay-up on Scaling in Tension

Sublaminate scaled specimens made from 0.25 mm thick plies with quasi-isotropic, fibre dominated and matrix dominated layups up to 16 mm thick were tested [10]. In-plane scaling by a factor of 8 showed reductions in strength with size of 33%, 20% and 7% for the fibre dominated, quasi-isotropic and matrix dominated cases respectively. The quasi-isotropic specimens showed a similar trend with hole size to the previous ones with 0.125 mm ply thickness, but higher values, indicating that the conventional hole size correction based on absolute hole size does not work. However the two sets of tests gave similar strengths when plotted against the ratio of hole size to ply thickness, highlighting the importance of this newly identified scaling parameter.

2.6 Finite Element Analysis Approach for Tensile Strength

An analysis approach was developed using cohesive zone interface elements between every ply to model delamination, and interface elements within the plies to model the splitting from the hole. A new cohesive zone element was developed in the explicit finite element software, LS-DYNA3D, which is simple and robust, and overcomes some of the problems of convergence and difficulties when the mode ratio changes during fracture propagation [11]. The key parameters are the mode I and II fracture energies, which were based on independent experiments. For fibre failure a statistical approach based on the Weibull strength distribution was implemented by integrating the stresses in the fibre direction and comparing with the stress-volume integral deduced from the scaled unidirectional tensile tests of the same material. The approach was extremely successful, correctly predicting the damage development, failure stresses and mechanisms across the whole range of specimens tested [10,11]. The correlation for quasi-isotropic specimens is shown in Fig. 1, and good predictions were also obtained for the other lay-ups. These results were all obtained with the same set of independently determined material parameters, with no empirical or other fitting factors. The analysis has also been used to study the difference between holes and cracks, and the effect of the specimen width to hole size ratio. Detailed maps of delamination and splitting were produced that were very helpful in understanding and interpreting the experiments, for example showing the importance of delamination from the hole edge, which becomes harder as the ratio of hole size to ply block thickness increases. This explains the traditional hole size effect, where relatively less delamination for larger holes leads to less splitting and associated stress relief at the notch, and hence lower strength. The same factor also explains the increase in strength with hole size seen for the thick ply block specimens, but here the delamination is the failure mechanism, and so strength increases with hole size.

2.7 Validation: prediction of stacking sequence effects on scaling in tension

The analysis was applied to all 12 possible stacking sequences for an 8-ply quasi-isotropic laminate, and the most interesting cases selected for experimental investigation. The analysis showed that the $(90_m/45_m/0_m/-45_m)_s$ stacking sequence should be less strong than the baseline $(45_m/90_m/-45_m/0_m)_s$ layup, with fibre fracture occurring for the m=1 and double size m=2 cases at similar stresses.

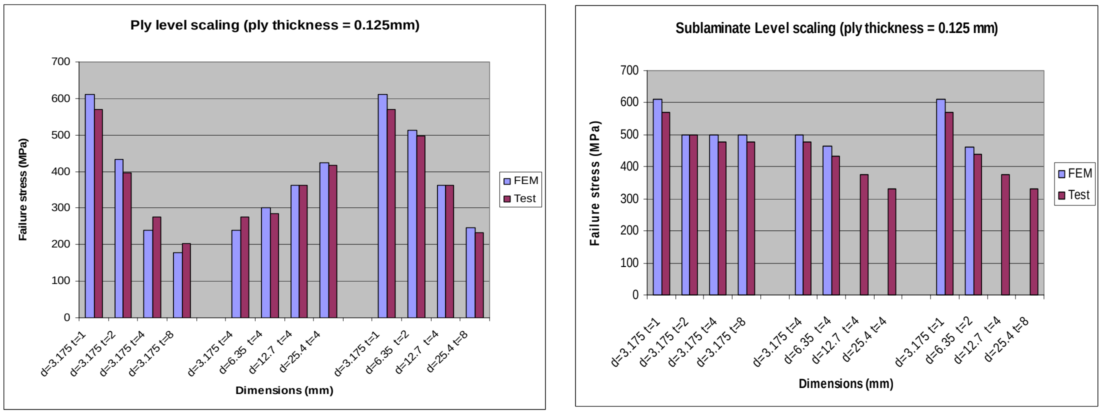

Fig. 1: Correlation of Experimental and Analysis Results for Ply and Sublaminate Scaling

On the other hand the $(45_m/-45_m/90_m/0_m)_s$ lay-up was predicted to be stronger, to fail by fibre fracture for m=1, but to show a significant drop in strength and switch in failure mode to delamination when scaled to m=2. Based on the results of the analysis, these specimens were made and tested, and both the failure mechanisms and strengths matched those shown by the analysis closely, validating the approach [12].

3. Compressive Strength Results

In order to meet the overall objectives, obtaining reliable experimental results is vital. Carefully thought experimental work with various specimen sizes was carried out using a specially designed fixture [13, 14] 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, finite element stress analysis, appropriate fracture models and the comparison of measured experimental data.

3.1 Unnotched UD Strength

Initial compression tests on UD 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). Damage initiated on the end of the specimen at the load introduction point. As a result of this 'compression in tab' type failure, the tab thickness was increased (at least end tab thickness ≥ specimen thickness); the results reported here are for such specimens. The stress-strain curves obtained for all unidirectional IM7/8552 specimens from back-to-back strain gauges indicated that bending due to misalignment had been successfully minimized. These curves showed similar stress-strain 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 was determined at 0.25 % applied strain and the results showed that the axial modulus was 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. A 3-D finite element stress analysis showed 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 severe discontinuity and reduced stress concentration factor but wouldn't be stiff enough to transfer the compressive load effectively leading to compression failure under the tab. 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 (1570 MPa) to 8 mm (869 MPa) thick specimen. 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 [13-14]. It may not be possible to achieve the same compaction, removal of voids or cure uniformity for the thicker laminates.

3.2 Unnotched Multidirectional Strength

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 stress 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 during the specimen cutting process, as a result of thermal stresses. It was identified from x-ray radiography that cracks parallel to the fibres in the 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. For specimens fabricated with the thicker pre-preg (0.25mm), the average failure stresses (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 by manufacturing defects. The thicker prepreg (0.25mm) was manufactured by squeezing two thinner plies (0.125mm) and during this process the fibres and layers became seriously misaligned/undulated. Such defects are less evident in the thinner prepreg specimens.

Table 2: Unnotched average compressive strength results for quasi-isotropic scaled specimens

Ply thickness: 0.125mm		
Dimensions	$[45/90/-45/0]_{ns}$	$[45_n/90_n/-45_n/0_n]_s$
30 x 30 x 2	658 MPa (3.15)	666 MPa (19.6)
60 x 60 x 4	675 MPa (6.6)	642 MPa (19.0)
120 x 120 x 8	644 MPa (14.0)	472 MPa (13.4)

Ply thickness: 0.25mm			
Dimensions	$[45/90/-45/0]_{ns}$	Specimen dimensions	$[45/90/-45/0]_{ns}$
30 x 30 x 2	655 MPa (2.03)	16 x 16 x 2	588 MPa (8.71)
60 x 60 x 4	588 MPa (4.36)	32 x 32 x 4	603 MPa (1.73)
120 x 120 x 8	-	64 x 64 x 8	541 MPa (4.9)

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

3.3 Notched Multidirectional Strength

3.3.1 Effect of thickness on open hole specimens

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, Fig. 2. 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 prior to fibre microbuckling. This causes stress redistribution that leads to an increased failure load.

3.3.2 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 (4mm) 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=0.125mm) and 22% reduction (ply thickness=0.25mm) in unblocked specimens and 32% reduction in blocked specimens, Fig 3. This strength reduction demonstrates the hole size effect in a finite width specimen. The values predicted by the cohesive zone model [13] were in good agreement with the measured failure stresses (less than 10% difference). The presence of the hole rather than fibre or other imperfections dominates the fracture process.

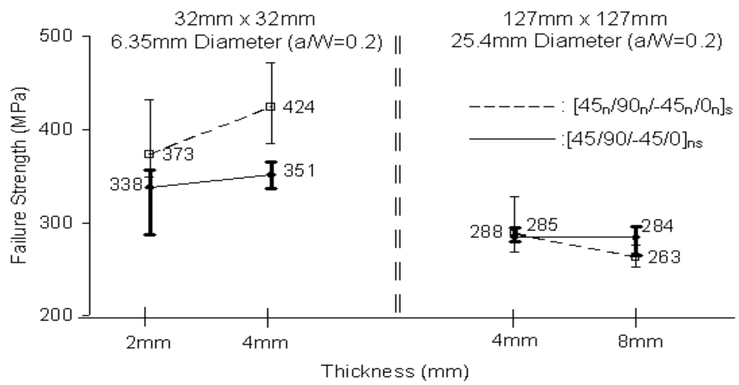

Fig.2: Average strength of open hole specimens as a function of thickness for IM7/8552 multidirectional laminates ($[45/90/-45/0]_{ns}$ and $[45_n/90_n/-45_n/0_n]_s$).

3.3.3.Three-dimensional scaling effects

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 ($[45_n/90_n/-45_n/0_n]_s$). The reduction rate in the failure stress, 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.

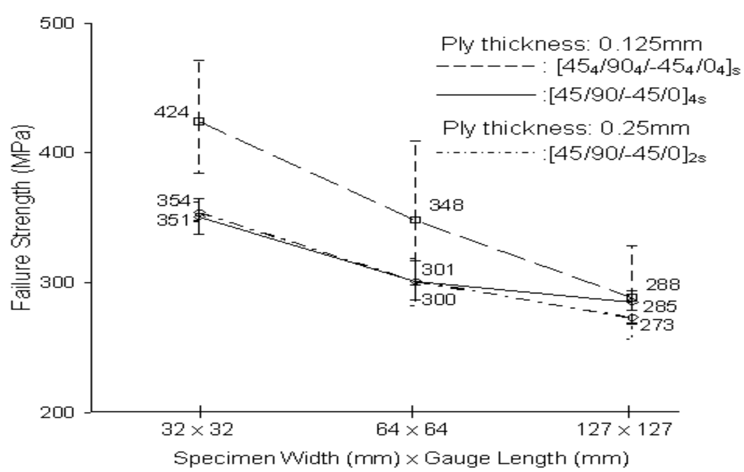

Fig.3: Average strength of 4mm thick open hole specimens as a function of gauge section size (length x width) for IM7/8552 laminates.

3.3.4 Stacking sequence effects

Fig 3 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. Fibre/matrix splitting was observed in the ply-level scaled specimens at an applied load of 42.8kN (75% of failure load) while 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 4mm thick open hole specimen with a 6.35mm hole diameter, the predicted fracture toughness by the Soutis *et al* fracture model [13] 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 than the sublaminate-level scaled one.

4. Concluding remarks

4.1 Tension

Unidirectional tensile strength of IM7/8552 reduced by 14% over a linear scaling factor of 8, whilst 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. This highlights the crucial effect of ply block thickness. Similar large variations of nearly a factor of 3 were seen on notched tests, and again the ply block thickness was crucial in determining delamination. The ratio of hole size to ply block thickness was also found to be important in controlling damage development and hence fibre failure – a scaling parameter that has not previously been recognised. Detailed finite element analysis using the approach developed can predict these effects, and can therefore be used to provide design guidelines and validate simpler criteria. The danger of premature delamination when the ply block thickness is large has been highlighted, and is particularly critical for small hole sizes. This could lead to unconservative predictions with conventional hole size correction factors as currently used in industry, of particular concern with the current trend to using thicker layers of material to reduce manufacturing costs.

4.2 Compression

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 to 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 for the unnotched strength to reduce 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 not affected by 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 no 1-D thickness effects in either 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 scaling, 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 additional 3-D scaling effect. 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]; the predicted fracture toughness of ply-level scaled laminate was 55 MPa $m^{1/2}$ while the sublaminate-level scaled specimens showed a lower value of 42 MPa $m^{1/2}$.

5. References

1. Wisnom, M.R., Size effects in the testing of fibre-composite materials, *Composites Science and Technology* 1999; 59:1937-57.
2. Jackson K.E., Kellas S. and Morton, J. Scale effects in the response and failure of laminates loaded in tension and in flexure. *Journal of Composite Materials* 1992; 26 (18): 2674-2705.
3. Lavoie J. A., Soutis C. and Morton J. Apparent strength scaling in continuous fibre composite laminates. *Composite Science and Technology* 2000; 60 (2): 283-299.
4. Daniel H.J. and Hsiao H.M. Is there thickness effect on compressive strength of unnotched composite laminates? *International Journal of Fracture* 1999; 95 (Special Issue): 143-158.
5. Soutis C., Lee J. and Kong C. Size effects on compressive strength of T300/924C carbon fibre-epoxy laminates. *Plastics Rubber Composites* 2002; 3(8): 364-370
6. Lee J. and Soutis C. Thickness effect on the compressive strength of T800/924C carbon fibre-epoxy laminates. *Composites Part A* 2005; 36: 213-227
7. Wisnom M R, Khan B, Hallett S R. Size effects in unnotched tensile strength of unidirectional and quasi-isotropic carbon/epoxy composites, *Comp Struct* 2008; 84:21-28.
8. B. G. Green, M. R. Wisnom and S. R. Hallett, An Experimental Investigation into the Tensile Strength Scaling of Notched Composites, *Composites Part A*, **38** (2007) 867-878
9. Pierron F, Green B, Wisnom M R and Hallett S R. Full-field assessment of the damage process of laminated composite open-hole tensile specimens. Part II: experimental results, *Composites A* 2007; 38:2321-32.
10. Wisnom M R, Green B, Jiang W-G, Hallett S R. Specimen Size Effects on the Notched Strength of Composite Laminates Loaded in Tension. ICCM16. Kyoto, 2007.
11. Jiang, W., S. R. Hallett, B. G. Green and M. R. Wisnom, A simple and robust interface element for analysis of delamination and splitting in composite materials and its application to scaled notched tensile specimens, *Int J Numerical Methods in Eng*, **69**(2007), 1982–95.
12. Hallett S R, Jiang W-G, Wisnom M R. The Effect of Stacking Sequence on Thickness Scaling of Tests on Open Hole Tensile Composite Specimens. AIAA Conf., April 2007.
13. Lee, J. and Soutis, C. Thickness Effect on the Compressive Strength of T800/924C Carbon Fibre-epoxy Laminates. *Composites A*, **36**(2), (2005), 213-227.
14. Lee, J. and Soutis, C., A study on the compressive strength of thick carbon fibre/epoxy laminates. *Composites Science & Technology*, (2007) **67**(10), (2007), 2015-2026.