SCALING EFFECTS IN NOTCHED COMPOSITES

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ABSTRACT

A programme of scaled tests on unnotched and open hole tension and compression specimens is summarized. Quasi-isotropic IM7/8552 carbon-fibre epoxy specimens have been tested using two different scaling techniques: sub-laminate-level ($[45/90/-45/0]_{ns}$) and ply-level scaling ($[45_n/90_n/-45_n/0_n]_s$), independently varying the thickness and in-plane dimensions. Significant scaling effects are shown, with both strength and failure mechanisms changing with specimen size and the thickness scaling method having a particularly important effect. Failure mechanisms and scaling behaviour are compared between tension and compression and models presented that predict the observed size effects from fundamental material parameters without any fitting factors.

Keywords: Notched strength, open hole, size effects, scaling

1. INTRODUCTION

Notched strength is an important topic as it is one of the design drivers for composite structures. There has been considerable research over the years, and the earlier work was reviewed by Awerbuch and Madhukar [1]. Scaling effects are also important, as the design of large structures is usually based on data from small coupons, and reduced scale models may be used to investigate full scale structural behaviour. There is substantial evidence of size effects in composites [2]. Reductions of strength with increasing size have been reported in un-notched tensile and flexural strength [e.g. 2-6] and in compression [2,7-12], but scaling of strength is still not well understood.

In notched specimens scaling is accompanied by the well known hole size effect whereby strength decreases with increasing hole size. Many researchers have investigated this [e.g. 13-19] and a number of models have been proposed which fit the experimental trends. Most studies have kept the width constant and so specimens are not truly scaled, and the varying finite width correction factors can obscure the underlying scale effect. Several studies have considered the effect of thickness on notched strength [e.g. 12, 20,21]. However, a comprehensive study of scaled unnotched and open hole tensile and compressive specimens independently varying thickness and in-plane dimensions has not been carried out before. Modelling of scaling effects is particularly challenging as in a fully scaled specimen the stress distribution does not change with size, and so simple stress analysis approaches that do not take account of damage are not able to predict changes in strength. Fitting parameters such as averaging distances are therefore required in most analyses.

The research presented here was jointly performed between the Universities of Sheffield (compression) and Bristol (tension). The overall aim 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. The paper summarises a substantial programme of research on scaled open hole tests in both tension [22] and compression [23]. Results of unnotched scaled tests are also included for both tension [6] and compression [24]. The main contribution of this paper is to bring all these results together and compare the behaviour and trends observed in tension and compression. Open hole results are normalized by unnotched strengths to facilitate comparison of relative tensile and compressive performance. A modeling approach for tension is briefly summarized [25] and a previously developed approach [26] is applied to the compression tests. It is shown that these models are able to predict the observed size effects from fundamental material parameters without any fitting factors, illustrating the importance of taking account of the different failure mechanisms in understanding and predicting behaviour and strength.

2. EXPERIMENTAL

A series of scaled tests were carried out in tension and compression on quasi-isotropic laminates of IM7/8552 carbon fibre-epoxy. The stacking sequence was $[45_m/90_m/-45_m/0_m]_{ns}$ where m and n represent two different ways of scaling the thickness: ply level scaling, where blocks of m plies of the same orientation are stacked together, and sub-laminate scaling, where the stacking sequence is repeated n times with a single ply of each orientation, as illustrated in Figure 1. The nominal ply thickness was 0.125 mm.

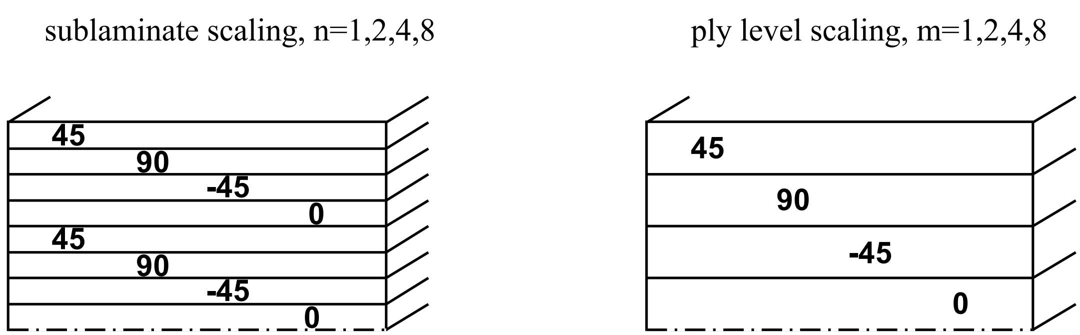


Figure 1. Thickness scaling approaches for $[45_m/90_m/-45_m/0_m]_{ns}$ laminates

The specimen configuration is shown in Figure 2. The ratios of width to hole size were kept constant at 5, and the length to hole size was kept at 20 for tension and 5 for compression. Holes were cut with tungsten carbide drills and reamed to final dimensions. Glass fibre tabs were bonded to the specimens to reduce gripping damage. Tests were carried out under displacement control, with six specimens of each size. The rate was scaled with specimen size in the tension tests to give a constant strain rate, whilst a constant rate was used in the compression tests. Anti-buckling guides were used on the 2 mm thick compression specimens.

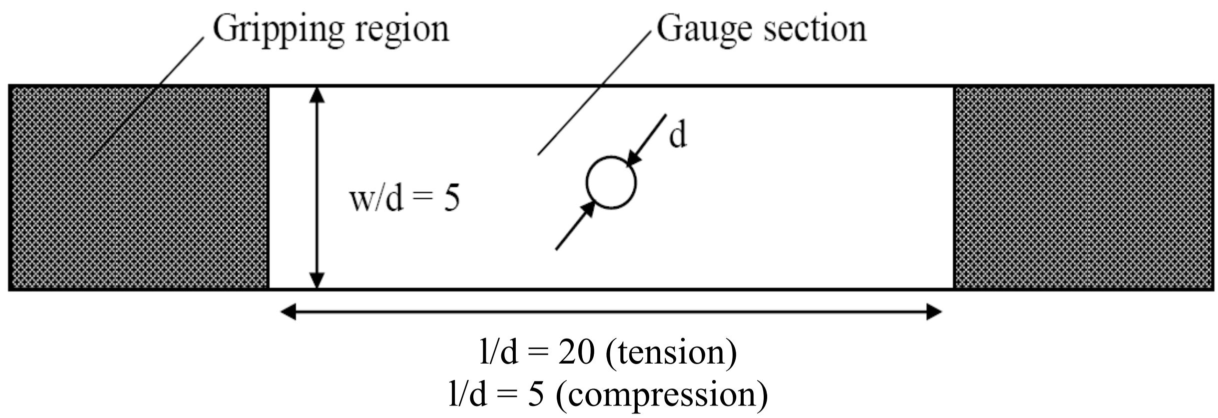


Figure 2. Specimen configuration

The test matrix is shown in Fig. 3, comprising of tests with constant in-plane dimensions and scaled thickness (1-D scaling), constant thickness and scaled in-plane dimensions (2-D scaling) and ones where all dimensions are scaled (3-D scaling). Specimens were tested from 8 mm thick down to 1 mm (tension) or 2 mm (compression), with hole sizes from 25.4 mm down to 3.175 mm (tension) or 6.35 mm (compression).

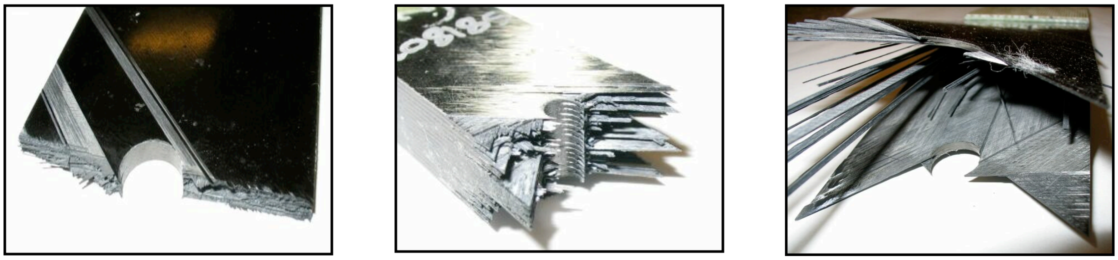
t (mm)	**Sublaminate-level Scaling Hole sizes (mm)**				**Ply-level Scaling Hole sizes (mm)**			
	3.175	**6.35**	**12.7**	**25.4**	**3.175**	**6.35**	**12.7**	**25.4**
1	T				T			
2	T	T+C			T	T+C		
4	T	T+C	T+C	T+C	T	T+C	T+C	T+C
8	T			T+C	T			T+C

Figure 3. Test matrix for open hole Tension and Compression

Three failure modes were identified in tension, as illustrated in Fig. 4 [22]. The larger sublaminate scaled specimens failed in a brittle manner, with a fairly clean fracture perpendicular to the loading direction. The other sublaminate scaled specimens and the larger of each of the two thinnest ply-level scaled failed with considerable pull-out between plies, and 0° ply fibre fracture running predominantly at 45° to the loading direction. The rest of the ply-level scaled specimens failed by delamination at the -45/0° interface. A summary of the results is given in Table 1. Failure is taken as the first significant damage event, defined as a drop in load of more than 5%. Some of the specimens failing by delamination were able to sustain load beyond this point, with the final failure load being either lower or higher, depending on the amount of fibre damage occurring during delamination propagation. However, since they had effectively lost their structural integrity, this event was still considered an appropriate definition of failure. Further details of the tests are given in [22].

The results of scaled unnotched tensile tests on the same laminates are also given in Table 1. These had constant ratios of width to thickness and gauge length to thickness of 8 and 30 respectively. Similar types of failure mechanism were observed as in the notched specimens. Further details of these tests are given in [6].

The different failure mechanisms have been explained in terms of the point at which fibre failure occurs during the progressive development of damage. This starts with 45° matrix cracks on the surface, stepping down through the laminate via delamination and further matrix cracks until reaching the -45/0° interface, at which point complete delamination occurs. If fibre failure occurs before significant damage, a brittle type failure is seen. If greater damage occurs first, the failure is pull-out, whilst complete delamination is seen if the stress does not reach a level sufficient to cause fibre failure. This is explained and illustrated in more detail in [22,25].



a) Brittle b) Pull-out c) Delamination

Figure 4. Different failure mechanisms in open hole tension

t (mm)	Sublaminate scaling: Hole diameter (mm)						Ply scaling: Hole diameter (mm)				
	0	3.175	6.35	12.7	25.4		0	3.175	6.35	12.7	25.4
1	842 (7.6)	570 (7.69)					842 (7.6)	570 (7.69)			
2	911 (2.0)	500 (3.95)	438 (2.44)				660 (3.3)	396 (5.18)	498 (6.45)		
4	929 (3.9)	478 (3.09)	433 (2.03)	374 (1.01)	331 (2.98)		458 (5.8)	275 (5.56)	285 (5.17)	362 (2.60)	417 (4.10)
8	-	476 (5.06)			332 (1.31)		321 (2.9)	202 (7.90)			232 (1.87)

Failure mode:	Delamination	Pull-out	Brittle

Table 1. Summary of scaled tension tests

Compression specimens all failed catastrophically [23]. There was no indication of damage from the load-displacement response or strain gauges except in the case of the 2 mm thick ply-level scaled specimens, where buckling initiated before fracture despite the anti-buckling guides used. This result should therefore be treated with some caution in comparing with the others. No premature buckling was observed in any of the other tests. Three mechanisms were seen, with similarities to those identified in tension, as shown in Figure 5. Sublaminate scaled specimens exhibited a brittle fracture straight across the laminate. Ply level scaled specimens 2 and 4 mm thick showed fracture at 45° and local delamination or push-out between plies, analogous to the pull-out seen in tension. The 8 mm thick ply level specimen failed by delamination without fibre failure.

a) Brittle b) Push-out c) Delamination

Figure 5. Failure mechanisms in open hole compression

Failure stresses are summarized in Table 2. Results from unnotched tests are also shown [24]. Failure mechanisms here were less clear cut due to the large amount of damage, and greater variability, especially for the ply-level cases. However the same basic types of failure were seen as for the open hole tests. X-rays showed that matrix cracks were present in the 90° and 45° plies of the 8 mm thick specimens before loading due to thermal residual stresses (for both compression and tension). Further details of the notched and unnotched compression tests are given in [23, 24].

The same argument can be used to explain the different failure mechanisms as for tension. Damage progresses in a similar way, although in this case the 45° and 90° matrix cracks are inhibited since they are subject to compression. If the stress in the 0° plies reaches a level sufficient to trigger microbuckling before significant damage, the failure is brittle. Greater sub-critical damage leads to a push-out failure, while for very thick ply blocks complete delamination occurs first.

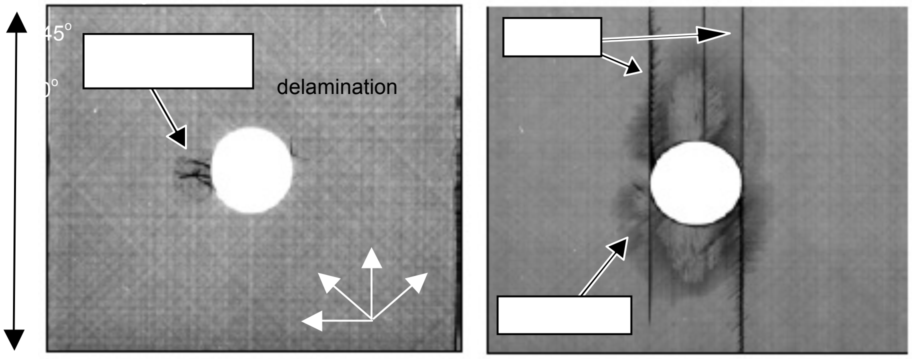
t	Sublaminate scaling					Ply scaling			
	Hole diameter (mm)					Hole diameter (mm)			
(mm)	0	6.35	12.7	25.4		0	6.35	12.7	25.4
2	658 (3.2)	338 (5.5)				666 (19.6)	373* (9.2)		
4	675 (6.6)	351 (2.9)	301 (3.6)	285 (2.2)		642 (19.0)	424 (7.5)	348 (12.6)	288 (8.4)
8	644 (14.0)			284 (4.1)		472 (13.4)			263 (4.2)

*indications of buckling prior to failure

Failure mode:	Delamination	Push-out	Brittle

Table 2. Summary of scaled compression tests

This is clearly seen in tests on 4 mm thick specimens with 6.35 mm diameter holes successfully interrupted at 98% of the failure load (figure 6). The sublaminate scaled specimens showed microbuckles initiating at the hole, but no 0° splitting, whereas the ply-level scaled specimens showed considerable delamination and splitting prior to microbuckle initation.



a) Sublaminate scaling b) Ply-level scaling

Figure 6. Interrupted compression tests on 4 mm thick specimens with 6.35 mm diameter holes (98% ultimate load)

3. DISCUSSION OF EXPERIMENTAL RESULTS

3.1 Effect of Thickness

Figure 7 shows the effect of thickness on the open hole tension results for the specimens with 3.175 mm diameter holes. The ply-level scaled specimens show a reduction of up to 64% in strength with increasing thickness because all the thicker ones failed by delamination, and the amount of energy available to drive the delamination depends directly on the ply block thickness. This trend mirrors the one seen in the unnotched specimens, where delamination is also crucial.

The sublaminate scaled specimens show a reduction of 18% from 1 mm to 2 mm thickness, but similar strengths between 2 mm and 8 mm. The higher strength of the 1 mm thick specimens is attributed to the way that damage can develop from the surface to reach the 0° plies, decreasing the stress concentration. With the thicker sublaminate scaled specimens it is more difficult for the damage to extend past the first 0° plies nearest the surface. This leads to earlier failure at the interior 0° plies due to the reduced damage and hence notch blunting. This trend is the opposite to the one seen in the unnotched tests, because in the latter the greater damage in the 1 mm specimen leads to failure, rather than relieving the stress concentration.

The same trends are also seen for both sublaminate and ply level scaled tension specimens with larger hole sizes.

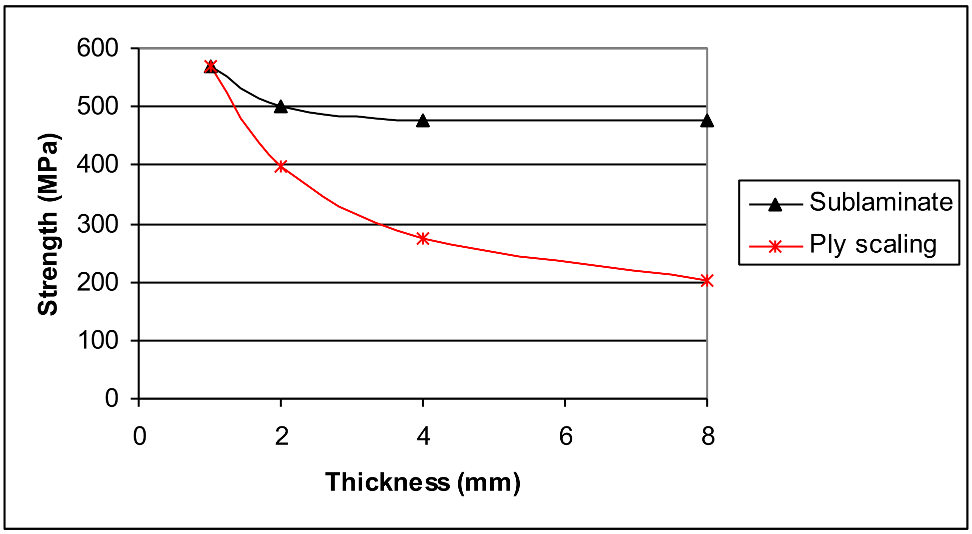


Figure 7. Effect of thickness on open hole tensile strength, 3.175 mm holes

Figure 8 shows the results for compression. The sublaminate scaled specimens show no significant effect of thickness on strength. However, tests were not carried out on 1 mm specimens with only a single sublaminate where a difference in behaviour was seen in tension.

The 8 mm thick ply level scaled specimens with 25.4 mm holes showed a small reduction in strength compared with the 4 mm ones, but more importantly a change in failure mode to

Affected by
buckling

delamination. This is consistent with what was observed in the unnotched tests. The results with 6.35 mm holes should be treated with caution in view of the indications of Euler buckling for the 2 mm thick specimens. Although there is only a single result showing a small thickness effect, delamination can be expected to be important in compression in other cases with very thick ply blocks. However it is less significant than in tension due to the lower absolute level of stress required to cause microbuckling compared with fibre failure in tension.

These trends are the same as those seen with the unnotched compression specimens: no significant effect of thickness on strength except for the 8 mm ply level case which failed by delamination at a lower stress than all the others.

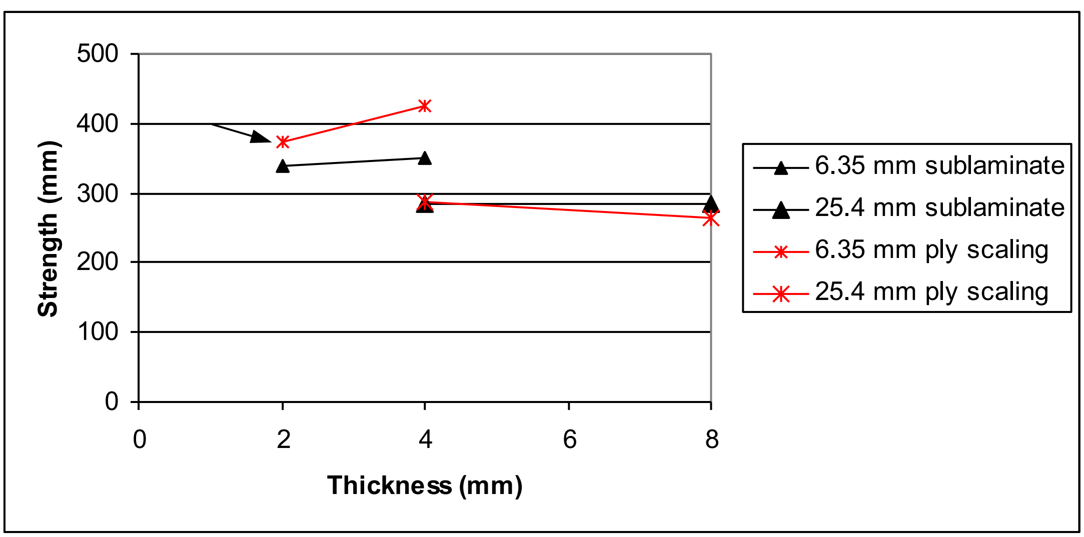


Figure 8. Effect of thickness on open hole compressive strength

3.2 Effect of In-Plane Dimensions

The effect of in-plane scaling on open hole tensile strength for the 4 mm thick laminates is shown in Figure 9. The sublaminate scaled specimens demonstrate the expected trend of decreasing strength with hole size, with a 31% reduction from 3.175 mm to 25.4 mm holes. However the ply level scaled specimens show the reverse trend, with a 52% increase in strength. This is because failure of the latter is due to delamination, which actually becomes harder as the specimen size to ply block thickness increases, as considered in more detail elsewhere [27]. On the other hand the decreasing damage with size in the sublaminate scaled specimens reduces the amount of stress relief, decreasing strength.

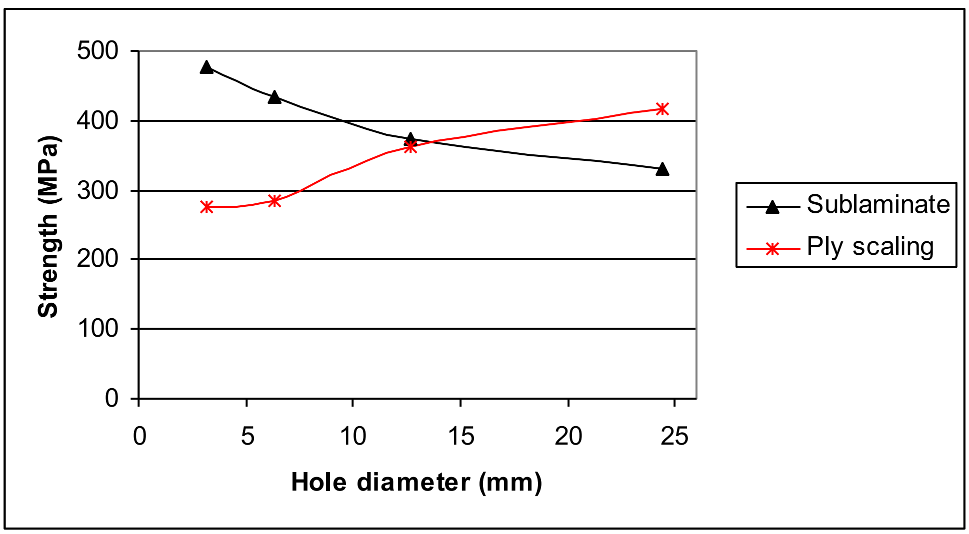


Figure 9. Effect of in-plane scaling on open hole tensile strength of 4 mm laminates

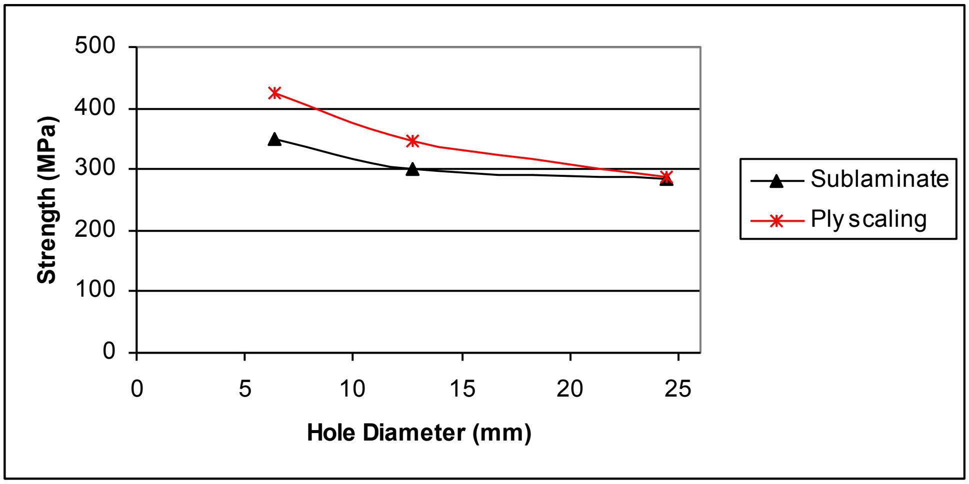


Figure 10. Effect of in-plane scaling on open hole compressive strength of 4 mm laminates

Figure 10 presents the results of changing in-plane dimensions on open hole compressive strength, showing a similar hole size effect for the sublaminate and ply level scaled specimens. The reductions in strength are 19% and 32% respectively, compared with the 24% for the sublaminate scaled tension tests over the same size range. The ply level scaled specimens are stronger, and this is attributed to the greater sub-critical damage with the thick ply blocks leading to more blunting of the stress concentration at the hole. The strengths are very similar for the largest hole size, because the ply-level specimens failed prematurely by delamination.

3.3 Comparison between tension and compression

Figure 11 compares the normalized results for the open hole tensile and compressive strength of the 4 mm thick sublaminate scaled specimens. The open hole strengths have been divided by the unnotched strengths of the same 4 mm laminates. The results have also been fitted with the average stress criterion [14] based on the 6.35 mm hole specimens. The averaging distances are 1.55 mm in tension and 2.34 mm in compression. The results for the other thicknesses are also shown, normalized by the unnotched strength of the baseline 4 mm laminates to allow comparison with the average stress criterion that does not account for different layups. The expected strength based on the stress concentration factor of 3.14 including the finite width correction factor is shown as well.

The fit to the average stress criterion in both tension and compression is good. For the 3.175 mm hole there is a considerable range of tensile strengths depending on the thickness, and the average stress criterion gives a value in the middle of the range. The results for 8 mm thick laminates overlie the 4 mm ones in both tension and compression.

The trends for the effect of in-plane scaling are very similar despite the very different tensile and compressive failure mechanisms. The performance in compression relative to the unnotched strength is better than in tension in every case, although the absolute values are lower.

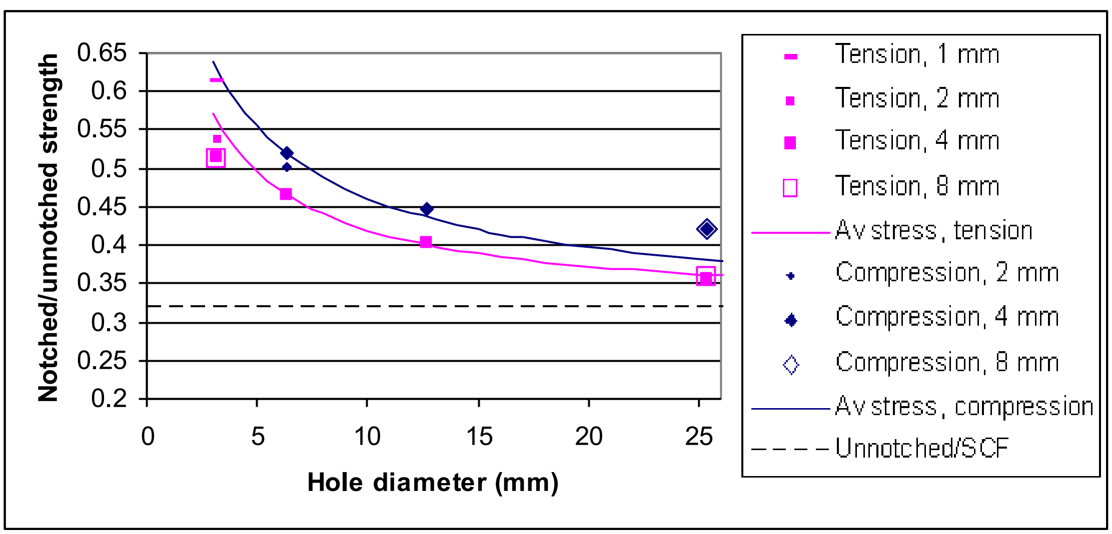


Figure 11. Comparison of tensile and compressive open hole strength, sublaminate scaling

Figure 12 shows the results for the ply level scaled cases, normalized by the same 4 mm specimen strengths as in Fig. 11 to facilitate comparison. The average stress criterion fits from Fig. 11 are also shown. Again the results show that the performance in compression relative to the unnotched strength is better than in tension. The only exception is the 4 mm thick specimen with 25.4 mm hole. In absolute terms the tensile specimens show higher strength except for the 8 mm thick case and the 4 mm one with 6.25 mm hole, which both fail very early due to delamination. The strength of the 4 mm ply level specimens in compression is particularly good – considerably better than for the sublaminate scaled specimens where plies are dispersed. This is attributed to the greater sub-critical damage blunting the stress concentration.

The trend shown for the ply level scaled specimens in tension is completely different from that in compression and from that given by the average stress criterion. The strong effect of ply block thickness on tensile strength is also very obvious. This shows the limitation of the average stress approach, which does not take account of the failure mechanisms, and the possibility that these may change with specimen size.

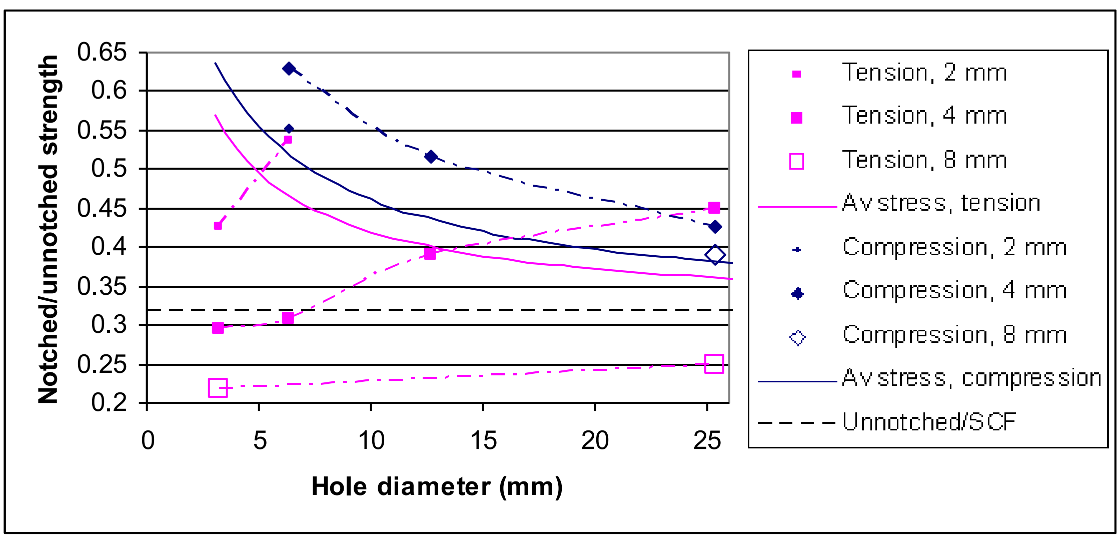


Figure 12. Comparison of tensile and compressive open hole strength, ply level scaling

4. PREDICTION OF FAILURE

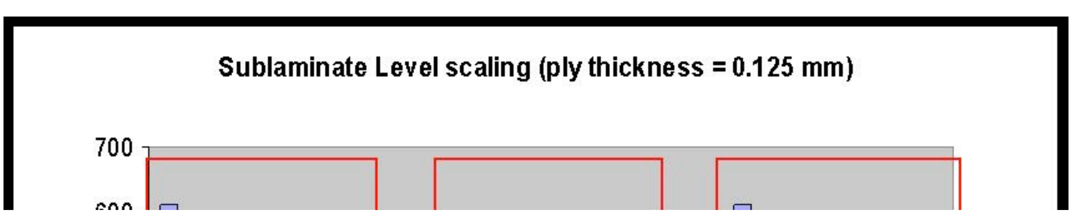
The variation of experimental results shown in Figure 12 illustrates the importance of the failure mechanisms in understanding and predicting behaviour. Approaches have been developed successfully to take account of these mechanisms in both tension and compression.

In tension it is crucial to model the development of splitting and delamination at the hole, which can either lead to complete delamination of the specimen, or modify the stress distribution controlling fibre failure. This has been done using finite element analysis with cohesive zone interface elements between all the plies to model delamination [25,28]. Similarly cohesive elements have been included within each ply to model potential splits initiating tangentially to the hole, as seen in the tests. Bi-linear traction-displacement relations are assumed, with a linear interaction criterion between mode I and II. The critical parameters are the Mode I and II fracture energies, which are taken from independent interlaminar toughness tests, and assumed to be the same for delamination and in-plane splitting. The analysis is implemented within the explicit code LS-Dyna. Thermal residual stresses were included. A Weibull approach was used to predict fibre failure. This is based on integrating the fibre direction stresses in the 0° plies in a post-processing operation, and assuming that failure occurs when the value of the Weibull stress-volume integral matches the value obtained in a unidirectional tension test at failure. The Weibull characteristic strength and modulus were obtained from tensile tests on different sized unidirectional specimens tapered to ensure gauge section failure [6]

This approach closely represents the pattern of splitting and delamination damage developing from the hole and at the free edge, as observed experimentally from interrupted tests, and shown in detail elsewhere [25]. It predicts the correct delamination or fibre failure mechanisms and all the trends for strength as a function of varying in-plane dimensions, and thicknesses seen in the tests for both ply-level and sublaminate scaling. The correlation between predicted and measured strengths is shown in Figure 13. The average difference across the 17 sets of results is 7%, and all cases are within 13%. Only independently evaluated properties were used in the analysis, with no fitting parameters. The same approach has also been shown to predict scaling effects successfully in open hole tension for other quasi-isotropic stacking sequences [29].

In tension all fibre failures occurred catastrophically, with no indications of broken fibres on any of the interrupted tests. An approach to fibre failure based on initiation was therefore appropriate. However in compression some microbuckling occurred before catastrophic failure, forming stable kink bands, as clearly shown in Figure 6a. The crucial aspect is therefore determining whether there is sufficient energy to allow these kink bands to propagate.

Soutis *et al.* [26] developed a model where the damage zone of microbuckling surrounded by delamination at the edge of the hole is represented as a through-thickness line crack. This equivalent crack is assumed to carry normal stresses which decrease linearly with the crack closing displacement, $2v$. The length of the equivalent crack represents the length of the microbuckle. When the remote load is increased the equivalent crack grows in length, thus representing microbuckle growth. The evolution of microbuckling is determined by requiring that the total stress intensity factor at the tip of the equivalent crack due to the combination of the remote stress and the stresses acting across the crack equals zero. The model predicts a relation between kink band length and stress that initially increases, but then reaches a peak and decreases. The peak value represents the stress at which unstable propagation occurs, and the corresponding critical kink band length is also predicted.



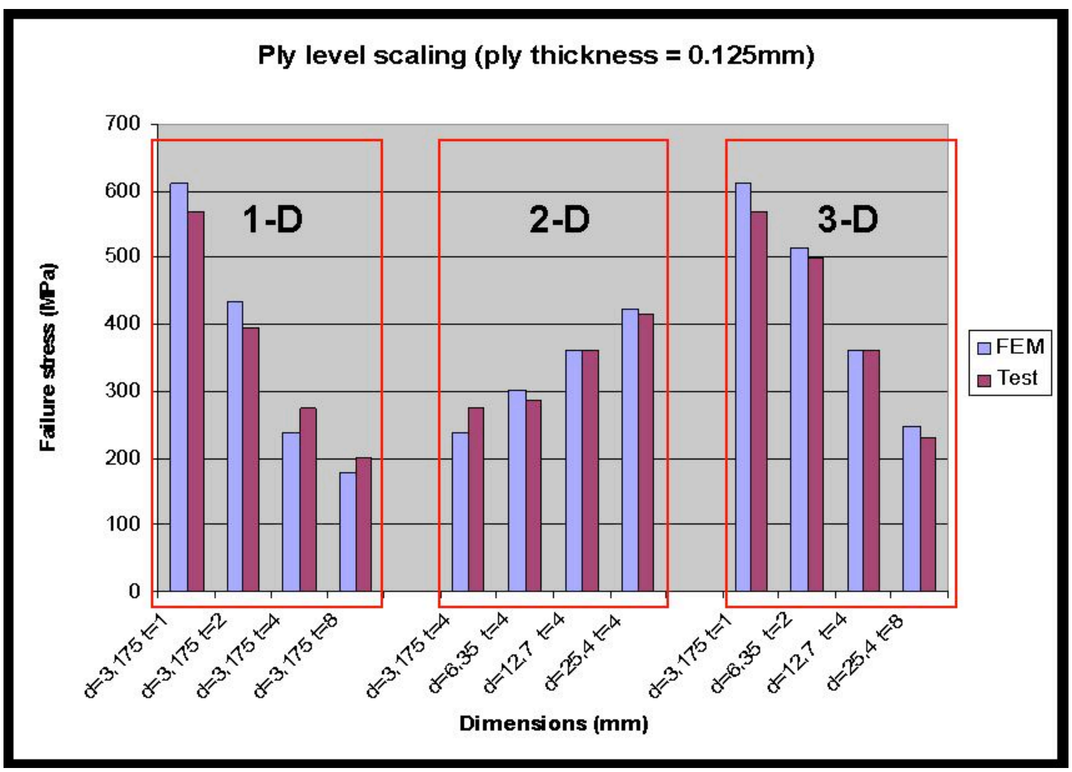


Figure 13. Correlation of open hole tension strength predictions

The model contains two unknown parameters, which can be measured independently: the unnotched strength σ_{un} and the critical crack closing displacement $2v_c$, which is related to the area G_C (fracture energy) under the assumed linear stress - crack displacement curve. For a linear softening cohesive zone law, the critical strain energy release rate G_C is given by

$$G_c = 2\int_0^{v_c} \sigma(v)\, dv = \sigma_{un}\, v_c \qquad (1)$$

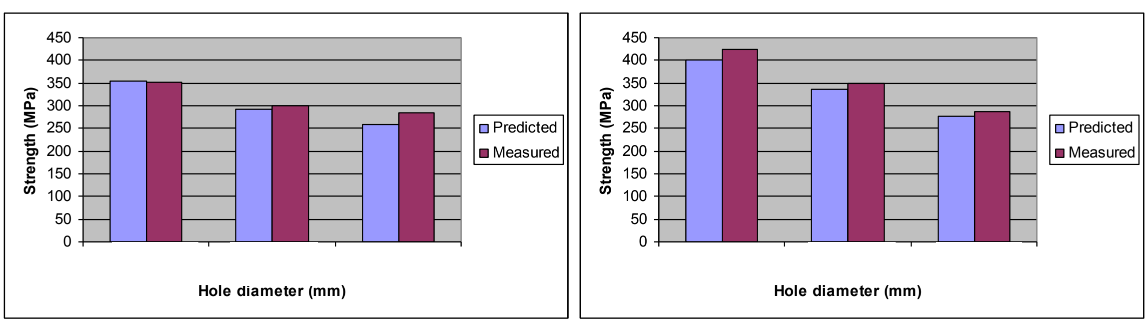
It is assumed that the fracture energy G_C represents the total energy per unit projected area dissipated by fibre microbuckling. Of course other damage modes may occur within this process zone like splitting, matrix plasticity in the off-axis plies and delamination, but the dominant damage mechanism is the fibre kinking or microbuckling.

It has been shown that $2v_c$ may be estimated satisfactorily from the measured kink band width [30]. For the sub-laminate level case the kink-band width w ($=2v_c$) from several optical micrographs obtained by sectioning was in the region of 70 to 90 μm. Using the average of 80 μm with the average measured unnotched strength of the 4 mm thick specimens of 675 MPa in equation (1), gives a critical fracture energy G_C=27 kJ/m^2. Using these values in the kink band propagation model gives the results shown in Fig. 14.

The correlation is very good. The model predicts a stable kink band length of 2.4 mm for the 6.35 mm hole case. This is about the same as that measured in the tests interrupted just before failure, as shown in Fig. 6a, further confirming the validity of the model. It is based on the open hole compressive strength being independent of thickness, consistent with the experimental results shown in Figure 11.

It is also interesting to note that the model gives virtually identical results to those using the average stress criterion fitted to the 6.35 mm hole case, as also shown in Figure 11. The averaging distance used was 2.34 mm, which corresponds closely to the kink band length shown in Figure 6a. However, this is just coincidence, since the stable kink band length varies with hole size whereas the averaging distance is supposed to be a constant, which is usually obtained by fitting the experimental data.

The model can also be applied to the ply-level scaling cases by assuming that the higher strengths are due to increased fracture energy as a result of the additional splitting and delamination. A fracture toughness of 55 MPa√m was determined from the average measured notched strengths [23]. Based on a laminate modulus of 62.7 GPa, this is equivalent to a critical fracture energy of G_C=48.3 kJ/m^2. Using this value gives the strengths shown in Fig.14b for the 4 mm cases. The correlation is good, although it is not based on an independently derived fracture energy as the sublaminate case was. The Equivalent Constraint Model developed by Soutis *et al*. [31-33] could be employed to estimate the additional energy dissipated in matrix cracking and delamination observed around the hole. However, in practice the higher values may actually be due to the reduction in the stress concentration as a result of the splitting shown in Fig. 6b. It should be possible to model this using the same finite element approach as that adopted for tension, including a cohesive zone model for compressive fracture as well. Such an approach should also be able to capture the delamination observed in the 8 mm thick ply level scaled specimens.



a) Sublaminate level scaling b) Ply level scaling

Figure 14. Correlation of open hole compressive strength predictions, 4 mm laminates

5. CONCLUSIONS

Scaled tests on quasi-isotropic IM7/8552 have shown significant size effects in both open hole tension and compression. The approach adopted for changing the thickness is crucial, with ply level scaling giving very different results from sublaminate level scaling because it alters the relative importance of delamination. This can change the failure mechanism, with specimens with thick ply blocks of the same orientation failing by complete delamination before fibre failure in both tension and compression. Sublaminate scaled compressive specimens and large tensile specimens where the plies are dispersed failed in a brittle manner, with relatively little damage. Other specimens showed intermediate behaviour, giving fibre dominated tensile and compressive failures, but with pull-out or push-out between plies accompanied by localised delamination.

The ply level tensile specimens showed a 64% reduction in strength from 1 mm to 8 mm thickness, very similar to the reduction seen in unnotched specimens. The sublaminate specimens showed an 18% reduction between 1 mm and 2 mm, and thereafter no significant change. The latter is the opposite trend to that seen with the unnotched specimens because the damage reduces the stress concentration rather than leading directly to failure. Compression specimens showed no convincing change in strength with thickness except for the 8 mm ply level case, which failed by delamination at 9% lower stress than thinner ones. These results mirror those seen in unnotched compression.

In-plane scaling of 4 mm thick sublaminate tension and compression specimens with dispersed plies showed reductions of 24% and 19% in open hole strength from 6.35 mm to 25.4 mm diameter. The trends are similar, despite very different mechanisms. In tension the damage at the hole decreases with size, reducing the stress relief and leading to a lower stress at which catastrophic failure initiates. In compression there is little damage before failure, and the critical factor is the amount of energy available to allow a microbuckle to propagate. Ply level scaled compression specimens with thick ply blocks showed a similar trend, but higher strength due to the effect of splitting at the hole. Ply level tension specimens all failed by delamination, with a 52% increase in strength from 3.175 mm to 25.4 mm hole size. The same factor of decreasing damage at the hole with increasing size leads to the opposite trend from the sublaminate scaled specimens because the damage causes final failure rather than delaying it.

The open hole tensile strengths are higher than the compressive strengths in all cases except for two of the thicker ply level specimens that failed very early due to delamination. However, the relative performance compared with the unnotched strength is higher in compression in all cases except the largest 4 mm sublaminate case.

These scaling effects can be predicted with models that represent the failure mechanisms accurately. Using finite element analysis with cohesive elements to model splitting and delamination at the hole and a Weibull criterion for fibre failure enabled all the different trends seen experimentally in tension to be captured, with an average correlation of strengths of 7% across 17 sets of data based on the same independently determined material parameters. Using a microbuckle propagation model enabled the sublaminate compression results to be predicted, with an average correlation of 4%. The same model was also applied successfully to the ply-level scaled cases, although would need to include representation of delamination and splitting to capture the full set of results from a single set of input parameters.

Acknowledgements

The authors gratefully acknowledge the support of the UK Engineering and Physical Sciences Research Council, Ministry of Defence and Airbus UK and supply of material by Hexcel.

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