SPECIMEN SIZE EFFECTS ON THE NOTCHED STRENGTH OF COMPOSITE LAMINATES LOADED IN TENSION

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Abstract

Scaling of the open hole tensile strength of carbon fibre-epoxy has been investigated experimentally and numerically including the effects of in-plane dimensions, specimen and ply thickness and layup. Results show that there is a strong size effect, with strength generally decreasing with increasing specimen dimensions and failure mechanisms also changing. Fibre dominated layups show the largest in-plane scaling. Quasi-isotropic laminates with thick ply blocks actually increase in strength with hole size. The ratio of the hole size to ply thickness appears to be a more important scaling parameter than the absolute hole size. Delamination is very important, and depends on this ratio as well as the absolute ply thickness. Finite element analysis simulating the splitting and delamination that occurs at the hole using cohesive zone interface elements, and with a Weibull criterion for fibre failure is able to represent the experimentally observed damage development, and gives excellent predictions for notched strength.

1. Introduction

Notched tensile 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 data from small coupons is often used to design large structures. 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. 2-8] 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. 9, 10]. 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.

This paper presents results of an experimental programme to investigate the effect of specimen size on tensile strength of carbon fibre specimens with a centrally located hole, and comparison with finite element analysis using cohesive zone interface elements. Excellent correlation is obtained for the effects of specimen size, ply block thickness and layup on damage development and strength, and the model is able to explain the experimentally observed trends and failure mechanisms.

2. Experimental

2.1 Test program

Specimens with a centrally located circular hole were tested in quasi-static tension. Constant width (w) to hole diameter (d) and length (l) to hole diameter ratios were used for all specimens, as shown in Fig. 1. The initial tests were quasi-isotropic, with stacking sequence $[45_m/90_m/-45_m/0_m]_{ns}$, with 0° being in the direction of the applied loading. The material was Hexcel IM7/8552, with a baseline nominal ply thickness of 0.125mm.

The subscripts m and n refer to the number of plies of each orientation, and represent two different ways of increasing the thickness of the laminate. Increasing m increases the number of plies of the

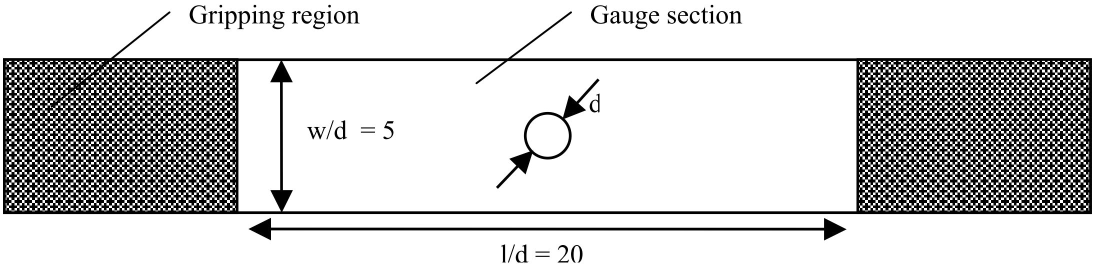


Fig. 1. Specimen Geometry

same orientation blocked together, i.e. increasing the effective ply thickness, referred to as ply-level scaling. Increasing n keeps a constant ply thickness, but increases the laminate thickness by increasing the number of repeated sublaminates, referred to as sublaminate-level scaling. The baseline specimen was 1 mm thick, 16 mm wide, with a gauge length of 64 mm and 3.175 mm diameter hole. The dimensions of the others were scaled up by a factor of 2 each time up to a maximum of 8.

The initial testing matrix included one dimensional scaling where only the thickness of the laminate is increased; two dimensional scaling, where only the in-plane dimensions are increased but the thickness kept the same and three dimensional scaling, where all dimensions are scaled simultaneously.

In-plane scaling tests have also been undertaken on 4 mm thick specimens made from 0.25 mm thick prepreg with the same $[45/90/\text{-}45/0]_{2s}$ quasi-isotropic layup, and for the fibre dominated and matrix dominated layups:

$$[45/0_2/\text{-}45/90/45/0_2/\text{-}45/0]_s$$

and

$$[45/90_2/\text{-}45/0/45/90_2/\text{-}45/90]_s$$

2.2 Quasi-isotropic Results

Results are summarised in Table 1. Failure is taken as being the first significant drop in load (greater than 5%). Thickness scaling gave decreases in strength of 17% for sublaminate and 64% for ply-level scaling for an increase in thickness by a factor of 8. Three dimensional scaling gave decreases in strength with size of 42% for sublaminate and 59% for ply-level scaling. In - plane scaling shows the expected hole size effect for sublaminate scaling, with a 31% decrease in strength. However there was an initially surprising 51% increase in strength over the factor of 8 size range for ply-level scaling where the ply block thickness is 0.5 mm, Fig. 2.

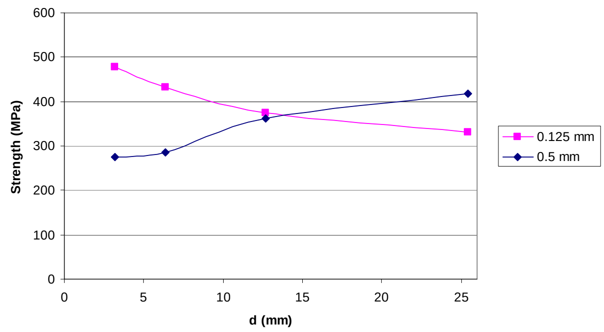
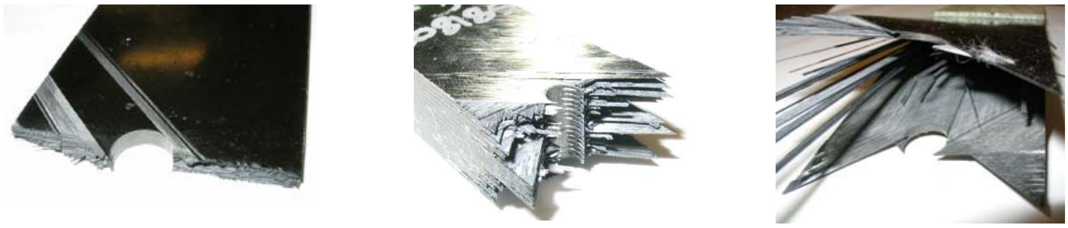


Fig. 2 Effect of ply block thickness on in-plane scaling, 4mm thick quasi-isotropic specimens

There were also differences in the failure mechanism. Sublaminate scaled specimens failed in a brittle manner with a fairly clean fracture for the 12.7 and 25.4 mm hole sizes, but with significant pull-out between plies for the smaller holes. All of the ply level scaled specimens with m = 2, 4, 8 failed by delamination at the -45/0 ply interface except for the m=2, 6.35 mm hole case which failed by pull-out. These failures are shown in Fig. 3. Further details of the experimental program can be found in [11].

2.3 Effect of Ply Thickness on In-Plane Scaling

Sublaminate scaled specimens with 0.25 mm ply thickness showed a similar trend to those with 0.125 mm plies, but were stronger for a given hole size except for the smallest specimen. The results were much closer to the previous ones when plotted against the ratio d/t of hole size to ply thickness, suggesting that this is the key scaling parameter, Fig. 4. This relates to how easily delamination can propagate at the hole edge, as discussed later.



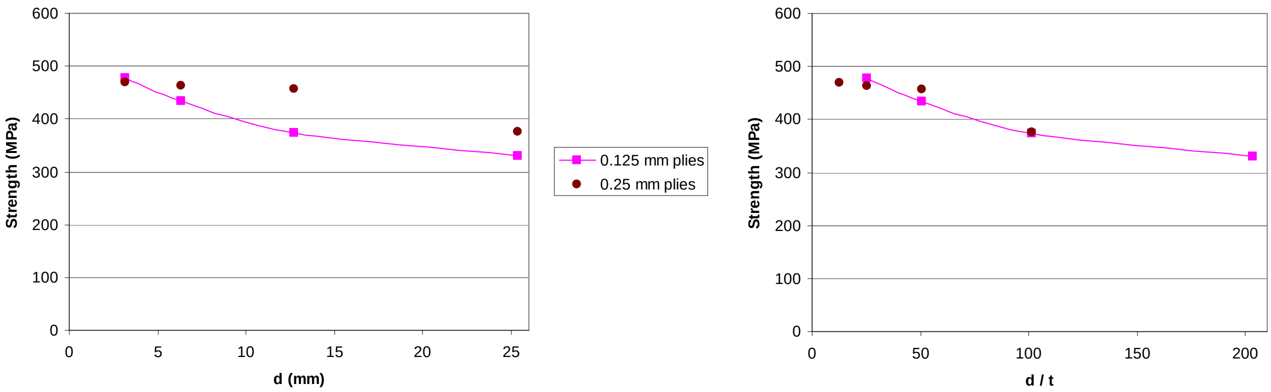
a) Brittle b) Pull-out c) Delamination

Fig. 3. Failure mechanisms

Thickness (mm)	Hole sizes (mm)							
	Sublaminate-level scaling				Ply-level scaling			
	3.175	6.35	12.7	25.4	3.175	6.35	12.7	25.4
1	570				570			
2	500	438			396	498		
4	478	433	374	331	275	285	362	417
8	476			332	202			232

Key to Failure Mechanism: Delamination (green), Pull-out (yellow), Brittle (blue)

Table 1. Failure stresses (MPa) and mechanisms for quasi-isotropic specimens with 0.125 mm plies



(a) (b)

Fig. 4. Quasi-isotropic hole size effect plotted against absolute (a) and relative hole size (b)

2.4 Effect of Layup on In-Plane Scaling

The effect of layup is shown in Fig. 5, with strengths divided by the modulus calculated from laminated plate theory to facilitate comparison. The fibre dominated layup showed an even stronger size effect than the quasi-isotropic, whilst the matrix dominated ones showed only a small effect, reflecting the relative importance of notch blunting due to 0° ply splitting in the different layups.

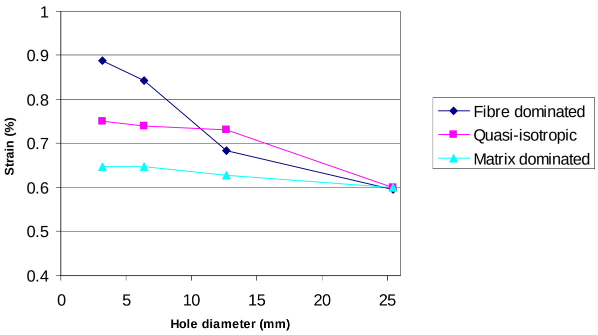


Fig. 5. Effect of layup on in-plane scaling, 0.25mm plies

3. Finite Element Analysis

3.1 Approach

Three dimensional finite element analysis was carried out using the explicit code LS-DYNA with interface elements to model the occurrence of sub-critical damage and failure [12]. A typical mesh is shown in Fig. 6. Interface elements were inserted between every ply to model delamination and at locations within each ply where the splitting was expected, as shown in Fig. 6.

A stress based Weibull failure criterion was used to predict fibre failure:

$$\sum_{i=1}^{\text{Total No of Solid Elements}} \left(\frac{\sigma_i}{\sigma_o}\right)^m V_i \quad \geq \quad 1 \qquad (1)$$

where σ_i is the stress in the fibre direction and V_i is the volume of element i, and σ_o and m are the Weibull modulus and characteristic strength for 1 mm^3 of material.

3.2 Correlation

The numerical predictions are shown compared with the experimental results for 0.125 mm plies in Fig. 7. It has not been possible yet to run the largest sublaminate level cases. The predicted strengths correlate extremely well with the test results, capturing all the trends and the wide variation in failure stress levels. In particular the opposing trends of decreasing and increasing strength for 4 mm thick sublaminate and ply-level in-plane scaled specimens are both captured by the analysis. The failure modes are also correctly predicted. It should be emphasised that this analysis is based on independently measured properties with no averaging distance or other fitting parameters.

Fig. 8 shows the correlation for the 0.25 mm ply specimens. Again the trends and the differences in strength as a function of layup are correctly captured.

3.3 Importance of Delamination

Detailed observations from the experiments and the analysis help to explain the results in terms of the sequence of damage development. Delamination is crucial, and this becomes more difficult with increasing hole size [13]. This explains both the conflicting trends shown in Fig. 2. For ply-level scaling with thick ply blocks, failure is controlled by delamination, and so the strength increases with hole size. On the other hand for sublaminate scaling with thin ply blocks delamination is not catastrophic, but promotes splitting which blunts the notch, leading to a decrease in strength with hole size.

4. Conclusions

There is a strong size effect in open hole tension, with both strength and failure mechanisms changing with specimen dimensions. Thickness scaling of quasi-isotropic specimens with 0.125 mm plies gave decreases in strength of 17% for sublaminate and 64% for ply-level scaling for an increase in thickness by a factor of 8. Three dimensional scaling gave decreases in strength with size of 42% for sublaminate and 59% for ply-level scaling. In-plane scaling showed the expected hole size effect for sublaminate scaling, with a 31% decrease in strength. However there was a 51% increase in strength over the factor of 8 size range for ply-level scaling.

Quasi-isotropic specimens with 0.25 mm plies were mostly stronger than those with 0.125 mm plies. Results for in-plane scaling were quite similar when plotted against the hole size to ply thickness ratio, suggesting that this is the important scaling parameter rather than the absolute hole size.

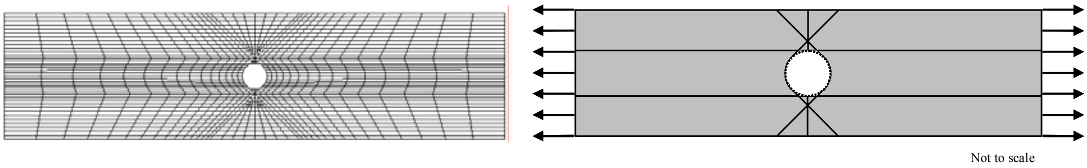
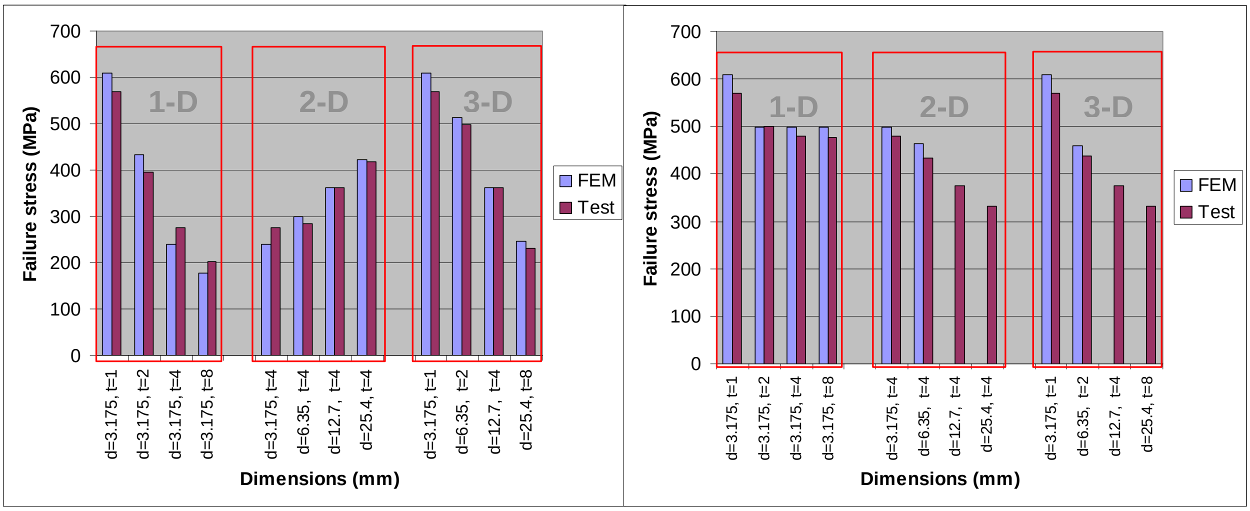


Fig. 6. Finite element mesh and location of potential split sites



(a) (b)

Fig. 7. Correlation of analysis and test for (a) ply-level and (b) sublaminate-level scaling

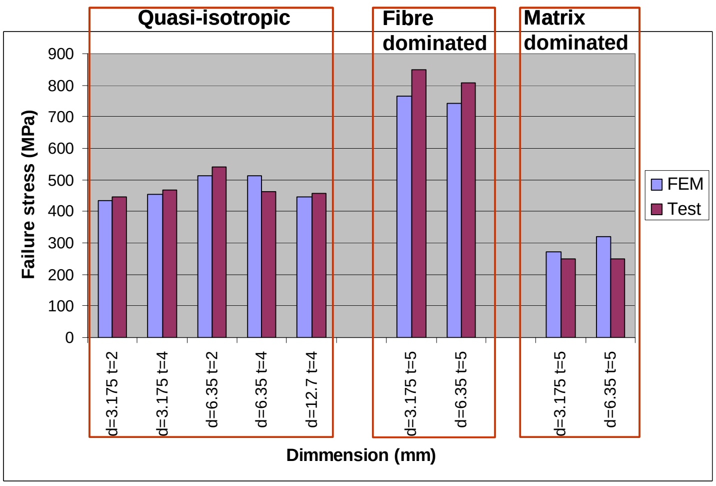


Fig. 8. Correlation of analysis and test for 0.25 mm ply specimens

The fibre dominated layup showed a stronger in-plane size effect than the quasi-isotropic, whilst the matrix dominated ones showed only a small effect.

Finite element analysis using cohesive zone interface elements to model the splitting and delamination at the hole was able to represent the experimentally observed damage development. A Weibull approach worked well for fibre failure. The predicted strengths and failure mechanisms correlated very closely with the experimental results, capturing all the trends and the wide variation in failure stress levels. The opposing trends of decreasing and increasing strength for sublaminate and ply-level in-plane scaled specimens are successfully captured by the analysis. These conflicting results can both be explained in terms of the effect of the ratio of hole size to ply thickness on delamination adjacent to the hole.

Acknowledgements

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