Int J Fract (2009) 158:169–181
DOI 10.1007/s10704-009-9333-8

ORIGINAL PAPER

The open hole tensile test: a challenge for virtual testing of composites

Stephen R. Hallett · Ben G. Green ·
Wen-Guang Jiang · Kin Hei Cheung ·
Michael R. Wisnom

Received: 6 November 2008 / Accepted: 25 February 2009 / Published online: 19 March 2009

Abstract The open hole tension strength is an important parameter for composite structures since it is can be a limiting factor in design. It is also difficult to characterise and predict through analytical or numerical methods since there exists a wide variation in experimental results depending on testing configuration. Here a range of such variations are presented and the behaviour explained in terms of the development of sub-critical damage in the form of intra-ply splits and inter-ply delaminations and their interaction with each other and also with fibre failure. A finite element based numerical analysis technique has been developed and applied to each case in turn, successfully predicting the failure modes, trends and strengths. This is sufficiently robust to form the basis for a virtual testing framework for the open hole tensile strength of composite materials.

S. R. Hallett (✉) · K. H. Cheung · M. R. Wisnom
Advanced Composites Centre for Innovation and Science,
University of Bristol, Queens Building, University Walk,
Bristol BS8 1TR, UK
e-mail: stephen.hallett@bris.ac.uk
URL: www.bris.ac.uk/composites

B. G. Green
Gurit UK, St Cross Business Park, Newport,
Isle of Wight PO30 5WU, UK

W.-G. Jiang
School of Mechanical Engineering, Yanshan University,
Qinhuangdao, PR China

Keywords Open hole tension · Composites · Scaling · Virtual testing · Interface elements

1 Introduction

The case for the requirement for predictive analysis tools is now sufficiently strong that it is widely accepted as being necessary to progress the development of advanced composite structures. The shear scale of testing required to go from simple coupon data to certified aircraft structure using the typical pyramid of testing (MIL HDBK 17 2002) means that predictive analysis tools have clear benefits in terms of cost reduction. If analysis is to replace some of the testing in this process however it is going to have to become a truly representative virtual test. It is of course crucially important that techniques making up any such virtual testing procedure undergo a rigorous validation to ensure accurate representation of test results. Virtual testing is however more than just stress analysis (Davies and Ankersen 2008; Cox and Yang 2006; Gonzalez and Llorca 2007). In order to predict complex structural behaviour it requires efficient, accurate models for material stress–strain behaviour. In the case of composites this requires prediction of the onset of damage and the evolution of material properties as damage increases. It is only through such models that engineers will be able to assess the true suitability of materials for use at the component level.

The open hole tensile test is important in deriving allowable stress levels for use in component design since open hole strength can be a limiting factor. It is also one of the simplest tests that combines unavoidable geometrical interaction with material properties, being cheap to undertake since it requires only limited machining of flat laminates. Thus it is on the border between a true materials test and a simple or small scale structural test. For this reason it is also sometimes used for material ranking to give an early indication of a material's structural performance. Also it is representative of common features in composite components causing stress concentrations such as fastener holes and cutouts. These attributes therefore make it a good test to try and replicate through virtual testing techniques. The complexities and variation in results obtained with variation in testing configuration however mean that this is a significant challenge.

Although standards exist for open hole tensile strength (ASTM 2002; SACMA 1994), results can be strongly dependent on testing configuration e.g. the well known hole (notched) size effect (Awerbuch and Madhukar 1985; Whitney and Nuismer 1974) or effect of layup (Lagace 1986; Walsh and Ochoa 1993). This creates difficulties for designers and modellers alike since small changes in parameters will affect data values produced. There is thus an increased requirement for predictive analysis to avoid expensive tests but paradoxically many predictive techniques require empirically derived calibration factors. Models which take account of the progressive damage development in the specimen are able to overcome some of these limitations (Chang and Chang 1987; Camanho et al. 2007).

Work at the University of Bristol has investigated a number of the different factors causing variations in open hole tensile strength and failure mode. A finite element modelling technique has been developed which has been able to capture variations both in terms of the failure mechanisms and the absolute values of strength. Having noted the success of this technique as a general and robust virtual testing capability for open hole tension loading of composites it should also be noted that due to the complexity these models, they can be extremely computationally intensive. The challenge remains to implement this approach in a simplified form which is able to model components at an industrially relevant scale. This paper summarises a number of the effects which have been investigated experimentally and characterised as well as predicted using the finite element analysis technique.

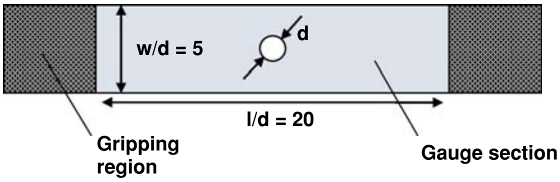


Fig. 1 Baseline specimen geometry

2 Experimental overview

All cases presented here have been tested using specimens manufactured from unidirectional carbon fibre/epoxy prepreg, IM7/8552. Most of these have a nominal ply thickness of 0.125 mm with the exception being the directed layups (see Sect. 4.4 below). The simplest quasi-isotropic laminate to be produced in this configuration is with one ply in each of the fibre directions in a symmetric layup. The baseline stacking sequence was chosen to be $[45/90/\text{-}45/0]_S$. This was selected as it is the stacking sequence least likely to fail by edge delamination with a 45° ply on the surface as per industrial practice. This was determined using a virtual crack closure technique (VCCT) to examine all permutations of ±45, 0 and 90° plies (Hallett et al. 2008). Figure 1 shows the relative in-plane dimensions used. A specimen hole diameter to width ratio of 5 was chosen as at this width the linear elastic stress concentration has reduced to the far field stress at the specimen edge. For the baseline case a 3.175 mm (1/8″) hole diameter was used. Specimens were loaded quasi-statically in tension in the 0° fibre direction. In all cases a load drop of 5% or greater was taken to be the point of failure. This introduces the baseline configuration but in the work presented here nearly all of these so called baseline parameters have been varied and their effect on strength investigated.

The sub-critical damage which develops at relatively low load levels prior to ultimate failure in open hole tensile specimens has been identified as being significant for determining the specimen strength and final failure mode. This has been described in some detail elsewhere (Hallett et al. in press) but owing to its importance and implications for virtual testing methods it is worth a brief overview of the generic damage processes here.

The first damage to occur in a specimen is matrix cracking. This starts at the free edge of the hole in the form of splits within the plies. These form in the fibre directions, typically at a point tangential to the hole, except in the case of the 90° ply where cracking is more extensive. Initially these splits are isolated and distributed around the hole edge but as loading increases they start to join up with each other by means of delaminations occurring between adjacent plies. This forms a typical triangular delamination area between the surface 45° split and the split in the 90° ply below. Figure 2 shows the matrix crack and delamination formation process schematically as well as a typical C-scan of a test interrupted before ultimate failure. The length of the splits also increases with increasing applied load. In the case of the 0° ply splits the growth in split length causes a decrease in the stress concentration and hence a blunting of the notch. In the case of the surface 45° split this eventually crosses the full width of the specimen and a triangular region of delamination is also formed at the point where this split meets the specimen edge (also visible in Fig. 2). A critical event in the development of the sub-critical damage is the point at which the delaminations at the hole and specimen edge joint up. It is at this point that the delamination can pass through the thickness of the laminate through a 90° crack and continue propagating along the 90/45 interface and ultimately reach the 0° ply. At this point the delamination can no longer continue to pass through the thickness of the laminate due to the absence of full width splits. It therefore propagates along the length of the specimen causing a major delamination area which is accompanied by a significant drop in load.

Although this is a generic description of the development of sub-critical damage, not all specimens follow this sequence through to completion, depending on variations in the parameters described above. This variation in geometric parameters also causes a variation in the rate of damage development and progression. As this damage is developing in the specimen, so the load on the laminate is also increasing. Eventually this load causes sufficient fibre direction stress in the load bearing 0° plies so as to cause fibre failure. The relative amount of sub-critical damage at the point at which the fibre failure stress is exceeded is a controlling factor on the strength and also failure mode of a given configuration. Three distinct failure modes have been identified for open hole tensile failure. The first is a brittle failure mode in which sub-critical damage development is limited and a relatively clean fracture surface is obtained, failing all plies (except 90°) by fibre fracture, perpendicular to the loading direction. The second is a pull out failure mode in which the sub-critical damage has progressed across the full width of the specimen and some of the off-axis plies are able to pull out from between each other without failing by fibre fracture. The third is a delamination failure mode in which the sub-critical damage has reached the 0° ply interface and propagates catastrophically back to the specimen grips without fibre failure. These different failure mechanisms are shown in Fig. 3.

It is the interaction between the different sub-critical damage mechanisms, ply splitting and delamination, and their interaction in turn with fibre failure that give the open hole tensile test the complexities which are explored and compared in this paper. When specimen parameters such as size, stacking sequence, layup or width are varied, so the interaction between the different damage mechanisms is varied too. This results in variable behaviour with specimen configuration which is what makes it such a notable challenge to predict open hole tensile strength from first principals using virtual testing techniques.

3 Analysis overview

If any analysis technique is to be sufficiently robust so as to be able to capture the variation in strength caused by variation in testing configuration using independent material parameters then it is necessary to include in the analysis such mechanisms as are causing this variation. It is with this in mind that a procedure has been developed in the finite element software LS-Dyna that explicitly accounts for the intra-ply splits, inter-ply delaminations and fibre failure and their associated interaction for predicting open hole tensile strength of composites (Hallett et al. in press; Jiang et al. 2007; Hallett and Wisnom 2006). This uses a solid element model with cohesive interface elements inserted both within the plies to model the ply splits and between each ply to model the delaminations. The ply split locations are chosen from a knowledge of the critical locations in experimental results and are generally inserted tangentially to the hole and at the point of highest stress concentration in the 90° ply. This results in a number of highly deformed elements around the hole edge which are subsequently removed. This does not affect the results since the development of the intra-ply splits sufficiently reduces the local stress concentration at the hole such that its exact shape is not significant. Figure 4

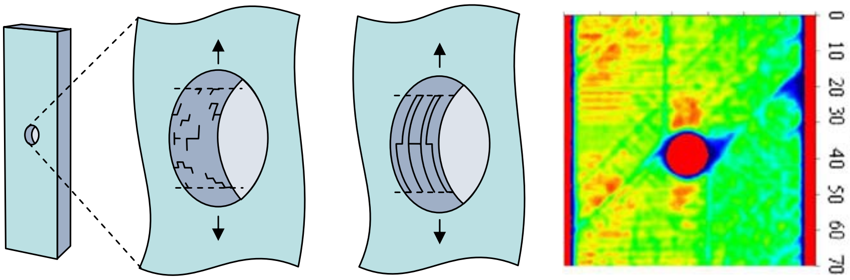


Fig. 2 Schematic showing development of damage at hole edge and c-scan of a specimen interrupted during loading

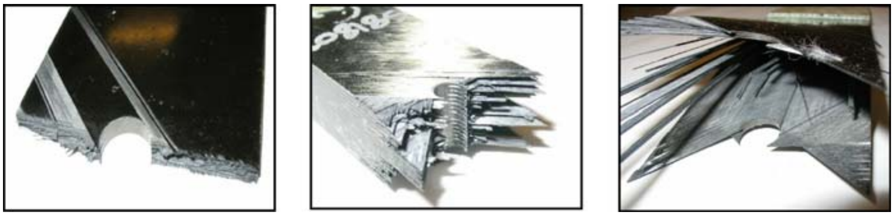


Fig. 3 Three different failure modes identified from experimental results

Brittle Pull-out Delamination

shows a typical mesh and the insertion of the interface elements into the model. Each ply block has been modelled with a single element through the thickness. Although this is not sufficient to capture the case of a tunnelling crack, the modelling of matrix cracks here is important only in so far as they are related to the delaminations. Previous work (Jiang et al. 2007) has indicated that results using this technique are not sensitive to the number of elements through the thickness in this case. Load was applied by means of linearly increasing prescribed displacement at the end of the specimen. In each case a model was run to find the stress at which significant delamination was predicted. With increasing displacement this occurred in all cases since the fibre failure prediction capability was implemented by post-processing of the stress results from the LS-Dyna model. The individual failure patterns are described in more detail later in this paper.

Fibre failure is predicted using a statistically based Weibull failure criterion. This is based on the assumption of equal probability of survival between two specimens of different size being related through Eq. 1.

$$\int_{V_1} \sigma^m \cdot dV = \int_{V_2} \sigma^m \cdot dV \tag{1}$$

Using a set of reference values from tests on unidirectional material ($m = 40.1$ and $\sigma_{unit} = 3131$ MPa for 1 mm^3 of the IM7/8552 material used here) the fibre failure stress of any other volume of material can be predicted (Hallett et al. in press). This was implemented as a post-processing routine on analyses that had been run to predict the delamination stress. Those analyses for which the Weibull criterion was satisfied before significant delamination were deemed to be either brittle or pull out failure modes i.e. those dominated by fibre failure. Those analyses in which there was significant delamination and an associated load drop greater than 5% before the Weibull criterion was satisfied were deemed to have failed by the delamination failure mode.

4 Experimental results and virtual testing predictions

A range of experimental cases have been studied which show a very clear variation in open hole tensile strength. In each case the variation in strength can be explained by the effect of the development of sub-critical damage. Each configuration was modelled using the technique described above with a single set of input parameters across all analyses, summarised in Table 1. This allows a greater insight to be gained into the role that the sub-critical damage plays in the variation in strength which in all cases was correctly predicted.

4.1 Thickness scaling regime

A comprehensive testing programme was carried out to fully investigate the effect of scaling on notched tensile strength (Green et al. 2007). In order to more clearly

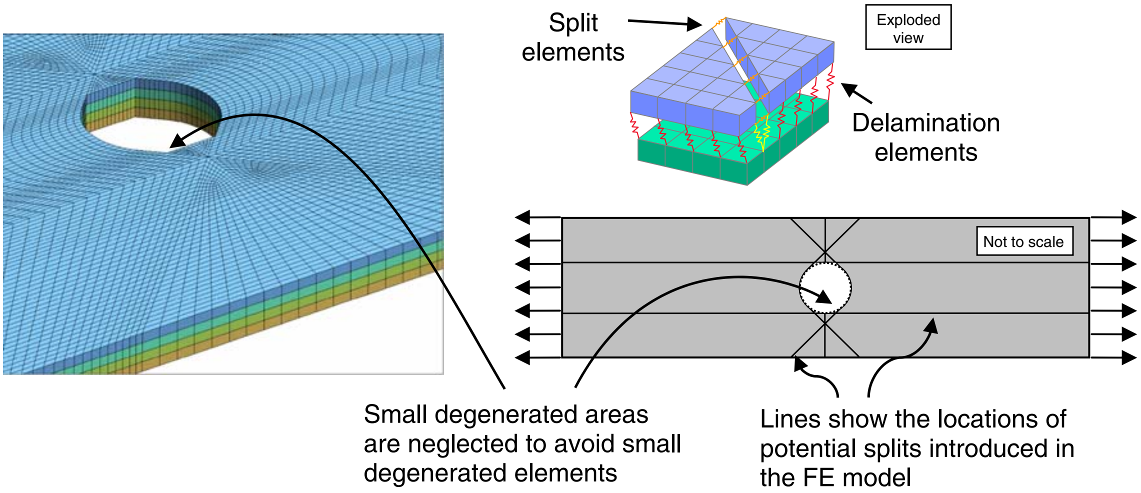


Fig. 4 Finite element model showing mesh details and also insertion of interface elements

Table 1 Material properties used in finite element analyses

IM7/8552 individual ply properties (1 = fibre direction)							
E_{11}	$E_{22} = E_{33}$	$G_{12} = G_{13}$	G_{23}	$\nu_{12} = \nu_{13}$	ν_{23}	α_{11}	$\alpha_{22} = \alpha_{33}$
161 GPa	11.4 GPa	5.17 GPa	3.98 GPa	0.32	0.436	$0.0°C^{-1}$	$3 \times 10^{-5}°C^{-1}$
Interface element properties							
G_{IC}	G_{IIC}	α	σ_I^{max}	σ_{II}^{max}			
0.2 N/mm	1.0 N/mm	1.0	60 MPa	90 MPa			

show the different sources of variation in strength and hence challenges that this poses for virtual testing this is examined as a series of individual cases here.

In order to increase the thickness of a laminate it is necessary to increase the number of plies. This can be done either by repeating the baseline sub-laminate block, i.e. $[45/90/–45/0]_{ns}$ which is termed sub-laminate scaling, or by increasing the number of plies in each direction which are laid down together, i.e. $[45_m/90_m/–45_m/0_m]_s$, for which the term ply level scaling has been used. From the baseline 1 mm thick specimen with a single ply block thickness and single sub-laminate, m and n = 1, both scaling methods were used to increase the thickness by factors of 2, 4 and 8.

The 1 mm specimen failed with a pull out type mode and a strength of 570 MPa. Increasing the number of sub-laminates in the half laminate to two (n = 2, 2 mm thick) caused a reduction in strength to 500 MPa. For n = 4 and 8 the strength further reduced to 478 and 476 MPa respectively. Increasing the thickness from the same 1 mm baseline specimen by the ply level scaling method caused a more substantial and continued reduction in strength; 396, 275 and 202 MPa for m = 2, 4 and 8 respectively. All of these cases failed by the delamination mode.

Looking at the predictions from the analysis it can be seen that these trends are well captured. Figure 5 compares the results with those from the tests. To more clearly understand the variation in strength with different thickness scaling regime one must look to the development of the sub-critical damage. This is shown from the analysis for the 4 mm thick cases of both the sub-laminate (Fig. 6) and ply level scaled specimens (Fig. 7). The 4 mm thick sub-laminate specimen was predicted to fail by fibre failure. Figure 6 shows a plot of the predicted delamination at each interface in the half model at the point at which the Weibull criterion was satisfied. The dark areas represent each of the fully failed interface elements at a given ply interface. Also shown is the splitting within all plies of each sub-laminate. It can be seen that the sub-critical damage is largely restricted to the first sub-laminate from the

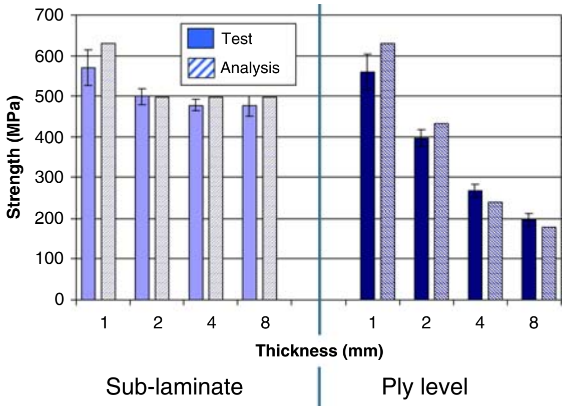


Fig. 5 Effect on strength for different thickness scaling regimes

surface. This is because the presence of the first 0° ply obstructs its passage through the thickness of the laminate. It was noted that there must be some small amount of damage in the other 0° plies, otherwise the strength would be lower—presumably softening but not complete failure of the interface elements. Even though the amount of sub-critical damage is relatively small it still has some notch blunting effect, thus causing a strength greater than the basic material strength multiplied by the linear elastic stress concentration factor. As the number of sub-laminates is increased so the effect of this notch blunting is reduced since it is restricted to the first sub-laminate. For the 4 mm ply level scaled specimen the analysis predicted a delamination type failure. In Fig. 7 the development of sub-critical damage is shown with increasing applied load. It can be seen that the first damage predicted to occur is the small triangular regions of delamination at the intersection of the surface 45° split and the hole and free edge. This develops into a full width delamination. This is the point of maximum stress after which the delamination is able to progress through the thickness of the laminate and reach the 0° ply interface where it propagates back to the grips. All of the 2, 4 and 8 mm ply level scaled specimens failed by delamination and were predicted to do so by the analysis. The decreasing strength can be explained through simple fracture mechanics arguments showing the increase in available energy to drive the delamination with increasing ply block thickness.

4.2 In-plane scaling

Further tests were done in which the open hole tension specimens were scaled in the in-plane direction only (Green et al. 2007). In this case the 4-mm thick specimen was taken as the baseline, with a 3.175 mm hole diameter (and hence w and l) scaled by factors of 2, 4 and 8 up to 25.4 mm keeping thickness constant. This was done for both the sub-laminate and ply level scaling methods. The smallest sub-laminate scaled specimen (3.175 mm hole diameter) exhibited the pull-out failure mechanism. As specimen size increased so there was a transition to the brittle failure mode. Results for the sub-laminate level scaled specimens followed the well documented hole size effect and were shown to have a good fit to the Whitney–Nuismer average stress criterion (Whitney and Nuismer 1974). This reduction in strength can be explained in terms of the reduction in notch blunting from the sub-critical damage at the hole which reduces in relative terms as the ply thickness to hole diameter ratio decreases (Wisnom and Hallett 2009). The increasing volume of material also causes a reduction in fibre direction strength as captured by the Weibull statistical effect.

The ply level scaled specimens in contrast all failed by the delamination mode. In this case an increase in strength with increasing in-plane dimensions was observed which has not been reported by other authors. The explanation for this is however still consistent with other results presented here. The same effect of decreasing sub-critical damage at the hole edge with decreasing hole diameter to specimen width ratio occurred as for the sub-laminate level scaled specimens. In this case since the final failure mode is caused by delamination, which is a propagation of the sub-critical damage, the delay in onset of this damage caused the specimen strength to increase.

Since the numerical analysis predicts the sub-critical damage that occurs in the specimen, which is important in driving the observed size effects, the models capture very well both the traditional hole size effect of the sub-laminate level scaled specimens and the newly observed trend for the ply level scaled specimens as shown in Fig. 8.

4.3 Stacking sequence

Since it has been shown that the progression of the damage through the thickness of a laminate is important, it can be expected that the order in which the ply directions are orientated through the thickness will affect results. Using the virtual testing technique all

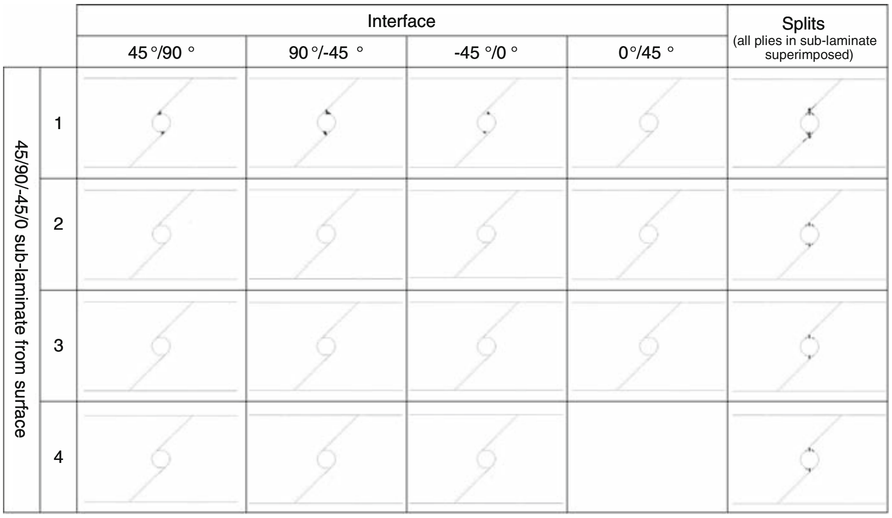


Fig. 6 Sub-critical damage development at predicted failure stress for 4 mm thick sub-laminate scaled specimen

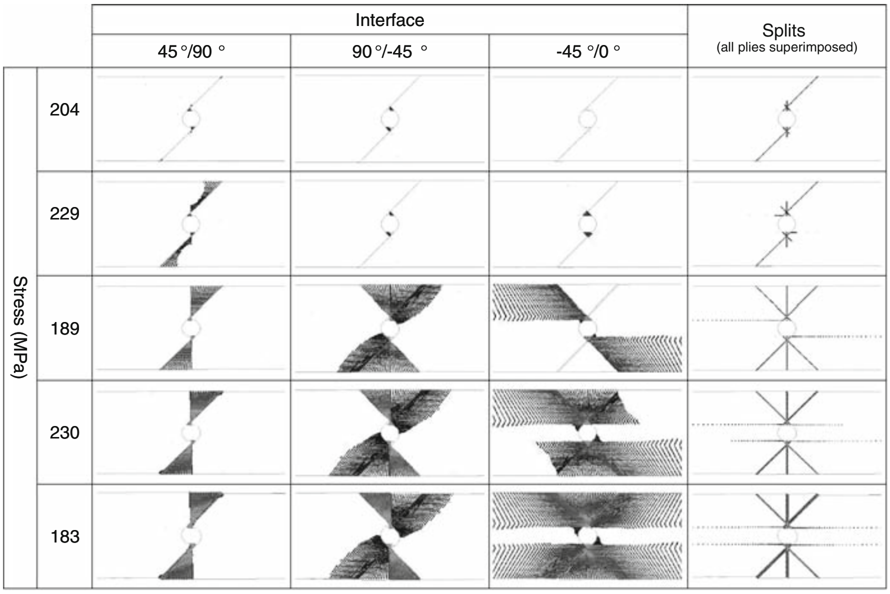


Fig. 7 Sub-critical damage and development of delamination with increasing applied displacement for 4 mm thick ply level scaled specimen

12 permutations of 45, 90, −45 and 0° plies in a 1 mm thick symmetric laminate were analysed to predict their strength (Hallett et al. submitted). All laminates were predicted to fail by fibre dominated failure modes (pull-out or delamination). The analysis did however show two distinct groups of failure strength. Laminates with 0° plies on the surface or centre-line had about 20% greater strength than those that didn't. Again this can be explained by the sub-critical damage development. The reduced constraint of the 0° plies on the surface or the thicker ply blocks created by having the 0° plies symmetric about the centre-line allowed greater splitting and hence notch blunting which led to an increased strength. This could be clearly seen on plots of the splitting damage in these laminates (Hallett et al. submitted). For all cases a delamination stress could also be calculated since the Weibull failure criterion was only applied after the analyses were complete as a post-processing routine. Since the interaction between delamination and fibre failure is of interest, two stacking sequences showing different ratios between stresses for these modes were selected for thickness scaling to 2 mm thick by the ply level scaling method. The first, $[-45/45/90/0]_S$, had the highest predicted fibre failure stress and the smallest difference to the predicted delamination stress and the second, $[90/-45/0/45]_S$,

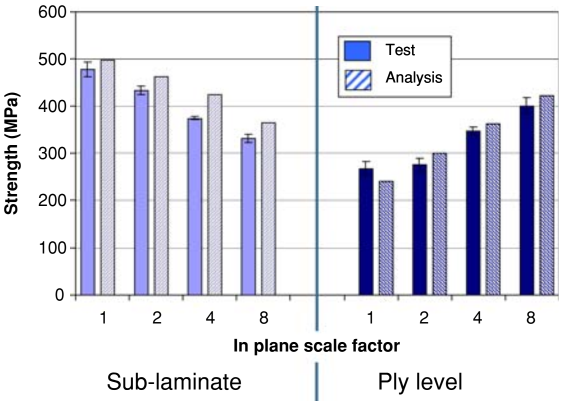


Fig. 8 Effect of in-plane scale factor on strength for sub-laminate and ply level scaled specimens

had one of the lowest predicted fibre failure strengths and the greatest difference to the delamination stress. By increasing the ply block thickness the propensity to delaminate was increased thus enhancing the interaction between the delamination and fibre failure. In the case of the first stacking sequence, due to the small difference between the failure stresses in the two modes, increasing the ply block thickness brought the predicted delamination strength below that of the predicted fibre failure stress and thus it exhibited a change in failure mode and also an associated reduction in strength. In the case of the second laminate there was initially a greater difference between predicted fibre failure stress and delamination. When the ply block thickness was increased it did reduce the predicted delamination stress but not to below that of the fibre failure stress, thus there was no significant decrease in strength. Each of these stacking sequences was tested at 1 and 2 mm thick as per the virtual test cases and the corresponding results and failure modes can be seen in Fig. 9.

4.4 Layup

As well as changing the order of the plies within a stacking sequence it is of course possible to change the relative percentages of plies in the given orientations. This will naturally cause a change in both stiffness and strength. Whilst these changes in laminate properties perhaps have a more obvious relation to the changes in testing configuration than those presented for scaling and stacking sequence effects, there remains a substantial challenge to virtual testing due to the complex nature of the damage evolution. In this case it will be seen that the generic description of damage development previously given for a quasi-isotropic laminate does not necessarily hold true and the virtual testing should be sufficiently robust to take account of this.

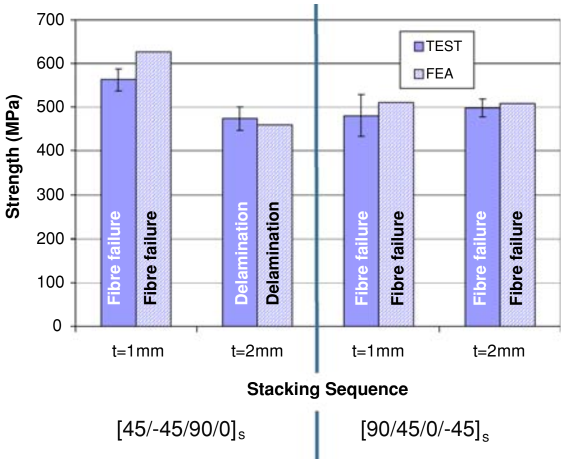


Fig. 9 Effect of stacking sequence on strength for 1 and 2 mm thick ply level scaled specimens

In this case two laminates were considered, one fibre dominated and the other matrix dominated. These had percentages of fibres in the 0/±45/90 directions in the ratios of 50/40/10 and 10/40/50 respectively. The actual stacking sequences were $[45°/0°/0°/-45°/90°/45°/0°/0°/-45°/0°]_S$ for the fibre dominated layup and $[45°/90°/90°/-45°/0°/45°/90°/90°/-45°/90°]_S$ for the matrix dominated layups. The test specimens were manufactured from the same layup but rotating the panel through 90° before cutting the test specimens. In this case a pre-preg with a nominal 0.25 mm ply thickness was used. This layup gave a 5 mm panel thickness. It should be noted that in order to get the required directional layup some blocking of the plies is inevitable. As was seen for the quasi-isotropic layups this will have knock on effects for the failure process. Here specimens with a 3.175 mm hole diameter were tested, giving a width of 16 mm to preserve w/d= 5.

The failure mechanism of the fibre-dominated laminates was classed as delamination as the specimens showed a characteristic drop on the load-displacement curve associated with large scale delamination but still had residual load carrying capacity due to the remaining 0° ply ligaments. In general these fibre-dominated laminates showed considerably different delamination characteristics compared to the quasi-isotropic ones, due to the large number of 0° plies present. Figure 10 shows the free edge of a specimen immediately after the first load drop. The extensive delaminations can clearly be seen, but in this case there are multiple delaminations throughout the thickness, either side of the 0° ply blocks, compared the single delamination interface (symmetric) in the quasi-isotropic specimens. Delamination generally occurred very suddenly, without the preceding stable propagation of the damage to the specimen edge and through the thickness seen in the quasi-isotropic laminates. The average failure stress was 824 MPa with a 2.17% coefficient of variation.

The matrix-dominated laminates behaved very similarly to the quasi-isotropic ones. The damage initiated at the hole in the form of isolated cracks and delaminations, before joining up to form more extensive delaminations between the off-axis plies around the hole edge. As with the fibre-dominated lay-up, the damage was more evenly distributed through the thickness of the laminate at the hole boundary, with the 0° plies not arresting the propagation of the damage as much as in the quasi-isotropic laminates. The damage then propagated across the width of the specimen, and was visible at the specimen edge prior to failure (Fig. 11). The failure mechanism can be described as pullout. The full width delamination did cause a drop on the load curve but not sufficient to trigger the 5% criterion imposed. It should however be noted that two out of six specimens tested showed an ability to carry a small amount of load post-failure; the other four showed a complete, instantaneous failure. This indicates that there is a significant amount of sub-critical damage and that this configuration is probably on the transition between delamination and pullout failure. The average failure stress was 249 MPa with a 2.38% coefficient of variation.

The analysis was applied to these tests. For the fibre dominated layup this predicted a delamination failure at 765 MPa. As with the experimental results the nature of the delamination failure was noted to be considerably different to the quasi-isotropic case. This is shown in Fig. 12 for the fibre dominated layup and the delamination pattern should be compared back to that shown in Fig. 7 for a quasi-isotropic laminate. It can be seen that the major delamination event causing the drop in the load propagated away from the hole in the direction of loading. Prior to this there is little stable damage growth across the width of the specimen which may explain the apparent sudden failure in the experimental result. It should also be noted that this delamination occurs at all interfaces adjacent to the 0° ply blocks as was observed in the tests.

The matrix dominated layup was also predicted to fail by delamination, at 272 MPa. The test result was described as a pullout type failure, but as noted, was thought to be on the transition between pull out and delamination. It can also be noticed that the analysis is similarly on a transition point. The Weibull failure criteria is satisfied at 210 MPa, after the maximum load of 272 MPa, but before the delamination has propagated fully back to the grips (104 MPa), as can be seen in Fig. 13. Whilst the analysis result has predicted failure to occur on the wrong side of the delamination/pull-out transition, the quantitative results are still in good agreement, see Fig. 14. Also shown in Fig. 14 for comparison is the result for the sub-laminate level scaled quasi-isotropic laminate with the same hole size. In this case the thickness is 4 mm since 5 mm was not tested or analysed but as can be seen from Fig. 5 once this thickness is reached results are independent of thickness.

4.5 Specimen width to hole diameter ratio

The final variation in specimen configuration to be discussed here is that of specimen width to hole diameter ratio. In the baseline quasi-isotropic configuration a width to diameter of 5 was chosen so as avoid any interaction between the stress concentration at the hole edge and the specimen edge. Using linear elastic assumptions this is normally taken to be sufficient to allow the stress at the free edge to be equal to the far field applied stress. It has however been shown through the previous investigations that the assumption of linear elastic behaviour is not necessarily correct. In a number of cases it has been the event of the damage at the hole edge and the specimen edge joining up which has precipitated ultimate failure. It could therefore be expected that increasing this distance over which the damage has to join up before it can propagate would increase the strength of a specimen. This would most likely be the case for the ply level thickness scaled specimens which failed by delamination and specimens which exhibited the pull out failure mode.

Tests were therefore carried out on specimens in which the width to hole diameter ratio (w/d) was increased from the baseline value of 5 to 10 (Cheung and Hallett 2008). For these tests 2-mm thick laminates

Fig. 10 Free edge of a fibre dominated layup specimen interrupted after first load drop showing significant delamination

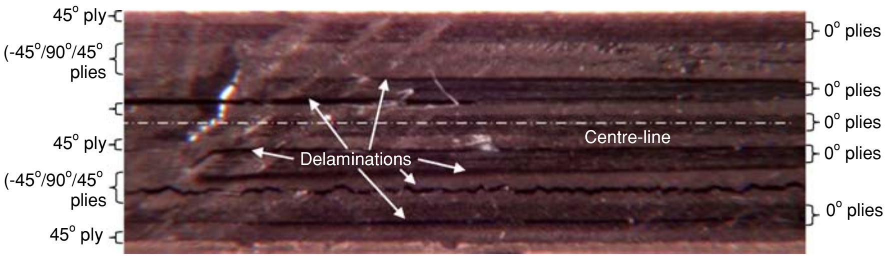
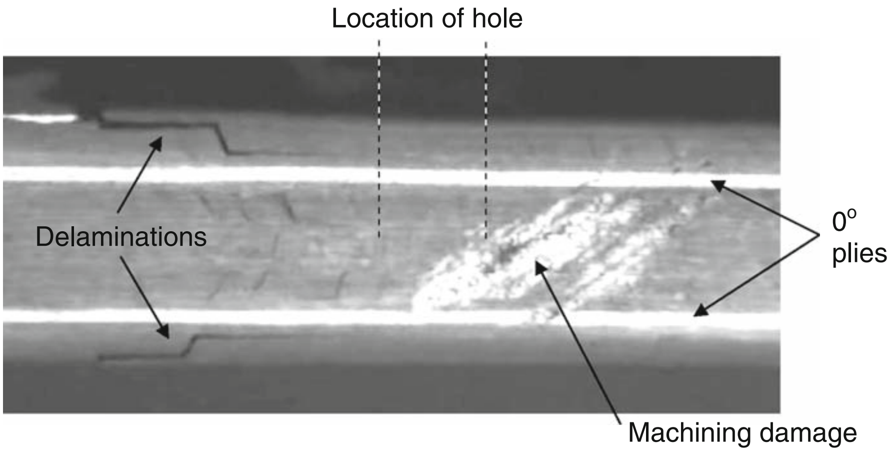


Fig. 11 Free edge of a matrix dominated layup specimen showing delaminations that have propagated from the hole prior to ultimate failure



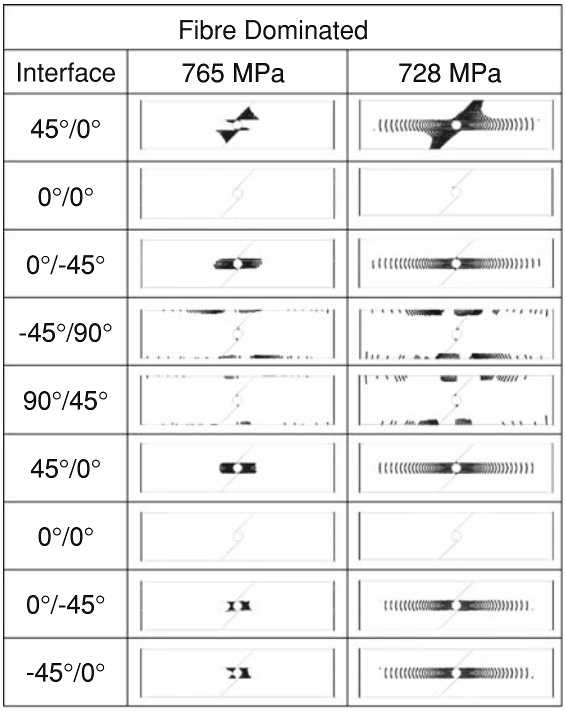


Fig. 12 Predicted delamination patterns for fibre dominated layup at maximum load prior to first significant load drop and just after

scaled in the thickness direction by both the sub-laminate and ply level scaled method were used. The hole diameter was 3.175-mm. In order to compare results with different w/d it is necessary to use a finite width correction factor, Y. All previous results discussed in this paper have been the uncorrected experimental or analysis results since w/d has been kept constant throughout. A closed-form solution for the finite width correction factor of a circular hole in an isotropic plate is given in the study of Peterson [1974] for a plate of width W;

$$Y = \frac{2 + (1 - d/w)^3}{3(1 - d/w)} \tag{2}$$

For the case of w/d = 5 this gives $Y = 1.05$ and for w/d = 10 it gives $Y = 1.01$. Using these values the 2 mm thick sub-laminate specimens with w/d = 5 (already shown uncorrected previously) and w/d = 10 gave strengths of 523 and 555 MPa respectively. The w/d = 10 result shows a slight increase on the w/d = 5 baseline value but still within the scatter of the experimental data which was approximately 5% for both data sets. It was noted that the w/d = 10 specimens showed a more brittle type failure compared to w/d = 5 as can be seen in Fig. 15a. This is indicative of the suggested difficulty for damage to join up across the width

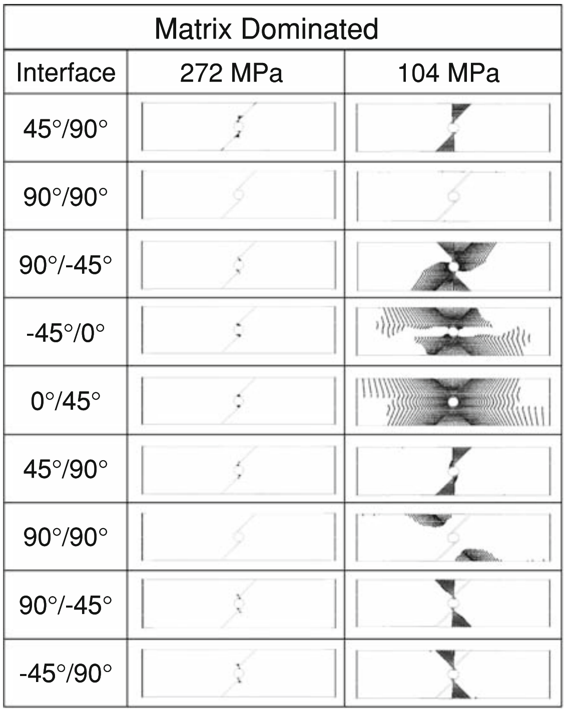


Fig. 13 Predicted delamination patterns for matrix dominated layup at maximum load prior to first significant load drop and just after

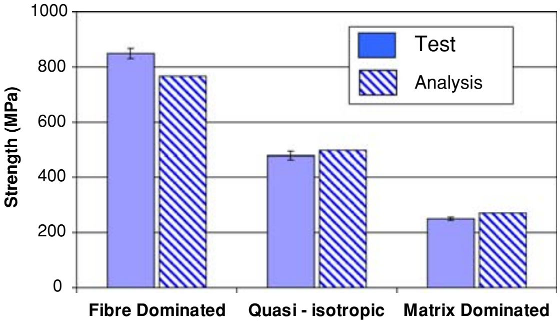


Fig. 14 Experimentally measured and predicted strengths for fibre and matrix dominated as well as quasi-isotropic layups

of the specimen but in this case it did not have any significant effect on strength. The 2 mm thick ply level scaled specimens in contrast showed a marked increase in strength for the w/d = 10 specimens which failed at 611 MPa (finite width corrected) when compared to 414 MPa for the baseline with the finite width correction factor applied. This is an increase of 47.5%. With the increase in width to hole diameter ratio the failure mechanism changes from delamination to pullout (Fig. 15b). This again can be attributed to the increased difficulty for the damage at the hole to join up with damage at the free edge. This is a necessary precursor to delamination at the 0° ply interface to occur. In the case of w/d = 10 the stress at which this occurs increases such that the fibre failure stress now is exceeded before the delamination event occurs, resulting in a pullout type failure.

These increased width to hole diameter tests have been modelled using the proposed virtual testing procedure. For the 2 mm sub-laminate thickness scaling a very slight increase in strength from 512 to 521 MPa (finite width corrected) is predicted. For the ply level scaled specimens the predicted increase is from 444 to 652 MPa. In this case the failure mode is predicted to remain as delamination. There is a significant change in the 0° delamination pattern which no longer spans the specimen width between the hole and free edge as for w/d = 5 but now propagates from the hole in the direction of loading, more similar to the fibre dominated laminate shown in Fig. 12. Overall however, when comparing the strengths, a reasonably good level of correlation is obtained, see Fig. 16.

5 Conclusions

From the work presented here it can been seen that there are a considerable number of parameters which can affect open hole tensile strength; thickness scaling regime, absolute thickness, in-plane dimensions, stacking sequence, layup and specimen width to hole diameter ratio. When the results are brought together and the reasons behind these variations analysed in some detail it can be seen that the one unifying factor is the effect of sub-critical damage. One of the most significant parameters to affect this is the ply block thickness. Where this is increased from the baseline of 0.125 mm it generally promotes intra-ply splitting and inter-ply delamination. Where the failure mode is dominated by fibre failure an increase in sub-critical damage will cause an increase in the amount of notch blunting and hence increase in specimen strength. Where the failure mode is one of delamination, an increase in sub-critical damage accelerates the progression towards ultimate failure and hence reduces the specimen strength. It is not only the absolute ply block thickness that affects results but also the ply block thickness to hole diameter ratio.

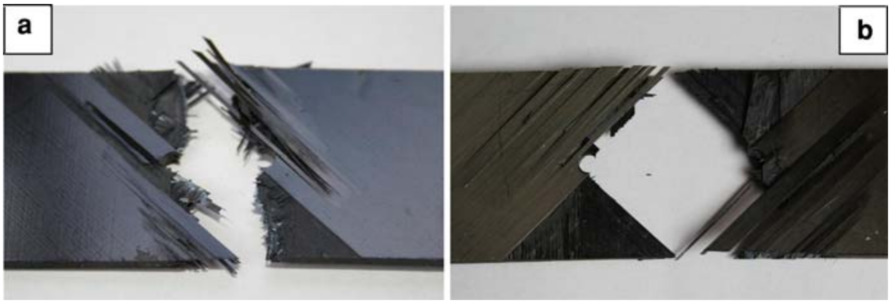


Fig. 15 Typical 2 mm thick failed specimens with w/d = 10 **a** sub-laminate level scaled **b** ply level scaled

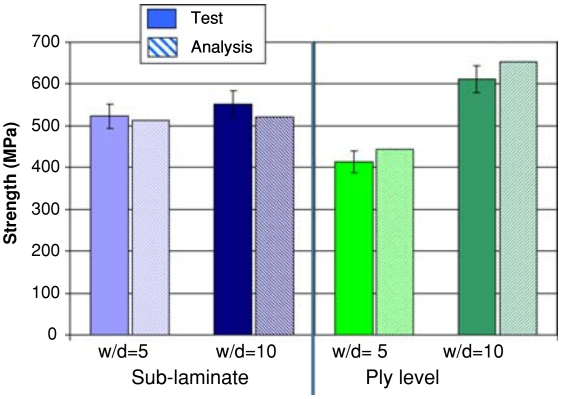


Fig. 16 Experimentally measured and predicted strengths (finite width corrected) for effect of w/d ratio

A decrease in this ratio results in a relative decrease in sub-critical damage. Thus with constant ply block thickness but increasing in plane dimensions, strength decreases with size for sub-laminate level specimens and increases with size for ply level specimens for the same reasons as above.

Stacking sequence too can affect the sub-critical damage since the location of the load bearing 0° plies affects the amount of splitting that occurs adjacent to the hole. Those stacking sequences that have larger splitting are ultimately stronger due to the amount of notch blunting. When the ply block thickness is increased the propensity to delaminate also increases. Due to the relative amount of splitting in the different stacking sequences this affects different laminates in different ways. The resulting change in failure mode for one of the laminates tested caused a significant reduction in strength while the second laminate saw little change. When the proportion of plies in the different fibre directions is varied from the quasi-isotropic layup it becomes difficult to avoid a certain level of ply blocking. This again affects the failure mode and for the laminates tested here a delamination failure was observed in the fibre dominated layup whilst it was shown that the failure of the matrix dominated layup was in a transition region between delamination and pull out failure.

Finally since it is the joining up of the sub-critical damage across the width of the specimen which is a critical event for the pull out and delamination failure modes it was shown that as this distance is increased so the failure becomes more brittle. This also increases the specimen strength when the failure mode changes from delamination to pull out.

If an analysis technique is to be sufficiently robust to be able to be used in a virtual testing framework, then it must necessarily be able to capture complex effects and variations in experimental results such as these. All of the effects reported here have been explained in terms of the development of damage within the specimens prior to ultimate failure. This has been included in the finite element modelling technique presented which takes account of the interaction between intra-ply splits, inter-ply delamination and fibre failure. These models have been applied to a large range of experimental tests and in all cases have been able to predict the failure and trends observed. This has been achieved with a single set of input parameters which are based on experimentally measured data with no empirical or fitting factors.

Acknowledgements The authors gratefully acknowledge Airbus UK, the Engineering and Physical Sciences Research Council, MoD and Hexcel for their support of this work.

References

ASTM (2002) Standard test method for open hole tensile strength of polymer matrix composite laminates ASTM standard D5766/D5766M-02

Awerbuch J, Madhukar MS (1985) Notched strength of composite laminates: predictions and experiments—a review. J Reinf Plast Compos 4(1):3–159. doi:10.1177/073168448500400102

Camanho PP, Maimi P, Davila CG (2007) Prediction of size effects in notched laminates using continuum damage mechanics. Compos Sci Technol 67(13):2715–2727. doi:10.1016/j.compscitech.2007.02.005

Chang FK, Chang KY (1987) A Progressive damage model for laminated composites containing stress-concentrations. J Compos Mater 21(9):834–855. doi:10.1177/002199838702100904

Cheung M, Hallett SR (2008) Investigation of the effect of specimen width on open hole tensile strength. Composites Testing for Model Identification (CompTest). Dayton 2008

Cox B, Yang QD (2006) In quest of virtual tests for structural composites. Science 314:1102–1107. doi:10.1126/science.1131624

Davies GOA, Ankersen J (2008) Virtual testing of realistic aerospace composite structures. J Mater Sci 42(20):6586–6592. doi:10.1007/s10853-008-2695-x

Gonzalez C, Llorca J (2007) Virtual fracture testing of composites: a computational micromechanics approach. Eng Fract Mech 74(7):1126–1138. doi:10.1016/j.engfracmech.2006.12.013

Green BG, Wisnom MR, Hallett SR (2007) An experimental investigation into the tensile strength scaling of notched composites. Composites Part A 38(3):867–878. doi:10.1016/j.compositesa.2006.07.008

Hallett SR, Wisnom MR (2006) Numerical investigation of progressive damage and the effect of layup in notched tensile tests. J Compos Mater 40(14):1229–1245. doi:10.1177/0021998305057432

Hallett SR, Green BG, Jiang WG, Wisnom MR (2009) An experimental and numerical investigation into the damage mechanisms in notched composites. Composites Part A. doi:10.1016/j.compositesa.2009.02.021

Hallett SR, Jiang WG, Khan B, Wisnom MR (2008) Modelling the interaction between matrix cracks and delamination damage in scaled quasi-isotropic specimens. Compos Sci Technol 68(1):80–89. doi:10.1016/j.compscitech.2007.05.038

Hallett SR, Jiang WG, Wisnom MR The effect of stacking sequence on thickness scaling of tests on open hole tensile composite specimens. AIAA J (in press)

Jiang WG, Hallett SR, Green BG, Wisnom MR (2007) A concise interface constitutive law for analysis of delamination and splitting in composite materials and its application to scaled notched tensile specimens. Int J Numer Methods Eng 69(9):1982–1995. doi:10.1002/nme.1842

Lagace P (1986) Notch sensitivity and stacking sequence of laminated composites. In: Whitney JM (ed) Seventh conferenceon composite materials: testing and design, ASTM STP 893, Philadelphia, pp 161–176

MIL HDBK 17 (2002) US Department of Defense

Peterson R (1974) Stress concentration factors. Wiley, New York

SACMA (1994) Recommended Test Method SRM 5R-94: open-hole tensile properties of oriented fiber-resin composites. Suppliers of advanced composite materials association

Walsh TJ, Ochoa OO (1993) Composites with multiple cutouts. Compos Struct 24(2):117–124. doi:10.1016/0263-8223(93)90033-M

Whitney JM, Nuismer RJ (1974) Stress fracture criteria for laminated composites containing stress-concentrations. J Compos Mater 8:253–265. doi:10.1177/002199837400800303

Wisnom MR, Hallett SR (2009) The role of delamination in strength, failure mechanism and hole size effect in open hole tensile tests. Compos Part A Appl S doi:10.1016/j.compositesa.2008.12.013.