Xu, X., Wisnom, M. R., Mahadik, Y., & Hallett, S. R. (2014). An experimental investigation into size effects in quasi-isotropic carbon/epoxy laminates with sharp and blunt notches. Composites Science and Technology, 100, 220-227. 10.1016/j.compscitech.2014.06.002

Published in Composites Science and Technology 2014, 100(21), 220-227
DOI: 10.1016/j.compscitech.2014.06.002

An Experimental Investigation into Size Effects in Quasi-isotropic Carbon/Epoxy Laminates with Sharp and Blunt Notches

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Abstract

An experimental investigation into size effects in notched $[45/90/\text{-}45/0]_{4s}$ carbon/epoxy laminates is carried out. The in-plane dimensions of the quasi-isotropic laminates are scaled by up to a factor of 8. Larger Scale 16 specimens with only their width and notch length being doubled were also tested as a further comparison. Interrupted tests and X-ray Computed Tomography (CT) scanning are carried out to study the damage at the crack tips. Sharp centre-notched tensile tests are compared to open-hole tests of the same notch length (hole diameter), material and stacking sequence. A similar strength reduction scaling trend is found for both configurations at the small sizes, except with higher tensile strength for the centre-notched specimens than the open-hole specimens. However, there is a cross-over point when the sizes increase, with the sharp notched results approaching an asymptote based on Linear Elastic Fracture Mechanics (LEFM), and the open hole results approaching an asymptote based on Weibull theory.

Keywords: A. Laminate; B. Fracture; B. Strength; C. Notch; Size effect

1. Introduction

With the intensive usage of composite materials, a serious concern arises: can small coupon tests yield reliable results for the construction of large structures? It is

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thus necessary to introduce the concept of size effects. In solid mechanics, the scaling problem of main interest is the effect of the size of the structure on its strength [1]. A size effect can be defined as a change in strength with specimen dimensions [2]. In the present paper, size effects are investigated experimentally for notched tensile strength with increasing specimen in-plane dimensions, and the applicability of scaling laws is considered.

Notched tensile strength of composites is a critical design driver. Open-hole quasi-isotropic specimens have been extensively tested to study strength scaling. For example, Green et al. [3] and Hallett et al. [4] studied scaled open-hole $[45/90/\text{-}45/0]_{4s}$ laminates concluding that the scaling was due to the sub-critical damage around the hole. A few studies with sharp notches of different sizes have been reported, but test data for in-plane scaled specimens are limited. For example, Daniel [5] reported tests on a series of central-notch graphite/epoxy laminates in which the overall dimensions of the specimens were kept the same and only the crack length was scaled, concluding that the failure at the tip of the crack takes the form of a damage zone consisting of ply sub-cracking, local delamination and occasional fibre breakage. Harris and Morris [6] carried out an experimental investigation into the effect of laminate thickness and specimen configuration on the fracture of centre-notched composite laminates. Kortschot et al. [7] tested scaled double edge-notched specimen of cross-ply carbon/epoxy composite laminates. The details of the damage development were studied through 2-D X-ray radiography. Bažant et al. [8] applied a size effect law to account for structural size effects in in-plane scaled edge-notched composite laminates, according to which the plot of the logarithm of the nominal strength versus the logarithm of size represents a smooth transition from a strength criterion asymptote at small scales, to an LEFM asymptote with - 0.5 slope at large scales. However, the detailed damage at the crack tips was not investigated. Coats and Harris [9] investigated the translaminate fracture behaviour of in-plane scaled centre-notched tension carbon/epoxy specimens to develop a residual strength prediction methodology for composite structures. They used 2-D X-ray radiography and fractography techniques to examine the notch-tip damage region in order to study the overall damage development ahead of the notch tips, but without assessment of the damage in individual plies or detailed comparison of damage for different sized specimens. Gonzales and Knauss [10] tested three sets of large in-plane scaled compact tension specimens highlighting that the influence of 'size-scaling' they found was according to fracture mechanics.

Another important question is the relation between strength of specimens with sharp and blunt notches. Few studies have directly compared the tensile strength of open-hole specimens to that of equivalent centre-notched specimens. Daniel [5] concluded that $[0/\pm45/90]_s$ specimens with holes and cracks of the same size had the same average failure stress. The NASA/Boeing Advanced Technology Composite Aircraft Structure (ATCAS) programme established a large tension fracture data-base covering small coupons to large panels. From the ATCAS data-base, Walker, et al. [11] found some centre-notched $[45/90/-45/0]_s$ laminates had higher average tensile failure stress than open-hole specimens of the same notch length (hole diameter), but there was no explanation.

In the present paper, an experimental investigation into in-plane scaled notched $[45/90/-45/0]_{4s}$ carbon/epoxy laminates is reported. Interrupted tests at 95% failure load are conducted and 3-D CT is applied to study the damage ahead of the crack tips. This gives details of the damage process in each ply not hitherto presented and the sizes of the damage zones are related to the sizes of the notches. The results are compared to those of open-hole laminates using the same material, stacking sequence and overall dimensions. A similar strength reduction scaling trend is shown for both types of notched laminates at the small sizes, except that higher nominal tensile strength is found with sharp notches compared to open-hole specimens of the same notch length (hole diameter). As the sizes increase, there is a cross-over point with results approaching different asymptotes. The reasons for this behaviour are considered, in terms of the different damage mechanisms, controlling factors, and scaling laws.

2. Test setup

A schematic of the in-plane scaled centre-notched specimens is shown in Fig. 1, referred to as the long variant. In-plane dimensions of the specimens are scaled by up to a factor of 8 as shown in Table 1. Larger centre-notched specimens with notch length C = 50.8 mm are referred to as the short variant with only their width and notch length being doubled, while their gauge length is kept the same as the one-size-smaller Scale 8 specimens. The largest specimens were not fully scaled due to limitations of the manufacturing and test facilities. Three tests of each of the smallest three sizes indicated that the short variant of specimens gave the same strength as the long variant within 3%. Finite element analysis has also been conducted, demonstrating that in the short variant specimens the closer boundaries in the length direction do not affect the stress distribution near the notches, justifying the use of the relatively shorter specimens. Five specimens for each of the smallest three sizes were tested. In contrast, four Scale 8 specimens and three Scale 16 specimens were tested. The end tabs are not scaled with the specimen sizes but determined by the grips of the different test machines as shown in Table 1.

The material used in these tests is Hexcel HexPly® IM7/8552 carbon-epoxy pre-preg with a nominal ply thickness of 0.125 mm. The stacking sequence is quasi-isotropic $[45/90/-45/0]_{4s}$ for all the sizes. The nominal overall thickness is 4 mm, which is very close to the actual thickness.

The centre-notches were firstly cut with a 1 mm end mill on a computer numerical controlled milling machine. Then the centre-notches were carefully extended to form a sharp crack manually by using 0.25 mm-wide piercing saw blades. Specifically, 2 mm through-the-thickness centre-notches were cut in the baseline specimens, which were extended and sharpened to 3.2 mm long manually. For the scaled up specimens, both the length of the initial machined centre-notches and the length of the final extended centre-notches were kept proportional to the specimen widths, but the notch radii were the same. According to Camanho and Catalanotti [12] who tested quasi-isotropic IM7/8552 carbon/epoxy laminates, a 1 mm wide notch is sharp enough to not affect measured fracture toughness. In addition, according to Laffan et al. [13], for cross-ply IM7/8552 carbon/epoxy laminates, when the notch radius is not bigger than 0.25 mm, the initial fracture toughness is not dependent on the notch radius. So the notch used in the present paper is considered to be sharp enough.

Instron hydraulic-driven test machines were used. The specimens were tested under displacement control with scaled loading rates with regards to the specimen widths, with a loading rate of 0.25 mm/minute for the baseline specimens.

Interrupted tests in which the tests were stopped at 95% of the average failure load of multiple specimens per case as shown in Table 2 were carried out. A single specimen of each size from the interrupted tests was examined by CT scanning to study the damage state. The samples from interrupted tests were soaked in a bath of zinc iodide penetrant for 3 days. A Nikon XTH225ST CT scanner was used to scan the scaled composite specimens from the interrupted tests. It has a 1 micron focal spot size and 225 kV, 225 W microfocus X-ray source.

Most of the open-hole results which were used to compare with the centre-notched results were from Green et al. [3]. The only set of open-hole specimens tested in the present paper was the biggest short variant because the data were not available in the above reference. The overall dimensions were kept the same as the short sharp notched variant, with the hole diameter being equal to the sharp notch length (C = 50.8 mm).

3. Results

3.1. Load vs. displacement response

From the typical load vs. cross-head displacement curve in Fig. 2, the response is seen to be approximately linear. Small load drops could be observed in some of the tests, but they are not obvious. Although the definitive average load levels at the small load drops cannot be reported, the typical values are shown in Table 2. The final failure was catastrophic in all the tests. The highest load level is taken as the failure load, from which the average nominal failure stress is calculated using the measured full widths and the nominal thicknesses of the specimens. The failures of all the specimens are fibre dominated, with the larger specimens exhibiting cleaner fractures, and the smaller ones more pull-out. Typical fracture surfaces are shown in Fig. 3. The centre-notched and open-hole test results are shown in Table 2.

3.2. Damage zone at crack tips

Interrupted tests in which the tests were stopped at 95% of the average failure load together with CT scanning were carried out. Although interrupted tests with CT scanning are not able to prove exactly what is happening in the other tests, they can provide promising images of the damage zones at the crack tips with a large amount of detail. The low C.V.s in Table 2, with a mean value of 2.5% indicate high consistency of the centre-notched test results, so the CT images should be representative of the damage close to failure in the other specimens. The largest ones were not scanned due to the limited number of specimens available.

Through the thickness, there is a double 0 degree ply block at the central symmetry plane, but outboard only single 0 degree plies. In the baseline specimen in Fig. 4, there is no fibre failure in the central double 0 degree ply block as shown in Fig. 4 (e). By comparison, local fibre failure occurs at the crack tips in the outboard single 0 degree plies as shown in Fig. 4 (d). This is because the central double 0 degree ply block has more energy available to drive splits to propagate than the outboard single 0 degree plies. Longer splits in the central double 0 degree plies blunt the stress concentration at the crack tips to a greater extent. Therefore, the local fibre breakage is retarded. The local fibre failure in the outboard single 0 degree plies does not fully propagate. Instead, it is arrested and other splits start to grow at the new crack front. In all the scaled up specimens, the splits in the central double 0 degree ply blocks are also longer than those in the outboard single 0 degree plies. However, local fibre failure is already present in the central double 0 degree ply blocks in all the larger specimens, as can be seen for example in the Scale 2 specimen in Fig. 5 (e). Apart from the differences in the central double 0 degree ply blocks, damage is similar in all other 0 degree plies.

In the baseline and scaled up specimens, 45 and -45 degree splits can be seen at the crack tips. No fibre failures are seen in any of the 45 or -45 degree plies in the baseline specimen in Fig. 4 (a) and (c) or in the Scale 2 specimen in Fig. 5 (a) and (c). However, due to the technical limitations of the CT scanning, the images of the bigger specimens in Fig. 6 and Fig. 7 provide fewer details at the crack tips.

There are plenty of 90 degree cracks distributed around the 45 and -45 degree splits, e.g. in the baseline specimen in Fig. 4 (b). In most of the CT scanning images, no obvious delaminations could be captured, although it is likely that local delaminations are present and help the splits in different plies join up.

Hallett et al. [4] showed through-thickness X-rays of the equivalent open-hole specimens of the same material, layup and dimensions up to 25.4 mm notch size from tests interrupted at 95% of the failure load. There was no fibre breakage in any of the open-hole specimens. However, in the present paper, the CT scanning images show that local fibre failure occurs in the centre-notched specimens, but further propagation is delayed by the multiple splits. Because of the high in-plane shear stress in the centre-notched specimens, 0 degree splits happen at lower stress levels than for the open hole tests. As shown in Fig. 8, splits are also able to grow longer, blunting the stress concentration, which explains the higher average tensile failure stress of the centre-notched specimens compared with open-holes with the same notch length (hole diameter) at the small sizes as shown in Table 2. This may also explain the higher results for sharp notches in the ATCAS data-base [11].

3.3. Damage zone size

In the present paper, the damage zone is defined as the region ahead of the crack tips in which the fibres break in some of the 0 degree plies before unstable failure. In Fig. 4 to Fig. 7 local fibre failure in the 0 degree plies together with multiple splits can be observed. The distance between the last split and the crack tip in all of the 0 degree plies was measured and the average distance was used to determine the size of the damage zone. The central double 0 degree ply block in the baseline specimen does not have any fibre breakage, so it is not included in the averaging. The sizes of the damage zones within the 0 degree plies in the baseline, Scale 2, Scale 4 and Scale 8 specimens are 0.50 mm (C.V. 14%), 1.13 mm (C.V. 13%), 2.16 mm (C.V. 8%) and 2.28 mm (C.V. 7%) respectively.

For metallic materials, there is a plastic zone ahead of the crack tips. The size of the plastic zone increases with the applied load, until it reaches a constant value. If the load keeps increasing, unstable crack propagation will happen, and cause catastrophic failure of the specimens. By comparison, for centre-notched composite laminates, the splits, delamination and local fibre failure ahead of the crack tips comprise an analogous damage zone. From interrupted tests stopped at 95% of the average failure load, the critical size of the damage zone shortly before final failure can be measured. At the small sizes, the critical size of the damage zone is roughly proportional to the notch length. When the specimens are further scaled up, the critical size of the damage zone increases more slowly towards a constant value as shown in Fig. 9, which is analogous to the plastic zone behaviour of metallic materials.

3.4. Size effects

Fig. 10 illustrates the centre-notched and open-hole tensile strength vs. notch length. Also shown on the graph are lines with slopes based on the expected scaling from LEFM, and from Weibull volume scaling theory [2], drawn through the largest centre-notched and open hole results respectively. Because both scaling laws are power-laws, the results are plotted on a log-log scale. The C.V. in the centre-notched tests is very low, 1%-4%, and so error bars have not been shown. In Fig. 10, the centre-notched specimens share a similar scaling trend as the open-hole specimens at the 3 smallest sizes, but with higher average tensile failure stress. When the notch length increases further, the tensile strengths of the centre-notched specimens approach the line with slope according to the scaling of fracture mechanics. By comparison, the open-hole strengths tend towards a strength limit with slope according to the scaling of Weibull theory.

The slope of the fracture mechanics scaling line in Fig. 10 is determined by the assumption of constant fracture energy with a value of $G_C = 92.7$ kJ/m^2, which has been calculated from Equations 1 [14] and 2 for the largest specimen size. According to Equation 1, the centre-notched strength is inversely proportional to the square root of the half crack size, giving a -1/2 slope on the log-log plot. The points representing the smaller specimens are asymptotic to the fracture mechanics line. This agrees with the scaling of the damage zones, which are approaching a constant size for the larger specimens. For the smaller sizes, the points representing the smaller specimens are progressively further away from the fracture mechanics line. Because the sizes of the damage zones in the smaller specimens are not so small compared to the notch sizes, the assumptions of LEFM are less valid.

$$K_C = \sigma_n f(\lambda)\sqrt{\frac{\pi C}{2}} \tag{1}$$

$$G_C = \frac{{K_C}^2}{E} \tag{2}$$

where, K_C is fracture toughness, $\sigma_n = 261$ MPa is the average nominal gross section failure stress of the largest specimens, $f(\lambda) = \sqrt{\sec(\pi\lambda)} = 1.025$ is a geometric parameter to account for the effect of finite width [14], C = 50.8 mm is the initial notch length of the largest specimen, W = 254 mm is specimen width, so $\lambda = C/2W = 0.1$, G_C is the fracture energy, E = 61.6 GPa is Young's modulus.

Similarly, the Weibull strength scaling line in Fig. 10 is drawn through the point representing the largest open-hole specimens. Applying a two-parameter Weibull distribution, the probability of survival, P(s), of a volume V subject to a stress σ is described in Equation 3 [2]. According to Equation 3, the strength σ_1 and σ_2 of two specimens of volumes V_1 and V_2 respectively can be related by assuming equal probabilities of survival as shown in Equation 4.

$$P(s) = \exp[-V(\sigma/\sigma_0)^m] \tag{3}$$

$$\sigma_1/\sigma_2 = (V_1/V_2)^{-1/m} \tag{4}$$

where, σ_0 is the characteristic strength of material, and m = 41 is the Weibull modulus, as determined experimentally from scaled unidirectional tensile tests on the same material [15], giving a reduction in strength by a factor of 1.034 for a doubling of in-plane dimensions.

The slope of the Weibull strength scaling line is determined by assuming equal probability of failure between open-hole specimens of different volumes. According to Equation 4, the open-hole strength is inversely proportional to the volume raised to the power of 1/41 or inversely proportional to the characteristic length to the power of 2/41 since both in-plane dimensions are scaled and the thickness is constant, giving a -2/41 slope on the log-log plot. The scaling of open-hole strength is due to the change in local damage associated with cracks initiating and joining up at the hole [16]. In the limit of a large specimen with little or no damage, this mechanism will be eliminated, and failure would be expected to be controlled by the fibre direction tensile strength at the hole edge. This is consistent with the largest two open hole strengths, which follow the Weibull strength scaling line. For the smaller sizes, the points representing the smaller specimens are progressively further away from the Weibull strength scaling line. This is because a damage zone develops, and becomes larger compared to the hole size, so the stress concentration is further blunted as the specimens become smaller.

4. Discussion

For the larger specimens the C.V.s are less than 3% as shown in Table 2, the results show a statistically significant size effect with about 25% reduction in mean from the Scale 8 to the Scale 16 tests [17], and a reduced number of specimens is therefore acceptable. The largest specimens are still useful as a further comparison despite the lower number and not being fully scaled.

Sutherland et al. [18] summarized analytical methods to account for size and scale effects in composites, such as the weakest link, extended weakest link and fracture mechanics approaches. Weibull theory is widely used as the scaling law for unnotched composite laminates [2]. It is based on the assumption that the failure of any one of its parts causes the chain as a whole to fail [19] (the weakest link condition). However, composite laminates are really quasi-brittle materials that do not fulfil such a condition [20]. Subcritical damage such as splitting and delamination can occur, resulting in a pull-out type of failure rather than a clean fracture. This is seen in Fig. 3 where there is progressively more damage visible in the smaller specimens. However, when development of damage is eliminated, as in the largest open-hole specimens, failure is immediately catastrophic, and does approach the expected Weibull scaling. The concepts of linear fracture mechanics give rise to another scaling law for composite laminates with sharp notches, which is represented by constant stress intensity and square-root length scaling [10]. However, CT scanning images show that the sizes of the damage zone in the smaller centre-notched laminates increase with the notch sizes, which indicates increasing fracture toughness. For larger specimens the damage approaches an approximately constant size, giving constant fracture toughness, a clean brittle fracture and the scaling approaches expected from fracture mechanics.

The present paper provides a good set of experimental data on size effects in notched quasi-isotropic composite laminates which will be valuable in assessing the performance of models for predicting strength. Neither Weibull theory nor fracture mechanics alone can fit the observed size effects in small scale notched laminates. Only when the specimens with different notches are big enough, are they asymptotic to either the fracture mechanics or Weibull strength scaling lines. It was necessary to go to specimens with notches larger than 25.4 mm to approach these limits, showing the need for caution in using results from small scale laboratory tests to predict large scale structural response.

5. Conclusions

The notched tensile strength of quasi-isotropic IM7/8552 composite laminates decreases with increasing specimen size for both sharp and blunt notches. Neither Weibull theory nor fracture mechanics alone can fit the observed size effects in small scale notched laminates. Only when the specimens with different notches are big enough, are they asymptotic to either fracture mechanics scaling for sharp notches or Weibull strength scaling for holes. This implies that when assessing the notched strength of quasi-isotropic composite structures, the specimen sizes used to obtain data need to be sufficiently big in order to get accurate predictions for even larger. Predictions will still be inaccurate for much smaller specimens.

The damage at the crack tips plays an important role in the failure of centre-notched tensile tests. This paper presents a definition of that damage zone in terms of the distance between the last 0 degree split and the crack tip over which the fibres in some of the plies are broken. The size of the damage zone can be measured directly from CT scanning images.

Tensile strengths were compared between centre-notched and open-hole specimens. The centre-notched specimens were found to be stronger than open-hole specimens of the same notch length (hole diameter) for small sizes. This is due to longer 0 degree splits in the centre-notched specimens blunting the stress concentration at the crack tips. There is a cross-over point between the centre-notched and open-hole strength as the sizes increase, with the damage zone approaching a constant size for the sharp notches, and being eliminated for the large holes.

Acknowledgements

The authors acknowledge Dr. Greg McCombe for carrying out the CT scanning of some of the centre-notched specimens.

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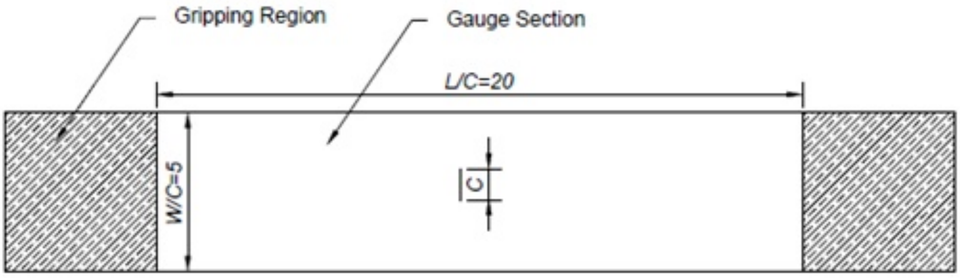


Fig. 1. Schematic of the in-plane scaled centre-notched specimens (the long variant).

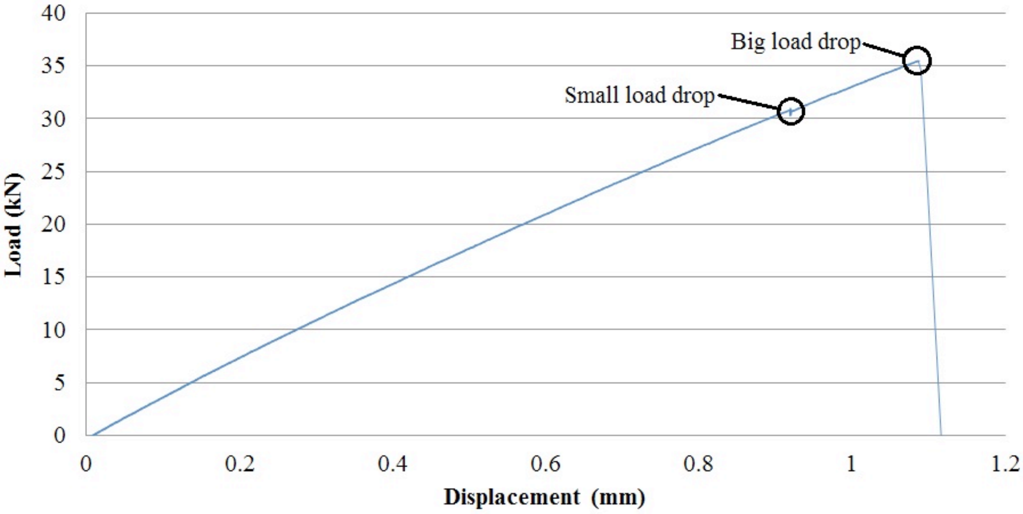


Fig. 2. Typical load-displacement curve of the baseline specimen ($C = 3.2$ mm).

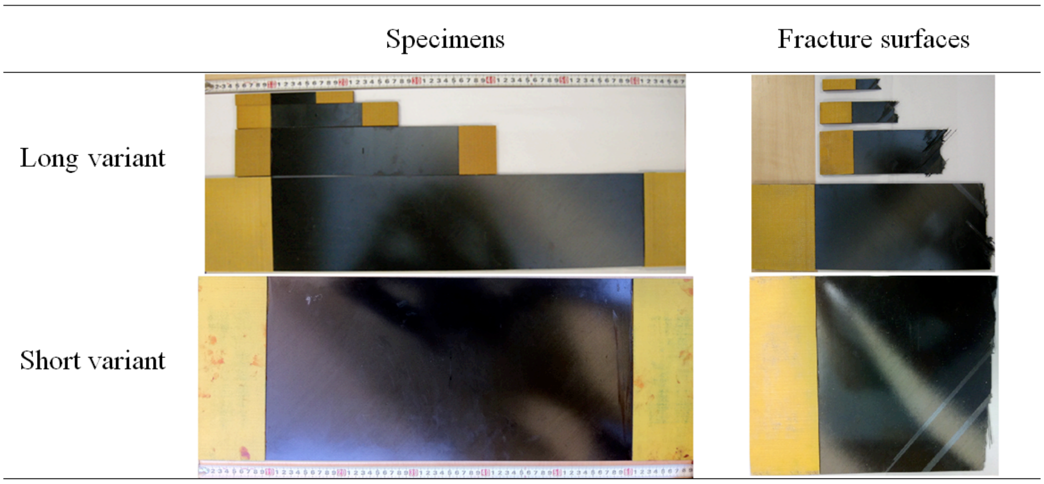
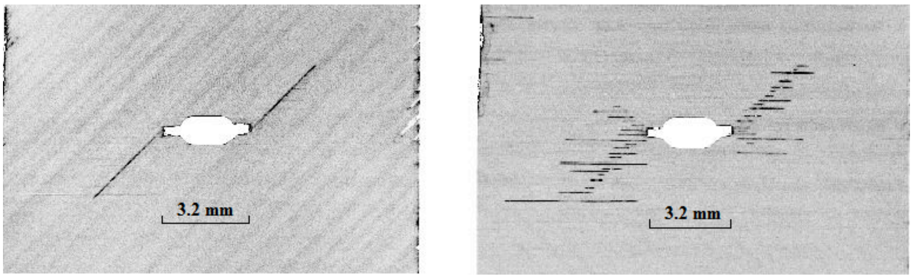
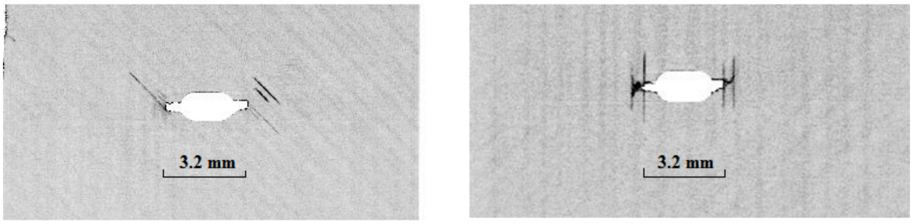


Fig. 3. Photos of the in-plane scaled centre-notched specimens and their fracture surfaces.



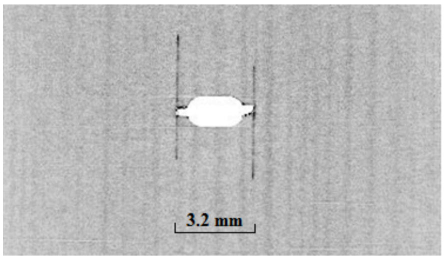
(a) Typical 45 degree ply

(b) Typical 90 degree ply



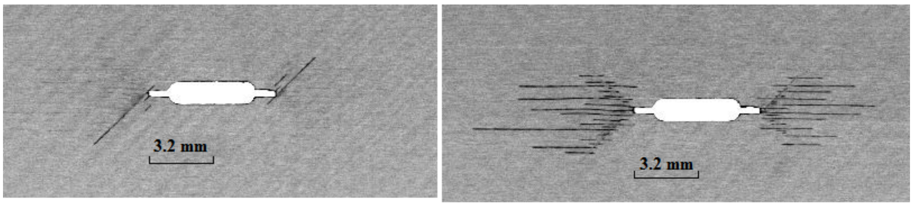
(c) Typical -45 degree ply

(d) Typical outboard single 0 degree ply



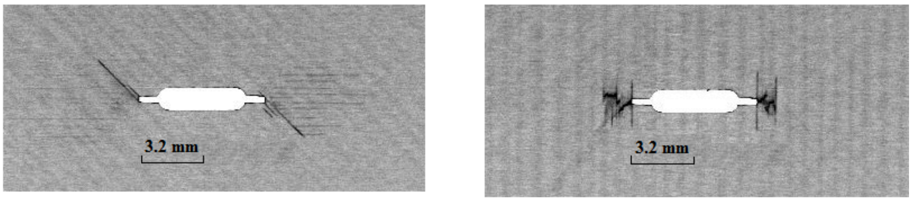
(e) Typical central double 0 degree ply block

Fig. 4. Typical CT scanning images of the baseline specimen ($C = 3.2$ mm).



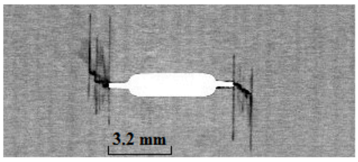
(a) Typical 45 degree ply

(b) Typical 90 degree ply



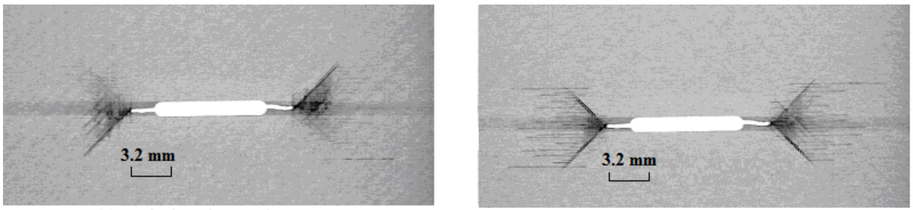
(c) Typical -45 degree ply

(d) Typical outboard single 0 degree ply



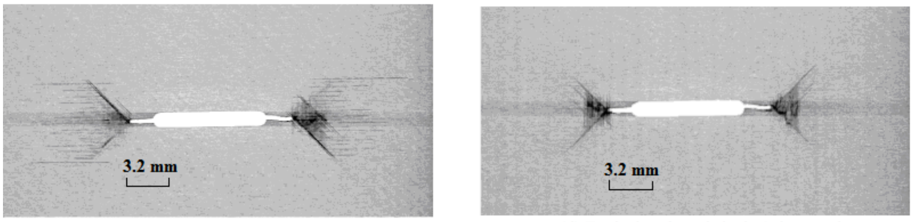
(e) Typical central double 0 degree ply block

Fig. 5. Typical CT scanning images of the Scale 2 specimen (*C* = 6.4 mm).



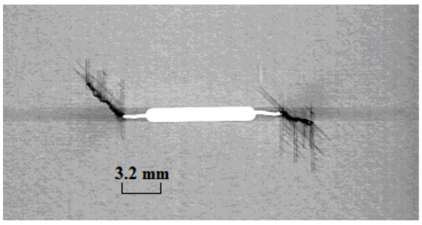
(a) Typical 45 degree ply

(b) Typical 90 degree ply



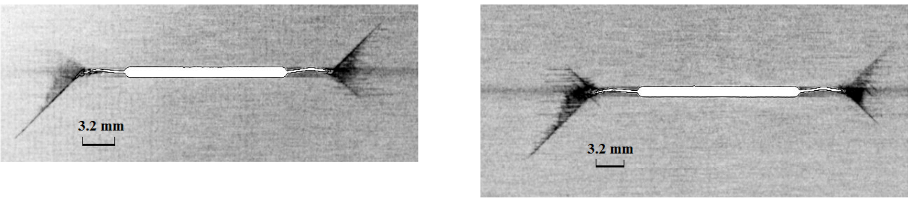
(c) Typical -45 degree ply

(d) Typical outboard single 0 degree ply



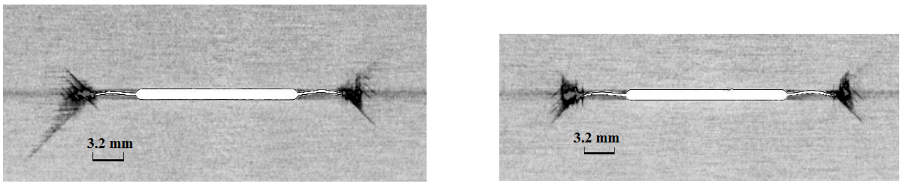
(e) Typical central double 0 degree ply block

Fig. 6. Typical CT scanning images of the Scale 4 specimen (*C* = 12.7 mm).



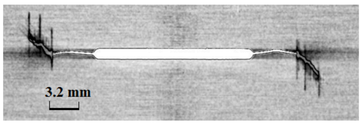
(a) Typical 45 degree ply

(b) Typical 90 degree ply



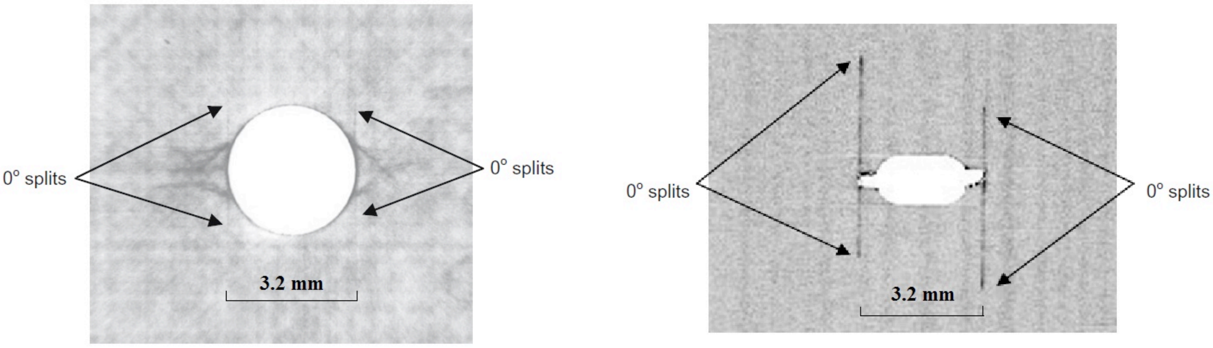
(c) Typical -45 degree ply

(d) Typical outboard single 0 degree ply



(e) Typical central double 0 degree ply block

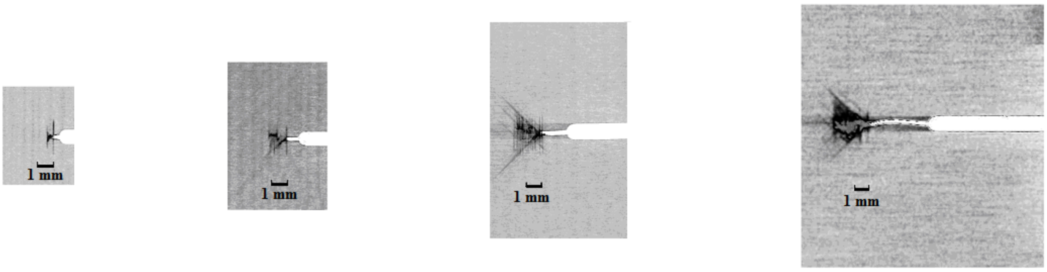
Fig. 7. Typical CT scanning images of the Scale 8 specimen (*C* = 25.4 mm).



(a) Open-hole specimen [4]

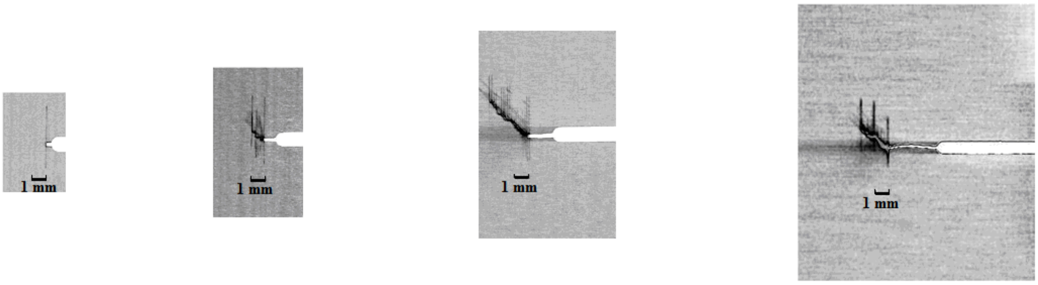
(b) Centre-notched specimen

Fig. 8. Comparison of the 0 degree splits in the baseline specimens at 95% of the average failure load.



C=3.2mm *C*=6.4mm *C*=12.7mm *C*=25.4mm

(a) Outboard single 0 degree ply



C=3.2mm *C*=6.4mm *C*=12.7mm *C*=25.4mm

(b) Central double 0 degree ply block

Fig. 9. Damage zones in 0 degree plies of the scaled specimens (images at same scale).

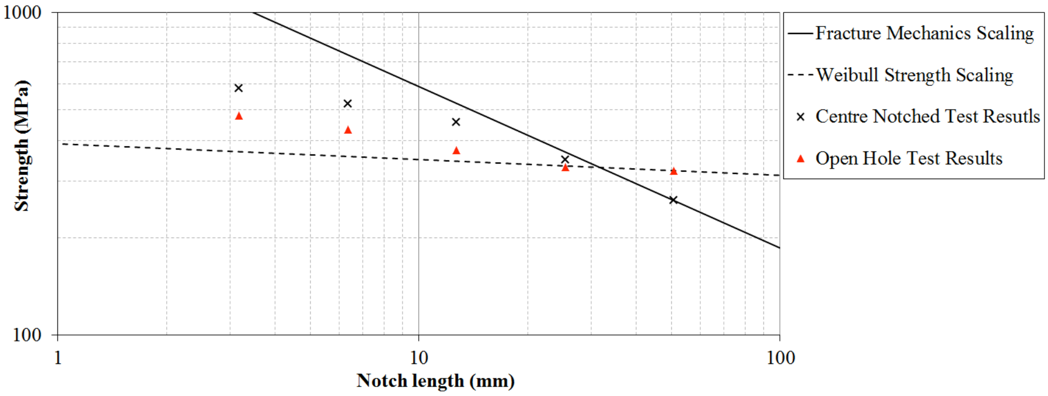


Fig. 10. Size effect curves.

Table 1. Dimensions of the in-plane scaled centre-notched specimens (mm).

Specimens	Notch length	Gauge width	Gauge length	End tab length
Baseline	3.2	15.9	63.5	50.0
Scale 2	6.4	31.8	127.0	50.0
Scale 4	12.7	63.5	254.0	50.0
Scale 8	25.4	127.0	508.0	100.0
Scale 16	50.8	254.0	508.0	100.0

Table 2. Notched tensile test results.

	Centre-notched tests			Open-hole tests	
Notch size (mm)	Strength (MPa) (C.V., %)	Number of specimens	Typical first load drop (MPa)	Strength (MPa) (C.V., %)	Number of specimens
3.2	582 (3.9)	5	514	478 (3.1) [3]	6
6.4	519 (2.0)	5	474	433 (2.0) [3]	6
12.7	456 (0.9)	5	425	374 (1.0) [3]	6
25.4	349 (2.7)	4	307	331 (3.0) [3]	6
50.8	261 (2.9)	3	234	323 (3.7)	3