SIZE EFFECTS ON STRENGTH OF NOTCHED CFRP LAMINATES LOADED IN BENDING

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ABSTRACT

This paper describes a series of experiments set out to explore the strength of notched monolithic composite panels with different dimensions and notch size loaded in bending. Two laminate thicknesses and two widths are tested. When varying the width, also the notch diameter is varied to retain a constant W/D- ratio. Accompanying tests in compression are performed and reported to allow evaluation of the full effects of bending. A limited fractographic analysis is also performed to study damage distribution after failure initiation. It has been shown that a larger hole results in a lower failure strain although the W/D-ratio is the same. As expected it has also been demonstrated that the far field failure strain is higher in bending than in compression.

Keywords: Failure of composites, compression, thick composite laminates

INTRODUCTION

More and more composite materials are used within primary load carrying aircraft structures. Examples are Boeing 787 and Airbus A350XWB where the composite content has increased to 50-60% by weight. As a reference the structural weight of the Saab Gripen fighter is approximately 20-25%.

With the aim to decrease manufacturing cost the structures are given a higher degree of integration and complexity. More integrated structures give fewer articles and fewer steps in the manufacturing chain. In many cases new innovative design solutions are a requirement to enable integrated structures. Good examples of this are Saab Aerostructures redesign of the A320 aileron and design of Boeing 787 “Bulk Cargo Door”, where manufacturing costs have been reduced considerably by innovative design solutions. Also the maximum thickness of laminated composite structures is increasing in aircraft structures. For example, the wing spars of the inner wings as well as the central wing box in modern aircraft are made from composite laminates with thickness exceeding 40 mm.

As a consequence of this development composite structures are expected to be exposed to higher interlaminar loads (bending, transverse shear etc.). An example of such a structure is an integrated stringer stiffened panel (where the fasteners are substituted by matrix plastic as load carrier between skin and stringers), facing a complex stress state due to the geometry and the combination of structural loads and loads due to fuel pressure. Furthermore there is a strive to, in a larger extend, permit operation in the post-buckled regime, which also contributes to the out of plane loads.

Cut-outs and holes are commonly used in the structure to facilitate placement of cables, as lightening holes, for inspection of inner structure etc. Such cut-outs result in notch stresses that are known to cause significant reduction in both tensile and compressive strength of a composite structure.

Traditionally composite structures are designed to minimize out of plane loading, due to the low interlaminar strength of the material. Because of this there is a lack of design tools and data that handles these loads. To facilitate the modern requirements on design mentioned above and to increase the potential and reduce conservatism during design there is a need to increase the knowledge regarding strength of out of plane loaded composite structures. The experimental study presented in this work is one step in this direction. Here laminate with two different thicknesses and widths as well as notch sizes are tested in bending. Accompanying tests in compression are performed and reported to allow evaluation of the full effects of bending.

EXPERIMENTS

Saab Aerostructures manufactured laminates from HTA/6376C carbon fibre/epoxy pre-preg, according to the Saab standard and test plan [1]. Two nominal laminate thicknesses were manufactured, 4.16 mm and 8.32 mm respectively, using the quasiisotropic layups $[(0/90/+45/-45)_4)]_S$ and $[(0/90/+45/-45)_8)]_S$.

Specimens were machined to a width of 36 mm and 156 mm with a 6 mm and a 25 mm drilled hole respectively, giving the same D/W-ratio. The specimens were manufactured to be tested in four point bending or compression.

Bending and compression tests

Bending tests were performed in a Zwick 150 kN electromechanical test rig using a specially manufactured bending rig according to Fig. 1. It should be noted that the span length of the specimen with 6 mm hole is only 210 mm compared to specimens with 25 mm hole that have a span length of 390 mm, see Fig. 1. During tests, the load and displacement were measured using the internal load cell and displacement recorder in the test rig. The bending tests were performed with a deformation test speed of 5 mm/min. The procedure during the bending tests was to load the specimens until a significant drop in load was recognized. The specimens were then unloaded and dismounted from the test rig. The failure was photographed using a digital camera. One specimen in each set was also subjected to fractographic analysis to determine failure distribution through the thickness. The fractographic analysis included inspection with ultrasonic C-scan and optical microscopy.

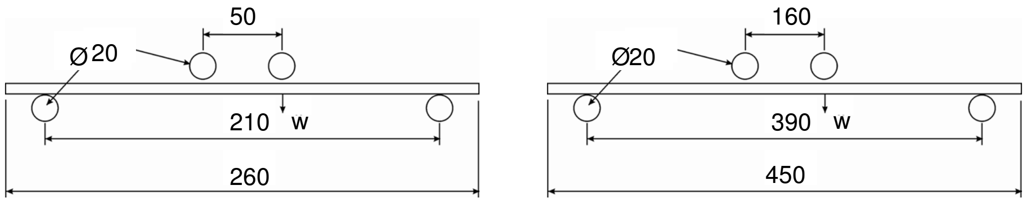

Fig. 1. Bending tests of laminate with 6 mm hole (left) and 25 mm hole (right) respectively.

Compression tests were performed on specimens with a width of 156 mm to fit in an existing rig. Antibuckling devices, depicted in Fig. 2, were used during the tests, which were performed in a 1000 kN MTS servohydraulic test rig in load control at a load rate of 2 kN/s. Compressive tests of the 36 mm wide specimens were performed in a 160 kN MTS servohydraulic test rig in load control at a load rate of 2 kN/s, with a sufficiently short free span to prevent global buckling of the specimen. The anti-buckling rig used in these tests is similar to the rig described in ASTM D7137, also known as the Boeing "compression after impact rig". However, the dimensions of the specimens are approximately 50 % larger. Furthermore the used rig is supplied with antibuckling plates with a window with a square opening of 100×120 mm to prevent global buckling of the specimens. In contrast the ASTM standard uses clamped/simply supported boundary conditions.

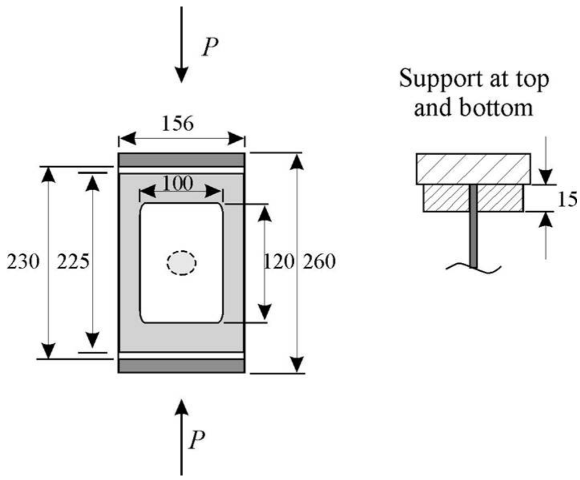

Fig. 2. Antibuckling device used during compression tests of the 156 mm wide specimens.

EXPERIMENTAL RESULTS

The results of the current tests of notched panels loaded in bending and compression are summarized in Table 1 below. The maximum far field strain is calculated using classical laminate theory. Furthermore, the far field failure strain has been normalized with respect to the results for the 4 mm laminates with 6 mm hole. In the table is also the observed failure mode presented, where c and t denotes compressive and tensile failure respectively.

Table 1. Summary of the results.

		Loaded in bending		Loaded in compression	
Hole diameter (mm)	Plate thickness (mm)	Normalized far field failure strain	Failure mode	Normalized far field failure strain	Failure mode
6	4.16	1.00	c+t	0.53	c
6	8.32	0.86	c+t	-	-
25	4.16	0.67	t	0.48	c
25	8.32	0.74	t	-	-

Bending tests

As seen in Table 1 there is a difference in failure mode between specimens with 6 mm hole and 25 mm hole as the specimens with the larger hole in general failed in tension, whereas specimens with 6 mm hole typically failed in tension and compression. In Fig. 3 is typical compressive and tensile failure of a specimen with a 6 mm hole depicted. In Fig. 4 a typical tensile failure of a specimen with a 25 mm hole is presented.

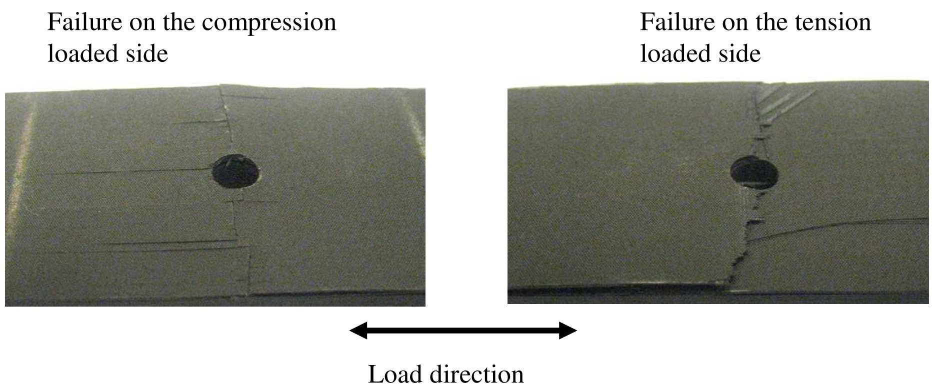

Fig. 3. Compressive (left) and tensile failure of a 8 mm thick specimen with a 6 mm hole.

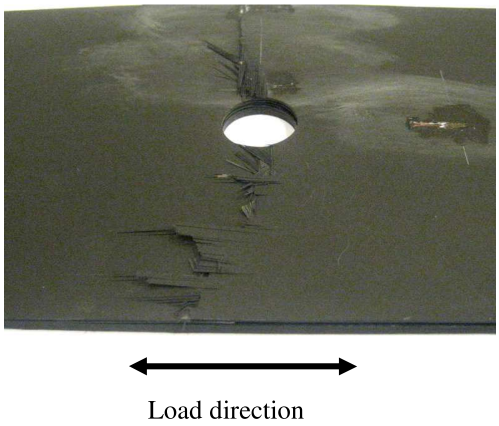

Fig. 4. Tensile failure of a 4 mm thick specimen with 25 mm hole.

Bending test of the first 4 mm specimen with 25 mm hole was interrupted when clear indications of damage initiation was seen on the load-displacement curve, as well as indications of damage growth could be heard. As seen in Fig. 5 tensile failure has started to grow at the hole boundary in the interrupted test.

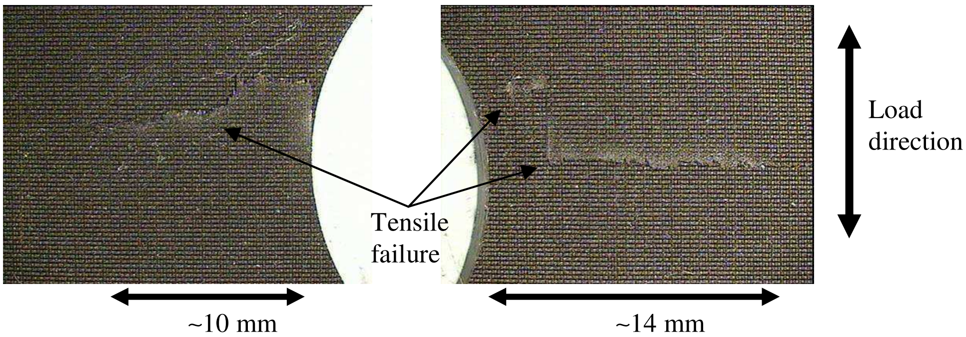

Fig. 5. Initiation of tensile failure in a 4 mm thick specimen with 25 mm hole.

The damage in the specimen shown in Fig. 5 was characterised by ultrasonic C-scan. In Fig. 6, a through-scan picture of the damage is depicted. The white circle indicates the position of the drilled hole, these C-scans were preformed with a 5 MHz transducer. The through-scan gives information of the total projected area of the damage in all interfaces.

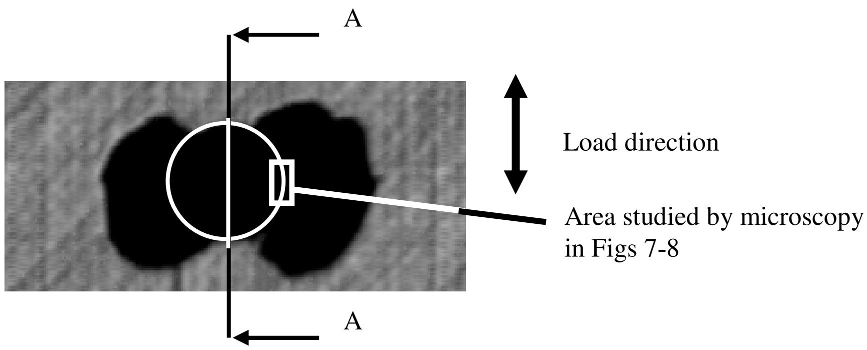

Fig. 6. Through-scan picture of the damage in the specimen depicted in Fig. 5.

Subsequently the specimen was cut at A-A, see Fig. 6, by the use of a hard metal saw to facilitate inspection of the damage distribution through the thickness at the hole boundary by the use of an optical microscope. Delaminations and matrix cracks are readily visible in the micrographs in Fig. 7.

When increasing the magnification it was also possible to detect fibre failures as shown in Fig. 7. Delaminations were found in the first 9 interfaces from the tensile loaded surface, although it was difficult to obtain high qualitative pictures of the damage in the hole boundary due to the curvature of the hole boundary and the small depth of field of the microscope.

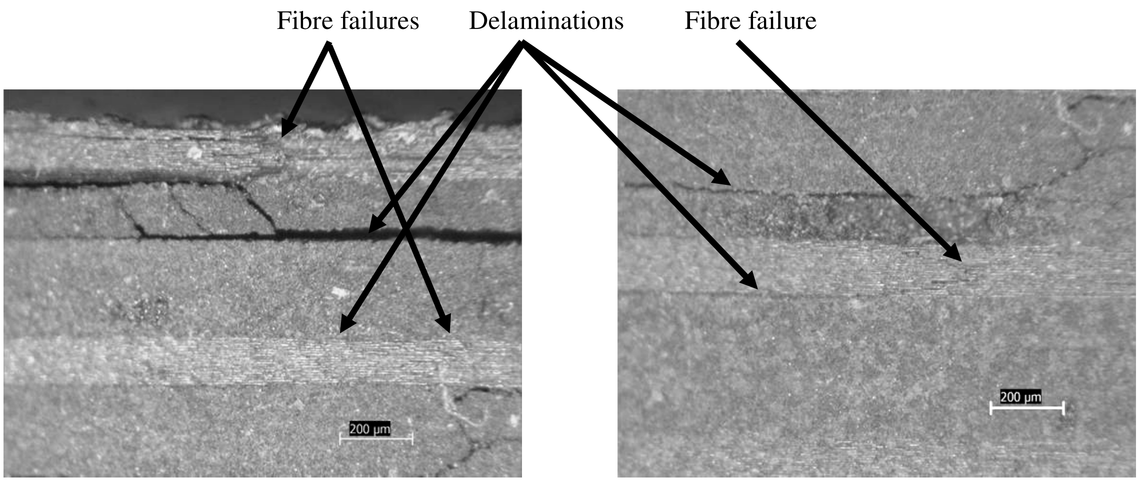

Fig. 7. Fibre failure, matrix cracks and delaminations in the tensile loaded side of the specimen. Left layer 1-7 and right layer 6-13 from the surface.

Compressive tests

For comparison, compression tests were performed on specimens with both a 6 mm hole and a 25 mm hole. The tests where performed with boundary conditions to prevent global buckling. As in the bending tests, load and displacement were measured with the internal load cell and displacement recorder in the test rig.

Results are summarised in Table 1. The maximum stress is the maximum load divided by nominal gross area of the specimens. The maximum far field strain was calculated from the maximum stress.

As seen in Table 1, the maximum stress is approximately the same for the specimens with 6 mm hole and 25 mm hole. The failure of the specimens with both 6 mm hole and 25 mm hole was compressive, apparently initiated by stress concentrations at the hole boundary.

DISCUSSION

The mean values of the results from both the bending and compression tests are summarised in Table 1. The results are summarised with regard to failure strain for the different loading conditions. The failure strain is calculated by laminate theory, using an in-house program at Saab Aerostructures. The calculated failure strain is based on the mean value from 4 or in some cases only 3 specimens.

The failure strain is observed to be much higher for specimens loaded in bending compared to those loaded in pure compression. Specimens with a 6 mm hole showed a significantly higher strain to failure than specimens with 25 mm hole although the W/D-ratio were the same for both load cases. It should also be noted that whan loaded in bending there was a difference in failure mode, as specimen with 6 mm hole exhibited both tensile and compressive failure, whereas specimen with 25 mm hole failed in tension. It should also be pointed out that for the specimens with 6 mm hole was a higher failure strain was obtained for the thinner specimens, whereas for the specimens with 25 mm hole a higher failure strain was obtained for the thicker specimens.

As pointed out by Wisnom [2], it is of fundamental importance to understand the failure behaviour of the material as specimens loaded in bending usually fail in tension despite the higher tensile strength of the material. It is further emphasised that the strength would be expected to be higher in bending than in compression because of the smaller volume of material being subjected to the maximum stress. As pointed out in [2] that when applying engineering methods to determine the failure strain errors can occur due to large deformations and nonlinearity. In these tests, strain gauges were used on some specimens and the recorded failure strain differed only a couple of percent with the calculated failure strain. A plausible theory, explaining the higher failure strain in bending than in compression, is that failure in compression is initiated by micro-buckling. However, when loaded in bending, due to the curvature of the specimen the occurrence of microbuckling is prevented.

Several papers have been published discussing size effect on both tensile and compressive strength of notched composite laminates [3, 4, 5, 6, 7]. Conclusions from these papers are that there is a significant reduction of the tensile notch strength with increased thickness and also with increased hole size when the W/D-ratio is constant. The compressive strength has been found to decrease with increasing hole size and increase with increased thickness. The results presented here with respect to the bending strength agrees well with these observation except for specimens with 6 mm hole where the strength decreased with increased thickness.

CONCLUSIONS

An expected effect of hole size on the bending strength has been observed as the failure strain of the thin laminates with 25 mm hole was only 65 % of the failure strain of the laminates with a 6 mm hole. Corresponding number for the thick laminates is that the laminate with 25 mm hole has 85 % of the strength of the laminate with a 6 mm hole.

The effect of laminate thickness is however somewhat contra dictionary as for laminates with 25 mm hole resulted in a 10 % higher failure strain for the thick laminates. Whereas for laminates with 6 mm hole the thinner laminates showed a 15 % higher failure strain. However it should be noted that the specimens with 25 mm hole failed in tension, whereas the specimens with 6 mm hole failed in compression and tension.

The calculated failure strain of the compressive loaded thin laminates with 6 mm hole was only 55 % of the calculated failure strain of the specimens loaded in 4-point bending. For the specimens with 25 mm hole the compressive failure strain was approximately 70 % of the specimens loaded in 4-point bending.

A need for a method to predict the strength of a laminate loaded in a combination of in-plane and out of plane loads (bending) during the design phase has been recognised. There is a potential with a methodology that can handle the difference in failure strain and failure mode, i.e. make use of the higher failure strain in bending. The tests presented in this work are an initial step to increase the knowledge needed to determine such a tool

ACKNOWLEDGEMENTS

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