AN EXPERIMENTAL INVESTIGATION INTO FATIGUE DAMAGE DEVELOPMENT IN OPEN AND BOLTED HOLE SPECIMENS

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Abstract
An extensive experimental program has been carried out to investigate and understand the sequence of damage development throughout the life of open-hole and bolted composite laminates under quasi-static loading and tension-tension fatigue. Quasi-isotropic carbon/epoxy laminates, with stacking sequence $[45_2/90_2/-45_2/0_2]_S$ *defined as ply scaled and* $[45/90/-45/0]_{2S}$ *defined as sub-laminate scaled, were used. Specimens were cycled at 5Hz with various amplitudes to* $1x10^6$ *cycles unless failure occurred prior to this limit. A number of tests from the open-hole study were interrupted at various points as the stiffness dropped and analysed for damage using X-ray CT. The ply level open-hole case showed a similar overall failure mode of delamination in quasi-static and fatigue loading. The sub-laminate case showed a failure mode change from quasi-static fibre dominated pull-out to delamination in fatigue. For the ply-level bolted case, the fatigue life increased, with a failure mode change from delamination in open-hole fatigue tests, to pull-out. It is shown in this paper how the role of delamination is critical in the case of fatigue loading and how this interacts with bolt clamp-up forces, even when delamination does not dominate in static tests.*

1. Introduction

Fibre-reinforced composites laminates are increasingly being used to manufacture load bearing primary structures in the aerospace industry as composites offer a much greater strength to weight ratio than metals. The initial perception was that composite materials don't suffer from the effects of fatigue, however in recent years it has become well established that composites do exhibit damage under cyclic loading conditions. Laminates with stress concentrations have complex damage sequences and failure events, and show a wide variety of effects not observed in un-notched laminates.

A concise scaling effect study in the quasi-static strength of open-hole tension specimens was carried out by Green [2] which found that delamination is a significant failure mode for ply-level open-hole tests where the hole diameter to ply block thickness ratio is smaller, allowing delaminations to occur at lower stresses. This results in increasing failure stresses for increasing in-plane dimensions using constant thicknesses In contrast for the sub-laminate level cases the reduction in the amount of damage propagating through the gauge section for configurations with larger hole-diameters means that there is a reduced amount of stress relief leading to earlier fibre-dominated failure.

In previous fatigue related work, Spearing and Beaumont [11] concentrated on tension-tension fatigue of notched Carbon/Epoxy (T300/914) and Carbon/Polyetheretherketone

(PEEK) laminates using an R ratio of 0.1. NDT (non-destructive testing) techniques included X-radiography to produce images of the damage. It was also shown how prolonged exposure to the zinc iodide dye penetrant can accelerate the growth of damage in the specimens.
Other early work was carried out by Mohlin et. al [4, 5] using tetrabromoethane (TBE) enhanced X-ray radiography to study delamination growth in notched/carbon epoxy laminates under compressive fatigue loading.
The main limitations of this early work is the 2D nature of damage characterisation, and the inability to separate out the global damage into individual delamination interfaces and ply cracking orientations. Fatigue damage in composites is distinctly 3D in character and therefore more recent techniques such as X-ray computed tomography (CT) are much more suitable for the evaluation of the micromechanical behaviour of fatigue damage development. Work by Scott et. al. [10] and Moffat et. al.[3] has proven the capability of this technique to identify damage progression in notched carbon-epoxy specimens under quasi-static loading to failure.

Joints which use fasteners are very standard in the assembly of aircraft structures. The complex failure modes of composites materials and the requirement for fasteners demands more rigorous attention to design than for traditional alloys. Bolt filled-hole, along with open-hole tension tests are widely used in industry to aid the understanding of the behaviour of the tensile strength of bolted joints.

Factors affecting the characteristics of open and filled-hole laminate strengths include, ply orientation, washer pressures and washer sizes. There is still very little understanding of the mechanisms and causes of the differences in failure strength between the filled-hole and open-hole specimens. An experimental study was carried out to investigate the effects of clamp-up on the net-tension (quasi-static) failure of composite plates with bolt filled-holes by Yan et al. [13]. Bolted joints (100% bolt bearing load) and non-bolt bearing load (100% bypass tensile load) conditions were investigated. For bolted joints which failed under a net-tension mode, the bolt clamping force increased the strength of the joint irrespective of the layup. There have been many quantitative studies into the tensile strength and fatigue behaviour of bolted composite joints with single and multiple numbers of bolts [8, 9, 12].

The aims of the work in this paper was to further understand how the failure modes seen in the open-hole test program [7] are further influenced by bolted clamp-up forces, and to compare and contrast to failure modes of open-hole tests.

2. Experimental Procedure

The material used is Hexcel's carbon fibre-epoxy unidirectional (UD) prepreg system, IM7/8552, with a nominal ply thickness of 0.125 mm [1]. The specimen dimensions are shown in figure 1. The ratio of width to hole diameter were chosen as they represent the minimum distances needed to allow the stress states to return sufficiently close to their original values at the edges thereby giving dimensions offering the lowest strengths, and using the least amount of material.

In order to measure the clamping force around the hole, a bush was made with two "rigid" washers of diameter 6.35mm separated by the composite (figure 1). On the bush, strain gauges were bonded at opposite sides to measure the axial compressive strain so as to calculate the stresses with accuracy and to ensure that there was no bending of the bush.

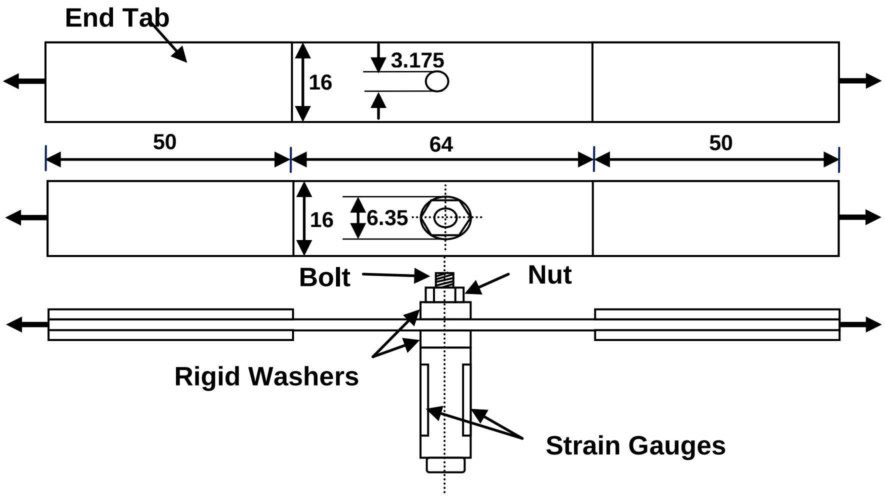


Figure 1. Open and bolted hole specimen dimensions.

Quasi-isotropic carbon/epoxy laminates, with stacking sequence $[45_2/90_2/-45_2/0_2]_S$ and $[45/90/-45/0]_{2S}$ were used. The first, with plies blocked together is termed as ply-level scaled, and the second, with repeated sub-laminate units is termed as sub-laminate-level scaled (figure 2). The load bearing plies in the 0 direction are not at the surface and are thus more protected from impact damage, which is consistent with standard industry practice. These configurations were chosen as the ply-level specimens exhibited delamination dominated failure in quasi-static testing, with sub-laminate level specimens showing a fibre dominated pull-out type failure [1].

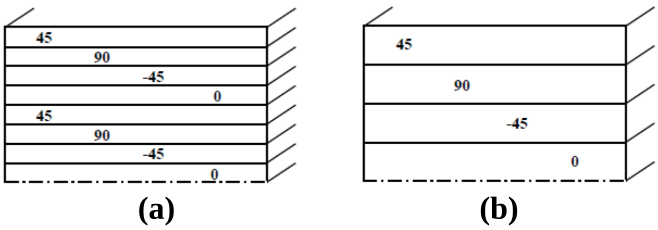


Figure 2. (a) Sub-laminate-level, and (b) Ply-level layups.

Quasi-static tests were carried out using a crosshead speed of 1mm/min in all cases. The fatigue tests were run at various percentages of the average static failure load. Fatigue tests were run in load control at constant amplitude, with an R ratio of 0.1 and frequency of 5Hz. Each test was left to run to 10^6 cycles unless failure (defined as a 15% loss of stiffness) occurred prior to reaching this limit. 10^6 cycles is commonly used in the aerospace industry and is appropriate for the number of load cycles experienced during the useful life of an aircraft. Fatigue tests were carried out at 40%, 50%, 60%, 70% and 80% of the nominal failure load P_{max} for ply level open-hole tests, and 50%, 60%, 70% and 80% severities for bolt-filled ply-level specimens. For sub-laminate open-hole specimens, 55%, 60%, 65%, 70% 80%, 85% and 90% was used, and 80%, 85% and 90% severities was used only for the bolt-filled sub-laminate-level specimens. To characterise the effect of damage propagating under fatigue from the hole and free edge, an effective stiffness, E_{eff}, is calculated by using equation 1 below:

$$E_{eff} = \frac{(P_{max} - P_{min})}{A(\epsilon_{max} - \epsilon_{min})} \approx \frac{P_{max}}{A(\epsilon_{max} - \epsilon_{min})} \qquad (1)$$

where P_{max} is the load at peak amplitude, P_{min} is the load at the valley, A as the gross cross sectional area of the specimens and ε is the strain measured using a clip gauge extensometer recorded over a gauge length of 50 mm symmetric about the hole for each specimen.

A number of open-hole tests were interrupted at various points as the stiffness dropped with increasing cycles, using 60% severity tests in the ply-level case and 80% severity tests in the sub-laminate case in order to accurately determine a sequence of damage events leading to catastrophic failure in fatigue using X-ray CT [6].

3. Quasi-Static Open-Hole Testing

Previous analysis of quasi-static tests [2] showed the distinct failure modes described here. The open-hole quasi-static tests were repeated to ensure consistency and to be able to calculate fatigue parameters. Failure is taken as the first load drop greater than 5% on the load-displacement curve and can correspond to either of the failure mechanisms described. Multiple batches were required due to the extensive nature of the test programme. The strengths and failure modes for the quasi-static tests are summarised in table 1.

Layup	Number of Specimens	Batch	Strength (MPa)	CV (%)	Failure Mode
Ply-level	5	1	418.1	6.6	Delamination
Ply-level	3	2	446.8	3.1	Delamination
Ply-level	4	3	395.7	5.4	Delamination
Sublaminate	5	1	581.4	2.9	Pull-out
Sublaminate	4	2	531.8	3.1	Pull-out

Table 1. Summary of the failure modes and strengths for each configuration and batch.

3.1 Delamination Failure

Delamination, shown in figure 3b, initiates under the surface 45° ply and propagates through thickness via matrix cracks, and thus through the interfaces of the neighbouring 90° and -45° plies finally reaching the interface between the -45 and 0 plies near the centre of the laminate. When a single load drop is observed, the delaminations fill the entire gauge section of the -45/0 interface instantaneously. However for some specimens, there are several distinct load drops (figure 3a), due to the delaminations occurring asymmetrically either side of the hole.

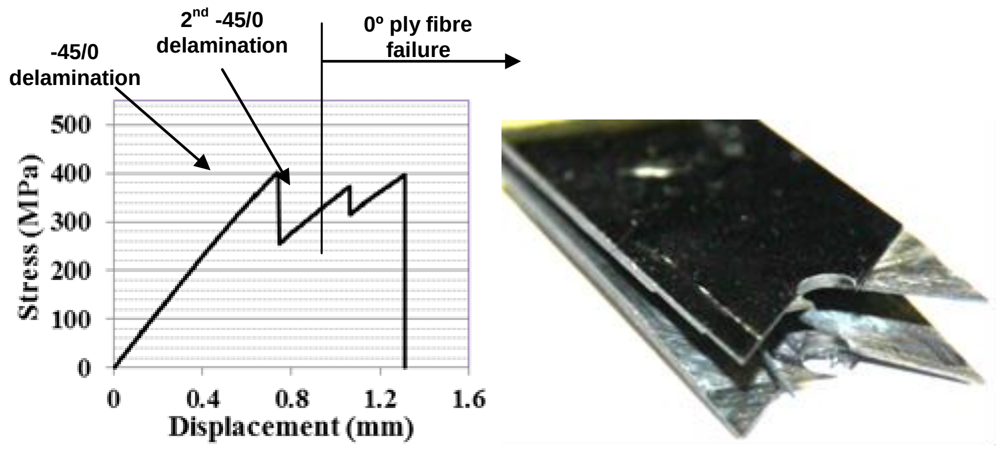


Figure 3. (a) Typical load-displacement curve for a ply-level specimen (b) Specimen which has failed by delamination.

3.2 Pull-out Failure

Pull-out failure occurs when the fibre failure stress of the 0º plies is reached during full width delamination. Failure is thus a combination of delaminated plies "pulling-out" and fibre-failure as seen in figure 4b. This failure mechanism occurred in the sub-laminate level specimens. A typical stress-displacement curve is shown in figure 4a.

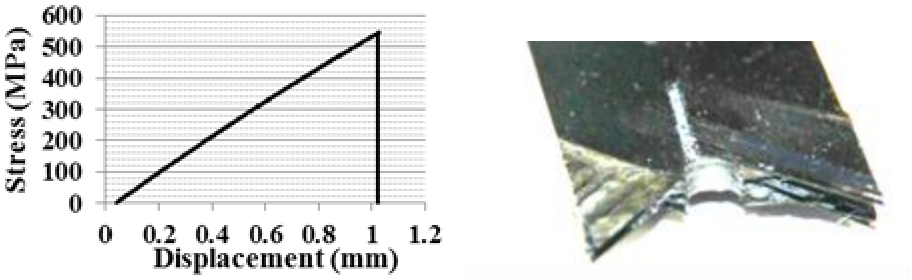


Figure 4. (a) Typical load-displacement curve for a sub-laminate-level specimen (b) Specimen which has failed by pull-out.

4. Quasi-Static Bolted-Hole Testing

Two washer pressures (23MPa and 70MPa) were investigated for each layup under quasi static loading. The ply-level specimens (open-hole failure by delamination) using a washer pressure of 23MPa, had an average failure strength of 476.8MPa (4.4% CV). Two of the five specimens failed via pull-out, and three out of five specimens failed by delamination. Therefore applying a washer pressure of 23MPa around the hole-edge, increases the stress required for delamination to some transition point by which there is a failure mode change to pull-out. When the washer pressure is increased to 70MPa, pull-out failure occurs for all five specimens with an average failure strength of 505.1MPa (2.9 % CV) of 2.9 %. The failure strengths of the bolt filled sub-laminate specimens using a washer pressure of 23 MPa were found to be 526.2 MPa with a CV of 2.0%, and for the washer pressure of 70MPa, at 544.1 MPa with a CV of 3.1% over 5 specimens in each case. For bolt-filled hole sub-laminate tests for both washer pressures, there was very little difference from the open-hole strengths. All specimens at both washer pressures failed by pull-out as per the open-hole case.

5. Open-Hole Tension Fatigue

An S-N diagram is a plot of the fatigue life at each level of fatigue stress, σ_{max}, the maximum applied stress. This is normalised with respect to the static OHT strength, σ_{UTS}, on the y axis of the S-N plot in figure 6. Failure is considered to be a 15% loss in normalised stiffness. The failure criterion was chosen as it represents the approximate transition from stable crack growth to more unstable crack growth. Run-outs were consistently observed at 40% severity for ply-level specimens. For sub-laminate level specimens, an initial result at 60% severity gave a run-out to $1x10^6$ cycles without satisfying the failure criterion. A second result using the same severity indicated a stiffness loss which satisfied the failure criterion. The severity was thus reduced to 55% where run-outs to $1x10^6$ cycles were consistently observed.

For the baseline sub-laminate specimens, fatigue failure appeared to follow a very similar trend to that of the ply level specimens with delamination dominating in all but the very highest severities (>90%). It is notable that this differed significantly from the quasi-static failure which was dominated by fibre failure (pull-out) with major delamination not progressing along the length of the specimen. It can thus be seen how the role of delamination is critical in the case of fatigue loading, even when it does not dominate in static tests.

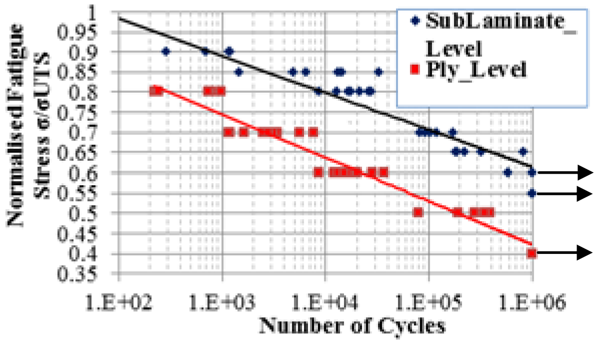


Figure 6. Plot showing both ply and baseline sub-laminate SN curves for hole diameter of 3.175 mm with run-outs indicated using arrows.

Figures 7a and 7b show a typical plot of normalised stiffness for ply and sub-laminate level specimens. It can be seen that there is very little drop in stiffness as a function of number of cycles, until the onset of catastrophic failure. For clarity, one result from each severity as shown in the stiffness plot. The ply-level tests show a more abrupt decrease in the stiffness from the starting plateau, whereas the sub-laminate shows more progressive damage evolution resulting in a gradual decline from the initial stiffness. The majority of the stiffness loss is due to the delamination of the -45/0 interface in each case.

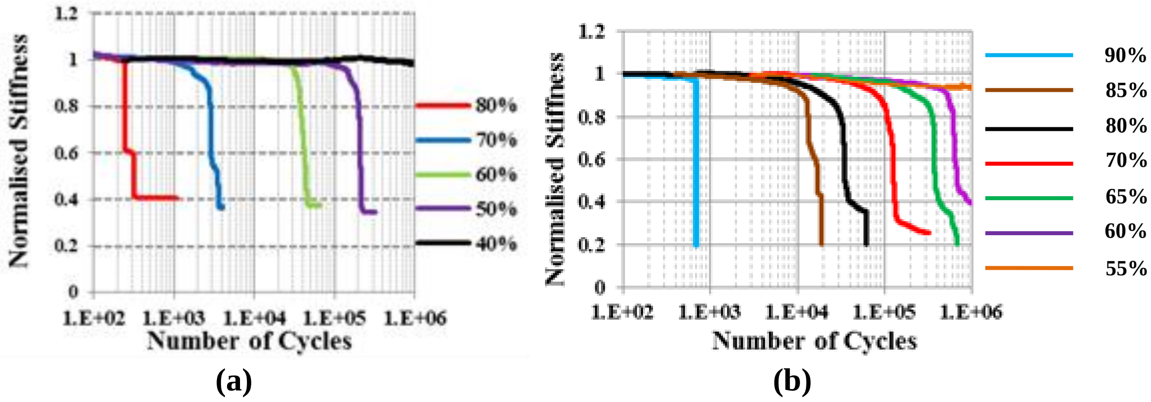


Figure 7. Typical fatigue stiffness curves at each severity for the (a) ply-level and (b) sublaminate level test programs.

6. Bolted Hole Tension Fatigue

A bolt pressure of 70MPa was used for all fatigue tests. For the bolted ply-level case, a minimum of 3 specimens were tested at 80%, 70% and 60% severity with a single run-out test at 50% severity. The results show a remarkable increase in the number of cycles to failure for the severities tested in comparison to the open-hole specimens. The failure mode in each ply-level bolted fatigue case is delamination.

All bolted sub-laminate specimens tested failed by pull-out under fatigue loading, whereas for open-hole specimens they failed by delamination in all but the highest of severities. The bolt clamp-up thus completely inhibits delamination failure in this case, causing the substantial rise in fatigue life. There is notably less scatter than for the ply-level case as the failure mode is fibre-dominated. Figure 9a, and 9b shows a clear shift in the SN curve to failure at a higher number of cycles for each bolted case.

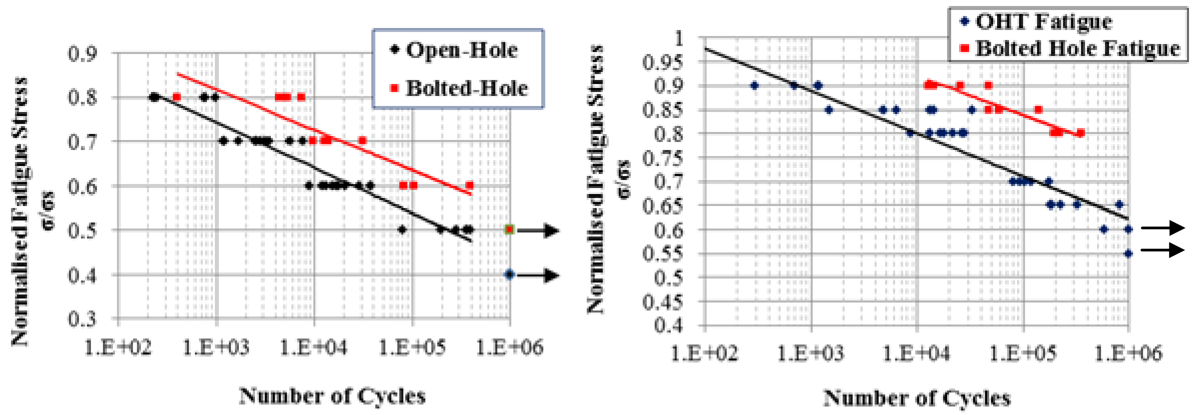


Figure 9. The relationship between open-hole and bolted-hole in fatigue loading for (a) ply-level specimens, and (b) sub-laminate specimens.

The fatigue strength is due to the clamp-up pressure which delays the onset of delamination from the hole-edge. For the majority of the bolted specimens with the ply-level configuration, once damage starts to propagate there is an initial decrease in the stiffness which satisfies the failure criterion, but the stiffness curve then levels out at a plateau at approximately half way through the total stiffness decrease (figure 10). This can be attributed to the clamp-up pressure which inhibits propagation of the 2nd asymmetric delamination of the -45/0 interface. There are also some delaminations initiating from the specimen edges. Figure 11 shows the extent of the fatigue damage for a 60% severity ply-level bolted-hole specimen, B012, which typifies the delay in propagation of the 2nd delamination of the -45/0 interface, and specimen B013 which shows the full extent of the damage after the complete loss in the stiffness.

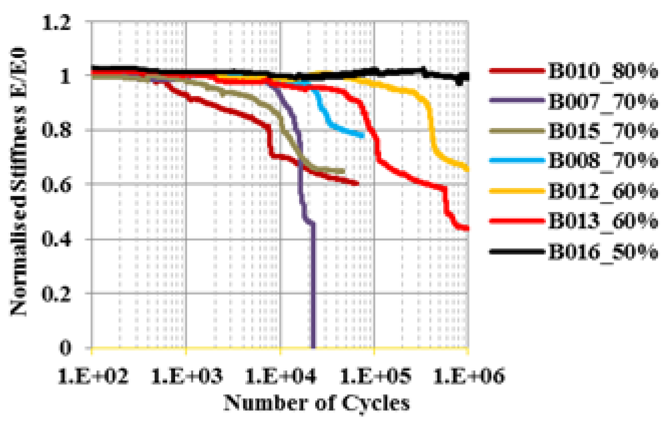


Figure 10. Bolted ply-level fatigue tests.

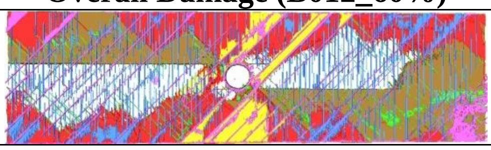
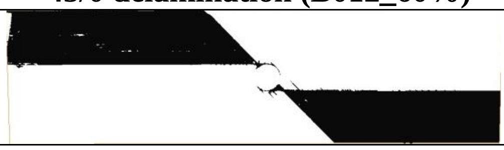
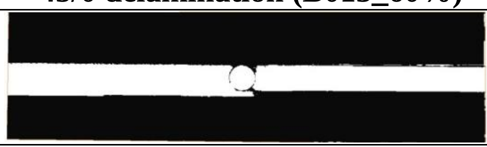
Overall Damage (B012_60%)	Overall Damage (B013_60%)
	
-45/0 delamination (B012_60%)	**-45/0 delamination (B013_60%)**
	

Figure 11. The damage state for specimens B012, and B013 at 60% severity after 1E6 cycles.

Conclusions

For the ply level open-hole specimens, damage follows a similar pattern to the quasi-static failure where the damage initiates in the surface ply in the form of matrix cracks and progressive to extensive delamination. In contrast the bolted specimens followed a different damage pattern. The static strengths were greater than for the open-hole tests and this was accompanied by a change in failure mode to pull-out failure due to delamination growth being inhibited by the clamping forces. For a given severity the fatigue life of the bolted specimens is greater than for open-hole tests, with delamination failure dominating as the failure mode.

For the sub-laminate scaled open-hole specimens, fatigue failure followed a very similar trend to ply-level, with delamination dominating in all but the very highest severities (>90%). This differed from the quasi-static failure which was dominated by pull-out with no delamination progressing along the length of the specimen. For the bolted case the fatigue life increases, with a failure mode change from delamination, as in open-hole fatigue tests, to pull-out.

The results for both layups show a notable increase in the number of cycles to failure for the bolted hole specimens in comparison to open-hole specimens. This is primarily due to the fatigue delamination being delayed by the bolt clamping due to an increase in initiation stress.

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