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An experimental investigation into quasi-static and fatigue damage development in 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 bolted-hole composite laminates under quasi-static loading and tension–tension fatigue. Quasi-isotropic carbon/epoxy laminates, with stacking sequence $[45_2/90_2/\text{-}45_2/0_2]_S$ defined as ply scaled and $[45/90/\text{-}45/0]_{2S}$ defined as sub-laminate scaled, were used. Specimens were cycled at 5 Hz with various amplitudes to 1×10^6 cycles unless failure occurred prior to this limit. For all cases an R ratio of 0.1 was used. Bolt washer pressures of 23 MPa and 70 MPa were investigated. For the ply-level case, the quasi-static test showed both delamination and fibre-dominated pull-out failures for a washer pressure of 23 MPa, and pull-out failure only for 70 MPa. Delamination dominates in fatigue tests. For the sub-laminate case the tests failed by pull-out in both quasi-static and fatigue tests for all washer pressures. 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. A number of tests were analysed for damage using X-ray CT scanning and comparisons of damage are made with tests from previous open-hole studies.

1. Introduction

Fibre-reinforced composites laminates are increasingly being used to manufacture load bearing primary structures in the aerospace sector as composites offer a much better strength to weight ratio than metals. Joints which use fasteners are very commonplace in the assembly of aircraft structures. The complex failure modes of composites materials and the requirement for fasteners however demand a more rigorous approach 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 rather limited understanding of the mechanisms and causes of the differences in failure strength between the filled-hole and open-hole specimens. Previous work in this area includes an experimental study 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. [1]. Bolted joints (100% bolt bearing load) and non-bolt bearing load (100% bypass tensile load) conditions were investigated. For bolted joints which failed in a net-tension mode, the bolt clamping force increased the strength of the joint irrespective of the layup. There have also been other quantitative studies into the tensile strength and fatigue behaviour of bolted composite joints with single and multiple numbers of bolts [2–4].

Persson and Eriksson [3], for example, investigated various different conditions of multiple row bolted joints to include geometry (width, spacing, and edge distances), laminate configuration, fastener type, and environmental conditions. They found that the most significant factors were the ratio of bolt diameter to specimen width, and the ratio of hole diameter to laminate thickness when using single-lap joints containing four fasteners and two rows. However very little work is available in the literature on the interactions between the sub-critical damage and the bolt clamp-up forces.

Previous work has investigated open-hole tension damage mechanisms in detail under static loading [5] and fatigue [6–8]. These studies found that delamination plays a significant role in cases with thick ply blocks, where the hole diameter to ply block thickness ratio is relatively small. This results in increasing failure

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stresses for increasing in-plane dimensions using constant thicknesses. In contrast for cases with dispersed plies and repeated sublaminates through the thickness 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 at the hole-edge, leading to earlier fibre-dominated failure. The effect of out of plane compressive stress on enhancing delamination strength is well known in composites [2]. It is thus expected that when the same configurations as tested in open-hole tension are subject to bolt clamping forces, this will have a direct effect on the damage formation and hence ultimate strength.

Since the understanding of formation and propagation of damage is of great importance to the overall failure of open-hole tension specimens, particularly in fatigue, this was investigated and characterised using X-ray Computed Tomography (CT) scanning in Refs. [6,8]. In other earlier fatigue related work, Spearing and Beaumont [9] 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. [10,11] 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 three dimensional 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. [12] and Moffat et al. [13] has proven the capability of this technique to identify damage progression in notched carbon-epoxy specimens under quasi-static loading to failure.

In this paper the role of bolted clamp-up forces is examined in regard to its effect on the formation of damage in bolted-hole tension tests both in static and fatigue. The damage is characterised through X-ray CT scanning of tests interrupted at various stages of the damage formation and results are compared against previous open-hole tension fatigue work [6,8,14].

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 [15]. The specimen dimensions are shown in Fig. 1. Holes were drilled using a brad-point (also known as lip and spur), tungsten carbide drill bits. The lip and spur (also known as the brad point) drill bit, is optimised for drilling wood. Conventional drill bits may wander prior to initial contact with a flat surface, the sharp point of the spur pushes into the material keeping it in line. When drilling wood across the grain there is a tendency for the long fibres to pull-out around the circumference of the hole-edge rather than being cleanly cut. This also applies to composite materials which like wood contains many fibres. The lip and spur drill bit cuts the outer periphery of the hole prior to the inner cutting edges, planing the base of the hole. Thus the lip ensures that the fibres at the hole-edge are cut cleanly rather than pulling them out and splintering them.

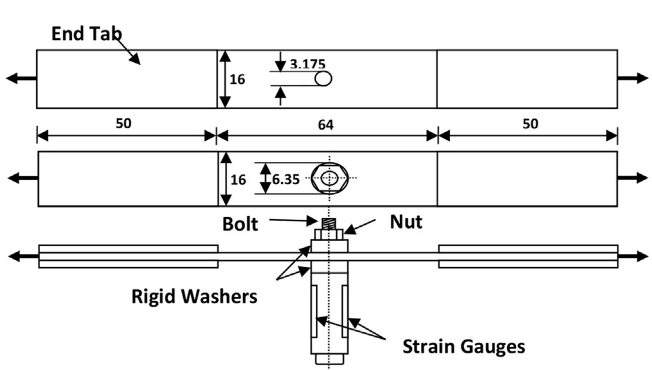

Fig. 1. Open and bolted hole specimen dimensions.

Drilling parameters used in this paper were 1500 rpm (spindle speed), with a feed rate of 1 mm/min. If drill speed is too high then the propensity to generate heat is increased, if too low then the risk of back face delamination damage is enhanced. The specimen was clamped to a back plate in order to minimise back-face breakout. The drilling method used here is consistent with previous open-hole quasi-static and fatigue work carried out by the authors [6,8].

Quasi-static open-hole tests carried out by Green et al. [5] used reamed holes when preparing specimens of the same configuration. X-ray images in Ref. [16] show minimal damage in areas not affected by mechanical loading. X-ray images in Refs. [6,8] show similar low levels of drilling damage and more importantly, close agreement was obtained between the quasi-static tensile results from Ref. [5] and those obtained in Refs. [6,8], thus indicating that hole drilling quality was sufficient so as not to influence the results.

The ratio of width to hole diameter chosen represents the minimum distance needed to allow the elastic stress states to return sufficiently close to their original values at the edges, thereby giving dimensions offering the lowest failure forces, and using the least amount of material. The geometry used here had a W/d ratio of 5 to ensure consistency with previous extensive work on open-hole tensile specimens [5–8], which was based on an industrial test standard. This is slightly lower than the recommended W/d ratio of 6 in the ASTM D6742 standard.

In order to measure the clamping stress around the hole, a bush made from 6082-T6 aluminium alloy, with strain gauges bonded at opposite sides was used. These were calibrated so as to accurately calculate the clamping stresses and to ensure that there was no bending of the bush. Two "rigid" 4 mm thick aluminium washers of diameter 6.35 mm were then placed adjacent to the composite (Fig. 1) to apply the contact load. This gives a washer diameter to hole diameter ratio of 2:1. A4 class 70 stainless steel M3 bolts were used, with a measured thread diameter of 2.95 mm (using digital Vernier callipers). The hole diameter of the specimens was 3.175 mm (1/8 inch), thus the bolt thread diameter is a clearance fit with respect to the specimen holes so as to eliminate contact stress at the hole edge as an experimental variable.

The hole-diameter of the washer and bush is 3.1 mm with a maximum allowable shift of 0.15 mm with respect to the bolt. Care was taken when tightening to ensure that the washer remained central with the hole.

Quasi-isotropic carbon/epoxy laminates, with stacking sequence $[45_2/90_2/\text{-}45_2/0_2]_S$ and $[45/90/\text{-}45/0]_{2S}$ were used. The first, with plies blocked together is termed 'ply-level scaled', and the second, with repeated sub-laminate units is termed 'sub-laminate-level scaled'. 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 open-hole ply-level specimens exhibited delamination dominated failure in quasi-static testing, with sub-laminate level specimens showing a fibre dominated pull-