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Experimental investigation of damage progression and strength of countersunk composite joints

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ABSTRACT

An experimental investigation is conducted into the damage progression and strength of bolted joints with fibre-reinforced composite laminates and countersunk fasteners. The main goal of the experimental investigation is to characterise the effect of the countersink geometry on the load-carrying capacity of single lap joints in comparison to the straight-shank case. The effects of bolt torque, clearance and countersink height ratio on the damage progression and joint strength are also studied. Experimental tests and detailed microscopy studies are conducted on a bearing test specimen with a straight-edged hole, and several single-lap joint configurations with countersunk fasteners. It is found that introduction of the countersunk hole roughly halves the bearing stress, and causes delamination for some configurations. This delamination is primarily located at the start of the countersink region, though is found to be triggered by other damage mechanisms and has only minor influence on the results. Bolt torque increases the density of through-thickness damage though limits its extension from the hole edge, whilst bolt clearance causes localisation of the damage region. Increasing the ratio of the countersink depth to the laminate thickness reduces the extent of bearing and promotes bending, with a change to net section failure at large ratios.

1. Introduction

Despite the many advantages of adhesive bonding, bolted joints are still used in aerospace structures because of the ease of assembly/disassembly and airworthiness certification. However, the introduction of bolts leads to complicated three-dimensional (3D) stress fields near the bolt hole [1]. In the case of composite skin structures, the use of countersunk fasteners elevates the stress concentration above that for straight-sided holes. The higher stresses due to the countersunk fastener further reduce the joining efficiency of laminated composites. To take full advantage of fibre-reinforced composite materials in structural elements, it is necessary to investigate techniques to improve the structural efficiencies of bolted joints, particularly those involving countersunk fasteners. This in turn requires a thorough understanding and modelling capabilities of the effect of the countersink geometry and the influence of the joint parameters.

Research in the field of bolted joints has mostly concentrated on straight shank bolts, with limited work on countersunk bolted joints. Various authors [2,3] have found the primary failure mode in pin-bearing damage is shear cracking formed by accumulated compression failure in each individual ply of the laminate. Detailed microscopy has found that the principal damage mechanisms of the shear cracks are fibre kinking, fibre–matrix shearing and matrix compression. Delamination has also been found to be a major failure mode in bearing damage [4], particularly in interaction with other modes.

Research on the influence of bolted joint parameters on the joint strength and damage progression has also been dominated by investigations into straight-shank bolts. Bolt torque (BT) has been investigated by several authors for straight-shank bolts [5,6] and found to increase bearing and failure loads, as well as limit delamination. Clearance (CL) in straight-shank bolt holes has been found to reduce the bolt contact area [7–9], affecting the load transfer, high stress regions and joint bearing loads. With regards to countersunk joints, recommendations for joint design to promote bearing failure are given in an ASTM standard [10], and summarised in Fig. 1, though the effects of variation within these guidelines are not covered.

In contrast to the considerable literature available on straight-shank bolts, the literature with regards to countersunk joints is not as comprehensive. A few investigations have focused on the contact condition of the bolt [8,11,12], or the application with multi-bolt joints [13]. These investigations have typically focused on describing the joint behaviour using the load history, and detailed

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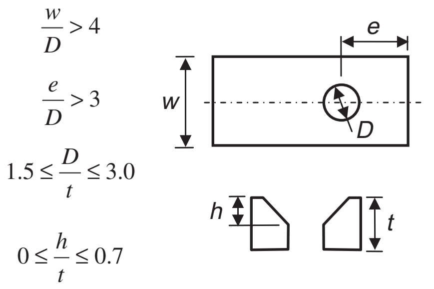

Fig. 1. Specimen design guidelines to promote bearing failure (adapted from Ref. [10]).

Table 1
Specimen dimensions (mm).

	t	Fabric ply layup	D	A
Bearing	3.52	$[0,45]_{4S}$	6.35	n/a
BT (all)	3.52	$[0,45]_{4S}$	4.76	9.56
CL (all)	3.52	$[0,45]_{4S}$	4.76	9.56
HT_0.56	3.52	$[0,45]_{4S}$	4.76	9.56
HT_0.64	3.08	$[(0,45)_3,0]_S$	4.76	9.56
HT_0.76	3.52	$[0,45]_{4S}$	6.35	12.71

microscopy of countersunk joints under a range of joint configurations have not been published in open literature. Further, the majority of literature on composite bolted joints relates to unidirectional tape material, and the damage mechanisms and joint behaviour of laminates manufactured using fabric plies have not been reported.

In this paper, results are presented from an experimental investigation into the damage progression and strength of countersunk composite single-lap joints. The specimens investigated are manufactured from fabric material with variations in bolt torque, clearance and countersink height to laminate thickness (HT) ratio h/t. A focus of the investigation is a detailed study of the load-carrying capability and damage mode initiation, progression and interaction. Results from a numerical investigation into the stress distributions are also presented, to provide further insight into the load paths and stress distributions for each configuration.

2. Specimen configuration

Experimental tests were conducted in two configurations: a bearing test, and single-lap joints with countersunk bolts. Both specimens were designed according to the recommendations to promote bearing failure in the ASTM standard [10]. The details of the specimens are given in Fig. 2 and Table 1, where the bearing test was equivalent to the lower laminate of the single-lap joint (with no extensometer tab). The bearing test used a straight-edge hole, whilst all other specimens were single-lap joints with countersunk holes. The specimens were all manufactured using plain weave carbon/epoxy T300/970 pre-preg (nominal ply thickness 0.22 mm). Specimens were tested in a 100 kN MTS hydraulic test machine. Strain gauges (SGs) were used as shown in Fig. 2, though the bearing test used only one strain gauge at the SG3 location.

In the bearing test, a single laminate with a straight-edge circular hole was gripped on one end and loaded in bearing by a steel pin through the hole. An extensometer was placed between the laminate edge and the loading grip. In the single-lap joints test, the specimens were gripped on the edge of each laminate and loaded in tension. An extensometer was placed between tabs as shown in Fig. 2. Variations in the single-lap joints included different levels of bolt torque, bolt clearance, and countersink height to laminate thickness ratio h/t, each at three levels as summarised in Table 2. Bolt torque was introduced using a calibrated torque wrench, and clearance was introduced by increasing the diameter of the straight-edge portion of the bolt hole only. The specimens were loaded in displacement control at 0.5 mm/min until ultimate failure, though one bearing test specimen was only loaded until the onset of non-linearity.

Following testing, microscopy was conducted on one specimen of each configuration, and for the bearing test the specimen loaded to only the onset of non-linearity was also inspected. Sections were taken along the loading direction (x-axis) and at 45° to the loading direction, where the cross-section labelling for microscopy and

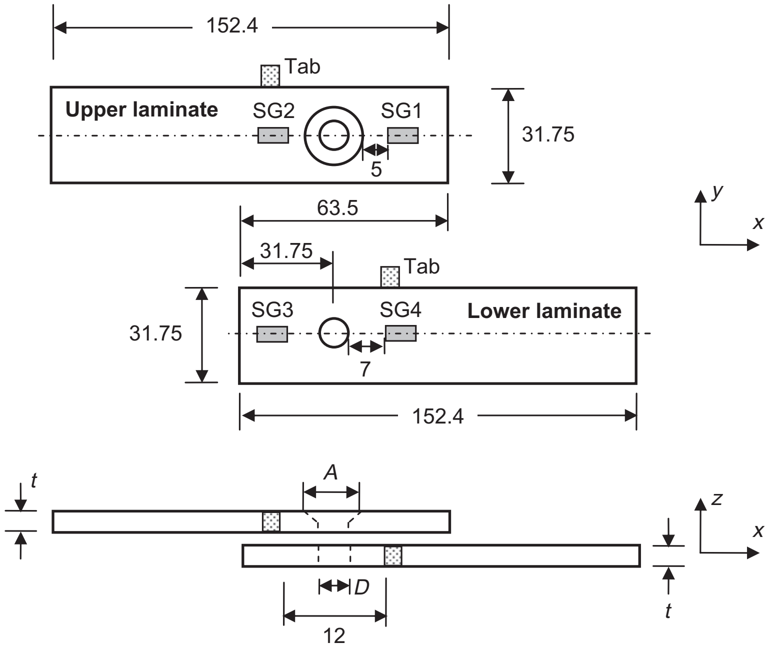

Fig. 2. Countersunk joint geometry and dimensions (mm), strain gauge locations and extensometer tabs.