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Effects of laminate thickness, tapering and missing fasteners on the mechanical behaviour of single-lap, multi-bolt, countersunk composite joints

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ABSTRACT

This paper presents an experimental investigation into the effects of joint thickness, laminate taper and missing fasteners on the stiffness, strength and load distribution in single-lap, multi-bolt, countersunk composite joints. It is demonstrated that three-dimensional digital image correlation can be used to detect the load at which first bearing failure occurs, and hence, the limit load of the joint. It is shown that laminate thickness has a significant effect on joint stiffness and ultimate load, both of which rise with increase in joint thickness. Considering laminate taper, significant weight savings may be achieved by reducing the thickness of the laminates outside the overlap region of the joint. Save small reductions in joint stiffness, tapered joints display little or no difference in terms of ultimate load and load distribution when compared to constant thickness joints. It is found that missing fasteners can cause significant losses in load-carrying capacity (up to 11.4%). In terms of load distribution, it was found that bolts in the vicinity of the empty hole, together with bolts located in the same column (i.e. the line of bolts parallel to the applied load) as the empty hole, experience significant increases in load.

1. Introduction

In composite aircraft structures, many challenges still exist to understanding structural behaviour, and these greatly affect design for minimum weight and fuel savings. One such challenge is the design of multi-bolt joints, where load distribution among fasteners has a significant effect on the mechanical behaviour of the structure. Due to the brittle nature of composite materials, an uneven load distribution may be of some concern, as little or no stress relief occurs around the bolt–hole, thus causing premature failure at the most highly loaded bolt. Many different design variables have a direct effect on load distribution, and a good understanding of these is essential. In terms of load distribution, much is now understood about the mechanical behaviour of multi-bolt composite joints in terms of:

- Experimental testing [1–6].
- Detailed numerical modelling [2,7–9].
- Efficient analytical/numerical modelling [3,4,10-18].
- Bolt–hole clearance [1,5,7,8,12,13,16,17].
- Bolt-torque and friction forces [2,7,9,11–13,16].

For this paper, of particular interest are the effect of stacking sequence (with respect to laminate thickness), laminate taper and the effect of missing fasteners. While it is important to quantify the global stiffness and the ultimate load of the joint, it is equally important to understand the load distribution. Early efforts to quantify the load distribution were restricted to analytical or numerical modelling with a lack of experimental evidence [10,15,18]. To gain a better understanding of mechanical behaviour and to validate analytical and numerical models, many different experimental methods have been developed to quantify the load distribution in multi-bolt composite joints.

McCarthy et al. [1] carried out an experimental analysis of bolt–hole clearance effects in single-lap, protruding-head, 3-bolt composite joints. The bolts were arranged in a single column[1] and quasi-isotropic, carbon-fibre/epoxy laminates were examined. The clearance at each hole was varied from test to test and instrumented fasteners were used to measure the load distribution in the joint. This was achieved by milling out a narrow slot and placing ±45° strain gauges in the bolt at the faying surface of the laminates. These tests revealed that the load was shared equally between the outer bolts in joints containing all neat-fit holes and that a delay in load take-up occurred at clearance fit holes. While

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[1] Bolts in a line parallel to the applied load are defined as a column of bolts.

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this paper gave a good insight into the mechanical behaviour of multi-bolt composite joints, it was limited to elastic analysis due to the expense and time constraints in manufacturing instrumented fasteners. Friberg [3,4] and Ekh and Schön [2] used a similar approach to measure the load distribution experimentally.

A more cost-effective approach was developed in [6] to study the failure behaviour of double-lap, protruding-head, multi-bolt composite joints. The load distribution was measured by placing a row of strain gauges between each bolt–hole. The bypass stresses were found by integrating the strain across the width of the specimen and the load distribution was determined by drawing free-body diagrams of the joint. Lawlor et al. [5] used this method to study the effect of bolt–hole clearance on the failure mode, load and location in double-lap, protruding-head, 3-bolt composite joints. It was noted that the presence of varying bolt–hole clearance not only had a significant effect on final failure, but also had an effect on the first significant failure event in the joint. The first significant failure event, defined as the first major drop in stiffness of the joint, occurred when the critical bearing strength of one bolt–hole was exceeded and this behaviour was captured in the load distribution analysis. When failure occurs at one bolt–hole, the load is redistributed among the remaining fasteners, which experience a sudden rise in bolt-load.

In the experimental methods developed so far, the failure behaviour in double-lap specimens has only been considered. In [5,6], it was mentioned that the use of strain gauges to extract the bypass stresses (and hence, the load distribution) is not applicable to single-lap specimens, due to the presence of friction and bending stresses in the sample. In this paper, this assumption will be investigated using single-lap joints with different thickness (and hence, different degrees of bending stress).

As well as clearance effects, the effect of bolt torque and friction forces on load distribution in protruding-head, multi-bolt joints, has been investigated by [2,7,9,11–13,16]. McCarthy and Gray [16], who carried out both analytical and detailed finite element studies, found that increasing the bolt torque simply delays the load take-up at all fasteners in single-lap, 3-bolt joints, while the load-sharing capacity does not change (i.e. the two outer bolts carry more load than the inner bolt). Ekh and Schön [2], who carried out both experimental and detailed finite element studies, came to a similar conclusion. In this paper, a torque will be applied to the fasteners and so, the friction forces will be become significant. In addition, since all previous studies have mainly involved protruding-head fasteners, the focus has been changed to countersunk fasteners in this paper. Since many aircraft members are assembled with countersunk fasteners in single-lap configurations, particularly on aerodynamic surfaces, an investigation of load distribution in countersunk multi-bolt joints has been carried out in this paper.

Also, apart from a numerical study on elastic behaviour [4], very little evidence on the effect of missing fasteners on the stiffness, ultimate strength and load distribution in multi-row,[2] multi-column joints has been presented in the open literature and is thus investigated in this paper.

In summary, the following information regarding the design and mechanical behaviour of multi-bolt countersunk joints will be investigated:

- The effect of joint thickness (and hence, joint weight) on the stiffness, ultimate load and load distribution in multi-bolt joints.
- The effect of laminate taper (and hence, potential weight reduction) on the stiffness, ultimate strength and load distribution in multi-bolt joints.

[2] Bolts in a line perpendicular to the applied load are defined as a row of bolts.

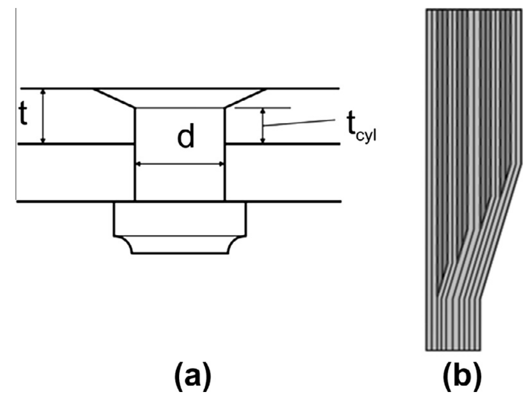

Fig. 1. Descriptions: (a) a schematic of the dimensions d, bolt diameter, t, laminate thickness, and t_{cyl}, the cylindrical thickness of a countersunk bolt; (b) laminate scale-up taper.

- A new method to extract the load distribution in multi-row, multi-column joints.
- The effect of missing fasteners on the stiffness, ultimate load and load distribution in multi-row, multi-column joints.

2. Problem description

Fig. 1(a) shows a schematic of the dimensions d (bolt diameter), t (laminate thickness) and t_{cyl} (laminate thickness in the non-countersunk region). The purpose of this paper is to examine the influence of the d/t ratio, d/t_{cyl} ratio and laminate taper on the mechanical behaviour of single-lap, multi-bolt, countersunk composite joints. The effect of missing fasteners is also investigated. The joints were assembled from laminates of different thickness and all laminates were unsymmetric balanced stacking sequences. The stacking sequences, A, C and E are given in Table 1 and represent minimum thickness, low compression/tension axial load and high compression/tension axial load fuselage skin panels, respectively. Joining of tapered laminates, illustrated in Fig. 1(b), is also examined. Tapering a laminate allows a relatively thin skin panel to be fastened to an airframe support structure, such as a frame, using countersunk fasteners while observing design rules governing the minimum allowable cylindrical thickness, t_{cyl}, for countersunk holes. The taper angle used obeys a ply drop off ratio of 1:20 in the direction of loading.

The test matrix is outlined in Table 2 and the specimen geometries are given in Figs. 2 and 3. The ratios $w/d \geqslant 6$, $e/d \geqslant 4.5$ and $p/d \geqslant 4.5$ were used for all joint configurations. In terms of d/t_{cyl} ratio, the two main joint configurations under investigation are the thick and intermediate thickness joints, detailed in Table 2, while

Table 1
Stacking sequences investigated (three different thicknesses).

Code	Lay-up	Plies	t[a]	Application
A	+45/90/−45/0/0/−45/90/+45/0/0/−45/90/+45	13	1.625	Minimum thickness area
C	+45/90/−45/0/0/0/−45/0/90/0/+45/0/0/0/−45/90/+45	17	2.125	Low axial loads in compression/tension
E	+45/90/−45/0/0/0/+45/−45/0/0/0/+45/90/−45/0/0/0/−45/+45/0/0/0/−45/90/+45	25	3.125	High axial loads in compression/tension

[a] Thickness (units = mm) based on the nominal thickness of a one cured ply (1 ply = 0.125 mm).