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STRESS DISTRIBUTION OF SECONDARY BENDING IN SINGLE-LAP BOLTED JOINTS WITH DISSIMILAR JOINING PLATES AND PLATE TYPES

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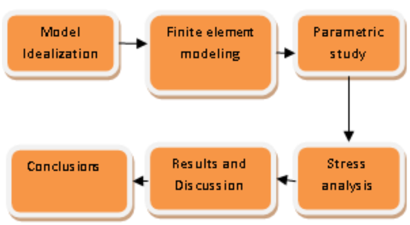
Graphical abstract



Abstract

Single-lap joints are an important class of bolted joint in the aerospace and civil engineering sectors. This type of joint is preferred as it can reduce weight and hence help to optimize fuel efficiency. However, bolted single-lap joints exhibit secondary bending due to eccentricity of the applied loads. Flexural of plates during tensile loading alters the contact regions in the single-lap joint significantly, resulting in more non-linear behaviour and a stress gradient across the plate thickness. 3-D bolted single-lap joint were modelled in ABAQUS CAE incorporating the effect of the bolt tension from application of a tightening torque. Current 3-D model used elastic properties based on smeared-out properties, the effect of joint construction is considered further by examining the stress in a composite-composite joint and comparing with a composite-steel joint. In a related investigation the effect of varying composite thickness in the composite-steel joints is also studied.

Keywords: Woven fabric CFRP, stress distribution, finite element modelling, bolted joints, secondary bending

1.0 INTRODUCTION

Several studies have been reported investigating the effect of lateral constraint on composite bolted joint strength. Net-tension and shear-out failure are catastrophic failure-types leading to a preference for bearing mode. Most experimental work includes investigation on transition of net-tension or shear-out to bearing failure known as critical *W/d* and *e/d* respectively. For a testing series of CFRP laminate configurations and hole sizes, Collings [1], investigated critical *W/d* and *e/d* ratio. Similar observations were also found in glass/epoxy laminates by Kretsis and Matthews [2]. They emphasised that bearing strength and micro-mechanism of failure are strongly dependent on lay-up orientations. Larger holes undergo less stress concentration relief prior to failure, which relates to reduced strength for larger holes.

Smith *et al*. [3] investigated the behaviour of CFRP single-lap bolted joints to compare with double-lap joints. Single-lap joint showed lower strengths and slightly different failure mechanisms due to secondary bending phenomenon and this was more significant for large *W/d*. Failure mechanisms are exhibited where local damage initiation (one or a combination of local tension, shear or bearing) and final failure is given as appreciable damage and hole elongation (net-tension) or catastrophic compression failure at the washer edge (remote bearing). Smith *et al.* [3] also suggested using thicker laminates will improve predictions, but no further testing was reported.

Riccio and Marciano [4] investigated damage onset and propagation under tensile loading in single-lap joints to compare with numerical modelling [5]. They found protruding bolts able to sustain more load prior to damage onset but less in damage evolution. The damage area with protruding bolts is distributed all round the hole due to the contact between bolt head and top composite plate while damage area in a countersunk bolt is localised between the hole and the plate edge. They also found that damage distributions in composite-composite joints is not uniform along the thickness, more damage is localised where damage onset was observed. More uniform damage distribution in composite-aluminium configurations has been found.

Secondary bending and bolt bending in single-lap joint create a non-uniform contact stress distribution between the bolt and hole edge. Ireman [6] developed a bolted single-lap joint model to investigate non-uniform stress distributions through the thickness of the laminate in the bolt vicinity. He modelled a rigid plate to represent the lateral support used to eliminate secondary bending. Good agreement between measured and calculated strain were obtained. However, secondary bending was greater in the experiments than the FEA models due to using overly-stiff elements. A clamped condition case reduced the strain level compared to finger-tight conditions, and higher strain level were found in countersunk bolts compared to protruding head bolts. Ekh and Schon [7] studied the effect of secondary bending and found that it has potential to shift the failure mode and affect the strength. Secondary bending increased the contact area between bolt and hole edge which reduced the bearing stress and increased the bearing strength. Secondary bending also increased the plate bending and generated more severe net-tensile conditions leading to reduced net-tensile strength. Therefore, it is difficult to predict the bearing strength with this effect of secondary bending and this must be evaluated on an individual basis.

3-D FEA have been computationally expensive, and restrictions in mesh size in layered models can produce problems in element aspect ratio. A relatively limited amount of work has been reported in the 3-D analysis of bolted joints. Using 3-D FEA and assuming a perfectly rigid pin and frictionless contact, Matthews *et al*. [8] studied stress distributions around a single-bolt and considered three configurations: pin-loaded hole, finger-tight bolt and fully tightened bolt. In fully tightened bolted joints, significant through-thickness compressive stress was present but in the pin-loaded case, the maximum through-thickness tensile stress, σ_{zz} was found to be about 7% of the bearing stress. Marshall *et al.* [9] also performed a similar study investigating the effect of clamping load and stacking sequence. They concluded that an improved stress profile resulted from clamping where fibre axial, transverse stresses and shear stresses were reduced and less anisotropic materials were shown to exhibit lower stress concentration factors. Both studies considered double-lap joint in their analysis and the contact surface is considered uniform through the laminate thickness.

As the single-lap joint exhibits secondary bending due to the eccentricity of the load, a 3-D model exhibits non-uniformity of contact stresses as the tension load is applied. This is also the case in double-lap joints but to a much lesser extent. Bolt torques induce lower interlaminar tensile direct stress or higher interlaminar compressive direct stress near the hole. Riccio [5] developed a 3-D progressive damage FEA model based on Hashin's failure criteria and ply discount degradation rules for bolted single-lap joints. The ply discount method is easily implemented as when failure occurs, the elastic material properties are set to zero or small fraction of original value (0.1 was used in this case). He analyzed in-depth damage onset and propagation under tensile loading and correlated with experimental data for both protruding and countersunk bolt heads. Numerical and experimental load-displacement curves were shown to be in good agreement.

2.0 FINITE ELEMENT MODELLING TECHNIQUES AND APPROACHES

The elastic properties used in the current model are based on smeared-out properties and include the out-of-plane elastic properties given in [10]. As bending behaviours occurs in a single-lap joint, implementation of smeared-out properties may not properly represent bending as flexural rigidity of stacked material is dependent on layer sequence. Cross-ply woven lay-up is arguably better represented as smeared-out than a quasi-isotropic woven system because of similar repetitive sequence in adjacent layers. The other components are made from isotropic stainless steel which has a modulus elasticity of 210 N/mm^2 and Poisson's ratio of 0.3.

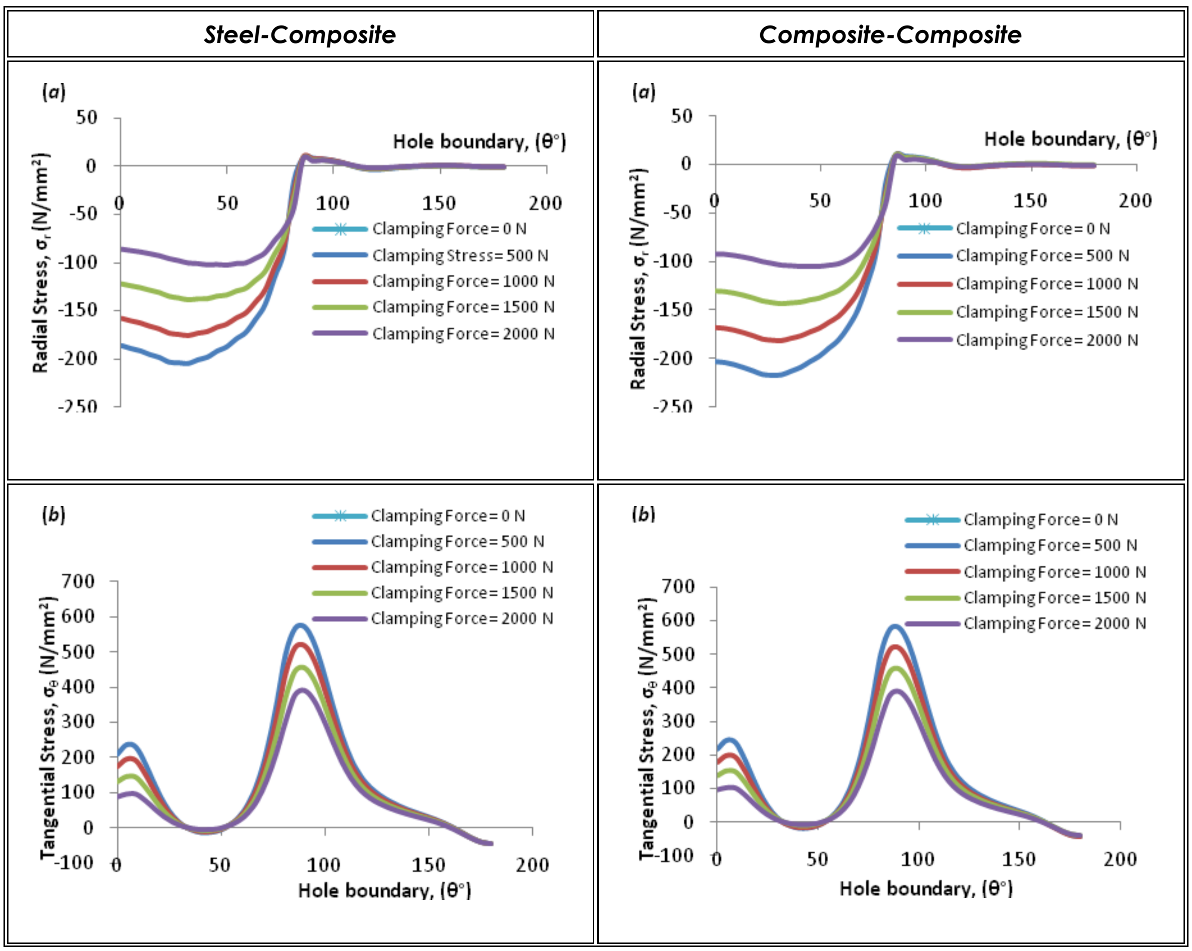
Six components are assembled in each model of the single-lap joint. Parameters that are varied are joining plates and plate thickness. Sufficient mesh refinement is used to ensure the strength predictions are mesh independent. Mesh is refined in the vicinity of the hole edge in the composite (and steel) plates and the volume under the washers, as ultimate failure occurred within these regions. The boundary conditions are assigned so that one end is held fixed and displacement is applied to the other end. Two load steps are implemented which apply the clamping load (Step 1) and the far-field tensile load (Step 2). Each model is assigned a clamping load (finger-tight or T=5 N m). Each contact surface pair is assigned with master-slave interaction which includes an appropriate friction coefficient. The friction coefficients used are the same as those used in the bolted double-lap joints. This is an important step as load transfer will affect the stress distributions and therefore, strength predictions. The nine contact surfaces involved in the respective single-lap joint model.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Different Materials Combination

This sub-section compares the stress distributions in material combination in bolted single-lap joints. Steel-composite (C-S) and composite-composite (C-C) joints are studied using the PX4 lay-up with a 10 mm hole size and different clamping loads. The C-C configurations are used commonly in aerospace industry to reduce weight. This study considers significant differences of stress distributions between both joint configurations.

A steel plate (E = 210 N/mm^2) has about four times higher modulus than CFRP (~ 50 N/mm^2) resulting in a higher flexural rigidity and reduced secondary bending. Bending behaviour is shown only in CFRP plates. Both CFRP plates in the C-C joint showed hole elongation that produced large displacement prior to ultimate failure compared to a smaller hole elongation in C-S configurations due to higher yield strength in steel plate. From Figure 1 the stresses in 1*(a)* - 1*(c)* are averaged across the plate thickness at the hole circumferences and net-section plane, all in the CFRP plate. The top and bottom plane in CFRP plate of both configurations showed almost the same stress distribution in both configurations, as given in Figure 2. Therefore, it will be sufficient to study only C-S configuration in future work.



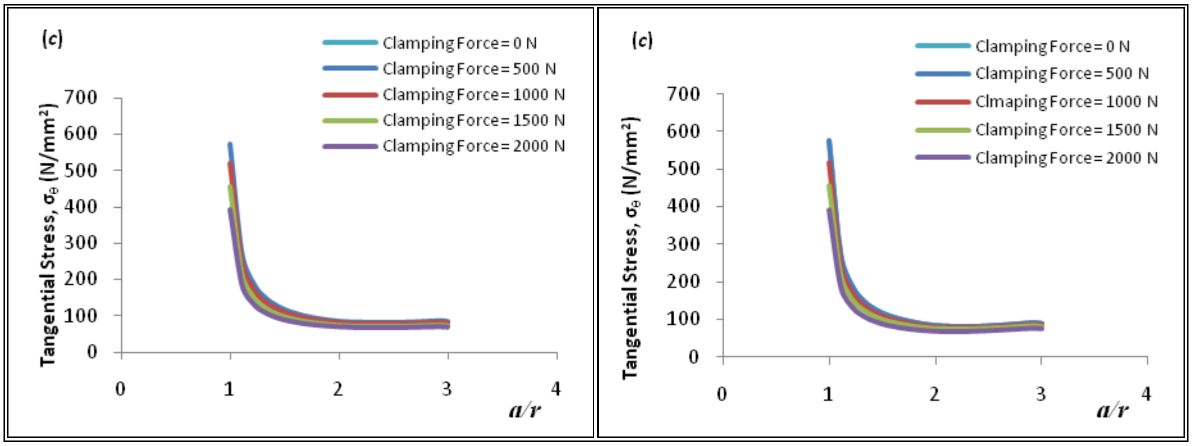
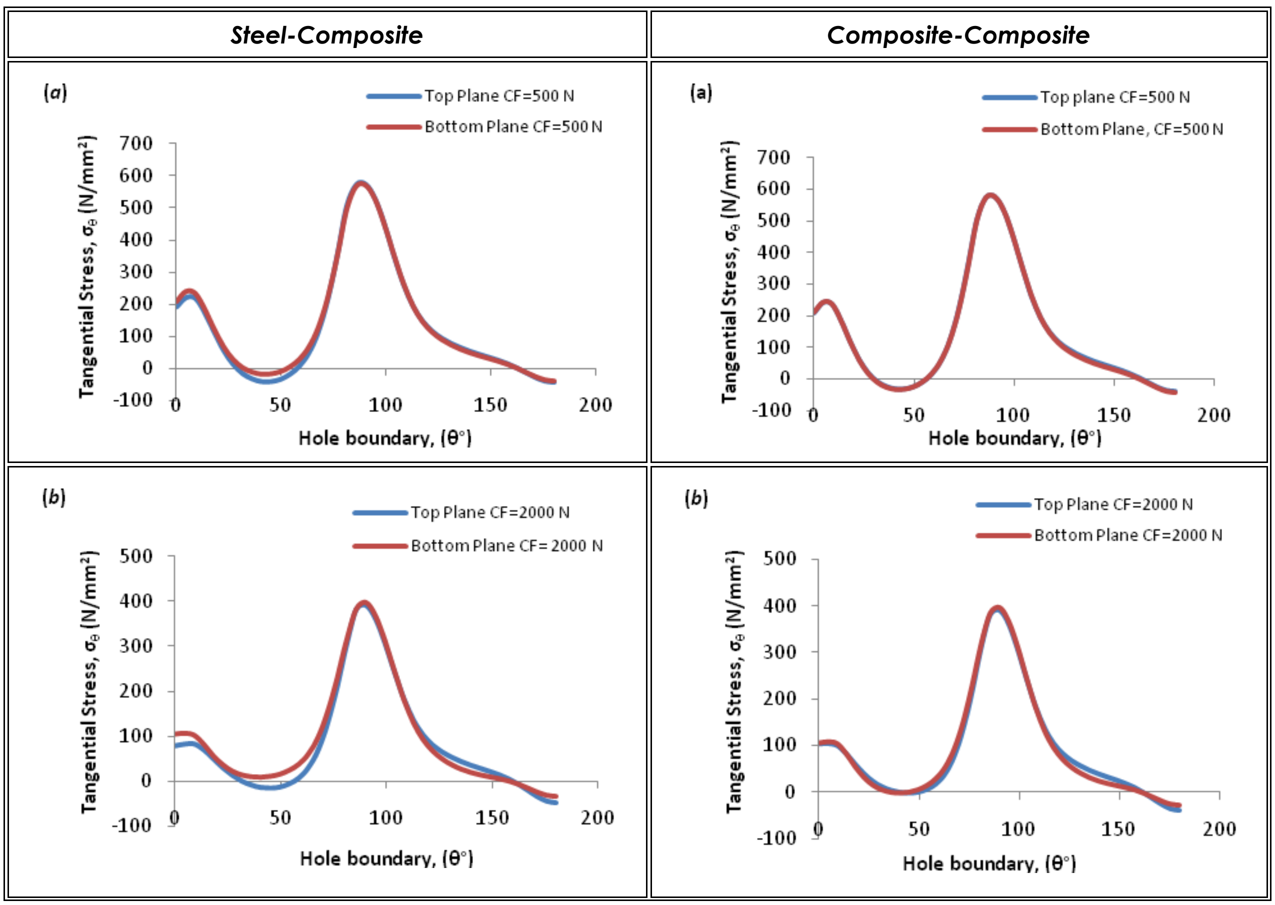


Figure 1 Comparison of stress distributions in C-C and C-S combinations using PX4 CFRP with d = 10 mm and a nominal stress of 250 N/mm². (a) Radial stress around the hole boundary (b) Tangential stress around the hole boundary (c) Tangential stress on net-tension plane



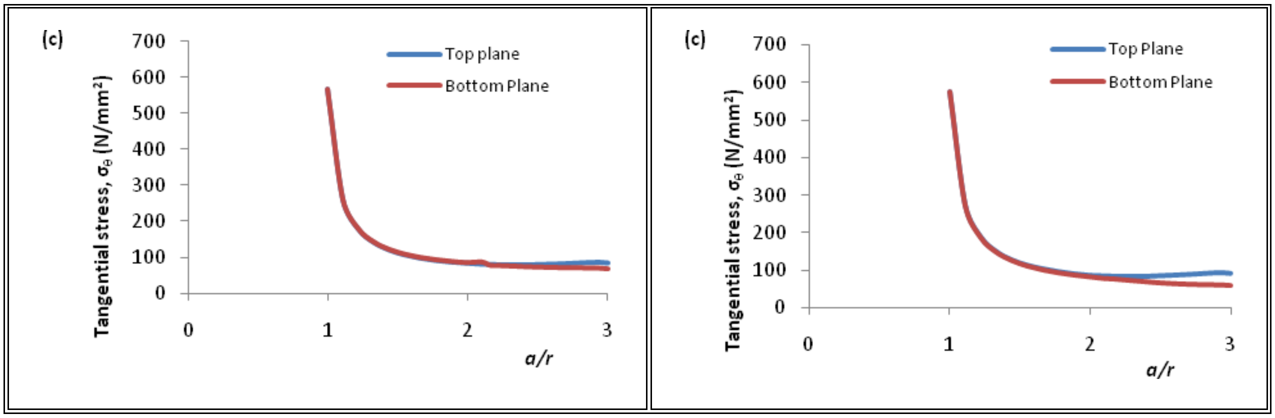
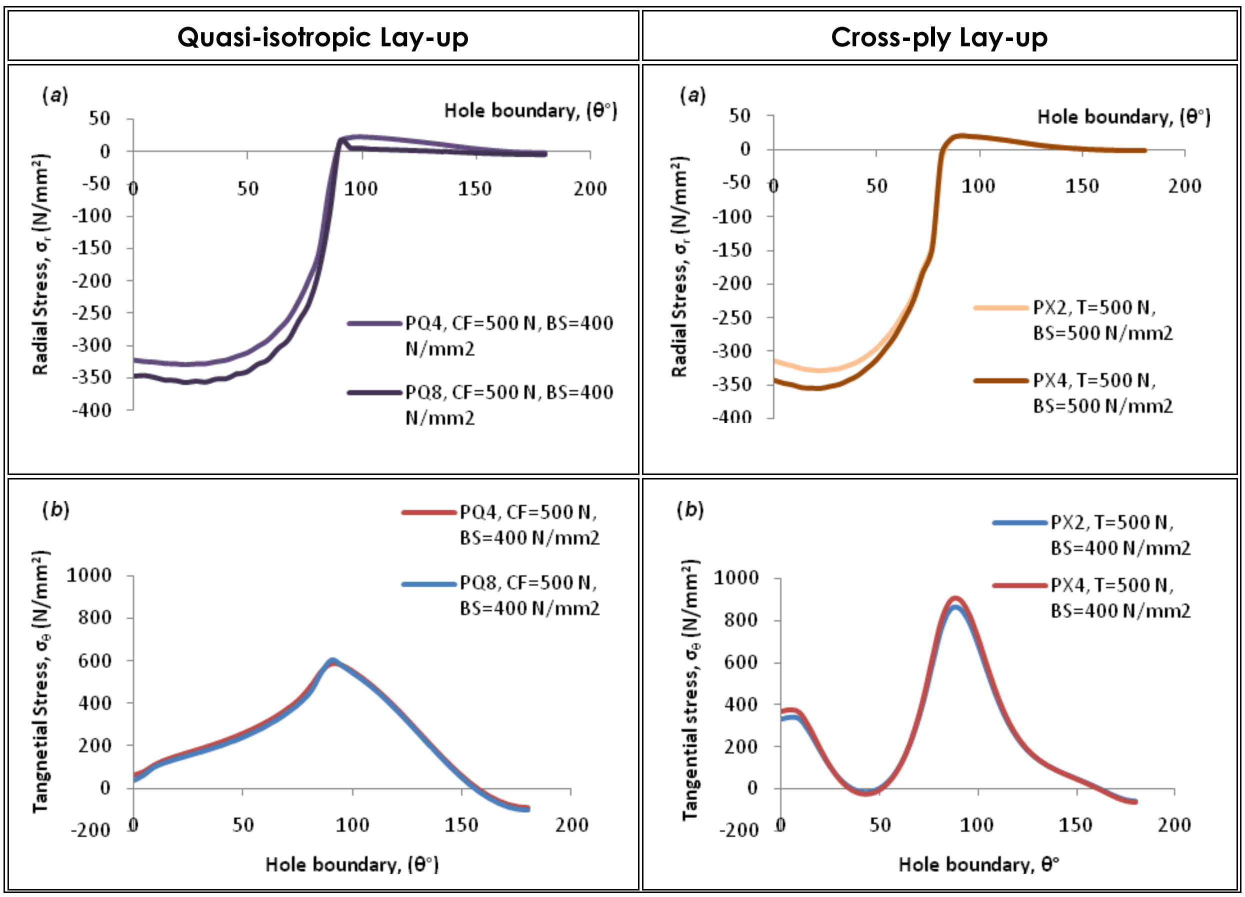


Figure 2 Comparison of stress distribution at top and bottom plane using PX4 CFRP with *d*= 10 mm and a nominal stress of 250 N/mm² in C-C and C-S configurations. (a) Tangential stress around the hole boundary with clamping force = 500 N (b) Tangential stress around the hole boundary with clamping force = 2000 N (c) Tangential stress on net-tension plane with clamping force = 2000 N



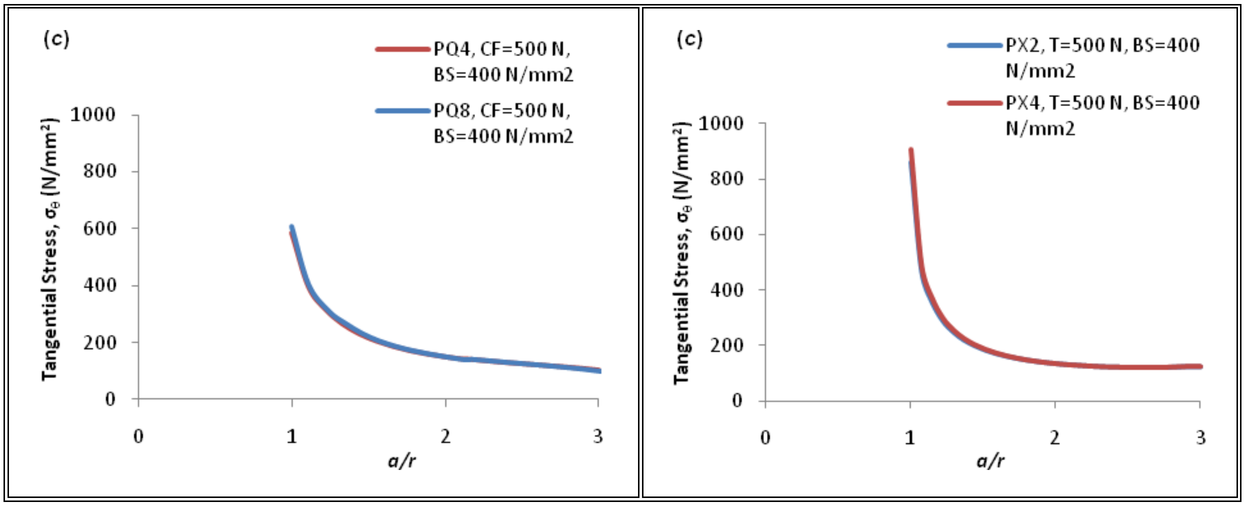


Figure 3 Comparison of stress distribution in quasi-isotropic (PQ4 and PQ8) and cross-ply (PX2 and PX4) lay-ups with *d* = 10 mm at an applied bearing stress of 400 N/mm² and clamping force = 500 N (a) Radial stress around hole boundary (b) Tangential stress around hole boundary (c) Tangential stress at net-tension plane

3.2 Effect of Plate Thickness

The previous sub-section discussed behaviour of different plate types (with different flexural rigidity) in single-lap joints. Second moment of area, *I* is largely dependent on plate thickness, *t*. Thicker CFRP plates show larger flexural resistance than thinner plates, resulting in lower secondary bending effects in thicker plates. Thicker laminates showed insignificant increases in bearing stress at failure when clamp-up is increased from finger-tight condition to *T*=5 N m. This is because load transfer through friction is less in thicker laminate resulting to less pronounced difference between clamped and finger-tight conditions. In this parametric study, all joint systems were modelled with a bolt load of 500 N.

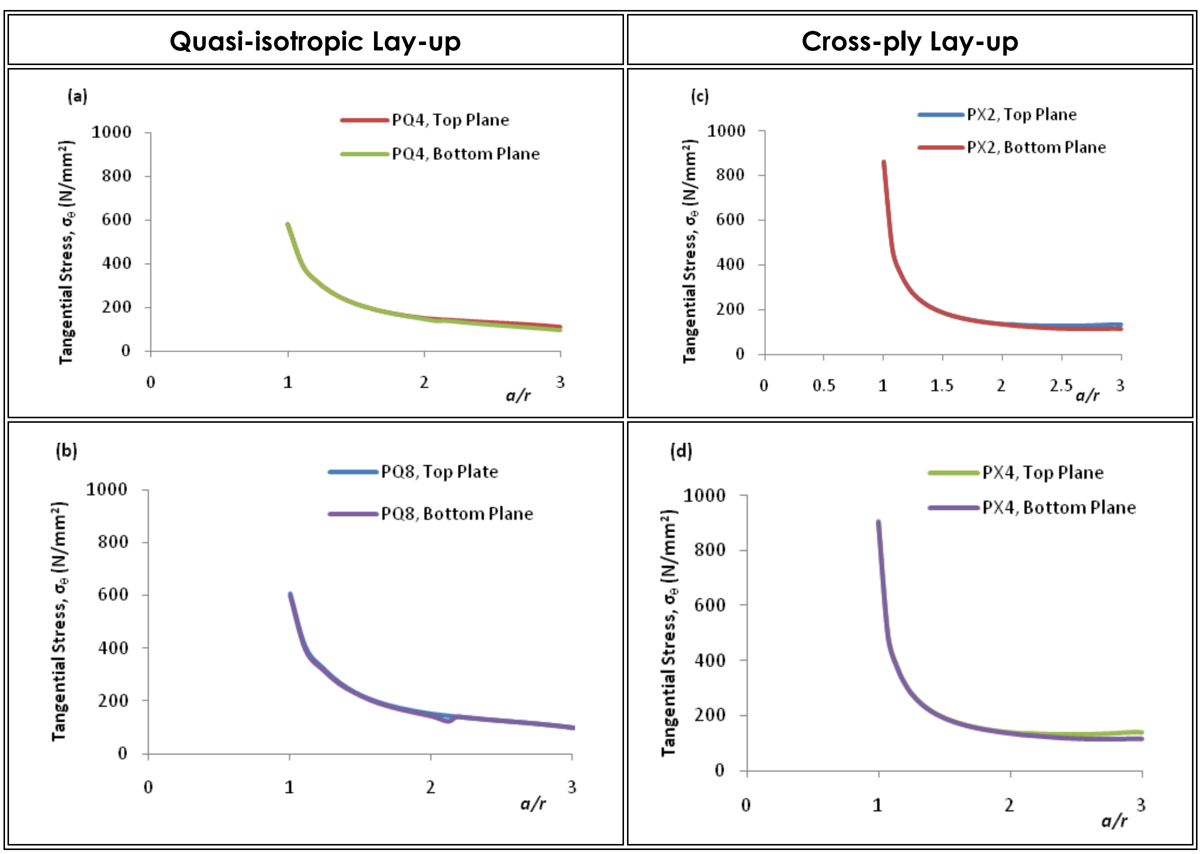


Figure 4 Comparison of stress distribution in quasi-isotropic and cross-ply lay-ups with *d*= 10 mm on top and bottom plane at an applied bearing stress of 400 N/mm² and clamping force = 500 N (a) PQ4, (b) PQ8, (c) PX2, and (d) PX4

Figure 3 show the average radial and tangential stress distributions around the hole edge in joints for two different lay-ups type (quasi-isotropic and cross-ply), each one at two different thicknesses (PQ4/PQ8, PX2/PX4). The radial stress distributions in Figure 3*a* showed a small increase with thickness. This is expected because there is a smaller contribution from frictional load transfer in the thicker laminate. Slightly larger tangential stress in thicker plates (thickness has doubled) of both lay-up systems (Figure 3*b* and 3*c*). As has already been mentioned in the lay-up studies of the double-lap joint [10], tangential stress in cross-ply lay-up (as a results of larger amount of 0° plies) produced higher tangential stress than quasi-isotropic lay-up. Figure 4(*a-d*) showed comparison of all lay-ups investigated at top and bottom planes, but insignificant difference is seen.

4.0 CONCLUSION

Due to secondary bending, the stress distribution through the CFRP woven fabric system single-lap joint changes significantly. Secondary bending, bolt tilting and bolt bending tend to give more complex phenomenon in single-lap joints. The effect of joining materials and plate thickness were investigated by conducting stress distribution study. Good correlation with theoretical were found.

Acknowledgement

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