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Stress distribution study on multi-holes configurations in woven fabric kenaf composite plates

K Supar\(^1\) and H Ahmad\(^1\)

\(^1\) Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor Darul Ta’zim.

Corresponding author: khairisupar@gmail.com

Abstract. In structures applications, composite components are joined by bolted connection is commonplace requires introduction of drilling multi-holes. In order to study the structures response of these material properly, a parametric study on stress analysis is required to take into account arrays of variation including lay-up types, multi-hole configurations, intensity of applied stress etc. The failure and fracture of composite plates is somewhat complex, stress analysis study from numerical modelling able to predict the location of crack exhibited. Current study implemented 2-D finite element analysis (FEA) modelling framework on various multi-holes configurations woven fabric kenaf composite (WFKC) plates, the findings are then compared with conducted experiment. It was found that in non-staggered holes, maximum stress occurred at the outer holes suggesting net-sectional failure to initiate and self-similar crack behaviour through plate thickness. On the contrary, net-sectional failure in staggered hole configurations are dependent upon smallest net-sectional area in any line perpendicular to plane axis. The stress analysis conducted provides good agreement with conducted experiment.

1. Introduction

Reported works available in the literatures are limited to single hole plate, where the crack initiation and crack propagations occurred along the net-section plane perpendicularly to the applied loading. However, in most construction design, connection between structure parts involved more than single-bolts leading to more complicated stress field as by-pass stress able to be transferred to the neighbouring bolts. Net-tension mode is associated with stress raisers at the vicinity of the hole edge, susceptible in multi-hole configurations due to by-pass stress transfer [1]. Net-tension failure is dependant upon bearing stress applied, by-pass stress transfer from neighbouring bolts increases linearly and bearing stress decreased concurrently prone to net-tension failure to occur. Many researchers studying the optimization of composite joint design [2-4], a study on multi-holes problem need to be carried out prior to multi-bolted design of composite materials in order to optimize joint efficiency during composite joining design phase. Eugene et al. [5] found the notched strength of double-column plate is greater than single-column plate counterparts. This implies that the presence of another holes in adjacent column along the loading direction in a plate would cause to maximum stress reduction as a results of stress relief. He also concludes that lower notched strength were observed in staggered configurations than non-staggered configurations counterpart. This is because extensive fibre breakages due to high maximum stress value in staggered configurations as given in finite element analysis (FEA) contours. Jia et al. [6] explained that the stress concentrations becomes more
concentrated and higher with hole size increment, where the larger hole size may reduce stiffness within hole locality in the form of separated length or the broken width [associated with damage zone length]. A classical approach to study stress distribution in quasi-isotropic composites of pin-loaded hole is carried out by deJong [2] using superposition method. Three stress distribution expression was developed, i.e., radial stress, $\sigma_r$, tangential stress, $\sigma_\theta$ and shear stress, $\tau_{xy}$ by assuming rigid pin and cosinusoidal radial stress distribution. The work is later extended to incorporate effect from clamp-up [3]. A parametric study on pin-loaded hole of six CFRP plate with different orthotropy and normalised plate width, $W/d$ ranged from 2 to 20 were reported by Crews et al. [4]. They found that maximum tangential stress, $\sigma_\theta$ in low $W/d$ and maximum radial stress in larger $W/d$ suggesting prone of net-tension and bearing failure occur respectively. Owing to discontinuities in composite plate, stress concentration occurred at the notch tip, higher stress concentration factor, $K_T^*$ in highly orthotropic lay-ups. Recently, with the excellence computing technology leading to aggressive implementation of finite element method in stress analysis study. Ahmad et al. [7, 8] compares stress distribution of single-bolted CFRP plates from analytical expression [2] and 3D FEA modelling in double-lap joints [7] and single-lap joints [8]. It was found that finite element modelling able to capture more physically realistic results than analytical expression due to simplistic assumption made in pin contact interactions. They also found that relatively higher tangential stress from FEA modelling due to analytical approach has not accounted for plate width effect. There is less study on stress distribution multi-hole problem available in the literature, however there are experimental observations [1] and stress concentration in multi-square holes using finite element method (FEM) [5] were reported.

Current work investigates stress distribution in multi-holes configurations of various staggered and non-staggered arrangement in different lay-ups, plate thickness and holes configurations. Finite elements analysis (FEA) were carried out by using ABAQUS CAE 6.13 and estimation of crack path in multi-holes configurations was investigated.

2. FEA modelling

2-D FEA modelling framework were carried out and description on idealizations and discretization, and testing series and boundary conditions are given in the following section.

2.1. Idealizations and discretization

Finite element modelling is carried out by implementing two-dimensional modelling framework using ABAQUS CAE Version 6.13 software package. Stress distributions of multi-holes configurations was carried out to include staggered and non-staggered multi-holes configurations as given in testing series as given in table 1. Three lay-up types were investigated in current work, i.e., cross-ply lay-up (PX2, PX4) and quasi-isotropic lay-up (PQ4). Elastic properties includes in-plane tensile modulus, $(E_x/E_y)$, shear modulus, $G_{xy}$ and Poisson’s ratio, $\nu_{xy}$ of WFRP used in the current work and were considered as “smeared-out” properties. These elastic properties were carried out experimentally using UTM machine following ASTM standard D3039.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Lay-up</th>
<th>Thickness (mm)</th>
<th>In-plane elastic properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$E_x$ (MPa)</td>
</tr>
<tr>
<td>Cross-ply</td>
<td>PX2 $(0^\circ/90^\circ)$,</td>
<td>1.8</td>
<td>2260.33</td>
</tr>
<tr>
<td>Cross-ply</td>
<td>PX4 $(0^\circ/90^\circ)_{2s}$,</td>
<td>3.8</td>
<td>2291.04</td>
</tr>
<tr>
<td>Quasi-isotropic</td>
<td>PQ4 $(0^\circ/90^\circ/\pm45^\circ)$,</td>
<td>3.8</td>
<td>2008.93</td>
</tr>
</tbody>
</table>

Table 1. Smeared-out elastic properties used in current work.

Figure 1 shows the meshing refinement at vicinity of hole edge and remaining plate regions were made coarser to reduce computational effort. It is important to refine the meshing at the vicinity of the
hole is sufficiently small to make sure the post-processing output is free from mesh refinement. Second-order plane stress element with element designation code of CPS8 was used as element type due to the plate is infinitely thin (less than 4 mm). A simplified 2-D modelling able to achieve faster convergence without sacrificing physical representation as compared to 3-D modelling framework which is highly time- and cost-consuming that lead to convergence difficulties.

![Figure 1. Meshing of multi-hole FEA model.](image1)

2.2. Testing series and boundary conditions
Woven fabric kenaf composite plates has a constant normalised pitch, $\frac{p}{d} = 3$ and constant plate width $W = 30$ mm with drilling open holes size of 5mm diameter, $d$ according to specified geometric dimension as given in figure 2. Five testing series were carried out in current works with various lay-up types, plate thickness, and spacing between adjacent holes. There are three non-staggered and two staggered multi-holes configurations investigated in current study as shown in Figure 2. In current work, a constant value of three in normalised pitch ($\frac{p}{d}$), normalised gage length ($\frac{g}{d}$) and edge distance ($\frac{e}{d}$) were implemented to assure that stress distributions possible compare with all testing series geometry.

![Figure 2. Testing plates geometry of all testing series tested.](image2)

The boundary condition and applied loading were properly assigned according to mechanical testing condition, where applied traction pressure was assigned on the right edge and left edge was assigned as fixed boundary as shown in figure 3. Multi-holes configurations are made full model as no existence of symmetrical axis due to some models (particularly in staggered-holes configurations) impossible to apply half-models to save time and computational effort.

![Figure 3. Boundary conditions of multi-hole FEA model.](image3)
3. Results and discussions
The stress distribution study has been carried out and the effects of various parameters were explained in the following section. Direction of angle along the boundary is given in figure 4.

![Figure 4. Direction of angle along boundary.](image)

3.1. Effect of various applied stress
Current work studied the tangential (or hoop) stress with various applied stresses between 20 - 40 MPa in configuration B (single-row three hole) of cross-ply lay-up (PX4) as illustrated in figure 2. Figure 5 shows the tangential stress, $\sigma_\theta$ distribution (a) along hole boundary and (b) across net-tension plane in hole 1 of outer hole, where outer hole demonstrated largest tangential stress compared to middle hole (hole 2). As expected, highest tangential stress occurred at net-sectional plane (90° to the direction of applied loading) and tangential stress is associated with net-tension failure across the net-sectional plane as given in figure 5(a). Various applied traction gives similar pattern on tangential stress distributions, where the tangential stress increased with increased traction magnitude. Owing to hole elongation due to applied loading, circular hole is now giving almost elliptical hole shape, therefore there is compression stresses exhibited at an angle of 0°-25°.

![Figure 5. Stress distribution in configuration B of PX4 lay-ups (a) along hole boundary and (b) along net-sectional plane.](image)

Figure 5(b) gives tangential stress along net-sectional plane from notch tip where largest stress is given at the notch tip and gradually reduced to applied stress at a certain distance. This distance is associated with damage zone length where extensive micro-damage events occurred. Calculation of normalized maximum tangential stress at the notch tip to far-field stress gives stress concentration factor, $K_{\tau\infty}$ gives a value of about 4.25 in PX4 with applied stress of 40 MPa (theoretical value for $K_{\tau\infty}$ in unidirectional cross-ply lay-up is 4.75). Similar finding were found in PQ4 with applied stress 40 MPa where stress concentration factor, $K_{\tau\infty}$ of 2.95 (against theoretical $K_{\tau\infty}$ in quasi-isotropic lay-up is 3).

3.2. Effect of adjacent holes
Figure 6 shows tangential stress (a) along hole boundary and (b) along net-tension plane in configuration B of PX4 lay-ups under uniform applied stress of 40 MPa. Curve of both outer holes in
configuration A is almost overlapped, but slightly lower curve exhibited in mid-hole. Hole 1 and 3 in configuration B exhibited largest tangential stress where the net-sectional failure prone to occur within the respective hole. Similarly maximum tangential stress at notch tip occurred in outer hole as shown in figure 6 (b).

![Figure 6. Tangential stress of PX4 lay-up of configuration B (a) along hole boundary and (b) along net-sectional plane with uniform applied traction of 40 MPa.](image)

Figure 7 displayed the stress contours of configuration A and B in PX4 lay-up, where the maximum stress occurred at the notch tip of outer hole as described above. In configuration A, there is no middle hole exist and both outer holes in configuration A has similar hole elongation due to linear elastic exhibited in composite plate. Therefore, it is expected that the failure occurred in one of the outer holes. On the other hand, hole elongation in middle hole (hole 2) is relatively small than the two outer holes and lower tangential stress were exhibited at the middle hole (from figure 6) leading to less likely the failure and fracture is initiated from middle hole. The crack is occurred in the outer hole as given in figure 7 (b). It is tally with conducted experiment where the failure is susceptible to occur at outer hole as shown in photograph of figure 7.

![Figure 7. Stress contours in PX4 lay-up (a) configuration A (b) configuration B (small pictures is the enlargement at the vicinity of outer hole as specified for visual clarity).](image)
3.3. Effect of lay-up types

Figure 8 showed stress distribution on configuration B between cross-ply lay-up (PX4) and quasi-isotropic lay-up (PQ4), both has similar nominal plate thickness of 4 mm. The stress distribution along hole boundary in cross-ply and quasi-isotropic lay-up exhibited different curve profiles. In cross-ply lay-up, the 0°/90° fiber orientation gives high tangential stress at 90° due to more fiber volume fraction of 0° fiber directions than quasi-isotropic lay-up counterpart, and due to absence of ±45° layer, more shallow curve (especially at angle 45°) is exhibited. In quasi-isotropic lay-up, stress distribution are more evenly distributed at angle 0° to 180° along the hole boundary.

![Figure 8. Tangential stress of configuration B (a) cross-ply (PX4) lay-up and (b) quasi-isotropic (PQ4) lay-up.](image)

3.4. Effect of various rows in non-staggered configurations

Figure 9(a) and 9(b) displays tangential stress distribution along hole boundary in configuration B and C respectively. In Figure 9(b), the plot given taken at the upper hole due to symmetrical stress distribution in lower holes. Larger tangential stress is exhibited in configuration C than configuration B, this is expected due to smaller net-sectional area in configuration C. Similar findings were reported by Eugene et al. [5], where larger stress occurred within pitch area in plates with larger holes number in double-row configurations. They also found from stress analysis results that the maximum stress along the fiber direction of 0° ply is reduced as additional holes are placed in a plate row.

![Figure 9. Tangential stress of PX4 lay-up in (a) configuration B and (b) configuration C.](image)
3.5. Effect of hole arrangement in staggered configurations
Figure 10(a) and 10(b) shows stress analysis on hole arrangement in staggered configuration, i.e., configuration D and E respectively. From figure 10(a), tangential stress along hole boundary at configuration D are similar in every holes but in configuration E (given in figure 10(b)), middle hole (hole 2) exhibited larger tangential stress than two outer holes (hole 1 and 3). In configuration D, it was found that the hole elongations are approximately equal in all open hole leading to similar stress distributions. On the other hand, in configuration E, the lower hole (hole 2) exhibited larger elongations leading to higher stress than two upper holes (hole 1 and 3). From stress-strain relationship, increasing hole elongation of composite plate (associated to plate displacement) exhibited higher stress at the notch tip.

![Figure 10](image1.png)

**Figure 10.** Stress distribution along hole boundary (a) configuration D and (b) configuration E.

It was found that the stress contours in configuration D at the vicinity of the hole is similar in all holes, but due to low net-sectional area, it is expected that failure and fracture is initiated and propagated along plane A-A. In-line with largest stress exhibited in hole 2 compared to other two holes as shown in figure 10, crack exhibited in hole 2 is perhaps not surprising. Similar observations were seen from experimental works (photograph) in configuration D and E as given in figure 11(a) and 11(b) respectively.

![Figure 11](image2.png)

**Figure 11.** Stress contours in PX4 lay-up of (a) configuration D (b) configuration E.
4. Conclusions
A 2-D FEA modelling of staggered and non-staggered multi-holes configurations has been implemented within FEA framework. The parametric study of stress analysis includes various applied stresses, effect of adjacent holes, lay-up types, hole arrangement in staggered and non-staggered configurations. Fracture and failure prone to occur at the outer holes for non-staggered arrangement due to higher tangential stress exhibited. On the other hand, net-sectional failure is demonstrated within lowest net-sectional area of any plane perpendicular to loading direction. This arguments is supported by experimental observations in both configuration types. Due to existing of bearing stress behind the bolt shank may alter the stress distribution in bolted joints problem. Therefore, further work in multi-bolted joints problem need to be conducted to explore the applicability of woven fabric kenaf composite in structures engineering works.

5. References

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