Stress Analysis of Composite Plates with Different Types of Cutouts

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Abstract
This research presents an experimental and theoretical investigation of the effect of cutouts on the stress and strain of composite laminate plates subjected to static loads. The experimental program covers measurement of the normal strain at the edges of circular and square holes with different number of layers and types of composite materials by using strain gages technique under constant tensile loads. A numerical investigation has been achieved by using the software package (ANSYS), involving static analysis of symmetric square plates with different types of cutouts. The numerical results include the parametric effects of lamination angle, hole dimensions, types of hole and the number of layers of a symmetric square plate. The experimental results show good agreement compared with numerical results. It is found that increasing the number of layers reduces the value of normal strain at the edges of circular and square holes of a symmetric plate and the maximum value of stress occurs at a lamination angle of $(30^\circ)$ and the maximum value of strain occurs at a lamination angle of $(50^\circ)$ for the symmetric square plates subjected to uni-axial applied load. The hole dimensions to width of plates ratio is found to increase the maximum value of stress and strain of a symmetric square plate subjected to uniaxial applied load. Moreover, the value of maximum stress increases with the order of type of circular, square, triangular and hexagonal cutout, whereas the value of maximum strain increases with the order of type of circular, square, hexagonal and triangular cutout.

Keywords: composite plate, stress analysis, laminate, cutout, numerical.

1. Introduction
The development of air and space vehicles with its peculiar requirements of structures which needed to be strong but light and flexible but tough, brought into a new breed of hybrid structural materials called reinforced composites. Fiber reinforced composite find increasing uses in aircraft and space vehicle structures, because of their high specific strength and stiffness properties, coupled with the flexibility in the selection of lamination schemes that can be tailored to match the design requirements [1]. Preliminary feasibility investigation, have revealed that the incorporation of high strength, high modulus glass or boron filaments in a low strength, low modulus and low density epoxy matrix can result in a composite material that offers the potential of a major break through in air and space vehicle design.

One of the first investigations in this field was reported by Forchet, M. M. [2], where the stress concentration factor for holes, grooves and fillets were determined by using different loading (pure tension, compression and bending) and using photo-elasticity method for determining the maximum value of stress from the change in photo-metric properties of certain solids due to the external load applied on the body under elastic conditions.

A thin plate of infinite extent containing a circular hole reinforced by uniformly thickening of one side of the plate in an annular region concentric with the hole subjected to an axially symmetric radial stress at infinity, has been solved by Wittrick [3,4]. Wittrick [3] obtained an asymptotic solution, valid for large stress at infinity and Wittrick [10] gave more general discussion of the axially symmetric problem, which contains an asymptotic solution for
the case when the added thickness is small. Waddoup's [5] considered the problem of predicting the reduction in strength of a composite laminate static strength of composite laminate containing circular holes subjected to uniaxial loading which is reduced to a much higher degree than in metals where local stress redistribution due to plastic deformation may occur at the notch boundary. Conversely, notched strength of composite laminates is not reduced in proportion to the stress concentration factor.

Cherry [6] studied the elimination of fastener hole stress concentration through the use of softening strips. He estimated that static strength loss created by holes in boron/epoxy laminate amounts to approximately one-third in tension and one half in compression.

Richard et al. [7] presented the three-dimensional finite element analysis based on an isoparametric formulation for laminated composite in bending. The problem investigated was the laminate under uniform extension. Circular, square and diamond shaped holes of varying size were cut-out of the laminate. Stress concentration factors were defined for the tensile and inter-Laminar shear stresses were reported for both angle-ply and bi-directional laminates.

A boundary layer theory for isotropic elastic plates with circular cutout was extended for laminated composite by S. Tang [8]. An analytical solution was obtained for the extension of an infinite plate with a circular hole. The inter-laminar shear stresses and the normal or “peel” stress near and the edge of the hole were estimated for orthotropic plates. Numerical examples were given for \((0^\circ / 90^\circ)\) and \((\pm 45^\circ)\) laminates plates.

The aim of the current work is to investigate experimentally the effect of opening (cutout) and number of layers of different types of composite materials on the normal strain at the edge of the hole of symmetric square plates. Moreover, theoretical work involves studying the effect of the following design parameters on the maximum stress and strain these design parameters are:

1- Lamination angle \((\theta)\) of each layer.  
2- The hole dimensions to width of plates ratio.  
3- Number of layers.  
4- Types of cutout.

2. Theoretical Considerations

The generalized Hooke’s law relating stresses to strains for anisotropic materials can be written in contracted notation as [9]:

$$\sigma_i = C_{ij}\varepsilon_j \quad i, j = 1, 2, ..., 6$$  \hspace{1cm} (1)

The strains in contracted notation are defined as:

$$\varepsilon_1 = \frac{\partial u}{\partial x}, \quad \varepsilon_2 = \frac{\partial v}{\partial y}, \quad \varepsilon_3 = \frac{\partial w}{\partial z},$$  \hspace{1cm} (2)

$$\gamma_{12} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}, \quad \gamma_{23} = \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}, \quad \gamma_{13} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}$$

The elasticity matrix \(C_{ij}\) has 36 constants in Eqn.(1). However, an elastic potential or strain energy density function exists which implies [10]:

\[\ldots\]
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\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\
C_{22} & C_{23} & C_{24} & C_{25} & C_{26} & 0 \\
C_{33} & 0 & C_{35} & C_{36} & 0 & 0 \\
C_{44} & C_{45} & C_{46} & 0 & 0 & 0 \\
\text{symmetric} & C_{55} & C_{56} & 0 & 0 & 0 \\
\text{symmetric} & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3 \\
\epsilon_4 \\
\epsilon_5 \\
\epsilon_6
\end{bmatrix}
\]

(3)

If there is one plane of material property symmetry, the stress-strain relation reduced to:

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\
C_{22} & C_{23} & C_{24} & 0 & 0 & C_{26} \\
C_{33} & 0 & C_{35} & 0 & 0 & C_{36} \\
C_{44} & C_{45} & 0 & 0 & 0 & 0 \\
\text{symmetric} & C_{55} & 0 & 0 & 0 & 0 \\
\text{symmetric} & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3 \\
\epsilon_4 \\
\epsilon_5 \\
\epsilon_6
\end{bmatrix}
\]

(4)

If there are two orthogonal planes of material property symmetry for a material, symmetry will exist relative to a third mutually plane. The stress-strain relations in coordinates aligned with principal material directions, (parallel to the intersections of the three plans of material symmetry) are:

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & \text{zeros} \\
C_{22} & C_{23} & C_{24} & \text{zeros} \\
C_{33} & C_{34} & C_{35} & \text{zeros} \\
\text{zeros} & C_{44} & C_{45} & C_{46} \\
\text{zeros} & \text{zeros} & \text{zeros} & \text{zeros} \\
\end{bmatrix}
\begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3 \\
\epsilon_4 \\
\epsilon_5 \\
\epsilon_6
\end{bmatrix}
\]

(5)

and are said to define an orthotropic material. Note that there is no intersection between normal and shearing stresses which occurs in anisotropic materials (by virtue of the presence of, for example, \(C_{14}\)). Similarly, there is no intersection between shearing stresses and normal strains as well as none between shearing stresses and shearing strains in different planes. Note also that there are now only nine independent constants in the elasticity matrix.

The principal directions of orthotropy often do not coincide with coordinate directions that are geometrically natural to the solution of the problem, as shown in Fig. (1). [9]. Thus a relation is needed between the stresses and strains in the principal directions and those in body coordinates.

The transformation equations for expressing stresses in an \(x-y\) coordinate system in terms of stresses in a 1-2 coordinate system [9],

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} =
\begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & -2\sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & 2\sin \theta \cos \theta \\
\sin \theta \cos \theta & -\sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\tau_{12}
\end{bmatrix}
\]

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Similarly, the strain transformation equations are:

\[
\begin{bmatrix}
\gamma_x \\
\gamma_y \\
\gamma_{xy}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
\]

If the laminate is thin, a line originally straight and perpendicular to the middle surface of the laminate which is assumed to remain straight and normal under deformation is equivalent to ignoring the shearing strains in planes parallel and normal to the middle surface in Fig. (2) [10]. In addition, the normals are presumed to have constant length, so that the strain perpendicular to the middle surface that is \( \gamma_z = 0 \) where \( z \) is the direction of the normal to the middle surface shown in Fig. (2). The displacement in the \( z \)-direction is given by (10). Since line ABCD remains straight under deformation of the laminate:

\[
\beta = \frac{\partial w}{\partial z}
\]

Then, the deformation of the laminate is

\[
v = v_0 + \frac{\partial w}{\partial z} z,
\]

\[
u = u_0 + \frac{\partial w}{\partial z} z,
\]

\[
\varepsilon_x = 2\beta (x - x_0) - \frac{\partial w}{\partial z} z,
\]

\[
\varepsilon_x = 2\beta (x - x_0) - \frac{\partial w}{\partial z} z.
\]
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\[
\varepsilon_x = \frac{\partial u}{\partial x} = \frac{\partial u_o}{\partial x} - z \frac{\partial^2 w_o}{\partial x^2}
\]

\[
\varepsilon_y = \frac{\partial v}{\partial y} = \frac{\partial v_o}{\partial y} - z \frac{\partial^2 w_o}{\partial y^2}
\]

\[
\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial u_o}{\partial y} + \frac{\partial v_o}{\partial x} - 2z \frac{\partial^2 w_o}{\partial x \partial y}
\]  (12)

Thus, the Kirchhoff or Kirchhoff-Love hypothesis has been readily verified to imply a linear variation of strain through the laminate thickness. By substitution of the strain variation through the thickness, Eqn.(12), in the stress-strain relations, the stresses in the \(k^{th}\) layer can be expressed in terms of the laminate middle surface strains and curvatures as:

\[
\begin{pmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{pmatrix} =
\begin{bmatrix}
Q_{11} & Q_{12} & Q_{16} \\
Q_{12} & Q_{22} & Q_{26} \\
Q_{16} & Q_{26} & Q_{66}
\end{bmatrix}
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\gamma_{xy}
\end{pmatrix} + z \begin{pmatrix}
k_x \\
k_y \\
k_{xy}
\end{pmatrix}
\]  (13)

Since the \(Q_{ij}\) can be different for each layer of the laminate, the stress variation through the laminate thickness is not necessary linear, even though the strain variation is linear.

The resultant laminate forces acting on a laminate are obtained by integration of the stresses in each layer or lamina through the laminate thickness, as:

\[
N_x = \int_{-h/2}^{h/2} \sigma_x dz
\]  (14)

Actually, \(N_x\) is a force per unit length (width) of the cross section of the laminate as shown in Fig.(3) [9]. The entire collection of force resultants for an N-layered laminate is defined as:

\[
\begin{pmatrix}
N_x \\
N_y \\
N_{xy}
\end{pmatrix} =
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}
\begin{bmatrix}
z_{k-1} & z_k
\end{bmatrix}
\]  (15)

Where \(z_k\) and \(z_{k-1}\) are defined in Fig. (4) [10]. Note that \(z_0 = -h/2\), these forces resultants do not depend on \(z\) after integration, but are functions of \(x\) and \(y\), the coordinates in the plane of the laminate middle surface.

The integration indicated in Eq.(15) can be rearranged to take advantage of the fact that the stiffness matrix for a lamina is constant within the lamina. Thus, the stiffness matrix goes outside the integration over each layer, but is within the summation of force and moment resultants for each layer. When the lamina stress-strain relations, Eq. (13), are substituted,

\[
\begin{pmatrix}
N_x \\
N_y \\
N_{xy}
\end{pmatrix} =
\sum_{k=1}^{N}
\begin{bmatrix}
Q_{11} & Q_{12} & Q_{16} \\
Q_{12} & Q_{22} & Q_{26} \\
Q_{16} & Q_{26} & Q_{66}
\end{bmatrix}
\begin{pmatrix}
\int_{z_{k-1}}^{z_k} \varepsilon_{xx} dz \\
\int_{z_{k-1}}^{z_k} \varepsilon_{yy} dz + z \int_{z_{k-1}}^{z_k} \gamma_{xy} dz
\end{pmatrix}
\]  (16)
However, it is noted that $e^x, e^y, f^x, f^y, k_x, k_y,$ and $k_{xy}$ are not functions of $z$ but are middle surface values so can be removed from under the summation signs. Thus, Eqn.(16) can be written as:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = A_{11} A_{12} A_{16} \begin{bmatrix} e_{xx} \\ e_{yy} \\ \gamma_{xy} \end{bmatrix} + B_{11} B_{12} B_{16} \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix}$$  \hspace{1cm} (17)

Where: $A_j = \sum_{k=1}^{N} (Q_j)_k (z_k - z_{k-1})$ and: $B_j = \frac{1}{2} \sum_{k=1}^{N} (Q_j)_k (z_k^2 - z_{k-1}^2)$ \hspace{1cm} (18)

3. Experimental Work

Polyester resin, Glass fibers (E-glass woven & random) and carbon fibers have the properties shown in Table (1) [11]. Types of fibers include:

1. Two types of random glass fibers of weight per unit area of (420 and 360 gm/m²).
2. Woven glass fibers of (280 gm/m²) and the angle between fibers in the weave and weft direction is (0°/90°).
3. Woven carbon fibers of (220 gm/m²) and the angle between fibers in the weave and weft direction is (0°/90°).

The specimens used in this study are prepared by hand-lay up molding for each type of reinforcement materials using mould with dimensions (20cm x 20cm x 2cm). Before pouring of the resin, mould surfaces should be dyed with chemically treated paraffin for the purpose of closing the spaces and to take the specimens easily from the mould. Then this material is modified with a piece of dwell and dye with an isolated material (tree-lack). This is a quickly dry soap liquid for the purpose of isolate the mould from the sample and can use the waxes to isolate the mould from the sample. After fibers arrangement inside the mould, the mixture (cobalt + polyester resins + hardener) is poured into the mould over the fiber and is stratified in layers. Then, the mould is left for (24) hours and the composite materials sheets are obtained.

The composite material is formed by using the procedure above and produced in hard and dry state forming a rectangular plate with (20cm x 20cm) dimensions and uniform thickness. Different types of fibers and number of layers can be used to produce many types of composite material with different thickness. Specimens with different thicknesses are cut first in equal rectangular form with 100mm length and 20mm width using iron scissors (cutter). The effective length of the specimen is 60mm, i.e. the ratio of (length/width) equal to (3). Circular and square holes are drilled with diamond – coated drill and dreamer sets by using a standard drill press and water cooling to avoid residuals stresses. The specimens used in this study are listed in Table (2)

4. Numerical Work

The dimensions of model used in (ANSYS) are (2a = 2b = 0.2 m), total thickness (0.006 m) and (D = 0.004 m), see Fig. (6).
Material properties assigned, in studying of the effect of lamination angle ($\theta$), for low modulus graphite–epoxy [13] are:

\[ E_1 = 132.3 \text{ GPa}, \quad E_2 = 10.7 \text{ GPa}, \quad G_{23} = 3.6 \text{ GPa}, \quad G_{13} = G_{12} = 5.6 \text{ GPa}, \quad \nu_{12} = 0.24. \]

Material properties assigned, in studying of the effect of $(D/2b)$ ratio, for the boron–epoxy layers are [7]:

\[ E_1 = 211 \text{ GPa}, \quad E_2 = 21 \text{ GPa}, \quad G_{12} = G_{13} = G_{23} = 6.6 \text{ GPa}, \quad \nu_{12} = 0.21. \]

5. Results and Discussion

Referring to Table (3), the different values of weight/area of the two types of random glass fibers seem to have a negligible effect on the value of strain. This suggests that within the values of weight/area used the effect is diminished; should higher values be used the effect would be notable. The strain decreases appreciably as the number of layers increases; a logical result in view of the increased stiffness. Finally, it is noted that the strain near a square hole is greater than that near a circular hole, which manifests the effect of sharp corners on the stiffness of materials.

Figs. (7 through 16) show the relation between the lamination angle ($\theta$) and maximum stress and strain of the five symmetric square plates shown in Fig.(6) which consist of (4, 6, 8 and 12) layers of the same thickness.

In Fig.(7), the maximum value of normal stress occurs at lamination angle of (30°), whereas the maximum value of strain seems to occur at lamination angle of (50°); the rate of change of strain with (\$\theta\$) in the range (\$\theta=10^\circ-40^\circ\$) is high, see Fig.(8). In the presence of a circular hole, as shown in Fig. (9), the lamination angle has a little effect on the max. stress induced in plates consisting of (6) layers or more. For a square hole, there exist two values of critical angle of lamination of max. Stress occurrence, as shown in Fig.(11). In general, the value of maximum stress increases with the order of type of circular, square, triangular and hexagonal cutout, whereas the value of maximum strain increases with the order of type of circular, square, hexagonal and triangular cutout.

Figs.(17-24) show the effect of $(D/2b)$ ratio on the maximum stress and strain of the five symmetric square plates shown in Fig.(6) which consist of (4, 6, 8 and 12) layers of the same thickness.

The maximum value of normal stress increases with increasing of the $(D/2b)$ ratio, and when $(D/2b)$ ratio becomes more than (0.3) the change of maximum stress becomes very high in the range of $(D/2b)$ ratio from (0.3-0.5); the maximum stress changes from (5.3-14.2) MPa. These results are only reasonable in view of the reduction in cross sectional area of the plate. The maximum strain value does not change linearly with increasing the $(D/2b)$ ratio as shown in Fig. (18). Also, the maximum value of strain, equal to $(360 \times 10^{-6})$, occurs at $(D/2b)$ ratio of (0.35); this means that the stiffness is decreased as the cutout dimensions are increased.

The shape of cutout affects the relation between both values of stress and strain with $(D/2b)$ ratio. In case of square, hexagonal and triangular holes, the maximum stress occurs at $(D/2b=0.45, 0.4 & 0.3)$ with values equal to (9.7, 26.4 & 24.3) MPa, as shown in Figs. (19, 21 and 23). The maximum strain does not change linearly with increasing $(D/2b)$ ratio for the case of square, hexagonal and triangular holes as shown in Figs.(20 &24), but the maximum value of strain increases with increasing the $(D/2b)$ ratio in a plate containing hexagonal hole as shown in Fig.(22).

In all figures, increasing the number of layers results in reducing the maximum value of stress and strain for any given type or dimensions of cutout.
6. Conclusions

The following points may be concluded:

1. The value of normal strain at the edge of square hole is greater than the value at the edge of circular hole of a symmetric plate of different types of composite materials.
2. The type of fibers (random glass fibers, woven glass fibers and woven carbon fibers) does not affect the value of normal strain.
3. Increasing the number of layers decreases the maximum value of stress and strain of a symmetric square plate subjected to uni-axial applied load.
4. The maximum value of stress occurs at a lamination angle of (30°) and the maximum value of strain occurs at a lamination angle of (50°).
5. Increasing the hole dimensions to width of plates ratio increases the maximum value of stress and strain of a symmetric square plate subjected to uni-axial applied load.
6. The value of maximum stress increases with the order of type of circular, square, triangular and hexagonal cutout, whereas the value of maximum strain increases with the order of type of circular, square, hexagonal and triangular cutout.

7. References

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Nomenclature

\[ A_{ij} \quad \text{Extension stiffness elements} \]
\[ B_{ij} \quad \text{Bending-extension coupling stiffness elements} \]
\[ C_{ij} \quad \text{Element of elasticity matrix} \]
\[ N \quad \text{Number of laminate layers} \]
\[ Q_{ij} \quad \text{Transformed stress-strain relation from principal to laminate coordinates} \]
\[ Q_{x}, Q_{y} \quad \text{Shear forces} \]
\[ N_{i} \quad \text{Stress resultants} \]
\[ u, v, w \quad \text{Displacements} \]
\[ u_{o}, v_{o}, w_{o} \quad \text{Middle surface displacements} \]
\[ x, y, z \quad \text{Rectangular coordinates} \]
\[ \beta \quad \text{Slope of laminate middle surface} \]
\[ \gamma_{ij} \quad \text{Shearing strain} \]
\[ \gamma_{o} \quad \text{Middle surface shear strain} \]
\[ \varepsilon \quad \text{Normal strain} \]
\[ \varepsilon_{o} \quad \text{Middle surface strain} \]
\[ \theta \quad \text{Angle of lamination} \]
\[ \sigma \quad \text{Normal stress} \]
\[ \tau \quad \text{Shearing stress} \]

Table (1): Properties of materials used in the experiments.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Density (kg/m^3)</th>
<th>Young modulus (GN/m^2)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>1.211</td>
<td>1.0602</td>
<td>0.38</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.56</td>
<td>76</td>
<td>0.22</td>
</tr>
<tr>
<td>Carbon fiber</td>
<td>1.406</td>
<td>190</td>
<td>-</td>
</tr>
</tbody>
</table>

Table (2): Description of specimens used in experimental work. Diameter or side length = 4mm, Total thickness = 2 mm

<table>
<thead>
<tr>
<th>Type of fibers</th>
<th>Weight/area (gm/m^2)</th>
<th>Volume fraction of matrix</th>
<th>Volume fraction of fibers</th>
<th>No. of layers</th>
<th>Type of hole</th>
<th>Length to width ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGF</td>
<td>420</td>
<td>0.45</td>
<td>0.55</td>
<td>4</td>
<td>Circular</td>
<td>3</td>
</tr>
<tr>
<td>RGF</td>
<td>420</td>
<td>0.42</td>
<td>0.58</td>
<td>4</td>
<td>Square</td>
<td>3</td>
</tr>
<tr>
<td>RGF</td>
<td>360</td>
<td>0.38</td>
<td>0.62</td>
<td>4</td>
<td>Circular</td>
<td>3</td>
</tr>
<tr>
<td>RGF</td>
<td>360</td>
<td>0.38</td>
<td>0.62</td>
<td>4</td>
<td>Square</td>
<td>3</td>
</tr>
<tr>
<td>RGF</td>
<td>420</td>
<td>0.46</td>
<td>0.54</td>
<td>8</td>
<td>Circular</td>
<td>3</td>
</tr>
<tr>
<td>RGF</td>
<td>420</td>
<td>0.35</td>
<td>0.65</td>
<td>8</td>
<td>Square</td>
<td>3</td>
</tr>
<tr>
<td>WCF+ WGF</td>
<td>220+880</td>
<td>0.43</td>
<td>0.57</td>
<td>5</td>
<td>Circular</td>
<td>3</td>
</tr>
<tr>
<td>WCF+ WGF</td>
<td>220+880</td>
<td>0.39</td>
<td>0.61</td>
<td>5</td>
<td>Square</td>
<td>3</td>
</tr>
<tr>
<td>WGF</td>
<td>280</td>
<td>0.41</td>
<td>0.59</td>
<td>8</td>
<td>Circular</td>
<td>2</td>
</tr>
</tbody>
</table>
Table (3): Experimental and numerical results of different types of composite materials

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>No. Layers</th>
<th>Type of hole</th>
<th>Strain (Experimental)</th>
<th>Strain (Numerical)</th>
<th>Discrepancy (%) (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random[1]</td>
<td>4</td>
<td>Circular</td>
<td>0.0189</td>
<td>0.0177</td>
<td>6.35</td>
</tr>
<tr>
<td>Random[1]</td>
<td>4</td>
<td>Square</td>
<td>0.019</td>
<td>0.0209</td>
<td>10</td>
</tr>
<tr>
<td>Random[2]</td>
<td>4</td>
<td>Circular</td>
<td>0.0191</td>
<td>0.0226</td>
<td>18.3</td>
</tr>
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\[
(*) \text{Discrepancy (\%)} = \frac{\varepsilon_{\text{exp.}} - \varepsilon_{\text{num.}}}{\varepsilon_{\text{exp.}}} 
\]

Figure (1): Lamina of arbitrary orientation of principal material

Figure (2): Deformation geometry in x-z
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Figure (3): In-plane on a flat laminate

Figure (4): Geometry of an n-layered laminate[10].

Figure (5): Photographs of the specimens after testing.
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Figure (6): Square plates with different cutouts subjected to tension with central hexagonal hole subjected to tension.

Figure (7): The effect of lamination angle on the maximum stress of asymmetric angle-ply laminates of a square plate.
Figure (8): The effect of lamination angle on the maximum strain of asymmetric angle-ply laminates of a square plate.

Figure (9): The effect of lamination angle on the maximum stress of asymmetric angle-ply laminates of a square plate with circular hole.

Figure (10): The effect of lamination angle on the maximum strain of asymmetric angle-ply laminates of a square plate with central circular hole.
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Figure (11): the effect of lamination angle on the maximum strain asymmetric angle-ply laminates of a square plate with central square hole.

Figure (12): The effect of lamination angle on the maximum strain of asymmetric angle-ply laminates of a square plate with central square hole.

Figure (13): The effect of lamination angle on the maximum stress of asymmetric angle-ply laminates of a square plate with central hexagonal hole.
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Figure (14): The effect of lamination angle on the maximum strain of asymmetric angle-ply laminates of a square plate with central hexagonal hole.

Figure (15): The effect of lamination angle on the maximum stress of asymmetric angle-ply laminates of a square plate with central triangular hole.

Figure (16): The effect of lamination angle on the max. Strain of asymmetric angle-ply laminates of a square plate with central triangular hole.
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Figure (17): The effect of \((D/2b)\) ratio on the maximum stress of asymmetric angle-ply laminates of a square plate with central circular hole.

Figure (18): The effect of \((D/2b)\) ratio on the maximum strain of asymmetric angle-ply laminates of a square plate with central circular hole.

Figure (19): The effect of \((D/2b)\) ratio on the maximum stress of asymmetric angle-ply laminates of a square plate with central square hole.
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Figure (20): The effect of $D/2b$ ratio on the maximum strain of asymmetric angle-ply laminates of a square plate with central square hole.

Figure (21): The effect of $D/2b$ ratio on the maximum stress of asymmetric angle-ply laminates of a square plate with central hexagonal hole.

Figure (22): The effect of $D/2b$ ratio on the maximum strain of asymmetric angle-ply laminates of a square plate with central hole.
Figure (23): The effect of (D/2b) ratio on the maximum stress of asymmetric angle-ply laminates of a square plate with central triangular hole.

Figure (24): The effect of (D/2b) ratio on the maximum strain of asymmetric angle-ply laminates of a square plate with central triangular hole.
تحليل الجهادات للألواف المرعكة ذات الأنواع المختلفة من القطعات

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الخلاصة:

يتعرض هذا البحث لدراسة عملية ونظرية للألواف المرعكة لإيجاد الجهادات والانفعالات تحت تأثير الأحمال الأسئتولوجية كذلك تم دراسة الألواف بوجود أجزاء مقطوعة للحصول على طريقة متعلق للجزء المقطع أي على أقل ما يمكن من الجهادات والانفعالات المتولدة. تضمن الجزء العملي قياس الانفعالات عند حافة الثقب (دائرية ومربعة) العمودية على اتجاه تسلسل الأحلاف (أحلاف نايك سكيوني) للألواف المصنوعة من عدد من الطبقات المختلفة وقد قياس انفعالات باستخدام تقنية محسسات الانفعال لغرض مقارنة بعض النتائج النظرية. تم إنجاز الجزء النظرية من هذا البحث باستخدام البرنامج الهندسي المعروف (ANSYS) الذي يعد طريقة العناصر المحدودة. أن التحليل السكيني تم دراسته للألواف المرعكة التي تحتوي على أشكال مختلفة من الثقوب. أن النتائج التي تخصص التحليل النظري تبين تأثير العوامل التصميمية المتصلة في زاوية التركيب، أبعاد الثقوب، عدد وسمك ونوع الطبقات الداخلة في تركيب الصفقة. أن النتائج المستخرجة بالطريقة العملية تتفق جيد مع النتائج النظرية. كما أستنتج أيضاً بأن زيادة عدد الطبقات يقلل من قيمة الانفعال الطولي عند حافات الثقوب الدائرية والمرعية وانقل بذلك لأن قيمة الإجهاد الأعظم يحدث عند الزاوية (итесь (0.3) قيمة الانفعال الأعظم يحدث عند الزاوية (0.5). وجد أيضاً بأن زيادة أبعاد الثقوب تزيد من الجهادات والانفعالات كما وجد أن أعظم إجهاد تزويدي بتغيير شكل الثقب من دائرياً إلى مربع إلى مثلاً إلى سداسيً وان أعظم انفعال تزويدي بتغيير شكل الثقب من دائرياً إلى مربع إلى سداسي إلى مثلاً.