An investigation on blunt notch behavior of fiber metal laminates containing notch with different shapes

Ebrahim Sadeghpour¹,², Mojtaba Sadighi¹,² and Soheil Dariushi¹

Abstract
In this study, the blunt notch strength of a fiber metal laminate with circular, elliptic and square notch shape has been studied up to failure point. Investigation of the stress concentration does not give a good idea about the strength in anisotropic plates and a failure criterion should be employed to evaluate failure. Therefore, an analytical method has been developed to evaluate stress components and predict the failure around the holes with different shapes. In order to obtain empirical results, specimens were manufactured by alternatively stacking aluminum and E-glass-epoxy layers according to the Glare standard. Analytical results show that the yielding of aluminum layers is the damage occurring to the plate initially. As a result, after the onset of the plastic flow in metallic layers the plate is not homogenous anymore, and conventional analysis cannot not be applied. An analytical model has been suggested to inspect the behavior of the plate at its ultimate load and is verified by ANSYS simulation. Comparison of different models indicates that numerical and theoretical models agree well with experimental test results. Also, the effect of aluminum thickness on strength has been examined analytically.

Keywords
Fiber metal laminate, Glare, blunt notch, tensile test, stress concentration, failure

Introduction
Fiber metal laminates (FMLs) are layered materials based on stacked arrangements of fiber reinforced plastic (FRP) layers such as glass fiber reinforced epoxy resin and thin metal sheets such as aluminum or titanium alloys.¹,² FMLs have advantages over both aluminum and fiber reinforced composites.³,⁴

FMLs have been shown to exhibit excellent fatigue and impact resistance, high specific static properties, flame resistance and ease of manufacture and repair.⁴,⁶

A great number of researches have been carried out on stress distribution around a hole in anisotropic bodies. Because of mathematical complexity in the theoretical solution, some researchers used numerical methods such as finite element method to evaluate stress distribution around a hole.⁷,⁸ Most of analytical solutions are based on complex variable method that was proposed by Lekhnitskii⁹ and Savin.¹⁰-¹³

Sharma¹² analytically studied the effect of fiber orientation, stacking sequence, and loading factor on stress concentration around openings with different shapes. Rezaeepazhand and Jafari¹³ used Lekhnitskii’s complex variable method to determine stress distribution around quasi-square holes. They described the effect of fiber orientation, material properties, bluntness and loading direction on the stress concentration around the hole.

Toubal et al.¹⁴ performed an experimental test to evaluate stress concentration around a circular hole.
and compared empirical results with that obtained by Lekhnitskii’s theory. Anlas and Tuzer utilized analytical approach with finite width correction factor to extend a method for designing a composite plate containing a circular hole. They used Tsai–Wu quadratic failure criteria to predict failure in the laminate and compared the strength of different specimens to obtain laminate with optimum lay-up configuration.

Tan investigated stress distribution and fracture pattern around an elliptic hole in a laminated composite. He carried out some experimental tests to inspect the effect of opening aspect ratio and opening length on the strength of the plate. Kannan et al. used three fracture models including inherent flaw model, point stress criterion and average stress criterion to evaluate the strength of composite laminate with a circular hole under tensile and compression loading. Yao et al. studied the fracture behavior of GFRP composites with a hole. They have discussed the damage initiation and crack growth in notched specimens. Lin and Lee studied the strength of a laminated composite with two types of circular holes, drilled and molded-in and observed higher failure strength in the case of continuous fiber.

Little attention has been devoted to FMLs containing a notch. Khatibi and Ye presented effective crack growth model to investigate the residual strength for various ARALL laminates containing circular hole. Wu et al. have studied the strength of Glare 4 with a circular hole and reported the delamination pattern and failure modes around the notch. Some authors used finite element method to analyze elastic-plastic response and expansion of plastic zone in metallic layers of various FMLs. The literature survey reveals that most of research works on FMLs containing a hole are limited to numerical modeling of structures with circular notch. In the present study, the blunt notch behavior of glass fiber reinforced aluminum with elliptic, circular and square notches has been studied. An analytical approach is developed to examine the yield strength of the laminate and its response at ultimate load. To support this model, finite element simulation is performed in ANSYS software. Theoretical model is verified by conducting tensile tests on Glare specimens with square or circular notch.

The analytical method is applied to analyze the effect of aluminum thickness on strength of specimens. Also, it is employed to inspect the influence of ellipse’s aspect ratio on failure response in specimens with elliptic notch.

**Analytical relations**

The analytical solution is based on Lekhnitskii’s theory for anisotropic plates containing a hole. It is assumed that the laminate is homogenous and symmetric. The dimension of the hole is small in comparison with the plate size. Therefore, the values of stress components can be considered uniform far from the opening.

Considering equilibrium equations, stress components can be introduced as Airy’s stress function. Based on compatibility and stress–strain relations the following partial differential equation for stress function, $F$, could be achieved.

$$a_{22} \frac{\partial^4 F}{\partial x^4} - 2a_{26} \frac{\partial^4 F}{\partial x^3 \partial y} + (2a_{12} + a_{16}) \frac{\partial^4 F}{\partial x^2 \partial y^2} - 2a_{16} \frac{\partial^4 F}{\partial x \partial y^3} + a_{11} \frac{\partial^4 F}{\partial y^4} = 0$$

(1)

The coefficients of the foregoing equation are the elastic constants that relate strain components to the average values of the stress components. Preceding equation can be written in form of four linear differential operators

$$D_1 D_2 D_3 D_4 F = 0, \quad D_k = \frac{\partial}{\partial y} - \mu_k \frac{\partial}{\partial x}$$

(2)

where $\mu_k$ is the roots of the characteristic equation

$$a_{11} \mu_k^4 - 2a_{16} \mu_k^3 - 2a_{12} \mu_k^2 - 2a_{26} \mu_k + a_{22} = 0$$

(3)

Lekhnitskii proved that the above equation has four complex roots that are pairwise conjugated. The stress function can be expressed as real terms of two functions of variables $z_1, z_2$

$$F = 2\text{Re}[F_1(z) + F_2(z)], \quad z_k = x + \mu_k y \quad (k = 1, 2)$$

(4)

Also, the components of force per unit length could be stated

$$N_x = 2\text{Re} \left[ \mu_1 \phi_1(z_1) + \mu_2 \phi_2(z_2) \right]$$

$$N_y = 2\text{Re} \left[ \phi_1(z_1) + \phi_2(z_2) \right] - 2\text{Re} \left[ \mu_1 \phi_1(z_1) + \mu_2 \phi_2(z_2) \right]$$

(5)

where $\phi_k$ is the first derivative of stress function with respect to $z_k$ and it should be calculated according to boundary conditions.

For elliptic opening a transform function is defined as

$$\zeta_k = \frac{z_k \pm \sqrt{z_k^2 - a^2 - \mu_k^2 b^2}}{a - i\mu_k b}$$

(6)
Which transforms the values of $z_1$ and $z_2$ at the edge of opening to a circle with unit radius. An exact solution for stress distribution around an elliptic hole could be achieved by assuming shear and normal stresses equal zero at the opening. Lekhnitskii suggested approximate solution for openings where their shapes slightly differ from ellipse. Their contours are given by relations

$$
\begin{align*}
x &= b(\cos \theta + \varepsilon \cos N\theta) \\
y &= b(\sin \theta - \varepsilon \sin N\theta)
\end{align*}
$$

where parameter $b$ determines the opening size, $c$ indicates the aspect ratio and $\varepsilon$ presents deviation from an ellipse. The boundary condition should be applied to find the stress function.

Because the laminate is symmetric, there appears to be no curvature in the plate due to in-plane loading. Consequently, the strain and stress components in each layer could be evaluated according to distribution of force per unit length.

It is supposed that failure occurs in the plate only because of in-plane stress components and therefore the effect of delamination is not regarded. It is assumed that aluminum layers behave elastic perfectly plastic. Composite layers also have linear behavior up to fracture point. To assess yielding load in aluminum and fracture in composite layers, von Mises and maximum stress failure criteria are used, respectively.

It is mentioned that homogeneity condition should be satisfied in the plate. If the laminate is only composed of composite layers this condition is viable up to fracture load. However, in FMLs yielding aluminum layers makes the laminate non-homogenous and the analytical relations cannot not be exerted. If the metallic layers reach to the plastic limit completely before ultimate failure, the condition will be obtained again and the preceding solution can be used to evaluate ultimate failure in the plate. A computer program was extended to implement analytical solution and subsequent steps were followed:

- Calculating matrix $A$ according to properties of aluminum and composite layers.
- Calculating complex variables $\mu_1, \mu_2$.
- Calculating mapping function.
- Calculating force per unit length components due to unit remote loading in $x$-direction ($N_x^0 = 1$).
- Calculating strain and stress components in each layer due to unit tensile load.
- Using failure criteria in each layer to assess maximum load that can be exerted on the plate to cause failure.

The above procedure was performed for various positions on the edge of the notch and the failure load was evaluated according to the weakest point that has minimum strength.

**Material and methods**

The following materials were used to manufacture specimens: aluminum 1050-H18 sheets with 0.5 mm thickness, unidirectional E-glass fiber (600 g/cm$^2$) and epoxy resin (Axson Epolam 2002 resin with Epolam 2002 hardener). The material properties are given in Table 1.

To make a stronger bonding between aluminum and composite layers, aluminum sheets were subjected to (p2) etches method.$^{27}$ The specimens were made by hand lay-up method followed by curing process at room temperature including pressurizing (about 1.5 bar) to reduce voids and removal of excess resin. No residual stress has been created in the laminate, since the cure cycle was at room temperature.

Specimen’s lay-up was according to Glare standard. To examine stress concentration and failure in aluminum and composite layers Glare 2A and 3 were chosen. The lay-up in Glare 2A is [Al/0/0/Al/0/0/Al] and for Glare 3 is [Al/0/90/Al/90/0/Al].$^{25}$

Rectangular plates with dimensions of 220 mm $\times$ 50 mm were prepared. To create an opening, the infinity condition for the plate should be regarded. The analytical model showed that a notch at the center of the plate with dimensions (diameter for circular notch and length for square hole) five times smaller than the width of the plate satisfies the above condition. CNC machine was used to create circular and square notches. The diameter of circular notch was 10 mm. In specimens with square notch, a 10 mm $\times$ 10 mm with rounded corner was made at the center of the plate. Uniaxial tensile test was carried out up to ultimate fracture of specimens (Figure 1).

<table>
<thead>
<tr>
<th>Table 1. Mechanical properties for aluminum and glass-epoxy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass-epoxy</td>
</tr>
<tr>
<td>$X_t = 1200$ MPa</td>
</tr>
<tr>
<td>$X_c = 700$ MPa</td>
</tr>
<tr>
<td>$Y_t = 150$ MPa</td>
</tr>
<tr>
<td>$Y_c = 300$ MPa</td>
</tr>
<tr>
<td>$S = 270$ MPa</td>
</tr>
<tr>
<td>$E_1 = 31$ GPa</td>
</tr>
<tr>
<td>$E_2 = 12$ GPa</td>
</tr>
<tr>
<td>$\nu_{12} = 0.25$</td>
</tr>
<tr>
<td>$G_{12} = 4.2$ GPa</td>
</tr>
<tr>
<td>$\sigma_{ult} = 3.65%$</td>
</tr>
</tbody>
</table>
Finite element simulation

Commercially available ANSYS 12 was used. Nonlinear element shell 91 is suitable for layered structure of FMLs. This element has six degrees of freedom and is defined by eight nodes, layer thickness, layer material direction angles and orthotropic material properties. Also, element shell 91 may be used for plasticity analysis and could be used to model the nonlinear behavior of aluminium. Material properties were defined according to Table 1.

Nonlinear and inelastic rate independent material model was used for aluminium layers. Considering elastic perfect plastic behavior for aluminium, isotropic hardening plasticity option with bilinear trend that uses von Mises yield criterion was chosen. In addition, linear orthotropic material model with elastic behavior up to failure point was applied to glass fiber reinforced composite layers.

A square plate with a central hole was created. The length of the plate was defined five times greater than the hole dimension to meet the infinity condition for the plate. The plate was first meshed with coarse mesh. Then the meshing of the area around the hole was refined to get a mesh-size independent solution. A uniform loading with 100 sub-steps in $x$-direction was exerted on the vertical sides of the plate.

Results and discussion

Stress concentration

To investigate stress distribution in a fiber metal laminate with a circular hole, a Glare 2A plate under unit remote loading in $x$-direction was considered ($N_x = 1$) and the analytical approach was applied to estimate the stress components. Glare 2A is symmetric relative to $x$- and $y$-axes, therefore the values of stresses are presented for angular position between $0^\circ$ and $90^\circ$ at the circumference of the notch (Table 2).

As shown in Table 2, normal stress in $y$-direction and shear stress have been produced due to the stress in $x$-direction around the notch. Although the values of $N_y$ and $N_{xy}$ are smaller compared to $N_x$, however, these two components may be important in composite layers where their transverse and shear strengths are considerably smaller than longitudinal strength. As a result, for anisotropic bodies where their strengths are not the same in different directions, calculation of stress concentration around the hole does not lead to a clear conclusion about failure in the plate and consequently a failure criterion should be employed to evaluate strength and failure location.

Blunt notch behavior of a Glare plate

In subsequent sections, the failure in a notched FML plate under uni-axial tension loading has been studied.
The strength of laminated composites could be defined as the load that causes failure in the first layer or first ply failure strength. In the following section, it will be shown that this value is equal to yield strength of the laminate in which the aluminum layer reaches the plastic limit. Also, the strength may be introduced as the maximum load that can be tolerated before final failure of the laminate or ultimate strength.

Glare 2A with a circular notch. According to the analytical modeling, high stress in aluminum layers that is more than its yield strength causes the first damage to the plate. Aluminum layers tolerate a greater portion of the load, because of higher elasticity modulus relative to the glass-epoxy. Therefore, yielding in aluminum layer is the first occurred failure in the laminate and aluminum yield strength determines the yield strength of the laminate. The value of the yield strength can be found in Table 3. Failure begins at a point with a tangential angle equals $90^\circ$ on the circle circumference. To assess the yield strength in ANSYS, stress at this point was obtained.

Due to increasing load on the plate, the plastic zone spreads through aluminum layers (Figure 2). Expansion of plastic zone is similar to what was predicted by Sahin for layered woven fiber-reinforced steel. Consequently, the plate is not homogenous anymore and analytical equations are not valid. To study the behavior of the plate after the yield load, the ANSYS model was examined. By growing the plastic region in metallic layer, the load on the composite layer will be enhanced. Two ways of final failure in the plate can be presumed: (a) fracture takes place in the aluminum layer because of exceeding maximum strain; (b) composite layers break according to maximum stress criterion. Since the failure strain of glass-epoxy is smaller than aluminum, composite layers break earlier and their strength is responsible for the ultimate strength.

If the composite strength is great enough, a large portion of aluminum layers will reach their plastic limit, as it was mentioned by Iaccarino. As a result, by considering elastic perfect plastic behavior for aluminum, the plate is homogenous in ultimate load and analytical relations can be applied to evaluate the ultimate strength. For this purpose, the strength of composite laminates without aluminum layers should be calculated and then added to the strength of aluminum layers that are in plastic regime.

Table 3. Yield strength for different specimens obtained by three models.

<table>
<thead>
<tr>
<th>Models</th>
<th>Circular notch (kN/m)</th>
<th>Square notch (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Glare 2A</td>
<td>Glare 3</td>
</tr>
<tr>
<td>Analytical</td>
<td>165</td>
<td>145</td>
</tr>
<tr>
<td>ANSYS</td>
<td>150</td>
<td>140</td>
</tr>
</tbody>
</table>

Figure 2. Expansion of plastic zone in aluminum layer by load rising.

Figure 3. Failure initiation according to max stress criterion at ultimate load for composite layer.

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<td>145</td>
</tr>
<tr>
<td>ANSYS</td>
<td>150</td>
<td>140</td>
</tr>
</tbody>
</table>

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results corresponding to the location of failure initiation and its mode.

According to Wu et al.,\textsuperscript{22} delamination around the notch in Glare specimens allows greater plastic deformation in aluminum layers and increases ultimate load. Because of delamination, strain continuity condition is not satisfied in the laminate; therefore delamination imposes limitation to the theoretical approach. In the present analytical model, it was assumed that delamination between aluminum and composite layers occurred after yield load and near the ultimate load. Also, this issue has been reported by Wu et al. In the evaluation of ultimate strength, as it was mentioned, the strength of yielded aluminum layers was separately added to the strength of laminate. As a result, the strain continuity condition that was violated because of delamination does not affect the analytical model. In addition, comparison of analytical and experimental results indicates that delamination has no significant effect on the results.

**Glare 2A with square notch.** Aluminum plays the main role in determining yield strength of plates containing a square notch similar to the specimens with a circular hole. Both analytical and ANSYS models predicted that yielding in aluminum layer initiates at a point on the corner of the square. To assess yield strength, variation of stress at this point due to the increasing load was investigated. As mentioned in Tables 3 and 4 the value of yield strength predicted by analytical method is close to ANSYS simulation.

To evaluate the ultimate strength in Glare 2A with square notch ANSYS simulation was carried out.

**Glare 3 containing a circular or square notch.** The presence of 90\(^\circ\)-lamina is the main difference between Glare 3 and 2A. 90\(^\circ\)-lamina has lower strength and elasticity.

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### Table 4. Ultimate strength for different specimens obtained by three models.

<table>
<thead>
<tr>
<th>Models</th>
<th>Circular notch (kN/m)</th>
<th>Square notch (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glare 2A</td>
<td>750</td>
<td>675</td>
</tr>
<tr>
<td>Glare 3</td>
<td>460</td>
<td>500</td>
</tr>
<tr>
<td>Analytical</td>
<td>720</td>
<td>640</td>
</tr>
<tr>
<td>ANSYS</td>
<td>710</td>
<td>620</td>
</tr>
<tr>
<td>Experimental</td>
<td>440</td>
<td>480</td>
</tr>
</tbody>
</table>

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**Figure 4.** Fracture in: (a) 0-lamina and (b) aluminum layer at ultimate load for circular notch.

**Figure 5.** Aluminum layer at ultimate load.

**Figure 6.** Tensile test was carried out on this specimen to validate the preceding results. The location of fracture initiation and its mode are illustrated in Figure 7 for aluminum and composite layers. This figure demonstrates that experimental results are consistent with the two other approaches.
modulus compared to 0°-lamina and its response should be examined specially after yield load.

The yield strength for Glare 3 was evaluated similar to what was stated for Glare 2A and tabulated in Table 3. As discussed before, ANSYS model indicated that force on composite layers raises after yield load. The strength of glass-epoxy layers in longitudinal direction is remarkably higher than transverse direction.

The comparison of strength and elasticity modulus in longitudinal and transverse directions indicates that 90°-lamina fails earlier than 0°-lamina. ANSYS verified that 90°-lamina breaks before 0°-lamina and have no influence on ultimate load. Figure 8 shows 90°-lamina to be completely broken before ultimate load.

To apply the analytical solution for estimation of ultimate strength, the elastic-plastic regime should be inspected over the aluminum sheets at the ultimate load. ANSYS simulation confirmed that most regions of aluminum layers have departed the elastic limit. As expressed above, 90°-lamina breaks before ultimate load. Therefore, the analytical model should be modified such that only the strength of 0°-lamina is considered and the effect of 90°-lamina is neglected.

According to the tensile tests conducted on Glare 3 specimens, failure mode and its location in 0°-lamina and aluminum layers is similar to Glare 2A. The values of ultimate strength obtained by three models are compared in Table 4.

In order to validate the presented model with results that have been reported in literature, the notch strength of Glare 4 with circular notch was calculated and compared with what was experimentally obtained by Wu et al. They have studied specimens with different width and hole sizes. A specimen with 76.2 mm width and a ratio of hole diameter to width equaling to 0.125...
was chosen from their results. This ratio does not violate the infinity condition for the plate. The strength of the laminate, which was calculated by analytical model, is 368.5 MPa (673.8 kN/m), which is 12.5% less than what was reported by Wu.

The effect of aluminum thickness on specific notch strength of Glare

To compare specimens with different aluminum thickness, the specific strength should be considered. By dividing strength (in MPa) to the density of the plate the specific strength can be obtained. It was discussed previously that the yield strength in various Glare plates can be evaluated by using theoretical relations. However, analytical model that was suggested for ultimate strength in Glare 3 and 2A may be inapplicable for other Glare grades. For instance, in Glare 2B that only have 90°-laminate, after fracture of composite layers the aluminum layers partially reach the plastic limit, thus the homogeneity condition may not be obtained at ultimate load and theoretical model cannot be applied.

Analytical relations were employed to study the influence of aluminum thickness on specific strength. The thickness of each aluminum layer has been varied from 0.1 to 0.5 mm. Tables 5 and 6 compare the values of specific yield and ultimate strength for Glare 2A and 3 with circular and square notches. As it can be seen in Figure 9, the specific yield strength increases due to a rise in aluminum thickness. This point is reliable for other Glares with circular and square openings.

The specific ultimate strength for Glare 2A varies inversely with aluminum thickness. Higher specific strength of glass-epoxy compared to aluminum is responsible for decrease in specific ultimate strength. However, the decrease in specific ultimate strength for Glare 3 is smaller compared to Glare 2A. Because 90°-lamina has low strength and has no contribution to ultimate load, specific ultimate strength remains relatively constant due to increase in aluminum thickness.

The effect of aspect ratio on behavior of a plate with elliptic notch

Figure 10 shows a plate with an elliptic hole subjected to uni-axial tension load. The aspect ratio of the ellipse (c) is defined as the ratio of ellipse’s axes in longitudinal to transverse direction. A Glare 2A plate with an elliptic notch was considered and the influence of aspect ratio on the strength of the plate, failure mode and its location was inspected. Yield and ultimate strength for aspect ratio varying from 0.1 to 10 has been drawn in a logarithmic diagram (Figure 11).

As the aspect ratio increases, stress concentration in point B on the opening increases and therefore the yield strength decreases (Figure 11). Also, the ultimate strength of specimens with different aspect ratio has been evaluated. As can be seen in Figure 11, for small values of aspect ratio (c < 0.4) there is no change in ultimate strength. In this range, stress in y-direction at point A is responsible for the failure. The theoretical relations showed that due to uni-axial load in x-direction negative stress in y-direction appears at point A that is independent of aspect ratio. When this compressive stress is higher than transverse compressive strength of composite, failure will occur. This matter is consistent with what was predicted by Miami et al.²⁸ for crack growth in a carbon fiber reinforced epoxy plate with circular hole. For c > 0.4, ultimate strength varies inversely with aspect ratio and failure location moves to point B where the tensile strength of composite layers in longitudinal direction controls failure in the plate. Consequently, for small aspect ratio notch strength is constant and failure takes place at point A in transverse direction. For greater values of aspect ratio, fracture in composite layers initiates at point B in longitudinal direction.

### Table 5. Specific yield strength according to aluminum thickness.

<table>
<thead>
<tr>
<th>Aluminum thickness (mm)</th>
<th>Glare 2A</th>
<th>Glare 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>18.8</td>
<td>16.2</td>
</tr>
<tr>
<td>0.2</td>
<td>20.2</td>
<td>17.8</td>
</tr>
<tr>
<td>0.3</td>
<td>21.1</td>
<td>19.2</td>
</tr>
<tr>
<td>0.4</td>
<td>21.7</td>
<td>20.8</td>
</tr>
<tr>
<td>0.5</td>
<td>22.2</td>
<td>21.4</td>
</tr>
</tbody>
</table>

### Table 6. Specific ultimate strength according to aluminum thickness.

<table>
<thead>
<tr>
<th>Aluminum thickness (mm)</th>
<th>Glare 2A</th>
<th>Glare 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>140.6</td>
<td>76.3</td>
</tr>
<tr>
<td>0.2</td>
<td>127.8</td>
<td>73.9</td>
</tr>
<tr>
<td>0.3</td>
<td>118.5</td>
<td>72.1</td>
</tr>
<tr>
<td>0.4</td>
<td>111.5</td>
<td>70.8</td>
</tr>
<tr>
<td>0.5</td>
<td>106.0</td>
<td>69.8</td>
</tr>
</tbody>
</table>
Conclusion

An analytical approach has been extended to study the stress distribution and failure in fiber metal laminates containing square and circular notches. This method was verified by experimental results and finite element simulation.

Theoretical results show that the first ply failure strength is determined by aluminum yield strength for various Glare laminates. After yield load, plastic flow spreads through aluminum sheets and the plate is not homogenous anymore. Therefore, the analytical model cannot be applied until the plate meets the homogeneity condition again. This condition can be achieved at ultimate load, if composite layers have enough strength to allow aluminum sheets to mostly reach plastic regime. This assumption could be employed for FMLs where their composite layers have higher strength than aluminum layers.

Simulation with ANSYS indicates that in specimens like Glare 2A and 3 the above condition can be obtained and analytical solution could be used to evaluate failure of the plate at its ultimate load. For specimens with circular holes fracture occurs in longitudinal direction at a point with a tangential angle equaling 90° on the circle circumference. In specimens containing a square notch, the fracture initiates at a point on the corner of the square in transverse direction.

Increasing aluminum thickness slightly enhances the specific yield strength for specimens with different notch shapes. However, the specific ultimate strength varies inversely with aluminum thickness. This point is more obvious for Glare 2A that only have 0°-lamina. Moreover, analytical solution was employed for specimens with elliptic hole and shows that aspect ratio greatly contributes to the determination of strength and failure mode of the laminate.

Figure 9. (a) Specific yield strength and (b) specific ultimate strength for Glare 2A with circular notch.

Figure 10. A plate containing elliptic notch subjected to uniaxial tensile load.

Figure 11. Values of yield and ultimate strength according to aspect ratio.
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Conflict of interest
None declared.

References