Studies on Tensile Strength of Notched Woven Fabric Composites for Different Stacking Sequence

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Abstract. Present work emphasizes on the effect of stress concentration based on hole size, specimen width and stacking sequence on the fracture behavior of the woven-mat glass/epoxy reinforced composites both experimentally and numerically. In the present work three different stacking sequences: [45/-45], [0/90] and [30/60] were considered for the investigation. Laminates were fabricated using wet layup technique. Circular notches of six different diameters were considered for the analysis. Both notched and un-notched test specimens of all the configuration were subjected to tensile testing till fracture. Both experimental and analytical results show that stacking sequence has a significant influence on fracture stress in the presence of notch. Numerical results obtained using FEA were compared with experimental results. The obtained results showed that the notched fracture stresses were maximum for stacking sequence angles [+45/-45], and differ significantly from those of the [0/90] and [30/60]. The characteristic length (d_o) influenced by hole size and specimen width as per the point stress criterion (PSC).

1. Introduction
Composites with woven reinforcements are of special interest compared to their counterpart, unidirectional ones because of lesser cost of production, excellent out-of-plan properties, good drape ability and improved impact resistance [1,2]. Cut-outs or holes are to be made in composites parts, to assist their joining when used in structural applications. These holes made in composites negatively influence mechanical properties by creating stress concentrations and hence are of great importance for designers. Whitney and Nuismer derived point stress criterion(PSC) and average stress criterion(ASC) to predict the strength of composites with holes or cut-outs [3,4]. These models were further discussed while evaluating mechanical characteristics of composites with woven fabric and having discontinuities such as holes or notches [5,6]. Various models were proposed in literature to determine the influence of notches or holes on tensile strength of the woven composites. Waddoups et al [7] developed a model based on Linear Elastic Fracture Mechanics principle. As an alternative to this model, Whitney et al. [3, 4] developed a model to explain variation of tensile strength of structural
composites due to presence of holes or notches. Later this model was extended into three parameter based model by Pipes et.al [8, 9]. The three parameters considered were hole size, reference radius and notch sensitivity factor.

Later it was showed that above models developed for laminate composites could also be applied for calculating tensile strength of fabric composites with notch[9-11]. Finite element analysis was employed subsequently by Hwan et al to predict the notched strength of composite plates without using analytical solutions [12]. A combination of fracture and stress energies was used to formulate a phase-field model and was presented by Reinoso J et.al [13] for notched strength prediction. Recently an investigation was conducted to analyse the effect of stress concentration related various parameters on the mechanical properties [14].

1.1. Theoretical Background
As per Whitney et al. [3, 4], notched tensile strength of a composite laminate can be predicted by the PSC and ASC based two parameter model. This model majorly considers the stress distribution adjacent to the notch. According to PSC based model, it is assumed that failure occurs when the normal stress $\sigma_y$ generated at some fixed distance ($d_0$) or the average stress $\sigma_y$ generated over some fixed distance ($a_0$) near the notch will be equal to the strength ($\sigma_0$) of the un-notched material.

For a circular hole, the failure occurs as per the following Equations (1) & (2)

$$PSC = \sigma_y(x,0) \bigg|_{x=R+d_0} = \sigma_0$$  \hspace{1cm} (1)

$$ASC = \frac{1}{a_0} \int_0^R \sigma_y(x,0) \, dx = \sigma_0$$  \hspace{1cm} (2)

Along the X-axis The normal stress ($\sigma_y$) developed ahead of the hole can approximately be expressed by Reference [15].

$$\sigma_y(x,0) = \sigma_\infty \left[ 2 + \left( \frac{R}{x} \right)^2 + 3 \left( \frac{R}{x} \right)^4 - \left( \frac{R}{x} \right)^6 \right] \frac{1}{2} = \sigma_0, x > R$$  \hspace{1cm} (3)

Here, $K_T^\infty$ represents factor for stress concentration when an infinite orthotropic plate is considered. $\sigma_\infty$ represents uniform stress along the Y-axis for the similar plate containing a circular hole of radius R.

$$K_T^\infty = 1 + \frac{2}{\sqrt{a_{11} a_{22} - a_{12}^2 \frac{2}{a_{12}^2 + \frac{2}{a_{66}}}}} \left( \frac{1}{2} \right)$$  \hspace{1cm} (4)

where $a_{ij}$ denotes orthotropic in-plane stiffness of the laminate.

Substitution of equation (3) in (1), gives

$$\frac{\sigma_N^\infty}{\sigma_0} = \frac{2}{2 + A_1^2 + 3A_1^4 - (K_T^\infty - 3)(5A_1^6 - 7A_1^6)}$$  \hspace{1cm} (5)
\[ A_1 = \frac{R}{(R + d_0)} \]

\[ \sigma_0 = \text{Tensile strength of the laminate without notch or hole.} \]

\[ \sigma_N^\infty = \text{Strength of an infinite width plate with notch.} \]

A modification to the PSC was proposed by Karlak [16] in which \( d_0 \) is a function of the hole radius (R),

\[ d_0 = K_0 \sqrt{R} \]  

(6)

2. Experimental Analysis

Woven Glass/Epoxy laminates with 60% volume fraction was considered for investigation. They were fabricated using wet lay-up technique. The geometry & the dimensions of the straight-sided tension specimen with a hole in the middle are shown in Fig.7 All the static tension tests were conducted on UTM. Tensile loading was applied on the specimens till failure at room temperature. The experimental value were compared with FEA as shown in figure 1 to 6. The experimental results were having good agreement with Finite Element results. Table 1 shows the theoretical stress distribution around the notch.

3. Tensile Strength of Notched Laminates

Orthotropic Stress Concentration factor \( \left( K_T^\infty \right) \)

\[ K_T^\infty = 1 + \left( \frac{2}{a_{22}} \left( a_{11} a_{22} - a_{12} + \frac{a_{11} a_{22} - a_{12}}{2a_{66}} \right) \right)^{1/2} = 4.35 \]

3.1. Failure Strength of Notched Laminate in Tension

The relationship between applied tensile stress on notched laminate and unnotched laminate failure strength is given by

\[ \frac{\sigma_N^\infty}{\sigma_0} = \frac{2}{2 + A_1^2 + 3 A_1^4 - (K_T^\infty - 3)(5 A_1^6 - 7 A_1^8)} \]

\[ \sigma_0 = \text{Unnotched tensile strength of the laminate, found experimentally=205 N/mm}^2 \]

\[ \sigma_N^\infty = 0.9134 \times \sigma_0 = 0.9134 \times 205 = 187.25 \text{ N/mm}^2 \]

Failure strength of laminate=187.25 N/mm²

3.2. Failure Load of Laminate

Applied load at failure or Failure load of laminate \( \left( N \right) = \frac{\sigma_{N}^\infty \times \text{Area}}{187.25 \times 197.6 = 37 \text{ KN}} \)

Theoretical stress distribution is given by

\[ \sigma_y(x,0) = \frac{\sigma_{N}^\infty}{2} \left[ 2 + \left( \frac{R}{x} \right)^2 + 3 \left( \frac{R}{x} \right)^4 - (K_T^\infty - 3) \left( \frac{R}{x} \right)^6 - 7 \left( \frac{R}{x} \right)^8 \right], \quad x > R \]

\( R = 4 \text{mm}; \quad K_T^\infty = 4.35 ; \quad \sigma_{N}^\infty = 187.25 \text{ N/mm}^2 \)
Table 1: Theoretical Tensile Stress Distribution

| Distance X(mm) | 3  | 5  | 7  | 9  | 11 | 13 | 15 | 17 | 19 |
|----------------|----|----|----|----|----|----|----|----|----|
| Theoretical Stress Distribution $\sigma_y$ (MPa) | 833.26 | 241.65 | 210.79 | 200.33 | 195.52 | 192.94 | 191.40 | 190.42 | 189.75 |
| Normalized Stress $\sigma_y / \sigma_N$ | 4.45 | 1.290 | 1.125 | 1.070 | 1.044 | 1.030 | 1.022 | 1.017 | 1.013 |

3.3. Finite Element Analysis

Finite element analysis carried out on notched and unnotched laminates for stress analysis by using analysis software NISA Ver 12.0. The elements used were NKTP 32-3D composite shell element it has six degree of freedom, for the same geometrical configuration for both experimental and numerical analysis for comparing the obtained results. Few FEA results were shown in Figures 1 to 6. Comparisons between experimental test results and predictions of PSC and modified PSC is shown in figure 8. Relationship between notch strength and Characteristic length is shown in figure 9.
**Table 1:** Comparison of Failure Stress

| Method       | FEA  | Experimental |
|--------------|------|--------------|
| 10 mm dia, 0/90 stacking sequence | 150.5 MPa | 147 MPa |
| 10 mm dia, 45/-45 stacking sequence | 136 MPa | 135 MPa |

**Figure 5:** Stress distribution around the Notch (10 mm dia, 0/90 stacking sequence)
- Applied load: 20.7 kN
- Failure stress: FEA 110 MPa, Experimental 105 MPa

**Figure 6:** Stress distribution around the Notch (10 mm, 45/-45 stacking sequence)
- Applied load: 27.2 kN
- Failure stress: FEA 140 MPa, Experimental 138 MPa

**Figure 7:** Tension test specimen
- L = 150 mm
- W = 40 mm
- t = 4.8 mm

**Figure 8:** Comparisons between test results and predictions of PSC and modified PSC

**Figure 9:** Relationship between notch strength and characteristic length.
4. Conclusion

Based on the results of present study, the conclusions made are summarised below:

1. In the modified PSC the characteristic length ($d_o$) is denoted as a function of the geometry of the specimen ($2R$ and $W$). It was found that the experimental results and the predictions of the modified PSC model tightly agree.

2. As the characteristic length ($d_o$) decreases an increase in ($\sigma_N/\sigma_0$) is observed.

3. There is a definite staking sequence dependence on the strength of laminates with holes.

4. The Von Mises stress value for laminate with hole is always higher than the laminate without hole.

5. The stress induced is maximum in 45/-45 stacking sequence and minimum in 30/60 stacking sequence.

5. References

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