Effect of ply orientation, staking sequence and notch geometry on the failure behaviour of glass fibre-reinforced epoxy composite laminates: A numerical investigation

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Abstract. A detailed numerical failure analysis was conducted for unidirectional glass fibre-reinforced epoxy composite laminates having an elliptical cut-out at the centre using Hashin’s damage model. The major axis, \( a \), of the elliptical cut-out was fixed while the minor axis, \( b \), was varied in such a way, that its upper extreme represented a situation of the plate with a circular hole, while the lower extreme of it represented the presence of a sharp crack in the structure. For angle ply cases, plies oriented along the material direction predicted an ever-increasing load replicating an elastic analysis without any damage accumulation. Such exceptionally higher stiffness and resistance to deformation were much anticipated, as the uniaxial tensile load was applied along fibre direction which shares a large portion of the load in comparison to the matrix material. While the plies oriented perpendicular to the direction of the material behaved as the weakest stack-up sequence in resisting uni-axial tensile load. Multi-angle hybrid composites predicted uneven failure behaviour. For the different combinations of multi-angle layups and minor axis, \( b \), different trends for peak loads were observed. Interestingly, extension-shear coupling was observed for a few configurations which were marginally negligible for others. The variation of opening stress along the transverse direction predicts some very interesting observations. For the higher value of \( b \), the opening stress decreases as we moved away from the irregularity. However, the situation of a plate with a sharp crack (\( b \to 0 \)) showed the effect of crack tip blunting. Near the vicinity of the sharp crack, the opening stress first dropped, then picked up, and again kept on decreasing as we move away. The drop in the stress near the vicinity of the sharp crack is attributed to the blunting of the crack tip.

1. Introduction
Owing to their excellent weight to strength ratio, physical, chemical and mechanical properties fibre reinforced hybrid composite materials are used extensively in engineering components such as aircraft, automobiles, and wind turbines. Irregularities such as notches, voids, and cracks are inevitable in the structures. Industrial application of composite materials requires drilling of holes or grooves on it for fixation and connectivity ([1], [2], [3]) which act as favourable sites for crack initiation and propagation. A century ago, people started studies addressing the issues of stress localization in the vicinity of the hole. Forchet [4] being the front runner in this field studied stress concentration factors for holes, grooves, and fillets under different loading (pure tension, compression, and bending) using the photo-elasticity method and determined the maximum value of stress experienced by the body under elastic conditions. The impact of shape and size of notches and loading conditions on the failure of composite materials has been the theme of various research activities conducted in the recent past ([5], [6]). Composite laminates with an elliptical hole at the centre were also investigated ([7], [8]).
The objective of the article: Effect of ply orientation and stacking sequence on the failure of glass fibre-reinforced epoxy composite plats having elliptical cut-out of varying minor axis is the objective of the article in hand. Such studies have been carried by various researchers ([9], [10]).

2. Hashing damage criteria

Due to involved anisotropy, the mechanical behavior and failure of composite materials are difficult to understand as compared to homogenous and isotropic materials ([11], [12]). Various failure criterions have been developed to address failure behavior in composite materials. They are broadly classified into two types: failure criterion non-associated with failure modes and failure criterion associated with failure modes. The non-associated failure criterion is not concerned with the actual failure mechanism, instead, they focus on the gross macroscopic failure events. They are phenomenological models based on curve fitting. Tsai-Wu and Tsai-Hill are commonly used first-generation failure criteria for predicting failure of orthotropic materials ([13], [14], [15]). Though these criteria could predict failure of material point they don’t account for the influence of strength and stiffness degradation. Hence, they are non-associated with failure modes. The associated failure criterion known as the second generation failure criteria can capture progressive material damage by the degradation of stiffness and strength after material failure. Hashin’s damage criteria are the associated failure criterion ([16], [17]). In recent times extended finite element method has also been used for modelling damage imitation and propagation in composite structures.

3. Geometry, loading and boundary condition

A thin composite plate of uniform thickness of height, ‘$h = 25$ mm’, width ‘$w = 25$ mm’ and thickness, ‘$t = 1$ mm’ has been modelled in Abaqus 6.20 [18] as a 2-dimensional plane stress continuum shell element. Different elliptical cut-out of major axis fixed as $a = 5$ mm and varying minor axis, $b = 0, 1.25, 2.5, 5$ mm has been considered at the centre of the plate, as shown in Figure 1(a). With a fixed major axis, $a = 5$ mm, the upper limit of the minor axis, $b = 5$ mm replicate plate with a circular cut-out, while the lower limit $b = 0$ mm introduces a sharp crack in the plate. The geometry has meshed in such a way that, enough elements are present near the cut-put to effectively capture the damage as shown in Figure 1(b). One end of the composite plate is completely restrained against all the rotational and translational degrees of freedom while a uni-axial displacement controlled monotonic load is applied on the other edge.

4. Material properties

Declaration for unavailability of in-house test data and future test plan: Respecting the time and resource constraint in the current affiliate organization, the orthotropic property of the unidirectional glass fibre-reinforced epoxy composite material has been adapted from the literature [19] as listed in Table. 1. Meanwhile we have started building a sophisticated composite test facility. In the subsequent manuscript, we would be able to show in-house test results. All the orthotropic elastic properties of the composite plate were assumed in the principal material directions and defined as ‘Lamina Properties’ in Abaqus 6.20 [18].

5. Stacking sequences for composite plate

The composite plate has been modelled with eight plies of glass uni-directional fibre-reinforced epoxy layers. Each ply of ply thickness $t = 0.125$ mm was considered making the total thickness of the composite plate 1 mm. The fibre’s orientations angle, $\theta$, measured in anticlockwise direction is the angle between the longitudinal direction, $L$, and the principal material directions, $F$, of the composite plate as shown in Figure 2(a)-(b).
Figure 1. Composite plate with a various elliptical cut-out (a) Load and boundary condition (b) Finite element mesh.

Figure 2. Stacking sequences for angle ply laminates.

Table 1. Material properties of glass fibre-reinforced epoxy laminate.

| Mechanical Property | Value | Unit   |
|---------------------|-------|--------|
| $E_1$               | 55000 | MPA    |
| $E_2$               | 9500  | MPA    |
| $G_{12} = G_{13}$   | 5500  | MPA    |
| $\nu_{12}$          | 0.33  | MPA    |
| $X^T$               | 2500  | MPA    |
| $X^C$               | 2000  | MPA    |
| $Y^T$               | 50    | MPA    |
| $Y^C$               | 150   | MPA    |
| $S12$               | 50    | MPA    |
| $G_{f,c}$           | 12.5  | N/mm   |
| $G_{f,c}$           | 12.5  | N/mm   |
| $G_{m,c}$           | 1.0   | N/mm   |
| $G_{m,c}$           | 1.0   | N/mm   |
6. Damage stabilization

The composite plate has been modelled with eight plies of glass uni-directional fibre-reinforced epoxy layers. Each ply of ply thickness \( t = 0.125 \) mm was considered making the total thickness of the composite plate 1 mm. The fibre’s orientations angle, \( \theta \), measured in anticlockwise direction is the angle between the longitudinal direction, \( L \), and the principal material directions, \( F \), of the composite plate as shown in Figure 2(a)-(b).

To avoid the convergence issue which is inevitable in highly non-linear and non-smooth numerical failure simulation, viscous damage stabilization was invoked. For \( a = 5 \) mm and \( b = 5 \) mm, replicating the situation of the plate with a circular hole, a parametric study was carried out for \( \theta = 45^\circ \) angle ply laminate to look into the impact of damage stabilization factor on the macroscopic force-deflection response as shown in Figure 3. A smaller value of the damage stabilization factor predicted higher peak load at the cost of computational time. ‘Viscosity' = 0.001 sec. was considered as the damage stabilization factor for all the cases as reported by Lapczyk and Hurtado [19].

![Figure 3. Effect of viscosity on the macroscopic force-deflection response of \( \theta = 45^\circ \) angle ply laminate.](image)

![Figure 4. Macroscopic force-deflection for different angle ply orientations.](image)

7. Results and discussion

Angle ply laminate analysis

For \( a = 5 \) mm and \( b = 5 \) mm, replicating the situation of the plate with a circular hole, different angle ply situations such as \( \theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ, 90^\circ \) to the principal material the direction was considered as shown in Table 2.

| Case | Stacking Sequences |
|------|--------------------|
| 1    | \([0^\circ/0^\circ/0^\circ]\) \(_{2S}\) |
| 2    | \([+30^\circ/+30^\circ/+30^\circ/+30^\circ]\) \(_{2S}\) |
| 3    | \([+45^\circ/+45^\circ/+45^\circ/+45^\circ]\) \(_{2S}\) |
| 4    | \([+60^\circ/+60^\circ/+60^\circ/+60^\circ]\) \(_{2S}\) |
| 5    | \([+90^\circ/+90^\circ/+90^\circ/+90^\circ]\) \(_{2S}\) |

For all the angle ply cases, the macroscopic force-deflection response was linear until the damage was initiated. Plies oriented as \([0^\circ/0^\circ/0^\circ]_{2S}\), predicted an ever-increasing load replicating an...
elastic analysis without any damage accumulation as shown in Figure 4. Such an exceptionally higher stiffness and resistance to deformation were much anticipated, as the uni-axial tensile load was applied along fibre direction which shares a large portion of the load in comparison to the matrix material. On the other hand, plies oriented as \([+90^\circ]/+90^\circ/+90^\circ/+90^\circ]_{2S}\), behaved as the weakest stack-up sequence in resisting uni-axial tensile load. Intermediate ply orientations, \([+30^\circ]/+30^\circ/+30^\circ/+30^\circ]_{2S}\), \([+45^\circ]/+45^\circ/+45^\circ/+45^\circ]_{2S}\) and \([+60^\circ]/+60^\circ/+60^\circ/+60^\circ]_{2S}\) showed damage accumulation lying in between the two extreme cases of \([0^\circ]/0^\circ/0^\circ/0^\circ]_{2S}\) and \([+90^\circ]/+90^\circ/+90^\circ/+90^\circ]_{2S}\). The preliminary study demonstrated that structures having more plies aligned along the fibre direction will have a better resistance of the structure against deformation.

**Multi-angle ply laminate analysis**

In actual situations, engineering structures are acted by complex loading conditions. Hence, the plies are arranged in different orientations in the actual structure. In the second phase of our study, a numerical failure study was conducted on the multi-angle, \([0^\circ]/+\theta/-\theta/+90^\circ]_{2S}\) composite laminate layups as listed in Table 3.

**Table 3.** Stacking sequences for multi-angle ply analysis.

| Case | Stacking Sequences |
|------|--------------------|
| 1    | \([0^\circ]/+30^\circ/-30^\circ/+90^\circ]_{2S}\) |
| 2    | \([0^\circ]/+45^\circ/-45^\circ/+90^\circ]_{2S}\) |
| 5    | \([0^\circ]/+60^\circ/-60^\circ/+90^\circ]_{2S}\) |

**Case 1:** For, \(b = 0\) mm and \(b = 1.25\) mm, the lay-up \([0^\circ]/+30^\circ/-30^\circ/+90^\circ]_{2S}\) predicted almost the same peak load. However, there was a stiff fall from the peak load for \(b = 2.5\) mm and \(b = 5\) mm as shown in Figure 5(a). Though the fibre damage in tension was identical for all the values of \(b\) the matrix damage in tension was maximum observed for \(b = 0\) mm as shown in Figure 7(a). No extension-shear coupling was observed for the lay-up \([0^\circ]/+30^\circ/-30^\circ/+90^\circ]_{2S}\) and any combination of minor axis, \(b\).

**Case 2:** As compared to \([0^\circ]/+30^\circ/-30^\circ/+90^\circ]_{2S}\), the next lay-up \([0^\circ]/+45^\circ/-45^\circ/+90^\circ]_{2S}\) predicted entirely different trend. The peak load was much higher for \(b = 0\) mm than for \(b = 1.25\) mm and \(b = 5\) mm as shown in Figure 6(a). Fibre damage in tension was unevenly distributed for all the values of \(b\). However, the matrix damage in tension was widespread for \(b = 5\) mm, but it was much localized for \(b = 0, 1.25, 2.5\) mm as shown in Figure 8. There were very minimal extension-shear coupling phenomenon this configuration.
Figure 7. Macroscopic force-deflection response for $[0^\circ/ +30^\circ/ -30^\circ/ +90^\circ]$ layup analysis.
Figure 8. Contour of fibre and matrix damage for $[0^\circ/ +45^\circ/ -45^\circ/ +90^\circ]_{2S}$ layup analysis.
Case 3: As compared to \([0^\circ]/+30^\circ/-30^\circ/+90^\circ\) \(_{2S}\), the next lay-up \([0^\circ]/+45^\circ/-45^\circ/+90^\circ\) \(_{2S}\) predicted entirely different trend. The peak load was much higher for \(b = 0\) mm than for \(b = 1.25\) mm and \(b = 5\) mm as shown in Figure 6(a). Fibre damage in tension was unevenly distributed for all the values of b. However, the matrix damage in tension was widespread for \(b = 5\) mm, but it was much localized for \(b = 0, 1.25, 2.5\) mm as shown in Figure 8. There were very minimal extension-shear coupling phenomena in this configuration.

![Figure 9](image)

**Figure 9.** Macroscopic force-deflection response for \([0^\circ]/+60^\circ/-60^\circ/+90^\circ\) \(_{2S}\) layup analysis.

![Figure 10](image)

**Figure 10.** Peak load vs minor axis, \(b\).

The numerical failure study of the composite notched plate predicted increasing peak load with increasing \(b\) for the stacking sequence, \([0^\circ]/+30^\circ/-30^\circ/+90^\circ\) \(_{2S}\), as shown in Figure 10. However, the stacking sequences \([0^\circ]/+45^\circ/-45^\circ/+90^\circ\) \(_{2S}\) and \([0^\circ]/+60^\circ/-60^\circ/+90^\circ\) \(_{2S}\) showed a distinct trend. With increasing \(b\) first the peak load decreased and then increased. This trend was more prominent in the stacking sequences \([0^\circ]/+45^\circ/-45^\circ/+90^\circ\) \(_{2S}\) than \([0^\circ]/+60^\circ/-60^\circ/+90^\circ\) \(_{2S}\).

The variation of opening stress, \(\sigma_{ij}\), along the transverse direction predicts very interesting behaviour. For \(a = 5\) mm and \(b = 5\) mm replicates the situation of the plate with a circular hole. Opening stress, \(\sigma_{11}\) increases as the stacking sequence changes from \([0^\circ]/+30^\circ/-30^\circ/+90^\circ\) \(_{2S}\) to \([0^\circ]/+60^\circ/-60^\circ/+90^\circ\) \(_{2S}\) as shown in Figure 12. For \(a = 5\) mm and \(b = 2.5\) mm, a similar trend was observed. However, there was a stiff fall in the values of opening stress, \(\sigma_{11}\), as we moved away from point, \(A\), as shown in Figure 13. The situation \(a = 5\) mm and \(b = 1.25\) mm predicted almost same trend for \([0^\circ]/+30^\circ/-30^\circ/+90^\circ\) \(_{2S}\) and \([0^\circ]/+45^\circ/-45^\circ/+90^\circ\) \(_{2S}\) as shown in Figure 14. Finally, the combination \(a = 5\) mm and \(b = 0\) mm replicating the situation of a plate with a sharp crack predicted a different behaviour. Near the vicinity of the sharp crack, the opening stress, \(\sigma_{11}\), first dropped, then picked up and again kept on decreasing as we move away from point, \(A\) as shown in Figure 15. The drop in the stress near the vicinity of the sharp crack is attributed to the blunting of the crack.
Figure 11. Contour of fibre and matrix damage for $[0^\circ/ +60^\circ/ -60^\circ/ +90^\circ]_{2S}$ layup analysis.
Conclusions

In the present work, Hashin’s damage model has been used in modelling the failure behaviour of unidirectional glass fibre-reinforced epoxy composite laminates having an elliptical cut-out at the centre. Following are the inferences that can be drawn from the study:

- For angle ply cases, plies oriented along the material direction predicted an ever-increasing load replicating an elastic analysis without any damage accumulation. Such exceptionally higher stiffness and resistance to deformation were much anticipated, as the uni-axial tensile load was applied along fibre direction which shares a large portion of the load in comparison to the matrix material.

- For angle ply cases, plies oriented perpendicular to the direction of the material behaved as the weakest stack-up sequence in resisting uni-axial tensile load.
For multi-angle composites, different fibre orientation and stacking sequences predicted very uneven failure behaviour.

For different combinations of multi-angle layups and minor axis, $b$, different trends for peak loads were observed.

Interestingly, extension-shear coupling was observed for a few configurations which were marginally negligible for others. The variation of opening stress along the transverse direction predicts some very interesting observations.

For the higher value of $b$, the opening stress along the transverse direction decreases as we moved away from the notch.

Composite plate with a sharp crack predicted and showed the effect of crack tip blunting. Near the vicinity of the sharp crack, the opening stress first dropped, then picked up, and again kept on decreasing as we move away. The drop in the stress near the vicinity of the sharp crack is attributed to the blunting of the crack tip.

9. Future Work

Though, the engineering components are subjected to multi-axial loading and experience a triaxial state of stress. However, for ease of understanding, the materials are mainly characterized experimentally in idealized uni-axial tests. A detailed experimental and numerical study has been planned for the future, where complex loading conditions and the effect of an aggressive the environment will be considered.

Data availability

Dr Faizan Mohammad Rashid, Assistant Professor, Dept. of Mechanical Engineering, Birla Institute of Technology and Science (BITS-Pilani) holds the propriety right of the numerical data generated in the above findings. It may be shared based on request.

CRediT author statement

Conceptualization, Investigation, Original draft preparation, Reviewing and Editing: Faizan Mohammad Rashid; Methodology, Validation, and Data analysis: Krishna P.G.R and Faizan Mohammad Rashid.

Conflicts of interest

The authors declare no conflict of interest.

Funding

Present research activity was carried out as one of the research activities under the ongoing broad project titled ‘Numerical failure analysis of structures at different stress-state and subjected to different strain-rate using the finite element methods’ supervised by Dr Faizan Mohammad Rashid as Principal Investigator. The project is funded by the Birla Institute of Technology and Science, Pilani (BITS Pilani), Pilani Campus, Rajasthan, India via the Researcher Initiation Grant scheme (Serial No: 146).

Acknowledgements

The corresponding author, Dr Faizan Mohammad Rashid, would like to thank his wife Mrs. Tahsin Rakhshan, daughter Zaina Faizan and son Ammar Mohammad Rashid for their support and encouragement while preparing the manuscript.
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