Failure Analysis of Boron/Epoxy Composite Laminates with Square Cutouts in Various Size under Uniaxial Tension

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Abstract. Composite laminates have received much interest in precise engineering fields such as aerospace and automotive industries. Understanding the failure behaviour of laminated composites is important when designing modern structures, but many studies only focus on laminates without cutouts. In practice, the structures are designed with cutouts to accommodate the space for fasteners, such as rivets, screws and bolts. This study analyses the failure behaviour of Boron/Epoxy composite laminates with square cutout of various sizes under uniaxial tension. In this study, failure analysis was performed using a Finite Element Analysis (FEA) software, ANSYS, for laminated composite plates with square cutout. The laminas were arranged in the sequence of [θ/0/θ]s where the fibre angle, θ ranges from 0˚ to 90˚. The failure load was predicted based Maximum stress theory. For better visualisation, failure curves are plotted and analysed. Prior to that, the numerical validation procedure has proved the accuracy of the simulation as the results obtained from analytical approach (Matlab) and simulation (ANSYS) are in close agreement. The failure curves show that the Boron/Epoxy composite laminate has weaken seven times due to the square cutout. Such information is vital when designing a structure. Even though more rigorous research should be conducted, it could not be denied that the current study has contributed significant fundamental knowledge. The novelty of this work is that a new set of failure envelopes for Boron/Epoxy laminates with various cutout sizes was developed.

1. Introduction

Composite materials are widely used in current industries such as automotive, aerospace and shipbuilding due to its properties which is high strength to weight ratio [1]. Furthermore, the properties of composite materials are tailorable, allowing them to offer a variety of other superior features as compared to conventional materials; such as high specific strength, toughness, good corrosion and wear resistance properties [2]. In actual applications, the structural components are provided with openings or cutouts to comply with certain functional requirements such as easy access to damage inspection, provide access for fuel lines, hydraulic lines and electrical lines, cutouts to be used as doors and windows, and also decrease the total structural weight [3]. The presence of these cutouts drastically alters the strength of composite laminates. Besides, the stress distribution within the structure may be complicated by these cutouts, in which the stress field is differ in different areas, resulting in a loss of stability at an extremely low level of stress [4]. For that reason, in order to avoid early failure and catastrophic failure to happen, it is important to fully understand the failure behaviour of laminated composite plate with various cutout sizes so that strength of the structure can be fully utilise. Modern composite structure design needs a thorough understanding of the failure and deformation behaviour of composite materials. Therefore, recently many studies were carried out to analyse the performance of...
composite structure under a variety of loading conditions by conducting advanced computational method or experimental method [5]. However, experimental method is very difficult, time consuming and expensive. This is due to the fact that they need numerous repeat tests and a large number of samples to account for changes in lamination scheme and loading conditions [6]. As a result, finite element analysis has always been an alternate approach for doing failure analysis in order to save time and cost [7]. Many types of failure criteria available recently to perform failure analyses, the most failure criteria used in industry is Maximum Stress Theory. Maximum Stress Theory is the simplest one; but yet generating results with acceptable accuracy [8]. This theory can be represented by equation (1); 

\[ \sigma_1 = X_t \text{ or } X_c, \sigma_2 = Y_t \text{ or } Y_c, \tau_{12} = S \]

There are various of research has been done regarding the failure analysis of composite laminates with cutout under various loading [9][10]. Alaattin Aktas [11] studied the effect of W/D and E/D ratio on failure mode and failure load of composite laminates having single and double hole… .... experimental and numerical analysis were performed under various load. The maximum failure load and failure modes were observed. Rayhan [12] analysed the buckling behaviour of composite panel with circular cutout where the side of the cutout was reinforced with stiffener under various loading using Ansys software. The elastic buckling response of the composite panels are observed. Kumar et al [13] study failure and stability of a composite laminate with cutout of various shapes and sizes under combined in-plane loads. Various lamination sequence of composite laminates with various cutout shapes and sizes was also studied. The cross-ply laminates with cutout were found to have strength of postbuckling deformation and the angle ply and quasi-isotropic composite laminates gave high buckling strength. Lakshminarayana et al [14] analyse the failure behaviour of composite laminates with circle and ellipse cutout. The studied was conducted using ANSYS software based on Hashin’s failure theory. Composite laminates with ellipse cutout were found to have lower ultimate failure load as the size and orientation of ellipse cutout increases.

The main objective of this study was to simulate and investigate the effect of various square cutout sizes on deformation and failure behaviour of Boron/Epoxy composite laminates under uniaxial tension load. The failure loads that the composite laminates with various cutout were compared with composite laminates without cutout. The novelty of this work is that a new set of failure envelopes for Boron/Epoxy laminates with various cutout sizes was developed. Based on literature review, there is reported study that has attempted to solve this problem. This information is important when designing a structure since this type of material are used widely in many applications such as aircraft parts and various sporting goods parts including tennis racket and fishing rods.

2. Methodology
In general, the work done in this study is divided into two (2) major stages involving numerical validation and failure analysis of Boron/Epoxy composite laminates.

2.1 Numerical Validation
Numerical validation is a technique to prove the present model and finite element implementation are precise and valid by comparing the results with analytical approach using Matlab programme developed in-house. For this stage, a Boron/Epoxy composite laminates with a lay-up of \([\theta_4/0/-\theta_4]\), was generated under uniaxial load. The maximum displacement for both the x- and y-directions was determined by varying the fibre angle orientation, from 0° to 90°. Results obtained from simulation and analytical approach are tabulated and plotted. For the numerical validation, a square plate geometry (without cutout) with length, \(a = 279 \text{ mm}\), thickness of each lamina is, \(h = 0.09 \text{ mm}\) was considered and constrained at one end. Table 1 shows the material properties of the Boron/Epoxy.
### Table 1. Material properties for Boron/Epoxy

| Properties     | Values | Nomenclature                                                                 |
|----------------|--------|-------------------------------------------------------------------------------|
| E₁             | 217 GPa| Principal Young’s moduli in fiber direction and other two transverse directions |
| E₂ = E₃        | 21 GPa | Poisson’s ratios associated with planes 1-2, 1-2 and 2-3, respectively        |
| V₁₂ = V₁₃ = V₂₃| 0.3    | Poisson’s ratios associated with planes 1-2, 1-2 and 2-3, respectively        |
| G₁₂ = G₁₃ = G₂₃| 7 GPa  | Shear moduli associated with planes 1-2, 1-2 and 2-3, respectively            |
| Xₜ             | 1380 MPa| Normal strength (tensile or compressive, respectively) of lamina in fiber direction-1 |
| Xₙ             | 2760 MPa| Normal strength (tensile or compressive, respectively) of lamina in fiber direction-1 |
| Yₜ             | 83 MPa | Normal strength (tensile or compressive, respectively) of lamina in fiber direction-1 |
| Yₙ             | 276 MPa| Normal strength (tensile or compressive, respectively) of lamina in fiber direction-1 |
| S              | 124 MPa| Shear strengths of lamina                                                    |

2.2 Failure Analysis of Composite Laminate

In this study, a Boron/Epoxy composite laminate with square cutout of various sizes was studied. The main aim of this study was to analyse the effect of cutout size on the failure behaviour of composite laminate under uniaxial tensile load, where three different cutout sizes, denoted as A₁, A₂ and A₃, were evaluated. The area A₁ corresponds to the square cutout with an aspect ratio (i.e., c/b, where c is the size of the square cutout and b is the width of the laminate) of 0.14, whereas the areas A₂ and A₃ correspond to the areas of cutout with aspect ratios of 0.28 and 0.42, respectively. Table 2 shows the dimension of the cutouts. Lamination scheme of [θ₄/0₄/θ₄⁻], was analysed in this study, where the fibre angle, θ ranges from 0° to 90°. The failure analysis was performed to predict the failure load by employing Maximum Stress failure criterion, available in the using FE simulation software (ANSYS). For the current study, a square laminate with length, a = 279 mm, thickness of each lamina is, h = 0.09 mm is considered. The plate was constrained as shown in Figure 1 (a). Figure 1 (b) shows the meshing of laminate with square cutout, using 8-noded shell elements. Similar to the numerical validation, the material investigated was also Boron/Epoxy as shown in Table 1.

![Figure 1.](image-url)
Table 2. Details of cutout dimensions

| Cutout shape | Cutout size | Ratio | A1     | A2     | A3     |
|--------------|-------------|--------|--------|--------|--------|
| Square       | c/b         | 0.140  | 0.280  | 0.420  |        |

3. Results and Discussion

3.1 Numerical Validation

Table 3 presents the results of both analytical and finite element method. Both approaches are closely similar with errors ranging from 0% to 2.3% for both the x- and y-directions in regard to the angles of fibre orientation. Based on the result, since the maximum error is less than 3%, it can be inferred that the findings can be acceptable and the generated models are correct. For better understanding, the comparison on displacement using analytical and finite element method (ANSYS) are plotted graphically in Figure 2.

Table 3. Comparison between finite element simulation and analytical results for composite laminates under uniaxial tension load.

| θ˚  | Load (kN) | Analytical (x (mm)) | Simulation (ANSYS) (x (mm)) | x (%) | y (%) |
|-----|-----------|----------------------|-------------------------------|-------|-------|
| 0   | 1000      | 0.61                 | 0.62                          | 1.63  | 0.00  |
| 15  | 1000      | 0.70                 | 0.71                          | 1.00  | 2.32  |
| 30  | 1000      | 1.06                 | 1.05                          | 0.66  | 0.92  |
| 45  | 1000      | 1.48                 | 1.48                          | 0.14  | 1.10  |
| 60  | 1000      | 1.59                 | 1.59                          | 0.31  | 1.70  |
| 75  | 1000      | 1.56                 | 1.56                          | 0.00  | 0.00  |
| 90  | 1000      | 1.54                 | 1.55                          | 0.78  | 0.00  |

Figure 2. Comparison results on maximum displacement using analytical and simulation (ANSYS) approach.
3.2 Failure Analysis of Composite Laminates

Figure 3. Failure curves for composite laminates with and without cutouts

Figure 3 represents the failure curves for solid Boron/Epoxy composite laminates and Boron/Epoxy composite laminates with cutout. The failure curve for solid plate exhibits a decreasing trend, while laminates with cutout show an increasing trend. It is found that the failure curve for solid composite laminates is decreasing until at angle 45˚, then the curve slightly increases at angle 60˚ and decreases again until at 90˚. The highest stress value for solid composite laminates is 1380 MPa at angle 0˚ where the fibre angle is parallel to the tension load. The lowest stress value for solid composite laminates is 296 MPa at angle 45˚.

Figure 4. Failure curves for composite laminates with cutouts of various sizes

Figure 4 focuses on the failure curves for Boron/Epoxy composite laminates with cutout only. For the composite laminates with cutout, the trends are similar for all cutout sizes. Where, the failure curves increase until at angle 60˚of ply orientation before gradually decrease until at angle 90˚. The highest stress value for laminates with various cutout sizes are 187 MPa (A1), 138 MPa (A2) and 99 MPa (A3) at angle 60˚. The lowest stress value for laminates with various cutout sizes are 81 MPa (A1), 62 MPa (A2) and 42 MPa (A3) at angle 0˚. It can be seen that failure loads that the laminates can withstand decrease as cutout size increases from A1 to A3.

Based on the graphs, there is a huge difference between laminates with and without cutout. The failure curves for the laminates with cutout has lower stress value compared to the solid laminates. This shows that the cutout has greatly reduce the tensile strength of composite laminates.

4. Conclusion

This study has successfully analysed the failure behaviour of Boron/Epoxy composite laminates with square cutout of various sizes subjected to uniaxial tension using commercial software (ANSYS).
Several findings could be deduced from the study. Firstly, the square cutout has weakened significantly the strength of the composite laminates. Among all, the patterns of the failure curves are very much influenced by the angle of fiber orientation. This indicates that the fiber angles have significant effect on the strength of hybrid composite laminates. Besides, the failure load magnitude decreases as the size of the cutout increases. The results pertaining to this study are novel as it has never been reported by any other researchers before. In conclusion, this study has enhanced knowledge about performing failure analysis composite laminates with various square cutout sizes using commercial finite element software.

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