Response of composite laminate with various cut-out combinations to tension load

Kanu Priya Jhanji, Amit Kumar R, Debajit Das and Shivanshu Sarkar

School of Aeronautical Sciences, Hindustan Institute of Technology and Science,
Chennai, India – 603103
E-mail: kanujhanji@gmail.com

Abstract: All parts like adaptor plates, swash plates, repair patches and components providing way to wires have multiple cut-outs and as composites are replacing metals and alloys in many of these components it is necessary to understand the composite material’s reaction to mechanical loads in presence of cut-outs. In this work, experiments were conducted to note the impact of combination of various cut-outs on the UTS (ultimate tensile strength) of GFRC. Result shows that specimens containing combination of square and circular cut-outs can carry highest loads before failure as compared to other combinations.

1. Introduction

Composites are well known materials preferred in almost all the fields and have high importance in structural applications. Due to their ability to be of tailored nature and many other advantages like high corrosion resistance, high strength, high stiffness and low weight they take-over the application of metals and alloys. As composites are anisotropic in nature, working on composites and their response to any work is also different from metals. Presence of cut-outs, notches are inevitable in structures as their presence make many works especially assembly and repair works easy. Smaller cut-outs are common in plates joined by mechanical fastener for assembly, patches made for repairs and larger cut-outs are commonly seen in aircraft and car windows. Design of any component demands deep rooted knowledge of the behavior of structure in presence of cut-outs. This behavior changes with change in material. Many researchers got captivated by the composite materials and had done a lot of work on applications of cut-outs in composites. The main reason behind this interest is the significant changes which were observed due to the presence of any kind of damage and cut-outs were found to be the site of crack/damage initiation. The crack initiation may be the result of interaction between various failures occurred in inter laminar and intra-laminar region of multilayered composites. The properties of many structures get altered due to presence of cut-outs and notches, which in turn affects the performance and make structure less efficient. So, a lot of effort has been made to find solution to this problem and to study every parameter meticulously. Although a combination of various geometrical shaped cut-outs are found in transport vehicles and aircrafts, most of the works are done only on circular cut-outs.

Alaattin Aktas [1] studied the effect of E/D and W/D ratio on failure load and failure mode of composite laminates having single hole and double holes filled with pin on the centerline. The numerical analysis and experimental analysis was performed under tension, compression and shear load. The failure modes and maximum failure load variations were observed. Faruk Şen et al [2, 3] carried out an experimental investigation to understand the effect of stacking sequence and joint geometry on the failure mechanism and bearing strength of composite laminate. The further studies also estimated effect of pre-moments on the failure nature of composite laminates with bolted joints. A Lakshminarayana et al [4] conducted a parametric study to understand the behavior of material by considering its failure load variations with parameters like cut-out orientation, cut-out size and plate thickness. The finite element method based software tool ANSYS was used to observe the progressive
failure under uniaxial compression load. Two types of cut-out shapes i.e. circular and elliptical were studied in detail. The failure started at first ply near the sharp edges of the cut-outs followed by matrix failure, fiber breakage in the intermediate plies and ended with rupture of last ply. Tsau et.al [5] used Hashin's failure criteria to study the damage initiation and progression when biaxial tensile load was applied on composite laminate with circular hole. Yi Liu et al [6] developed a fixed grid evolutionary structural optimization method to optimize the cut-out shape and understand the material response to single and multiple cut-outs. Stacking sequence, multiple cut-out interaction and circular and elliptical shaped cut-out impacts on composite behavior was studied. A significant stress concentration improvement and reduction in cut-out caused failure was observed and the mutual interactions between cut-outs were ignored. The angle ply laminates were found to be most suitable for cut-outs and the bidirectional composite laminates gave highest performance with diamond cut-outs as compared to other shapes. M Mohan Kumar et al [7] performed a parametric study on metals having different shaped cut-outs oriented at different angles and having variation in bluntness ratio. Sharp edges were observed to be the damage initiation sites where stress concentration was very high. The stress concentrations were also increased as the angle of orientation was moved far from the direction of load. SudhirSastry Y.B. et al [8] conducted a modal analysis on a fuselage structure and recorded the response by changing the materials like aluminum, glass fiber/epoxy composite and carbon fiber/epoxy composite and by changing the cut-out shapes and ply orientations. Anand A et al [9] used ANSYS software to analyze the stress distribution and deformation in glass/epoxy composite having multiple circular cut-outs. He observed that the increase in size of a cut-out increases both stress and deformation. A.R. Abu Talib et al [10] studied the response of Kenaf29 fiber/epoxy composite laminate incorporated with hole under tensile and compressive loading. Both experimental and analytical methods were used to understand the nature of failure in the region enclosing the cut-out. The effects of fiber orientation were also studied. A Khechai et al [11] studied the strain distribution around circular, square and rectangular cut-outs in aluminum and unidirectional E-glass composite laminates. Both experimental and numerical analysis was conducted to understand the response of metals and composites by varying the shape and fiber orientation and diameter to width ratio. DIC technique was used to note the strain distributions while testing the materials under tension. Satish D. Watsar et al [12] performed experimental and finite element investigation on ability of load bearing and stress concentration around various shaped holes. Plates with circular cut-outs were found to be most efficient. I.M. Daniel [13] summarized the failure mechanisms of fiber reinforced composites under various loads like longitudinal tension, longitudinal compression, transverse tension, transverse compression and in-plane shear. The effect of ply stacking sequence, hole diameter and lamination geometry and biaxial stresses was also considered. S.P. Nag et al [14] performed an experimental and finite element study to analyze the reaction of composite laminate made of 2/2 twill weave T300 carbon fiber and epoxy when variation in the hole geometry was done. Fiber breakage criterion was proposed to study the failure due to notch. It was observed that the stress concentration is directly proportional to hole diameter. The small hole specimens showed stress concentration in longitudinal fibers whereas large hole specimens showed a minor shift of stress concentration near the hole edge. It was also observed that the laminate with larger hole fractured early. PVN Likhith et al [15] studied the experimental response of glass fiber epoxy laminate to tension load when notches like square and circle were introduced. It was showed that laminates with circular cut-out can withstand more loads as compared to laminates with square cut-out.

2. Materials and Methods

2.1 Production of laminated plate

In this work, an attempt has been made to study the material behavioral changes as combination of cut-outs exists along centerline of the direction of load application. Three shapes i.e. circular, square and diamond are considered in this study. These cut-outs were introduced in the glass fiber/epoxy laminates and tensile tests were conducted to note the response of laminates. This study helps the designer to understand the impact of multiple cut-outs on tensile strength and provide deep insight into the failure response of composites under tension.

GFRC (Glass Fiber Reinforced Epoxy Composite) was fabricated at RPI, Bangalore by following combination of hand layup and vacuum bagging techniques. E-Glass 300gsm fibers were used as
reinforcement phase and combination of LY556 and HY951 were used as the matrix phase. Resin to hardener ratio was maintained as 10:1.

The alternate laying up of bidirectional E-glass fiber fabrics and resin-hardener mixture resulted in a composite laminate of 500 mm* 500 mm* 2 mm. The rollers were used after each layer to remove excess resin and entrapped air by uniformly distributing resin throughout the surface. Curing was achieved by vacuum bagging process at room temperature for 24 hours followed by heating at 100°C for 2 hours. Mylar sheets were used as the bottom and top cover of the lay-up to provide good surface finish. Prepared laminate is shown in figure 1.

![Prepared Laminate](image1.jpg)

**Figure 1.** Prepared Laminate

### 2.2 Preparation of test specimens

After fabrication, the laminate was checked for visible defects and any other non-uniformity at the surface. The 500 mm* 500 mm laminate was then cut into various parts of 25 mm width and 250 mm length by using abrasive water jet cutting method. The cutting process involves the cutting of materials by a high stream water jet coming out through a narrow orifice nozzle. This smooth cutting operation resulted in good surface finish and negligible micro-damages. Water jet cutting operation is shown in figure 2 (a) and cut specimens are shown in figure 2 (b).

![Water jet cutting operation](image2a.jpg)
![Cut specimens](image2b.jpg)

**Figure 2.** (a) Water jet cutting operation (b) cut specimens

For creating cut-outs on the surface, firstly the center of the specimen was marked followed by marking of cut-out centers at equal distance from the center of specimen. Then the holes were created by using a vertical drilling machine pointed 3.2 mm drill bit at the centerline of the specimen and square, diamond cut-outs were also initiated by creating the hole with a small drill. After introduction
of holes, edges of the square and diamond cut-outs were marked with pen on the surface. Edges were then filed with fine files to give cut-outs shape of square and diamond. All the cut-outs have same area.

Aluminum grips were then provided at the specimen edges. A 500 mm * 500 mm, 1 mm thick aluminum sheet was first marked with lines and divided it into various parts of area 50 mm * 25 mm pieces. Then the manual cutting machine was used to cut the pieces in marked dimensions. After cutting the aluminum pieces were slightly hammered to flatten any uneven surface. Then the surface friction was increased by making random patterns on the surface with a thick needle. The aluminum tabs were joined by applying suitable adhesive and pressure at the specimen edges for 24 hours. The drilling on composite surface and cutting of aluminum sheet is shown in figure 3 (a) and (b).

![Figure 3](image)

**Figure 3.** (a) Drilling on composite surface (b) Cutting of aluminum tabs

3. Experimental Set-up

Experiments were conducted on all the specimens with the help of 400 KN Universal Testing Machine. Before starting the test, digital computer was connected to the machine and input data of the specimen was filled in computer to obtain corresponding output values. Firstly, the screws of the upper jaw were opened to fit one edge of the specimen till grip end and after that screws were tightened with suitable key. Then the upper edge of the machine was brought closer to fit the other end of the specimen in lower jaw. The gauge length of specimen was maintained as 150 mm. Once the specimen was fixed, tensile load was applied gradually to pull the specimen and corresponding stress-strain values were shown on computer screen. The test ended when the specimen failed by sudden rupture. Tensile test set-up is shown in figure 4.
4. Results and Discussions

Results are obtained for each group specimens carrying three identical composite specimens having combination of cut-out shapes (i.e. diamond and square; square and circle; and diamond and circle) present along the centerline of the specimen in direction of load application. The results are presented in the form of stress-strain curves obtained during tensile testing. The failure behavior of the specimens was observed by capturing the pictures of damaged specimens after test. The individual, averaged and maximum tensile strength values of all the specimens are shown in table 1. Results of three groups (CS, CD and SD) of specimens are summarized in it.

CS (circle-square) cut-out group contains a total of three specimens, each having circle-square cut-outs present at their center. It has been indicated from the results that the CS1 has highest tensile strength of 0.317 kN/mm² as compared to CS3 and CS2 whose strengths are 0.300 kN/mm² and 0.289 kN/mm² respectively. CS 1 has highest area of resistance to load as its thickness is higher than other two specimens. So, the load bearing capacity of CS1 is greater than CS2 and CS3 specimens.

CD (circle-diamond) cut-out group consists of three specimens, each having circle and diamond cut-outs presence at their center. Results have shown that both CD1 and CD3 have tensile strength 0.288 kN/mm² and they also have same area of resistance. CD 2 is less thick than CD1 and CD3, so its strength is also lower i.e. 0.279 kN/mm²:

SD (square-diamond) cut-out group also contains three specimens, each with square and diamond cut-outs at their center. SD1 has highest area of resistance, so it has highest strength of 0.284 kN/mm² as compared to other two specimens SD 2 and SD3. SD2 has lowest strength among all three specimens (SD1, SD2 and SD3) as its area of resistance is lowest.

So, it has been clearly shown that if area of resistance is more, strength of the composite is also high and vice-versa.

| Specimen | Dimension (width*thickness) (mm²) | Ultimate Strength (kN/mm²) | Average Ultimate Strength (kN/mm²) | Maximum Ultimate Strength (kN/mm²) |
|----------|----------------------------------|-----------------------------|-----------------------------------|-----------------------------------|
| CS1      | 2.3 x 25                         | 0.317                       |                                   | 0.317                             |
| CS2      | 2.0 x 25                         | 0.289                       | 0.302                             |                                   |
| CS3      | 2.1 x 25                         | 0.300                       |                                   | 0.317                             |
| CD1      | 2.1 x 25                         | 0.288                       | 0.285                             | 0.288                             |

Figure 4. Tensile test setup
The stress-strain curves of all the specimens are of similar nature. Three phases are observed in the curves i.e. first phase shows linear increase in stress and strain which shows the elastic nature of the material (till first damage), second phase shows the plastic deformation (damage initiation and propagation) and third phase shows the rupture (final damage). There is sudden drop in the curve which was the response corresponding to rapid accumulation of damage and failure in brittle fashion. The stress-strain curves of fiber glass epoxy composites having combination of circle-square cutouts, circle-diamond cut-outs and square-diamond cut-outs are shown in figure 5-7. The points corresponding to first damage and final damage are marked in all curves and area between these two points shows the elongation of material.

| Specimen | Dimension (width x thickness (mm²)) | Ultimate Strength (kN/mm²) | Average Ultimate Strength (kN/mm²) | Maximum Ultimate Strength (kN/mm²) |
|----------|-------------------------------------|-----------------------------|-----------------------------------|-----------------------------------|
| CD2      | 2.0 x 25                            | 0.279                       |                                   |                                   |
| CD3      | 2.1 x 25                            | 0.288                       |                                   |                                   |
| SD1      | 2.1 x 25                            | 0.284                       |                                   |                                   |
| SD2      | 1.9 x 25                            | 0.273                       | 0.278                             | 0.284                             |
| SD3      | 2.0 x 25                            | 0.278                       |                                   |                                   |

Figure 5. Stress-strain curves of fiber glass epoxy composites having combination of circle-square cut-outs

Figure 6. Stress-strain curves of fiber glass epoxy composites having combination of circle-diamond cut-outs
Figure 7. Stress-strain curves of fiber glass epoxy composites having combination of square-diamond cut-outs

The stress-strain curves nature is similar to the one shown by A Khechai [11] for [90]-symmetric laminates having a notch at center. The first damage followed by rapid plastic deformation resulted in final damage. Failure behavior observed resembles the results of composites under tension load in studies of I.M. Daniel [13]. All specimens failed at the region near to the cut-outs. Various types of damages were observed in this region like delamination, fiber breakage, fiber-matrix breakage and micro-cracks.

In the group of composites having circle-square cut-out combination, the failure started in the form of delamination in transverse direction to loading at the lower edge of square, which was followed by crackpropagation towards the circle and finally the material failed by combination of fiber pull-out and fiber- matrix breakage. The group specimens before and after test are shown in figure 8 (a) and (b).

Figure 8. Composite laminates with circle-square cut-out combination
(a) Before Test (b) After Test

The group of composites having circle-diamond and square-diamond cut-out combinations showed similar kind of failure mechanism as the failure occurred near sharp edges of diamond normal to direction of loading. The damage started by delamination at both the edge points. As the load was further increased it was accompanied by micro-cracks, which accumulated very fast and grew in transverse direction.
Finally, the specimen broke into two separate parts having pulled out fibers all over at the separation boundary. These two group of specimen images taken before and after testing are shown in figures 9 (a) and (b) and 10 (a) and (b).

**Figure 9.** Composite laminates with circle-diamond cut-out combination (a) Before Test (b) After Test

**Figure 10.** Composite laminates with square-diamond cut-out combination (a) Before Test (b) After Test

Failures in the vicinity of cut-outs are shown in figure 11-13.

**Figure 11.** Failure mechanisms observed in composite laminates with circle-square cut-out combination
Figure 12. Failure mechanisms observed in composite laminates with circle-diamond cut-out combination

Figure 13. Failure mechanisms observed in composite laminates with square-diamond cut-out combination

5. Conclusions
This research work investigated the response of E-glass fiber epoxy composites with various cut-out combinations under tensile load by conducting the experiments on three similar samples in each group of cut-out combination. This study will help the design engineers to understand the stress-strain response and failure mechanisms of the composites laminates with multiple cut-outs of variable geometric shapes. Similar type of failure was observed around the circular, square and diamond cut-outs as mentioned in previous studies. The group of specimens with circle-square cut-outs (CS specimens) showed the highest tensile strength followed by specimens with circle-diamond (CD specimens) and square-diamond cut-outs (SD specimens). All specimens failed in a brittle manner with very less elongation between points marked with first damage and final damage. The crack was transferred from square’s lower edge to direction along circle’s transverse axis in case of CS specimens whereas in other two cases failure loads were majorly taken by diamond cut-outs which resulted in failure along diamond’s diagonal in horizontal direction.

References

[1] AlaattinAktas April 2011 Failure Analysis of serial pinned joints in composite materials Indian Journal of Engineering and Material Science Vol. 18 pp 102-110.

[2] FarukŞen and Murat Pakdil 2008 Effect of Stacking Sequences on Failure Behavior of Pinned
E- Glass/Epoxy Composite Plates Journal of Polyechnic Vol 11 No 2 pp.147-151.

[3] FarukSen, OnurSayman, ResatOzcan and RamazanSiyahkoc 2010 Failure Response of Single Bolted Composite Joints under Various Preload Indian Journal of Engineering and Material Sciences Vol.17 pp 39-48.

[4] A Lakshminarayana, R Vijayakumar and G KrishnamohanaRao 2016 Progressive failure analysis of laminated composite plates with elliptical or circular cutout using finite element method IOP Conf. Series: Materials Science and Engineering Vol 149.

[5] Li-RenTsau and Plunkett R 1993 Finite element analysis of progressive failure for laminated FRP plates with inplane loading Engineering Fracture Mechanics Vol 45 Issue 4 pp. 529-546.

[6] Yi Liu ,Feng Jin Qing Li 2006 A strength-based multiple cutout optimization in composite plates using fixed grid finite element method Composite Structures Vol 73 Issue 4 pp.403-412.

[7] M Mohan Kumar, Rajesh S, Yogesh H and Yeshaswini B R 2013 Study on the Effect of Stress Concentration on Cutout Orientation of Plates with Various Cutouts and Bluntness International Journal of Modern Engineering Research (IJMER) Vol.3 Issue.3 pp-1295-1303.

[8] SudhirSastry Y.B, Sindhura G and Sarwade A.G 2013 Modal Analysis of Composite Fuselage like structures with cut-outs International Journal of Engineering Research and Technology Vol 2 Issue 11 pp. 3812-3825.

[9] Anand.A and ManjunathaBabu. N.S, Mohan Kumar. K 2016 Stress Concentration Study of Laminated Composite with Multiple Holes by Finite Element Analysis American Journal of Engineering Research Vol 5 Issue-10 pp-238-243.

[10] A.R. Abu Talib , A.A. Ramadhan, A.S. MohdRafie and R. Zahari 2013 Influence of cut-out hole on multi-layer Kevlar-29/epoxy composite laminated plates Materials and Design Vol 43 pp. 89 – 98.

[11] A. Khechai, A. Tati, B. Guerira, A. Guettala and P.M. Mohite 2018 Strength degradation and stress analysis of composite plates with circular, square and rectangular notches using digital image correlation Composite Structures Vol 185 pp. 699–715

[12] Satish D. Watsar, Prof. Ajay Bharule 2015 Stress Analysis of Finite Plate with Special Shaped Cutout, International Journal of Scientific Engineering and Research Vol 3 Issue 4 pp.145-150.

[13] I. M. Daniel 1976 Failure Mechanisms In Fiber-Reinforced Composites Proceedings of ARPA / AFML, Review of Progress in Quantitative NDE.

[14] S.-P. Ng, K.J. Lau, P.C. Tse 2000 3D finite element analysis of tensile notched strength of 2/2 twill weave fabric composites with drilled circular hole Composites: Part B Vol 31 pp. 113–132.

[15] K. Priyajanji, R.Amit Kumar, PVN Likhith 2018 Influence of Circular and Square cutouts
on fiber/glass epoxy composite laminate under tensile loading IJE TRANSACTIONS A: Basics, Vol. 31 No. 1 pp. 104-109.