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Influence of Circular and Square Cut-outs on Fiber Glass/Epoxy Composite Laminate under Tensile Loading

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ABSTRACT

Use of composites for a range of structural application in aircrafts, space-crafts, automobiles, etc., has widely spread in the last few years. Other than weight reduction, cut-outs provide pathways to link different aircraft parts. In this paper, an experimental investigation was conducted to study the effect of a cut-out on the tensile strength of the fiber glass/ epoxy composite plate. Geometry of the cut-out is one of the important factors which can critically alter the mechanical properties. So, cut-outs with various geometrical shapes such as square and circle were introduced in the fiber glass/ epoxy composite plate and tensile tests were performed under ambient conditions. It was determined from the tests that specimens with circular cut-out have higher tensile strength as compared to specimens with square cut-out.

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1. INTRODUCTION

Composite materials have huge demand in the aircraft industry due to their various positive contributions towards mechanical properties like high specific density and high specific strength, low sensitivity to fatigue loads and low weight, etc. Thin and hollow structures provide further reduction in weight of the structure by removal of excess materials. This weight reduction in aerospace industry and automotive industry is achieved by means of providing cut-outs in the structures through which various parts are connected either by wires or other means. Cut-outs are also needed for various other purposes like pathway for mechanical fasteners, repairs and to access damaged areas in the structure. According to the requirements, different types of cut-outs such as square, rectangular and circular are used in various aircraft and automotive components. Cut-outs are also the cause of failure in many components as the stress concentration increases near the cut-out region and cracking occurs.

In past, many researchers have made efforts to understand the mechanical behavior of composite structures in the presence of cut-outs. An experimental and finite element investigation of diverse cut-outs on load bearing capacity and stress concentration reveals that the stress concentration factor of plate with circular cut-out is least among various shapes [1]. A similar analysis performed on steel plate to study the variations in the stress concentration due to presence of circular, square and triangular cut-outs in different orientations divulged an increase of orientation from the base line (x-axis) results in rise in stress concentration. The stress concentration factor and von-Mises stress were found highest in plates with triangular cut-out and least in plates with circular cut-out [2]. In a study related with stress distribution of isotropic and orthotropic plates consisting of various centrally located cut-outs such as circular, square, triangular and hexagonal, it was observed that the stress is highest at the lower corner of cut-out parallel to the applied load. Sharp corners were found to be the cause of high stress concentration in hexagonal and square geometries. The increase in fiber angle resulted in significant reduction of maximum stress [3]. Analytical and numerical models with

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coupled strength and energy criterion were used to analyze the effect of various hole-diameters for both isotropic and orthotropic plates. The strength of all plates decreased with increase in diameter of the hole [4]. A three dimensional finite element method revealed that the stress and strain are not always maximum at the mid plane of the plate and vary with the thickness of the plate [5]. The influence of cut-out on the ultimate failure load of Kenaf 29 fiber/epoxy laminate having different fiber orientation using both experimental and analytical methods were used to understand the criticality of the failure in the nearby region of the cut-out. The fiber orientation affected the ultimate tensile and compressive strength of the laminate [6]. An experimental investigation on the glass/epoxy laminate containing circular cut-out located at the center, and effect of the variations in the size of the cut-out and fiber- angle orientations on the ultimate compressive load was studied as well. It was found that laminate containing small sized cut-out has more load carrying capacity and this capacity decreases as the size of the cut-out increased. The cross-ply laminate can carry more loads under compression as compared to other configurations [7]. The influence of static loading on composite laminate having cut-outs were studied by varying factors like different number of layers, lamination angle and types of composite materials. Both experimental and numerical analysis technique was used to determine the changes in stress-strain under tensile loading. Composite laminate with circular cut-out has least strain and stress [8]. A parametric study on the metal plate containing cut-outs with different geometries such as cut-out orientation from the base line and bluntness ratio were studied and it has been revealed that as the angle of orientation increase from the baseline the stress concentration factor increase along with it and sharp edges provide more stress concentration as compared to blunt edges [9]. Analysis on the thin Fiber Reinforced Polymer laminates under tensile and various other types of loading showed that the failure of all the specimens under tensile load originate from the weakest region. Any kind of defects or flaws can act as the cause of failure of the material/ component. The location of failure relies upon the location of the defect [10]. Various parameters such as abrasive materials, hydraulic pressure, cutting orientation, traverse rate and standoff distance effects the cutting process of glass/epoxy laminate through abrasive water jet cutting operation [11].

The goal of this study is to perform experiments on the woven fiberglass/epoxy laminates with and without cut-outs and observe the variations in the mechanical properties when tensile load is applied under ambient conditions. E-glass cross ply laminates with circle and square cut-outs at the center were used in this study. The circular cut-out has uniform area whereas square cut-out perpendicular to the axial length is studied because stress concentration is more at the corners of the square cut-out taken along the axial length, so the latter position of square cut-out is not expedient. The area of all the cut-outs is constant.

In previous research, the focus was on response of composites with notches under compression loads. This research work is focused on the response of woven glass/epoxy laminates under uniaxial tension. Also, the effect of various types of cut- outs on the load bearing capacity has been discussed.

2. EXPERIMENTAL INVESTIGATION

2. 1. Composite Laminate Fabrication and Preparation of Test Specimens

In this research, E glass fibers were selected to form a bidirectional fabric which has thickness of 0.285mm.The epoxy resin along with hardener in the ratio 10:1 was used to provide a perfect bond between the matrix and reinforcement phase of the fiberglass/epoxy laminate. The thickness of the composite laminate was obtained by stacking the seven alternate layers of E-glass fabric and epoxy resin manually. Curing was performed at room temperature for 24 hours and at 100^{0}C for two hours by using vacuum bag technique. The properties of E- glass fiber and epoxy resin are shown in Tables 1 and 2.

TABLE 1. E-glass fiber properties

S.No.	Mechanical Properties	Values
1.	Density (kg/m^3)	2.6 *10^{-12}
2.	Modulus of Elasticity (MPa)	8.1 *10^4
3.	Poisson’s Ratio	0.23
4.	Bulk Modulus (MPa)	5 *10^4
5.	Shear Modulus (MPa)	3.3 *10^4
6.	Tensile Strength (MPa)	2050
7.	Compressive Strength (MPa)	5000

TABLE 2. Properties of Epoxy Resin (Hardener HY951and Resin LY556)

S.No.	Mechanical Properties	Values
1.	Coefficient of Thermal Expansion (K^{-1})	5.6 *10^{-5}
2.	Modulus of Elasticity (MPa)	3200
3.	Poisson’s Ratio	0.35
4.	Bulk Modulus (MPa)	3.556 *10^3
5.	Shear Modulus (MPa)	1.852 *10^3
6.	Tensile Strength (MPa)	88

Different cutting techniques like laser cutting, plain water jet cutting and abrasive water jet cutting can be used on the graphite epoxy laminates. Due to heat dissipation laser cutting was not preferred as it causes delamination and various other damages to the material. Plain water jet cutting also results in delamination of the materials but it only occurs at very high speeds. In comparison to laser cutting and plain water jet cutting technique, abrasive water jet cutting is favorable because it provides good surface finish and prevents the occurrence of micro-damages. In this work, abrasive water jet cutting technique was implemented to cut all the specimens into the required dimensions. To eject an extremely high velocity jet through a nozzle orifice, highly pressurized water stream was passed through it at the speed of 900m/s. Natural garnet sand particles were mixed in this thin coherent water stream and projected on the surface of the laminate to perform the cutting operation. All the specimens are of thickness 2 mm, their length is 250 mm and width is 25mm. Aluminum tabs are glued at edges of all the specimens to provide proper grip between specimen and the machine jaws. Geometry of the specimens along with aluminum tabs is shown in Figure 1. The same testing procedure is followed through the test as mentioned in the ASTM D3039.

As geometry of the cut-out has great influence on the maximum load bearing capacity of a material or structure, the two most commonly used shapes i.e. square and circle were inscribed in the composite specimens and tests were performed. The failure location changes with variation in the type and size of cut-outs. The ratio of diameter of the hole to the width of the specimen plays important role towards strength variation. The area of both the cut-outs was kept as 8 mm^2.

The specimen property variation is determined by applying tensile load to three categories of specimens i.e. Category 1: Virgin Specimens; Category 2: Centered circular cut-out specimens; Category 3: Centered square cut-out specimens. Each category has 3 specimens and all tests were performed at room temperature. All the specimens are shown in Figures 2-4.

2. 2. Test Procedure and Equipment Used

The test was conducted under quasi-static tensile load for all the specimens.

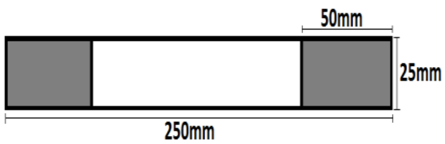

Figure 1. Geometry of the specimen

Figure2. Category 1 Specimens

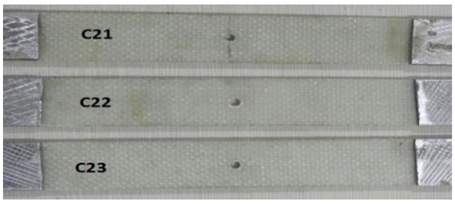

Figure 3. Category 2 Specimens

Figure4. Category 3 Specimens

A specimen was placed between the upper and lower jaws of the hydraulic machine and clamped manually to avoid any slippage during the test. The machine and the specimen setup are shown in Figure 5.

The gauge length was maintained at 150 mm and the load was applied to pull the specimen in y- direction. The load was varied in steps from zero to the point of fracture of the specimen and the corresponding stress-strain curve was obtained from the computer connected with the hydraulic machine. The same procedure was followed to test specimens of all the categories.

3. RESULTS AND DISCUSSIONS

This section presents the results obtained from the experimental investigation of both intact and notched fiber glass/epoxy laminates under tensile load.

Figure 5: Machine and specimen set-up

A total number of nine specimens was tested, which includes three specimens from each category. i.e. 3 virgin specimens, 3 specimens with circular cut-out and 3 specimens with square cut-out.

The results are presentd in Figures 6-8. Figure 6 shows the stress vs. strain curve for Category 1 specimens (C11, C12, and C13). Figures 7 and 8 signify the variation in stress and strain of fiber/glass epoxy laminates in the presence of cut-outs. These figures show stress-strain curve for Category 2 specimens (C21, C22, and C23) and Category 3 specimens (C31, C32, and C33).

For all specimens, stress-strain curves show nonlinearity in the beginning due to fluctuations of loads, and as the machine gets stable, a linear phase is observed until the damage has initiated which is followed by rapid growth and fracture. The properties of all specimens are presented in Table 3.

From the plots and the table it is evident that the Category 1 specimens have the highest strength in comparison with the Category 2 and 3 specimens. So, any kind of cut-out results in the reduction of the strength. Introduction of circular cut-out and square cut-out resulted in approximately 20-25% and 30-35% strength reduction, respectively. Strength is more in specimens having circular cut-outs as compared to specimens with square cut-outs. Strain is greatest in Category 1 specimens followed by category 2 and 3 specimens.

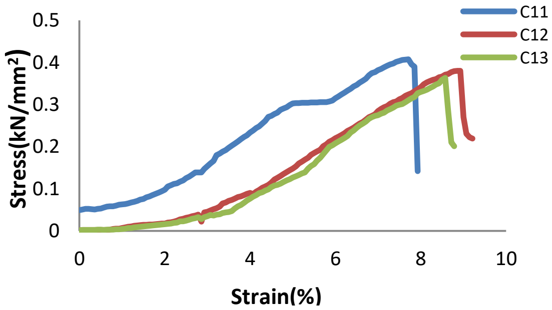

Figure 6. Stress-Strain curve for Category 1 Specimens

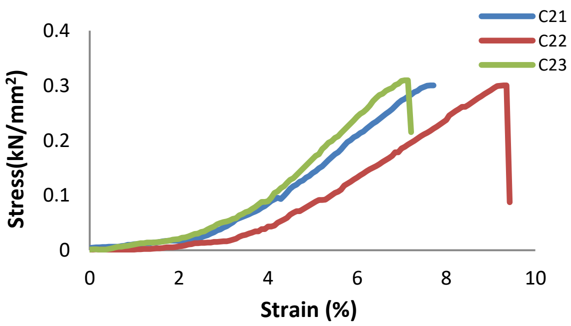

Figure 7. Stress-Strain curve for Category 2 specimens

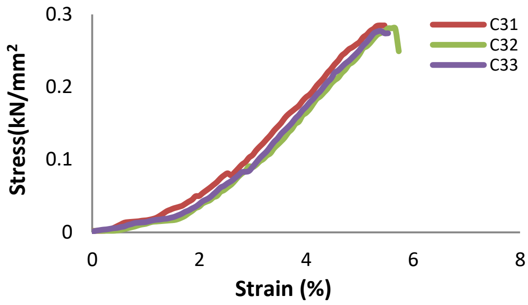

Figure 8. Stress-Strain curve for Category 3 specimens

TABLE 3. Properties of all the Specimens

Specimen	Dimension (length*width) (mm^2)	Ultimate Strength (kN/mm^2)	Strain %	Average Ultimate Strength (kN/mm^2)	Average Strain %
C11	250.15*25	0.395	8.4		
C12	250*25.1	0.407	7.9	0.394	8.5
C13	250.1*249	0.380	9.2		
C21	249.8*252	0.310	7.2		
C22	250.3*249	0.300	7.8	0.303	7.9
C23	250.16*25	0.300	8.8		
C31	250.2*248	0.285	5.7		
C32	250*25.2	0.281	6.1	0.281	5.9
C33	249.9*251	0.277	6		

Failure modes of all configurations are shown in Figures 9-11.

The virgin specimens failed in the region towards the top edge (edge near to application of load) due to greater stress at that particular region. The specimens failed in brittle fashion with fiber pullout and fiber-matrix de-bonding along the fibers.

All notched specimens showed multiple failures at various locations. The entire set of notched specimens showed de-lamination and fiber pullout. In case of circular specimen, the failure occurred in a direction normal to the direction of load.

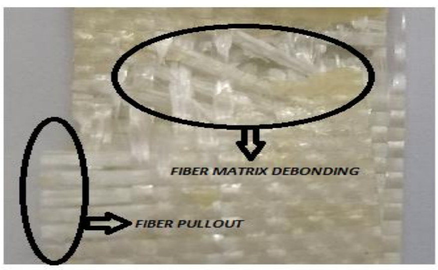

Figure 9. Virgin specimen after failure

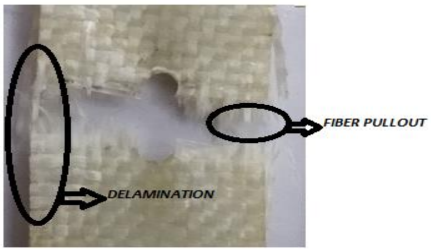

Figure 10. Specimen with circular notch after failure

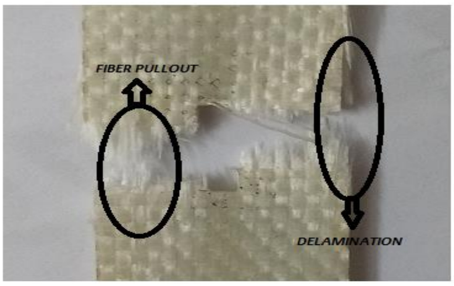

Figure11. Specimen with square notch after failure

In specimens having square notch, the failure started near top right corner and propagated towards the center.

4. CONCLUSIONS

This work provided the essential information to design any component with and without cut-out. It is evident from this paper that the presence of cut-out results in the reduction of resistance to the applied tensile load. Both strength and strain decreases in the order: Category 1, Category 2 and Category 3. Square cut-outs results in greater reduction of the load bearing capacity of fiber glass/epoxy laminates as compared to circular cut-outs, so circular cut-outs are more preferred where usage of cut-out in the structure is inevitable.

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چکیده

استفاده از کامپوزیت‌ها برای طیف وسیعی از کاربردهای سازه‌ای در هواپیما، سفینه‌های فضایی، خودرو و غیره در چند سال اخیر به طور گسترده‌ای گسترش یافته است. به غیر از کاهش وزن، قطعات بریده شده روش‌هایی را برای اتصال قطعات مختلف هواپیما فراهم می‌کنند. در این مقاله، یک مطالعه‌ی تجربی برای بررسی تأثیر شکل برش بر روی مقاومت کششی ورق کامپوزیت شیشه الیاف/اپوکسی انجام شده است. هندسه‌ی برش از عوامل مهمی است که می‌تواند خواص مکانیکی را به طور چشم‌گیری تغییر دهد. بنابراین، قطعات بریده شده از صفحه‌ی کامپوزیتی فیبر شیشه/اپوکسی با اشکال هندسی مختلف مانند مربع و دایره انتخاب و آزمایش‌های کششی تحت شرایط محیطی انجام گرفت. از این آزمون‌ها مشخص شد که آزمونه‌های با برش دایره‌ای دارای استحکام کششی بالاتر نسبت به نمونه‌هایی با برش مربع هستند.

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