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# Effect of Buckling on Glass Fiber/Epoxy Plate

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**Abstract:-** This study presented an experimental study of the behavior of woven glass fiber/epoxy with ply orientation (+45º/-45º/+45º)s composite laminated panels under compression. Compression tests were performed on to eighteen fiber-glass laminated plates with and without different shapes of cut-outs using the compressed machine. The maximum load of failure for each of the laminated plates under compression has been determined experimentally. A parametric study was performed as well to investigate the effects of varying the centrally located holes and notches cut-out. These results indicated that a cut-out can have a significant effect on buckling, fracture and energy absorption response of a compression-loaded panel. The results indicated that the plates without cut-out exhibited higher fracture load and energy absorption than plates with cut-out.

**Keywords:-** Glass fiber/epoxy; Composite laminated panels; Cut-out; Buckling.

## I. INTRODUCTION

Many studies on woven fabric (textile) composite laminated structures have been carried out due to their increasing use in many engineering fields such as aerospace, marine structures, automobiles, civil, biomedical, sports equipment and mechanical engineering. One of the most important reasons for using composite materials is that these materials have resistance under buckling loads. The laminated composite structures have been investigated to determine their buckling loads, generally using rectangular plates. If a hole has geometrical differences, it is difficult to obtain the buckling load of the plate. Cut-outs are often found in composite structures. These are provided in structural components for ventilation and sometimes to lighten the structure. In aircraft components (such as wings, spars, fuselage and ribs) cut-outs are necessary for access, inspection, electric lines and fuel lines or to reduce the overall weight of the aircraft.

Most structures are assembled by a number of individual structural elements connected to form a load path. These connections or joints, in general, can be classified as adhesively bonded, mechanically fastened (bolted or riveted) or a combination of both. Mechanical joints usually have some type of bolt holding the different pieces of the structure, which needs a hole to be drilled into the composite laminate. Besides this, the hole in the structural laminate can serve as an access area of any purpose. The prediction of the notched strength of a given laminate has been extensively studied in the last three decades. Most of the analytical solutions and experimental investigations concentrated on wide laminates with a hole. Research into the implications of unequal rivet load distribution in the failures and damage tolerant design of metal and composite civil aircraft riveted lap joints has been conducted by Sathiya et al. [1]. Meanwhile, stress concentration and buckling behavior of shear loaded composite panels with reinforced cut-outs were studied by Guo [2]. Load - displacement behavior of glass fiber/epoxy composite plates with circular cut-outs subjected to compressive load was experimentally investigated by Hakim et al. [3], while the buckling of tension-loaded thin-walled composite plates with cut-outs was studied by Kremer and Schürmann [4].The buckling behavior of 1×1 rib knitting laminated plates with cut-outs has been proposed by Mevlüt and Mehmet [5]. However, in their study the laminates with and without holes were investigated. Buckling load factors have been determined for different aspect ratio by Nagendra et. al. [6]. He found that buckling load factor increases as the aspect ratio increases up to 1.11, then the buckling load factor decreases, with the increase of aspect ratio. He mentioned that buckling load factor decreases up to d/D ratio equals to 0.25. The mechanical behavior of unidirectional fiber-reinforced polymer composites subjected to tension and compression perpendicular to the fibers is studied using computational micromechanics by Lei et. al. [7].

This manuscripts presents an experimental study of the behavior of woven glass fiber/epoxy with ply orientation (+45º/-45º/+45º)s composite laminated panels under compression.

## II. METHODOLOGY

### A. Open Mould Processes

Only one mould surface was used in the open mould process. This single mould represented the glass table surface and the matrix materials used were thermosetting resins of epoxy, while the reinforcement materials used was E-glass fibers. Depending on the desired thickness (4.2 mm), the matrix resins and the reinforcement fibers were applied to the mould surface layer by layer; hand lay-up process was applied in this work. The fiber reinforcement was used in the form of woven roving. After the lay-up process, the curing treatment would be necessary for rigid thermoset matrices. Depending on the type of resin used, a little pressure was necessary during curing figure. Figure 1 shows Schematic Diagram for Open Mould Process.

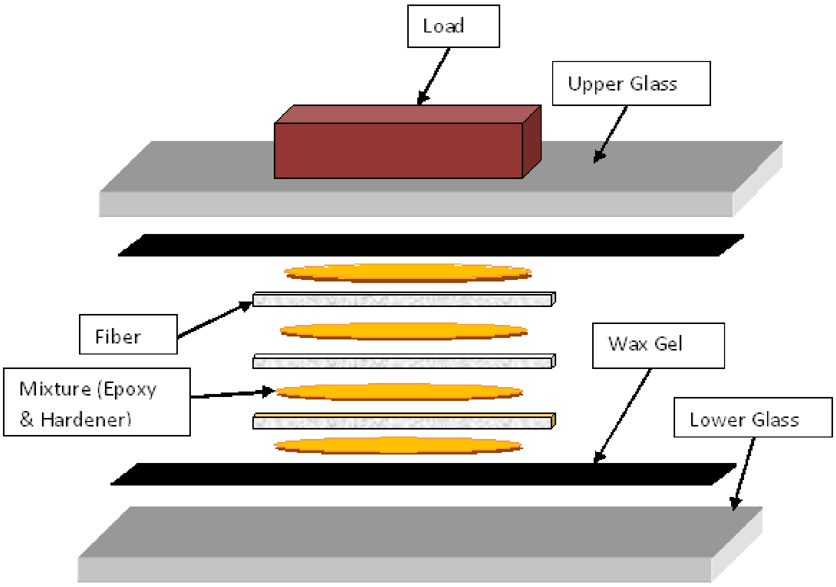



**Fig. 1** Schematic Diagram showing the Open Mould Process

The first step of the hand lay-up process was cleaning the surface of the mould, followed by the application of a release agent for ease of part removal. In the second step, a thin gel coating was applied to the outside surface of the mould because the surface quality of the product was important. The gel coating resin was performed pellicularly, it was applied to the mould by using a piece of sponge.

The third step began when the gel coat was partially set. The sample was laid-out between two glass plates by laminating the mixture onto the fibers layer-by-layer, in this hand lay-up step, as the name suggested the resin and fiber forms were manually applied to the open mould as successive layers, the resins were generally catalyzed by hardeners and accelerators.

Each layer was consolidated by a roller to ensure that the resin impregnated the fiber and that any air bubbles that were present were removed as this would otherwise decrease the mechanical strength of the final product depending on the thickness of the product. Alternating layers of resin and reinforcement may be added. After each new layer had been added, it was rolled out manually. The fourth step was the curing stage which was applied in order to harden the part. During curing, the liquid or viscous form of the matrix resin transformed into a hardened rigid state due to the extensive cross linking of the thermosetting polymeric structure. Time, temperature and pressure were the three main parameters influencing the degree of cross linking in the curing process. In thermosetting the resins, curing would start at room temperature, which was rather slow. Increased temperature will decrease the time necessary for the curing process to be completed.

In the present study, the time necessary was (24 hours) with room temperature at (25°C). A little pressure was necessary during curing by applying a flat glass surface to ensure all layers would stick together and to make the specimen surface flat and smooth. In the fifth and final step, the component was removed from the mould, and the big sample was then ready for trimming and other surface finishing processes.

Seven big rectangular plates of glass fiber/Epoxy with (+45°/-45°/+45°)s orientation were ready for the finishing and cutting process into 21 specimens that the buckling tests would be applied on them after the cut-out process for the 18 specimens and three specimens have remained without cut-out. The sizes of the form of the specimens that were needed should be marked out in this step using a marker pen in order to cut them accurately and perfectly. By using the cutting in the workshop, the cutting processes should be done carefully, bearing in mind the safety instructions on each machine. Each plate had lines that were made earlier during the required sizes of the specimen. By cutting the plates according to these lines would form the specimens. After the cutting process, the measurement of the dimensions for each specimen would ensure that all the dimensions were the same for all each specimen.

Twenty one specimens of glass fiber/Epoxy with (+45°/-45°/+45°)s orientation were ready for the cut-out process in order to cover all the factors which were required to compare amongst them in this work. The part to be cut consisted of straight lines, a hole and curve geometry which was drawn using the AutoCAD drafting software. This 2D drawn design was exported into the (.dxf file) format and was used in the Zech Laser machine software in order to generate the cutting path. . Six shapes of cut-out were marked out; each shape of the cut-out had 3 specimens as shown in Figure 2 and Figure3. The shapes of the cut-out of plates are:

1) Plate with a circular hole cut-out
2) Notched plate with half circular cut-out
3) Plate with square hole cut-out
4) Notched plate with half square cut-out
5) Plate with rhombus hole cut-out
6) Notched plate with half rhombus cut-out.

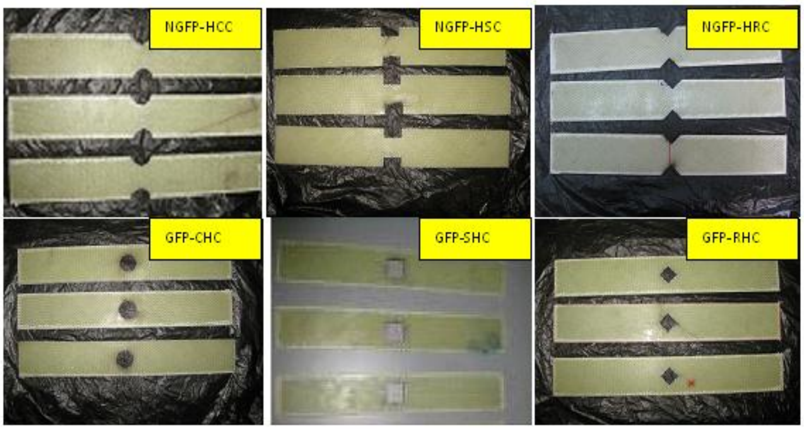



**Fig. 2** Typical Photograph, the Shapes of Cut-out of Glass Fiber/ Epoxy

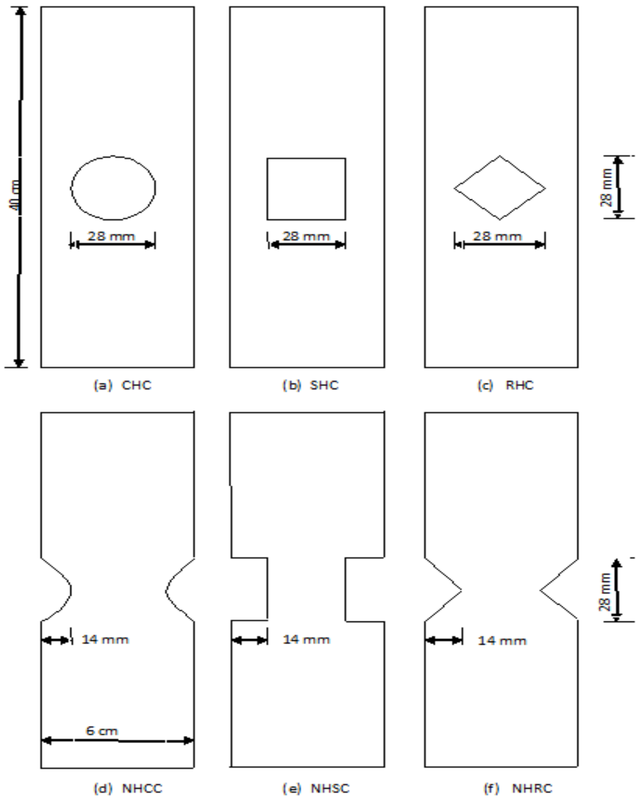



**Fig. 3** Schematic to Cut-outs Dimensions by Using Laser Machine

**B. Energy Absorbed (EA)**

The total energy absorbed (EA) is represented by the area under the load/displacement curve, and it can be obtained from the equation:

$$EA = \int_{S_i}^{S_f} F_{av} ds \Rightarrow F_{av}\left(s_f - s_i\right)$$

Where $F_{av}$ is the mean failure load and ($S_f$, $S_i$) are the final and the beginning of the failure distance respectively (the distance of the plastic zone). The units of EA are in kJ. To simplify the calculation, the area under the curve can be divided into two regions.

Firstly, the energy absorbed in the elastic region (EEA) can be calculated by finding the area of the triangle which is formed by the two perpendicular sides $F_i$ and $S_i$, as shown in Figure 4. The area can be calculated from the equation:

$$EEA = \frac{1}{2} \times F_i \times S_i$$

where $F_i$ is in kN, and $S_i$ is in meters, thus, the results are in kN.m (kJ).

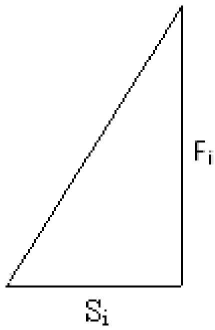



**Fig. 4** Schematic diagram to the Area of the EEA

The total work (Wt) is represented by the area under the load/displacement curve, and can be obtained numerically by integrating the load displacement curve.

$$W_t = \int_{s_i}^{s_f} P \, ds$$

where $P$ = Load

$S_i$ = Beginning of axial distance

$S_f$ = Final axial distance

Secondly, the energy absorbed in the plastic region (PEA) also plays an important role. The post-crush stage is generally more important due to its strong influence on the energy absorption parameters. Therefore, the work done at the plastic stage ($W_P$) can be calculated as;

$$W_P = \int_{s_p}^{s_f} P \, ds \Rightarrow P_m\left(s_f - s_p\right)$$

where $P_m$ = Load at the plastic stage

$S_f$ = Final axial distance

$S_p$ = Axial distance at the beginning of the plastic stage

**C. Buckling Test**

The perforated and un-perforated, glass fiber/Epoxy laminated plates were subjected to a uniform uniaxial compression load, $P$ in the $y$-direction. The lower and upper horizontal edges of the plate were clamped into the clamping zone of the INSTRON machine. The depth of the plate which was clamped both at the top and bottom of the test samples were $d_1$=$d_2$=80mm and the active length was 240mm.

The two unloaded vertical edges were unconstrained from the transverse in-plane motion, which was defined as a movable edge or free support. In all cases herein, the cut-out boundary was a free edge as well. The test sample must be put in the center of both the upper and lower clamping zone, aligned with the $P$ in the $y$-direction in order to give an accurate loading result. As prescribed, the same initial setting of the machine was set to all compression tests before the testing, in which the crosshead speed was 10 mm/min and data collection rate (capture rate) was 8 pts/sec. The loading rate depends on the machine which did not exceed 50 kN. The test and data collection would be stopped once when the sample was broken.

For the buckling behavior of each specimen, photos were taken at several stages through the crushing process. These photos gave a clear idea of the way and stages for the failure mode of each specimen as illustrated in Figure 5. In addition, these photos would give a close look for the mode of failure whether it was a matrix cracking, a fiber delamination or a combination of these types. The data acquisition system which was linked with the INSTRON machine was used to record all the necessary results (including the maximum load, average load, displacement, stress, strain, energy absorption and useful related mechanical properties). After all the buckling tests were completed, all the data were taken from the computer by using a floppy disk and all the reports were printed out directly after each test.

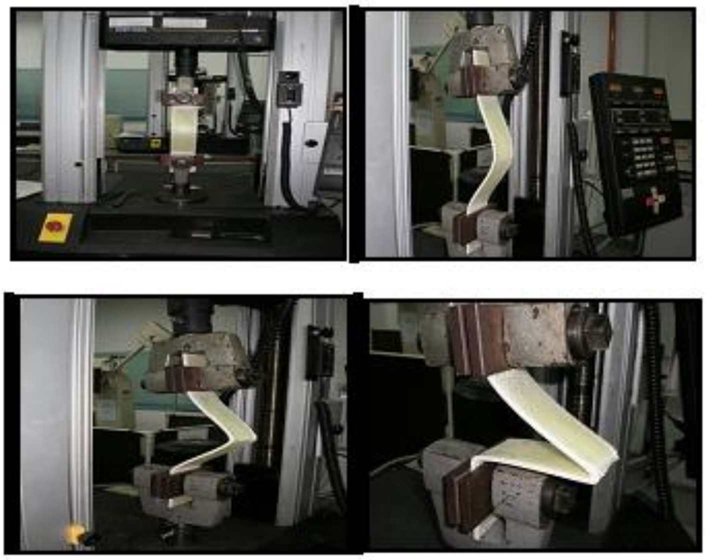


**Fig. 5** Failure History of the ±45° PGFP

## III. RESULTS AND DISCUSSION

From the experiment, it was found that the ±45° Notched Glass Fiber Plate with the Half Rhombus Cut-out can carry a higher load before the fracture load of (2.11KN) as compared to the other types of the notched plates and the ±45° Glass Fiber Laminated Plate with a Circular Hole Cut-out can carry a higher load before the fracture load of (1.82kN) as compared to the other types of the central cut-out plates. It has also been found that the ±45° glass fiber laminated plate without any cut-out records the highest fracture load value compared to the plates with the cut-out. Figures 6 and Figure 7 show the fracture load of the ±45° glass fiber laminated plate.

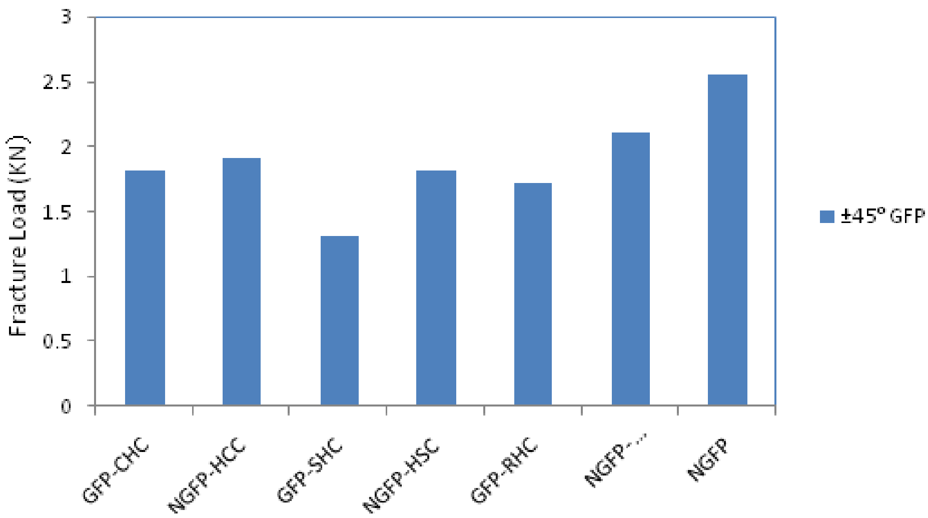



**Fig. 6** Fracture Load (KN) of ±45° GFP

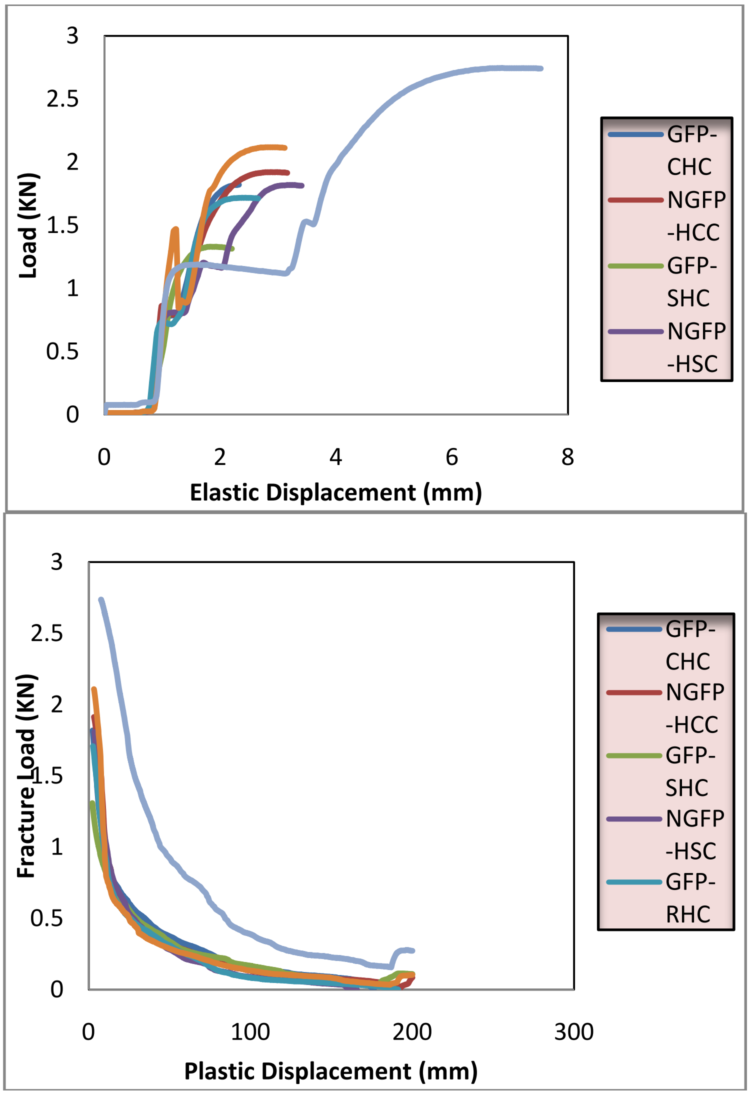



**Fig. 7** Fracture Load (KN) of ±45° GFP – Elastic and Plastic Zones

Figure 8 shows the load-displacement curve of the central circle cut-out glass fiber laminated plate of the ±45° orientation angle, and from this Figure the curve can be divided into two main parts; 1) the first part represents the elastic zone and 2) the second part shows the plastic stage. It can be seen from Figure 9(a) that the elastic part can be divided into four zones. The first zone of (1-2) shows the pre-bucking zone which represents the linearity of the curve, whereby the plate is still without any failure, and the load is applied starting from 0kN until it reaches the critical load (Fcr) of 0.7799kN. In this zone the specimen supports an increasing load in a linear form till it reaches the critical load (Pc). From the critical load zone of (2-3), the micro-cracks in the matrix phase begin to grow, causing the curve to fluctuate slightly after which the (3-4) zone of the elastic part appears in the post-buckling zone. In this zone a slight delamination occurs in the structure of the plate, leading to the buckling failure. In this zone the load increases again because the fiber supports the structure and as it recovers from the micro-cracks in the epoxy and delamination, due to the elastic behavior of the material, any point of the curve in this zone would return to the origin if the specimen is unloaded. From the same Figure the influence of delamination increases and the fiber layers start to fracture in the (4-5) zone, leading to the slight fluctuation of the curve until the load reaches the maximum value of 1.82kN, which represents the fracture load (Ffr).

Figure 9(b) shows the plastic behavior of (5-6). The curve then drops sharply due to the fiber layers having been completely fractured with the extensive fiber failure in the cut-out area associated with the loss in stiffness, at which the fiber fracture results in the catastrophic failure of the laminated panel. These catastrophic failures appear to be caused by the interlaminar, intralaminar and crack failures which initiate the near high strain concentrations on the free edge of the circular cut-out panel.

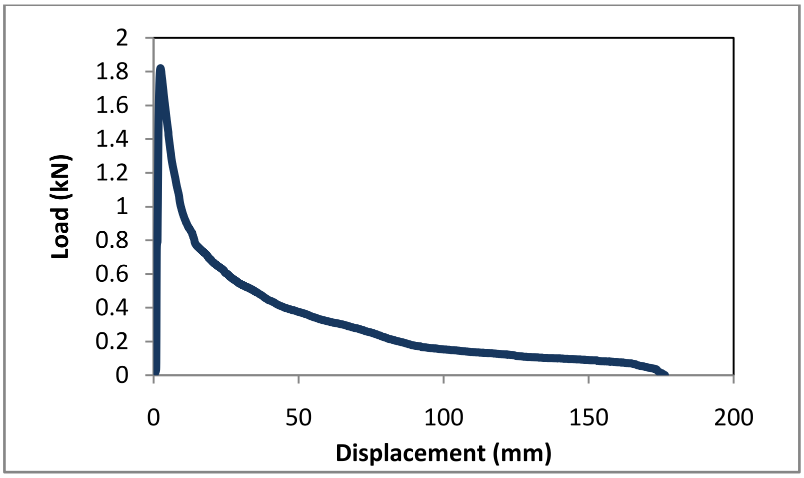
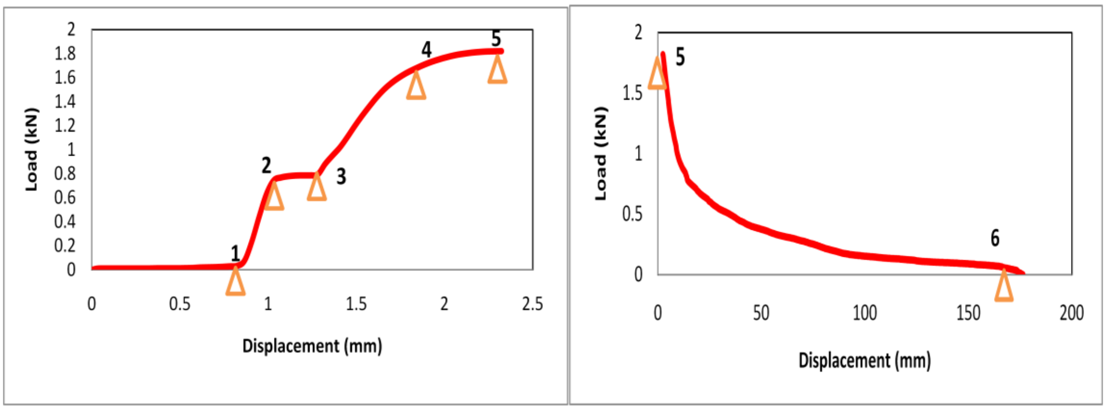



**Fig. 8** ±45° Load-Displacement Curve GFP-CHC




(a) Elastic Area (b) Plastic Area

**Fig.** 9 Different Sections of Elastic and Plastic Curves for the ±45° GFP-CHC Specimen

Figure 10 shows the load/displacement curve of the ±45° notched glass fiber plate with half a rhombus cut-out. It is evident from this figure that the curve can be divided into two rejoins the elastic and plastic region. The elastic region shown in Figure 11a, it is divided into four stages. The first stage of (1-2) displays the pre-buckling behavior which starts from 0KN up to the critical load (Fcr) of 1.466kN whereby at this stage the initiation and growth of the matrix crack in the cut-out area of the laminated plate occurs as there is no stiffness reduction observed. The matrix cracks initiate other damage mechanisms, such as the delaminations in which case the crack initiates only a small delamination in the cut-out area causing the curve to fluctuate slightly after which the curve rises again in an elastic and linear behavior as shown in stage (3-4). The influence of the initiation and growth of the delamination combined with the interaction of the matrix crack increases in stage (4-5), leading to the fiber fracture at load ($F_{fr}$) of 2.111KN.

The plastic rejoin then appears of (5-7) as shown in Figure 11b. Sudden and dramatic drop occurs indicating a fiber fracture which visually appears on the wall of the specimen at the edge of the cut-out of the specimen due to the high strain concentrations on the free edge of the cut-out which then propagates as shown stage (5-6).

As the load continues to be applied, the graph shows a downward fluctuation caused by the propagation of the fiber fracture and delaminating failure to the neighboring layers which still have higher stiffness than the upper layers as shown in stage (6-7). It has been found that the NGFP-HRC records the highest value of the buckling load as compared to the different shape cut-out groups of the ±45° glass fiber laminated plates.

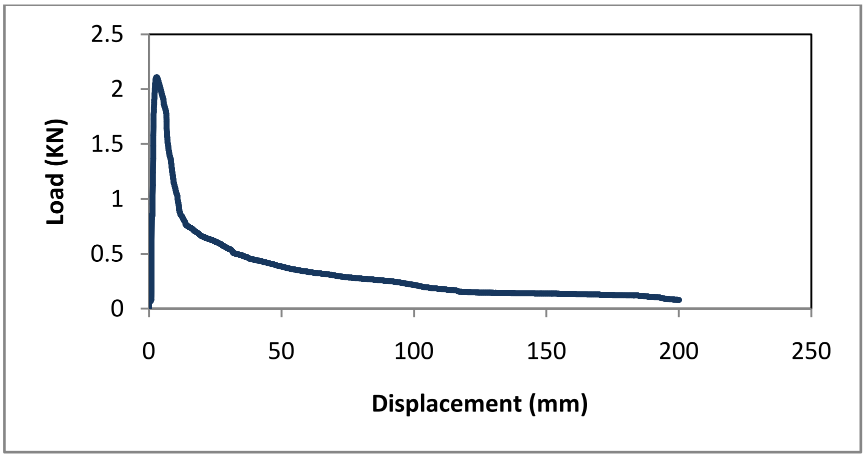
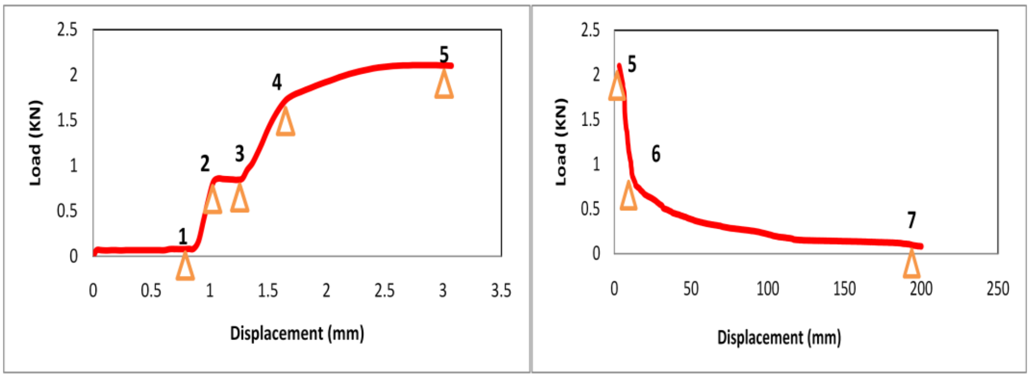



**Fig. 10** ±45°Load-Displacement Curve NGFP-HRC




(a) Elastic Area (b) Plastic Area

**Fig. 11** Different Sections of Elastic and Plastic Curves for the ±45° NGFP-VSC Specimen

Figure 12 shows the energy absorption of the ±45° glass fiber laminated plates. It has been found that NGFP significantly records a higher value of (208.86J) as compared to the glass laminated plates with the various cut-out shapes The results show that the energy absorption of the fiber-reinforced composite plates is found to be sensitive to the change in the cut-out shapes and which was attributed to the change in the stress concentration, elastic stiffness, buckling and the fracture behavior. The ±45°NGFP-HCC records highest value of energy absorption of (100.4336J) as compared to the ±45° notched plates and ±45°GFP-CHC records highest value of energy absorption of (95.2815J) as compared to the ±45° centrel cut-out plates.

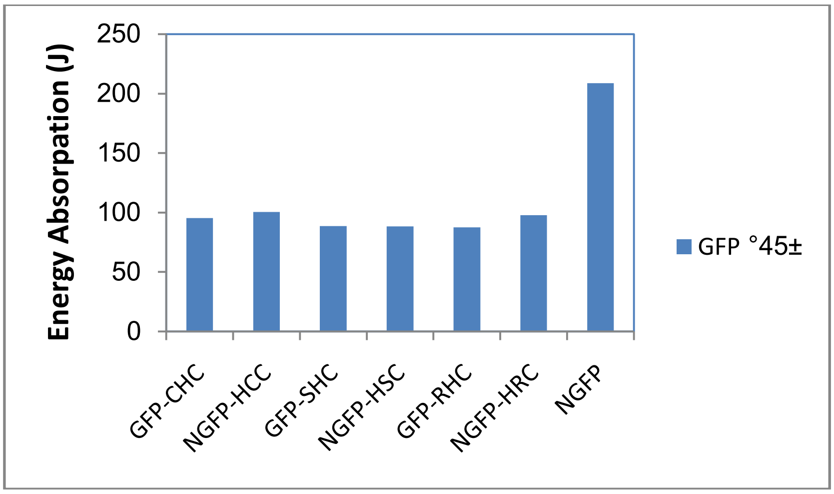



**Fig. 12** Energy Absorption for ±45° Glass Fiber Plates

## IV. CONCLUSION

Geometric discontinuities cause an object to experience a local increase in the intensity of a stress field. Cut-outs cause stress concentrations in the cross sectional area of the structure.
High local stresses can cause the structure to fail more quickly than if it isn't there. Engineers must design the geometry to minimize stress concentrations.

Buckling and Fracture load of laminated composite plates with various cut-out shapes had been investigated under an axially compressive load, a parametric study was performed to investigate and compare the behavior and the fracture load of each of the fiber-glass laminated plates by varying the cut-out shapes The comparisons of the fracture loads and the energy absorption are made among the ±45° glass fiber laminated plates and that with different cut-out shapes have also been investigated.

**Nomenclature**

| | |
|---|---|
| PGFP | Normal Glass Fiber/Epoxy Plate without Cut-out |
| GFP-CHC | Glass Fiber/Epoxy Plate with a Circular Hole Cut-out |
| NGFP-HCC | Notched Glass Fiber/Epoxy Plate with Half Circular Cut-out |
| GFP-SHC | Glass Fiber/Epoxy Plate with Square Hole Cut-out |
| NGFP-HSC | Notched Glass Fiber/Epoxy Plate with Half Square Cut-out |
| GFP-RHC | Glass Fiber/Epoxy Plate with Rhombus Hole Cut-out |
| NGFP-HRC | Notched Glass Fiber/Epoxy Plate with Half Rhombus Cut-out |
| EA | Total Energy Absorption |
| P | Load |
| Fav | mean crushing load |
| EEA | Elastic Energy Absorption |
| $F_i$ | Initial Failure Load (Fracture Load) |
| $S_i$ | Beginning of axial distance |
| Wt | Total Work |
| $P_m$ | Load at post crush stage |
| $S_f$ | Final axial distance |
| *Sp* | Axial distance at post crush stage |
| $W_P$ | work done at post crush stage |
| PEA | Plastic Energy Absorption |
| SEA | Specific energy absorption |
| M | Mass |

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