Technical Report

Load–displacement behavior of glass fiber/epoxy composite plates with circular cut-outs subjected to compressive load

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A B S T R A C T

An experimental study of the behavior of woven glass fiber/epoxy composite laminated panels under compression is presented. Compression tests were performed on 16 fiber-glass laminated plates with and without circular cut-outs using the compressed machine. The maximum load of failure for each of the glass-fiber/epoxy laminated plates under compression has been determined experimentally. A parametric study was performed as well to investigate the effects of varying the centrally located circular cut-out sizes and fiber angle-ply orientations on to the ultimate load. The experimental work revealed that as the cut-out size increases, the maximum load of the composite plate decreases. Also, it has been observed that cross-ply laminates possess the greatest ultimate load as compared to other types of ply stacking sequences and orientations.

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1. Introduction

In recent years, it would appear that progress has been in the development of engineering advanced materials, especially composite laminated materials. Many studies on the woven roving fabric (textile glass fiber material fabrics woven from continuous filament in roving form with 0/90 degrees) composite laminated structures have been carried out due to increasing use in many engineering fields, such as aerospace, marine structures, automobiles, civil, biomedical, sport equipments and mechanical engineering. Cut-outs commonly appear in the structures due to the requirement of stability maneuverability, low weight optimization and accessibility of other systems. During operation, these structural elements may experience compressive loads and thus lead to buckling and post buckling. Their buckling and post buckling behaviors play an important role in determining safe operating conditions and effective designs for these structures. Woven fabric composite laminated structures are one of the famous and common structures used in the engineering field. Woven fabric glass-fiber is a way of weaving by interlacing the fiber-glass thread of the weft and warp on a loom. Their attractive properties such as light weight, high strength, high stiffness, low density and low fabrication cost attracted many researchers and designers’ attentions. They also possess excellent damage tolerance and impact resistance.

Several studies have been performed previously using woven fabric composites. Work by de Freitas and Reis [1] showed the failure mechanisms on composite specimens subjected to compression after impact. The delaminated area of composite panels due to impact loading depends on the number of interfaces between plies and it influenced more on the buckling failure mechanisms than stacking sequences. Several investigations have been done by Walker, Hilburger et al. and Ghannadpour et al. [2-4] showed the buckling behavior of composite laminated panels with cut-outs under compression. The buckling behavior is affected by the cut-out size, panel curvature, boundary conditions and ply angles. Christopher and Steven, David, Buyukozturk et al. [5-7] studied the effects of fiber orientation on compressive strength of composite laminates. These works has implications in the selection of composite failure criterion for compression performance and the selection of laminate architectures for optimum combinations of compressive and shear behaviors. Kuo et al. [8] investigated the responses of three-dimensional carbon/carbon composites under axial compression and transverse shear. By using a 3D weaving technique, two types of performances with different bundle sizes of the weaving yarns were prepared for assessing its influence on the failure behavior. Another study by Takeda et al. [9] developed the progressive failure methodology for glass/epoxy plain weave fabric-reinforced laminates subjected to tensile loading under cryogenic temperatures. Kelkar et al. [10] examined the biaxial braided carbon/epoxy composites with different braid angles (25°, 30°, and 45°), carbon/epoxy unstitched, stitched and Z-pinnded plain (woven composites) under tension and compression fatigue loading for aerospace appli-
cations. Zhu et al. [11] presented an experimental study of in-plane large shear deformation of woven fabric composite. During the test, the cross-sectional profiles of fabric samples were traced, helping to build up a theoretical model of the composite sheets during their large shear deformation. Further researches such as Naik and Venkateswara [12] investigated the high strain rate behavior of composites under compressive loading by using compressive split Hopkinson pressure bar (SHPB). It showed that the compressive strength is enhanced at high strain rate loading compared with that at quasi-static loading. Yin et al. [13] conducted compressive after impact test to evaluate mechanical performance of the laminated composites before and after crack healing. High performance composite components often consist of layers (or “plies”) of unidirectional FRP stacked in a specified sequence to form a laminate construction. Both the orientation (with respect to any loading) of the fibers in a given layer as well as the relative orientation of successive layers within a laminate, can significantly affect a component’s mechanical properties. Liu, Li, Fan and Sun [14] found obvious differences in dynamic behaviors and susceptibility to adiabatic shear band (ASB) for different specimen. In the 0° plies specimen, no localized flow is observed. The specimen of 45 degrees exhibit slight localized shearing and the specimen of 90 degrees localized ASB was firstly observed at an angle of 45 degrees with respect to the fibrous orientation followed by cracking, which is greatly desirable for kinetic energy penetration applications.

The main objective of this study is to carry out the experiment analysis for the woven glass fiber/epoxy composite laminated plates with and without holes subjected to quasi-static compressive load. The ultimate load and material behavior of the composite laminated plates under compression have also been studied. Finally, a parametric study is performed to investigate the effect of varying the fiber orientations and different central holes sizes onto the strength of the laminates.

The findings of this paper give an increased understanding of the behavior of woven glass fiber/epoxy composite laminated panels under compression loading. This knowledge will assist engineers, researchers and composite community that using composite material for automotive and aerospace industry it is very attractive to be the main structures for many components.

### 2. Specific energy absorbed (SEA)

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

$$W_t = \int_{S_p}^{s_f} P \, ds$$  \hspace{1cm} (1)

Where $P$, $S$, and $S_p$ are the load, beginning of axial distance and final axial distance respectively. The post-crush stage is generally more important due to its strong influence on the crashworthiness parameters. Therefore, the work done at post crush stage ($W_p$) can be calculated as;

$$W_p = \int_{S_p}^{s_f} P \, ds \Rightarrow P_m(s_f - S_p)$$  \hspace{1cm} (2)

Where $P_m$ is the mean load at post crush stage, $S_f$ is the final axial distance and $S_p$ is the axial distance at post crush stage.

The specific energy absorption (SEA) is a good indicator of the energy absorption capability of composite structures. The specific energy absorption per unit mass (kJ/kg) may be made from the following expression:

$$\text{SEA} = \frac{W_p}{M}$$  \hspace{1cm} (3)

where $M$ is mass of specimen.

### 3. Experimental work

#### 3.1. Preparation of test samples

Sixteen glass fiber/epoxy flat samples with and without centrally located circular cut-outs which consist of six layers and different fiber orientations were fabricated using the hand lay-out technique and were cured at room temperature. Six layers were chosen due to optimum design thickness requirement of the compression test machine, possessing good mechanical properties and symmetrical maneuverability. Increasing the number of layers leads to increasing in thickness of sample. The hand lay-out technique is described as following steps as per one big sample (fixed on one stacking sequence and fiber orientations only): (a) six layers fiber of desired stacking sequence and fiber orientations are cut. (b) A mixture of epoxy and hardener is made following the ratio 4:1, and the volume of this mixture must be controlled as the same for other big samples are made, to control the thickness of samples. (c) The sample is laid-out between two glasses by laminating the mixture onto the fibers layer-by-layers. (d) The big sample is fabricated after the drying process is finished. (e) The individual plates then are cut from the big sample plate, and fabricated into testing size and shape. (f) The central holes are made by using drilling machines -upped with holesaw, with three different sizes where the diameters are fixed at 22 mm, 28 mm, and 38 mm respectively; the drilling speed must be maintained at 350 RPM for all the samples and all the drilling velocities same for three different holes diameter. The stacking sequences and fiber orientations studied are as follows: $[0°/+90°/0°], \ [0°/60°/30°], \ [90°/45°/0°], \ [45°/−45°/45°]$, and $[45°/−45°/45°]$. There are two precautions that must be alerted to in the hand lay-out technique in order to ensure consistency of their physical and mechanical properties: (1) was using the same volume of mixture to lay-out each big sample to maintain the same thickness of the samples. (II) Ensuring that the fiber orientations are exactly consistent during the hand lay-out process to avoid losing their mechanical properties. Fig. 1 shows the fabricated specimen whereby Fig. 2 illustrates the geometry of glass fiber laminated plates containing a central circular hole with length $l$, of 400 mm, width $w$, of 60 mm, thickness $t$, of 5.8 mm, and holes diameter $D$. The plates without holes have the same dimensions and geometry as that of the plates with holes.
First, all the sixteen specimens (fiber-glass laminated plates) are prepared for running the compression test. The geometry of the specimen, the boundary conditions and the load conditions are as discussed previously. The testing facility (INSTRON machine) has been used for all the compression tests and is shown in Fig. 4. Hydraulic clamping device is used to clamp both ends of the plate during compression. As prescribed, the same initial setting of the machine were set to all compression tests before the testing, in which the crosshead speed was 5 mm/min and data collection rate (capture rate) is 4 pts/s. The loading rate depends on the machine which is not exceeding 50 kN. The test and data collection will be stopped once when the sample is broken. Fig. 5 shows an enlarged schematic drawing of buckling mode of the test specimen during the compressive test performing. The data acquisition system which was linked with the INSTRON machine was used to record all the necessary results (including maximum load, average load, displacement, stress, strain, energy absorption and useful mechanical properties).

4. Results and discussion

The experiment was performed under quasi-static compressive loading for all the sixteen glass fiber panels up to final fracture. It has been observed that all the laminated plates buckled globally until complete fracture occurred as expected. Fig. 6 shows the final deformed and damaged shapes of all the plates after the compression tests. Figs. 7–10 show the comparison of load versus displacement curves for all the fiber-glass laminated plates, with and without holes, different holes diameters and different angle orientations. It is interesting to note that all the laminates behave in a similar fashion whereby their behavior is almost linear before reaching the peak load. On the other hand, beyond that peak points of the load–displacement curves majority of the laminates experienced large displacements before fracture, which proved that these woven laminates are able to absorb large amounts of energy before fracture. For all cases the symmetric angle ply laminates of [(0°/90°/0°)], underwent the largest inelastic deformation before failure. These findings suggest that this type of ply configuration is capable of absorbing large amounts of energy before fracture, where the energy absorbed is given by the area under the load–displacement curve. A similar trend has been observed from the experimental results, in which the ultimate load of the plate with angle orientation of [0°/90°/0°], has the highest value, followed by angle orientations of [0°/60°/30°], [90°/45°/0°], and [45°/−45°/45°], comparisons made within their same hole sizes’ group. It has also been observed in Figs. 7–10 that the laminates can carry the higher load before buckling when the holes size decreases. Findings showed that the maximum load decreases when the holes size increases because losing mass and area of the structure will lower the strength stability to resist the external and internal force. Table 1 summarizes the ultimate loads and specific energy absorption capabilities for all the laminates with the four different types of stacking sequences and cut-out sizes. The results have revealed that fiber orientation directly affects the distribution of load between the fibers and the matrix. The contribution of the fibers to the composite properties is a maximum only when they are aligned parallel to the loading direction. Another finding showed that 0° and 90° ply play an important role in contributing the maximum load in the combination due to direct resistance to the loading. Meanwhile, the 30°, 60°, 45° or −45° ply performed the lower maximum load because of their arrangement in the composites. However, the 30°, 60°, 45° or −45° ply has good performance to resist the in-plane shear load or stress.

3.2. Experimental setup

The fine or perforated fiber-glass laminated plates are subjected to uniform uniaxial compression load, \( P \) in \( y \)-direction as shown in Fig. 3. The lower and upper horizontal edges of the plate are clamped into the clamping zone of the INSTRON machine. The depth of the plate which is clamped both at the top and bottom of the test samples are 70 mm. The two unloaded vertical edges are unconstrained from the transverse in-plane motion, which is defined as a moveable edge or free support. In all cases herein, the cut-out boundary is 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 \( y \)-direction in order to give an accurate loading result. The testing conditions will be discussed below:

![Fig. 1. Test specimens.](image)

![Fig. 2. Geometry of fiber-glass laminated plate with central hole.](image)
Fig. 3. Load and boundary conditions of the test specimen.

Fig. 4. INSTRON machine.

Fig. 5. Schematic of plate's buckling mode during the compressive test.
5. Failure mechanism

Failure mechanism after the buckling impact is an important study for the engineers and designers. Figs. 11–14 show the photomicrograph (50 ×) to show the failure modes of each of the specimens with different stacking sequences. Under the unidirectional longitudinal compressive load, most of the test specimens had undergone the same failures. These failures are including broken fibers, debonding, matrix cracking, delamination, notch and then going to fail. Only for those plates with [45°/−45°/45°/45°/−45°/45°] angle orientations, fibers broken is few to happen due to the fibers perform the microbuckling in shear mode. For known, the fiber and the matrix are carrying the load when subjected to compressive load. If the fiber carrying load is exceeding its strength, first fracture of the fiber is expected to occur. The like for the matrix, a crack is formed at the fiber break area when the compressive load carried by the matrix exceeds its uniaxial strength. If the load is subjected continuously, the debonding will occur because of insufficient fiber/epoxy bond strength. Near the free edge, delamination also occurs due to low bonded strength. Some notches will form at the edge or surface of the plate as well, where usually happened in the imperfection area of the plate.
Fig. 8. Load–displacement curve of the composite plates ($D = 28$ mm) with different angle orientations.

Fig. 9. Load–displacement curve of the composite plates ($D = 38$ mm) with different angle orientations.

Fig. 10. Load–displacement curve of the composite plates (without central hole) with different angle orientations.
Table 1
Ultimate loads and energy absorption of the glass fiber/epoxy laminates.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Central hole diameter size (D)</th>
<th>$P_{\text{max}}$ (kN)</th>
<th>$P_{\text{avg}}$ (kN)</th>
<th>$S$ (mm)</th>
<th>$W_t$ (J)</th>
<th>SEA (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0°/90°/0°],</td>
<td>Without hole (mm)</td>
<td>6.2585</td>
<td>2.5023</td>
<td>52.7662</td>
<td>132.0369</td>
<td>0.631</td>
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<tr>
<td>22</td>
<td>5.8438</td>
<td>2.4295</td>
<td>34.7604</td>
<td>84.4504</td>
<td>0.410</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>5.4224</td>
<td>2.2455</td>
<td>35.0368</td>
<td>78.6751</td>
<td>0.383</td>
<td></td>
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<tr>
<td>38</td>
<td>4.0975</td>
<td>1.7652</td>
<td>36.3502</td>
<td>64.1654</td>
<td>0.321</td>
<td></td>
</tr>
<tr>
<td>[0°/60°/30°],</td>
<td>Without hole (mm)</td>
<td>5.7322</td>
<td>2.4300</td>
<td>46.4215</td>
<td>112.8042</td>
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<td>22</td>
<td>5.2595</td>
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<td>4.7533</td>
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<td>50.3712</td>
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<tr>
<td>[90°/45°/0°],</td>
<td>Without hole (mm)</td>
<td>5.0429</td>
<td>2.2164</td>
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<td>38</td>
<td>3.2764</td>
<td>1.2282</td>
<td>39.7767</td>
<td>48.8537</td>
<td>0.229</td>
<td></td>
</tr>
<tr>
<td>[45°/45°/45°],</td>
<td>Without hole (mm)</td>
<td>3.8456</td>
<td>1.8821</td>
<td>56.0230</td>
<td>105.4409</td>
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Fig. 11. Failure mechanism of plates with [0°/90°/0°/90°/0°] angle orientation.

Fig. 12. Failure mechanism of plates with [0°/60°/30°/60°/0°] angle orientation.
6. Conclusions

An experimental study of the behavior of the woven glass/epoxy laminated plates subjected to quasi-static axial compressive load has been presented. Sixteen fiber-glass laminated plates were fabricated. They are separated into four different angle-ply orientations groups. Each of the groups consists of one fine plate and three different holes sizes plates. The ultimate load of the woven fiber-glass laminated plates under quasi-static compression load was found. A parametric study was performed to investigate and compare the behavior and the ultimate load of each of the fiber-glass laminated plates by varying the central holes sizes and fiber angle-ply orientations respectively. The comparisons of ultimate load are made among the plates with the same angle-ply orientations with different center holes sizes; contrastive and comparisons of ultimate load among the plates with the same center holes sizes with different angle-ply orientations. From the experiment, it was found that the cross-ply laminated plates possess the highest ultimate load as compared to the other types of orientation angles and ply stacking sequences, and the plates can carry the higher load before the initial buckling failure when the holes size decreases.

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References


