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COMPARATIVE STUDY OF CROSS-PLY LAMINATED COMPOSITE MATERIALS AND EFFECT OF BUCKLING RESPONSE WITH AND WITHOUT CUTOUTS

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In this work, finite element analysis has been done along with experimental test and conducted using numerical and experimental tests of the buckling response of quasi-static compressive loading of six layers woven cross-ply laminated composite material [0º/90º/0º] with centrally square and circular cutouts. The effect of cut-out shape and its size with a buckling load were obtained experimentally and numerically. Compression experiment has been performed by using INSTRON machine, and the experimentally obtained buckling loads are compared with a numerical results obtained by ANSYS simulation program. Both experimental and numerical results are showing good agreement. It is noticed that the buckling load of the composite plate has been decreased with the increasing of the size of cutout. The cutout area, cutout ratio (d/w), fiber weight, plate thickness and fiber type of the plate has a major effect to the load of the cross-ply laminated composite plates.

Keywords: cut-out, composite plate, buckling load, compression and cross-ply laminated

1 INTRODUCTION

Rapid growth and increasing demands of the transportation and manufacturing industries, most of the products are fabricated by the advanced materials especially fiber reinforced composites, to meet the requirements of advanced design, cost saving and physical and chemical properties (for the safety reasons). long fiber composite reinforced were used by several researchers such as Sandeep Olhan et al, they are studied behavior of the composite materials of long glass fiber were carried out using (SEM-scanning electron microscope) method, a brittle failure and deformation as noticed by fiber and micro cracks [1]. Thus the use of composite materials is experiencing a widely and fast developing progress in some industries like aerospace, marine, automotive, biomedical, civil, military services and so on as a results of their excellent mechanical properties such as high strength (strength-to-weight ratio), high stiffness, high tear resistant, ease to handle and low fabrication cost [2-4]. Those industries have driven much of the development of our most sophisticated composite systems being used nowadays. Another interesting study of composite tailoring is cutout perforation on the structure. Cut-outs are oftentimes used in composite material. These materials are provided in composite structural components for isolation and ventilation, stability maneuverability and sometimes for lightening the structure.

For instance, aerospace applications such airplane components like fuselage, wing, ribs and spar where cut-outs are required for installation, inspection, accessing, of hydraulic and electric lines, fuel lines as well as to minimize the weight of these aircraft [4]. Through the operation, these devices and elements may exposure to compressive loads and lead to buckling mode and post buckling. For this, Hakim S. sultan Aljibori et al. studied structural system instability and load-displacement behavior that is becomes a main attention in safe design and reliable of the composite structures. Composite laminated structures are one of the well-known and popular structures used in the most of applications especially in engineering field. Woven roving fabric fiber is a way of texture by tangle the fiber thread of the weft and warp [5]. The attractive mechanical properties and the buckling of such perforated structure or making a hole in these plates have interest of many researchers over the last years. Many researchers have obtained the behavior of buckling mode of composite laminated plates as an experimentally, analytically and finite element analysis. Xu et al. [3] studied the effect of stability of curved woven roving composite materials by utilized linear and non-linear analysis. Another work of finite element method was presented by Jain and Kumar [4], they studied of advance or post buckling effect of symmetric laminates with a central cut-out under axial compression load. It is observed that the parameters like cut-out size, shape and the position of the cutout that have a essential influence on the buckling loads, first failure loads and strength of the composite laminates. Hakim et al., and Ghannadpour et al. [5,6) investigated the buckling mechanism of the laminated composite plates with elliptical and circular cut-outs subjected to compression test. Both studies have showed that the effects of shape and size cut-out as well as plate fiber orientations, stacking sequences and boundary conditions have a huge effect on the buckling behavior of the plates. Several numerical investigations have been done by Özben, T. Kremer et al., Zhong et al. and Aydin Komur et al. [7-10] to determine the buckling load of the composite plates with various boundary conditions and cutouts under varying in-plane load. The exist of cut-out in the composite plate has the consequential effect on the buckling load of the plates during compression. Züleyha Aslan & Sahin M. [11] reported numerically and experimentally investigations the effects of delamination mode with multiple large delamination on the critical load and compressive failure load of fiber/epoxy composite laminates. They discovered that the delamination size near-surface influences the buckling load and compressive failure load of composite structure, however, the size of underneath delamination has no considerable effect at all. Compressive buckling studies on composite plate using metal matrix composite also studied by M. Fateh. Altan & M. E. Kartal [12] also investigated under biaxial static compression loading, the changes of buckling factors of symmetrically laminated plates with central rectangular hole reported by Damodar R et al. [14], they studied the buckling behavior and failure analyses of compression-loaded quasi-isotropic curved panels with and without cutouts. Results acquired are depended on the presence of cutout. Another finite element analysis work was done by Mevlüt Tercan & Aktas M. [15] to investigate the cutout affects (including elliptical, central circular/ rectangular or square cutouts) shapes on the buckling of knitting glass/epoxy composite laminated plates. It has shown that the buckling loads depend on the level of tightness and the cutout area. Besides the influential parameters affect the buckling behavior of the composite plates as discussed above, the effect of various woven densities of the fiber to the buckling load is another interesting subject to examine. This research has been studied experimentally by Osman Asi [16]. The objective of current study is to study the load-displacement behavior and buckling load of the cross-ply laminated plate with a centrally circular/square cutout under quasi-static loading experimentally and computationally. The effects of cut-out shape, cutout size, type of fiber and fiber thickness have been studied. Finally, the experimental and computational results have been compared to carry out an ideal agreement. The findings of this paper have given a great exposure of knowledge to the engineers or designers dealing with the selection of the materials in order to utilize the composite materials economically, maintainability, safety optimization and reliability.

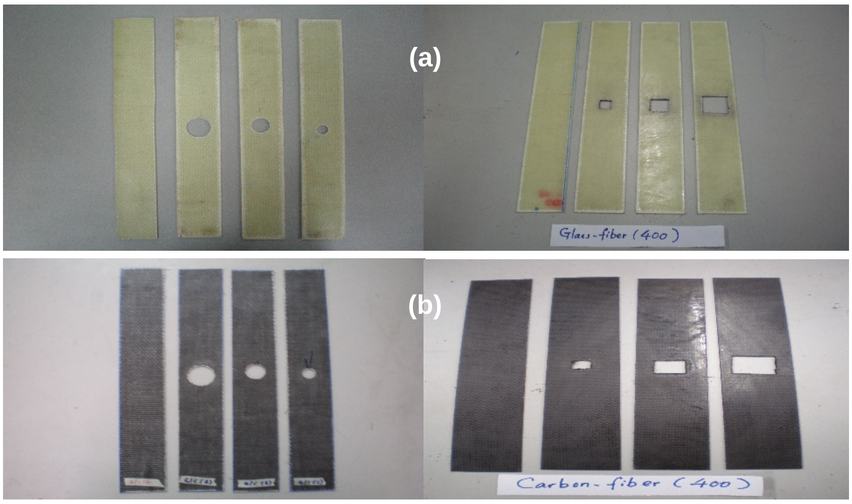
2 EXPERIMENTAL WORK

2.1 Laminated composite plates Fabrication

The cross-ply laminated plates consist of six layers of fibers are oriented symmetrically at [0˚/90˚/0˚] s stacking sequence and were manufactured by using hand lay-out technique. Four types of fibers were selected to fabricate laminates. The used fibers were E-glass fiber 600 g, E-glass fiber 400 g, carbon fiber 400 g and Kevlar-29 200 g. Epoxy resin with hardener liquid was prepared and mixture in the mass ratio of 4:1. The lamination process is started by impregnating the fibers layer-by-layer with the epoxy. The fibers were laminated on a smooth glass surface with another smooth glass pressed on the top of the laminates. After the impregnation, a constant pressure of 4kPa was applied on the laminates for 24 hours at room temperature for the curing process. After the curing process, the laminates were taken out and cut into pieces of test size and shape. The central circular cutout sizes were chosen as 16 mm, 26 mm and 36 mm and the cutouts were made by a drilling machine equipped with hole-saw. The central square cutout sizes were selected as (16 × 16) mm, (26 × 26) mm and (36 × 36) mm and the cutouts were fabricated by using the CNC laser machine. Figure 1 shows the plates without and with three different sizes of central circular/square cutouts: (a) E-glass fiber, 400gram composite plates. (b) Carbon fiber, 400gram composite plates and (c) Kevlar-29, 200gram composite plates. Figure 2 explains the shapes of laminated composite plates with a central circular and square cutout. The cutout diameter (d) for circular of 400mm, Length (L) for square cutout of 400mm and width w of 60mm. Thickness of the plates are followed by their fiber types and weights individually.

2.2 Determination of the Mechanical Properties

Mechanical properties of current composite plates are procured under quasi-static conditions according to the standards of ASTM. The tensile test was performed by using INSTRON Testing Machine (Figure 3) with a load capacity of 50kN at a cross-head speed was 1mm/min. Three specimens from each fiber type composite plates were used for testing. The average mechanical properties obtained from the experimental results are listed in Table 1. In this table, Ex, Ey and Ez are Young's modules corresponding to x, y and z planes; Gxy, Gyz and Gxz are the shear modules corresponding to x-y, y-z and x-z planes respectively; and Prxy, Pryz and Prxz are Poisson's ratios.



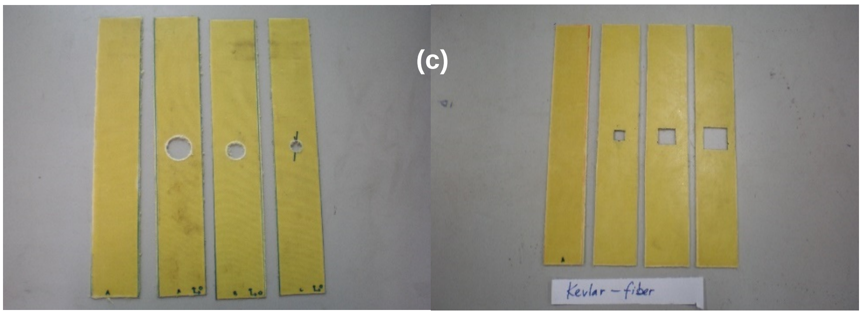


Fig. 1. Test specimens of laminated composite plates without and with three different sizes of central circular & square cutouts: a) Glass Fiber, Carbon Fiber and Kevlar Fiber

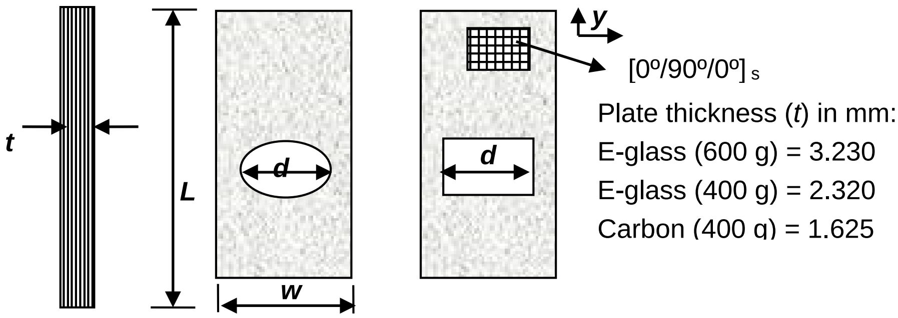


Fig. 2. Schematic Diagram of Geometry of laminated composite plate

Table 1. The mechanical properties of laminated composite plates

	Ex (GPa)	Ey (GPa)	Ez (GPa)	Prxy=Pryz=Prxz	Gxy=Gyz=Gxz (GPa)
E-glass (400 gram)	72.40	7.10	7.10	0.22	2.40
Carbon (400 gram)	224.00	14.00	14.00	0.20	14.00
Kevlar-29 (200 gram)	61.00	4.20	4.20	0.35	2.90

2.3 Experimental buckling test

The laminated composite specimens were subjected to quasi-static test with a compressive loading. The loads were applied in axial direction by INSTRON machine (Figure 3) with load capacity of 50kN and the specimens were clamped between two clamping devices, lower device was stable in position during the test, while the upper device was forced to move downwards. The depths of clamping for the test specimens at the upper and lower zones were 70mm and the cutout boundary was a free edge. For all the specimens, the same initial settings of the machine are set before the test, such as the crosshead speed was fixed at 10mm/min and the data capture rate was 4pts/sec. the buckling process and the actual pre-buckling deformation of the composite plate and Schematic diagram test of plate are shown in Figures 4 and 5.

Fig. 3. Testing machine with data acquisition

Fig. 4. Buckling process and deformation shape of a laminated composite plate during compression test

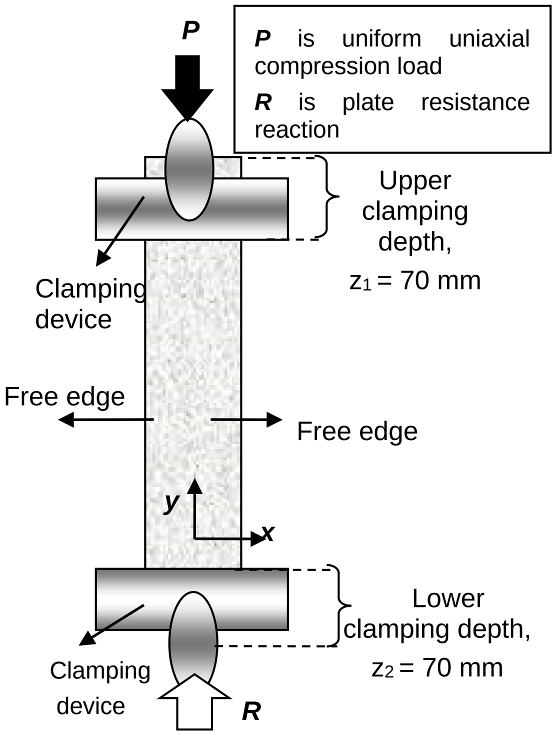


Fig. 5. Schematic Diagram of Compression Loading and boundary conditions

3 NUMERICAL BUCKLING ANALYSIS

In the current study, Eigen-value buckling analysis was carried out for the composite structure as plates with and without central circular and square cutouts. These plates were analyzed using numerical ANSYS software. The load was found by resolve the eigen-values and the eigenvectors that represented the buckling mode. Figure 6 display the boundary conditions with the typical meshing considered the same as experimental conditions. SHELL 99 with six degree of freedom was selected as the element type along with elastic structure and orthotropic material. Real constant was defined by entering the values of number of layers, fiber angle orientations and thickness of ply. To simulate and explain the clamped loaded edges, the displacement of X, Y, Z and the rotations RX, RY, RZ (Figure 6) of all nodes were equal to zero. Figure 7 explain the number of plies, fiber orientations and thickness of composite laminates. To mesh the shell, free and mapped meshing with “concatenating” operation was used. Better meshing skill was important to yield better and accurate results. The meshing of the test specimens was illustrated in Figure 8 by the ANSYS program. To apply loading on top of shell, a unit pressure was utilized along with the upper nodes. To perform Eigen-buckling, pre-bucking system was switched on and extraction mode operated before proceeding to final result. Finally, the buckling load of the first buckling mode was normally always as our favorite result.

Figure 6 displays the boundary conditions with the typical meshing of laminated composite plate, Figures 7 and 8 represented the number of plies, fiber orientations and thickness of composite laminates and the meshing of test specimens with and without cutout.

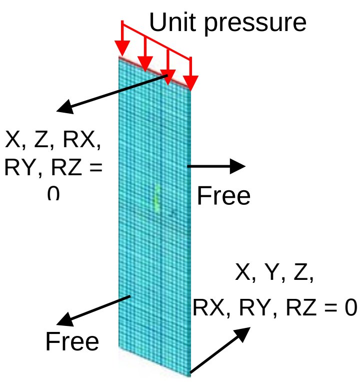


Fig. 6. The boundary conditions of laminated composite plate with typical meshing

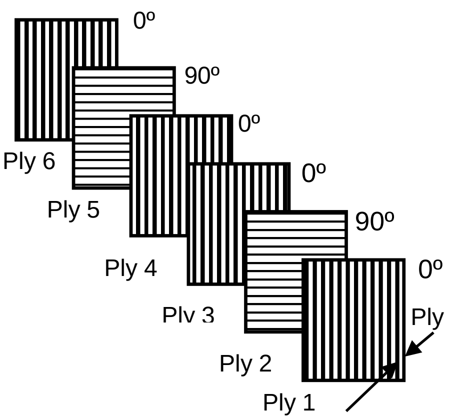


Fig.7. Number of plies, fiber orientations and thickness of composite laminates

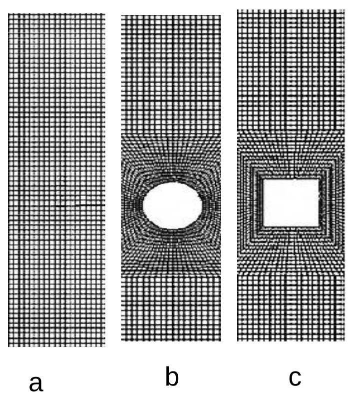


Fig. 8. The meshing of plate: (a) Plate without cutout, (b) Central circular cutout plate and (c) Central square cutout plate

4 RESULT AND DISSCUSION

In this work, the load results were done experimentally and numerically for cross-ply laminated [0º/90º/0º]$_s$ composite plates with and without central circular/square cutouts for the glass fiber, carbon fiber and Kevlar-29 fiber types. The results of glass fiber types are obtained only experimental. The experimental results produced the load-displacement curve of each of the specimens, while the numerical results are obtained from the nodal solution graphics simulated by ANSYS program. The experimental and numerical buckling loads data for all the test specimens were explained in Table 2. It is presents good acceptance between the experiment and numerical predictions. For glass fiber type plates, the differences are in between 0.03 – 2.47 %; for carbon fiber type plates, the differences are found in the range of 0.52 – 2.70 %. The differences for the Kevlar-29 type plates are slightly higher, lying in the range of 1.47 – 8.24 %, and these are also acceptable. Further, it is noticed that the load is greatly depended on its cutout size (preferable in term of cutout ratio, *d/w*). The load is decreasing with the increase of this ratio. It is also noticed that the load of the plate with circular cutout was higher than that of the plate with square cutout. In addition, for the same cutout sizes on plates, the carbon fiber plate always has the highest buckling load, following by the E-glass fiber plate and Kevlar-29 fiber. The load of the plate is affected by their fiber weight and thickness as well. Figures 9-15 show the experimental results of load-displacement diagram for the cross-ply laminated composite plates, with and without central circular/square cutouts. Similarly, Figure 16-18, from show the nodal solution graphics for the cross-ply laminated plates, with and without central circular/square cutouts

Table 2. Experimental and numerical buckling load of laminated plates

Plate type	Cutout size (mm)	*d/w* ratio	Buckling load(kN)		Differences (%)
			Experimental	Numerical	
E-glass fiber 600gm	Without cutout	0	1.152	-	-
	Circular *d* = 16	0.40	1.057	-	-
	Circular *d* = 26	0.65	0.987	-	-
	Circular *d* = 36	0.90	0.812	-	-
E-glass fiber 400gm	Without cutout	0	0.411	0.411	0.05
	Circular *d* = 16	0.40	0.383	0.390	1.82
	Circular *d* = 26	0.65	0.364	0.357	2.47
	Circular *d* = 36	0.90	0.301	0.298	1.06
	Square (16×16)	0.40	0.365	0.366	0.03
	Square (26×26)	0.65	0.344	0.34860	1.25
	Square (36×36)	0.90	0.272	0.269	0.44
Carbon fiber 400gm	Without cutout	0	0.462	0.460	0.52
	Circular *d* = 16	0.40	0.435	0.425	2.40
	Circular *d* = 26	0.65	0.404	0.399	1.49
	Circular *d* = 36	0.90	0.350	0.341	2.65
	Square (16×16)	0.40	0.420	0.410	2.70
	Square (26×26)	0.65	0.392	0.386	1.41
	Square (36×36)	0.90	0.322	0.313	2.52
Kevalr-29 fiber 200gm	Without cutout	0	0.343	0.337	2.01
	Circular *d* = 16	0.40	0.277	0.280	1.47
	Circular *d* = 26	0.65	0.250	0.259	3.86
	Circular *d* = 36	0.90	0.219	0.220	8.24
	Square (16×16)	0.40	0.254	0.266	4.49
	Square (26×26)	0.65	0.240	0.250	5.24
	Square (36×36)	0.90	0.197	0.202	2.48

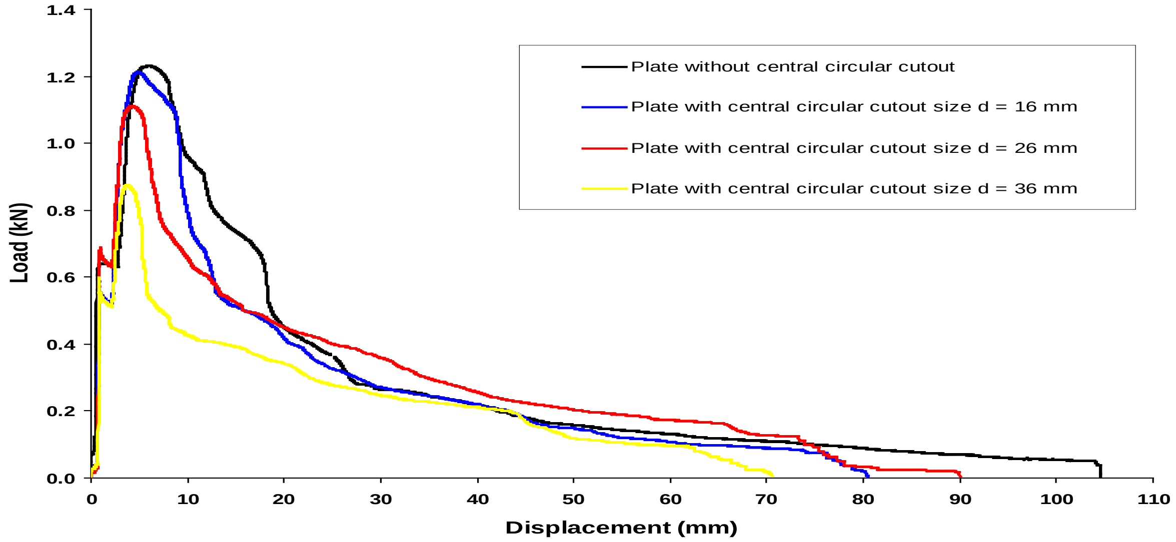


Fig. 9. Load-displacement curves of cross-ply laminated E-glass fiber 600 gram plates with different central circular cutout sizes.

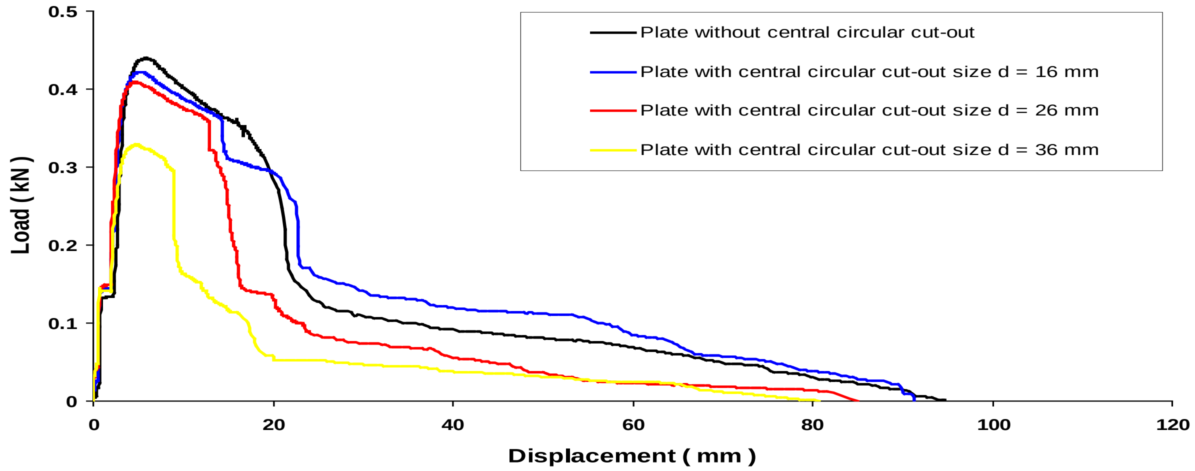


Fig. 10**.** Load-displacement curves of cross-ply laminated E-glass fiber 400 gram plates with different central circular cutout sizes.

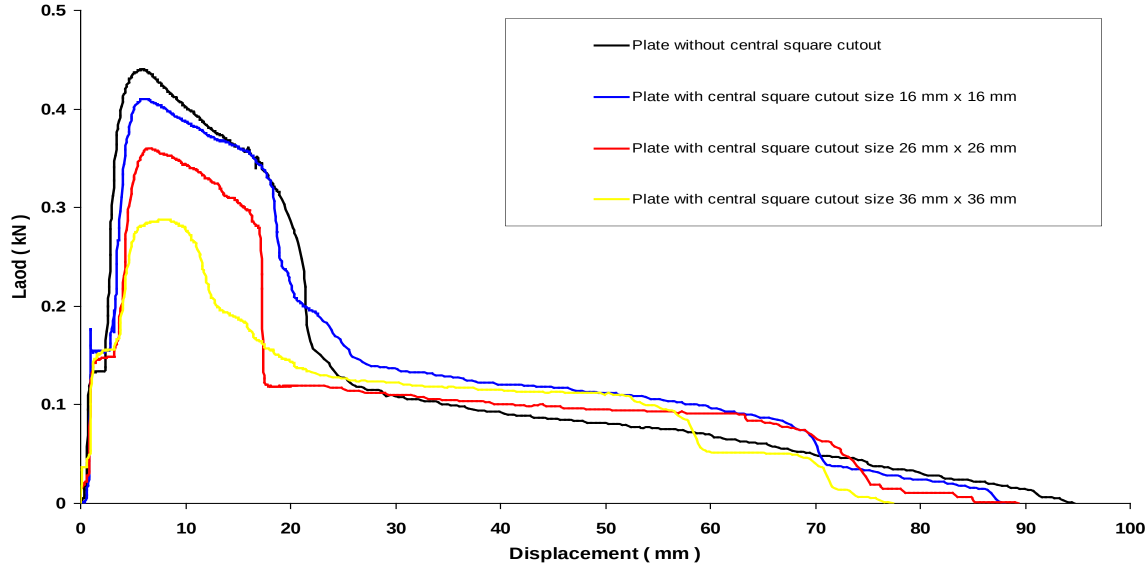


Fig. 11. Load-displacement curves of cross-ply laminated E-glass fiber 400 gram plates with different central square cutout sizes.

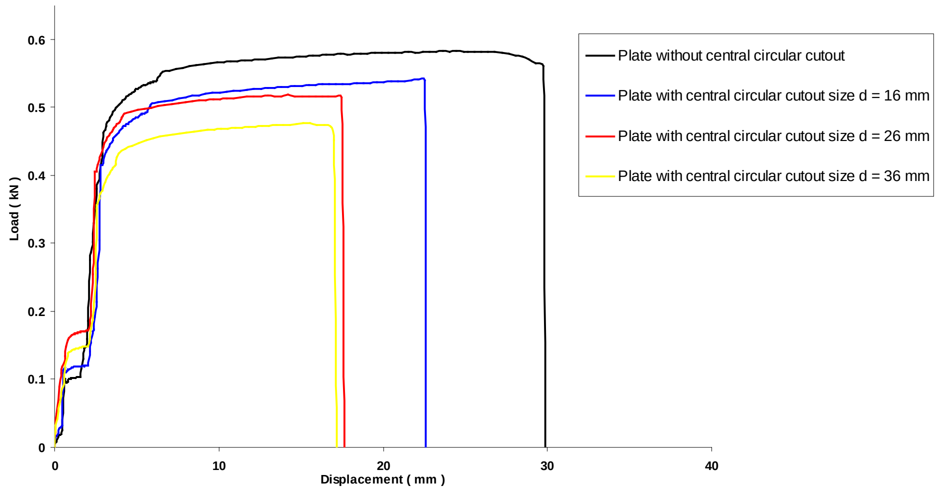


Fig. 12. Load-displacement curves of cross-ply laminated carbon fiber 400 gram plates with different central circular cutout sizes.

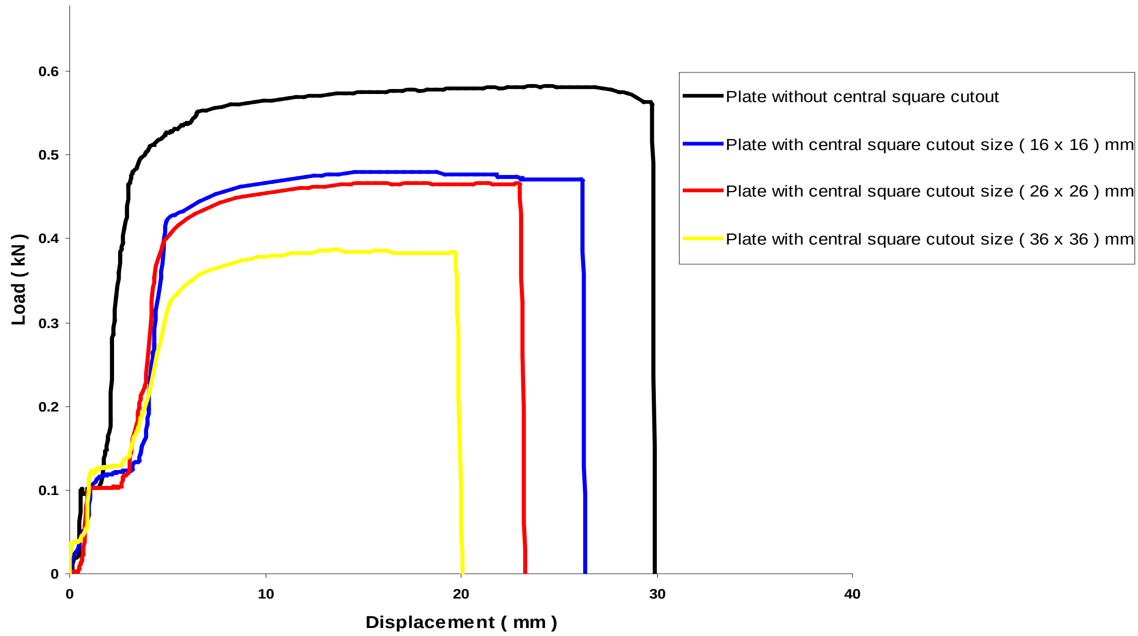


Fig. 13**.** Loa v. displacement diagram of cross-ply laminated carbon fiber 400 gram plates with different central square cutout sizes.

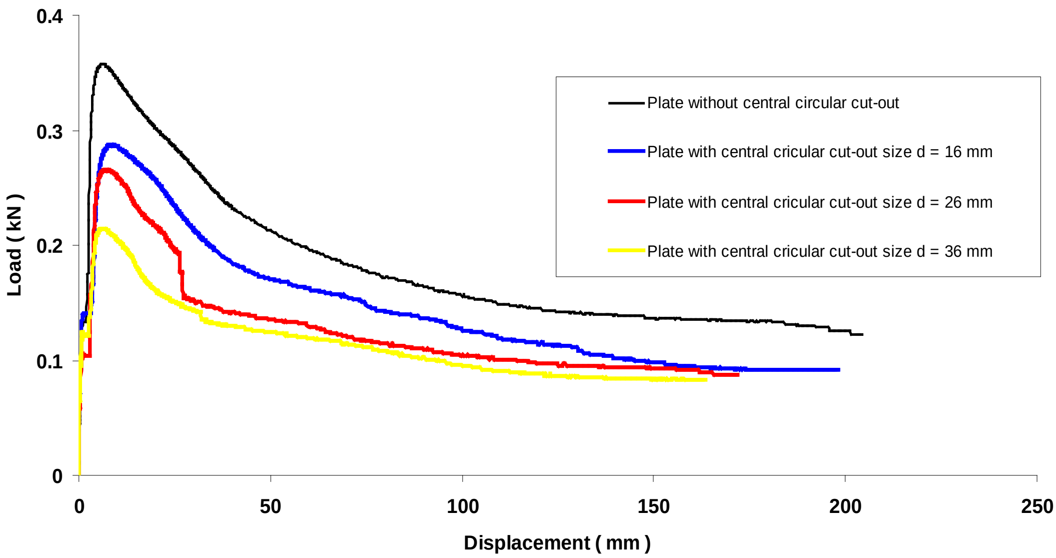


Fig. 14. Loa v. displacement diagram of cross-ply laminated Kevlar-29 fiber 200 gram plates with different central circular cutout sizes.

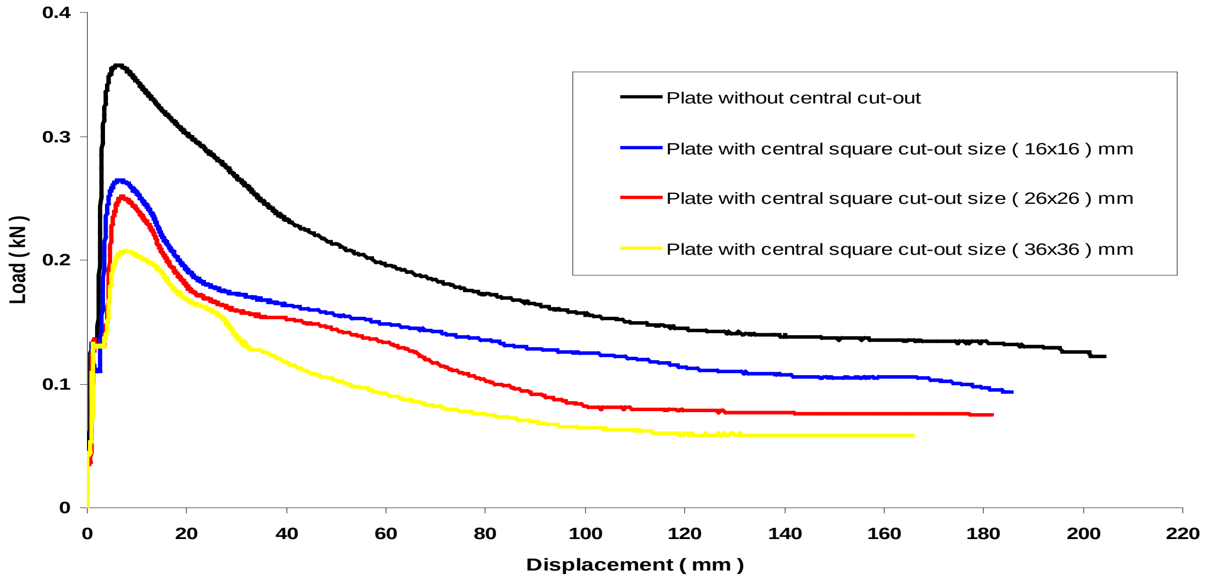
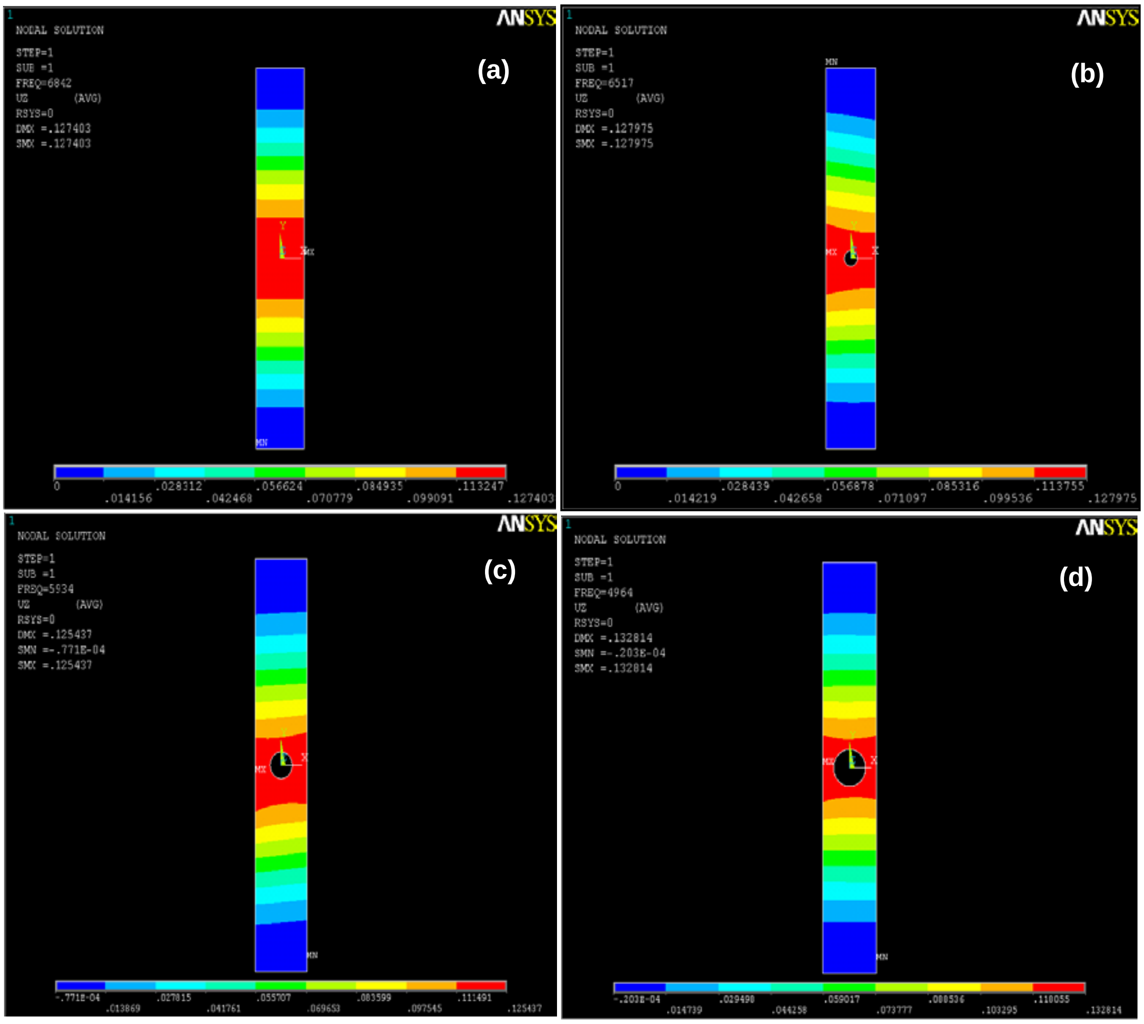


Fig. 15. Loa v. displacement diagram of cross-ply laminated Kevlar-29 fiber 200 gram plates with different central square cutout sizes



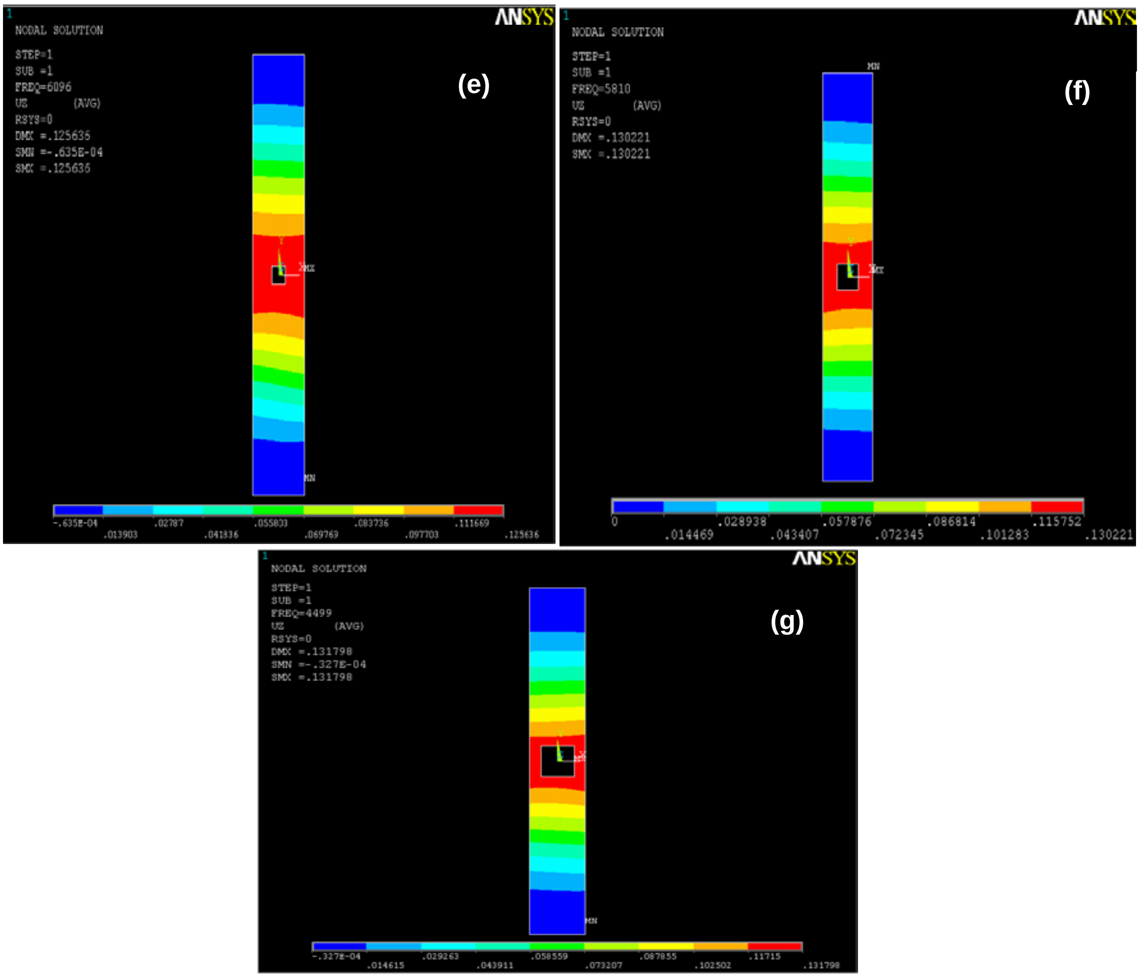
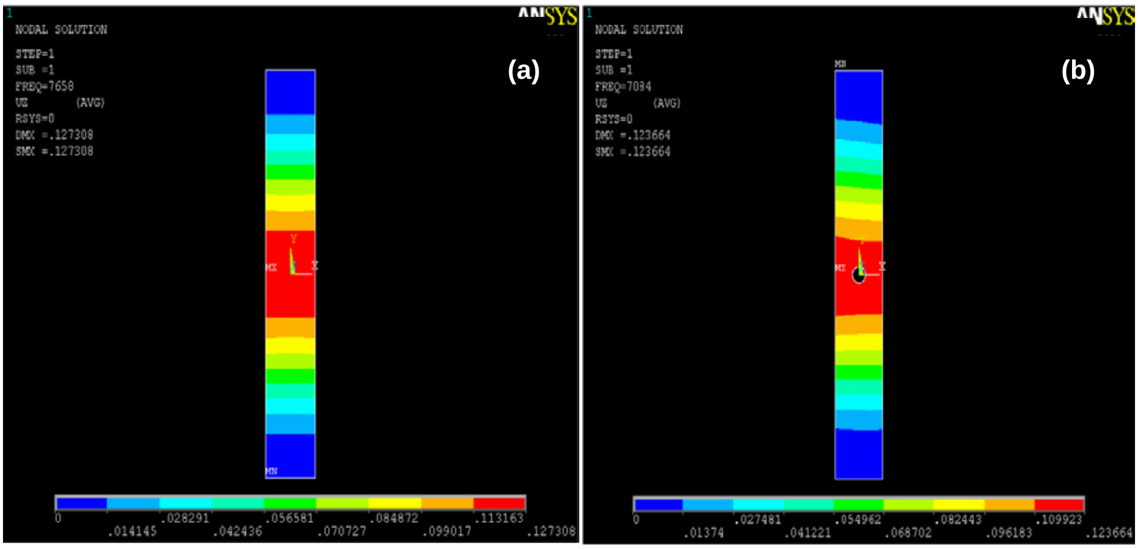


Fig. 16. Nodal solutions for cross-ply laminated E-glass fiber (400 gram) plates. (a) plate without cutout; (b-d) plates with central circular cutout d = 16 mm, 26 mm and 36 mm respectively; (e-g) plates with central square cutout sizes (16 × 16) mm, (26 × 26) mm and (36 × 36) mm respectively



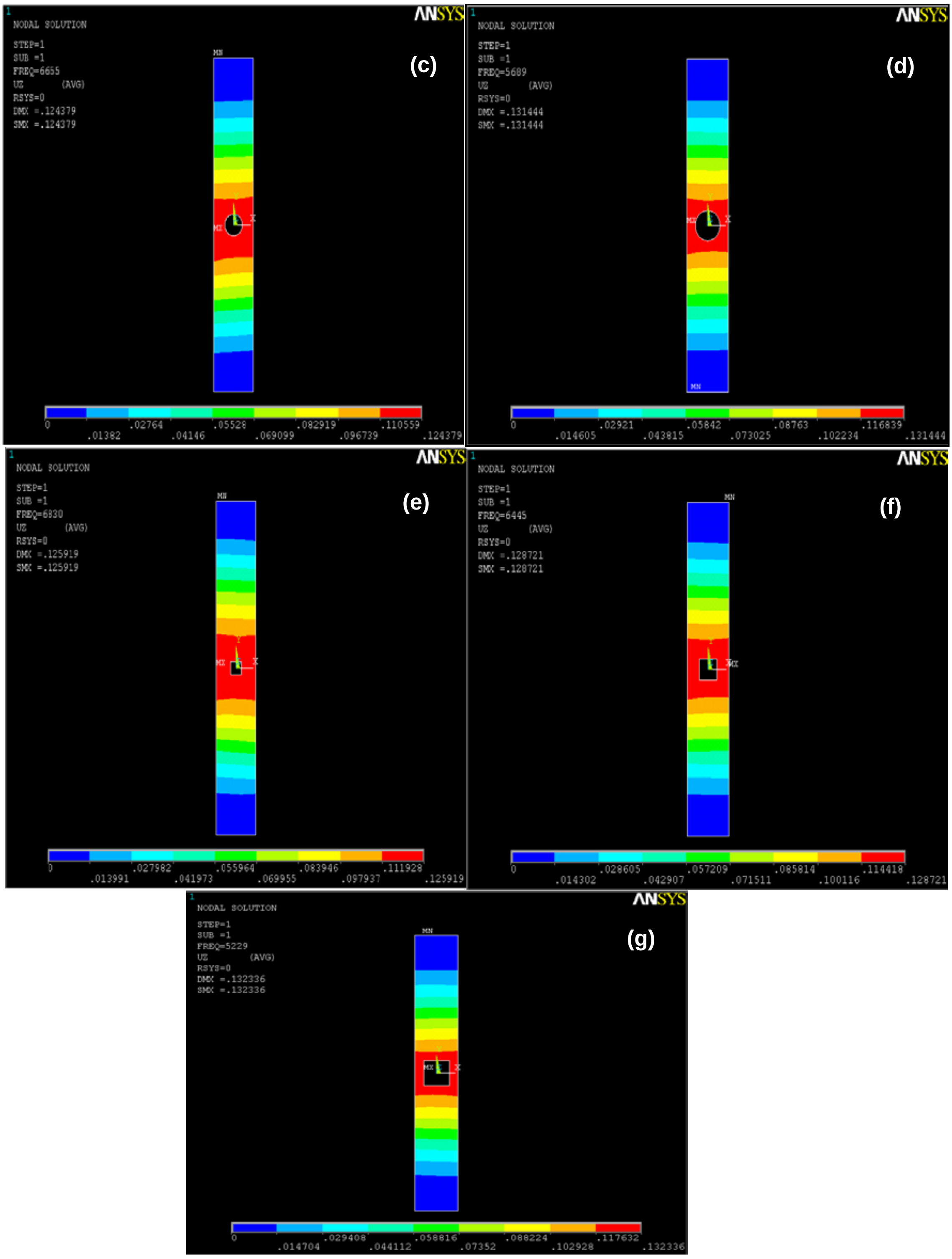


Fig. 17. Nodal solutions for cross-ply laminated carbon fiber (400 gram) plates: (a) plate without cutout; (b-d) plates with central circular cutout *d* = 16 mm, 26 mm and 36 mm respectively; (e-g) plates with central square cutout sizes (16 × 16) mm, (26 × 26) mm and (36 × 36) mm respectively.

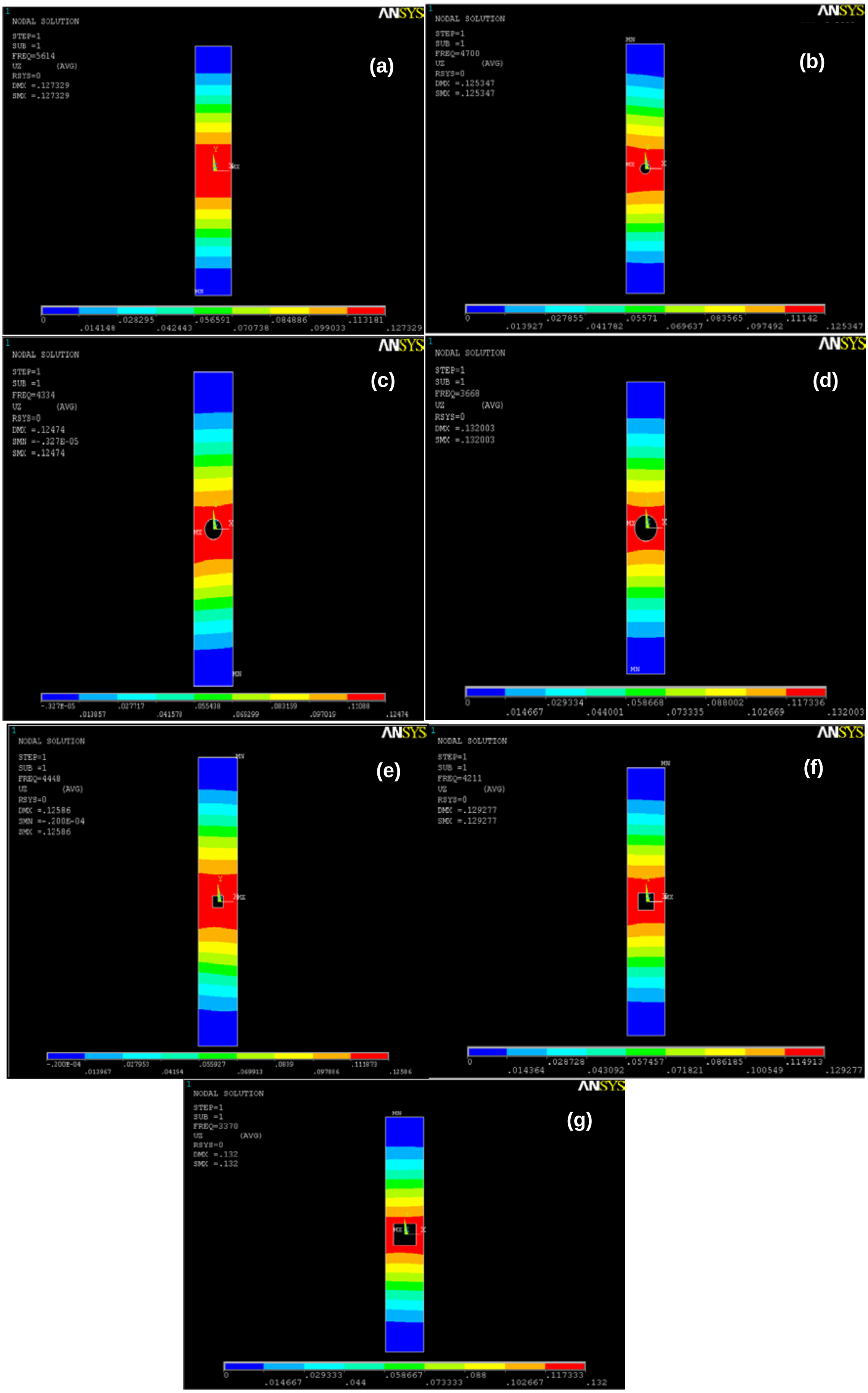


Fig. 18. Nodal solutions for cross-ply laminated Kevlar-29 fiber (200 gram) plates. (a) plate without cutout; (b-d) plates with central circular cutout, d = 16 mm, 26 mm and 36 mm respectively; (e-g) plates with central square cutout sizes (16 × 16) mm, (26 × 26) mm and (36 × 36) mm respectively.

4.1 Effect of fiber weight and plate thickness

In this part, experimental buckling loads of the E-glass fiber 600 gram and 400 gram plates are considered. For the same cutout size and fiber type (E-glass), the laminated fiber plate weigh 600 g is always having higher buckling load (about 2.7 times) than that of fiber plate weigh 400 g. The more weight of fiber needs more matrix material to compose a flat composite plate, which leads to higher plate thickness. Plates of higher thickness caused due to firm bonding of more fiber and matrix had become stiffer against compressive load resulted the increased buckling load.

4.2 Effect the shape of cut-out

Due to design requirements, the various cut-out shapes can be used. For the same fiber type and cutout size, the plate with central circular cutout has higher buckling load (about 1.02 – 1.11 times) than that of the plate with central square cutout reflects the effect shape of cutout on buckling load. This behavior was explained by noticed that, the central cutout area which was subtracted from the plate is the main cause. With the same cut-out diameter or width, the area of square is higher than that of a circle. Therefore, the more area is subtracted the more loss of mass in the central of the plate will be experienced, which will cause a loss in central stiffness and as a result it will lead to buckle at a lower loading.

4.3 Effect of fiber type

In the wake of the demands of structural effectiveness, Engineers are dedicated to improve the properties of composites by manipulating fiber type. In this work, three types of fibers, E-glass fiber, carbon fiber and Kevlar-29 fiber are actually compared with their buckling loads. Results show that carbon fibers are the ideal materials for structural requirements like high strength at lower weight, high modulus and stiffness with great energy absorption capacity. E-glass fibers are having moderately good strength, stiffness and higher resistance to chemical corrosions. Kevlar-29 fibers are not the ideal materials in this study. They have a very low resistance to axial failure; it is because of anisotropic properties of fiber and lower shear stiffness.

4.4 Effect of cutout size

Cutout size is normally preferred by referring to cutout ratio; *d*/*w* (*d* is the cutout width or diameter, and *w* is the plate width). Many researchers tend to use this term to investigate the relation between the cutout ratio *d*/*w* and buckling load. In this work, it is observed that the plate has no cutout or smaller cutout has higher strength than that of the plate having larger cutout. The effect is due to loss of mass (less material) in the centre caused loss of the interfacial bond between the matrix and fibers. The interface between the fiber and matrix is accountable, for carry and transmitting the loading from the matrix to reinforced fibers, which engage the greater part of composite structure strength. As a result, when cutout size is getting bigger means the bonding is getting loose, which reduce the strength of the plate. Inherently, the central location of cutout is leading to reduce in bending stiffness in the center of plate and it gains more importance of size of cut-out increases. Thus the more losing in bending stiffness caused by the increasing of central cutout size will result in more reduction of buckling strength.

4.5 Buckling load versus cutout ratio(d/w)

The buckling load agreement of experimental and numerical predictions results is having a good tolerance. Figure 19 and 20 presents the comparisons of buckling load versus cutout ratio between the experimental results and numerical results for all the specimens. It is seen from the Figures that the results acquired from numerical buckling analysis are very close to the experimental buckling load results. As mentioned before, the buckling load of the plate decreases with the increase of the cutout ratio.

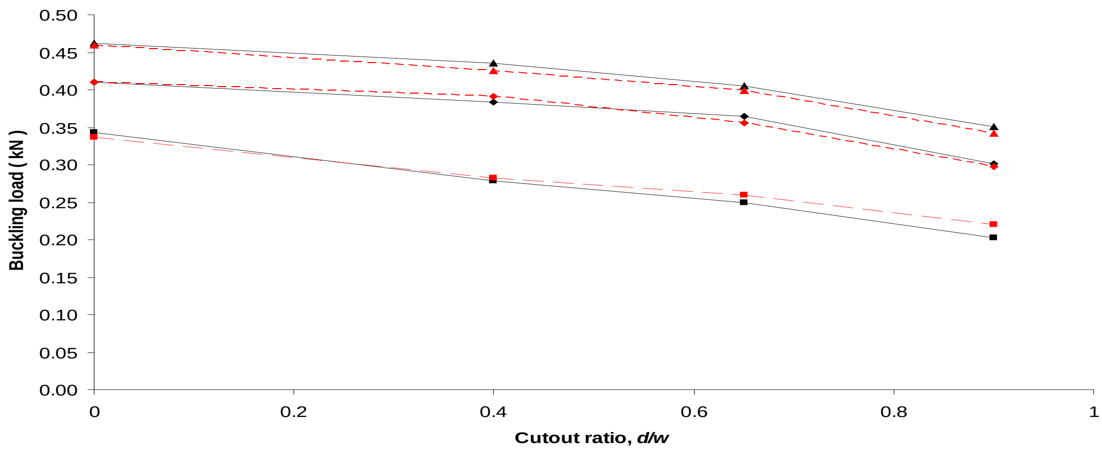


Fig. 19. Buckling loads versus cutout ratios for composite plates with and without central circular cutouts

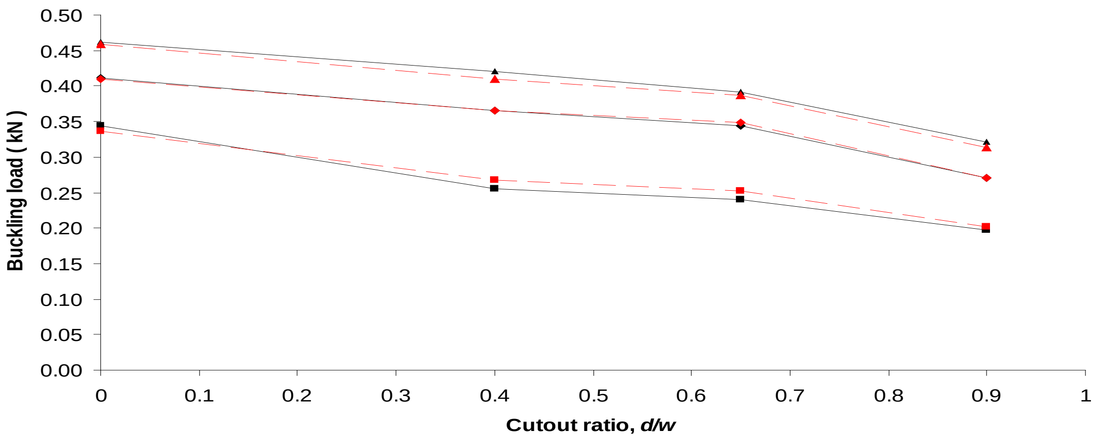


Fig. 20. Buckling loads versus cutout ratios for laminated composite plates with/without central square cutouts

5 CONCLUSION

The conclusions are summarized as follows:

1. For all cases of symmetrical ply laminates, the cross-ply laminates [0˚/90˚/0˚]$_s$ were subjected the huge inelastic pre-failure and deformation before final failure and this kind of ply arrangement was able of absorb a great amount of energy before fracture.
2. With increasing the size of central cutout, the cutout ratio increases proportionally and the load of the laminated plate also reduced.
3. A loss of mass (hole) in the center of the laminated plate loses the interfacial bonding of its matrix and fibers. The strength of plate reduces as the bonding loosens.
4. More fiber combines with more matrix material during composite making, resulting to increase of plate thickness. Thicker plate produces higher stiffness strength to buckling at load.
5. Central bending stiffness of the laminated plate reduces because of the central cutout size increase which leads to reduce in buckling resistance of the composite plate.
6. For the same fiber type and cutout size on plates, the plate with central circular cutout has shown higher buckling strength than that of the plate with central square cutout.
7. Carbon fibers are showing the best mechanical properties than those of E-glass fibers and Kevlar-29 fibers. They have the highest buckling load, great modulus of strength in low weight.
8. The low compressive strength of Kevlar-29 is due to the anisotropic properties and low shear stiffness. Although its compressive strength is low, it underwent a huge displacement without heavy damage and crack before its failure. This indicates that the Kevlar-29 has a good capability to withstand shearing.

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