Structural Engineering and Mechanics, Vol. 35, No. 3 (2010) 335-348
DOI: http://dx.doi.org/10.12989/sem.2010.35.3.335

Cutout shape and size effects on response of quasi-isotropic composite laminate under uni-axial compression

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(Received April 16, 2009, Accepted January 27, 2010)

Abstract. Cutouts are often provided in structural and aircraft components for ventilation, for access, inspection, electric lines and fuel lines or sometimes to lighten the structure. This paper addresses the effects of cutout shape (i.e., circular, square, diamond, elliptical-vertical and elliptical-horizontal) and size on buckling and postbuckling response of quasi-isotropic (i.e., $(+45/-45/0/90)_{2s}$) composite laminate under uni-axial compression. The finite element method is used to carry out the investigation. The formulation is based on first order shear deformation theory and von Karman's assumptions are used to incorporate geometric nonlinearity. The 3-D Tsai-Hill criterion is used to predict the failure of a lamina while the onset of delamination is predicted by the interlaminar failure criterion. It is observed that for the smaller size cutout area there is no significant effect of cutout shape on load-deflection response of the laminate. It is also concluded that the cutout size has substantial influence on the buckling and postbuckling response of the laminate with elliptical-horizontal cutout, while this effect is observed to be the least in case of laminate with elliptical-vertical cutout.

Keywords: buckling; composite laminates; cutouts; failure; postbuckling; strength.

1. Introduction

Composite panels with cutouts of various shapes are found in automotive, naval and aircraft structural components to provide openings for access for hydraulic lines, electrical lines, fuel lines, damage inspection, and sometime for ventilation and to reduce the overall weight of the structure. Generally, composite panels can sustain greater compressive load beyond the buckling load. During the application, these panels may be subjected to complex loading conditions. Further, the presence of cutouts of various shapes forms free edges in the composite laminates, which in turn cause high interlaminar stresses (Robert 1975) leading to loss of stiffness and premature failure of laminates due to onset of delamination. It is thus important for the design engineer to understand the stability, overall strength and failure characteristics of composite panels with cutouts of various shapes and sizes for their efficient design.

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Of the early investigations related to buckling behavior of laminated plates with circular cutouts are the works by Nemeth (1988), Lin and Kuo (1987), Srivatsa and Krishna Murthy (1992) and Britt (1994). Nemeth (1988) studied the buckling behavior of rectangular symmetrical angle-ply laminates with a circular cutout, both under compressive stress loading and displacement loading. Lin and Kuo (1987) used FEM to investigate the critical loads of rectangular laminates with a circular hole. A parametric study of the compression buckling behavior of stress loaded composite plate with a central circular cutout using FEM based on Classical Lamination Plate Theory (CLPT) was carried out by Srivatsa and Krishna Murthy (1992). Brit (1994) presented results of a parametric study of the buckling behavior of simply supported and clamped laminates with a central and an elliptical hole. It was shown that for certain cutout orientation angles, panels with a circular cutout had higher buckling loads than panels with an elliptical cutout even though the elliptical cutout was smaller in area. Shanmugam *et al.* (1999) have used the FEM to develop a design formula to determine the ultimate load carrying capacity of axially compressed square plates with centrally located perforations (circular or square). They concluded that the ultimate load capacity of the square perforated plate is affected significantly by the hole size and the plate slenderness ratio. In addition to this, Akbulut *et al.* (2001) investigated the buckling behavior of composite laminates with central square hole using first order shear deformation theory. More recently, Ghannadpour *et al.* (2006) studied the effects of circular and elliptical cutouts on the buckling behavior of rectangular composite plates and concluded that plates that have a cutout can buckle at loads higher than the buckling loads for corresponding plates without a cutout.

Moreover, a detailed review of early investigation on buckling and postbuckling behavior of laminated composite plates with cutouts has been documented by Nemeth (1996). Thereafter, Kong *et al*. (2001) analyzed, numerically and experimentally buckling and postbuckling behaviors of composite plates with a circular hole and showed that buckling and postbuckling behaviors largely depend on the size of the hole and the stacking sequence of the composite plate. Jain and Kumar (2004) studied the postbuckling response of symmetrical square laminates with central circular and elliptical cutout under uni-axial compression and observed that the cutout shape, size and its alignment have a substantial influence on the reserved strength of the laminate beyond buckling. Guo (2007) conducted numerical and experimental studies to investigate the effect of reinforcements around cutouts on the bucking behaviour of composite panels under shear load and determined the best cutout reinforcement. Singh and Kumar (2008) have investigated the effects of rectangular cutout size and aspect ratio on prebuckling and postbuckling behavior of various laminates under uni-axial compression and concluded that laminates with small square cutouts have more postbuckling strength than without cutout. Very recently, Kumar and Singh (2010) investigated the effects of boundary conditions on buckling and postbuckling responses of composite laminates with various shaped cutouts.

It is manifested that a substantial work has been carried out into the buckling of composite laminates mostly with circular/square cutouts. Further, very few investigations include effects of non-circular cutouts on prebuckling and postbuckling responses, failure loads and failure characteristics of composite laminates. The aim of present investigation is to explore the effects of circular and non-circular (i.e., square, diamond, elliptical) cutouts and their sizes on prebuckling and postbuckling responses, failure loads and failure characteristics of a simply-supported quasi-isotropic (i.e., $(+45/-45/0/90)_{2s}$) laminate under uni-axial compression.

2. Methodology

A special purpose program was developed to carry out the study which is based on the finite element formulation using the first order shear deformation theory with nine noded Lagrangian element having five degrees of freedom per node. The nonlinear analysis is carried out using von Karman's assumptions. The nonlinear algebraic finite element equations are solved by Newton-Raphson technique. Failure of a lamina is predicted by tensor polynomial form of the 3-D Tsai-Hill criterion, wherein five stress components (three in-plane stresses and two transverse shear stresses) were calculated at mid thickness of each layer using the constitutive relations. The onset of delamination is predicted by the interlaminar failure criterion (Singh 1996, see the Appendix). Three components of transverse stresses required for interlaminar failure criterion were calculated at gauss points on each interface of two neighboring layers of each element by utilizing the in-plane stress variation (calculated from nodal values of these in-plane stresses) in equilibrium equations. Total failure is said to have occurred when the onset of delamination occurs or when the plate is no longer able to carry any further increase in load due to very large transverse deflection.

Properties of the material (Reddy and Reddy 1992) of the laminate are presented in Table 1. For this present study, a full square plate of size 279 mm × 279 mm × 2.16 mm with ply thickness 0.135 mm and having the lamination sequence $(+45/-45/0/90)_{2s}$ (i.e., total 16 layers, bottom layer being the first layer) is considered with central cutouts of various shapes (i.e., square, circular, diamond, elliptical-vertical and elliptical-horizontal) and sizes. Three sizes of cutouts designated as

Table 1 Material Properties of T300/5208 (pre-peg) graphite-epoxy

Mechanical properties	Values	Strength properties	Values
E_1	132.58 GPa	X_t	1.52 GPa
E_2	10.80 GPa	X_c	1.70 GPa
E_3	10.80 GPa	$Y_t = Z_t$	43.80 MPa
$G_{12} = G_{13}$	5.70 GPa	$Y_c = Z_c$	43.80 MPa
$\nu_{12} = \nu_{13}$	0.24	R	67.60 MPa
ν_{23}	0.49	$S = T$	86.90 MPa

Table 2 Details of cutout shapes and their dimensions

Size of square laminate, b (mm)	Cutout type	Ratio*	Cutout size		
			A_1	A_2	A_3
279	Square	c/b =	0.140	0.280	0.420
279	Circular	d/b =	0.158	0.316	0.474
279	Diamond	c/b =	0.140	0.280	0.420
279	Elliptical-Vertical	e/b =	0.112	0.223	0.335
		f/b =	0.224	0.447	0.670
279	Elliptical-Horizontal	e/b =	0.224	0.447	0.670
		f/b =	0.112	0.223	0.335

*Refer Figs. 1, 2 for various notations

A_1, A_2 and A_3 (having areas equal to the area of square cutouts with aspect ratios, i.e., c/b equal to 0.14, 0.28 & 0.42, respectively) have been considered. Details of the cutout shapes and dimensions are given in Table 2. All edges of the square laminated plate are kept simply supported and the compression load being applied on the edge $x = b$; where, b refers to the width of the square plate. Results for failure loads and corresponding deflections are presented in the following non-dimensionalized forms:

Uni-axial compression in the x-direction $N_x b^2/E_2 h^3$

Maximum transverse deflection $w_{\max}/h$

Where, E_2 is the transverse elastic modulus of a lamina; h is the thickness of the laminate; b is the width of the square plate; N_x is the uni-axial compression loads per unit width of the plate along x-direction; and w_{max} is the maximum transverse deflection.

3. Description of FE model

To fix the number of elements to be used in the finite element analysis, a convergence study was conducted (using 72, 96, 120, 144 and 168 elements) for square cutouts of smallest size (i.e., c/b = 0.14) and largest (i.e., c/b = 0.42) size in the present study. The convergence of buckling and first

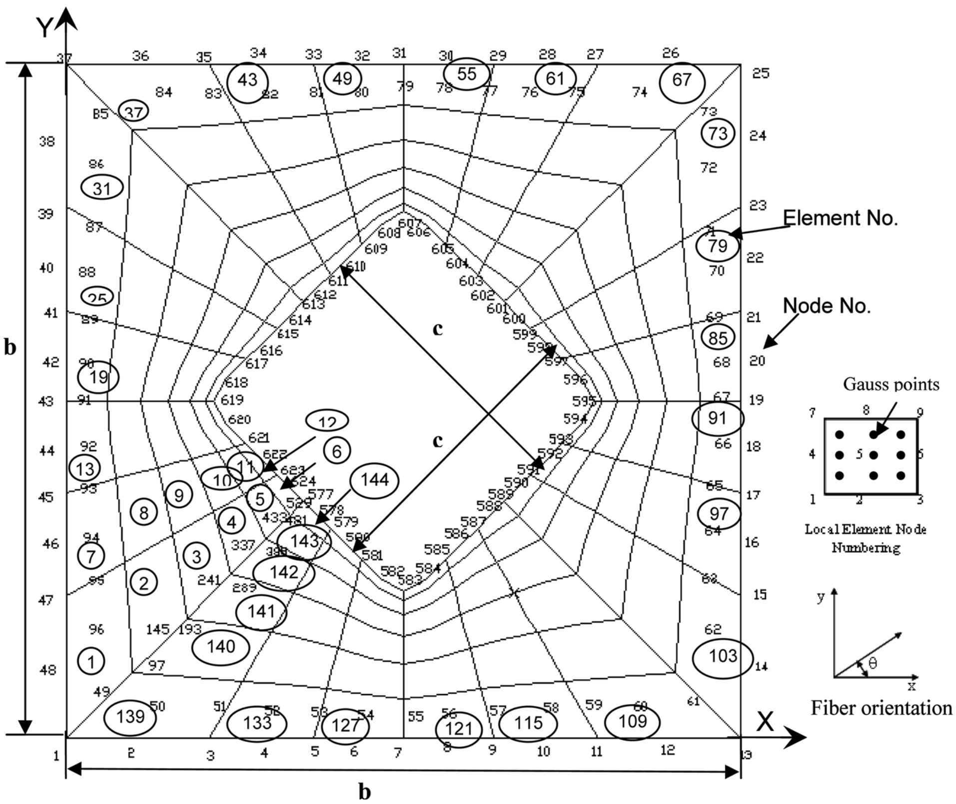

Fig. 1 Finite element mesh along with element- and node-numbering scheme for a typical square laminate with diamond cutout

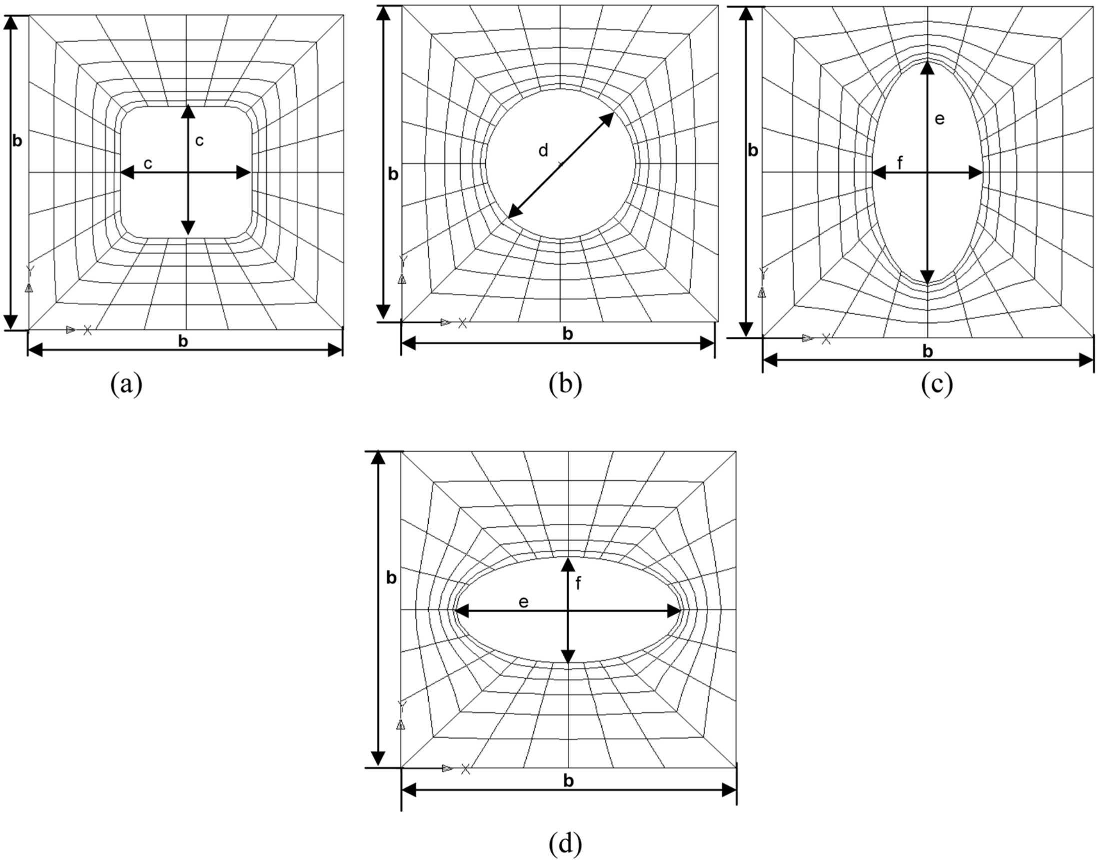

Fig. 2 Meshing of square laminate with (a) square, (b) circular, (c) elliptical-vertical, and (d) elliptical-horizontal cutouts

ply failure loads of a uniaxially compressed simply-supported quasi-isotropic laminate was checked. It was found that convergence (approximately 1%) in buckling load can be obtained even at lesser number of elements, but to have the convergence of the same order of magnitude for first-ply failure load 144 elements are adequate for both sizes of square cutout. Schematic of finite element mesh along with element- and node-numbering scheme for a typical square laminate with diamond cutout is illustrated in Fig. 1. Schematics of finite element mesh for square laminate with cutouts of other shapes are shown in Fig. 2.

4. Verification of results

The accuracy of the developed program is first checked by comparing values of buckling and first-ply failure loads with the results available in literature. A comparison of non-dimensionalized buckling loads (i.e., $N_x b^2/E_2 h^3$), for various laminates with all edges simply supported, available in literature and the present study is shown in Table 3. For comparison purposes, the laminate dimensions and material properties are taken same as given in the respective references of the table.

Table 3 Comparison of non-dimensional buckling load

Reference	Cutout shape & size	Stacking sequence	Stacking sequence	$N_x b^2/E_2 h^3$	
				In reference	In present study
Srivatsa and Murthy (1992)	Circular (d/b = 0.2)	$(\pm45)_{6s}$	$(\pm45)_{6s}$	56.5	58
Srivatsa and Murthy (1992)	Circular (d/b = 0.2)	$(0/\pm45/90)_s$	$(0/\pm45/90)_s$	37	40.5
Jain and Kumar (2004)	Circular (d/b = 0.5)	$(\pm45/0/90)_{5s}$	$(\pm45/0/90)_{5s}$	13.84 (25.42)*	14.3 (28.3)
Jain and Kumar (2004)	Elliptical (e/b = 0.5 & f/b = 0.25)	$(\pm45/0/90)_{5s}$	$(\pm45/0/90)_{5s}$	13.05 (24.3)	13.75 (25.4)
Ghannadpour *et al.* (2006)	Circular (d/b = 0.5)	$(0/90)_{2s}$	$(0/90)_{2s}$	6.39	7.1

*Values in brackets represent non-dimensionalized first-ply failure load

A good agreement has been observed between the results available in literature and the present study. Further, a comparison of the first-ply failure load is made with the results for *C4* specimen (i.e., a 24-ply orthotropic laminate with stacking sequence $(\pm45/0_2/\pm45/0_2/\pm45/0/90)_s$, and having length and width equal to 508 mm and 178 mm, respectively) presented by Engelstad *et al.* (1992) using the Tsai-Wu criterion. The *C4* specimen was subjected to axial compression in the direction of length with loaded edges clamped and unloaded edges simply supported. The first-ply failure load obtained in the present investigation is 1.89 P_c, where P_c is the buckling load of the laminate, while that reported by Engelstad *et al.* (1992) is 2.0 P_c (Non-dimensionlized buckling load i.e., $P_c b^2/E_2 h^3$ is 17.79). This difference of about 5% in failure loads is because of the fact that Engelstad *et al.* (1992) considered the uniform end shortening in the application of uni-axial compression as against the uniform stress resultant in this investigation. Moreover, a small initial imperfection in the laminate has been considered by Engelstad *et al.* (1992), whereas no such imperfection is included in the present investigation. In addition to the above, a good concurrence has also been observed in the first-ply failure loads (based on Tasi-Hill failure criterion) obtained by Jain and Kumar (2004) and those obtained in the present study as shown in Table 3.

In addition, the accuracy of the program is also checked by comparing values of buckling loads with experimental results of Nemeth (1988) and Kong *et al.* (2001). They have analyzed symmetric square laminates with central cutouts having d/b ratios 0.105 and 0.20, respectively, for loaded edges clamped and unloaded edges simply supported boundary conditions. The material properties and dimensions of the laminates considered are the same as used by both investigators. The value of buckling load found by Nemeth (1988) for $(\pm60)_{6s}$ laminate was 24.465 kN which is very close to the corresponding value (i.e., 24.05 kN) found in the present study. Kong *et al.* (2001) analyzed $(0/\pm45/90)_s$ laminate, and the values of buckling loads (in terms of P_c/bh) found by Kong *et al.* (2001) and in the present investigation are 11.25 MPa and 12.8 MPa, respectively, which are in good agreement.

5. Results and discussion

In this section the responses of square quasi-isotropic laminate (i.e., $(+45/-45/0/90)_{2s}$) with and without central cutouts of various shapes (i.e., square, circular, diamond, elliptical-vertical and elliptical-horizontal) and sizes are investigated under uni-axial compression load applied on edge $x = b$. All the four edges are taken as simply supported. Fig. 3 shows the load-deflection response and the values of failure loads of the laminate without cutout. Fig. 4 represents the load-deflection

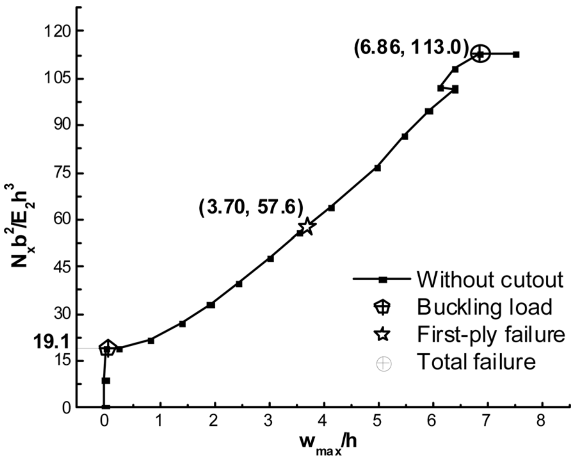

Fig. 3 Load-deflection response of quasi-isotropic laminate without cutout

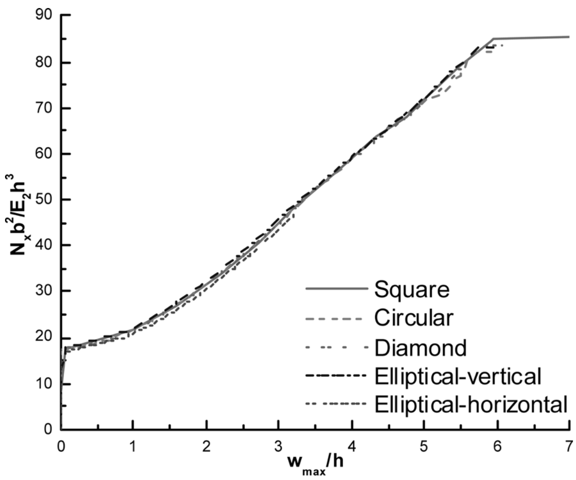

Fig. 4 Load-deflection responses of quasi-isotropic laminate with cutouts of size A_1 and of various shapes

Table 4 Details of failure results for $(+45/-45/0/90)_{2s}$ laminate with cutouts of size A_1 and of various shapes

Cutout shape	Buckling load	First-ply failure load	Total failure load$^{\Theta}$	$(w_{max}/h)^*$	FE$^{\oplus}$	FL$^{\otimes}$	FG$^{\varnothing}$	Mode of first-ply Failure
Square	17.7	53.1	85.3	3.53	73	1	2	Transverse$^{\#}$
Circular	17.7	53.1	82.2	3.52	73	1	2	Transverse
Diamond	17.8	53.0	83.6	3.56	73	1	2	Transverse
Elliptical-Vertical	18.2	53.0	83.2	3.53	73	1	2	Transverse
Elliptical-Horizontal	17.2	46.8	46.8	3.21	84	Interface 13	-	Early onset of Delamination causes the failure

$^{\Theta}$Total failure is said to have occurred because of onset of delamination or complete loss of stiffness due to large transverse deflection

*Non-dimensionalized maximum transverse displacement at first-ply failure

$^{\oplus}$First failed element number; $^{\otimes}$First failed layer number of the first failed element

$^{\varnothing}$First failed gauss point of the first failed layer of the first failed element

$^{\#}$Transverse mode of failure refers to the failure of lamina in a direction perpendicular to the fiber direction (i.e., matrix failure) responses of the laminate with cutouts of smallest size, i.e., cutout size A_1 (Table 2), and the corresponding details of failure characteristics for the same cutout size are shown in Table 4. The first observation is that the presence of cutout decreases the buckling and failure loads. As compared to the laminate without cutout, maximum reductions in the buckling load (about 10.2%) and the first-ply failure load (about 18.8%) are observed for the laminate with elliptical-horizontal cutout, whereas, the minimum reduction in buckling load (about 4.60%) is observed for the laminate with elliptical-vertical cutout. It is also to be noted that the decrease in first-ply failure load (about 7.81%) is minimum and the same for the laminates with square, circular, diamond and elliptical-vertical cutouts.

It can also be observed from Table 4 that for the same cutout area (for cutout size A_1) the laminate with elliptical-vertical cutout has the highest buckling load, while the laminate with elliptical-horizontal cutout has the lowest buckling load. For cutout size A_1, there is no significant effect of cutout shapes on postbuckling response & failure characteristics of the composite laminate, except total failure of the laminate with elliptical-horizontal cutout. It is clear from Table 4 that laminates with square, circular, diamond and elliptical-vertical cutout bear more or less same values and failure characteristics (i.e., non-dimensionalized maximum transverse deflection at first-ply failure, first failed element number, first failed layer number of the first failed element, first failed gauss point of the first failed layer of the first failed element and the mode of first-ply failure) associated with first-ply failure and total failure. But, in the case of laminate with elliptical-horizontal cutout, the early delamination near the cutout edge (i.e., element 84, Fig. 1) is the cause of total failure, while for other shaped cutouts the first-ply failure occurs before total failure near the outer loaded edge of the laminate (i.e., element 73, Fig. 1) with transverse mode of failure. Here the transverse mode of failure refers to the failure of lamina in a direction perpendicular to the fiber direction due to in-plane stresses transverse to fiber direction (i.e., matrix failure).

The load-deflection response and details of failure characteristics of the laminate with cutout of various shapes and size A_2 are shown in Fig. 5 and Table 5, respectively. It is clear from Table 5 that for cutout size A_2, the effect of cutout shapes is more considerable as compared to cutout size A_1 (Table 4). Like in the case of laminates with cutouts of size A_1, the laminates with elliptical-vertical and elliptical-horizontal cutouts of size A_2 have maximum and minimum postbuckling

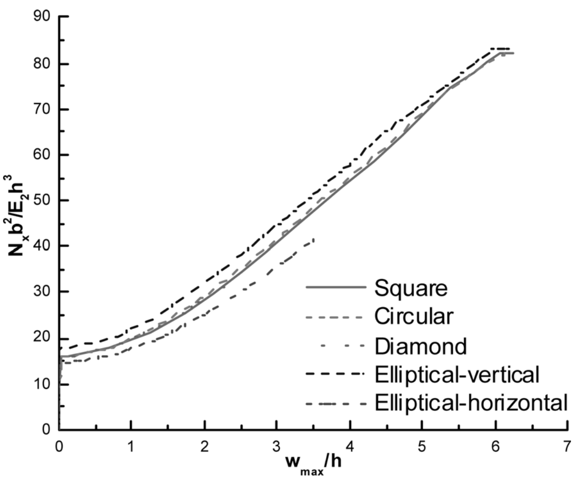

Fig. 5 Load-deflection responses of quasi-isotropic laminate with cutouts of size A_2 and of various shapes

Table 5 Details of failure results for (+45/−45/0/90)$_{2s}$ laminate with cutouts of size A_2 and of various shapes

Cutout shape	Buckling load	First-ply failure load	Total failure load$^{\Theta}$	$(w_{max}/h)^*$	FE$^{\oplus}$	FL$^{\otimes}$	FG$^{\varnothing}$	Mode of first-ply Failure
Square	16.0	53.4	82.4	3.94	73	1	3	Transverse#
Circular	16.0	53.8	82.1	3.87	73	1	2	Transverse
Diamond	16.1	31.9	31.9	2.31	96	Interface 15	-	Early onset of Delamination causes the failure
Elliptical-Vertical	17.9	54.1	83.1	3.7	73	1	2	Transverse
Elliptical-Horizontal	14.7	41.1	41.8	3.46	90	14	9	Transverse

$^{\Theta}$Total failure is said to have occurred because of onset of delamination or complete loss of stiffness due to large transverse deflection
*Non-dimensionalized maximum transverse displacement at first-ply failure
$^{\oplus}$First failed element number; $^{\otimes}$First failed layer number of the first failed element
$^{\varnothing}$First failed gauss point of the first failed layer of the first failed element
#Transverse mode of failure refers to the failure of lamina in a direction perpendicular to the fiber direction (i.e., matrix failure)

strength, respectively, for a particular value of transverse deflection (see Fig. 5). Further, an insignificant increase in the first-ply failure loads is observed in the case of laminates with square, circular and elliptical-vertical cutouts with the increase in cutout size from A_1 to A_2. For all shaped cutouts, the mode of first-ply failure is transverse failure, excluding laminate with diamond shaped cutout, wherein the early onset of delamination causes the total failure before first-ply failure occurs. Location of first-ply failure remains at outer edges of the laminate in the case of laminates with square, circular and elliptical-vertical cutouts, whereas the first-ply failure occurs near the cutout edge in the laminates with diamond and elliptical-horizontal cutouts.

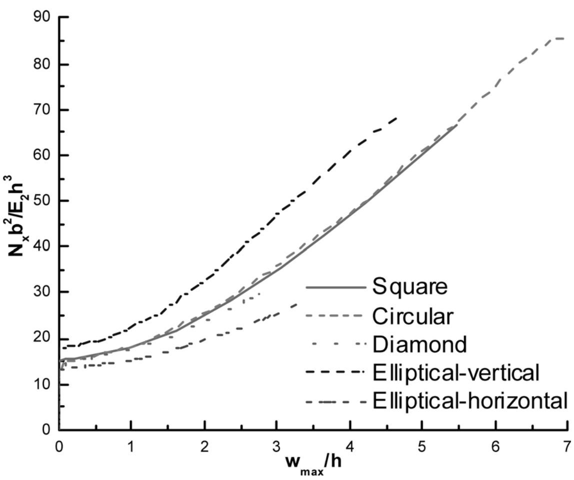

Fig. 6 Load deflection responses of quasi-isotropic laminate with cutouts of size A_3 and of various shapes

Table 6 Details of failure results for $(+45/-45/0/90)_{2s}$ laminate with cutouts of size A_3 and of various shapes

Cutout Shape	Buckling load	First-ply failure load	Total failure load$^{\Theta}$	$(w_{max}/h)^*$	FE$^{\oplus}$	FL$^{\otimes}$	FG$^{\varnothing}$	Mode of first-ply Failure
Square	15.4	49.4	66.5	4.17	78	14	6	Transverse$^{\#}$
Circular	15.2	45.5	85.2	3.79	90	3	9	Transverse
Diamond	15.1	30.4	30.4	2.8	67	Interface 15	-	Early onset of Delamination causes the failure
Elliptical-Vertical	18.2	42.3	68.3	2.68	60	4	3	Transverse
Elliptical-Horizontal	13.5	27.3	27.3	3.26	90	Interface 15	-	Early onset of Delamination causes the failure

$^{\Theta}$Total failure is said to have occurred because of onset of delamination or complete loss of stiffness due to large transverse deflection
*Non-dimensionalized maximum transverse displacement at first-ply failure
$^{\oplus}$First failed element number; $^{\otimes}$First failed layer number of the first failed element;
$^{\varnothing}$First failed gauss point of the first failed layer of the first failed element
$^{\#}$Transverse mode of failure refers to the failure of lamina in a direction perpendicular to the fiber direction (i.e., matrix failure)

Load-deflection response and details of failure characteristics for cutout size A_3 are shown in Fig. 6 and Table 6, respectively. As observed from Fig. 6 and Table 6, that the effect of cutout shapes is most significant in laminates with cutout size A_3 as compared to cutout sizes A_1 & A_2 (mentioned earlier with reference to Tables 4, 5, respectively). Also, the laminate with elliptical-vertical cutout has maximum reserve postbuckling strength, while the laminate with elliptical-horizontal has the minimum reserve strength. The mode of first-ply failure in laminates with square, circular and elliptical-vertical cutout is the transverse matrix failure, and in the case of laminates with diamond and elliptical-horizontal cutouts, the early onset of delamination takes place. Further, except in the case of laminate with diamond cutout of size A_3, cutout edge is the critical location of first-ply failure.

Effects of cutout size on load-deflection responses of the laminates with square, circular, diamond, elliptical-vertical and elliptical-horizontal cutouts are shown in Fig. 7. It is apparent that the buckling and postbuckling strength of the laminate for a particular value of deflection reduces with increase in cutout size from A_1 to A_3, except in the case of laminate with elliptical-vertical cutout, wherein the buckling load is almost same (within 2%) for all sized cutouts, but the first-ply failure is minimum for large size cutout (i.e., A_3). Hence, there is no significant effect of cutout size on load-deflection response of the laminate with elliptical-vertical cutout, while this effect is most considerable in the case of laminate with elliptical-horizontal cutout. Further, it can also be observed from Tables 4-6 that with the increase of cutout size the location of first-ply failure shifts from boundary edges of the laminate to the edge of the cutout in all cases, except in case of laminate with elliptical-horizontal cutout, wherein the location of failure remains at cutout edge. This can be attributed to the fact that as the cutout edge approaches towards the outer edge of the laminate, more stress concentration is caused at the cutout edge and, hence, the first-ply failure takes place at

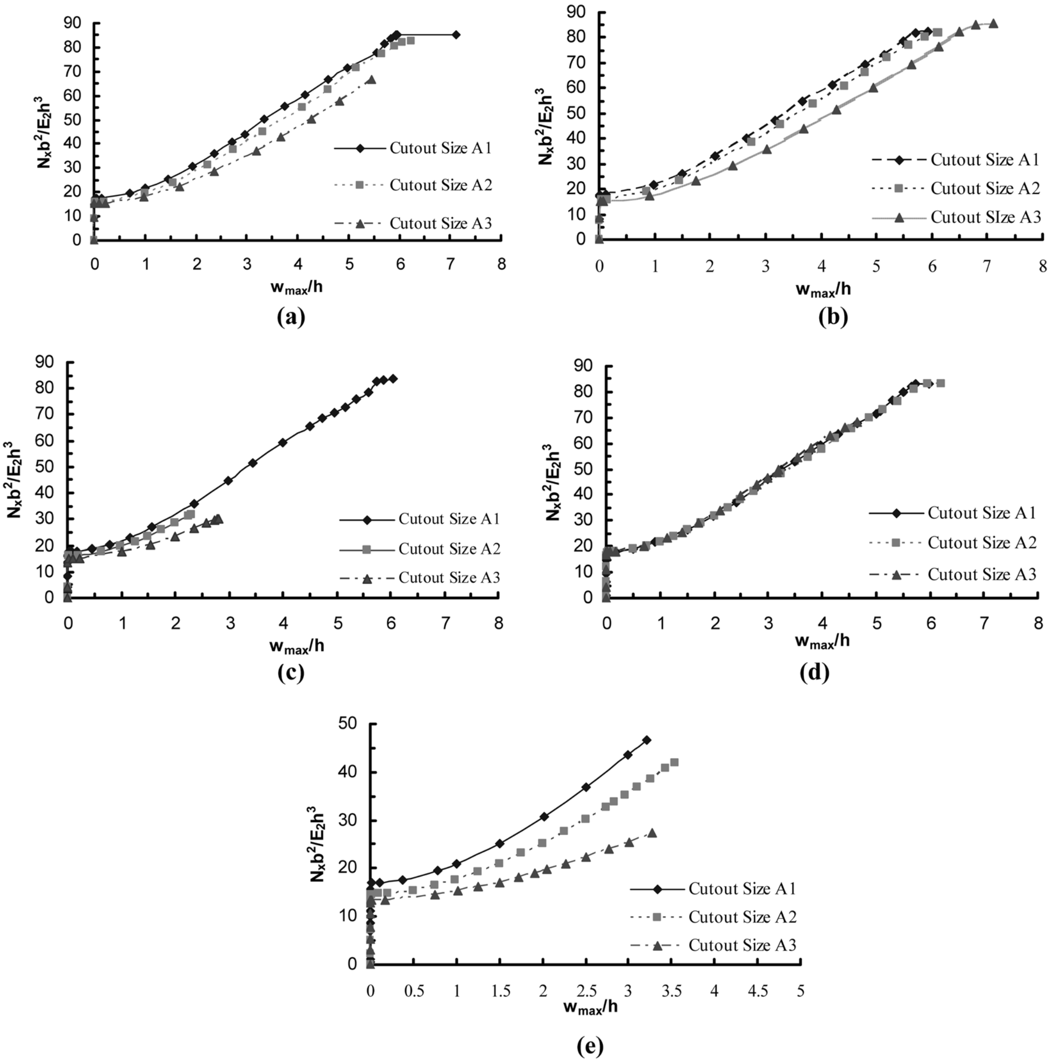

Fig. 7 Cutout size effects on load-deflection responses of quasi-isotropic laminates with (a) square, (b) circular, (c) diamond, (d) elliptical-vertical, and (e) elliptical-horizontal cutouts

cutout edge.

It can also be noticed from Figs. 4, 5 and 6 that the laminate does have reasonable reserve strength beyond buckling in the postbuckling range, irrespective of cutout shapes and sizes. Using these curves, actual postbuckling strength of the laminates can be determined if the maximum allowable transverse deflection is known.

6. Conclusions

Based on the investigations made on effects of cutout shape and size on response of quasi-isotropic laminate under uni-axial compression, the following important conclusions can be made:

1. A laminate with cutout has reasonable reserve strength beyond buckling in the postbuckling range, irrespective of cutout shapes and its sizes.
2. The introduction of cutout reduces the buckling load of the laminate and it reduces further with increase in cutout size. However, the laminate with elliptical-vertical cutout has least effect of cutout and its size on buckling load and the load-deflection response.
3. For the same cutout area, the laminate with elliptical-vertical cutout has the maximum buckling and postbuckling strength and the laminate with elliptical-horizontal cutout has the minimum.
4. The effect of cutout shape on load-deflection response is more significant in the case of cutouts of large cutout area.
5. The load-deflection responses of laminates with square, circular and diamond cutouts are more or less same for the same cutout area. However, for larger cutout area (about 18% of the laminate area), the failure load and failure mode of laminate with diamond cutout is significantly different from that of square & circular cutouts.
6. A laminate with an elliptical-vertical cutout has higher buckling and postbuckling strength compared to the one with elliptical-horizontal cutout of the same area.
7. A laminate with smaller sized cutout is more likely to fail first near the edge of the laminate, and as the cutout size increases the location of failure shifts towards the cutout edge, irrespective of cutout shapes.

Acknowledgements

The present work is the part of CSIR project (No. 22(0442)/07/EMR-II) and K.K. Birla Academy project. The financial support by CSIR, New Delhi and K.K. Birla Academy to execute the project is highly appreciated.

References

Akbulut, H. and Sayman, O. (2001), "An investigation on buckling of laminated plates with central square hole", *J. Reinf. Plast. Comp.,* **20**(13), 1112-1124.
Brit, V.O. (1994), "Shear and compression buckling analysis for anisotropic panels with elliptical cutouts", *J. Sound Vib.,* **32**(11), 2293-2298.
Engelstad, S.P., Reddy, J.N. and Knight, N.F. (1992), "Postbuckling response and failure prediction of graphite-epoxy plates loaded in compression", *AIAA J.*, **30**(8), 2106-2113.
Ghannadpour, S.A.M., Najafi, A. and Mohammadi, B. (2006), "On the buckling behavior of cross-ply laminated composite plates due to circular/elliptical cutouts", *Comput. Struct.*, **75**, 3-6.
Guo, S.J. (2007), "Stress concentration and buckling behaviour of shear loaded composite panels with reinforced cutouts", *Compos. Struct.*, **80**(1), 1-9.
Jain, P. and Kumar, A. (2004). "Postbuckling response of square laminates with a central circular/elliptical cutout", *Compos. Struct.*, **65**(2), 179-185.
Kong, C.W., Hong, C.S. and Kim C.G. (2001), "Postbuckling strength of composite plate with a hole", *J. Reinf. Plast. Comp.,* **20**(6), 466-481.
Kumar, D. and Singh, S.B. (2010), "Effects of boundary conditions on buckling and postbuckling responses of composite laminate with various shaped cutouts", *Compos. Struct.*, **92**, 769-779.
Lin, C.C. and Kuo, C.S. (1987), "Buckling of laminated plates with holes", *J. Compos. Mater.*, **23**, 536-553.
Nemeth, M.P. (1988), "Buckling behavior of compression loaded symmetrically laminated angle-ply plates with

holes", *AIAA J.*, **26**, 330-336.
Nemeth, M.P. (1996), "Buckling and postbuckling behavior of laminated composite plates with a cutout", *Technical Report: NASA-96-tp3587*, NASA Langley Technical Report Server.
Reddy, Y.S.N. and Reddy, J.N. (1992), "Linear and nonlinear failure analysis of composite laminates with transverse shear", *Compos. Sci. Technol.*, **44**(4), 227-255.
Robert, M.J. (1975), *Mechanics of Composite Materials*, 1st Edition, McGraw-Hill Kogakusha Ltd., Tokyo.
Shanmugam, N.E., Thevendran, V. and Tan, Y.H. (1999), "Design formula for axially compressed perforated plates", *Thin Wall. Struct.,* **34**(1), 1-20.
Singh, S.B. (1996), "Postbuckling response, strength and failure of symmetric laminates", Ph.D. Dissertation, Indian Institute of Technology, Kanpur, India.
Singh, S.B. and Kumar, D. (2008), "Postbuckling response and failure of symmetric laminated plates with rectangular cutouts under uniaxial compression", *Struct. Eng. Mech.*, **29**(4), 455-467.
Srivatsa, K.S. and Krishna Murty, A.V. (1992), "Stability of laminated composite plates with cut-outs", *Comput. Struct*., **43**, 273-279.

Notations

The following symbols are used in this paper:

b	: in-plane dimensions of the square plate in x- and y-direction;
c	: dimensions of square and diamond cutouts;
d	: diameter of circular cutout;
e & f	: major and minor axes of the elliptical cutout;
E_1, E_2 and E_3	: principal Young's moduli in fiber direction and other two transverse directions, respectively;
G_{12}, G_{13} and G_{23}	: shear moduli associated with planes 1-2, 1-3 and 2-3, respectively;
h	: thickness of the square plate;
N_x	: applied uni-axial compression loads per unit width in x-direction;
R, S and T	: shear strengths of lamina in planes 2-3, 1-3 and 1-2, respectively;
w_{max}	: maximum transverse deflection;
X_t and X_c	: tensile and compressive strengths of lamina in fiber direction, respectively;
Y_t and Y_c	: tensile and compressive strengths of lamina in direction transverse to fiber, respectively;
Z_t and Z_c	: tensile and compressive strengths of lamina in principal material direction-3, i.e., perpendicular to plane of lamina, respectively;
ν_{12}, ν_{13} and ν_{23}	: Poisson's ratios associated with planes 1-2, 1-3 and 2-3, respectively;
σ_3	: transverse normal stress component in principal material direction 3;
σ_{DN}	: peel strength equal to the tensile normal transverse strength of lamina;
σ_{DS}	: interlaminar shear strength equal to transverse shear strength corresponding to the plane 1-3 of lamina;
θ	: fiber orientation with respect to x-direction; and
τ_{13}, τ_{23}	: transverse shear stress components in principal material planes 1-3 & 2-3, respectively.

Appendix

Interlaminar failure criterion (Singh 1996)

As per the interlaminar failure criterion, the onset of delamination takes place when the interlaminar transverse stress (calculated by integration of equilibrium equations) components satisfy the following expression:

$$\left(\frac{\sigma_3}{\sigma_{DN}}\right)^2 + \frac{\tau_{13}^2 + \tau_{23}^2}{\sigma_{DS}^2} \geq 1$$

Where, σ_3 is the transverse normal stress component; τ_{13}, τ_{23} are the transverse shear stress components in principal material planes 1-3 and 2-3, respectively; σ_{DN} is the peel strength and σ_{DS} is the interlaminar shear strength; these are taken equal to the tensile normal transverse strength and transverse shear strength (corresponding to the plane 1-3) of lamina, respectively.