Buckling analysis of quasi-isotropic symmetrically laminated rectangular composite plates with an elliptical/circular cutout subjected to linearly varying in-plane loading using fem

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Abstract- In this paper the effects of circular and elliptical cutout on the buckling behavior of a sixteen ply quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plate $[0°/+45°/-45°/90°]_{2s,}$ subjected to various linearly varying in-plane compressive loads, numerically. Further, this paper addresses the effects of size of elliptical cutout, orientation of elliptical cutout, plate aspect ratio (a/b), plate length/thickness ratio(a/t) , boundary conditions on the buckling bahaviour of symmetrically laminated rectangular composite plates subjected to various linearly varying in-plane compressive loading is carried out using Finite element method (FEM). The results show that the buckling loads of rectangular composite plates subjected to linearly varying in-plane loads are decreased by increasing of cutout positioned angle β and increasing of c/b and d/b ratios . The magnitudes of buckling loads are decreased by increasing the plate aspect ratio (a/b) and length/thickness (a/t) ratio. It is observed that the buckling loads for composite plates under CC type boundary conditions are higher than those under CS type boundary conditions, irrespective of cutout shape ,size ,orientation of cutout and type of linearly varying in-plane compressive load. It is observed that the buckling loads for composite plates under L4 type loading are higher than those under L1, L2 and L3 type loading, irrespective of cutout shape ,size ,orientation of cutout and boundary conditions.

***Keywords*:** Buckling; Symmetrically laminated rectangular composite plates; Finite element analysis; cutout; Quasi-isotropic; Aspect ratio; Linearly varying in-plane load; Boundary conditions.

Nomenclature

a Length of the plate
b Width of the plate
c major axis diameter of the cutout
d Minor axis diameter of the cutout
t thickness of the plate
β cutout orientation angle with respect to x axis
a/b aspect ratio
a/t length/thickness ratio
Nx Applied compression load per unit width in x-direction

I. INTRODUCTION

Composite laminates have been used increasingly in aeronautical, automobile and marine industries due to their high stiffness and strength-to-weight ratios, long fatigue life, resistance to electrochemical corrosion and other superior material properties of composites. A true understanding of their structural behaviour is required, such as the deflections, buckling loads and modal characteristics, the through-thickness distributions of stresses and strains, the large deflection behaviour and, of extreme importance for obtaining strong, reliable multi-layered structures, the failure characteristics [1].

Studies on buckling analysis of plates under non-linear compressive loads have been very few. Plate problems are often idealizations of portions of a much larger overall stiffened or built-up structure-an aircraft wing or a ship or a multistoried building, for instance, and hence the loads that cause buckling are those exerted by the adjoining free –body on the plate; thus, uniform loading is an exception rather than the rule because the elastic forces between the free bodies depend on their relative stiffness.It is necessary to analyse plates subjected to various types of simple, assumed edge load distributions so as to understand their qualitative and quantitative influence on the buckling behavior [2]. In general, the analysis of composite laminated plates is more complicated due to their anisotropic and heterogeneous nature. Less attention has been paid on the buckling of rectangular composite plates with cutouts. Due to the practical requirements, cutouts are often required in structural components to produce lighter and more efficient structures. For example, cutouts in wing spars and cover panels of commercial transport wings and military fighter wings are needed to provide access for hydraulic lines, electrical lines and for damage inspection [3].

II. LITERATURE REVIEW

Jana and Bhaskar [2]carried out a buckling analysis of a simply supported rectangular plate subjected to various types of non-uniform compressive loads. Chai et al.[4] investigated the influence of boundary conditions , plate aspect ratios on the optimal ply angle and associated optimal buckling loads of antisymmetrically laminated composite plates under various linearly varying in-plane loading conditions. Hurang Hu et al.[5] investigated the buckling behavior of a graphite/epoxy symmetrically laminated composite rectangular plate under parabolic variation of axial loads. The influence of plate aspect ratio and fiber orientation have been investigated.

Nemeth [6]carried out buckling analysis of infinitely long symmetrically laminated graphite/epoxy composite plates that are subjected to linearly varying edge loads, uniform shear loads or combination of these loads. Zhong and Chao [7]studied the effects of plate aspect ratios, load intensity variation and layup configuration on the buckling behavior of simply supported symmetrical cross-ply composite rectangular plates. Sarat and Ramachandra [8]studied the effects of boundary conditions, non-uniform inplane loading, plate aspect ratio and length/thickness ratio on the buckling behavior of rectangular composite plates.

Arthur and Kang[9] , Kang and Arthur [10] presented the exact solutions for buckling analysis of rectangular plates having two opposite edges simply supported when these edges are subjected to linearly varying loads and the other two edges may be clamped, simply supported or free. Hsuan-The and Bor-horng Lin [11] investigated the influence of end conditions, plate aspect ratio's and cutouts on the optimal fiber orientations and the associated optimal buckling loads of symmetrically laminated composite plates under uniaxial compression load.The critical buckling loads of composite plates were calculated by the bifurcation buckling analysis implemented in the ABAQUS finite element program.

Hsuan-The Hu and Zhong-Zhi [12]Chen investigated the influence of end conditions aspect ratio's, cutouts, lateral loads on the optimal fiber orientations and the associated optimal buckling loads of unsymmetrically laminated plates. Baba and Baltaci [13] [14] carried out a buckling analysis of rectangular composite laminates with a central circular hole. A numerical and experimental study was carried out to determine the effects of anti-symmetric laminate configuration, cutout and length/ thickness ratio ,boundary conditions on the buckling bahaviour of Eglass-epoxy composite plates.

Dinesh kumar and Singh [15] studied the effects of boundary conditions on buckling and post buckling bahaviour of axially compressed quasi-isotropic laminate, $(+45/-45/0/90)_{2S}$ with various shaped cutouts (circular, square, diamond, elliptical-vertical and elliptical-horizontal) of various sizes using the finite element method. Eiblmeir and laughlan [16] [17] investigated the effect of different sized cutouts, with and without various types of reinforcement's boundary conditions and width of the circular reinforcement rings on the buckling behaviour of symmetrically laminated CFRP square panels loaded in pure shear or in uni-axial compression, using finite element method.

Guo [18] [19] investigated the effect of reinforcements around cutouts on the stress concentration and buckling bahaviour of symmetrically laminated carbon/epoxy composite panel under in-plane shear load. Four different types of cutout reinforcements made of a range of materials were evaluated. In the analysis, finite element method and an analytical method based on the laminate theory were employed to perform parametric studies on the various reinforcement designs. Numerical results and experimental results were compared. Mehmet and Murat [20] carried out buckling analysis of symmetrically laminated cross-ply reinforced concrete plates with a central rectangular hole under biaxial in-plane loadings considering simply supported and clamped boundary conditions.

Husam et al. [21] investigated the effect of cutout size, cutout location, fibre orientation angle and type of loading on the buckling load of square composite plates with circular cutout. Hani aziz ameen [22] studied the effect of the shapes, sizes, radii of corner of cutout and number of layers on the critical buckling load of the composite laminated plate. Srivatsa and murthy [23] investigated the effect of boundary conditions , fibre orientations, cutout sizes on the critical buckling load of laminated fibre-reinforced plastic square panels. Results were obtained using FEM based on CLPT.

Ghannadpour et al. [24] studied the influence of a cutout on the buckling behaviour of rectangular symmetric cross-ply laminates made of polymer matrix composites (PMC). Finite element analysis was also carried out to predict the influence of cutout on the buckling bahaviour of these plates. Jain and Kumar [25] performed the post buckling analysis of symmetric square laminates with a central cutout under uniaxial compression by finite element method. The governing finite element equations were solved using the Newton-Rapson method. For the purpose of analysis, laminates with circular and elliptical cutouts were considered with a view to examine the effect of cutout shape , size and the alignment of the elliptical cutout on the buckling and the first-ply failure loads of laminates.

Shufrin et al. [26] [27] carried out buckling analysis of symmetrically laminated rectangular plates with generally supported laminated plates subjected to a general combination of in-plane shear, compression and tension loads using a semi-analytical extended Kantorovich approach. Kumar and Singh [28] investigated the post buckling response and progressive failure of thin, symmetric rectangular laminates with various lay-ups and plate aspect ratios, under in-plane shear loads. First order shear deformation theory was used with a finite element procedure. The effect of four in-plane boundary conditions on the buckling loads, post buckling response and failure loads was presented

Aydin, Faruk sen, Atas, Arslan [30] studied the effects of an elliptical/circular cutout on the buckling load of woven glass-polyster square composite plates. A numerical study was carried out to study the effects of symmetric cross-ply and angle-ply laminate configuration on buckling load.

In this paper the effect of circular and elliptical cutouts on the buckling behaviour of quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plates under various linearly varying in-plane compressive loading is carried out using FEM. This study also contains the effect of cutout orientation angle β, different sizes of cutout, plate aspect ratio a/b and length/thickness a/t and boundary conditions on the buckling behaviour of rectangular composite plates subjected to linearly varying in-plane compressive load.

III. BUCKLING ANALYSIS

In this study, a numerical study using finite element method has been carried out to investigate the effect of circular and elliptical cutouts on the buckling response of quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plates subjected to various linearly varying in-plane compressive loading .Furthermore, the effects of plate aspect ratio a/b, plate length/thickness ratio a/t, cutout orientation angle β, size of cutout, boundary conditions on the buckling response of quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plates under various in-plane compressive loading.

The lamina consists of graphite fibers as reinforcement material and epoxy as matrix material. The material properties of graphite/epoxy are taken from reference [11] and listed in Table I.

Table I: Material properties of the graphite/epoxy composite material [11]

E_{11} (Gpa)	E_{22} (Gpa)	ν_{12}	$G_{12} = G_{13}$ (Gpa)	G_{23} (Gpa)
128	11	0.25	4.48	1.53

The geometry is as shown in Fig.1.The width of the plate' b' is 100mm and the length of the plate 'a' is 200mm. The thickness of each layer of this sixteen layer laminate is 0.125mm and 't' is the thickness of the plate. In this work the cutout shape was assumed an elliptical hole centered in the rectangular plate. The diameters of the major and minor axis dimensions are c and d respectively. The parameters c and d are changed according to selected ratios, hence the elliptical hole is also positioned as circular hole when c/b and d/b are equal. So, the effect of circular hole is also analyzed at the same conditions. Briefly ,the buckling analysis is performed for both various elliptical holes and circular holes . The laminated plates are also analyzed without a hole when c/b=0 or d/b=0 to compare the effects of having a cutout and without a cutout conditions on buckling loads.

In this study quasi-isotropic $[0°/+45°/-45°/90°]_{2s}$ symmetrically laminated rectangular plates are analyzed.

The buckling loads of the plates with elliptical/circular hole are obtained by commercially available finite element software ANSYS. The plates are modeled using eight noded multi-layered shell elements (SHELL 91). The SHELL 91 [29] element type illustrated in Fig.2 has 8 nodes with 6 degrees of freedom at each node; translations along x, y, z directions and rotations about the nodal x, y and z axes. SHELL 91 can be used for layered applications of a structural shell model. Up to 100 different layers are permitted for applications with the sandwich option turned off. The different models and mesh structures are made because of the different cutout dimensions and angles. A sample mesh structure is shown in Fig.3. As seen from this figure, small meshes are set in the vicinity of the cutout where large stress concentrations are expected. The boundary conditions and mesh structure of the model are illustrated in Fig 3 clearly.

The boundary conditions have a significant influence on the buckling behavior of quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plate with cutout subjected to various linearly varying in-plane compressive loads. In this study the quasi-isotropic rectangular composite plate is evaluated at two different boundary conditions.

Two types of boundary conditions, namely CC and CS are considered; CC refers to a plate with two longitudinal edges (x=0 and x=a) clamped and the other two edges free (i.e y=0and y=b) and CS refers to a plate with one edge (x=0) clamped , other edge (x=a) simply supported and the other two edges free (i.e y=0 and y=b).

Four types of loading conditions are considered, namely L1, L2, L3 and L4 which are shown Fig.4. The in-plane compressive load Nx is applied on the edge x=a.

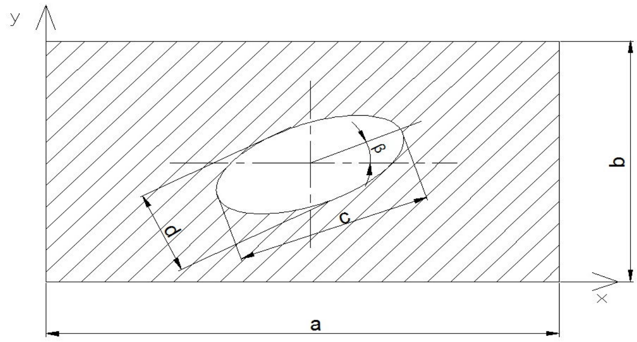


Fig.1.Geometry of the model.

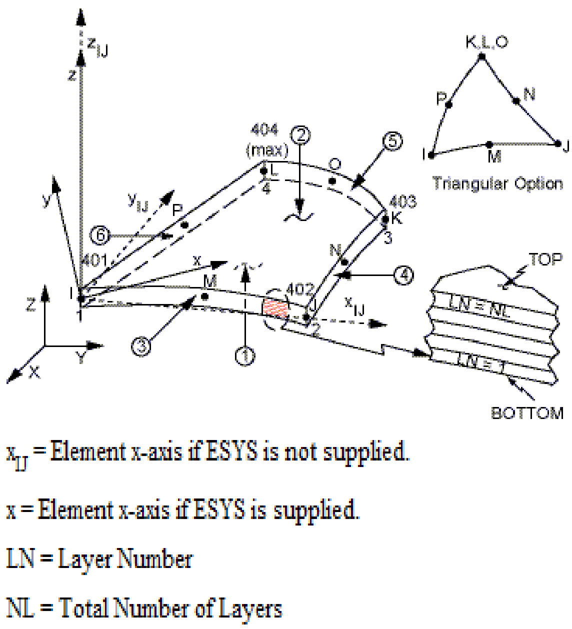
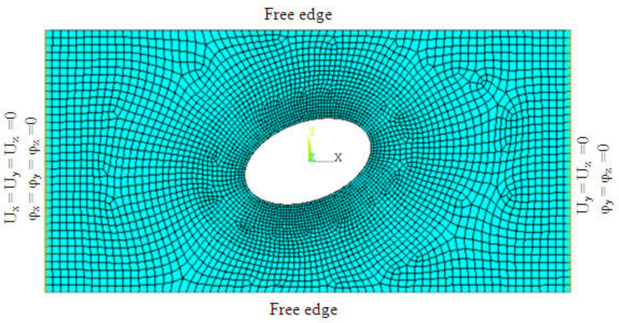
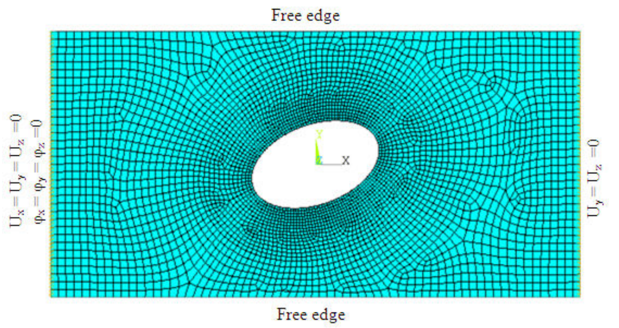


Fig.2 SHELL 91 element geometry [29]

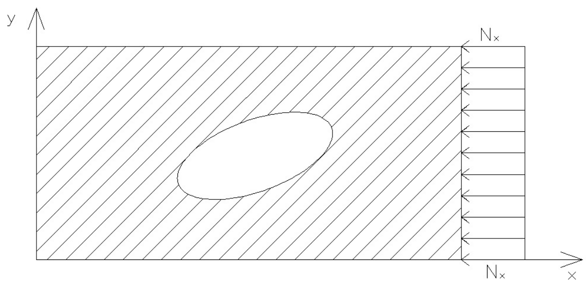


a) CC type boundary condition

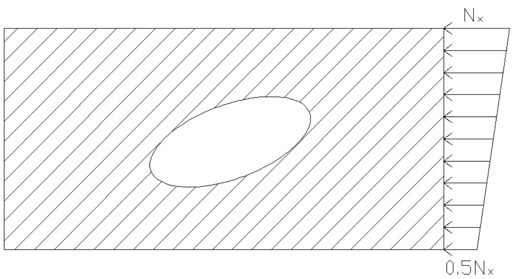


b) CS type boundary condition

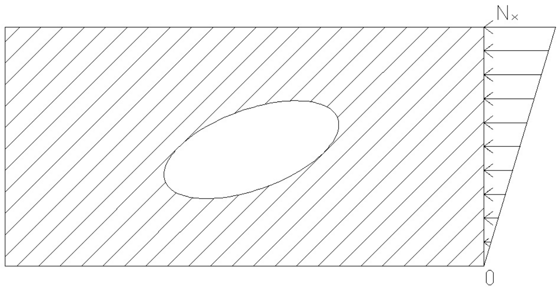
Fig.3 .Boundary conditions and finite element mesh of the laminated plate



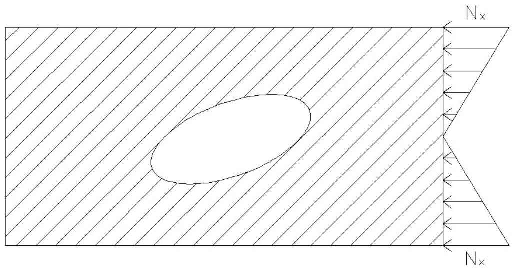
a) L1 loading condition



b) L2 loading condition



c) L3 loading condition



d) L4 loading condition

Fig.4. Details various loading conditions

IV RESULTS AND DISCUSSION

A. Effect of boundary conditions, various linearly varying in-plane compressive loading and cutout orientation β on buckling load.

The effects of boundary conditions, various linearly varying in-plane compressive loading, cutout orientation β and c/b and d/b ratios on the buckling loads are shown in Fig. 5. Fig. 5a, 5b, 5c, 5d reveals that the buckling loads are decreased by increasing cutout orientation β, c/b and d/b ratios , irrespective of boundary conditions and various linearly varying in-plane compressive loading conditions.

From Fig. 5a, 5b, 5c and 5d it is understood that the buckling load of the quasi-isotropic $[0°/+45°/-45°/90°]_{2s}$ rectangular composite plate with CC type boundary condition is 2 times higher than the buckling load of the composite plate with CS type boundary condition.

The second important point from the Fig.5, the buckling load of the quasi-isotropic $[0°/+45°/-45°/90°]_{2s}$ rectangular composite plate with L4 type loading condition are higher than those under L1, L2, L3 type loading conditions, irrespective of cutout shape, size , orientation of cutout and boundary conditions.

As seen from Fig. 5a, 5b,5c and 5d ,the buckling load of the quasi-isotropic $[0°/+45°/-45°/90°]_{2s}$ rectangular composite plate with L4 type loading condition is approximately 2 times higher than the buckling load of the composite plate with L1 type loading condition for a particular size, orientation of cutout and boundary condition.

According to Fig.5a, for quasi-isotropic [0°/+45°/-45°/90°]$_{2s}$ rectangular composite plate with a/b=2, c/b=0.5, d/b=0.1 and subjected to L4 type loading condition and CC boundary condition, the decrease in the buckling load by increasing the cutout orientation from β=0° to β=90° 17.19%. For the same plate with L1 type loading condition and CS boundary condition, the decrease in the buckling load by increasing the cutout orientation from β=0° to β=90° is 13.19%.

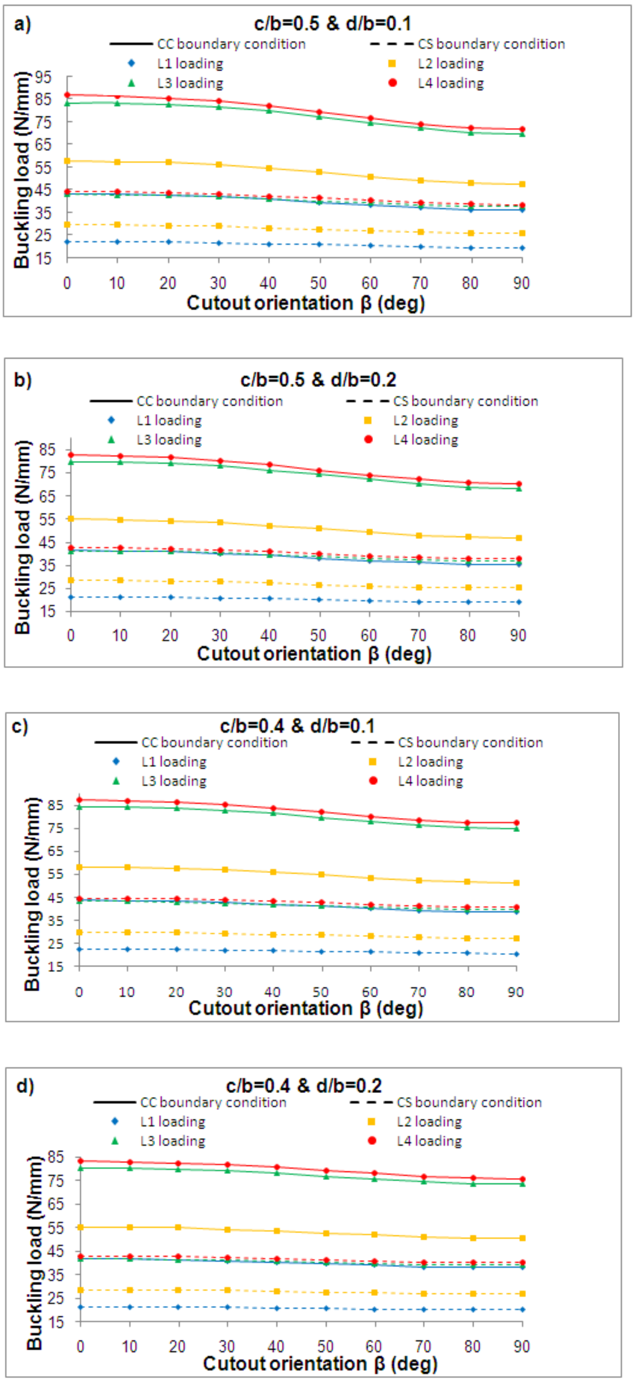


Fig.5: Effect of boundary conditions, various linearly varying in-plane loading, and cutout orientation β on buckling load.

B. Effect of c/b, d/b ratios, boundary conditions, various linearly varying in-plane compressive loading and on buckling load.

The effects of boundary conditions, various linear,ly varying in-plane compressive loading , c/b and d/b ratios on the buckling loads are shown in Fig. 6.

According to Fig.6a, the reduction in buckling load is very fast when cutout orientation β=0°. As seen from the figure 6a for quasi-isotropic [0°/+45°/-45°/90°]$_{2s}$ composite plate with a/b=2, c/b=0.5, β=0° , subjected to L4 type loading and CC boundary conditions, the decrease in the buckling load by increasing the d/b ratio from 0 to 0.5 is 25.74%. For the same plate subjected to L1 type loading and CS boundary conditions, the decrease in the buckling load by increasing the d/b ratio from 0 to 0.5 is 23.29%.

As seen from Fig.6b, the reduction in buckling load is very rapid when cutout orientation β=90° for d/b ratios between 0 and 0.1 and for other d/b ratios the decrease in buckling load is very low. Second important point from the figure 6a, for quasi-isotropic [0°/+45°/-45°/90°]$_{2s}$ composite plate with a/b=2, c/b=0.5, β=90° , subjected to L4 type loading and CC boundary conditions, the decrease in the buckling load by increasing the d/b ratio from 0 to 0.5 is 25.74%. For the same plate subjected to L1 type loading and CS boundary conditions, the decrease in the buckling load by increasing the d/b ratio from 0 to 0.5 is 23.29%. When c/b equals to d/b the cutout becomes circular.

According to Fig.6c, the reduction in buckling load is very slow when cutout orientation β=0°. As seen from the figure 6a for quasi-isotropic [0°/+45°/-45°/90°]$_{2s}$ composite plate with a/b=2, d/b=0.1, β=0° , subjected to L4 type loading and CC boundary conditions, the decrease in the buckling load by increasing the c/b ratio from 0 to 0.5 is 4.49%. For the same plate subjected to L1 type loading and CS boundary conditions, the decrease in the buckling load by increasing the c/b ratio from 0 to 0.5 is 3.32%.

According to Fig.6d, the reduction in buckling load is very fast when cutout orientation β=90°. As seen from the figure 6d for quasi-isotropic [0°/+45°/-45°/90°]$_{2s}$ composite plate with a/b=2, d/b=0.1, β=90° , subjected to L4 type loading and CC boundary conditions, the decrease in the buckling load by increasing the c/b ratio from 0 to 0.5 is 20.91%. For the same plate subjected to L1 type loading and CS boundary conditions, the decrease in the buckling load by increasing the c/b ratio from 0 to 0.5 is 16.08%.

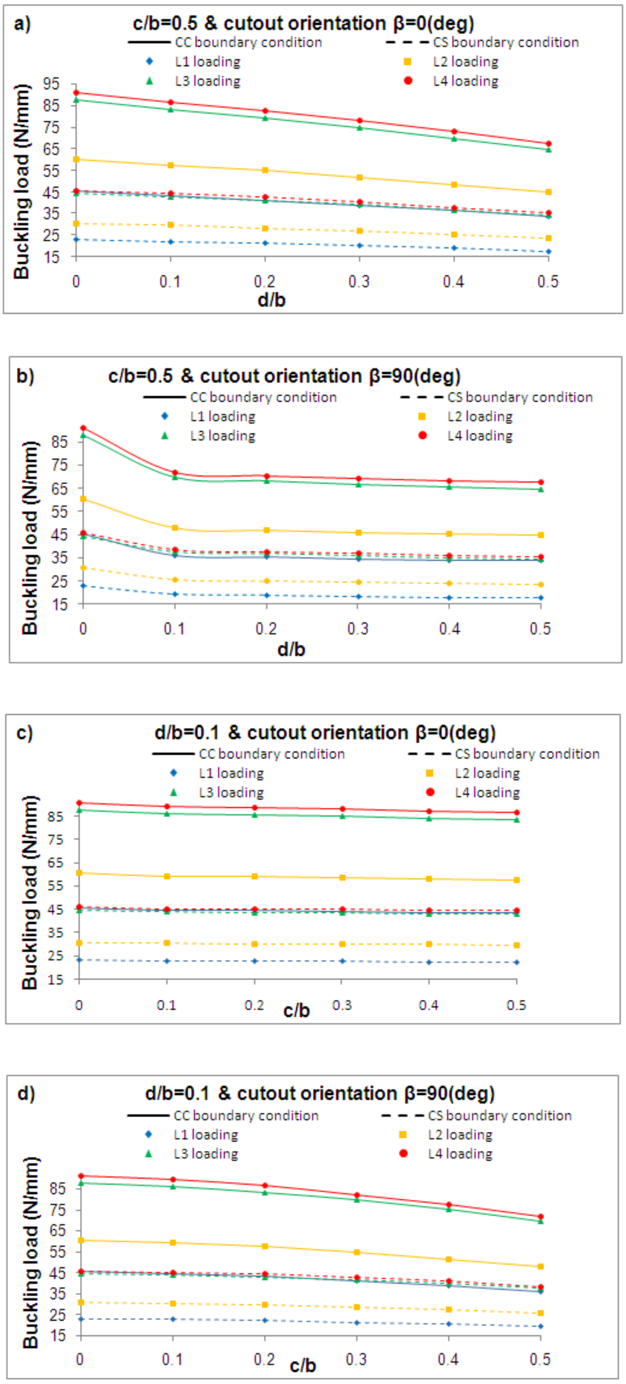


Fig.6: Effect of boundary conditions, various linearly varying in-plane loading, and c/b, d/b ratios on buckling load.

C. Effect of the plate aspect ratio

This section deals with the effect of plate aspect ratio a/b, boundary conditions, cutout orientation β and various linearly varying in-plane compressive loading on the buckling behavior of quasi-isotropic symmetrically laminated rectangular composite plates with elliptical cutout. In this study the plate aspect ratios selected are 2, 2.5, 3, 3.5 and 4.As seen from Fig. 7a and 7b, the buckling loads are decreased as the plate aspect ratios are increased, irrespective of boundary conditions, cutout orientation and various linearly varying in-plane compressive loading.

As seen from fig.7a and 7b, for quasi-isotropic $[0°/+45°/-45°/90°]_{2s}$ composite plate with c/b=0.5, d/b=0.1, β=0°, subjected to L4 type loading and CC boundary conditions, the decrease in the buckling load by increasing the plate aspect ratio a/b from 2 to 4 is 74.76% and for the same plate with β=90° is 72.73%.

According to Fig. 7a and 7b, for quasi-isotropic $[0°/+45°/-45°/90°]_{2s}$ composite plate with c/b=0.5, d/b=0.1, β=0°, subjected to L1 type loading and CS boundary conditions, the decrease in the buckling load by increasing the plate aspect ratio a/b from 2 to 4 is 74.98% and for the same plate with β=90° is 73.23%.

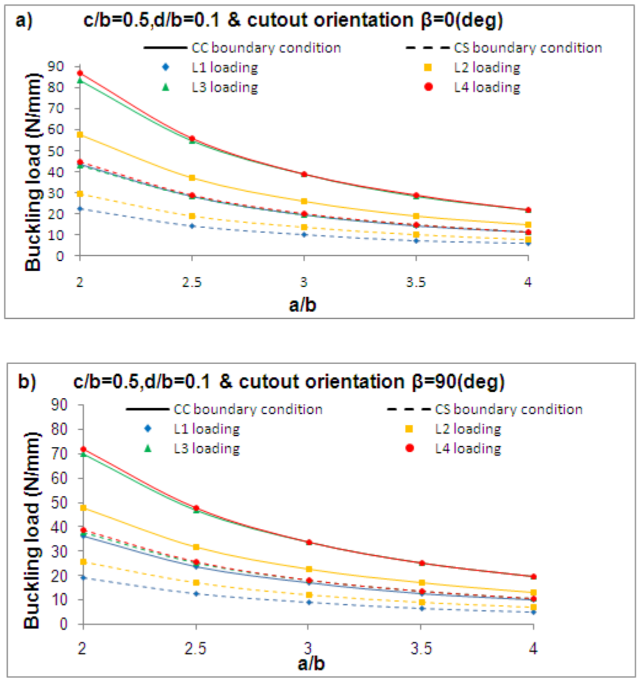


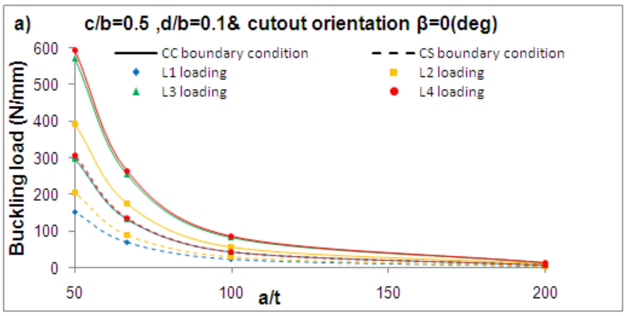
Fig.7: Effect of plate aspect ratio a/b , boundary conditions, various linearly varying in-plane loading and cutout orientation β on buckling load.

D. Effect of a/t ratio on buckling load

Fig. 8 shows the effect a/t ratio, cutout orientation β, boundary conditions and various linearly varying in-plane compressive loading conditions on the buckling behavior quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plate $[0°/+45°/-45°/90°]_{2s}$, with an elliptical cutout. In this study the plate length/thickness ratios selected are 50, 66.66, 100 and 200. As seen from fig.8, as length/thickness a/t ratio increases the buckling load decreases, irrespective of orientation of cutout, boundary conditions and various linearly varying in-plane compressive loading conditions.

According to Fig.8a and 8b, for quasi-isotropic rectangular composite plate
$[0°/+45°/-45°/90°]_{2s}$ with c/b=0.5, d/b=0.1, β=0° subjected to L4 type loading and CC boundary conditions, the decrease in the buckling load by increasing the a/t ratio from 50 to 200 is 42.08 times and for the same plate with β=90° is 42.67 times.

According to Fig.8a and 8b, for quasi-isotropic rectangular composite plate with c/b=0.5, d/b=0.1, β=0° subjected to L1 type loading and CS boundary conditions, the decrease in the buckling load by increasing the a/t ratio from 50 to 200 is 42.65 times and for the same plate with β=90° is 43.05 times.



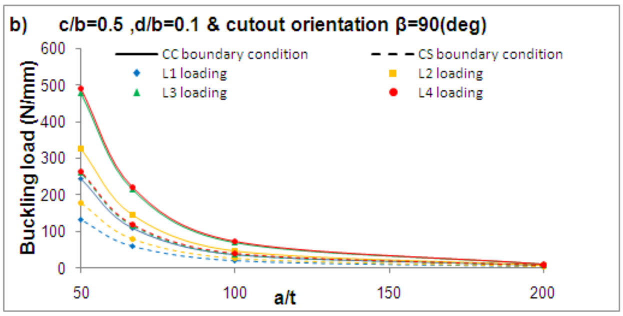


Fig.8: Effect of plate length/thickness ratio a/t, boundary conditions, various linearly varying in-plane loading and cutout orientation β on buckling load.

V. CONCLUSIONS

On the basis of present study, which has dealt with the effect of boundary conditions and various linearly varying in-plane compressive loading conditions on the buckling behaviour of a sixteen ply quasi-isotropic graphite/epoxy symmetrically laminated rectangular composite plate $[0°/+45°/-45°/90°]_{2s}$, with an circular/elliptical hole ,the following conclusions can be made.

The magnitudes of buckling loads are decreased by increasing of cutout positioned angle β and increasing of c/b , d/b ratios, , irrespective of boundary conditions and various linearly varying in-plane compressive loading conditions

The magnitudes of buckling loads are decreased by increasing the plate aspect ratio a/b, irrespective of cutout shape, size, orientation of cutout, boundary conditions and various linearly varying in-plane compressive loading conditions.

As the plate length/thickness a/t ratio increases the buckling load decreases, irrespective of cutout shape, size, orientation of cutout, boundary conditions and various linearly varying in-plane compressive loading conditions.

The buckling load of quasi-isotropic rectangular composite plate is highly influenced by its boundary conditions. The buckling load for the plate with CC type boundary condition is higher than the buckling load for the plate with CS type boundary condition

The magnitude of the buckling load for the plate under L4 type loading condition is higher than those under L1, L2 and L3 type loading, irrespective of cutout shape, size, orientation of cutout, boundary conditions and various linearly varying in-plane compressive loading conditions.

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