Lateral Buckling of Textile Composite Cantilever Beams with Central Cutouts

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***Abstract* - The aim of this study is to investigate the effects of knitting tightness level and some geometric parameters such as the shape of cut-out, bluntness and cut-out orientation on the lateral buckling load of weft-knitted 1x1 rib composite cantilever beams with central cut-outs. Four different cut-out shapes are considered; circle, square, regular triangle and elliptical. The results show that the lateral buckling load decreases with the increase of knitting tightness. The lateral buckling load decreases gradually while the cutout shape changed from elliptical to triangle which means big cut-outs cause the weakest beams under the lateral buckling load. Cut-out bluntness and orientation have negligible effect on the lateral buckling load.**

1. INTRODUCTION

Textile composites are being increasingly used in advanced structures in aerospace, automobile, and marine industries. They have many advantages such as ease of handling, high adaptability, light weight, and high specific stiffness. Textile composites can be divided into three basic categories according to the textile forming techniques used for composite reinforcement: (i) woven fabrics, (ii) knitted fabrics, and (iii) braided fabrics. Compared to the other conventional textile fabrics, knitted fabrics possess high productivity and low cost. Additionally, knitted fabric composites are usually more isotropic than woven fabric composites and they have higher extensibility which means better formability to fit in complicated shapes. All these advantages of knitted composite materials have motivated the researchers to investigate their properties [1].

There are two types of knitted fabric those manufactured by (i) weft knitting and (ii) warp knitting. For weft knitting there is only a single feed of yarn coming into the machine at 90^0 to the direction of fabric production and this yarn forms a row of knit loops across the width of the fabric. In warp knitting there are multiple yarns being fed into the machine in the direction of fabric production, and each yarn forms a line of knit loops in the fabric direction. The knitting directions are also named wale and course.

It is well known that thin composite beams are very susceptible to flexural–torsional/lateral buckling depending on the geometry of the cross-section, the material properties, and the boundary and loading conditions. Hindman et al. [2] has determined of lateral-torsional buckling loads of composite woods having a rectangular cross-section. Turvey[3] conducted a series of tests on rectangular cross-section pultruded GRP cantilever beams, which are loaded in their stiffer plane of symmetry by means of a single point load acting through the centroid of the cross-section at the free end. Karaagac et al. [4] calculated the critical buckling loads of laminated composite cantilever beams having rectangular cross-sections, subjected to vertical end loading, by using FEM. Lawson et al. [5] have investigated lateral buckling behaviors of I-section composite cellular beams, subjected to uniform distributed loads, by using both FEM and experimental studies. Brooks and Turvey[6] conducted a series of tests in order to investigate the lateral buckling behavior of pultruded GRP I-section cantilever beams. Eryigit et al. [7] investigated the effects of hole diameter and hole location on the lateral buckling behavior of woven fabric laminated composite cantilever beams.Erklig et al. [8] investigated the effects of different cutouts (circular, square, triangular and elliptical) on the lateral buckling behavior of composite beams made of polymer matrix composites.However, no specific work has been done so far for related to the weft-knitted composite beams subjected to lateral loading.

In this study, the lateral buckling behaviour of 1x1 rib knitting glass/epoxy perforated laminated beams investigated numerically. The weft-knitted composite plates are manufactured in three different tightness levels, namely low (K_1), medium (K_2), and high (K_3). The mechanical properties of the plates are determined according to ASTM standards. Determined mechanical properties are used in the numerical analyses. Four different parameters are investigated; knitting tightness levels (low, medium and high), the shapes of central-polygonal cut-outs (triangle, square, circular and elliptical), and bluntness (a counter measure of radius ratio, r/R) and orientation of polygonal cut-outs (θ). In order to investigate the effect of these parameters on the lateral buckling behaviour, ANSYS software package is used. Validation of the numerical model is done by using experimental data from the literature.

2. MANUFACTURING OF THE WEFT-KNITTED 1X1 RIB COMPOSITE BEAMS

The weft-knit 1x1 rib fabrics are manufactured in three different tightness levels, namely low (K_1), medium (K_2), and high (K_3). The schematic diagram and photograph of the knitted fabrics are shown in Fig. 1.

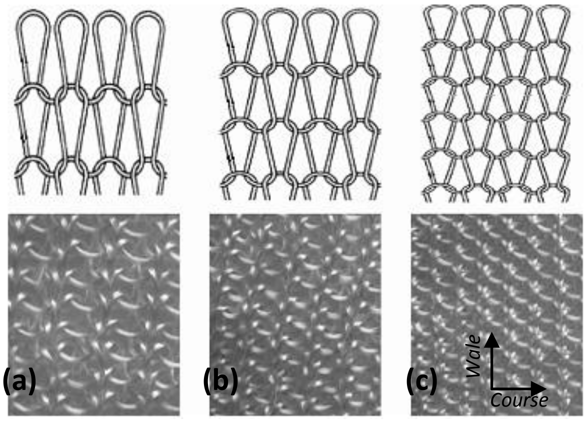


Figure 1. The illustration and photographs of knitted fabrics (a) low, (b) medium and (c) high tightness

Tightness factor of those levels are calculated from the following formula [1];

$$K = \frac{\sqrt{tex}}{l} \qquad (1)$$

where K is the tightness factor, Tex is the count or linear density of yarn, and *l* is the loop length (mm). In order to find the loop length a course of the fabric is de-knitted and yarn length of the course is measured. Then, yarn length of the course is divided by the number of loops in the course. Ten measurements are performed to obtain the average loop length. Areal weight, course density and wale density of the fabrics and the fiber volume fraction of the composite panels which is calculated from the weight of fabrics and panels are given in Table 1.

Table 1. The material properties

	Areal weight (g/m^2)	Course density (course/cm)	Wale density (wale/cm)	Fiber volume fraction (%)	Tightness factor K
Tightness level					
Low (K_1)	374	4	3	59	9.3
Medium (K_2)	478	5	3	61	10.3
High (K_3)	621	7	3	65	13.7

The thickness of each fabric for low, medium and high tightness are of 0.388 mm, 0.48 mm and 0.6 mm, respectively. The fabrics are constructed on a five gauge flatbed knitting machine from 200 tex glass yarn with a slight twisting. The laminates are manufactured from the five layers of the fabric and epoxy matrix. To obtain the flat composite laminates, the knitted-fabric preforms were put into a mould whose wale directions were parallel to each other's and epoxy matrix was impregnated. After the impregnation, the hot press machine was set at a temperature of 130^0C, pressure at 15 MPa, and 3.5 h for the whole pressing process. Then the complete set-up is cooled to room temperature. At the end of the process, laminate thicknesses of the composites are of 2.4±0.4 mm.The mechanical properties are obtained under static loading conditions according to the ASTM standards. The mechanical tests are carried out by using UTEST Tensile Testing Machine of 50 kN load capacity at a ratio of 1 mm/min. The mechanical properties of the knitting laminated composite plates as a function of tightness level are listed in Table 2. Determined mechanical properties are used in the numerical analyses.

Table 2. The mechanical properties of the weft-knitted 1x1 rib composite plates.

	Measured				Assumed		
	E_1	E_2	G_{12}	υ_{12}	$E_3=0.6E_1$	$G_{23}=G_{13}=G_{12}$	$\upsilon_{23}=\nu_{13}=0.6\upsilon_{12}$
Tightness level	(MPa)	(MPa)	(MPa)	-	(MPa)	(MPa)	-
Low (K_1)	7396.2	4710.0	626.7	0.19	4437.2	626.7	0.11
Medium (K_2)	7001.5	4503.7	601.4	0.22	4200.9	601.4	0.13
High (K_3)	6010.3	2981.1	507.8	0.25	3606.2	507.8	0.15

3. NUMERICAL VERIFICATION

In order to check the accuracy of the finite element model, an example taken from the literature is analysed and then numerical results are compared to those obtained experimentally. The geometry and dimensions of the cantilever composite beam used for the validation of finite element method is shown in Fig. 2.

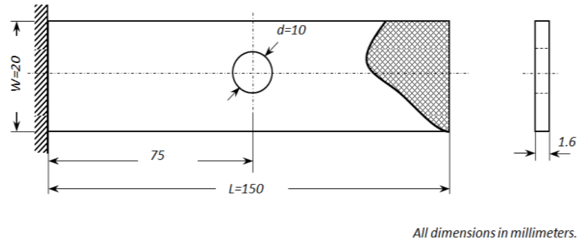


Figure 2. The geometry and dimensions of the cantilever composite beam

The composite beams are woven glass-epoxy composite with the dimensions of 150 x 20 x 1.6 mm (length x width x thickness). The diameter of the central circular cut-out is 10 mm. Three different fibre orientations, namely, $[(0/90)_4]_s$, $[(30/-60)_4]_s$ and $[(\pm45)_4]_s$ are analysed. The material properties are given in Table 3.

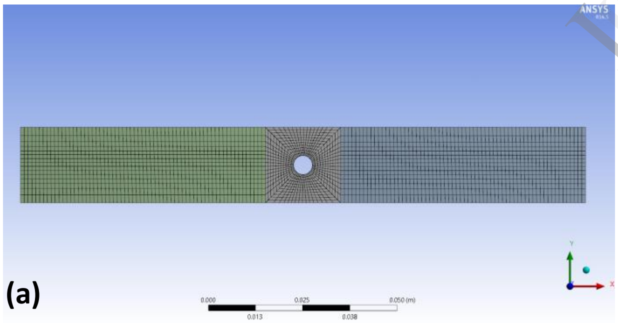
Table 3. The mechanical properties of the laminated composite beams [8]

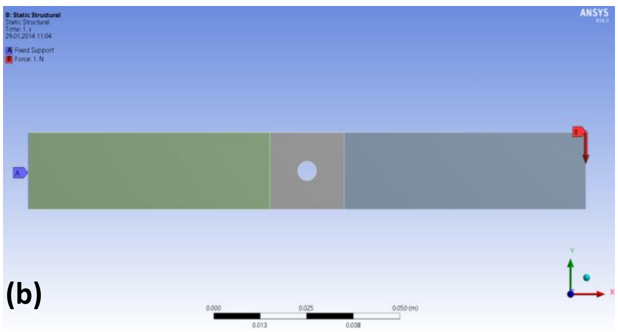
Measured			*Assumed*		
E_1=E_2	G_{12}	υ_{12}	E_3=0.6E_1	G_{23}=G_{13}=G_{12}	υ_{23}=υ_{13}=0.6υ_{12}
(MPa)	(MPa)	(-)	(MPa)	(MPa)	(-)
20200	3561	0.215	12120	3561	0.129

One end is clamped and single vertical load was acted at the free end of the beams in order to calculate lateral buckling load. The lateral buckling load is determined by solving for eigenvalues and the corresponding eigenvectors represents the buckled mode shape. Due to the presence of a cut-out, smaller and larger number of elements is used in the vicinity of the cut-outs (Figure 3). Table 4 shows the comparison of experimental and numerical lateral buckling values of the composite beam with/without hole for different fibre orientations and close agreement is found.

Table 4. The comparison of the lateral buckling loads.

Fiber orientation	Lateral Buckling load (N) (without hole) Experimental [8]	Present study	Error (%)	Lateral Buckling load (N) (with circular cut-out) Experimental [8]	Present Study	Error (%)
[(0/90)₄]ₛ	20.53	20.45	3.9	22.35	19.91	10.9
[(30/-60)₄]ₛ	28.16	27.45	2.5	21.56	24.55	13.8
[(±45)₄]ₛ	24.60	22.32	9.2	20.52	22.79	11.1





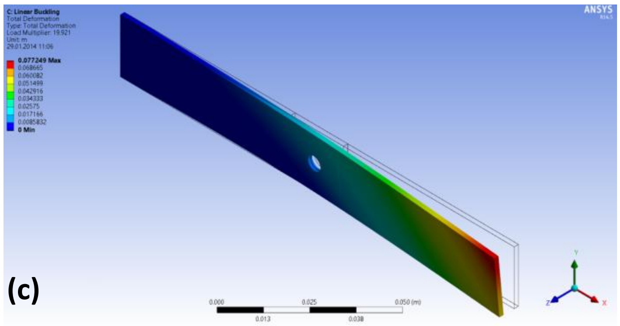


Figure3. (a) Mesh structure, (b) boundary and loading conditions and (c) laterally buckled shape.

4. STATEMENT OF THE PROBLEM

4.1. Case Study-I

The weft-knitted composite beams are of 100 x 25 x 2.4 mm (length x width x thickness). We consider four cut-out shapes – circle, square, regular triangle and the elliptical. For the square and triangle cut-outs the concept of inscribing circle is used, as shown in Fig. 4a, to compare with the corresponding circular cut-out. The solid-lined circles are the inscribing circles in the polygons. The diameter size of the circular cut-out (2R) is 10 mm.

The rotation angle θ represents how the cut-outs are oriented from the baseline (+x axis) and shown in Fig. 4b. Due to the symmetry of the polygonal cut-outs, the rotation angle (θ) increment 3° is applied for the square cut-outs; hence, a total of fifteen cases are considered from 0^0 to 45^0. For the triangle and elliptical cut-outs, the angle of increment 2^0 is applied. Therefore, a total of fifteen cases are considered from 0^0 to 30^0 for the triangle cut-outs while a total of forty-five cases are considered from 0^0 to 90^0 for the elliptical cut-outs.

As shown in Fig. 4b, a term ‘bluntness’ is defined as the ratio of the edge radius (r) to the inscribing circle radius (R). Accordingly, bluntness is a counter measure to the radius ratio (r/R) because bluntness decreases as the radius ratio increases. For an extreme example, a circular cut-out has a unit radius ratio but it has zero bluntness. We consider a total of five different degrees of bluntness including 0.2, 0.4, 0.6, 0.8, and 1.0 for the square and triangular cut-outs.

As shown in Fig. 4c, the diameters of the major and minor axis dimensions of ellipse are presented by b and c; respectively. The diameter of the major axis (b) is 10 mm. c/b ratio are changed from 0.0 to 1.0 with an increment of 0.2. The beams are analysed without a hole when c/b= 0 to compare the influences having a hole and without a hole conditions on lateral buckling loads. The elliptical hole is also positioned as circular hole when c/b = 1, the effect of circular hole is also analysed at these same conditions.

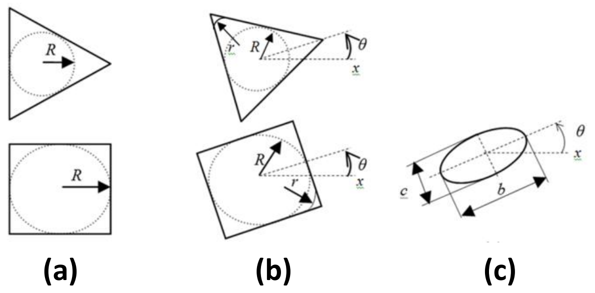


Figure 4. The illustration of (a) inscribing circle, (b) cut-out orientation and bluntness, and(c) elliptical cutout

The boundary conditions are taken to be the same as the model used for the verification. A refine mesh process is performed for surrounding of the hole due to the close areas of the cutout is crucial for FEM solutions. The convergence study is performed to ensure that the number of elements is enough to give a converged solution. For an example, a sample mesh structure is shown in Fig. 5. Additionally, the element number of created some models are presented in Table 5. In total, 990 models with different cutout shapes and bluntness have been analysed.

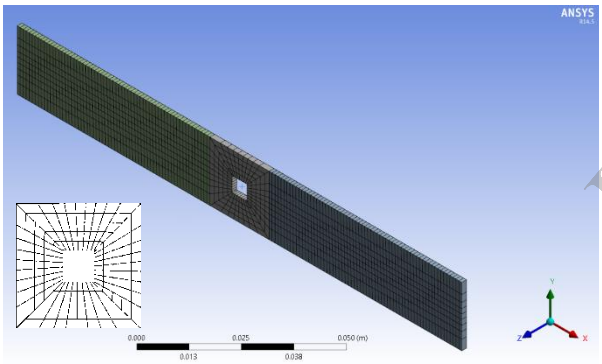


Figure 5. Weft-knitted composite beam with square cut-out

4.2. Case Study-II

The cut-out shapes; circle, square and regular triangle, but equal areas are considered in this case. As in case study I, the diameter size of the corresponding circle is 10 mm. The area of the circular cut-out is 78.539 mm^2. Therefore, length of side of the square cut-out and regular triangular cut-out are chosen as 8.862 mm and 13.467 mm respectively.

Table 5. The element and node number of created models.

Cut-out (θ=0, c/b=0.2, r/R=0)	Element number	Node number
Square	2766	3059
Elliptical	2659	2894
Circular	2602	2792

5. RESULTS AND DISCUSSION

5.1. The results of Case Study-I

By considering the design variables– knitting level, cut-out shape, the degree of bluntness, and cutout rotation-the critical lateral buckling load is obtained. Table 6 shows the lateral buckling load with respect to cut-out shape and knitting level. In this table, an interesting result is that the lateral buckling loads decreases while the tightness level increases from low to high. It is also seen that the composite beams without cut-out have the maximum lateral buckling load. It is expected, because the stiffness is higher than the others. The critical lateral buckling load decreases gradually while the cut-out shape changed from elliptical to triangle. In case of triangle cut-outs, the critical lateral buckling load is being the lowest because the area removed from the beam is greater than the others.

Table 6. The lateral buckling loads (N) with respect to cut-out shapes and tightness level (c/b=0.2, r/R=0.0, θ=0^0).

Tightness level	Cut-out Shape				
	No cut-out	*Elliptical*	*Circular*	*Square*	*Triangle*
Low (K_1)	42.848	42.294	39.645	38.541	35.888
Medium (K_2)	39.745	39.232	36.781	35.761	33.317
High (K_3)	33.638	33.212	31.172	30.261	28.263

Figure 6 presents the effect of c/b ratio and cut-out orientation on the lateral buckling load of the cantilever beam with an elliptical for different knitting tightness levels. It is observed that the critical lateral buckling load increases with the increase of cut-out orientation up to 22^0 then the lateral buckling load begins to decrease. The lateral buckling load takes its minimum value when the cut-out orientation is 90^0. The lateral buckling load decreases with the increase of c/b ratio. It is observed that while c/b ratio increases from 0.2 to 0.8, the cut-out orientation has fewer effects on the composite beams since the cut-out shape turns into from elliptical to circular as previously mentioned.

Figure 7 shows variation of lateral buckling load for square cut-out with bluntness and cut-out orientation. It is observed that the critical lateral buckling load increases with the increase of cut-out orientation up to 12^0 then the lateral buckling load begins to decrease. The lateral buckling load takes its minimum value when the cut-out orientation is oriented at 45^0. The lateral buckling load increases with the increase of bluntness. This is because the removed area from the beam is being reduced. It can be concluded that while bluntness increases from 0.0 to 1.0, the cut-out orientation has fewer effects on the composite beams since the cut-out shape turns into circle.

Figure 8 shows the effect of bluntness and cut-out orientation on lateral buckling load of the beam with a triangular cut-out. If degree of θincreases, the lateral buckling load begins to decreases. The lateral buckling load takes its maximum value when cut-out orientation is 0^0 while the lateral buckling load takes its minimum value when the cut-out oriented at 30^0.

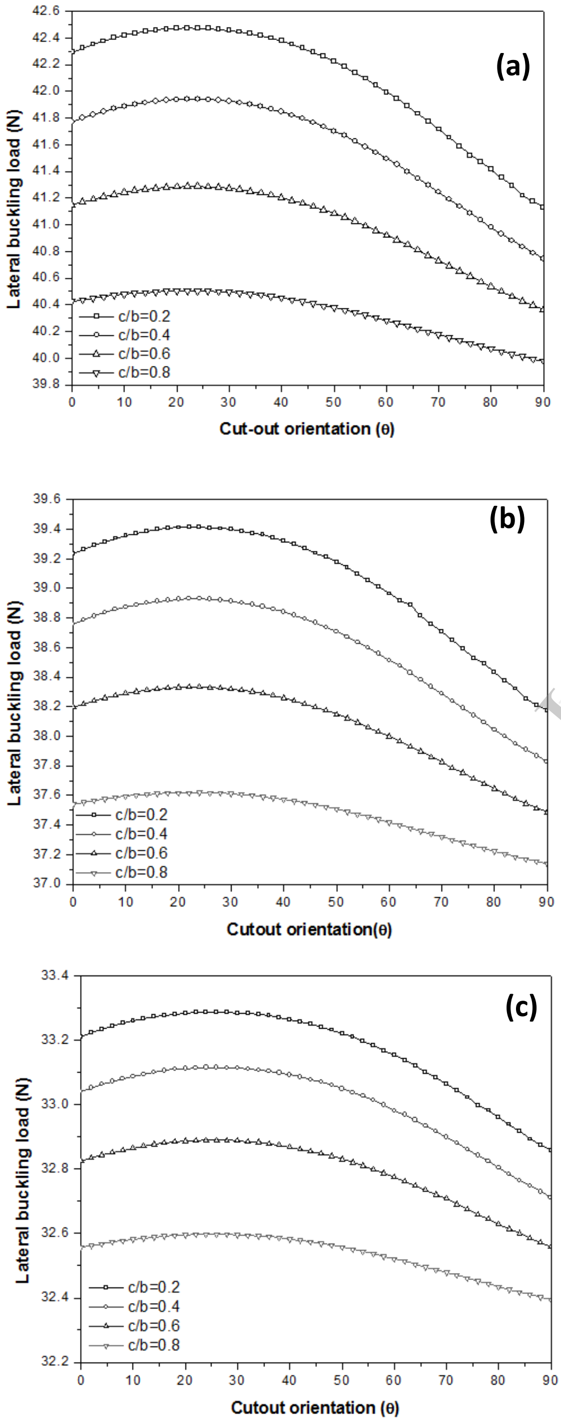


Figure 6. Variation of lateral buckling load for elliptical cut-out with different c/b ratio and cut-out orientation (a) low tightness, (b) medium tightness and (c) high tightness level

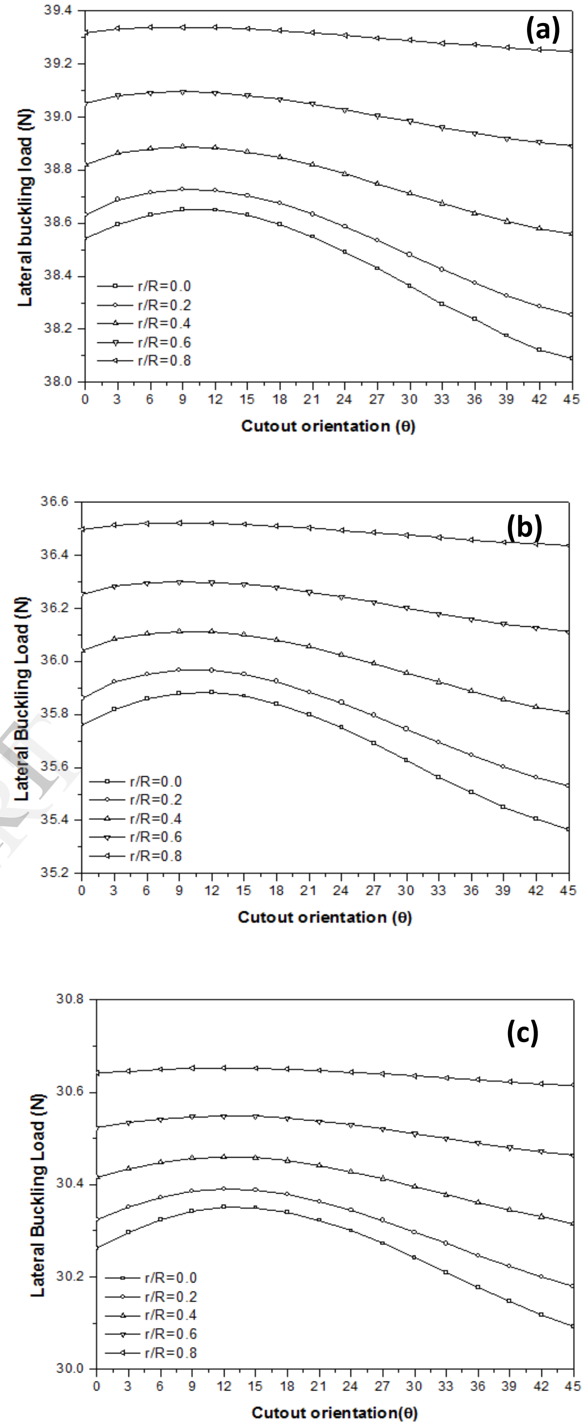


Figure 7. Variation of lateral buckling load for square cut-out with bluntness and cut-out orientation (a) low tightness, (b) medium tightness and (c) high tightness level

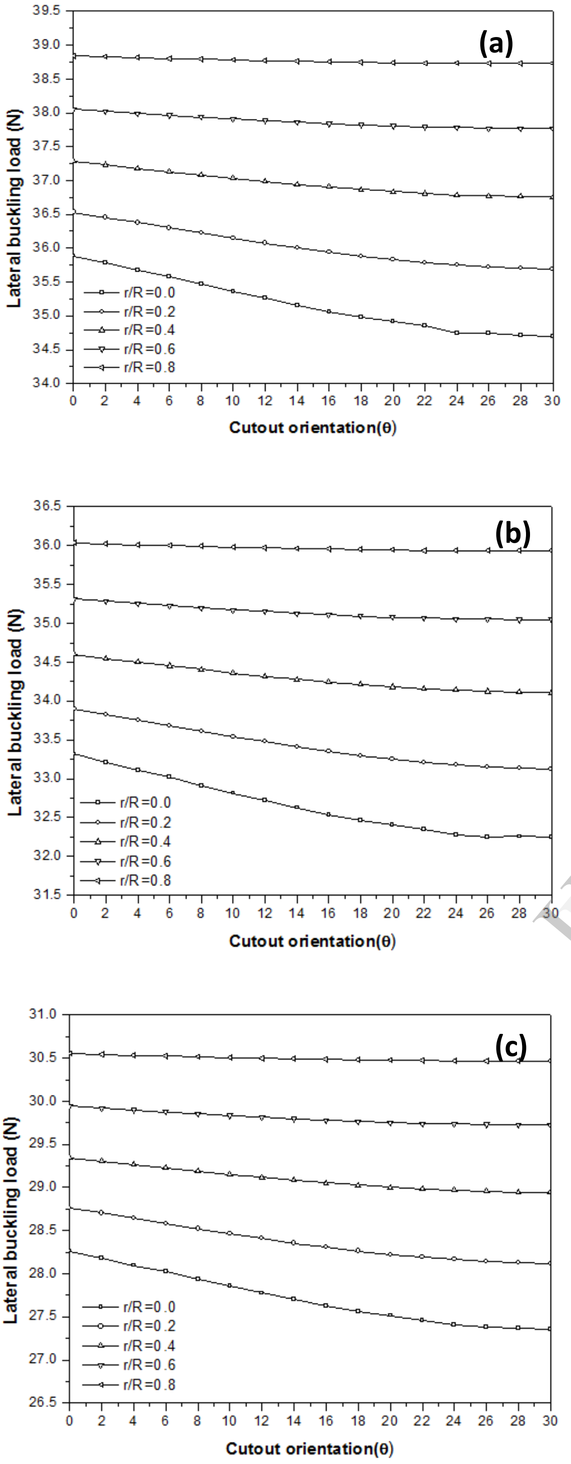


Figure 8. Variation of lateral buckling load for triangular cut-out with bluntness and cut-out orientation (a) low tightness, (b) medium tightne ss and (c) high tightness level

5.2. The results of Case Study-II

The lateral buckling loads with respect to cut-out shapes having equal areas and knitting level are given in Table 7. It can be concluded that the beam with a circular cut-out offer safer cases than others. It is possible to say that the cut-out shapes do not have important effects on the lateral buckling loads when the cut-outs have equal areas.

Table 7. The lateral buckling loads (N) with respect to cutout shapes with equal areas and tightness level (r/R=0.0, $\theta=0^0$).

Tightness level	*Cut-out shape*		
	Circular	*Square*	*Triangle*
Low (K_1)	39.645	39.456	38.725
Medium (K_2)	36.781	36.608	35.932
High (K_3)	31.172	31.029	30.458

6. CONCLUDING REMARKS

In this study, the lateral buckling behavior of weft-knitted 1x1 rib glass/epoxy composite cantilever beams have been investigated numerically. Four parameters are investigated as follows: knitting tightness levels (low, medium and high), the shapes of central-polygonal cutouts (triangle, square, circular and elliptical), bluntness and orientation of polygonal cutouts (θ).

The conclusions can be summarized as follows:

- The knitting tightness level has important effect on lateral buckling load. The lateral buckling load decreases while the tightness level increases from low to high.
- The critical lateral buckling load decreases gradually while the cutout shape changed from elliptical to triangle which means big cutouts cause the weakest beams under the lateral buckling load.
- Cut-out bluntness and orientation have negligible effect on the lateral buckling load of composite beams.

7. REFERENCES

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