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Buckling behavior of pultruded composite beams with circular cutouts

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Abstract. In this experimental and numerical study, the effect of plate thickness, the diameter of circular cutout, the distance between circular cutouts and rowing orientation angle effect (θ) on the buckling load of E-glass/vinylester pultruded composite beams with single and double circular cutouts, were investigated. The composite beam having 2, 4, and 6 mm thicknesses was produced as [Mat/θ/Mat/θ/Mat] by using pultrusion technique. Seven different fiber angles as 0°, 15°, 30°, 45°, 60°, 75°, and 90° were chosen for investigation of rowing orientation angle. The distances between each circular cutout were selected as 15, 30, 45, 60, and 75 mm in the case of double circular cutouts. The diameters of circular cutouts were chosen as 2, 4, 6, 8, and 10 mm to investigate the effect of cutout size. The experimental buckling loads were compared with the results calculated from the numerical analysis. ANSYS 11 commercial software was used for numerical study. A good agreement was obtained between numerical and experimental results.

Keywords: buckling load; diameter of circular cutout; pultruded E-glass/vinylester; finite element method

1. Introduction

Pultrusion is an economical manufacturing process in which unidirectional fibers, woven, and nonwoven mats, such as continuous filament mat (CFM) are impregnated in resin and pulled through a heated die to produce long structural components with a constant cross-section. These components are currently being used in a variety of applications due to their high strength, low cost, lightweight and durability. Unlike laminated composites, pultruded composites are usually thicker and can have the same volume as traditional metallic structural profiles. There are additional advantages of thick-section pultruded composites, such as being corrosion resistant and electrical or magnetic insulators in transmission towers. These structural profiles are increasingly used when these advantages are required. Besides the above advantages, pultruded composites have relatively low elastic modulus, which may result in significant proportion of the total deformation, and a reduction in local and global buckling loads. Thus, a good understanding of the buckling behavior of pultruded composite beams is necessary in order to improve structural

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reliability and performance (Wang 2002, Mottram 2004, Haj-Ali and Kilic 2002, 2003, Roberts and Mısrı 2003, Ranganathan and Mantena 2003).

The buckling of composite laminated plates has received the attention of many researchers over the past years. Saha *et al*. (2004) have performed an experimental study to investigate the circular cutout effect on the compressive strength and failure strain of E-glass fiber/isophthalic polyester resin matrix pultruded composite plates with and without cutouts for two different thicknesses. The compressive strength was found to be higher for 6.3 mm thick material as compared to 12.7 mm thick material. However, as the ratio of cutout diameter to specimen width increased, the differences between two thicknesses become less significant. The strain at the cutout edge was also found to be higher as the diameter of the cutout increased. Yapıcı *et al*. (2005) have examined the buckling behavior of thermoplastic composite plates of four symmetric and antisymmetric layers with circular cutouts. Two different reinforced materials are used, one of them is a galvanized steel wire and the other is a woven galvanized wire. Both symmetric and antisymmetric unidirectional plates show sharp decreases with increase in the cutout diameter. The highest and lowest buckling loads are found for $[45°/-45°]_2$ and for $[15°/-15°]_2$ orientated plates, respectively. Tercan and Aktas (2009) have done an experimental and numerical study to determine the buckling behavior of 1x1 rib knitting (low, medium and high level tightness) glass/epoxy plates with four different cutouts as central circular/elliptical cutout, central square/rectangular cutout, edge semi-circular/ semi-elliptical cutout, and edge semi-square/semi-rectangular cutout, and also without cutout. Results are showed that the buckling load of a plate with circular/elliptical cutout is higher than the plate with square/rectangular cutout for both central and edge cutouts. Baba (2007) has investigated the influence of boundary conditions, length/thickness ratio and ply orientation on the buckling load for rectangular plates with various cutout shapes. She has conducted the tests on laminated composites with circular and semicircular cutouts under various boundary conditions and she stated that the results showed a complex interaction between plate orthotropy and boundary conditions.

Yazıcı (2008, 2009) has performed a numerical and experimental study to investigate the effects of cutout size, fillet radius and fiber orientation angle on the buckling behavior of steel woven fiber-reinforced polypropylene thermoplastic matrix composite plates with square cutout. Buckling loads do not show a crucial difference by variation of the square cutout corner fillet radius and square cutout orientation angle. The buckling loads reduce by increasing the cutout size. Yeh *et al*. (2007) have analyzed the buckling of laminated metal–matrix composite (MMC) plates with a central square cutout under compressive biaxial loading using the finite element approach. The MMC plates have displayed some interesting buckling patterns and initial buckling shapes when subjected to different combination of cutout sizes and boundary conditions. For the same cutout size, plate aspect ratio, and boundary conditions, the results showed that the critical buckling behavior of the plates was primarily influenced by the edge boundary conditions rather than by the laminated stacking sequences.

Yazıcı *et al*. (2003) have done a numerical and experimental study to illustrate the influence of reinforcing angle and U-notch dimensions of multilayered rectangular glass/epoxy plates by using the finite element analysis. According to results, the effect of notch depth is stronger than that of the notch root radius on buckling loads of plates. Akbulut and Ural (2007) have investigated the corner notch size, plate thickness ratio, material modulus ratio and stacking sequences effect on the critical buckling load of simply supported composite plates with corner circular notches under uniaxial and biaxial static loadings by using the first- order shear deformation theory (FSDT). Results showed that the critical buckling loads become the largest for the corner notch radius to plate length ratios in the range from 0.2 to 0.3 for $[0°]_4$ orientated plates and from 0.4 to 0.5 for $[0°/90°]_2$ orientated plates. And also, when the laminated plates are subjected to biaxial loadings, the plates are more easily buckled than those under uniaxial tension and compression.

Baltacı *et al*. (2006) have performed the cutout size, location, thickness variation and boundary condition influence on the critical buckling load of composite circular plates having circular cutouts subjected to uniform radial load by using the finite element method. And also the buckling mode shapes of the composite plates are determined. Results showed that the critical buckling load increases by increasing the radius of cutout to plate radius ratio, the distance between the location of the cutout and the center of the composite circular plate. It decreases by increasing the cutout size and thickness variation of the composite circular plate. Arman *et al*. (2006) have done an experimental and numerical study to investigate the effect of a single circular delamination around the circular cutout on the critical buckling load of woven fabric laminated composite plates. Results showed that the important decreases occur in the critical buckling loads after a certain value of the delamination diameter and the different fiber orientations also affect the critical buckling load.

Aktas (2009) has investigated the effect of length-to-thickness ratio, aspect ratio, Young modulus ratio, load ratio and boundary conditions on the buckling behavior of the simply supported carbon/epoxy laminated composite plate under biaxial loading analytically and numerically. From the results, it can be said that the buckling load increases by decreasing the length-to-thickness ratio, the aspect ratio, the Young modulus ratio and load ratio. And also the buckling load decreases with increase of the number of simply supported edge. Papadopoulos and Kassapoglou (2004) have developed a method based on a polynomial expansion of the out of plane displacement of the plate and energy minimization to calculate the buckling load of rectangular composite plates under shear loading. The predictions of the present method are found to be in excellent agreement with the special cases of isotropic plates or anisotropic plates. Anil *et al*. (2007) have examined the effects of different laminates, fiber orientation angles and length to thickness ratios on the buckling behavior of thin and thick laminated composite plates with both uniaxial and biaxial loads (both compressive and shear) including transverse shear effect. Results are showed that the transverse shear plays a dominant role on the critical buckling loads in the case of length/thickness ratio increases. And also results showed that the critical value of the fiber orientation angle remains almost same for shear buckling load with change in length to thickness ratio.

Although there has been considerable investigation about buckling behavior of composite plates, but in the existing literature almost no work has been done on the buckling behavior of pultruded composite beams having single or double circular cutouts. This study intends to point out the effect of plate thickness, diameter of circular cutout, distance between center point of circular cutouts, and rowing orientation angle on the buckling behavior of E-glass/vinylester pultruded composite beams with single and double circular cutouts. Three different plate thickness values as 2, 4, and 6 mm, five different diameter of circular cutout values as 2, 4, 6, 8, and 10 mm, and seven different rowing orientation angles as 0°, 15°, 30°, 45°, 60°, 75°, and 90° were selected. The circular cutout was located symmetry center of pultruded composite beam having single cutout (SC). Also five different distance values as 15 (DC15), 30 (DC30), 45 (DC45), 60 (DC60), and 75 mm (DC75) was chosen between center point of circular cutout on the equal distance from symmetry center of composite beam with double circular cutouts.

2. Material and method

This study has three sub steps. Firstly, E-glass/vinylester pultruded composite beams were manufactured and then the mechanical properties of this material were determined according to ASTM standards. Secondly, the experimental buckling study was carried out. And finally, the numerical buckling analysis was performed by using ANSYS 11 commercial software.

2.1 Material production and determination of the mechanical properties

Pultrusion is a highly automated process to manufacture constant cross-section shaped profiles from composite materials. The pultrusion system is schematically given in Fig. 1. It consists of five subsections as a creel which contains continuous reinforcement materials, resin bath which has a long gradual exit slope to ensure good fiber impregnation, guidance devices which preform fiber before heating, a heating section which is heated to the required temperature, and a pulling mechanism which moves the product continuously at a constant speed. The pultruded composite is finally cut by using high precision diamond saw. During the manufacturing process, three die zone temperatures were maintained in the heating section as pre-heating (110°C), heating (170°C), and cooling (130°C) respectively, and 30 cm/min pulling speed.

E-glass/vinylester pultruded composite beam having 15 × 6 mm^2 cross-sectional area was manufactured in 4 m length in Pul-tech FRP Company, Usak, Turkey. This pultrusion was made with filament rowing as 4800 txt and layers of continuous mat, the primary purpose of which was to hold together the rowing during the pultrusion process. The rowing/mat ratio of pultruded specimens were approximately 70/30 in weight. The mat with 450 gr/m^2 was used in the top, bottom, and middle layers of pultruded composite beam. The volume fraction of E-glass fiber (Mat and rowing) is approximately 58%.

The mechanical properties of E-glass/vinylester pultruded composite beams were determined under static loading conditions according to the ASTM 3039-76 standards (ASTM 1990). The mechanical tests were carried out in the Department of Mechanical Engineering of Usak University by using UTEST Tensile Testing Machine of 50 kN load capacity at 1 mm/min cross-head speed. The mechanical properties of the E-glass/vinylester pultruded composite beams were given in Table 1. In this table, E_1, E_2 and E_3 are Young's modules and G_{12}, G_{13} and G_{23} are the shear modules, and ν_{12}, ν_{13} and ν_{23} are the Poisson ratios corresponding to the 1-2, 1-3 and 2-3 planes, respectively.

In Table 1, $E_3 = 0.6E_2$, $G_{13} = G_{23} = G_{12}$, and $\nu_{13} = \nu_{23} = 0.6\nu_{12}$ were assumed in the view of

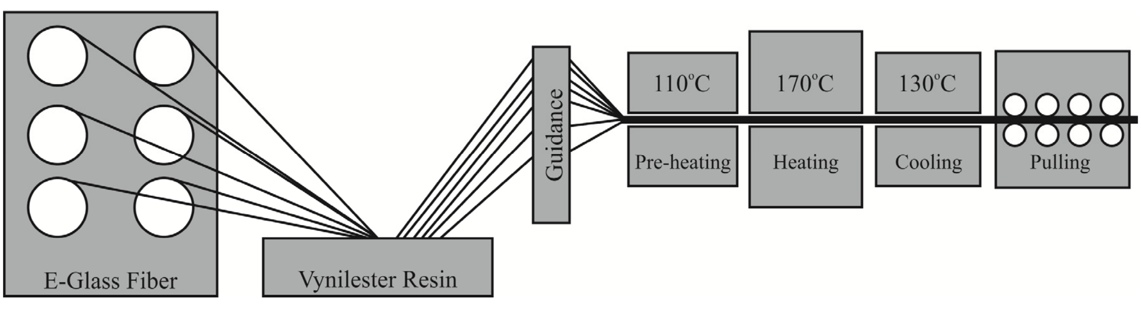


Fig. 1 Schematic presentation of used pultrusion system

Table 1 Mechanical properties of E-glass/vinylester pultruded composite beam

Measured				Assumed		
E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12}	$E_3 = 0.6E_2$ (MPa)	$G_{12} = 0.6G_{13} = 0.6G_{23}$ (MPa)	$\nu_{13} = \nu_{23} = 0.6\nu_{12}$
17200	5370	1100	0.28	3222	660	0.168

some authors (Balcıoğlu 2013, Tercan and Aktas 2009, and Arman *et al*. 2006). For each mechanical property five test specimens were subjected to tensile test under room temperature. The mechanical properties were obtained by taken average of the test results of five specimens.

2.2 Experimental study

Experimental study in this paper was carried out in order to confirm convenience for created numerical model in finite element analysis. For this reason, three different specimens made of E-glass/vinylester pultruded composite beam which have 6 mm thickness, 0° rowing orientation angle, SC and DC15 and DC30 with 6 mm diameter were selected (Fig. 2). The specimens with double cutouts have two different distance as 15 mm and 30 mm between center point of each circular cutouts (Figs. 2(b)-(c)).

For the buckling tests, UTEST tensile testing machine with 50 kN load capacity was used at Department of Mechanical Engineering, Usak University. The buckling tests were carried out by using compression feature of the tensile test machine at constant velocity of 1 mm/min. All buckling tests were performed five times at room temperature. So, there were totally 15 tests carried out. The buckling specimens were tested under clamped-clamped boundary conditions for loading direction and free for unloading direction. The buckling load which occurs in the first buckling mode was considered as critical buckling load, so the other buckling modes were not considered in the experimental study.

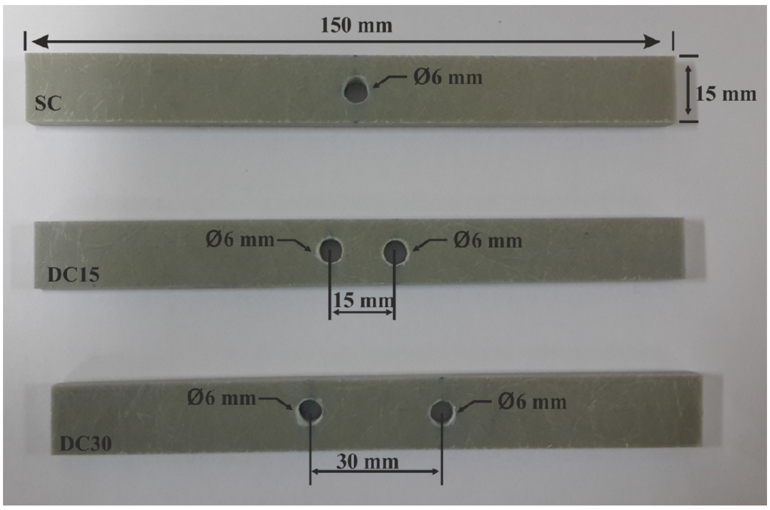


Fig. 2 The dimensions of pultruded beam for (a) SC; (b) DC15; and (c) DC30

The critical buckling loads of the specimens were determined by using Southwell Plot Method from load-displacement curves. The Southwell Plot Method is a well-known technique for determining the critical load of a structure. According to this method, the displacement to load ratio plot of a column approaches to a straight line, whose inverse slope and abscissa-intercept are the critical load and the initial lateral imperfection of the column, respectively (Balcıoğlu and Aktas (2012, 2013) This method is illustrated on whatever load-displacement curve which obtained from experimental study in Fig. 3.

When structural members, which have lower cross-sectional area relative to its longitudinal length, exposed to axial load; they can be buckled. As a result of buckling, fiber-matrix decomposi-

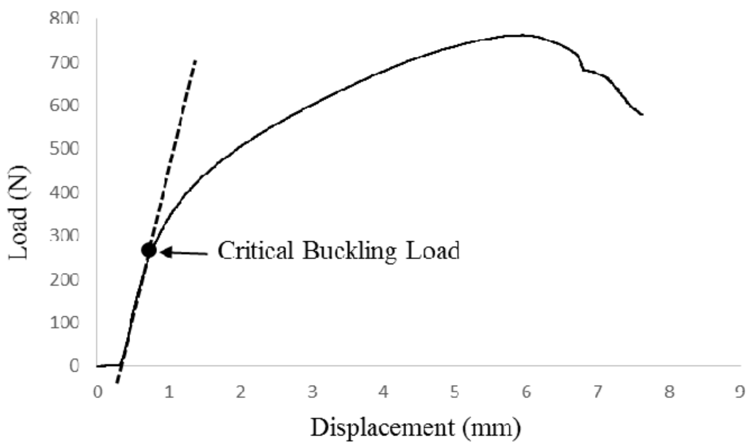
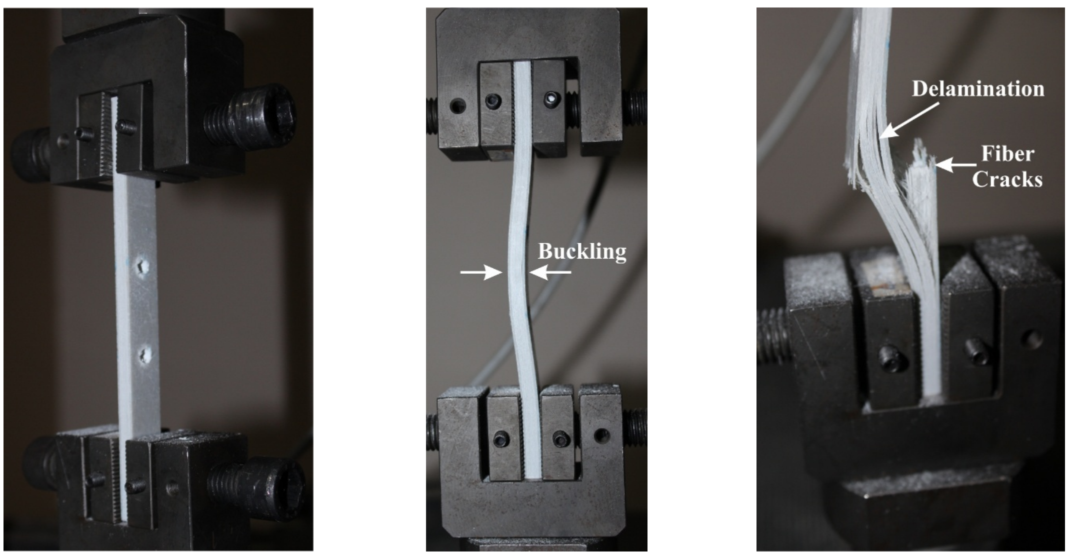


Fig. 3 The determination of the critical buckling load for DC15 by using Southwell Plot Method



(a) (b) (c)

Fig. 4 The illustration of (a) clamped boundary condition; (b) buckling mode; and (c) damage critical buckling values of pultruded composite beam for DC30

Table 2 The critical buckling load values of experimental and numerical results

Specimens	Critical buckling load (N)		% Error
	Experimental	Finite element analysis	
SC	360.70	353.61	1.96
DC15	312.20	337.14	7.98
DC30	315.01	338.82	7.56

tion damage, which is named delamination in literature, can be observed in fiber reinforced composite materials. While delamination damage is increasing depends on buckling deformation; load-bearing capacity of fiber reinforced structural members lost. Finally, the structural member will be damaged completely. This phenomenon was observed in the experimental study. Delamination and fiber cracks occurred in the test specimens as illustrated in Fig. 4(c).

The comparisons between experimental and numerical results in the same conditions are shown in Table 2. It is seen from this table, the critical buckling loads obtained from numerical buckling analysis close to the critical buckling loads obtained from experimental study and the error values were at the acceptable level. That showed the numerical model used in finite element analysis is convenient.

The finite element analysis was provided completion of studies at shorter duration as well as gaining economic advantages. Therefore; the effect of plate thickness, diameter of circular cutout, distance between center point of circular cutouts and rowing orientation angle on the buckling load of E-glass/vinylester pultruded composite beams with single or double circular cutout were investigated numerically.

2.3 Numerical study

In this sub step, the effect of plate thickness (2, 4, and 6 mm), diameter of circular cutout (2, 4, 6, 8, and 10 mm), distance between center point of circular cutouts (15, 30, 45, 60, and 75 mm) and rowing orientation angle (0°, 15°, 30°, 45°, 60°, 75°, and 90°) on the buckling load of E-glass/vinylester pultruded composite beams with single or double circular cutout were investigated by using ANSYS 11 commercial finite element software. Each of the models has five layers and the dimensions of the layers are 150x15 mm^2. The thickness of each layers for 2, 4 and 6 mm are of 0.4, 0.8 and 1.2 mm, respectively.

The numerical models with single and double cutouts were meshed with quadratic composite shell elements based on first order shear deformation theory (FSDT). The eight-nodded SOLID46 multi-layered solid element was used for the numerical study. SOLID46 solid element has six degrees of freedom per node: translations in the nodal x, y and z directions and rotations about the nodal x, y and z-axes. The plates were clamped (UX = 0, UY ≠ 0, UZ = 0, ROTX = 0, ROTY = 0, ROTZ = 0) along the top edge and also clamped (UX = 0, UY = 0, UZ = 0, ROTX = 0, ROTY = 0, ROTZ = 0) along bottom edge and free on the other sides. The compression load was applied uniformly in y-axes according to rowing direction. In order to achieve buckling analysis, two different solvers were used in Ansys 11. These are nonlinear analysis and eigenvalue analysis, respectively. In this study, the eigenvalue analysis was used to obtain critical buckling load for E-glass/vinylester pultruded composite beams loaded axially. The numerical model and boundary condition for SC with 6mm thickness were showed in Fig. 5.

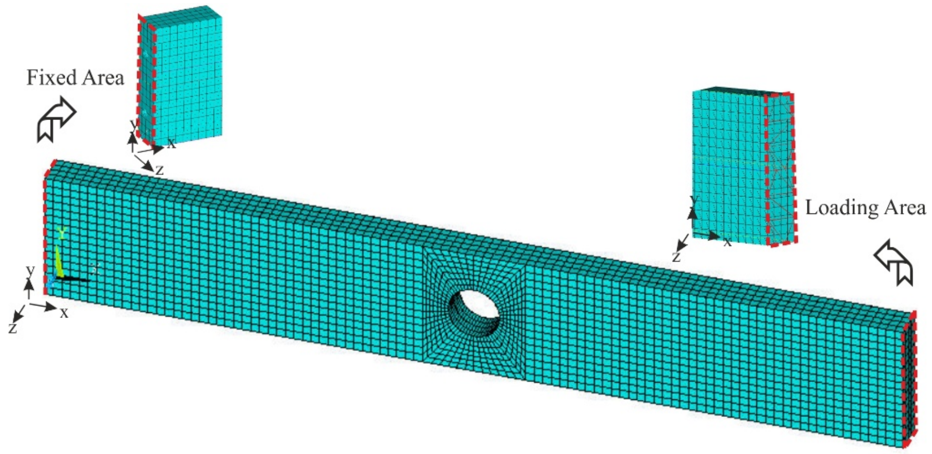
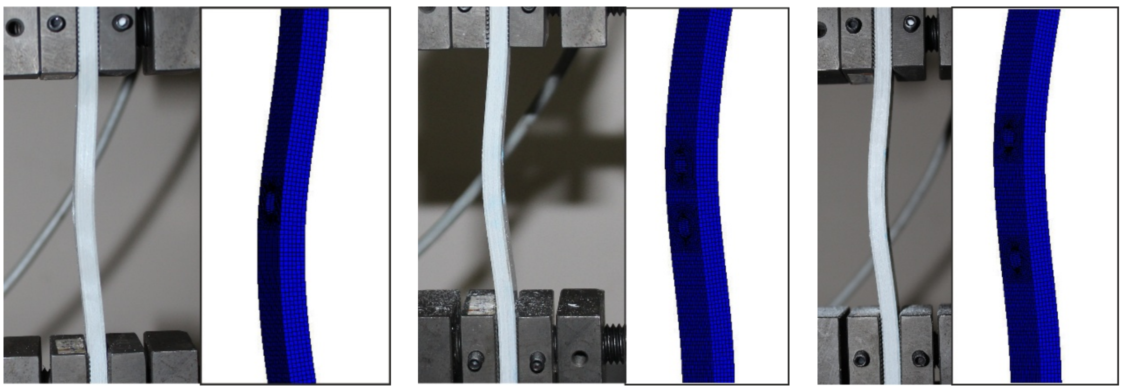


Fig. 5 The numerical model and boundary condition for SC with 6 mm thickness



(a) (b) (c)

Fig. 6 The first buckling mode for experimental and numerical study of specimens for (a) SC; (b) DC15; and (c) DC30

In the numerical study, the effect of four different geometric parameter as plate thickness, diameter of cutout, distance between center point of circular cutouts, and rowing orientation angle on the critical buckling load of E-glass/vinylester pultruded composite beams were investigated. For this reason 315 numerical models which have about 15000 nodes were created.

The first buckling mode obtained from experimental and numerical studies is given for single and double circular cutouts in Fig. 6. From this figure, we can say that the numerical deformation has nearly same with experimental ones for each test specimen.

3. Results and discussion

In this study, the effect of plate thickness (2, 4, and 6 mm), diameter of circular cutout (2, 4, 6, 8, and 10 mm), distance between center point of circular cutouts (15, 30, 45, 60, and 75 mm) and rowing orientation angle (0°, 15°, 30°, 45°, 60°, 75°, and 90°) on the buckling behavior of E-glass/vinylester pultruded composite beams were investigated. In the experimental study, only three different specimens made of E-glass/vinylester pultruded composite beam, having 6 mm thickness, 0° rowing orientation angle, single and double circular cutouts with 6 mm diameter, were tested.

The critical buckling load variation with rowing orientation angle and diameter of circular

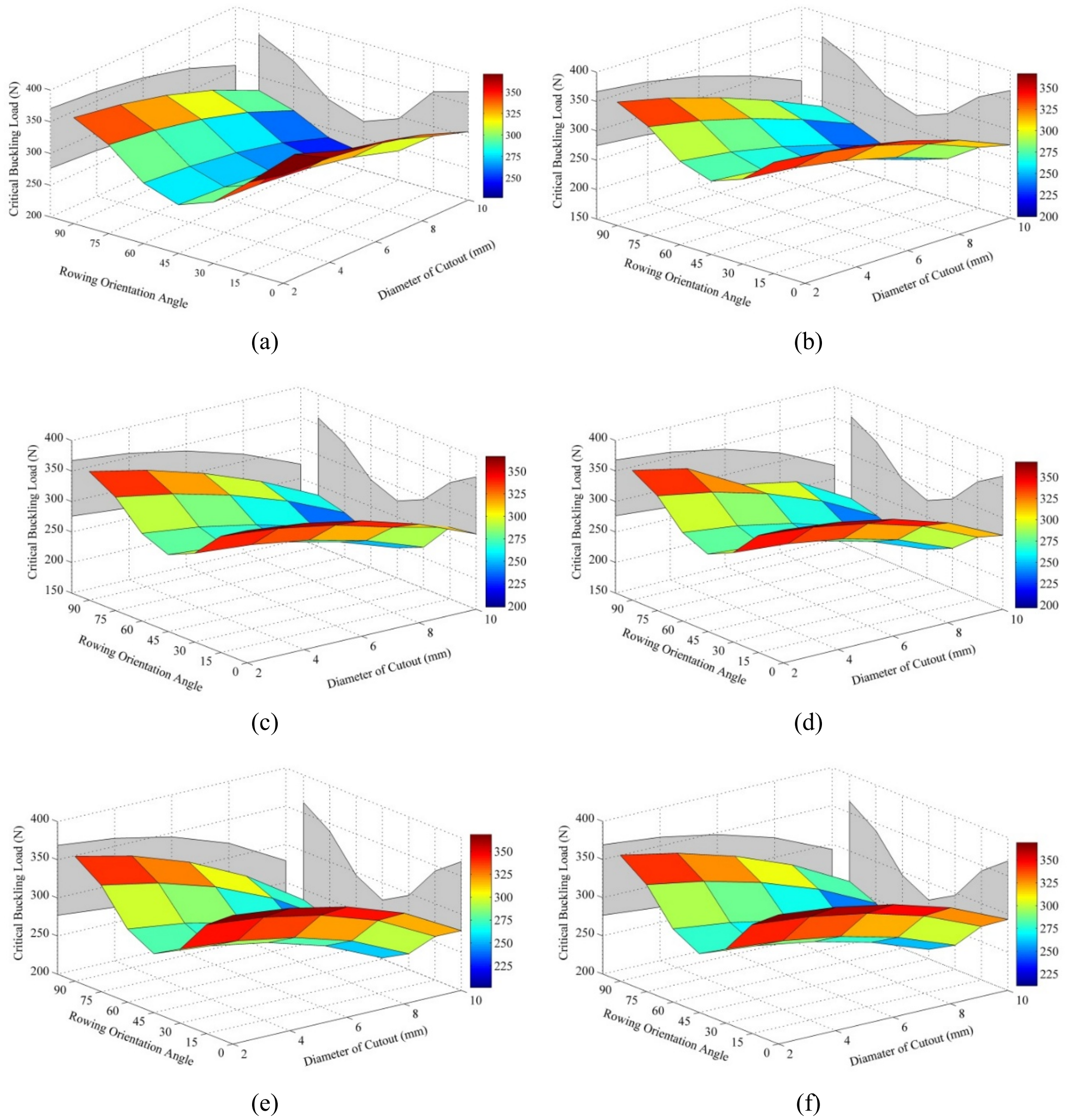


Fig. 7 The changing of critical damage load of pultruded E-glass/vinylester composite beam having 6 mm thickness for (a) SC; (b) DC15; (c) DC30; (d) DC45; (e) DC60; and (f) DC75

cutout for specimens having 6 mm plate thickness was given in Fig. 7. The critical buckling load behavior of specimens with 6 mm plate thickness, which depend the rowing orientation angle and diameter of circular cutout, shows similar behavior with the critical buckling load of specimens with 2 mm and 4 mm thicknesses. The graphs, which belong to specimens with 2 mm and 4 mm thicknesses, were not given in the Fig. 7 for making an effective assessment.

When graphs on Fig. 7 investigated, rowing orientation angle went to 45° from 0°, the critical buckling load reduced about 25%. On the other hand, rowing orientation angle went to 90° from 45°, the critical buckling load increased about 20% for all numerical models. These changings show that the specimen with 0° rowing orientation angle has the maximum value for the critical buckling load. However, the specimen with 45° rowing orientation angle has the minimum critical buckling load. When the effect of circular cutout diameter on the critical buckling loads is investigated in the Fig. 7, it can be seen similar behavior for all numerical models.

The critical buckling load is reduced by the reducing diameter of circular cutout from 10 mm to 2 mm. In other words, the maximum critical buckling load was achieved in specimen having 2 mm circular cutout. Increasing in the diameter of circular cutout will be caused the decreasing cross sectional area. In this situation, the specimens will be easily buckled. It can be seen from the Fig. 7, the load-bearing capacity of E-glass/vinylester pultruded composite beam is reduced about 74% by increasing diameter of circular cutout from 2 mm to 10 mm. The extensive decision obtained from graphs on Fig. 7 is that the specimens, which have 0° rowing orientation angle and 2 mm cutout, show the maximum buckling load.

The effect of distance between center point of double circular cutouts and plate thickness on the critical buckling load for numerical model having 0° rowing orientation angle and 2 mm cutout diameter investigated in Fig. 8. In this study, the first (critical) buckling mode was investigated. It is known that the thinner plate has lower buckling load than the thicker one and the higher effective area under compressive load has higher buckling load. Therefore, the effect of distance between center point of double circular cutout and the plate thickness on critical buckling load for specimens having different rowing orientation angle from 0° and different cutout diameter from 2 mm, was not included in this study.

When looked at the changing in the critical buckling load with plate thickness it can be seen on ig. 8, the critical buckling load is increased with increasing of plate thickness. If the plate hickness is increased to 4 mm and 6 mm from 2 mm, the critical buckling load is increased about 293% and 766%, respectively. This situation showed that the most effective parameter for the critical buckling load is plate thickness among the others.

In Fig. 8, 0 mm distance value is represented the critical buckling load of specimens with single cutout. When compared the experimental and the numerical results of specimens having SC and DC15; increasing number of cutout from 1 to 2, the critical buckling load was reduced 4% and 1%, respectively. As understood from the slope of approximate horizontal lines when distance value between center point of circular cutouts increase till 75 mm for specimens with double cutouts, the critical buckling load is increased about 0.6%. This phenomenon showed that the number of cutout and distance between center point of circular cutouts did not extremely effect the critical buckling load.

As the general result; in this study the maximum critical buckling load as 370 N was achieved in the specimen having 0° rowing orientation, 6 mm thickness, and single cutout. On the other hand, the minimum critical buckling load as 31.89 N was achieved in the DC15 specimen having 45° rowing orientation with 2 mm plate thickness. For the critical buckling load, the difference between these two configurations is about 11 times.

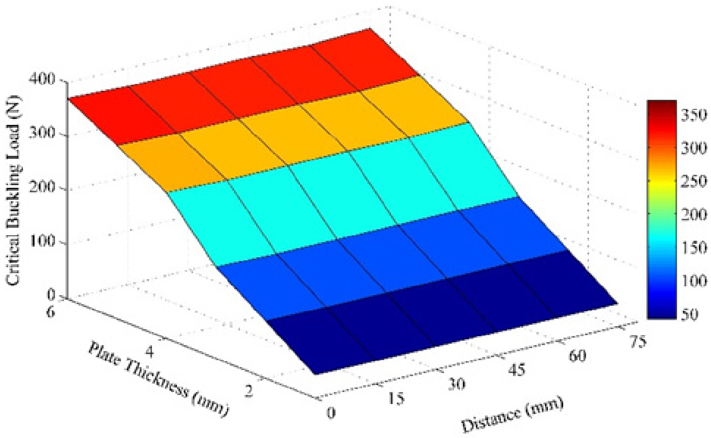


Fig. 8 The effect of distance between center point of circular cutouts and the plate thickness on critical buckling load

4. Conclusions

In this experimental and numerical study; the thickness of plate, the diameter of circular cutout, the distance between circular cutouts and rowing orientation angle effect on the critical buckling load of E-glass/vinylester pultruded composite beams with single or double circular cutouts were investigated. From the results of this study, the following conclusions can be drawn:

- The maximum critical buckling load was achieved in specimen having 0° rowing orientation angle.
- The specimens having small cutout diameter were showed the maximum strength against to buckling. So that, the maximum critical buckling load was achieved in specimen with 2 mm cutout diameter.
- The critical buckling load increases by increasing plate thickness. The maximum critical buckling load is obtained for specimen with 6 mm plate thickness.
- The number of cutout and distance between center point of double circular cutouts did not extremely effected the critical buckling load.
- The critical buckling load of E-glass/vinylester pultruded composite beams with single or double cutouts can be enhanced 11 times by changing rowing orientation angle.

5. Conclusions

The results obtained from the FEM analysis have been compared with these given by the analytical model proposed in the paper. The parameters of the beam taken as an example are given in Subsection 2.2 and Section 3. A good agreement can be seen between the buckling loads obtained from both models – the difference is less than 1%. As to the strength analysis the maximum normal stresses in the upper face are 211 MPa, according to the analytical model, and 214 MPa according to the FEM model. The maximum shear stresses are: 0.53 MPa and 0.52 MPa, respectively.

References

Akbulut, H. and Ural, T. (2007), "An investigation on buckling of composite laminated plates with corner circular notches", *J. Thermoplast. Compos. Mater.*, **20**(4), 371-387.

Aktas, M. (2009), "Buckling behaviour of carbon/epoxy laminated composite plates under biaxial loading", *Adv. Compos. Lett.*, **18**(3), 85-93.

Anil, V., Upadhyay, C.S. and Iyengar, N.G.R. (2007), "Stability analysis of composite laminate with and without rectangular cutout under biaxial loading", *Compos. Struct.*, **80**(1), 92-104.

Arman, Y., Zor, M. and Aksoy, S. (2006), "Determination of critical delamination diameter of laminated composite plates under buckling loads", *Compos. Sci. Tech.*, **66**(15), 2945-2953.

ASTM (1990), "Standard test method for tensile properties of fiber-resin composite D 3039-76", *American Society for Testing and Materials*, PA, USA.

Baba, B.O. (2007), "Buckling behavior of laminated composite plates", *J. Reinf. Plast. Compos.*, **26**, 1637-1655.

Balcıoğlu, H.E. and Aktaş, M. (2012), "Lateral buckling behavior of laminated composite materials with delamination", *Proceedings of the 14th International Materials Symposium*, Denizli, Turkey, October.

Balcıoğlu, H.E. and Aktaş, M. (2013), "An investigation on lateral buckling of laminated composites with delamination", *Ind. J. Eng. Mater. Sci.*, **20**(5), 367-375.

Baltacı, A., Sarıkanat, M. and Yıldız, H. (2006), "Buckling analysis of laminated composite circular plates with holes", *J. Reinf. Plast. Compos.*, **25**(7), 733-744.

Haj-Ali, R. and Kilic, H. (2002), "Nonlinear behavior of pultruded FRP composites", *Compos.: Part B*, **33**(3), 173-191.

Haj-Ali, R. and Kilic, H. (2003), "Nonlinear constitutive models for pultruded FRP composites", *Mech. Mater.*, **35**(8), 791-801.

Mottram, J.T. (2004), "Determination of critical load for flange buckling in concentrically loaded pultruded columns", *Compos.: Part B*, **35**(1), 35-47.

Papadopoulos, L. and Kassapoglou, C. (2004), "Shear buckling of rectangular composite plates with two concentric layups", *J. Reinf. Plast. Compos.*, **23**(1), 5-16.

Ranganathan, S. and Mantena, P.R. (2003), "Axial loading and buckling response characteristics of pultruded hybrid glass-graphite/epoxy composite beams", *J. Reinf. Plast. Compos.*, **22**(7), 671-679.

Roberts, T.M. and Masrı, H.M.K.J.A.H. (2003), "Section properties and buckling behavior of pultruded FRP profiles", *J. Reinf. Plast. Compos.*, **22**(14), 1305-1317.

Saha, M., Prabhakaran, R. and Waters, W.A. (2004), "Compressive behavior of pultruded composite plates with circular holes", *Compos. Struct.*, **65**(1), 29-36.

Tercan, M. and Aktas, M. (2009), "Buckling behavior of 1 × 1 rib knitting laminated plates with cutouts", *Compos. Struct.*, **89**(2), 245-252.

Wang, Y. (2002), "Bearing behavior of joints in pultruded composites", *J. Compos. Mater.*, **36**(18), 2199-2216.

Yapıcı, A., Şahin, Ö.S. and Arıkan, H. (2005), "Buckling of metal-reinforced thermoplastic composite laminated plates with holes", *J. Reinf. Plast. Compos.*, **24**(13), 1379-1386.

Yazıcı, M. (2008), "Buckling of square perforated thermoplastic composite plates", *J. Reinf. Plast. Compos.*, **27**(10), 1059-1070.

Yazıcı, M. (2009), "Influence of cut-out variables on buckling behavior of composite plates", *J. Reinf. Plast. Compos.*, **28**(19), 2325-2339.

Yazıcı, M., Özcan, R., Ülkü, S. and Okur, İ. (2003), "Buckling of composite plates with U-shaped cutouts", *J. Compos. Mater.*, **37**(24), 2179-2195.

Yeh, H.Y., Le, R.M. and Yeh, H.L. (2007), "Buckling of metal-matrix composite plate with a square hole", *J. Reinf. Plast. Compos.*, **26**(5), 525-540.

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