In-plane Failure and Strength of Pin-Ended Circular Fiber-Reinforced Polymer Arches Considering Local Buckling

Daliya C P[1], Asst. Prof. Gokul Raveendran K[2]

Abstract— In civil engineering fiber-reinforced polymers are seeing increasing use in various infra structure applications. The use of fiber-reinforced polymer composite arches has been seen as a solution for rapid construction with low future maintenance requirements. FRP arches offer unique characteristics such as high stiffness and strength to weight ratios, high corrosion resistance, reducing construction time and complexity relative to conventional cast-in-place concrete structures. This paper presents a numerical investigation of in-plane failure and strength of FRP arches considering plate local buckling behaviour. Pin-ended circular fiber-reinforced polymer arches having a box section subjected to a load uniformly distributed over full span of arch are considered in the investigation of their failure modes and strength. To verify this solution a finite element parametric study is conducted on a number of FRP arches by considering aspect ratio of the cross section, flange to web thickness ratio, arch slenderness, and height to thickness ratio of plate components and rise to span ratio etc. Response of arches with different fiber orientations and number of layers are also studied.

Index Terms — Box section, Composite Structures, FRP arch, In-plane failure, Local buckling, Thin walled structure.

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1 INTRODUCTION

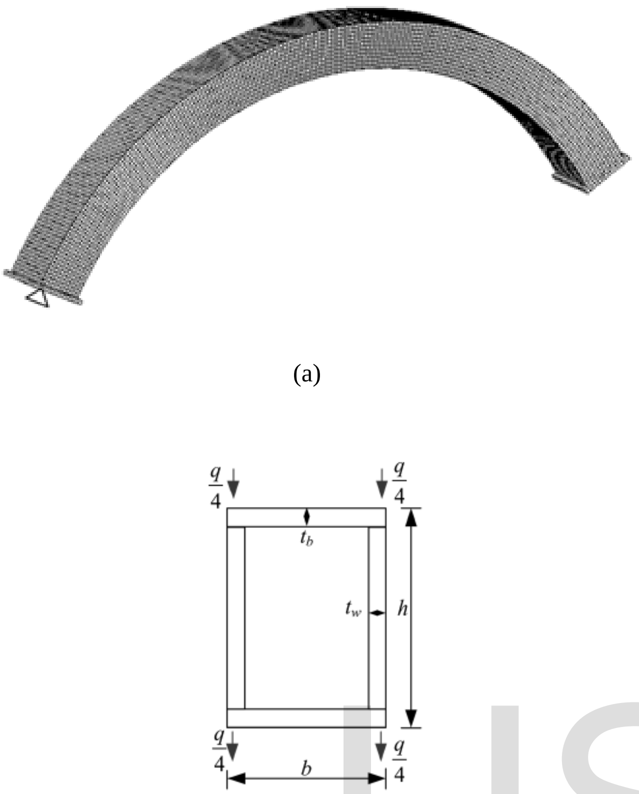
LAMINATED composites are one of the most advanced engineering materials that we use today. They have extensive industrial application due to their light weight nature. In the past 20 years, experiments have been conducted to investigate the applicability of using FRP composite in bridge, and tunnel structures including the applications of FRP composite beam, deck, column, and arches. Arches are capable of spanning long distance, while supporting significant weight and they used as main structural component with their unique mechanism of resisting load. They resolve forces into compressive stresses and in turn eliminating tensile stresses. Ever J et al [5] studied glass-fiber-reinforced plastic (GFRP) beams produced by the pultrusion process and the most failure modes were precipitated by local buckling of the thin walls. Pizhong Qiao et al [7] concentrated on analytical study of local buckling of discrete laminated plates or panels of fiber-reinforced plastic (FRP) structural shapes. Flanges of pultruded FRP shapes were modelled as discrete panels subjected to uniform axial in-plane loads. From the analysis results, the critical buckling stress resultant and the critical value of the number of buckled waves over the plate aspect ratio were obtained. Laszlo P.Kollar [6] has developed explicit expression for axially loaded and for bent box and the local buckling analysis of FRP composite open and closed thin walled section beams and columns were studied.M. A. Bradford et al [12] investigated the strength and design of pin-ended circular arches with sinusoidal corrugated web under combined in-plane loads. Hang Chen et al. [14] analysed the in-plane failure and strength of pin-ended circular steel arches considering coupled local and global buckling. Many of the preceding studies focused on the global buckling strength and design of arches and buckling behavior of beams, ignoring the effects of local buckling of plate components on the strength of arch. As with thin walled box beams, it is well known that local buckling of the plate components may occur before a laminated composite arch reaches its global ultimate load. Accordingly, local buckling of the plate components should be taken into account when determining the strength of arch.

This paper investigates the influence of local buckling of the plate components on the in-plane strength of pin-ended circular arches having thin walled box section subjected to a load uniformly distributed over full span of arch. Buckling analysis of laminated composite arches with box sections are done in finite element software ANSYS 15. Modal analysis was carried out for sections of different aspect ratio and arch slenderness. The effect of the plate height to thickness ratio, thickness of plate, rise to span ratio of arches are explored. Influence of number of layers and angle of fiber orientation for symmetric angle ply on plate buckling load is also studied by considering same as well as different lay-up configurations in webs and flanges of laminated composite arch.

2 METHODOLOGY

Modelling of laminated composite arches were done using Finite Element Software package ANSYS 15. FE models of pin-ended circular arches having thin walled box section have been formulated by using the shell element SHELL181 and the beam element BEAM188 of ANSYS. The shell element models can predict the local buckling behavior of plate components, while the beam element cannot. The beam element model is included in the study, based on Timoshenko beam theory.

- [1] *Currently pursuing masters degree program in Structural engineering, Vidya academy of science and Technology, APJ Abdul Kalam Technological University, India, PH-9961258317. E-mail: daliya.chalakkal@gmail.com*
- [2] *Assistant Professor,Department of Civil Engineering, Vidya academy of science and Technology, India, E-mail: gokul.r.k@vidyaacademy.ac.in*



(a)

(b)

Fig.1. circular arch: (a) shell element model; (b) cross section and applied loads

In order to focus on the in-plane buckling behavior of arches having thin walled box section, the global out-of-plane deformations of the arch are fully restrained. For shell element model, the out of-plane displacements at the intersection of flanges and webs are fully restrained and for beam element model, the uniformly distributed load may be applied along the centroidal axis of the arch. To avoid detrimental bending in the flange, the loads should not be applied to the flanges directly. In the case of shell element model, the uniformly distributed load q is applied evenly at the four corners of the box section along the arch, 0.25q at each corner so that their resultant will act as the centroid of the box section.

To simulate the real situation at the ends, an infinitely rigid end plate is connected to the flanges and webs at the ends of the arch and the end plates is pinned to the abutment. Fig.1 shows the boundary conditions and applied loads. Validation is carried out for a steel arch subjected to uniformly distributed load [15] and also for the buckling behavior of FRP box beam [9].Using this modeling technique, sections with different aspect ratios, height to thickness ratios and fiber orientation for symmetric ply were modelled and their buckling load determined through modal analysis. Lay-up configurations for the models were selected by studying stiffness, generated by a pre written Microsoft Excel Sheet.

3 FAILURE MECHANISM OF ARCHES

In order to clarify the influence of local buckling of plate components on the ultimate load carrying capacity of arches, a steel arch under a load uniformly distributed over the full span of the arch is investigated. In the FE investigation, the thicknesses of the flange and web are both t = 10 mm. A bilinear elastic-plastic stress-strain curve having a Young's modulus of E = 206 GPa, Poisson's ratio of 0.3, and yield stress fy = 235 MPa is adopted for the steel. Steel arches with the web height-to-thickness ratios of h/tw=50 and 100, the rise-to span ratio of f/L=0.3, the arch slenderness of λg=80, the flange-to-web thickness ratio of tf/tw=3 and the flange width-to-thickness ratio of b/tf =25 are used in the FE analysis.The results from FE modelling compared with the findings of [15]. The corresponding variations of the dimensionless axial force N/Ny with the dimensionless horizontal displacement w/L at the quarter span of arch are shown in Fig.2.Where w is the horizontal displacement at the quarter span of the arch and L is the span of the arch, N_Y is expressed as $Af_{y,}$ in which A is the area of cross section and f_y is the yield stress. And ultimate load carrying capacity of arch corresponding to the uniformly distributed load is represented as N = qR, in which q is the uniformly distributed load and R is the radius of the circular arch.

It can be seen from Fig.2 that the FE results for steel arches with h/tw =50 obtained from the shell element model and the beam element model are in good agreements, indicating that no buckling occurs locally. But for a steel arch with the same global slenderness but with a different web height-to-thickness ratio h/tw=100, the stability coefficient obtained from the shell element model is lower than that obtained from the beam element model, demonstrating that the web local buckling occurs and reduces the load carrying capacity of the arch. For steel arches subjected to a load uniformly distributed over the full span, they fail generally at 1/8 span of the arch, which is consistent with the findings of Guo et al. [15]

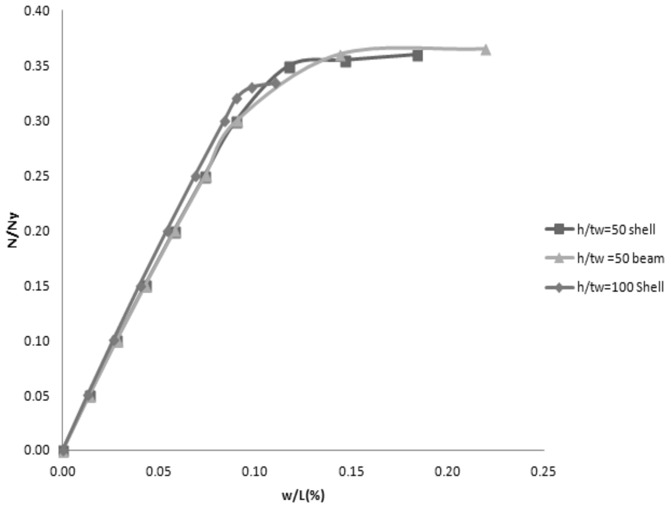


Fig.2. Load-displacement curves

4 LAMINATED COMPOSITE BOX BEAM

Consider a symmetric carbon-epoxy box beam, as shown in Fig.3, with geometrical parameters *l* = 210 mm, h= 17.5 mm, 2b = 17 mm, t_1= 1.5 mm, t_2= 1 mm, and elasticity constants E_L= 114576 Mpa, E_T = 9981.7 Mpa, G_{LT} = 4664.8 Mpa, μ_{LT} = 0.325. When the beam is supported simply and subjected to a concentrated load P at mid-span, with ply angle of first layer 0° and second layer 45°, the vertical displacements are shown in Fig.4. The results are compared with values obtained from a FEM analysis with ANSYS 15, which employs an 8-node iso-parametric laminated shell element for mid-span displacement vs concentrated load P. The present analysis results are compared with the model analysis results obtained from Wu Yaping et al. [9]. It can be observed that analysis predictions of this paper agree closely with the ANSYS analysis results.

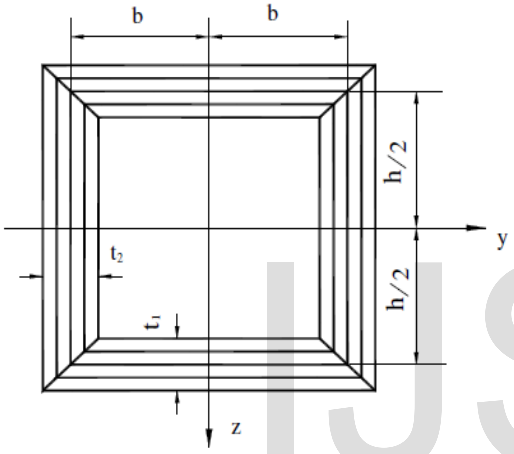


Fig.3. Cross section of composite box beam

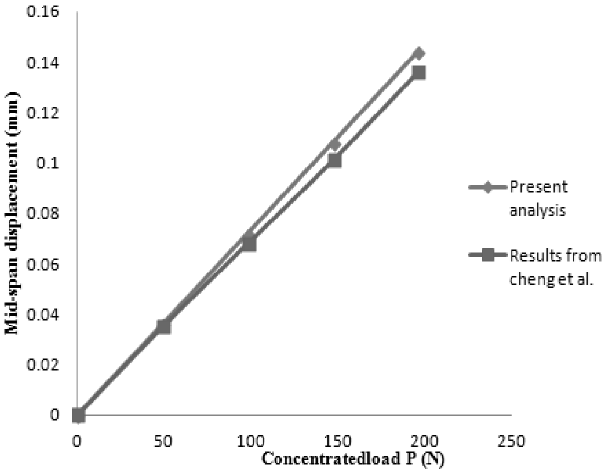


Figure.4. Mid-span displacement vs load P

5 FACTORS AFFECTING STRENGTH OF FRP ARCHES

The study of laminated composite arches is carried out by using carbon-epoxy as the fiber-reinforced polymer material.Its material properties are E_L= 114576 Mpa, E_T = 9981.7 Mpa, G_{LT} = 4664.8 Mpa, μ_{LT} = 0.325. A number of factors may influence the load-carrying capacity and buckling load of fiber reinforced polymer composite arches. It is well known that local buckling of plates affects the global in-plane strength of thin walled structures. However, the local buckling of arches with thin walled box section is much related to the cross section parameters such as web height to thickness ratio, flange to web thickness ratio and aspect ratio of cross section. The load-carrying capacity of arches may also affected by rise to span ratio, arch slenderness, the effect of lay-up sequence and angle of fiber orientation on the buckling load for symmetric lay-ups. The influence of these parameters on the buckling load should be investigated.

5.1 Influence of Arch Slenderness and Plate height to Thickness Ratio

To investigate the influence of the arch slenderness and the height to thickness ratio, FRP arches having symmetric carbon-epoxy thin walled box section with geometric parameters such as rise to span ratio f/L = 0.3, flange width to thickness ratio b/t_f = 40, flange to web thickness ratio t_f/t_w = 3 are used. The arch is pin-ended and subjected to a load uniformly distributed over full span. The variations of the buckling load obtained from the finite element models of arches having different plate height to thickness ratios are shown in Fig.5. These results of FE model with shell elements show that buckling load of arches are significantly affected by the plate height to thickness ratios. When the height to thickness ratio h/t increases from 100 to 150, the buckling load decreases rapidly.This is because the plate buckling stress decreases significantly and for arches with h/t > 150, the decrease of plate buckling stress becomes small. The buckling load decrease with an increase of the arch global slenderness for all values of the plate height to thickness ratio as shown in Fig.5. However, the difference of buckling load of the arches having different height to thickness ratio decrease as the arch global slenderness increases and almost vanishes when λ_g =300. It can also be seen that the combined influence of both the slenderness λ_g and the plate height to thickness ratio h/t on buckling load is quite complicated.

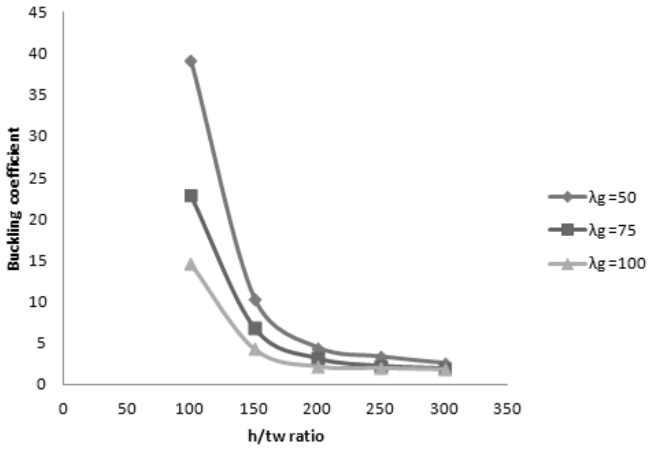


Fig.5. Buckling coefficient vs h/tw ratio

It can be concluded that for arches with a relatively large global slenderness λg and a small ratio h/t, the influences of the local buckling of its plates on the load-carrying capacities are small. For arches with a small global slenderness λg, their buckling coefficient is large if the h/t ratio of their cross sections is small. In this case, the plate components do not buckle locally. However, as the plate h/t ratio increases, local buckling of plate components may occur and this will reduce the bucking coefficient of the arch significantly.

5.2 Rise to Span Ratio

To study the influence of rise to span ratio f/L on the load carrying capacity of composite arches, different arches having same cross section with h/t = 50 t_f/t_w =1 and curvature length with λg = 60 as shown in Fig.6.were used. A typical influence is demonstrated in Fig.7.as variations of the dimensionless displacement w/L with the dimensionless load N/Ny for arches having the rise-to-span ratios f/L = 0.2, 0.3 and 0.4. It can be seen from Fig.6 that the differences between the dimensionless load-carrying capacities of arches with different rise to span ratios are very small for f/L =0.3 and 0.4, Which shows that the local plate buckling is not much related to the rise-to-span ratio of the arch. Hence, the elastic-plastic buckling of arches is not sensitive to their rise-to-span ratio f/L, which is consistent with the results of [14]

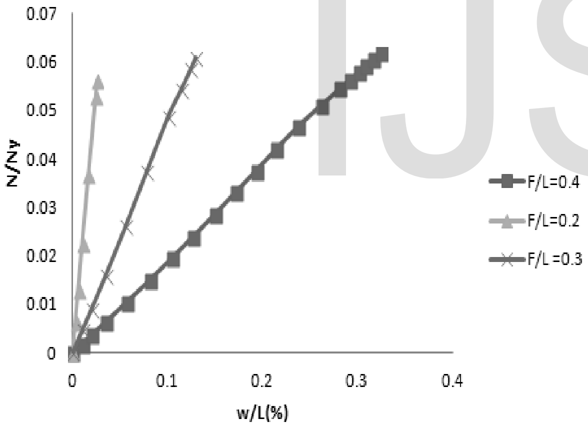


Fig.6. Load-displacement curves

5.3 Flange to Web Thickness Ratio

To investigate the influence of the flange to web thickness ratio on the buckling behavior of fiber-reinforced polymer arches having a thin walled box section, the following study is carried out. For this, arches with same cross section and rise to span ratio and different flange to web thickness is considered.Rise to span ratio 0.3, aspect ratio of cross section is 1.25, flange width to thickness ratio b_f/t_f =50 and laminate thickness 1 to 8 mm are taken for the study. The FE results are shown in Fig.7. for the buckling behavior of FRP arches under different flange to web thickness ratios.The Fig.7 shows that buckling coefficient increases with an increase of flange to web thickness ratio.

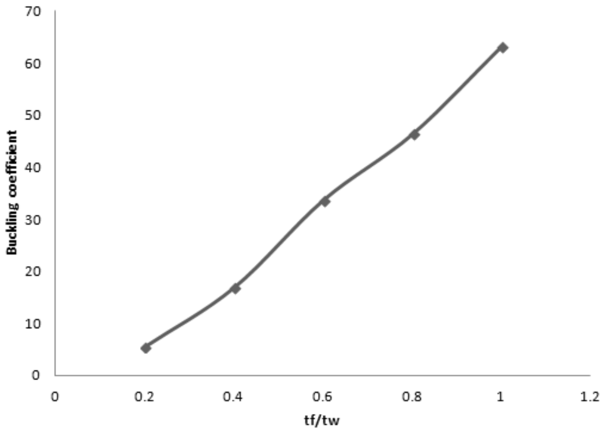


Fig.7. Buckling coefficient vs Flange to web thickness ratio

5.4 Aspect Ratio of Cross section

The influence of the aspect ratio h/b on the buckling coefficient of laminated composite arches having thin walled box section is demonstrated in Fig.6, where the arches have the different aspect ratios h/b = 1.0, 1.25, 1.5, 2.0 and 2.5 but have the same rise-to-span ratio f/L = 0.3, the same flange to web thickness ratio t_f/t_w = 1, and the same plate width-to-thickness ratio b/t = 50. The results in Fig.6.were obtained from the FE model analysis of shell element models. The height-to-thickness ratio of plate components of these arches will increases with an increase of the aspect ratio h/b of the cross section. From the results of these FE models, it can be seen that the buckling coefficient decreases with an increase of the aspect ratio h/b and indicates that local buckling behavior of FRP arches may dominate their load-carrying capacity.

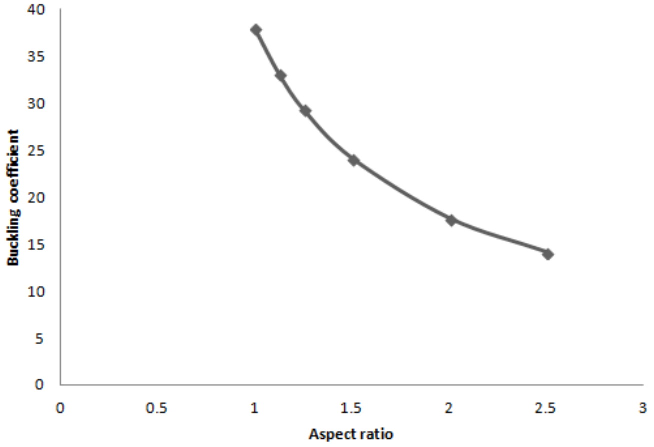
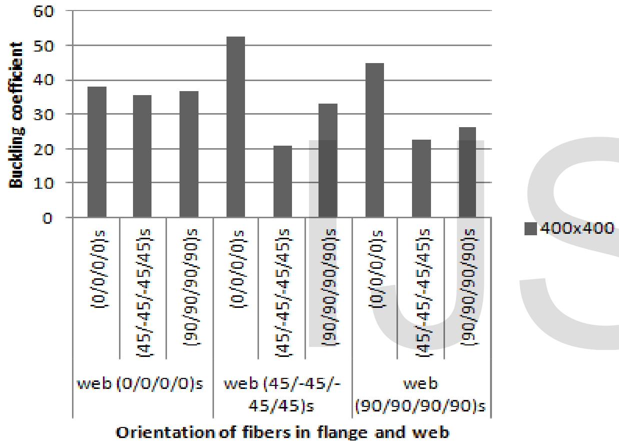


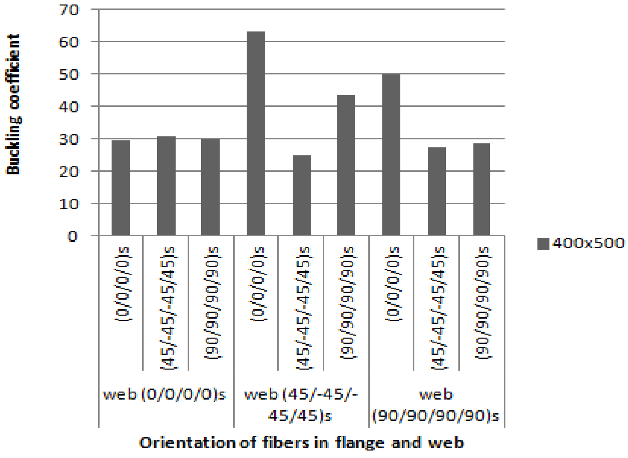
Fig.8. Buckling coefficient vs Aspect ratio

5.5 Effect of Fiber Orientation in Geometric conditions

In order to identify the effect of fiber orientation in flange and web for the plate buckling of pin-ended circular FRP arches having thin walled box, carbon-epoxy is used. The FRP arch is subjected to uniformly distributed load of 1 N/mm over the full span of the arch. Laminate thickness of 8 mm is provided for both flange and web. Lay-up considered was symmetric with 8 numbers of layers. The laminated composite arch having thin walled box section of different dimensions such as 400 mm x 400 mm, 400 mm x 500 mm, 400 mm x 800 mm with 15000 mm arch span were modelled and modal analysis was carried out. Study is done for sections with same as well as different lay-up in web and flanges. Fig.9 shows how the fiber orientation in flange and web influences the buckling coefficient for carbon epoxy composite arches.From this study it is observed that for different fiber orientations $[0/0/0/0]_s$,$[45/45/45/45]_s$, $[90/90/90/90]_s$ in flange and web, the buckling coefficient is maximum when fiber orientation of flange is $[0/0/0/0]_s$ and fiber orientation of web is $[45/45/45/45]_s$.



(a)



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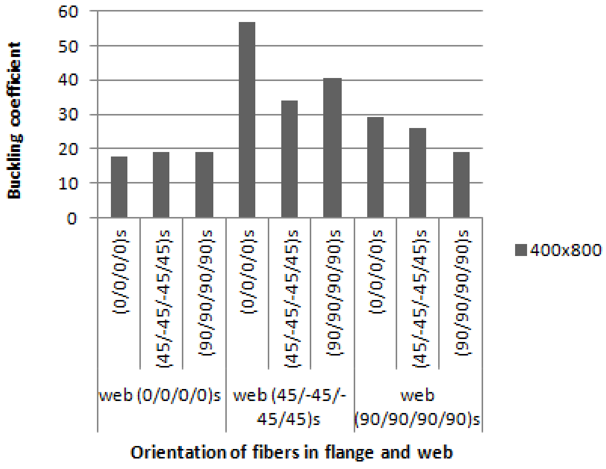


(c)

Figure.9. Buckling coefficient with fiber orientations of flange and web for different geometric conditions ;(a)15000x400x400 :(b)15000x400x500 ;(c) 15000x400x800

5.6 Effect of Fiber Orientation in Laminate Thickness

Next study is carried out to investigate the influence of angle orientation of fibers with different laminate thickness on the buckling behavior of FRP arches. Carbon-epoxy is used as the composite material and loading configuration is uniformly distributed load of 1 N/mm over the full span of the arch. Different laminate thickness is provided for both flange and web. Lay-up considered was symmetric with 8 numbers of layers. Laminate thicknesses of 6 mm and 4 mm are used for the analysis. From the Table 1.it is observed that for different fiber orientations $[0/0/0/0]_s$, $[45/45/45/45]_s$, $[90/90/90/90]_s$ in flange and web, the buckling coefficient is maximum when fiber orientation of web is $[45/45/45/45]_s$. Also we can said that as the thickness of laminates increases the buckling behavior reduces and large value for buckling coefficient is obtained. Graphical representation of buckling coefficient with different fiber orientations are shown in Fig.10.

TABLE 1.BUCKLING BEHAVIOR WITH ORIENTATION OF FIBERS

Orientation in web	Orientation in flange	Buckling coefficient		
		tf=6 tw=6	tf=4 tw=6	tf=6 tw=4
(0/0/0/0)s	(0/0/0/0)s	15.823	12.064	6.1466
	(45/-45/-45/45)s	12.887	10.566	4.4236
	(90/90/90/90)s	12.704	11.083	4.1604
(45/-45/-45/45)s	(0/0/0/0)s	40.582	24.153	21.485
	(45/-45/-45/45)s	13.022	8.3846	9.6448
	(90/90/90/90)s	19.767	9.8808	10.619
(90/90/90/90)s	(0/0/0/0)s	29.853	18.03	16.47
	(45/-45/-45/45)s	13.011	6.5345	9.1207
	(90/90/90/90)s	11.609	5.4993	7.9879

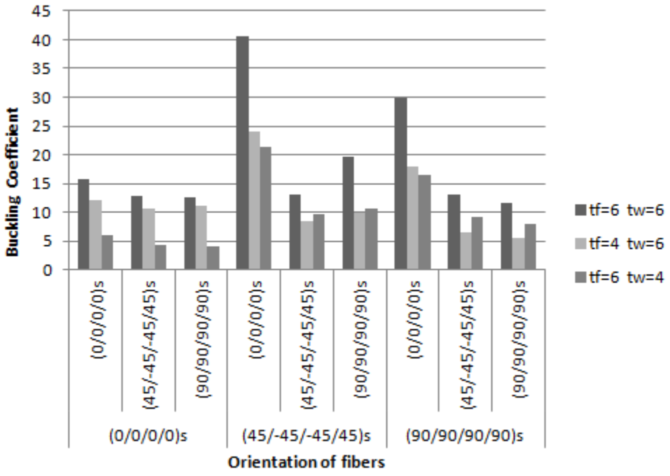
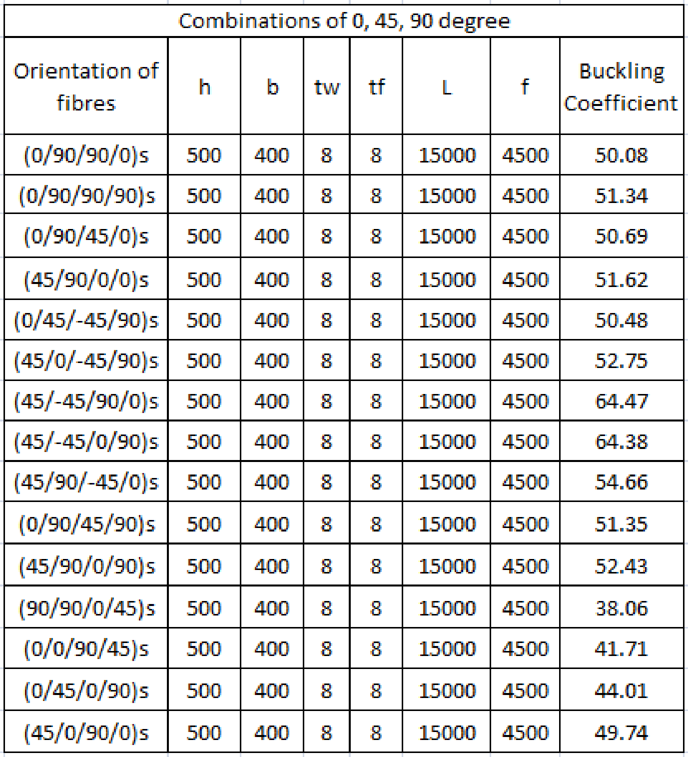


Figure.10. Buckling coefficient with fiber orientations of flange and web for different laminate thickness

5.7 Same lay-up Configurations for Flange and Web

To investigate the influence of lay-up configurations in web and flange, combinations of three angle orientations of fiber such as 0°, 45°, 90° are taken based on previous studies. **.** Lay-up considered was symmetric with 8 numbers of layers. FRP arch having cross section 400mmx500mm and span 15000 mm is considered for FE modeling.

TABLE 2 .BUCKLING BEHAVIOR WITH ORIENTATION OF FIBERS



Combinations of 0, 45, 90 degree							
Orientation of fibres	h	b	tw	tf	L	f	Buckling Coefficient
(0/90/90/0)s	500	400	8	8	15000	4500	50.08
(0/90/90/90)s	500	400	8	8	15000	4500	51.34
(0/90/45/0)s	500	400	8	8	15000	4500	50.69
(45/90/0/0)s	500	400	8	8	15000	4500	51.62
(0/45/-45/90)s	500	400	8	8	15000	4500	50.48
(45/0/-45/90)s	500	400	8	8	15000	4500	52.75
(45/-45/90/0)s	500	400	8	8	15000	4500	64.47
(45/-45/0/90)s	500	400	8	8	15000	4500	64.38
(45/90/-45/0)s	500	400	8	8	15000	4500	54.66
(0/90/45/90)s	500	400	8	8	15000	4500	51.35
(45/90/0/90)s	500	400	8	8	15000	4500	52.43
(90/90/0/45)s	500	400	8	8	15000	4500	38.06
(0/0/90/45)s	500	400	8	8	15000	4500	41.71
(0/45/0/90)s	500	400	8	8	15000	4500	44.01
(45/0/90/0)s	500	400	8	8	15000	4500	49.74

Laminated composite arch with same lay-up configurations for flange and web are modeled and studied. A total of 77 lay-up configurations were considered and some of the best results are listed in Table 2. Buckling behavior of FRP arch varies with change in lay-up configurations. It is also seen from the Table 2, that the buckling coefficient is even changes with the order of laminae in the laminate. The fiber orientation of laminate is closely related to its stiffness parameters such as orthotropic and rotational restraint parameters, which can be explained using extensional and bending stiffness of composite panels [16].So it can be concluded that, the buckling behavior can be influenced by the lay-up configuration of laminate and maximum buckling coefficient is obtained for orientation of flange and web with [45/-45/0/90]s or [45/-45/90/0]s.

5.8 Effect of No of Layers

To study the effect of number of layers in the laminate, FE models are prepared with different number of laminates. The study is limited to 1 to 8 number of laminates. For this, rise to span ratio 0.3, flange to web thickness ratio t_f/t_w =1, flange width to thickness ratio b_f/t_f =50 and angle orientation of fibers in flange 0 degree and angle orientation of fibers in web 45 degree are chosen. Fig.11. shows the analysis results based on the variation in number of layers with the buckling coefficient. From Fig.11 it is well known that, there is a slight increase in buckling coefficient with no of layers of laminae in the laminate of flange and web of a FRP arch having a box section.

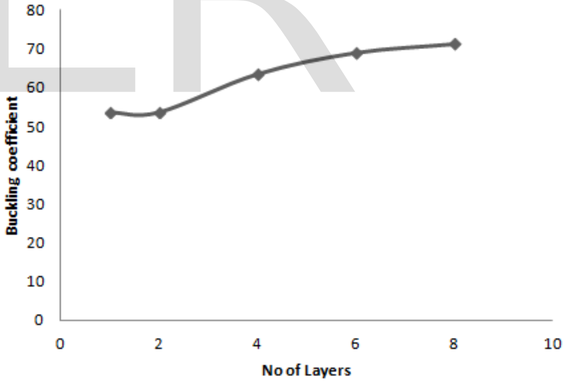


Figure.11. Buckling coefficient with number of layers in the laminate

7CONCLUSION

The in-plane failure and strength of pin-ended laminated composite circular arches having thin walled box section subjected to a load uniformly distributed over full span of the arch were investigated numerically using finite element models of shell elements. The buckling load is an important parameter in the analysis of the composite arches. The influences of a number of factors, such as the height-to-thickness ratio of the plate components, the aspect ratio of the box section, the rise-to-span ratio of the arch, the global slenderness of the arch, flange to web thickness ratio, number of layers in a laminate and angle orientation of fibers on buckling coefficient and strength of composite arches were investigated.

From the studies it was found that the factors such as height to thickness ratio of plate components and their aspect ratio are significantly effect the buckling coefficient of arches with thin walled box section. The flange to web thickness ratio of the cross section also influences the buckling coefficient of laminated composite box arch.The buckling behavior of laminated composite arches are significantly influenced by the orientation of fibers in the laminated plate.Here the study is conducted for a limited number of angle orientations.Same lay-up Configurations as well as different lay-up configurations for webs and flanges are included in the investigation. From the study, we can say that buckling coefficient is maximum when the fiber orientation in web is $[45/45/45/45]_s$, which is due to the influence of extensional stiffness and bending stiffness parameters of laminated composite plates.There for maximum load carrying capacity of arch will be obtained in that angle of fiber orientation.

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