Buckling characteristics and modes of FRP Pultruded I-column

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***Abstract*—For column buckling analysis is a critical area of study to determine overall section capacity subjected to axial load. FRP columns are manufactured using fiber and matrix composite lamina. Many researchers have studied the axial capacity of simply supported pultruded FRP column for various types of loadings. In this paper an attempt has been made to study the axial capacity of column subjected to point load for WF (wide flange) & NF (narrow flange) section. The validation has been made with experimental data. Further the parametric study has been carried out to study the mode of buckling with different length subjected to axial loads. The effect of ratio like b_f/b_w is also studied. The effect of slenderness on global lateral torsional buckling and local flange buckling under uniform axial loading is also studied.**

***IndexTerms*—FRP,Pultruded I-column, axial strength, buckling characteristics and modes.**

I. INTRODUCTION

The use of Fiber-reinforced plastic structural sections in construction projects is increasing. For structural designers fiber-reinforced plastic is an attractive material choice when factors such as corrosion resistance, light weight or electromagnetic transparency are important. Pultruded composite beams and columns are being extensively used for civil engineering structural applications. They have many advantages over conventional materials (steel, concrete, wood, etc.), such as high corrosion resistance and light weight. Mass production of composite structural members (e.g. by pultrusion) makes composite materials cost-competitive with conventional ones. Pultrusion is an efficient process for the manufacture of straight, long-fibre reinforced composite profiles with a different cross-section and shapes.

Pultrusion is a continuous process of raw materials, typically resin and reinforcing materials, forming profiles of constant cross section in continuous length. Pultrusion gets its name from the method by which the profiles are made. Raw materials are literally pulled by what we call "the puller." "The puller" is the machine made up of pulling pads, which grip the product, and a drive system which keeps the product moving. "The puller" is located just before the final cut-off saw. The process starts with the reinforcements. Typically, unidirectional glass roving is the fiber that runs along the length of the profile. Second, the fiberglass mat is added in, which is multidirectional reinforcement. Third is the resin, typically polyester or vinylester. The glass is "wet-out" with the liquid resin and pulled into a heated die. Just before all the material enters the die, surface veil may be added which enhances the final product's surface. Now that all the reinforcements have been "wet-out" and pulled into a heated die, the curing takes place. All the resins used in the pultrusion process have a catalyst or hardener added when the resin is mixed. This catalyst activated at about 200°F. Consequently, as the "wet-out" reinforcement pass through the heated die, the product changes from liquid to a solid profile with all the reinforcement laminated within. The product exiting the die is pulled by "the puller", which upon exiting can be cut to the desired length.

II. LITERATURE STUDY

John Tomblin& Ever Barbero, et al [1] studied local flange-buckling of thin-walled pultruded FRP columns. Experimental data are presented and correlated with theoretical predictions. The experimental and data reduction procedures used to obtain the local buckling loads are presented. To interpret local buckling test data, a new data reduction technique using Southwell's method is developed. The demonstration of the data reduction technique for the various type of column section and experimental condition is shown.Load were increase till the column was clearly buckled by eyesight. After analysis of result we can say that, all gauges had small movements from the initial application of load and then stabilized at a load until flange buckling occurred. In some case one flange buckled before the other, which may be caused by imperfections existing in that flange.

M. J. McCarthy & L. C. Bank, et al [2] have main objective to investigate the sensitivity of proposed design equation for local flange buckling. Also for the determination of accuracy of the equation that includes the effect of rotational restraint at web-flange junction. The equation can be used for design of macroscopically non-homogeneous member. The equation obtain in the past papers cannot give the accurate result. He examines the equation for the equation base on orthogonal plate theory for the local buckling stress for a plate. Also examine equation for the rotationally restrained web-flange junction. The rotational constant is higher in beams than in columns because the web does a better job of retraining the flange against buckling. In order to compare the equations the predicted strengths of the equations are compared with experimental results. This is done by calculating a professional bias, defined by equation which is ratio of experimental strength to predicted strength. If the professional bias is 1, it means the equation correlates perfectly with the result. If it is greater than 1 it means the equation is conservative and less than 1 means non-conservative. In general, the closer the professional bias value is to 1 the more accurate the equation is.

Daniel C. T. Cardoso, Kent A. Harries, et al [3] gives a simple accurate equation to determine the local buckling critical stress of pultruded GFRP I-sections is developed. The sections made with vinyl ester and polyester matrices were tested. The proposed expression is compared with experimental results, as well as results from numerical analyses using the finite-strip method (FSM). In this work, the Rayleigh Quotient method was used to determine local buckling critical loads. Equation was developed for an infinitely long plate that is able to accommodate the critical half-wave length. The equation proposed showed good agreement with numerical and experimental data. The VE sections exhibited slightly higher elastic properties than PE, but no noticeable differences were observed in the stub column tests.

R. J. Brooks, G. J. lbrvey,et al [4] consider series of lateral buckling tests on pultruded GRP I-section cantilever beams. Comparisons of the theoretical critical loads, determined from approximate formulae and numerical finite element eigenvalue analysis, with the test results are presented. They reveal that linear buckling analysis does not provide an accurate estimate, for use in design, of the maximum tip load that a GRP cantilever may support. The critical loads obtained from the finite element eigenvalue analysis are generally lower than the test loads observed at the onset of lateral buckling. Indeed, it appears that using full-section moduli in the classical Timoshenko critical load formula provides an overall correlation with the test results which is comparable with the best of the finite element eigenvalue analysis predictions. They suggested that incorporating initial deformations as well as pre-buckling deformations in an incremental finite element analysis may lead to a closer correlation with the test results.

Rami Haj-Ali, HakanKilic, et al [5]investigated Coupon tests and used to calibrate 3D micromechanical models and to verify their prediction for the non-linear elastic behavior of pultruded FRP composites. The material system is made from E-glass/vinyl ester composite plate with both continuous filament mat (CFM) layers and glass roving layers. Tension, shear and compression tests were performed, using off-axis coupons cut with different roving reinforcement orientation. The overall linear elastic properties are identified along with the nonlinear stress-strain behavior under in-plane multi-axial tension and compression loading. The tests were carried out of coupons with off-axis angles 0°, 15°, 30°, 45°, 60° and 90°, where each test was carried out three to five times. Finite element analysis is used to examine geometry condition end-clamping condition and axis orientation. Lower initial elastic modulus and softer nonlinear stress-strain responses observed in the tension compared to those in compression for all axis orientation. The nonlinear behavior can be attributed to the relatively low overall fiber volume fraction in pultruded composites and manufacturing defects such as micro cracks and voids. End coupling effect for the tested geometry is small at the center and allows extracting the non-linear stress-strain response of anisotropic.

A Lane and J T Mottram, et al [6]presented an experimental investigation concerning the buckling behavior of pultruded fibre-reinforced plastic (PFRP) columns. Local and global buckling modes occur concurrently in a violent and unstable manner at situation of the Combined buckling is describes. Wide-flange sections have a greater proportion of unidirectional fibre reinforcement oriented down the longitudinal axis in comparison with most other types of PFRP profile. The value of global buckling load increases as the column length decreases, which allows local buckling of the flanges to become the critical mode of failure for columns below a certain length. The rotational restraint at the web-flange interface is the main cause of the accurately modeling, and estimating the value. The non-linear effects are highly sensitive to imperfections. The two principal types of imperfection found in column buckling are load eccentricities and column imperfections.

Ever J. Barbero, Edgar K. Dede, et al [7] studied interaction of more than one buckling mode induce an unstable tertiary post-buckling path, causing imperfection sensitivity and premature failure. The existence of buckling-mode interaction is experimentally verified for intermediate length pultruded wide-flange columns subjected to uniaxial compression. Testing Section produced by pultrusion, with the geometry and material properties of the cross-section being fixed by the manufacturer. This section are used because of their high strength to weight ratio, resistance to environmental deterioration, and lack of interference with electromagnetic radiation. Length of the column is such that the predicted local and Euler loads are close, the experimental failure load may be lower than both loads, depending on the imperfections.

Ever J. Barbero&loannis G. Raftoyiannis,et al [8]has considered for long pultruded columns, overall (Euler) buckling is more likely to occur before any other instability failure and the buckling equation has to account for the anisotropic nature of the material. For short columns, local buckling occurs first leading either to large deflections and finally to overall buckling, or to material degradation due to large deflections (crippling). Because of the large elongation to failure allowed by both the fibers and the resin, the composite material remains linearly elastic for large deflections and strains unlike conventional materials that yield (steel) or crack (concrete) for moderate strains. Therefore, buckling is the governing failure for this type of cross-sections and the critical buckling load is directly related with the carrying capacity of the member.

III. Buckling of section

For the study of flexural buckling of FRP Pultruded I-column the various parameter are considering in this chapter. There are mainly three type of buckling mode of section.

1. Global Flexural Buckling
2. Global torsional Buckling
3. Local Buckling

1. Global Flexural Buckling

The term Global buckling is used to describe the commonly observed overall physical instability that can occur in compression member loaded by axial loads. Global buckling is referred as the Euler buckling. At the point of critical global buckling load is reached the entire section displaced laterally about one of the centroidal axis planes. In our case column is move about the weak (minor) axis.

$$\mathrm{Pcr} = \frac{\mathrm{Peuler}}{1 + P_{euler} / k_{tim} A_Z G_{LT}}$$

$$P_{euler} = \pi^2 E_L I / (kL)^2$$

$$k_{tim} A_Z G_{LT} = A_{web} G_{LT}$$

Where P_{cr} = critical Global Buckling load
K_{tim} = Timoshenko shear coefficient
A_Z = cross section area
G_{LT} = Shear modules of section
A_{web} = Area of web

Timoshenko shear coefficient is found out by below equation

For the symmetric section (EL, G_{LT}, υ_L are constant, $t_w = t_f$, b = h)

$$K_{tim} = \frac{80 /}{(192 + \upsilon L G_{LT} / E_{LT})\ (33)}$$

For the unsymmetric section (n = b / h; m = t_F b / t_W h)

$$\mathrm{Ktim} = \frac{20\,(1 + 3\,\mathrm{m})2}{(180\mathrm{m}^3 + 300\,\mathrm{m}^2 + 144\mathrm{m} + 60\,\mathrm{m}^2\mathrm{n}^2 + 60\,\mathrm{m}\,\mathrm{n}^2 + 24) + (\upsilon_L G_{LT} / E_{LT})\,(30\mathrm{m}^2\ 40\,\mathrm{mn}^2 + 60\,\mathrm{m}^2 + 6\mathrm{m} - 4)}$$

2. Global Torsion Buckling

Open-section compression members can buckle in a pure torsional mode. For doubly symmetric sections such as I-shaped profiles, the torsional rigidity is high and torsional buckling is seldom a limiting slate. However, for open sections in which the walls all meet at the centroid (such as a cruciform section). Torsional buckling can be critical. Neglecting the influence of shear deformation, the critical torsional buckling stress in a homogeneous member is

$$\sigma_{cr}^{tor} = \frac{1}{I_p}\left[\frac{\pi^2 E_L C_\omega}{(K_\omega L)^2} + G_{LT} J\right]$$

Where, A_z = cross-sectional area

I_P = the polar second moment of area

J = the torsional constant

C_ω = the warping constant

k_ω = end restraint coefficient for torsional buckling

L = the unbraced length of the member

G_{LT} is the previously defined in-plane shear modulus of the pultruded material

The critical torsional buckling load for homogeneous members is

$$P_{cr}^{tor} = \sigma_{cr}^{tor} A_Z$$

3 Local buckling

Conventional pultruded GRFP profiles are especially susceptible to local buckling when subjected to axial loads. It is due to the low in-plane moduli and the slenderness (width-to-thickness ratio) of the plate elements that make up the thin-walled profile. For the determination of the Local buckling load Kollar's method is used.

To use Kollar's method, first the buckling stresses (or loads) of the walls are determine with assuming they are simply supported at their restrained edges. These stresses are used to determine which wall buckles first and the coefficient of edge restrain for the critical wall. The final solution is then given by a closed form equation that includes the coefficient of edge restraint of the critical wall for the buckling stress of a restrained wall. Two types of simply supported walls are needed for the solution.

1. A wall that is free and simply supported on its edges under uniform axial stress. This solution is used to determine the critical stress in the flange of an I-shaped profile. It is Given in terms of flexural rigidities of flange as

$$(\sigma^{ss}_{free})_f = \frac{\pi^2}{t_f(b_f/2)^2}\left[D_L\left(\frac{b_f/2}{a}\right)^2 + \frac{12}{\pi^2}D_S\right]$$

t_f is the thickness of flange, b_f is width of profile and 'a' is the half-wavelength. Half-wavelength is equal to the length of the flange in special case. For long flanges the critical stress can be found as

$$\sigma^{ss}_{free} = \frac{4t_f^2}{b_f^2}G_{LT}$$

2. A wall that is simply supported along both edges under uniform axial stress. This solution is used to determine the critical stress in the web of an I-shape.

$$(\sigma^{ss}_{free})_f = \frac{2\pi^2}{t_f b_i^2}\left(\sqrt{D_L D_T} + D_{LT} + 2D_S\right)$$

For finding out the local buckling equation for an I-shaped profile in axial compression

$$k_{1-flange} = \frac{(D_T)_w}{d_w}\left[1 - \frac{(\sigma^{ss}_{free})_f (E_L)_w}{(\sigma^{ss}_{free})_w (E_L)_f}\right]$$

$$\sigma_{cr}^{local,I-flange} = \frac{1}{(b_f/2)^2 t_f}\left(7\sqrt{\frac{D_L D_T}{1+4.12\zeta_{1-flange}}} + 12D_S\right)$$

$$\zeta_{1-flange} = \frac{(D_T)_f}{k_{1-flange}\,(b_f/2)} = \frac{(E_T)_f t_f^3}{6k_{1-flange}\,b_f[1-(\nu_T)_f(\nu_L)_f]}$$

$$a_{I-flange} = 1.675\frac{b_f}{2}\sqrt[4]{\frac{D_L}{D_T}(1+4.12\zeta_{1-flange})}$$

$$P_{cr}^{local\ I-flange} = \sigma_{cr}^{local\ I-flange} A_Z$$

For finding out the critical load for the intermediate length

$$P_{cr}^{int} = k_i P_L$$

$$\sigma_{cr}^{int} = \frac{P_{cr}^{int}}{A_Z}$$

$$k_i = k_\lambda - \sqrt{k_\lambda^2 - \frac{1}{c\lambda^2}}$$

$$k_\lambda = \frac{1+(\frac{1}{\lambda^2})}{2c}$$

$$\lambda = \frac{kL}{\pi}\sqrt{\frac{P_L}{(EI)_{min}}} = \sqrt{\frac{P_L}{P_E}}$$

IV. VALIDATION STUDY

Material Geometry & properties

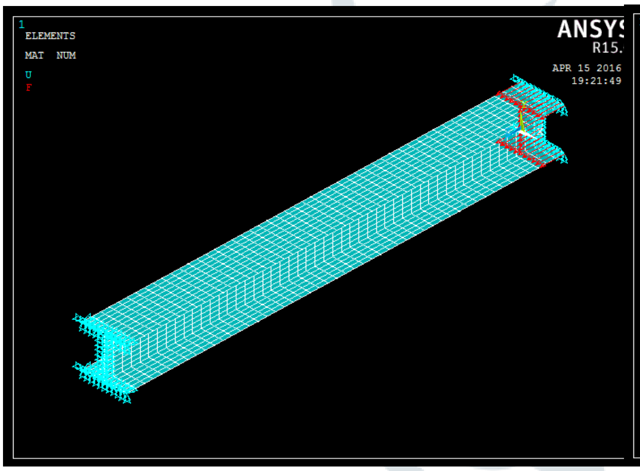
In this study, 100 x 100 x 6.32 mm, 100 x 100 x 6.34 mm of FRP I-column is studied, which were made with polyester (PE) by the Pultrusion process.The results of critical buckling loads for all profiles are compared to the experimental data from research work carried out by Daniel C. T. Cardoso.The 60% E-glass fibers and 40%polyester resin is used in pultrusion process.The laminaproperties of section are given as follows.

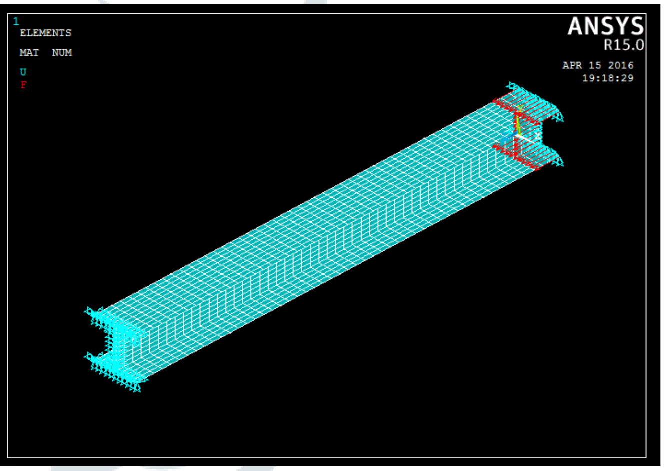
Table 1 Material Lamina properties

Exx	1.14 x 1010 Pa
Eyy	4.47 x 1010Pa
Ezz	1.14 x 1010 Pa
NUxy	0.272
NUyz	0.272
NUxz	0.446
Gxy	4.20 X 109 Pa
Gyz	4.20 X 109 Pa
Gxz	4.20 X 109 Pa

Modelling in ANSYS

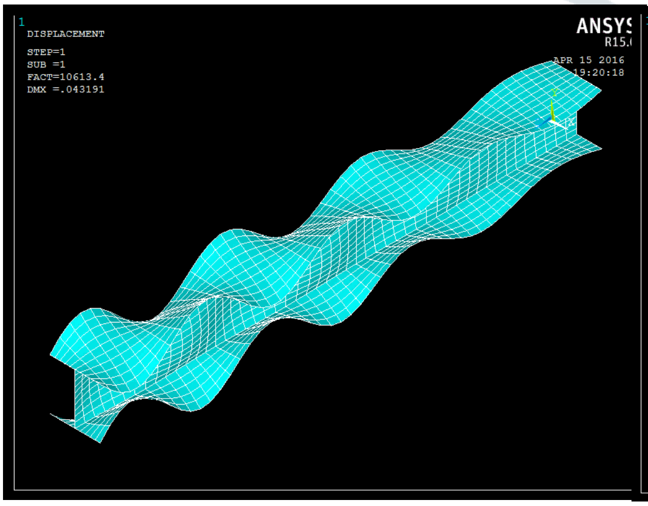
Each profile is modeled as stub column with end condition (Ux=Uy=Uz=0) at all nodes of the flange at one end other end condition (Ux=Uy=0) to obtain the critical load. Load on all right end nodes is applied and Eigen buckling analysis is carried out. Fz = 1N is applied as an initialization load for Eigen buckling. Modeling is done using shell 181, special element which facilitates the laminate analysis with orthotropic and anisotropic lamina stacking arrangement material. For the analysis the beam length is taken 400 mm.

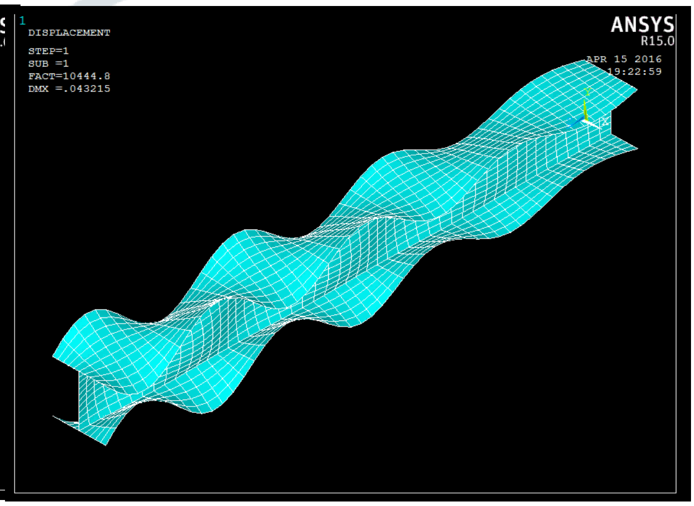




0.1 x 0.1 x 0.00632 m **0.1 x 0.1 x 0.00634 m**

Buckling mode of section





0.1 x 0.1 x 0.00632 m **0.1 x 0.1 x 0.00634 m**

Critical buckling load (Pcr)

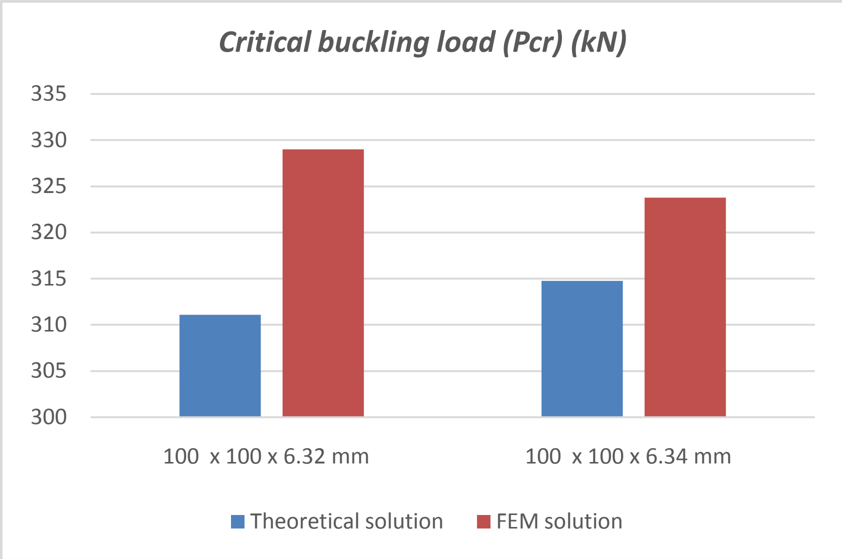


Figure 2 Critical buckling load comparison

	Theoretical solution (kN)	FEM solution (kN)
100 x 100 x 6.32 mm	311.10	329.00
100 x 100 x 6.34 mm	314.76	323.78

Table 2 Critical buckling load comparison between ANSYS and study done by Daniel C. T. Cardoso

Comparison of the result of ANSYS to theoretical solution

Wide flange profiles WF 100 x 100 x 6.4mm of FRP I-beam is studied. Theoretical solution is calculated as per equations for above model and it is compare with the model analyzed by ANSYS. Also the study of the critical load and the mode of buckling is carried out.

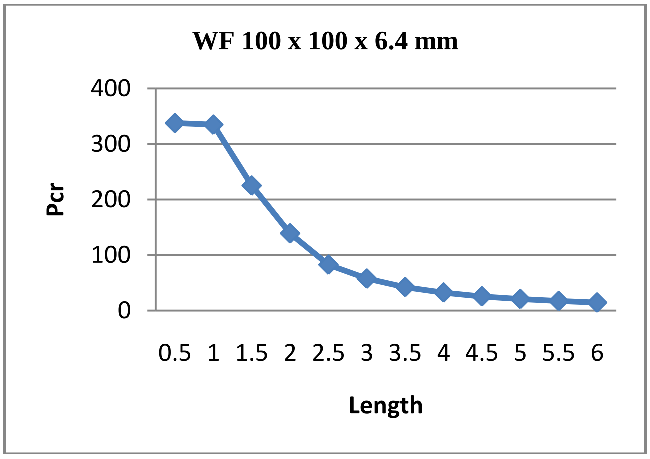
It is noticeable that the critical load is accounting only with for the local and Global Flexural buckling.

Length (m)	Mode of buckling	ANSYS (kN)	Calculation (kN)	% error
0.5	LB	337.68	311.08	7.88
1	LB	334.73	305.1	8.68
1.5	GB	225.12	202.92	9.86
2	GB	139.03	126.71	9.35
2.5	GB	82.64	75.485	8.66
3	GB	57.59	52.721	8.47
3.5	GB	42.40	38.869	8.35
4	GB	32.51	29.82	8.30
4.5	GB	25.69	23.53	8.44
5	GB	20.83	19.9	4.47

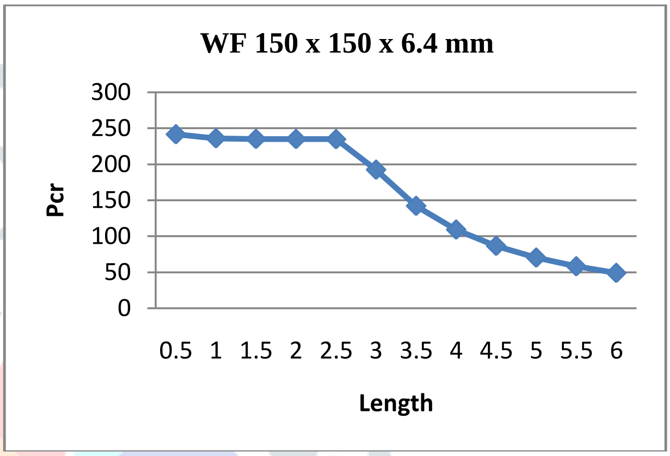
Parametric study for changing of length

In this study, three WF100 x 100 x 6.4mm, WF 150 x 150 x 6.4mm, WF 300 x 300 x 12.7 mm and threeNF 50 x 100 x 6.4mm,NF 75 x 150 x 6.4mm, NF 300 x 300 x 12.7 mm considered for the obtaining the critical load buckling and mode of buckling of critical section.

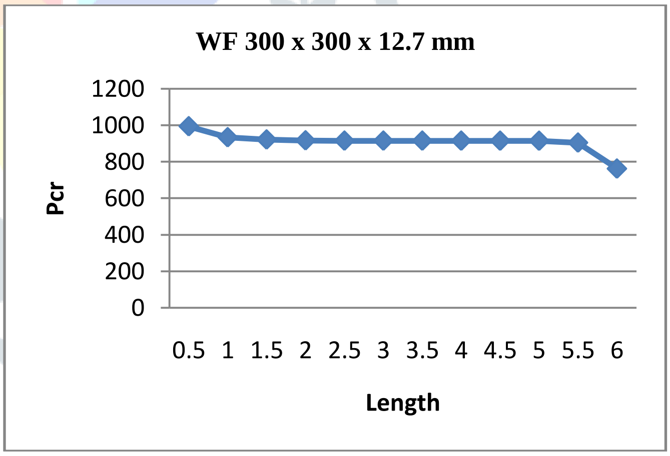
SECTION	WF 100x 100 x 6.4 mm	
Length (m)	Pcr (kN)	Mode of buckling
0.5	337.683	LB
1	334.738	LB
1.5	225.122	GB
2	139.035	GB
2.5	82.646	GB
3	57.598	GB
3.5	42.408	GB
4	32.519	GB
4.5	25.699	GB
5	20.832	GB
5.5	17.24251	GB
6	14.49467	GB



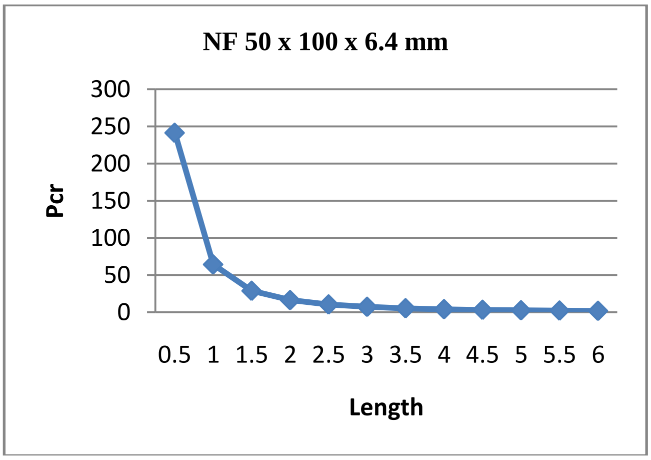
SECTION	WF 150 x 150 x 6.4 mm	
Length (m)	Pcr (kN)	Mode of buckling
0.5	241.71	LB
1	236.09	LB
1.5	235.25	LB
2	235.10	LB
2.5	234.85	LB
3	192.45	GB
3.5	142.10	GB
4	109.15	GB
4.5	86.42	GB
5	70.12	GB
5.5	58.02	GB
6	48.80	GB



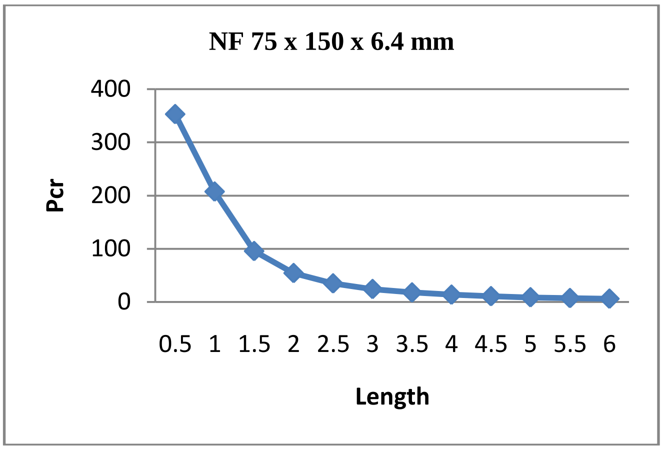
SECTION	WF 300 x 300 x 12.7 mm	
Length (m)	Pcr (kN)	Mode of buckling
0.5	994.697	LB
1	934.712	LB
1.5	922.498	LB
2	917.786	LB
2.5	916.143	LB
3	916.236	LB
3.5	916.174	LB
4	916.019	LB
4.5	915.802	LB
5	915.678	LB
5.5	905.541	GB
6	763.747	GB



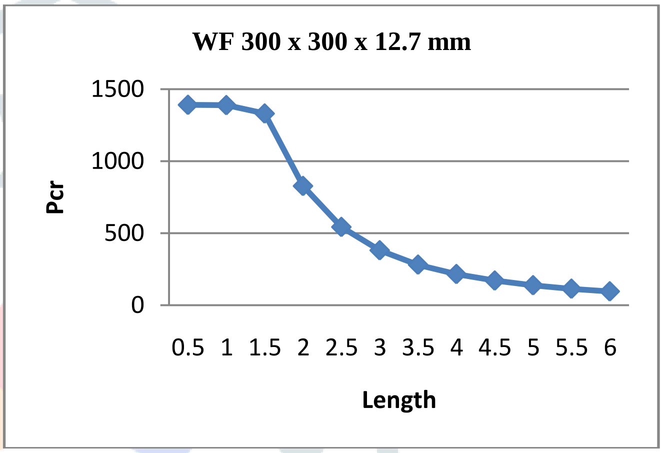
SECTION	NF 50 x 100 x 6.4 mm	
Length (m)	Pcr (kN)	Mode of buckling
0.5	241.37	GB
1	64.26	GB
1.5	28.79	GB
2	16.25	GB
2.5	10.41	GB
3	7.24	GB
3.5	5.32	GB
4	4.07	GB
4.5	3.22	GB
5	2.61	GB
5.5	2.15	GB
6	1.81	GB



SECTION	NF 75 x 150 x 6.4 mm	
Length (m)	Pcr (kN)	Mode of buckling
0.5	353.4	LB
1	207.67	GB
1.5	95.71	GB
2	54.34	GB
2.5	34.91	GB
3	24.29	GB
3.5	17.87	GB
4	13.69	GB
4.5	10.82	GB
5	8.77	GB
5.5	7.25	GB
6	6.09	GB



SECTION	WF300 x 300 x 12.7 mm	
Length (m)	Pcr (kN)	Mode of buckling
0.5	1391.43	LB
1	1389.42	LB
1.5	1331.32	GB
2	828.38	GB
2.5	543.95	GB
3	382.04	GB
3.5	282.37	GB
4	216.97	GB
4.5	171.83	GB
5	139.41	GB
5.5	115.35	GB
6	97.0145	GB



V. CONCLUSION

It can be said that the mode of buckling of section is directly dependent on the length of the section. Increasing in the length can resulting in changing in mode shape from local buckling to global buckling. For smaller length of section, mode of critical load is Local Buckling and for longer section it is Global Buckling.

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