RESEARCH ARTICLE

Numerical and Analytical study on Axial Compression behaviour of Pultruded GFRP members

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From last decade, due to its lighter weight, resistance to the environmental attack, high tensile strength and corrosion resistance as compare to other construction materials, Pultruded profiles are used as a new innovative material in civil engineering construction applications. This paper addresses the buckling behaviour of pultruded profile of I cross section when subjected to uniform axial compression. In this, three different sizes of I-sections made of glass fibre and embedded in polyester matrix with pinned-pinned support condition are used. The Numerical and analytical study has been carried out and results of both the analysis are validated with the experimental results given by previous researcher which is demonstrated to be effective for buckling phenomenon of Pultruded section. Numerical analysis has been carried out using commercially available software package ANSYS and analytical behaviour is done by using EuroCode "JRC report EUR 27666 EN". In the end, the results of numerical investigation are compared with analytical results and results are seems to be within range.

Introduction

A detailed Fiber Reinforced Polymer pultruded element can be used as a valid alternative to classic materials. Earlier its use was limited for constructions. But due to its durability property and high mechanical strength, the maintenance cost can be lowered as compared to other classic material [**1**]. Structural behavior of Fiber Reinforced Polymer (FRP) pultruded profiles will slightly vary from the result exhibited by the traditional materials. They have to be considered linear elastic, orthotropic behavior until failure, which occurs in brittle manner [**2**].

Previous studies of axial behaviour of pultruded GFRP have identified the following general conclusion as summarized by Cardoso *et al.* [**3**].

- Short columns, (local buckling) when plate relative slenderness $\lambda_p=(f_c/\ f_{crl})^{0.5} \leqslant\approx 0.7$, in which f_c is the material compressive strength and f_{crl} is the local buckling critical stress.
- Long columns, (global buckling) when $\lambda_p \geqslant\approx 1.3$.
- Intermediate columns, (local and global buckling) when slenderness ratios are falling in between long and short columns.

In this paper, three different sizes and lengths of concentrically loaded pultruded GFRP I-section column reinforced with polyester matrix and glass fiber which failed in global flexural buckling mode has presented.

Experimental buckling/failure loads are given by previous researcher. Numerical analysis is being carried by the application of finite element model using ANSYS software and Analytical validation is conducted by Euro code.

Numerical simulation

The main objective to presenting numerical model is to simulate similar behavior of Pultruded glass fibre reinforced polymer (PGFRP) I-section column experimentally tested and presented by previous researcher [**4**]. In order to bring this state, finite element model is first described below with element type, meshing, GFRP material properties, boundary condition and load type.

Finite element model

Numerical models of PGFRP I section columns are modeled using ANSYS software. In this, three PGFRP I-section columns having various different lengths, dimensions and same boundary conditions are tested under axial compression.

In this paper I-sections are modeled by SOLID 186 element. The SOLID186 is twenty nodded element with three DOF per node, i.e., in x, y, z directions. The element will have the ability in supporting plasticity, creep, hyper elasticity, stress stiffening, large strain and large deflection. Meshing is done after performing the convergence study of the model through mesh tool menu. For I-sections, element size of 15 mm is taken. This size is achieved by checking the convergence criteria. A graph (**Fig. 1**) is drawn between Load and Element size to check the optimum element size.

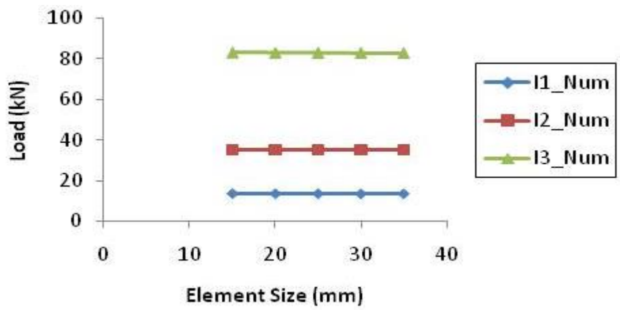


Fig. 1. Convergence Plot for I1,I2 and I3 sections.

Material properties

Material property inputs are done from the properties derived from experimental test by previous researcher [**4**]. Test database for the global flexural buckling of the Pultruded GFRP I shaped section profiles are given in **Table 1**.

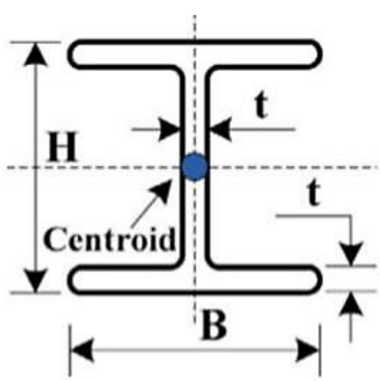


Fig. 2. Cross section of PGFRP I – section column [4].

Where, B = Width of Flange, H = Height of Web, t = Thickness of Flange and Web.

Boundary conditions and load type

All three I sections in database are subjected to axial compression under pinned-pinned boundary conditions [**4**]. At the bottom end, translational degree-of-freedoms along Y- and Z- axes are prevented but X-axis is free. The top end of column, the translational degree-of-freedoms along X- and Y-axes are prevented while vertical displacement i.e. Z-axis, is free. Loading is applied on top of the column by the concentrated force.

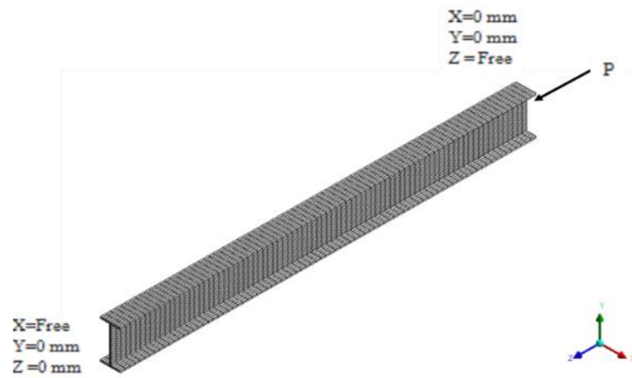


Fig. 3. FE model I-section and mesh with boundary condition and concentrated applied load.

Where, E_{LC} = Longitudinal modulus in compression, G_{LT} = in-plan shear buckling load, Etc = Transverse modulus in compression.

Buckling analysis

Critical buckling loads of sections mentioned in **Table 2** are determined using the both linear (Eigen-value) and the non-linear analysis. As linear analysis neglects, initial geometrical imperfections of the sections whereas nonlinear analysis take this in account. Yet, due to absence of the real geometrical imperfection data, artificial initial geometrical imperfections were being used [**6**]. Here, the Initial geometrical imperfection is first shape of buckling mode obtained from linear buckling analyses. This value is enough to avoid a numerical problem which is close to the bifurcation point [**2**].

Where, P-P = Pinned – Pinned condition, P_{EXP} = Experimental Buckling Load, P_{NUM} = Numerical Buckling Load, P_{ANA}=Analytical buckling load, $Error_{NUM}$= (P_{NUM}- P_{EXP}) /P_{EXP}, $Error_{ANA}$= (P_{ANA}- P_{EXP})/P_{EXP}. $Error_{NUM\ \&\ ANA}$ = (P_{NUM}- P_{ANA})/P_{ANA}.

To conduct nonlinear analysis for buckling equations following methods are available in ANSYS:

- The Newton Raphson method
- The Arc Length method

Table 1. Test database used in numerical modeling [4]

Source	Section	Dimension (mm)	Length (mm)	E_{LC} (MPa)	E_{TC} (MPa)	G_{LT} (MPa)	F_{LC} (MPa)	P_{EXP} (kN)	Slenderness Ratio (λ)
Seangatith and Sriboonlue [5]	I1	101.6 X50.8 X 6.35	1512	22500	7500	3150	219	12.9	157.84
	I2	152.4X 76.2 X 9.525	2112	22500	7500	3150	219	33.9	146.96
	I3	203.2 X101.6 X 9.525	2112	22500	7500	3150	219	81.9	111.27

Note: Experimental buckling loads are taken from previous researcher reported in reference [4].

Table 2. Buckling Loads of Experimental, Numerical and Analytical simulation.

S. No.	Section	Dimension (mm)	Length (mm)	End Condition	P_{EXP} (kN)	P_{NUM} (kN)	$Error_{NUM}$ (%)	P_{ANA} (kN)	$Error_{ANA}$ (%)	$Error_{Num\ \&\ Ana}$ (%)
1	**I1**	101.6 X 50.8 X 6.35	1512	P-P	12.9	13.64	**5.73**	13.39	**3.79**	**1.86**
2	**I2**	152.4 X76.2 X 9.525	2112	P-P	33.9	35.36	**4.31**	34.64	**2.18**	**2.07**
3	**I3**	203.2 X 101.6 X 9.525	2112	P-P	81.9	83.15	**1.53**	77.27	**-5.65**	**7.61**

Rapid convergence in nonlinear analysis is the specialty of the Newton Raphson method and it also seems to be very accurate method. Main drawback is load-controlled analysis. Therefore it fails when snap-though occurs. But Arc Length method permits to control load level, length of displacement increment and maximum displacement. So this method is used in nonlinear analysis. Through nonlinear analysis we can get initial failure loads and maximum axial shortening which gives exact value of buckling load [**4**].

Analytical study

In this paper, Euro Code "JRC report EUR 27666 EN" [**9**] is used for analytical approach to determine the buckling behaviour of PGFRP column and their results are compared with experimental and numerical results presented here in with. With low modulus of elasticity and high mechanical strength buckling behaviour of FRP column is governed by the ultimate behaviour of column [**7**].

All the formulae used in Euro Code "JRC report EUR 27666 EN" [**9**] are explained in **Appendix A**. To calculate the design resistance value $N_{c,Rd}$ requires calculation of critical stress of compressed flange $\left(f_{loc,k}^{axial}\right)_f$ and web $\left(f_{loc,k}^{axial}\right)_w$. Eulerian critical load should also be determined. The reduction factor χ which consider local and global instability interaction of element depends on slenderness λ used to determine compressive load carrying capacity $N_{c,rd2}$. The reduction factor assumes unitary value. For local-flexural interaction coefficient c is used where, c=0.65 (in absence of data). Compressive force of the profiled element $N_{c,rd1}$ takes into account the cross section area and compressive strength whereas $N_{c,rd2}$ is calculated by using reduction factor and compressive force (determine local instability). Minimum of $N_{c,rd1}$ and $N_{c,rd2}$ is consider as design value of compressive load.

Results and discussion

The section provides results of analytical and numerical study carried out in this paper. The results comprises Axial load-Axial displacement (load-deflection) curve, comparison between buckling load obtained by numerical and analytical simulation with available experimental data and buckling mode shape diagrams of the three pultruded columns.

- Axial load - Axial displacement (load-deflection) curve seems to be linear upto the failure. The increase in the section size also increases buckling resistance, which can be seen from the **Fig. 5**.
- The buckling deformed shapes are accurately predicted by finite element models. On compared to test results, buckling loads obtained during numerical simulation showed differences of upto 5% with the experimental results.
- In case of analytical simulation, it showed difference upto 3% with experimental results. Hence, Analytical modeling shows less error of percentage as compared to numerical one. This may be because of the safety factor, reduction factor, used in the formulae.
- Looking at the critical buckling mode shape from **Fig. 6(f)**, all the three specimens had the same numerical failure which shows buckling of web is more in mid span sections.
- Shape of first buckling mode is obtained through finite element modeling seems to be global-flexural failure similar to experimental condition determined by other researcher.

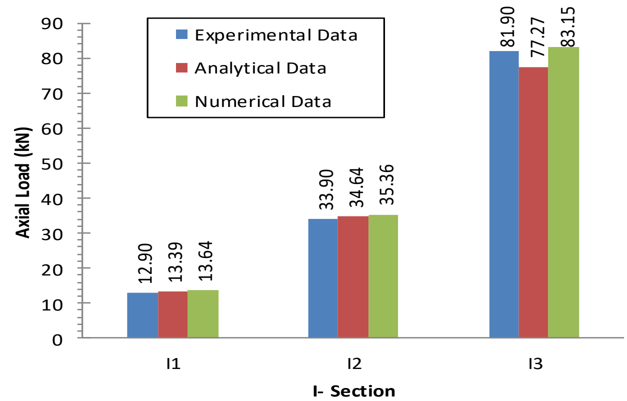


Fig. 4. Comparison between the buckling load obtained by Experiment, analytical and Numerical simulation of different I section.

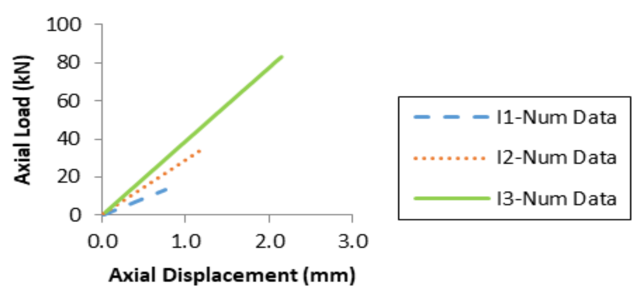
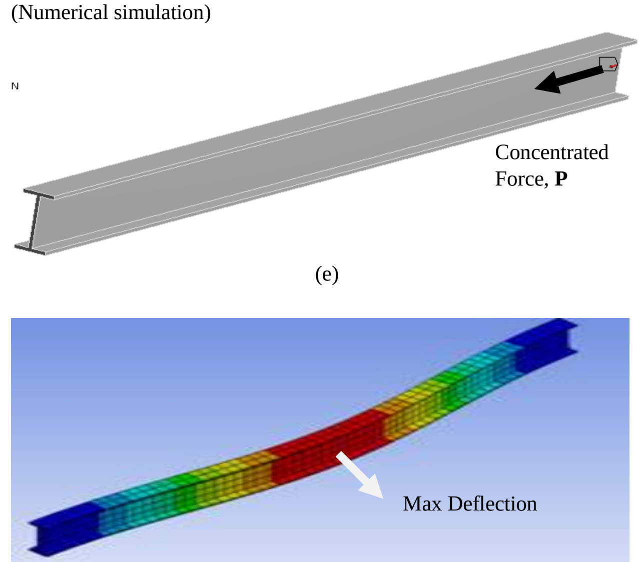


Fig. 5. Axial load vrs Axial displacement curves of pultruded columns (Numerical simulation)



(f)

Fig. 6. (e) FE model. (f) Failure mode of I3-section.

Conclusion

The study presented a numerical and the analytical study of on the buckling behaviour of PGFRP I-section column. Experimental results were available from the previous researcher. Numerical simulation is done by using finite element software and validated with analytical study, results of both simulation is matched with experimental results. Following conclusions are drawn:

- Non-linear analysis has been performed after Eigen value analysis. As Non-linear analysis simulate actual buckling behaviour, so it is preferable to conduct Non linear analysis.
- Buckling load calculated from numerical analysis seems in good agreement with experimental result with difference upto 5% approximately. (I1 = **5.73%,** I2 = **4.31%,** I3 = **1.53%**).
- In case of Analytical simulation, its results showed similarity between experimental data with difference upto 3% approximately. (I1 = **3.79%,** I2 = **2.18%,** I3 = **-5.65%**).
- Error due to Numerical and Analytical simulation from Table 2 shows variations within range which shows reliability of both the study for conducting buckling phenomenon of pultruded column.
- On comparison of buckling load obtained due to numerical and analytical study from Table 2, numerical buckling load is more than analytical one, this is because under compression loading instability of column is overestimated by numerical simulation. Therefore, care should be taken while performing numerical modeling.
- Axial load – Axial Displacement (load-displacement) curve (Figure 5) of three pultruded GFRP I section shows that section which has thicker wall thickness and lesser slenderness ratio will give longer linear behaviour.

Conflicts of interest

There are no conflicts to declare.

Keywords

PFRP, Column buckling, Numerical solution in ANSYS, PFRP strut section.

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Supporting information

Appendix A

This gives the brief summary of the formulae used in the EuroCode "JRC report EUR 27666 EN" [8] for the determination of critical buckling load under concentric compression of pultruded GFRP column.

$$\left(f_{loc,k}^{axial}\right)_f = 4G_{LT}\left(\frac{t_f}{b_f}\right)^2$$ Critical stress of compressed flange (1)

$$k_c = 2\sqrt{\frac{E_{TC}}{E_{LC}}} + 4\frac{G_{LT}}{E_{LC}}\left(1 - v_{LT}^2\frac{E_{TC}}{E_{LC}}\right) + 2v_{LT}\frac{E_{TC}}{E_{LC}}$$

Coefficient, depends on range of $\frac{G_{LT}}{E_{LC}}$ and v_{LT}, $k_{c,\min}$ =1.70 (2)

$$\left(f_{loc,k}^{axial}\right)_w = k_c\frac{\Pi^2 E_{LC}t_w^2}{12\left(1 - v_{LT}v_{TL}\right)b_w^2}$$ Critical stress of compressed flange (3)

$$N_{loc,Rd} = Af_{loc,d}^{axial}$$ Local instability of Pultruded elements (4)

$$\left(f_{loc,d}^{axial}\right) = \frac{\eta_c}{\gamma_m}\min\left\{\left(f_{loc,k}^{axial}\right)_f, \left(f_{loc,k}^{axial}\right)_w\right\}$$ Design value of local critical stress (5)

$$\chi = \frac{1}{c\lambda^2}\left(\phi - \sqrt{\phi^2 - c\lambda^2}\right)$$ Reduction factor (6)

$$\phi = \frac{1 + \lambda^2}{2}$$ (7)

$$\lambda = \sqrt{\frac{N_{loc,Rd}}{N_{Eul}}}$$ Slenderness Ratio (8)

$$N_{Eul} = \frac{\eta_c}{\gamma_m}\frac{\pi^2 E_{LC}I_{\min}}{L_0^2}$$ Eulerian critical load (9)

$$N_{c,Rd2} = \chi N_{loc,Rd}$$ Design value of the axial compressive resistance due to instability (10)

profiled element Compressive force (11)

$$N_{c,Rd} = \min\left\{N_{c,Rd1}, N_{c,Rd2}\right\}$$ Design resistance value (12)

Where, A= Area cross section, $f_{c,d}$ = Longitudinal compressive strength, G_{LT}= In plane shear modulus, E_{LC} = Longitudinal modulus in compression, Imin= Minimum MOI, L_0= Buckling length of the member, η_c = Conversion factor, Υ_m = Partial factor of safety, v_{LT} = Poisson's ratio associated with transverse strain when strained in longitudinal direction, v_{TL} = Poisson's ratio associated with the longitudinal strain when strained in transverse direction, t_f = Thickness of flange, t_w = Thickness of web, b_f = flange width, b_w = Web Width, c = 0.65.

Authors biography

Vinanti Kulkarni, MTech (Structures) student at National Institute of Technology (NIT) Raipur India working on the topic of Pultruded Fiber Reinforced Polymer material as a new construction material. She did her internship training from Central Building Research Institute, Roorkee in the field of Pultruded FRP. The main interest is use of Pultruded FRP in civil engineering construction field as a replacement of classic material.

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