Buckling analysis of cantilever pultruded I-sections using $ANSYS^{®}$

Kunj J. Patel[1], Satyen D. Ramani[2],

[1]*M.E. student, Civil Engineering Department, SAL institute of technology and engineering research, Gujarat, India.*

[2]*Asst. Professor, SAL institute of technology and engineering research, Gujarat, India.*

ABSTRACT

For steel beam buckling analysis is a critical area of study to determine overall section capacity subjected to bending. Pultruded I-beams are manufactured using fiber and matrix composite lamina hence is usually orthotropic compared to conventional steel I-beams. Many researchers have studied the buckling characteristics of simply supported pultruded FRP beams for various types of loadings. In this paper an attempt has been made to study the buckling characteristics of cantilever beam subjected to point load at free end 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 effect of fiber orientation along with fiber volume fraction on critical buckling loads.

Keyword: - *Pultruded I-beams, Fiber orientation, buckling characteristics, fiber volume fraction.*

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1. INTRODUCTION:-

By decades the use of composite material is increased. By good knowledge of the fundamental properties of composites the rise of composites can be explained.FRP profiles have been used over more over past few years, due to high ratio of strength to weight. In the construction industry, recent applications have shown the structural and cost efficiency of FRP structural shapes, such as thin-walled open sections made through so-called pultrusion process. FRP beam and column offers great benefits in placement of composites with the help of lighter machine and initial haulage. It also offers the less schedule of maintenance and offer easy attachment of fittings, with FRP structures being engineered for a long service life. The physical and chemical properties of the composites make them a very attractive material option for selection particularly in more corrosive environments where traditional materials are known to deteriorate. To realize these benefits, the world of FRP requires demystifying, and the selection of these products made more easily understood. Pultruded profiles for commercial and structural applications which are produced by many manufacture the world. Most manufacturers produce custom profiles for commercial applications. A number of industry groups represent and loosely coordinate the activities of pultrusion manufacturers. Leading groups are the Pultrusion Industry Council of the European Pultrusion Technology Association (EPTA) and the American Composites Manufacturers Association (ACMA). Commonly produced pultruded profiles are usually available as wide-flange, I, rectangular tube, channel, square tube, plate materials and angle profiles. Standard profiles range from width to approximately 12 in. (300 mm) and 2 in. (50 mm) in height and have material thicknesses of two in. (6 to 13 mm).At this time there is no proper guidelines for the design of framed structures using either pultruded structural profiles as there are for concrete structures strengthened with FRP strengthening systems or reinforced with FRP rebar. However, two design manuals are developed: The Euro comp Design Code and Handbook (Euro comp, 1996) and The Structural Plastics Design Manual (ASCE, 1984).

2. LITERATURE STUDY:-

M.M.Alinia, A.Dibaie, et al [1] studied buckling behavior of I-beams. The typical plated columns, one is 1m height and second is 4m height having similar section properties are considered. The web and flange width are assumed to be 1000mm and 300mm. The web and flange thickness is carried out 5mm and 30mm. During parametric studies for web and flange slenderness ratio, thickness is varied. Selections of flange and web thickness are as per limits defined in AISC360.The ABAQUS software is used in incremental nonlinear large displacement push over analysis.

The nonlinear push over analysis is carried out by utilizing the modified Risk method, allowing for both softening and stiffness hardening of plated structures.The structural elements are taken as four nodes doubly curved shell element S4R in ABAQUS. This element accounts for large rotation and finite membrane strains. The S4R element has three rotational and three translation of freedom at each node.it is based on isoperimetric formulation and uses one integration point on its mid-surface to form the element internal force vector. The reduced integrated formulation is used to reduce time and provide accurate results.

Ever J. barbero & Ioannis G. Raftoyiannis et al [2] has studied pultruded I-beams subjected to various loading conditions and their elastic buckling modes. The lateral and distortional buckling coupling to appear in thin-walled cross verify to their predict bending-twisting coupling and shear effects are accounted. The effect of volume fraction and fiber orientation in the matrix is taken into account for parametric study. The buckling strength determine as overall strength of the member. The energy criterion for equilibrium of structure is used for theory approach. The solution of the problem is attempted by Rayleigh-Ritz method. The pre buckling solution is derived using laminated beam theory. Coupling of local and lateral buckling modes always occurs due to the low stiffness of the material in the perpendicular direction to the beam axis. For high depth-width ratio, lateral buckling is the governing mode of failure. For low height-depth ratio coupled local and distortional buckling results in a reduced section. The simply supported beams with free warping in both the ends and having concentrated load at the centroid is considered in the specific cases, the theoretical formulation and the solution methodology can be easily applied for any boundary conditions.

Rami Haj-Ali, HakanKilic et al [3] has invested Coupon tests and they are used to calibrate 3D micromechanical models and to verify their prediction for the non-linear elastic behaviour 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 behaviour 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 behaviour 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 centre and allows extracting the non-linear stress-strain response of anisotropic material. Shear tests are used to calibrate the in situ nonlinear elastic properties of the matrix. The material has a lower initial stiffness and lower ultimate tensile stress in tension compared to the corresponding values of compression tests, regardless of thickness and angles approaching angle of 90’. Good scalability of material and geometry appear to exist between the ¼ and ½ in. thickness coupons tension and compression of axis (45’) tests can be used to determine the initial shear modulus of FRP pultruded material.

Lawrence C. Bank, et al [4] has considered the shear stiffness of pultruded FRP beam.. A new material stiffness property called shear modulus is taken into account for the shear deformation effects. Results of an experimental program conducted to obtain the section shear modulus for variety of FRP beams. The analysis of a rigid portal frame structure is presented to demonstrate the influence of the beam section stiffness properties on frame deflection and forces. The stiffness property can be obtained for standard putruded beams using test methodology that gives beam flexure modulus. Using the stiffness properties designers can take account for the effect of shear deformation.

J. Lee, S.-E. Kim, K. Hong et al [5] has studied lateral buckling of a laminated composite I-section beam. General analytical model applicable to the lateral buckling of section subjected to various loading types is developed. The model is based on classical lamination theory. It accounts for the material coupling for arbitrary laminate stacking sequence and various boundary conditions. The effect of the location of applied load on buckling capacity is also included. A finite element model and a displacement model is developed to predict buckling modes and critical loads of a thin walled composite beam with boundary conditions. Numerical results are obtained under, uniformly distributed load; pure bending and central point load with angle-ply laminates. The effects of location of applied load, types of loads and orientation of fiber are studied. Lateral buckling capacity of beams with transverse loads is affected by the fiber orientation as well as location of loads. The maximum buckling loads occurs near 45’ fiber angle for all cases of span to height ratio. For beam under pure bending with off-axis fiber orientation, orthotropic closed-form solution is not appropriate for lateral buckling loads due to existence of coupling stiffness.

Pizhong Qiao, Julio F. Davalos, Jialai Wang et al [6] has carried out an analytical study of local buckling of discrete laminated panels or plates FRP structural shapes. Flanges of FRP shapes are modelled as discrete panels subjected to uniform axial loads. Two cases with different boundary conditions and elastic restraints of composite plates are studied. Using the regression analysis simplified expressions for predictions of plate buckling stress resultants are formulated in terms of coefficients of boundary elastic restraints. The effects of restraint at the flange web connection are considered. The theoretical predictions show good agreement with experimental data and FEM eigen value analysis for local buckling of FRP columns. The present formulation can be applied to several cases to determine buckling capacities.

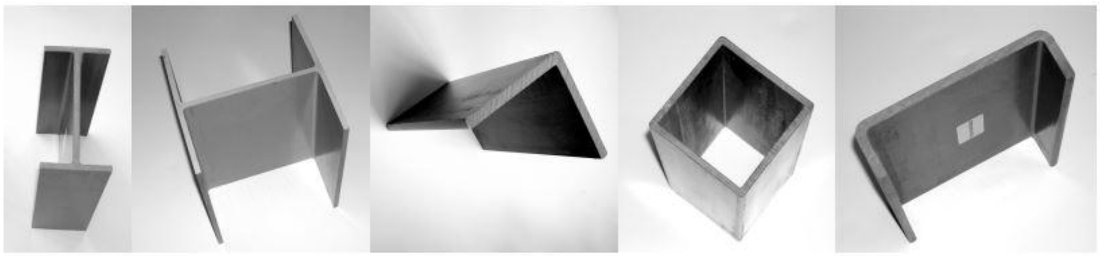


Fig-1: Pultruded profiles: I, wide flange, angle, tube, and channel

3. VALIDATION STUDY:-

3.1 Material Geometry & properties:-

In this study, two wide flange profiles WF 0.1 x 0.1 x 0.006m (4x4x1/4"), WF 0.15 x 0.15 x 0.0095m (6 x6 x3/8"), and two narrow flange profiles NF 0.1 X 0.2 X 0.0095m (4x8x3/8"), NF 0.07 X0.15 X 0.0095m (3x6x3/8") of FRP I-beams, which were manufactured by the pultrusion process and provided by Creative Pultrusions, Inc., Alum Bank, PA, are taken. The 60% E-glass fibers and 40% polyester resin is used in pultrusion process.The results of critical buckling loads for all profiles are compared to the experimental data from research work carried out by Luyang shan et al [7]. The lamina properties of section are given as follows.

Table -1: Material Lamina properties

Exx	1.14×10^{10} Pa
Eyy	4.47×10^{10} Pa
Ezz	1.14×10^{10} Pa
NUxy	0.272
NUyz	0.272
NUxz	0.046
Gxy	4.20×10^{9} Pa
Gyz	4.20×10^{9} Pa
Gxz	4.20×10^{9} Pa

3.2 Modelling in ANSYS:-

Each profile is modelled as cantilever beam with end condition (Ux=Uy=Uz=0) at all nodes of the flange and web at one end to simulate the experimental setup[7].Vertical node at mid height of web is applied and eigen buckling analysis is carried out.Fy=10 is applied as an initialization load for eigen buckling. Modelling 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 3m.Global lateral torsional buckling is observed as a critical buckling mode.corrosponding loads for 1^{st} mode of lateral torsional buckling for each of four section analysed is than compared with experimental data value obtained by Luyang Shan et al[7].

3.3 Critical buckling load (Pcr):-

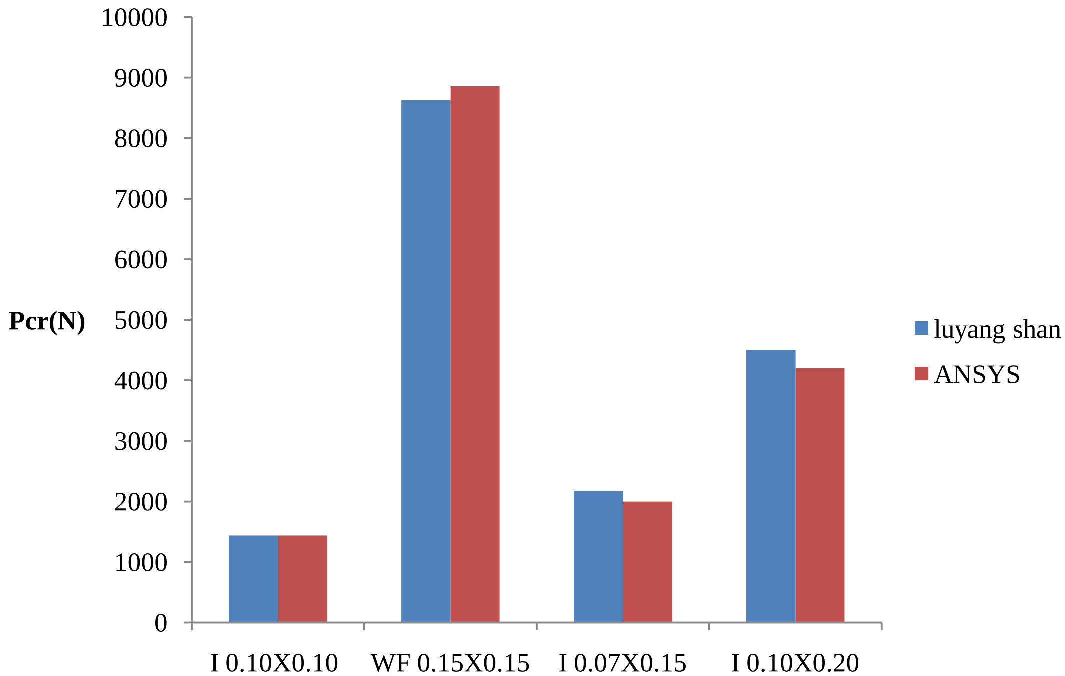


Fig-2: Critical buckling load comparison

Table -2: Critical buckling load comparison between ANSYS and study done by Luyang Shan

		Pcr (N)
WF 0.1m X 0.1m X0.006m	Luyang shan	1436
	ANSYS	1435
WF0.15mX0.15mX0.0095m	Luyang shan	8624
	ANSYS	8858
I 0.07mX0.15mX 0.0095m	Luyang shan	2174
	ANSYS	2000
I 0.10m X0.2mX 0.0095 m	Luyang shan	4503
	ANSYS	4200

Table-2 shows the comparision of critical buckling load from ANSYS & Luyang Shan. it can be concluded that the results are very well in the compliance range with experiment.

4. FIBER ORIENTATION STUDY:-

One narrow flange section (NF 0.1 x 0.2 0.0095 m) and one wide flange section (WF 0.15 x 0.15 x 0.0095 m) having different fiber volume fraction are taken as cantilever beam for study. Vertical 1 N load is applied on the middle node of web at free end. Material properties are taken as described in Table-1**.** The effect of different fiber orientation for different fiber volume fraction for cantilever beam is studied. Further in the study, all the possible buckling modes are examined to find the critical load values corresponds to global lateral torsional buckling mode (ltb) & local flange buckling mode (lfb). Critical load corresponds to lateral torsional buckling is denoted as P0 & local flange buckling load is denoted as PL. Buckled shape for a typical cantilever I-beam subjected to point load at free tip is shown for both case ltb and lfb in Fig-3.

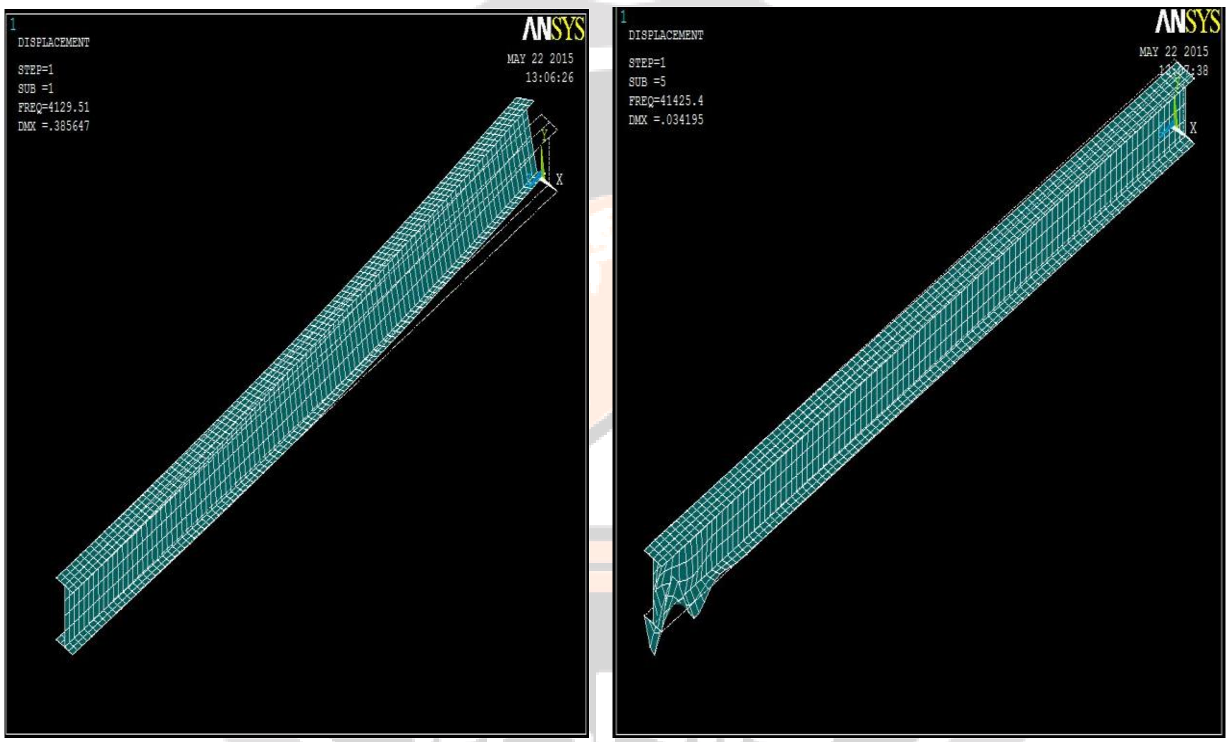


Fig-3: Global and local buckling modes

Table -3: Critical buckling loads for different fiber angles for cantilever beam (NF-profile)

Fiber volume Fraction = 15%

Fiber Angle	P0(N)	PL(N)	P0/PL
15’	1614	12706	0.127027
30’	1526.6	14330	0.106532
45’	1404.4	15650	0.089738
60’	1286.7	14286	0.090067
75’	1190.1	12581	0.094595

Fiber Volume Fraction = 30 %

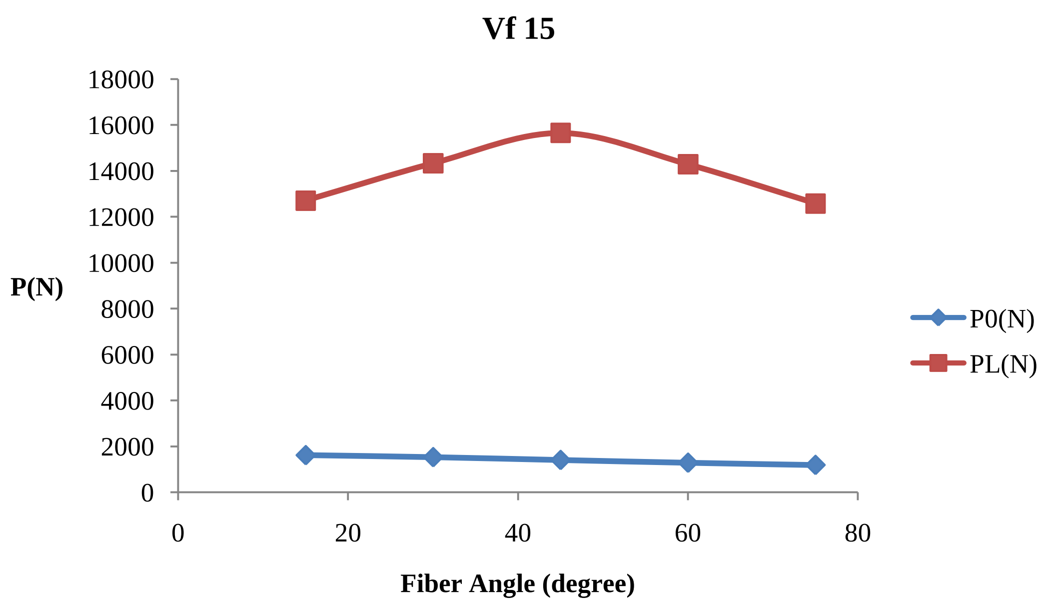
Fiber Angle	P0(N)	PL(N)	P0/PL
15’	2570.4	17379	0.147903
30’	2373.9	19428	0.12219
45’	2146	20923	0.102567
60’	1923.8	18687	0.102949
75’	1743.8	16911	0.103116

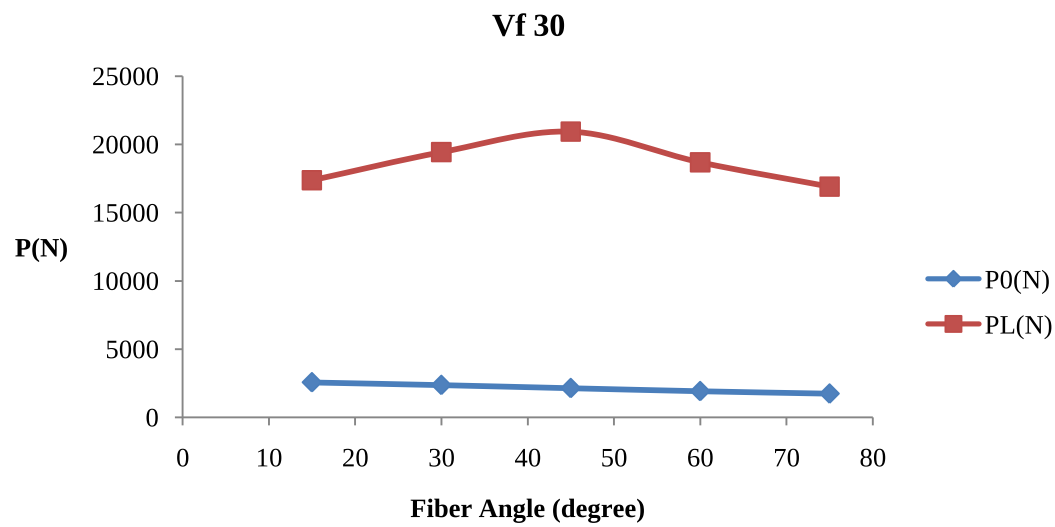
Fiber Volume Fraction = 60%

Fiber Angle	P0(N)	PL(N)	P0/PL
15’	4899.9	33881	0.144621
30’	4559.1	38212	0.119311
45’	4129.5	41425	0.099686
60’	3702.8	37068	0.099892
75’	3354.2	33097	0.101345

Where, P0 = Critical buckling load for 1^{st} mode of global lateral torsional buckling.

PL = Critical buckling load for 1^{st} mode of Pure Local flange buckling.





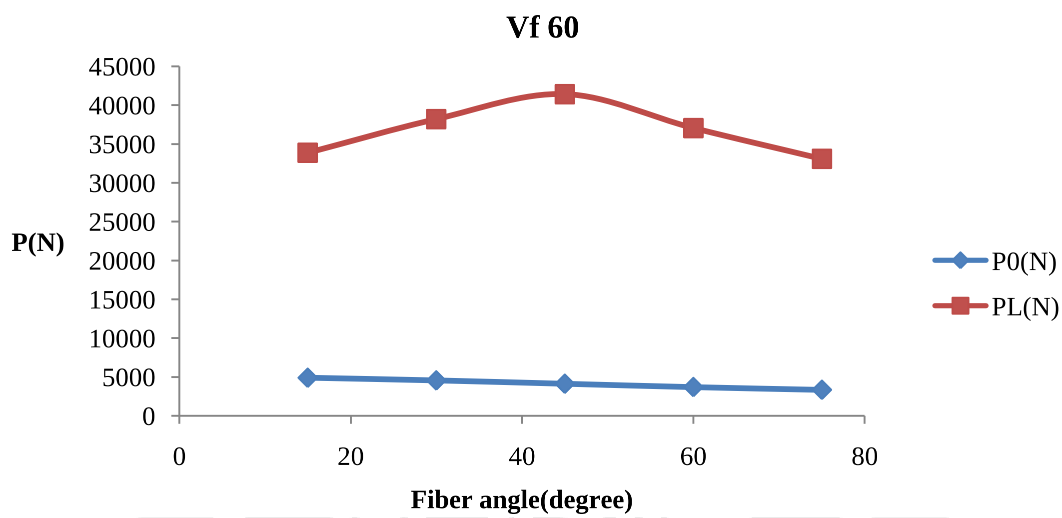


Fig-4: fiber Angle vs Critical buckling load (Cantilever beam-NF profile)

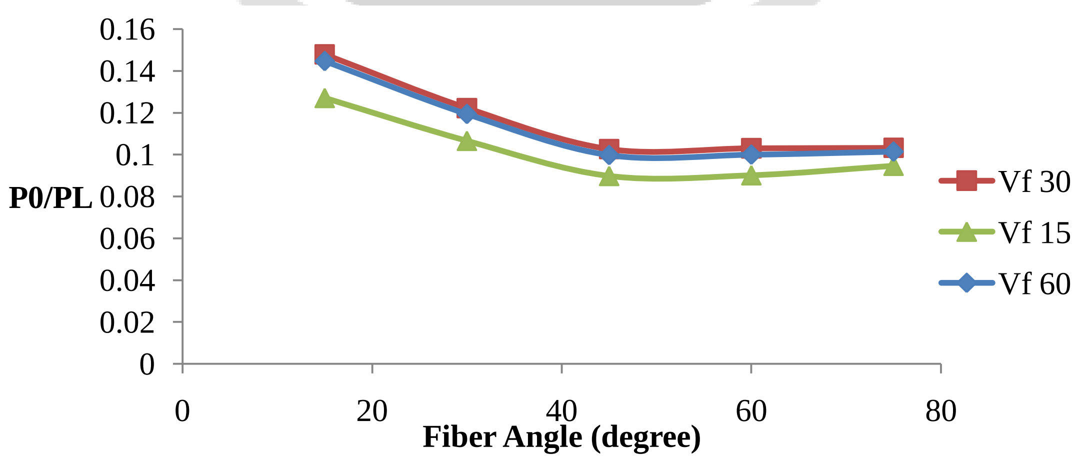


Fig-5: Fiber Angle vs P0/PL (Cantilever beam-NF profile)

Table -4: Critical buckling loads for different fiber angles for cantilever beam (WF-profile)

Fiber Volume Fraction = 15 %

Fiber Angle	P0(N)	PL(N)	P0/PL
15’	3421.6	6093.4	0.56153
30’	3241.2	6789.1	0.47741
45’	2975.2	7325.7	0.40613
60’	2720.9	6724.4	0.40463
75’	2543.2	6004.5	0.42355

Fiber Volume Fraction = 30%

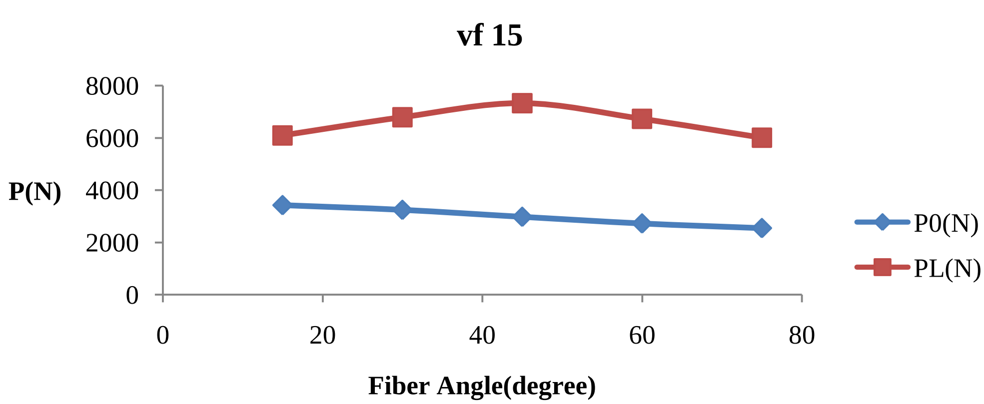
Fiber Angle	P0(N)	PL(N)	P0/PL
15’	5424	8473.3	0.64013
30’	5070.1	9432.4	0.53752
45’	4563.5	10105	0.45161
60’	4081.2	9055.2	0.4507
75’	3742.3	8210.7	0.45578

Fiber Volume Fraction = 60%

Fiber Angle	P0(N)	PL(N)	P0/PL
15’	10351	16495	0.62752
30’	9727.9	18473	0.5266
45’	8775.5	19889	0.44122
60’	7849.6	17860	0.43951
75’	7191.8	16040	0.44837

Where, P0 = Critical buckling load for 1st mode of global lateral torsional buckling.

PL = Critical buckling load for 1st mode of Pure Local flange buckling.



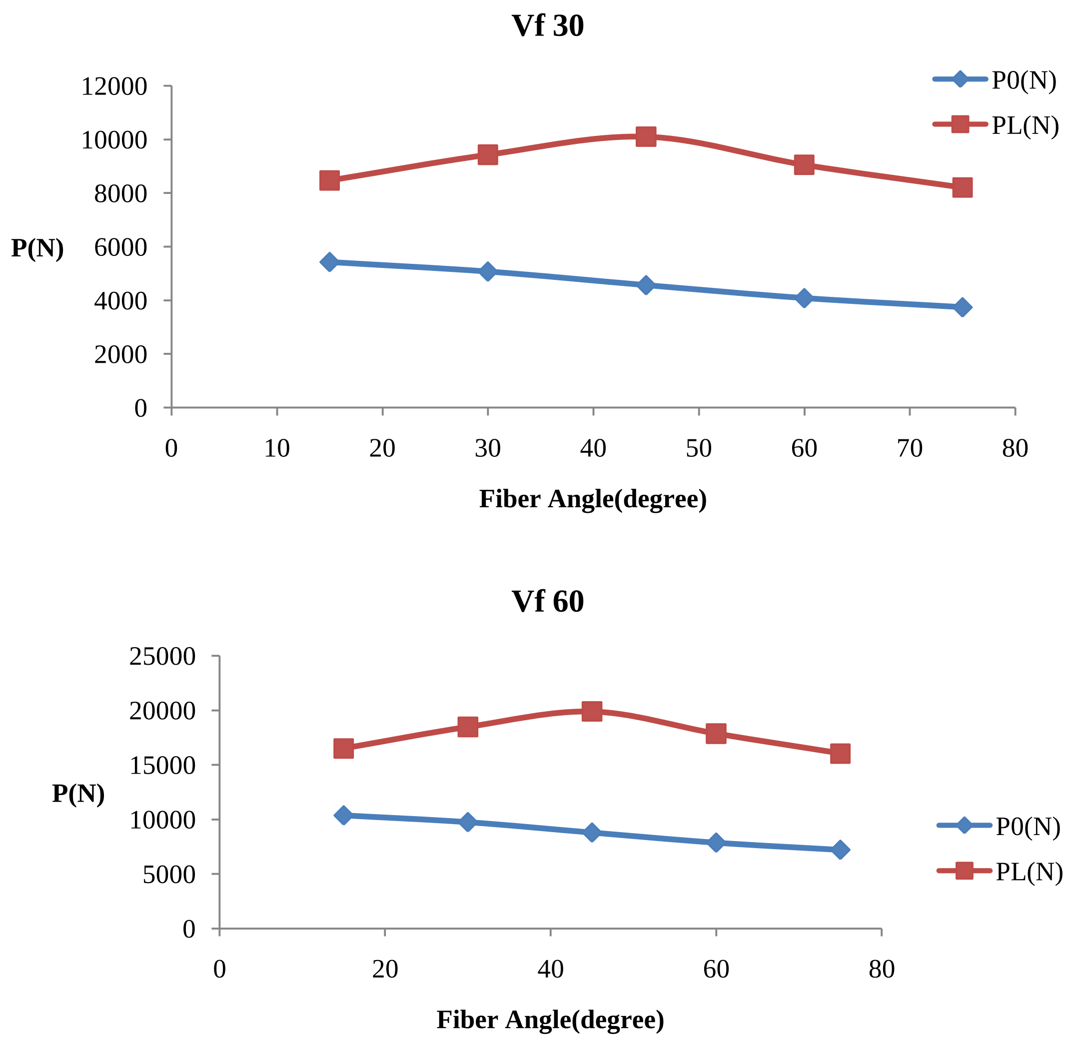


Fig-6: fiber Angle vs Critical buckling load (Cantilever beam-WF profile)

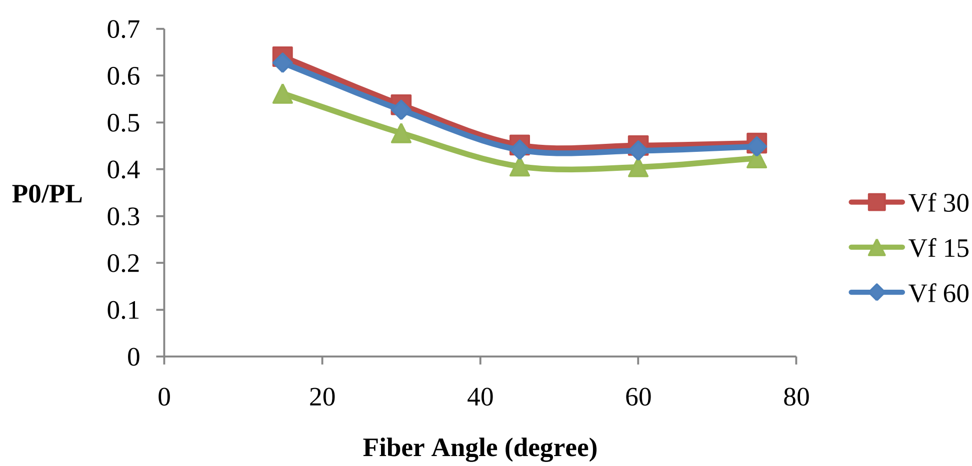


Fig-7: Fiber Angle vs P0/PL (Cantilever beam-WF profile)

5. RESULTS & CONCLUSION:-

The increase in PL can be explained due to increase of in plane shear resistence as the fiber angle increses. The minimum inplane buckling resistance is obtained for fiber orientation (45'/0'/+45'). Fig 5 & 7 shows the variation P0/PL with respect to fiber orientation which suggests that for (-45'/0'/+45'),the P0/PL is minimum. From the strength aspect the value of P0/PL should be minimum for optionized utilization of section strength.For fibr orientation being constant, the increase in fiber volume leads to increase of both P0 and PL which is in due cmpliance of other literature studies.[3,5].

Hence it can be concluded that for cantilever pultruded I-beam, the fiber orientation can be improve local flange buckling capacity but will not improve global lateral torsional buckling capacity.

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