NUMERICAL SIMULATION OF CIRCULAR HOLLOW STEEL COLUMNS CONFINED WITH FIBER REINFORCED POLYMER UNDER AXIAL COMPRESSION

Nusrat Khanum Zinia*[1], Faizah Ahsan Reza[2] and Wasi Uddin Ahmed[3]

[1]*Graduate Student, Department of Civil Engineering, Ahsanullah University of Science and Technology, Bangladesh, e-mail: ziniaaust@yahoo.com*

[2] *Graduate Student, Department of Civil Engineering, Ahsanullah University of Science and Technology, Bangladesh, e-mail: fareza91@gmail.com*

[3]*Graduate Student, Department of Civil Engineering, Ahsanullah University of Science and Technology, Bangladesh, e-mail: wickedsaymon71@gmail.com*

ABSTRACT

This paper presents a numerical investigation on circular hollow steel columns which are confined with FRP laminates under axial compression based on finite element analysis. Here, numerical simulation has been chosen rather than experiment because of sophisticated and time consuming experimental work. A study has been performed to find out the better performance of FRP implementation on bare steel column through the comparison of axial load vs axial shortening curves, failure mode, ultimate yield stress employing one, two and three ply FRP laminates respectively. Then these numerical results have been validated with the experimental works. Finally, a comprehensive parametric study has been carried out by varying the slenderness ratio that will provide a guideline to assume the ultimate load capacity of circular hollow steel columns of different slenderness ratio.

Keywords: *Steel, retrofit, column, FRP, slenderness ratio*

1. INTRODUCTION

Very recent years, steel structure has gained much more acceptance due to its numerous benefits like high strength, light weight, low construction period and so on. With the enhancement of the steel structures, the need for upgrading the existing structures is also enhanced. Due to environmental corrosion, fatigue failure and seismic effect, loss of load carrying capacity in steel structures has become a major concern worldwide. New and increased demands for retrofitting the damaged steel member to improve its poor performance, several methods have been implemented. If effective methods are used for strengthening, it is possible to bring the structure back to their desired services. In modern technology, as a high performance solution and smart retrofit technique FRP (Fiber Reinforced Polymer) is more preferable due to its superior mechanical and physical properties which make them quite promising for repairing and strengthening of steel structure.

A common failure mode of circular hollow steel column under axial compression and bending is local buckling at the column end which is termed as elephant's foot buckling. This failure appears after yielding and these inelastic local buckling results the deterioration of the load carrying capacity including the end of ductile response (Teng et al., 2006). This paper presents the behaviour of circular hollow steel columns confining with FRP layer under axial compression to predict the failure mode, ultimate capacity etc.

2. METHODOLOGY

For experimental analysis over FRP implementation, more sophisticated machinery is required and it is time consuming whereas numerical method is simpler compared to experiment to find out the solution within short. Besides, in Bangladesh FRP is an imported material with highly cost and also involves expensive experimental set up. That is why, software base simulation work using Abaqus of 6.10 version has been chosen to predict the behaviour of circular hollow steel columns confined with FRP under axial compression.

2.1 Dimensions of Simulated Model

In the simulated models steel is a solid element and FRP is a shell element. Each model has an outer diameter of 165 mm of 450 lengths with column thickness 4.2 mm. But the difference is that FRP thickness increases with the no. of ply increases which is 0.17 mm per ply except the bare steel tube. The variation of FRP thickness with the increase of no. of ply is shown in Table 1.

Table 1: Dimensions of simulated model

Models Name	Bare Steel Tube	Bare Steel Tube with 1 ply FRP Laminate	Bare Steel Tube with 2 ply FRP Laminates	Bare Steel Tube with 3 ply FRP Laminates
Outer Diameter(mm)	165	165	165	165
Length(mm)	450	450	450	450
Tube Thickness(mm)	4.2	4.2	4.2	4.2
FRP thickness(mm)	N/A	0.17	0.34	0.51

2.1.1 Geometric Modelling and Material Modelling

The geometry of models is described by elements and their nodes whereas the steel is a solid element and FRP is a shell element was mentioned before.C3D8R-Continum element 3-D 8-node Reduced integration with hourglass control was used to create bare steel model**.** S4R- four-node general-purpose shell, reduced integration with hourglass control, finite membrane strains was used to create FRP model. The simulated model is displayed in figure 1 and figure 2 which show the 3D mesh view of solid and shell element respectively.

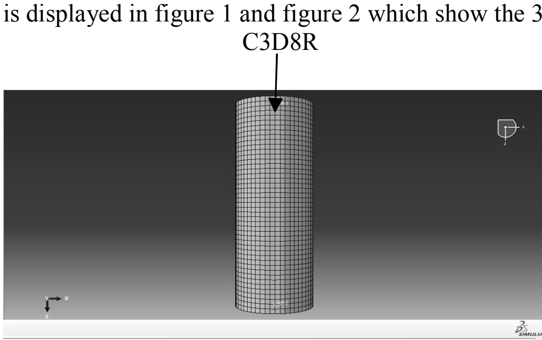

Figure 1: 3D mesh view of solid element

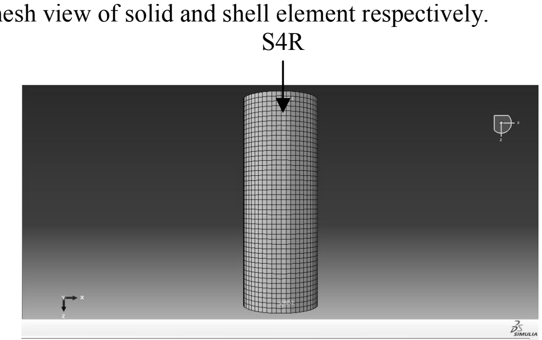

Figure 2: 3D mesh view of shell element

In the material modeling, for steel modeling the value of Young's Modulus 201,000 MPa and Poisson's Ration 0.3 were implemented for elastic behavior and the output of yield stress and plastic strain(Teng et al., 2006) is the plastic behavior of the simulated steel column. This combining elasto-plastic behaviour of bare steel tube is shown in Figure 3. FRP material only shows the elastic behavior of itself. It has no plastic behavior. So, only for elastic behavior Young's Modulus 80,100 MPa and Poisson's Ratio 0.28 were implemented. It develops a straight line equation shows in Figure 3.

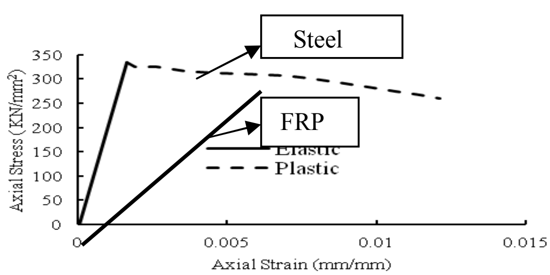

Figure 3: Combined graph of Elasto-Plastic Behavior of Bare Steel Column and Elastic Behavior of FRP (Teng et al., 2006)

2.1.1.1 Boundary Condition and Solution Strategy

For simulating the exact behaviour of experimental setup (Teng & Hu, 2006), fixed support was applied on the one end of the model and displacement was applied on the other end of the model. For providing uniform loading the top face was made rigid. It is shown in the figure 4 where the boundary conditions applied on the both sides.

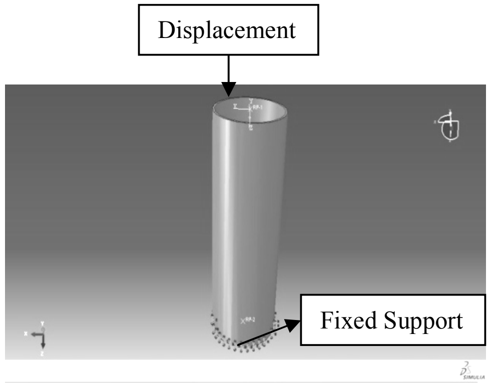

Figure 4: Applying Boundary Conditions

To simulate this FRP laminated steel columns, two types of solution strategy Newton-Raphson Method & Arc-Length method were adopted.In Newton-Raphson approach, the load is subdivided into a series of load increments.The load increments can be applied over several load steps.Before each solution, this method evaluates the out-of-balance load vector, which is the difference between the restoring forces (the loads corresponding to the element stresses) and applied loads. The program then performs a linear solution using out-of-balance loads, and checks for convergence .If convergence criteria are not satisfied, the out-of-balance load vector is re-evaluated, the stiffness matrix is updated and a new solution is obtained .This iterative procedure continue until the problem converges. In some non-linear static analysis, if this method is used alone ,the tangent stiffness matrix may become singular causing severe convergence difficulties .Such occurrences include non-linear buckling analysis in which structure either collapses completely or "snaps through" to another stable confuguration.For such situation the Arc-Length method is useful to avoid bifurcation points and track unloading. The Arc-Length method causes the Newton-Raphson equilibrium iterations to converge along arc, thereby often preventing divergence, even when the slope of the load vs. deflection curve becomes zero or negative. The constraint equation is forced to be satisfied at each iteration. The Arc-Length method can handle post yielding non-linear behavior of materials which show strain softening after yield point (Jain et al., 2003).

3. PERFORMANCE OF MODEL

The full finite element model including the entire length and cross-section of the column has been developed to predict the column behaviour under axial compression. The experimental model has similar characteristics to the extended model. The only difference between them is in the end conditions. The end plates used in the test columns were not modelled in the extended model as well as geometric imperfections were not provided in the simulated model. The results of this analysis along with the experimental results through the comparison curves of load vs. Shortening are presented in the following figures.

Figure 5 shows the load bearing capacity for both model (experimental & numerical) are same 698.844 KN at axial shortening of 0.7252 mm. Both the values decrease after reaching the ultimate value and fails after a certain displacement and numerical values of plastic zone is less than the experimental values which might be happened due to lack of similarities between experimental setup and finite element modeling like providing imperfections. The ultimate displacement was observed 5.8731 mm in experimental model whereas 6.00 mm in numerical.

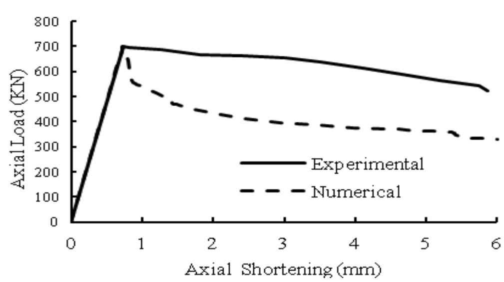

Figure 5: Combined Graph for Bare Steel Model

Figure 6 expresses the ultimate load bearing capacity is gained in experiment 750.2 KN in 8.509 mm axial shortening & for numerical model is 799.774 KN in 15 mm axial shortening. At the elastic part a little deviation has occured but the plastic part shows a clear deviation which called softening branch. But after a settlement of around 10 mm numerical model shows more capacity to sustain more load than experimental one. The ultimate displacement was observed 12.23 mm in experimental model & 15.00 mm in numerical model. But model shows it can carry a good amount of load after 15 mm and go on for some more shortening.

The Main difference between figure 6 and figure 7 is that with two ply FRP laminate model can sustain more shortening and the softening branch is reduced gradually.It might be happened due to force dominance. In one ply model ,outward force is greater than inward one. Increasing no of plies shows that after applying multi plies, inward force is increased. That's why minimize of softening branch is noticed. Experimental curve is seen to have sudden drop whereas in simulation, it does not fail suddenly. It gets a smooth shape before it fails at 15.00 mm shortening.

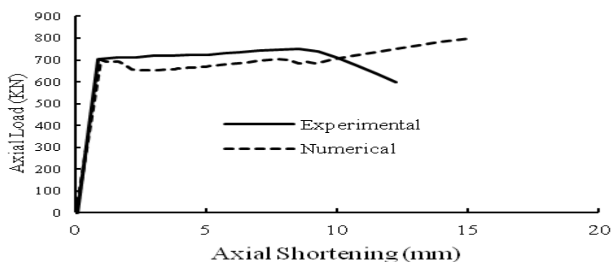

Figure 6: Combined Graph for Bare Steel Model Laminated with 1 Ply FRP

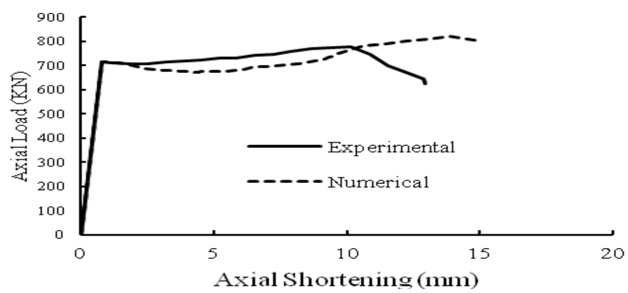

Figure 7: Combined Graph for Bare Steel Model Laminated with 2 Plies FRP

Figure 8 shows softening branch is much less than the previous figure as it gained much more inward force than having two ply.Again, here experimental setup fails drastically but numerical curve shows no drastic fail. There is a significant matter associated with load carrying capacity that all the experimental curves tend to increase after elasticity and fail abruptly.On the other hand, every numerical curve shows different softening branch than experimental curves and it might show the increase of inward force than that of outward force.Figure 8 shows a clear view that increasing no. of plies increase ultimate load bearing capacity of bare steel column.

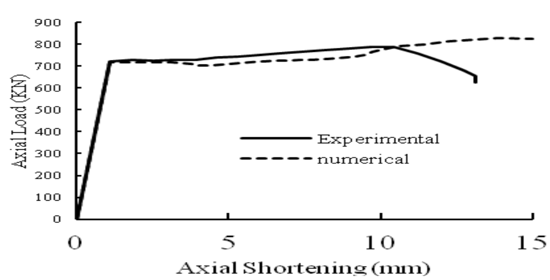

Figure 8: Combined Graph for Bare Steel Model Laminated with 3 Plies FRP

Figure 9 shows the clear deviation of experimental and numerical results of all models at the plastice zone.

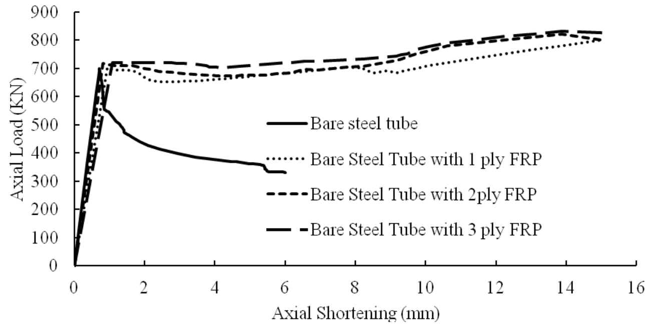

Figure 9: Combined Graph of All Models from Numerical Analysis

In Table 2 the values of strengths & displacements of different plies are given. It is quite clear that applying one or more plies of FRP increases the load bearing capacity. With increasing of FRP laminate every times ultimate strength goes high.

Table 2: The Values of Strengths & Displacements of Different Plies

Serial No	Model Type	Ultimate Strength(KN)	Ultimate Displacement(mm)
1	Steel Bare Model	698.844	6.00
2	Steel 1 Ply Model	799.774	15.00
3	Steel 2 Ply Model	820.517	15.00
4	Steel 3 Ply Model	830.517	15.00

Table 3 shows that increasing of FRP laminate increases the strength of steel hollow column where f_{ub} is the ultimate strength of bare steel column and f_{up} is the ultimate strength of FRP confined steel column.

Table 3: The Values of Strength Ratio & Percentage of Strength Gain of Different Plies

Serial No	FRP Ply Thickness (mm)	Strength Ratio (f_{up}/f_{ub})	Percentage of Strength Gain
1	0.17	1.144	14.44%
2	0.34	1.174	17.41%
3	0.51	1.188	18.84%

3.1 Parametric Study

The global stability of the column is controlled by the overall slenderness ratio which is defined as the ratio of the length of the column, L to the Radius of the Gyration of column, r_g. In this study, it was checked for Slenderness Ratio (L/r_g) for the model having single ply to observe the variation of strength ratio. Three different slenderness ratios 4, 10.90 and 20 were employed in the parametric study of columns for only one ply due to time lacking. It is observed that at first the ratio of ultimate strength increases with the increase of slenderness ratio. After reaching a peak value, it starts to decrease. Table 4 shows the detail of parametric study.

Table 4: Details of Parametric Study

SL No.	Length (mm)	Radius (mm)	Slenderness Ratio (L/r_g)	Ultimate Strength (KN)	Ultimate Displacement (mm)	Strength Ratio (f_{up}/f_{ub})
1	450	225	4.00	1992.290	0.756	1.0152
2	450	82.5	10.90	799.774	15.00	1.1443
3	450	45	20.00	381.517	3.875	1.0301

Figure 10 shows when slenderness ratio is increased from 4 to 10.9, strength ratio also increases. Again, if slenderness ratio is increased to 20, strength ratio decreases. The curve shows an ellipse type figure. It was taken only for three ratios and if it is possible to have more slenderness ratio it might show a better figure to understand properly. According to figure 10 and the equation, the peak value occurs at 11.75 of slenderness ratio. So it can be said that an interim value of slenderness ratio can be selected for future studies as it shows much strength gaining. For this further studies can be carried out to identify the exact slenderness ratio for optimum capacity for steel columns.

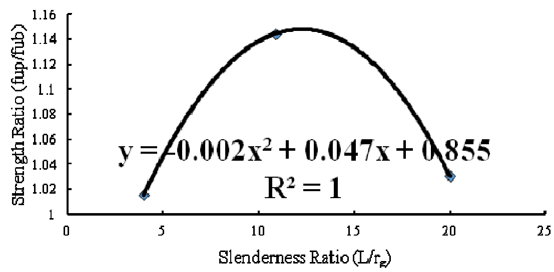

Figure 10: Parametric Study on Different Types of Strength Ratio with respect to Different Types of Slenderness Ratio

4. CONCLUTIONS

In this paper, the numerical simulation has been conducted to explore the full behavior of circular hollow steel columns confined with FRP under axial compression based on finite element modelling using finite element software ABAQUS. Firstly, limited research was performed to develop a finite element model of bare steel tube providing displacement controlled loading which results both side deformation at the ends. The numeric results have concluded that confinement of FRP enhances a significant amount of ultimate strength and load carrying capacity of bare hollow steel column that reduces the buckling effect. This results have been validated with the experiment and the better performance of FRP implementation has been clarified through the comparison of axial load vs. axial shortening curves. The parametric study has been performed only for Slenderness Ratio (L/r_g) in only one ply condition. To investigate the more exact prediction parametric study both two and three ply is required. The other parametric study like Overall Column Slenderness Ratio (L/d), Load Eccentricity Ratio (e/d) etc can be done to see different changes of strengthening. This work can be a good recommendation in seismic retrofitting, fatigue failure and corrosion resistance.

REFERENCES

Jain, R.(2003).Solution Procedure for Non-linear Finite Element Equations.Project Report ECI 284

Shinde,D.N.,M,P.Y.,V,N.V.(2014).Flexural Behaviour of Reinforced Cement Concrete Beam Wrapped With GFRP sheet, International Journal of Research in Engineering and Technology.

Teng,J.G.,Hu Y.M.(2006).Behaviour of FRP-jacketed circular hollow steel tubes and cylindrical shells under axial compression,Construction and Building Materials 21 (2007) 827–838.