Journal of Civil Engineering (IEB), 42 (2) (2014) 209-216

Journal of
Civil Engineering
IEB

Numerical simulation of steel HSS columns strengthened using CFRP

Urmi Devi and Khan Mahmud Amanat

Department of Civil Engineering
Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

Received 09 March 2014

Abstract

This paper presents a numerical finite element investigation to study the behavior of steel hollow structural section (HSS) columns strengthened with CFRP (Carbon Fiber Reinforced Polymer) materials. A three dimensional finite element model of steel HSS column was developed using shell element considering both material and geometric nonlinearities whereas CFRP strengthening was incorporated in the model with additional layers of shell elements. The developed finite element model was then used to simulate experimental studies done by past researchers. It has been found that good agreement exists between numerical analysis and past experimental results, which has established the acceptability and validity of the proposed finite element model to carry out further investigation.

Keywords: Steel HSS Columns, Material and Geometric Nonlinearities, CFRP Strengthening

1. Introduction

The use of Carbon Fibre Reinforced Polymer (CFRP) materials is gaining popularity day by day for strengthening and repairing of steel structures compared to other retrofitting techniques. Problems associated with the conventional retrofitting techniques such as added dead weight, long installation time, corrosion, reduced fatigue life etc. may be overcome with the use of CFRP materials due to its high strength and high stiffness-to-weight ratios, excellent corrosion resistance and fatigue properties and easy implementation characteristics (Shaat and Fam, 2007). Satisfactory results have been obtained by conducting research about upgrading metallic structures with advanced polymer composites (Hollaway and Cadei, 2002), strengthening steel bridge girder with CFRP plates (Millar et al., 2001) and also about upgrading reinforced concrete columns by jacketing with CFRP sheets (Darwish, 2004) etc.

Aging and overburdened structures need retrofitting to get satisfied with the modified and more stringent design codes and specifications of the recent years. Columns are one of the most essential elements in a structure that need to be strengthened. Through strengthening of steel columns using CFRP, the whole structure may perform better than that of rebuilding them. By only retrofitting the columns, vertical extension of floor, design fault removal, damage reduction due to lateral loads may be possible. In recent years, steel hollow structural section (HSS) columns have become increasingly popular in the steel construction industry (Shaat and Fam, 2009). Key and Hencock (1985) investigated the column behavior of cold formed square hollow sections with slenderness ratio ranging from 66 to 98. Shaat and Fam (2006) experimented steel square HSS slender columns of constant slenderness ratio strengthened with high modulus CFRP sheets and had been able to increase the column axial strength by up to 23%. The effectiveness of CFRP was also evaluated experimentally for different slenderness ratios (kL/r) by Shaat and Fam (2009). The maximum increase in ultimate load ranged from 6 to 71% and axial stiffness ranged from 10 to 17 % respectively depending on (kL/r).

Although such experimental studies provide satisfactory results regarding strengthening, more research is required in this field. Due to huge expense of such experiments, numerical studies are being preferable now-a-days. This paper focused on developing a three dimensional finite element model to investigate the behavior and axial strength of steel square column of Hollow Structural Section (HSS) strengthened using Carbon Fiber Reinforced Polymer (CFRP) considering both the geometric and material nonlinearities. The proposed finite element model is then used to simulate the experimental results from Shaat and Fam (2007).

2. Methodology for Finite Element Analysis

This section describes a finite element model to predict the responses of CFRP retrofitted steel HSS columns. The model accounts for both material and geometric nonlinearities by incorporating column initial straightness imperfections as well. To perform the modeling in a generalized way, a hollow square section is chosen in such a way that can help to ease the modeling procedure. For example corners of a general square HSS section are considered straight in the proposed model (Fig.1 and Fig.2).

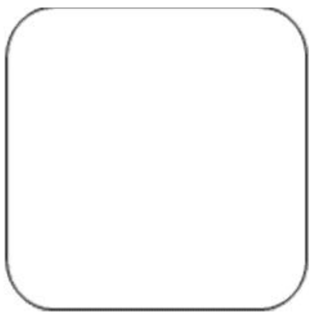

Fig. 1. Typical steel square AISC HSS column cross section.

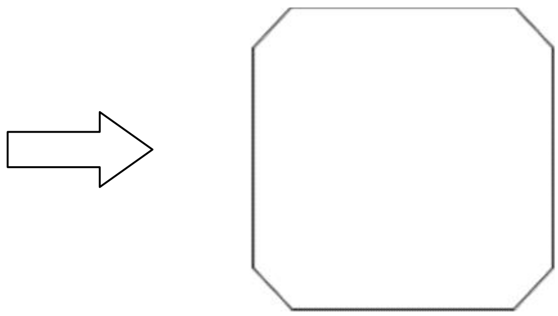

Fig. 2. Generalized column cross section for modeling.

Since this study is concerned with thin structural sections, shell element is the best option to get resemblance with the practical one. On account of this, four noded finite strain shell element having six degrees of freedom at each node has been used for steel square HSS column. Retrofitting materials involving CFRP, GFRP along with bonding material epoxy resin have been modeled with an additional equivalent layer of similar shell elements. In the experimental study of Shaat and Fam (2007), retrofitting materials are attached with the column in multiple layers using epoxy resin as a bonding material.

But in finite element method, it will be easier to create model if the layered configuration of retrofitting materials can be replaced by an equivalent material (Fig.3 and Fig.4).

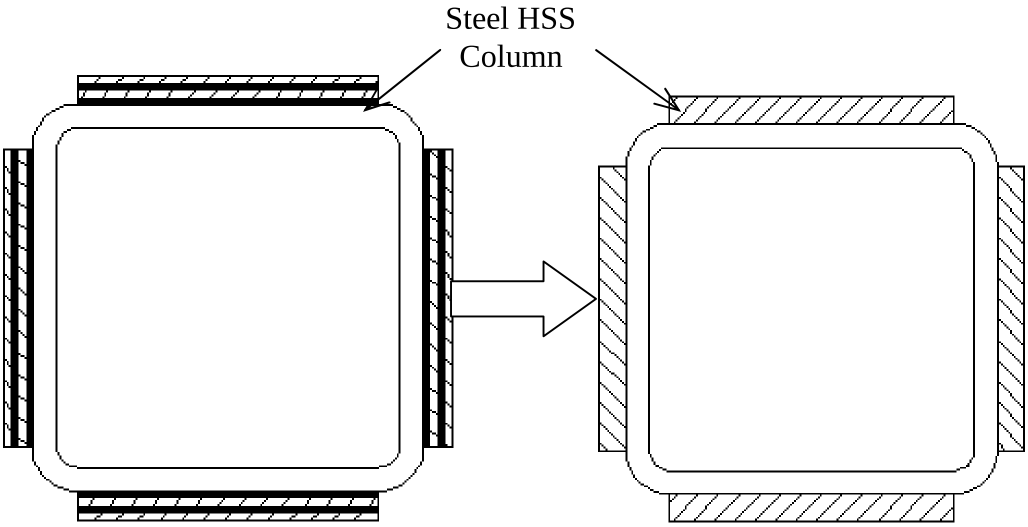

Fig. 3. Actual test features (Shaat and Fam, 2007).

Fig. 4. Equivalent idealization of the retrofitting materials.

Equivalency of the materials has been ensured in the following way. If the cross-sectional area and modulus of elasticity of different layers are A_1, A_2, A_3……… A_n and E_1, E_2, E_3……E_n respectively then the equivalence of different retrofitting layers (based on strain compatibility) is achieved as follows.

$$E_e = \frac{A_1E_1 + A_2E_2 + \cdots\cdots\cdots + A_nE_n}{A_1 + A_2 + \cdots\cdots\cdots + A_n} \tag{1}$$

$$F_{y_{eqv}} = \frac{A_1F_{y_1} + A_2F_{y_2} + \cdots\cdots\cdots A_nF_{y_n}}{A_1 + A_2 + \cdots\cdots\cdots + A_n} \tag{2}$$

$$A_{eqv} = A_1 + A_2 + \cdots\cdots\cdots + A_n \tag{3}$$

Restraints are provided in the model in accordance with the test setup of steel column's compression test (Shaat and Fam, 2007). Longitudinal dimension has been considered along the *z* direction whereas cross sectional dimensions have been considered along *x* and *y* directions. One end of the column is kept restrained for translation in all the *x*, *y* and *z* direction while the other end of the column is kept restrained in *x* and *y* direction translation. To prevent twisting of column about *z* axis, a corner node of column is additionally restrained in *x* and *y* translation. To force buckling about *y*-*y* axis only as was done in the experiment (Shaat and Fam, 2007) additional restraint against movement in *y* direction has been applied at mid height of the column. For load application, steel plates are modeled at both ends of the column using the same type of shell element as steel HSS column. The details of boundary conditions and loading are shown in Fig.5. Also some sketches of finite element mesh are shown in Fig.6, Fig.7 and Fig.8. For steel HSS columns and equivalent retrofitting materials, non-linear behavior has been incorporated in the model. The behavior of steel end plates which have been modeled for load application purpose is kept elastic.

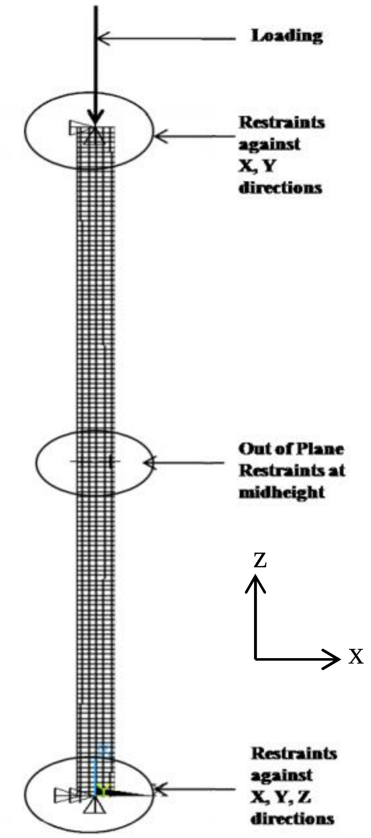

Fig. 5. Finite element mesh of steel HSS column along with boundary conditions and loading

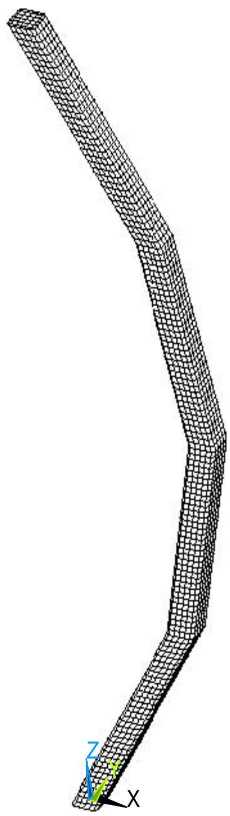

Fig. 6. Finite element mesh of column initial imperfection (exaggeration).

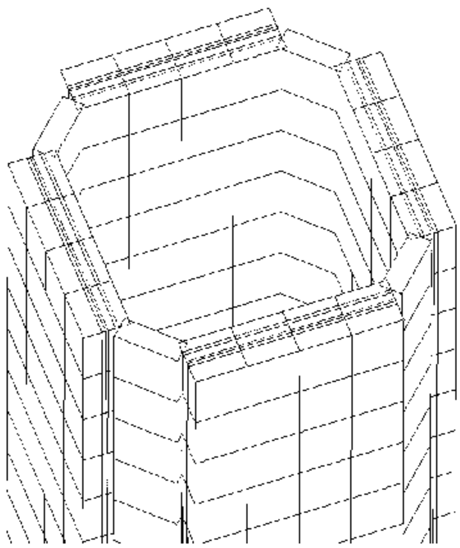

Fig. 7. Close view of 4-sided layered retrofitting materials.

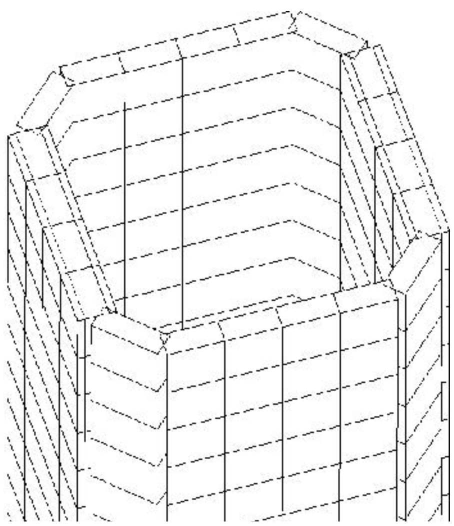

Fig. 8. Close view of the equivalent 4-sided retrofitting materials.

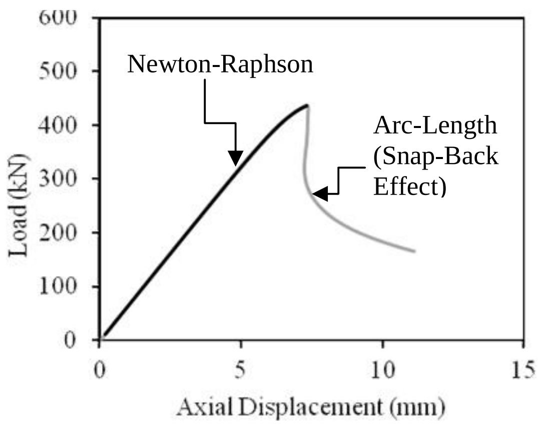

Fig. 9. Typical load vs. axial displacement behavior for square HSS column specimen for a non-compact section.

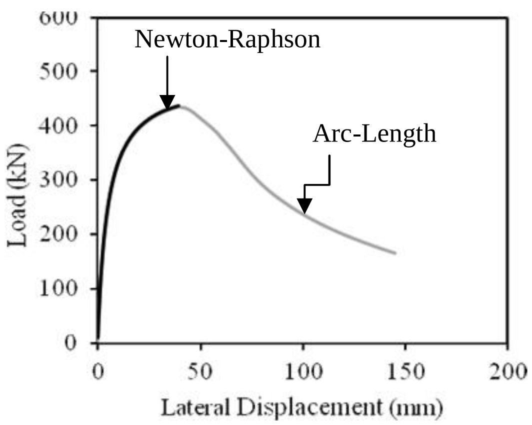

Fig. 10. Typical load vs. lateral displacement behavior for square HSS column specimen for a non-compact section.

For obtaining the load deflection diagram, nonlinear analysis has been performed both by considering Newton-Raphson method and Arc-Length Method. This is because, in detailed study of non-compact section, arc-length method gives better post-peak load deflection curve showing the snap-back effect whereas Newton-Raphson method stops at the peak. But for both methods peak occurs at the same point, so there will be no problem in determining the maximum strength gains if we want to continue in either of the method (Fig.9 and Fig.10). The typical deformed shape for the proposed model has been obtained like following (Fig.11).

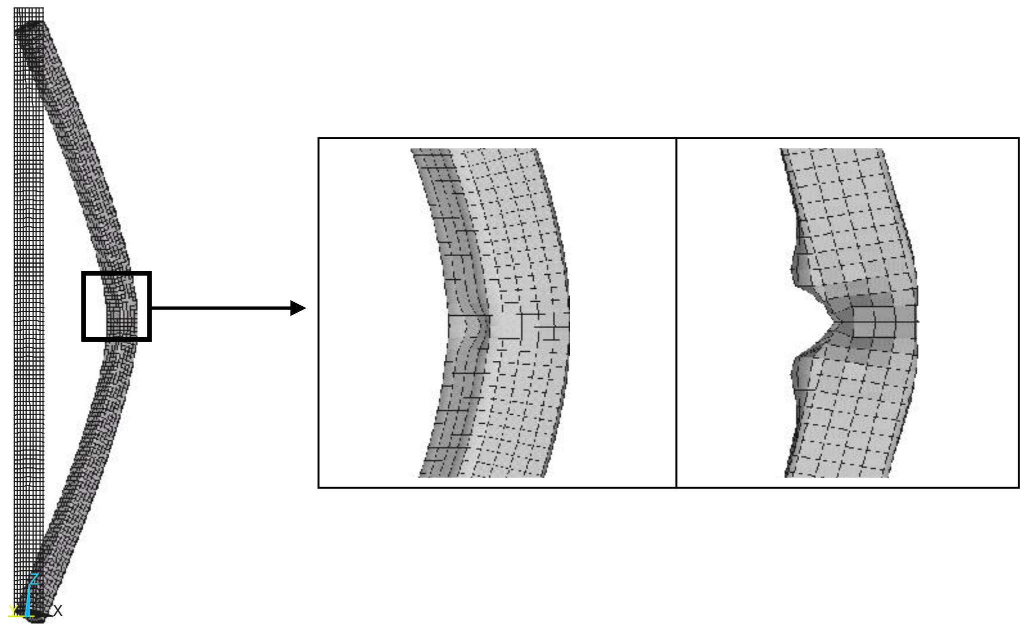

Fig. 11. (a) 3D view of typical deformed shape for square HSS column specimen. (b) Close view of deformed shape for square HSS column at point where maximum lateral deflection occurs (for compact section). (c) Close view of deformed shape (for non-compact section).

3. Simulation of Experiments

The proposed finite element model is used to simulate the experimental study to establish its reliability and acceptability. For this purpose, experimental study performed by Shaat and Fam (2007) has been taken into consideration. Tables 1 and 2 lists some basic data relevant to the experiments of Shaat and Fam (2007). A comparison between the results of numerical analysis and the experiment (Shaat and Fam, 2007) are given in Table 3 as well as in Fig.12, Fig.13 and Fig.14.

Table 1
Material Properties used in Shaat and Fam (2007)

Properties	Steel HSS Column	CFRP Sheets	GFRP Sheets	Epoxy Resin
Modulus of Elasticity (GPa)	200	230	14	3.18
Tensile Strength (MPa)	480	510	269	72.4

Table 2
Geometric Properties used in Shaat and Fam (2007)

Properties	Steel HSS Column	CFRP Sheets	GFRP Sheets	Epoxy Resin
Thickness (mm)	3.2	0.54	1.46	0.5
Length (mm)	2380	2380	2380	2380
No. of Layers	-	n = 1,3 and 5	1	-
Cross Section	89×89mm	74×0.54× n layers	74×1.46× 1 layer	74×0.5×1 layer

Table 3
Comparison between Experimental and Numerical Model Results

Specimen Identification	KL/r	Out of Straightness e' (mm)	Maximum Load		(Numerical Analysis/ Exp.) Ratio
			Exp. of Shaat and Fam (2007)	Numerical Analysis	
89 × 89 × 3.2 (Control)	68	6.60	295	268	0.91
89 × 89 × 3.2 (1L-2S)		0.92	355	400	1.13
89 × 89 × 3.2 (3L-2S)		7.04	335	364	1.09
					Mean = 1.043 Standard Deviation = ± 0.096

From Table 3, Fig. 12., Fig. 13. and Fig. 14., it has been seen that the results obtained from the numerical analysis are close enough to the results obtained from experimental study. The average of the ratios between peak load of numerical analysis and of experimental results is 1.043 and the standard deviation is ± 0.096.

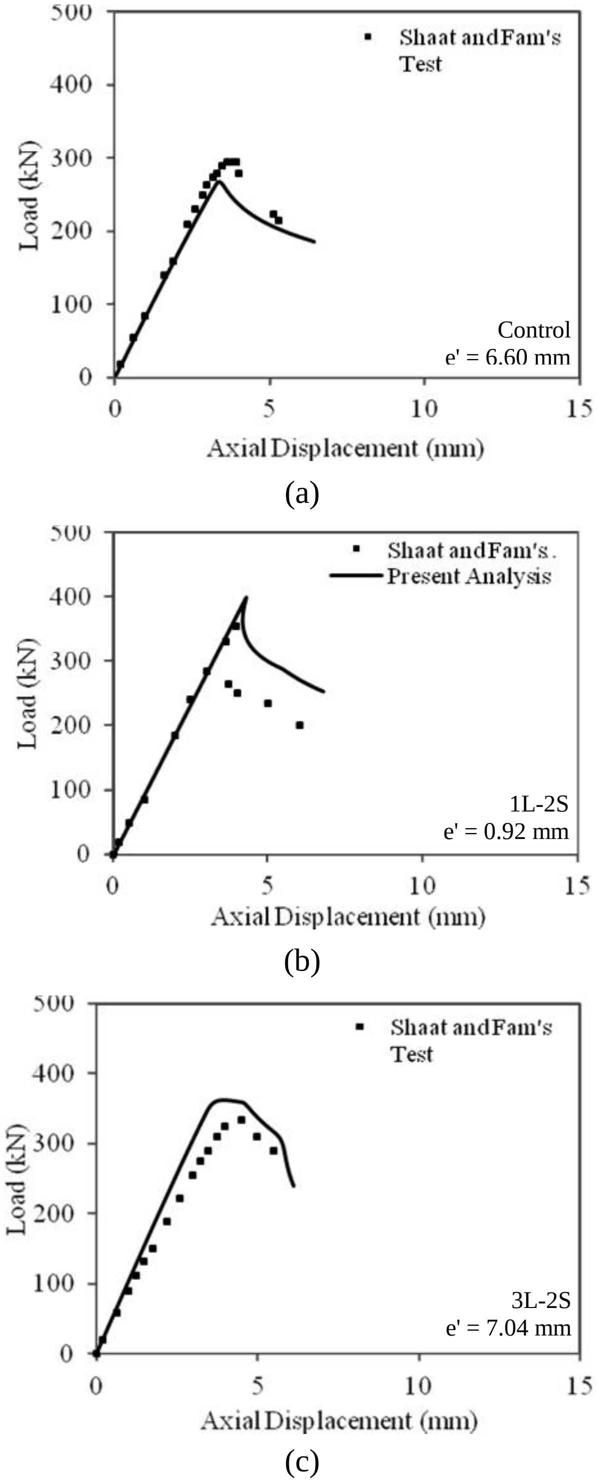

Fig. 12. Load vs. Axial Displacement behavior for axially loaded unstrengthened / strengthened HSS column specimen.

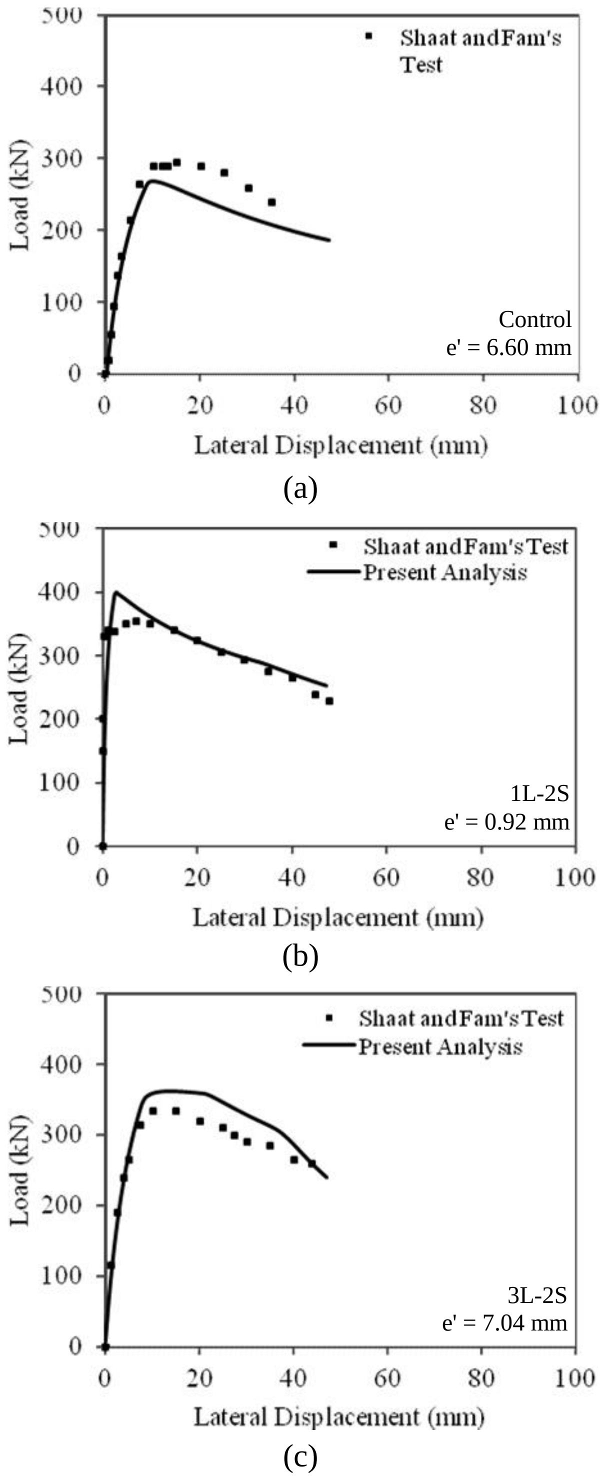

Fig. 13. Load vs. Lateral Displacement behavior for axially loaded unstrengthened / strengthened HSS column specimen.

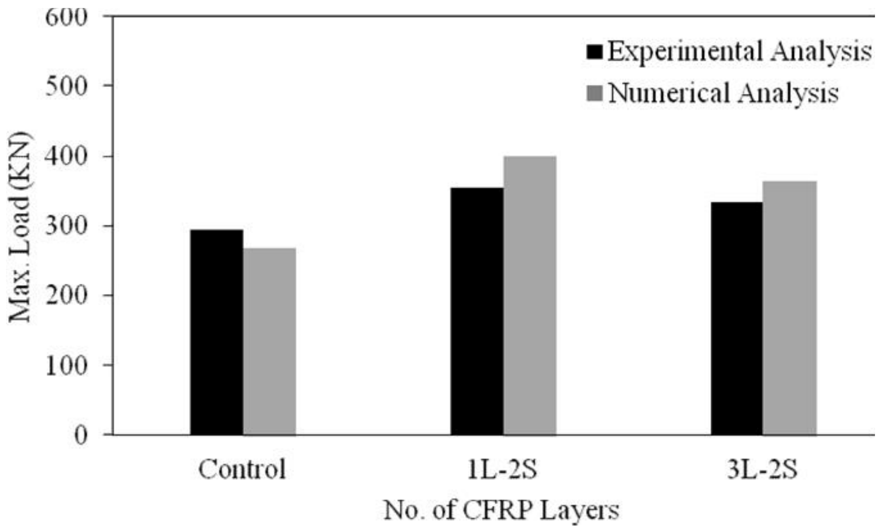

Fig. 14. Maximum load obtained for varying no. of CFRP layers from experimental and numerical analysis.

4. Conclusion

In this study, a numerical model for steel square Hollow Structural Section (HSS) has been developed for the purpose of predicting the increase in the axial load capacity of column strengthened using Carbon Fiber Reinforced Polymer (CFRP) materials. Experimental study performed by Shaat and Fam (2007) has been taken into consideration for modeling purpose. It has been shown that the FE modeling technique presented in this paper is reasonably accurate in predicting the ultimate compression capacity of CFRP retrofitted HSS sections. From the obtained results it can be said that instead of experimental study, the proposed finite element modeling technique can be satisfactorily used to predict the behavior of the steel HSS columns strengthened by CFRP retrofitting materials.

References

Darwish M. N. (2004), “Upgrading Reinforced Concrete Columns by Jacketing with Carbon Fiber-Reinforced Plastic (CFRP) Sheets”, ACI Structural Journal, 488-502.

Hollaway L. C. and Cadei J. (2002), “Progress in the technique of upgrading Metallic Structures with advanced Polymer Composites”, Prog. Struct. Eng. Mater., 4(2), 131-148.

Key P. W. and Hancock G. J. (1985), “An Experimental Investigation of the Column Behavior of Cold formed Square Hollow Sections”, Research Rep. No. R493, School of Civil and Mining Engineering, University of Sydney, Sydney, Australia.

Miller T. C., Chajes M. J., Mertz D. R. and Hastings J. N. (2001), “Strengthening of a Steel Bridge Girder Using CFRP Plates”, Journal of Bridge Engineering, ASCE, 6(6), 514-522.

Shaat A. and Fam A. (2006), “Axial Loading tests on Short and long Hollow Structural Steel Columns Retrofitted using Carbon Fiber Reinforced Polymers”, Canadian Journal of Civil Engineering, Vol. 33 (4), 458-470.

Shaat A. and Fam A. (2007), “Fiber-Element Model for Slender HSS Columns Retrofitted with Bonded High-Modulus Composites”, Journal of Structural Engineering, ASCE, 133 (1), 85-95.

Shaat A. and Fam A. (2009), “Slender Steel Columns Strengthened Using High-Modulus CFRP Plates fir Buckling Control”, Journal of Structural Engineering, ASCE, 13 (1), 2.