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Analytical study on the behaviour of concrete in-filled FRP tubular columns subjected to lateral cyclic loading

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Abstract - The purpose of this paper is to present a three-dimensional non-linear finite element analysis of concrete in-filled fiber-reinforced polymer (FRP) tubular columns subjected to lateral cyclic loading. Stress-Strain Confined model, Hashin's damage failure model, and plasticity model were used to model concrete, fiber-reinforced polymer tubes and steel reinforcement inside the tubes. The parameters involved in this study are strength of concrete, fiber orientation, thickness of the tube, and interfacial bonding. The load-deflection behaviour and failure patterns were investigated using finite element analysis. The results obtained from this numerical study that concrete in-filled FRP tubular columns with 5mm tube thickness showed higher load carrying capacity compared to columns with 3mm tube thickness. The results revealed that concrete in-filled FRP tubular columns with fiber orientation in hoop direction (0^0) have higher load carrying capacity and ductility when compared to columns with fiber orientation of 30^0 and 53^0. The results showed that there is no considerable difference in interfacial bonding of the concrete in-filled FRP tubular columns with different co-efficient of friction between FRP tubes and concrete.

Keywords - Finite Element Analysis; Fiber Reinforced Polymer tubes; Fiber orientation; Thickness of the FRP tube; Interfacial bonding.

INTRODUCTION

Fiber Reinforced Polymer (FRP) tubular columns are used to improve the strength and ductility of the structural members and provide several advantages, including a low weight-to-strength ratio, a high degree of confinement, and corrosion resistance. The FRP tube functions as a stay-in-place formwork, confining and strengthening the concrete structural element. Because of the linear elastic stress-strain behaviour of FRP, the confinement pressure generated by it increases continuously with the lateral strain of concrete, unlike steel-confined concrete, where the confining pressure remains constant when the steel is in plastic flow [1]. Due to the significant improvement in ductility and strength of confined concrete columns over the last two decades, their application has expanded dramatically, particularly in construction of structural members which are built to withstand seismic loading.

This research involves the non-linear Finite Element Analysis of concrete in-filled FRP tubular column, with different fiber orientations, thickness of FRP tube and interfacial bonding between the FRP tube and concrete surface. These parameters are chosen to understand the influence of these parameters on the behaviour of Concrete in-filled FRP tubular columns. To accurately reflect the non-linear behaviour of such structural members, numerical approaches must be used to make such predictions. It takes into account cracking and plasticity in concrete, as well as the effect of material and geometrical non-linearity.

FINITE ELEMENT MODELLING

Finite element analysis [FEA] is critical in modern structural engineering research for interpreting experimental results and gaining insight into the structural behaviour of concrete in-filled FRP tubular columns. During this research, the impact of the fiber orientation, thickness of the FRP tube and interfacial bonding on the behaviour of the concrete in-filled FRP tubular columns subjected to lateral cyclic loading were examined. The geometrical properties of the concrete in-filled FRP tubular column specimens were listed in Table I.

MODELLING

Modeling of Concrete

The confined concrete is modeled as 3-Dimensional Deformable 8-nodded solid brick element with reduced integration (C3D8R) by using Concrete Damaged Plasticity (CDP) model [2]. It encompasses all aspects of 3-dimensional non-linear inelastic behaviour of the confined concrete including confinement, damage mechanisms, as well as compressive, tensile, and plastic properties in the inelastic range. Up to 50% of the ultimate strength of confined concrete can be attributed to the linear elastic component of the stress-strain curve, which can be defined using two parameters as elastic modulus and Poisson's ratio.

The compressive strength of confined concrete (f'_{cc}) and the corresponding constrained deformation (f'_{co}) can be determined by equations (1) and (2), respectively. Equation (1) proposed by Richart et al. [3] and Equation (2) modified by Lam and Teng [4] which are used in this study to model stress-strain behaviour of concrete.

$$f'_{cc}/f'_{co} = 1 + 3.3\ f_{l,a}/f'_{co} \qquad (1)$$

$$\varepsilon_{cu}/\varepsilon_{co} = 1.75 + 12\ (f_{l,a}/f'_{co})\ (\varepsilon_{h,rup}/\varepsilon_{co})0.45 \qquad (2)$$

Where fl,a is the lateral confining pressure of FRP, $f_{l,a} = 2f_f t_f/D$; f_f is the tensile strength in hoop direction and t_f is the thickness of the FRP tube.

The Poisson's ratio was assumed to be 0.2 for confined concrete core material, and the elastic modulus was calculated using equation (3) from the American Concrete Institute (ACI 318 code) [5].

$$E_{cc} = 4700\sqrt{f'_{cc}} \qquad (3)$$

Where E_{cc} is the elastic modulus and f'_{cc} is the compressive strength of concrete. The grade of concrete used to model the concrete is M-25.

The equivalent axial stress-strain curve of the confined concrete is defined by distinguishing between the parabolic and a straight section of the curve is shown in Fig. 1 [4].

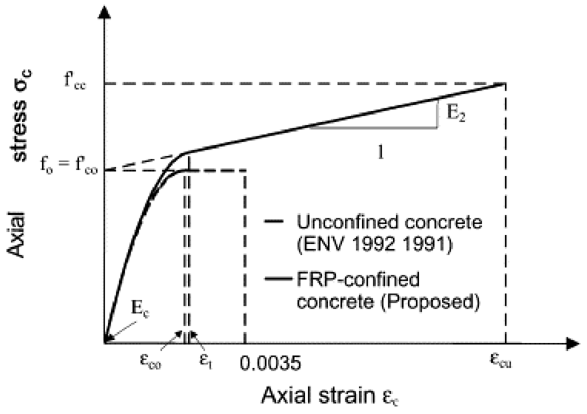

Fig. 1 Axial stress-strain curve of confined concrete [4].

Solid homogeneous section was assigned to the confined concrete under section assignment manager. Further modeling of confined concrete was done in the assembly of the other materials.

Modelling FRP Tube

The FRP tubes were modeled with 3-D deformable 4-noded doubly curved shell elements, and reduced integration (S4R), with six degrees of freedom at each node [2]. FRP tubes were modeled under the classical laminate theory with the elastic properties. The laminate strength, elastic properties, and damage progression are required to characterize the behaviour of FRP tubes. Material type "Lamina" is assigned to model the elastic behaviour of FRP tube, and the elastic modulus of hoop direction of FRP tube obtained from the Table II [6]. The Poisson's ratio was calculated to be 0.3.

In this study, the Hashin damage criterion [7] was utilized to describe all modes of failure of FRP tubes, including strength and damage behaviour, because this model accurately predicts fiber and matrix tensile and compressive damage. The Table III shows various parameters used to characterize the Hashin damage model of FRP tubes [6].

The homogeneous shell section had been assigned to the FRP tube by the section assignment manager. For FRP tubes, the composite layup property had been assigned in order to provide the shell thickness, fiber orientation and the integration points.

Modeling steel reinforcement bars and steel plates

The longitudinal and transverse reinforcement bars had been modeled using 3-Dimensional truss components with reduced integration. The longitudinal reinforcement was of 12 mm diameter and transverse reinforcement was of 8mm diameter with 120 mm c/c spacing. The elastic material properties were assigned to the steel bars with the elastic modulus of 200 GPa and the poisson's ratio of 0.3. The plastic material properties were assigned with the yield stress of 500MPa and the ultimate strain of 0.2. The steel plates were modeled on the top and bottom of the concrete in-filled FRP tubular columns in order to improve the rigidity while loading. These plates were also provided the same elastic and plastic properties as that of reinforcement steel bars.

Surface Interactions and Boundary Conditions

The accuracy of Finite Element Analysis is determined by the boundary conditions and material simulations. In order to avoid surface penetration, the interaction between the outer surface of the concrete and the inner surface of the FRP tube is treated as a normal hard contact, and frictional contact in the tangential direction of the component is specified and using the coefficient of friction of 0.25 and 0.5. The normal and tangential friction coefficients were 0.35 to simulate the connection between the concrete surface and the rigid steel plate surface using hard contact interactions and friction contact interactions. The surface of the concrete core material is the master surface and the surface of the steel plate is the slave surface. The surface of the rigid steel plate was used as the master surface by providing reference points in the plate to connect the node areas of the FRP tube. One constraint is provided for the steel plate as the rigid body and the other constraint is provided for the reinforcement as the embedded part in the confined concrete. The top of the columns remain unconstrained, while the bottom is constrained with all the degrees of freedom. The typical sectional view of concrete in-filled FRP tubular columns modeled using Finite Element Analysis software is shown in Fig. 2.

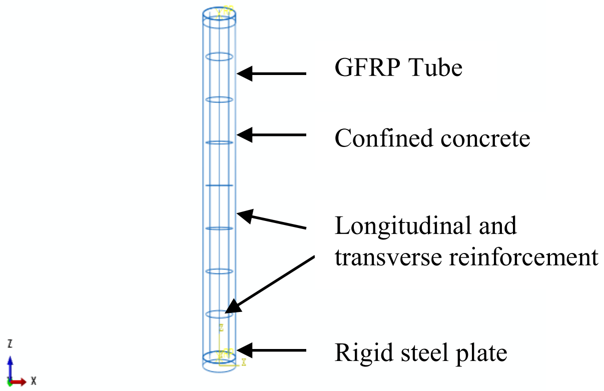

Fig. 2 Typical sectional view of concrete in-filled FRP tubular column modeled using Finite Element Analysis software.

TABLE I
(GEOMETRICAL PROPERTIES OF THE SPECIMENS)

Specimen Label	Height of the Column (mm)	Diameter of the Column (mm)	Internal Longitudinal Reinforcement	Lateral confinement	Thickness of the FRP tube (mm)	Fiber Orientation
C3F0	1000	150	Steel	GFRP	3	0^0
C5F0	1000	150	Steel	GFRP	5	0^0
C3F53	1000	150	Steel	GFRP	3	53^0
C5F53	1000	150	Steel	GFRP	5	53^0
C3F30	1000	150	Steel	GFRP	3	30^0
C5F30	1000	150	Steel	GFRP	5	30^0

TABLE II
(ELASTIC PROPERTIES OF GFRP TUBES [6].)

Elastic modulus, E1 (MPa)	Elastic modulus, E2 (MPa)	Poisson's ratio	Shear modulus, G1 (MPa)	Shear modulus, G2 (MPa)	Shear modulus, G3 (MPa)
28000	1040	0.3	5200	5200	3400

TABLE III
(HASHIN DAMAGE MODEL VARIABLES FOR GFRP TUBES [6].)

Tensile strength in longitudinal direction (MPa)	Compressive strength in longitudinal direction (MPa)	Tensile strength in transverse direction (MPa)	Compressive strength in transverse direction (MPa)	Shear strength in longitudinal direction (MPa)	Shear strength in transverse direction (MPa)
1200	140	40	40	20	20

Loading Pattern

The axial compressive and lateral cyclic loading ensures that the GFRP tube, Concrete core, and Steel plates are in constant contact. The displacement increment was used to apply axial and lateral cyclic loading to the top and lateral surfaces of the column. The displacement was applied to all nodes on the top and lateral surface of the concrete core confining them together, to imitate the stiff condition of the loading plate in the testing machine. The outputs of stresses, strains, deflections, and reaction forces at most important sites were saved and processed after the solution converged at each sub-step to obtain the axial and lateral load-deflection response, ultimate stress and strain for the specimens. The loading pattern applied to the concrete in-filled FRP tubular columns was presented in Fig. 3.

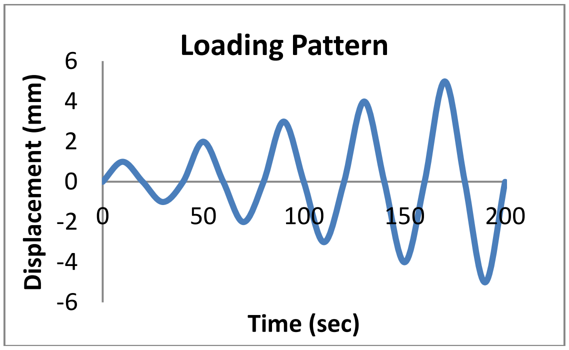

Fig. 3 Loading pattern applied to the concrete in-filled FRP tubular column.

RESULTS AND DISCUSSION

Load-deflection Behaviour

The Load-deflection curves of the concrete in-filled FRP tubular column specimens of different fiber orientations, thickness of the FRP tube and interfacial bonding between the FRP tube and concrete core were presented in Fig. 3. In the early stages of loading, a linear part was observed between load and the deflection of the FRP tube column. But after yielding, the load increased linearly, forming the second linear part of the curve. After that, the load reached the maximum capacity with the rupture of FRP tubes causing the load capacity to decrease rapidly as shown in Fig. 4. The load carrying capacity of column C5F0 was 2.08 times higher than the column C3F0, column C5F30 was 1.89 times higher than the column C3F30, column C5F53 was 3.17 times higher than the column C3F53. The FRP tube of greater thickness exhibits enhanced load carrying capacity and good confinement to the concrete core.

The load carrying capacity of column C3F0 was 1.29 times higher than the column C3F30 and 3.51 times the column C3F53 and column C5F0 was 1.43 times higher than the column C5F30 and 2.31 times the column C5F53.

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Failure Pattern

The Load-deflection responses of the columns exhibits a linear relationship up to about 70-80% of the failure load as presented in Fig. 4. It is observed that column C5F0 has contributed substantially resulting in higher load carrying capacity and lesser deflection than other concrete in-filled FRP tubular columns as shown in Fig 4. The Finite element analysis model crack mode is visualized by the maximum positive plastic deformation, and the concrete material that accurately represents the crack mode where the cracking pattern is perpendicular to the principal cracks. When the concrete cracks with its volumetric expansion, confinement of the concrete relieves the stress on the confined FRP tube until they fail simultaneously. Such failures results in sudden drop in the loading shown in Fig. 4.

Effect of GFRP Tube thickness

GFRP tubes with thicknesses of 3 mm and 5 mm were examined to observe their effect on column load carrying capacity and corresponding deflection. The columns with 5mm thickness (C5F0, C5F30, and C5F53) exhibits increase in load carrying capacity than columns with 3mm thickness (C3F0, C3F30, and C3F53) as presented in Fig. 5 (a), (b), and (c). Load carrying capacity of column C5F0 was 2.08 times higher than that of column C3F0 as shown in Fig. 5(a). The load carrying capacity of column C5F30 was 1.89 times higher than that of column C3F30 as presented in Fig. 5(b). The column C5F53 exhibits 3.17 times higher load carrying capacity than column C3F53 as shown in Fig. 5(c). As observed, the concrete in-filled FRP tubular column of thickness 5mm has the higher load capacity and lesser deflection of compared to the column thickness of 3mm. From Fig. 5 (a), (b), and (c), FRP tube with lesser thickness exhibit better ductility compare to other columns.

Effect of Fiber Orientation

The behaviour of concrete in-filled FRP tubular columns is significantly affected by the orientation of confined fibers. It is important to understand and to simulate the influence of fiber angle on the behaviour of FRP confined concrete. From the fig. 6(a), the load carrying capacity of column C3F0 was 1.29 times than the column C3F30 and 3.51 times than the column C3F53. The load carrying capacity of column C5F0 was 1.43 times higher than the column C5F30 and 2.31 times higher than the column C5F53 as shown in Fig. 6(b). It can be seen that the failure load of the specimen increases as the ply laminate angle increases in the length direction. It is observed that the fiber orientation in the hoop direction (0^0) contributes to the higher ultimate load. Therefore, it is concluded that as the arrangement of the fibers concerning the direction of the hoop increases, the efficiency of the fiber decreases significantly which is consistently reported in the previous research.

Effect of Interfacial Bonding

In this section, the influence of interfacial bonding on the load-deflection response of the concrete in-filled FRP tubular columns was considered. The coefficient of friction between FRP and concrete core was chosen to be 0.25 and 0.5 for the different thickness and fiber orientations of the FRP tube. From the fig. 7 (a) and (b), there is no changes in the Load-deflection behaviour with the frictional co-efficient of 0.25 and 0.5. It can be concluded there is not much changes in the interfacial bonding on the load-deflection behaviour of concrete in-filled FRP tubular columns.

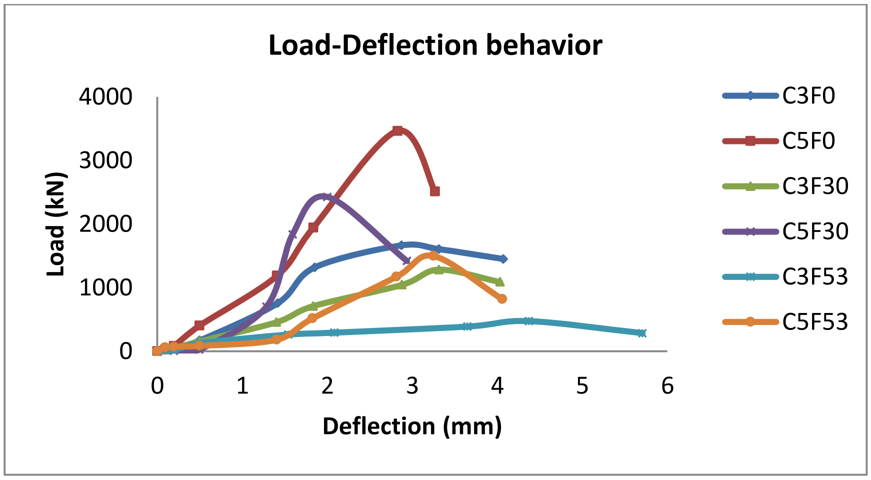
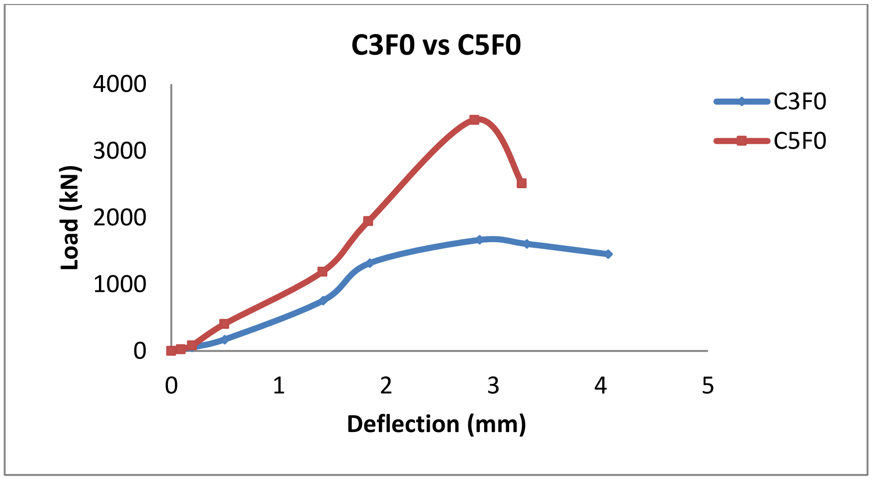
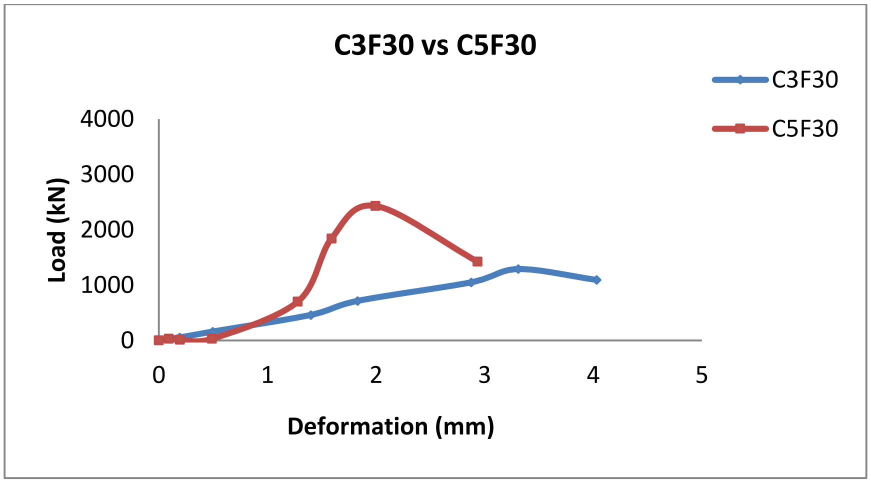


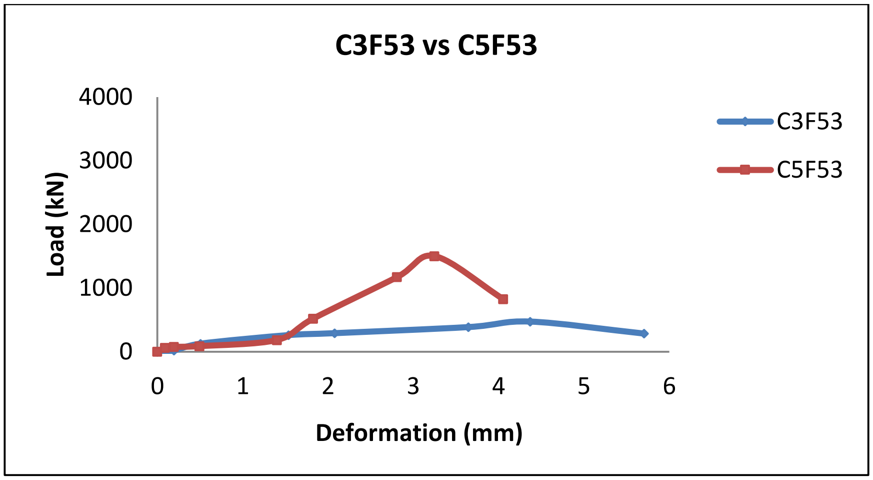
Fig. 4 Load-deflection behaviour of concrete in-filled FRP tubular column.



5(a)

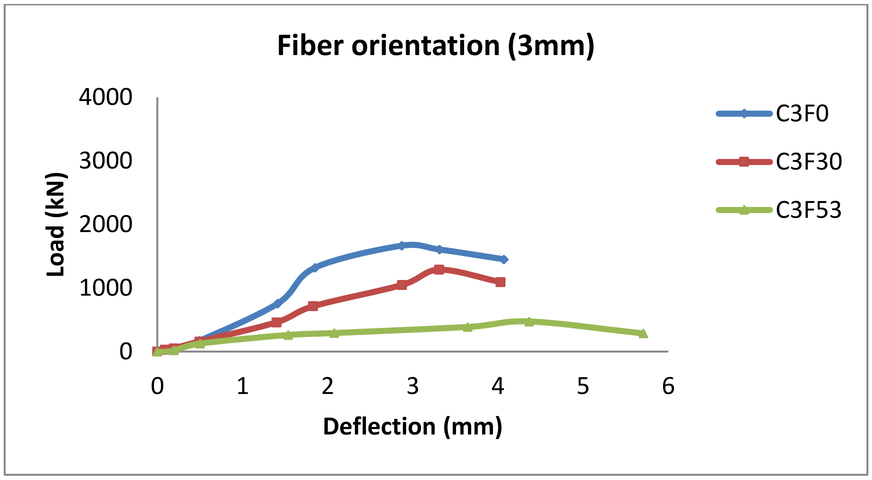


5(b)

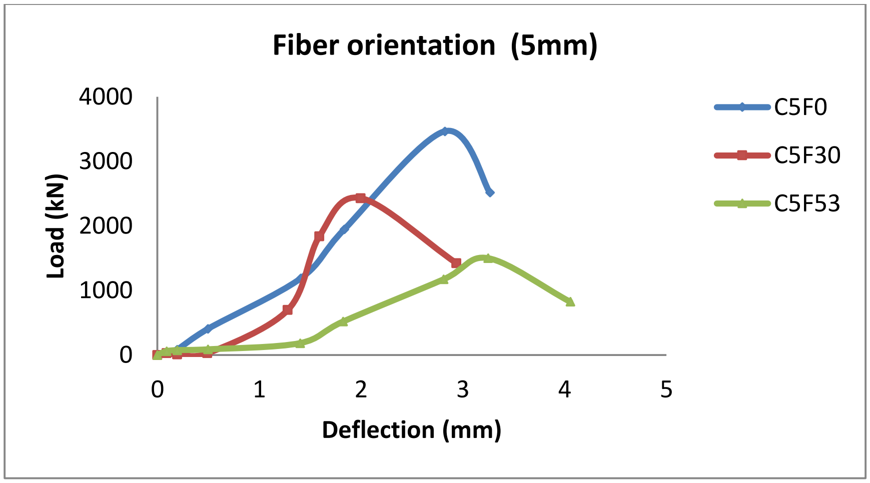


5(c)

Fig. 5 Effect of thickness of the FRP tube with 3mm and 5mm specimens (a) 0^0, (b) 30^0, and (c) 53^0.

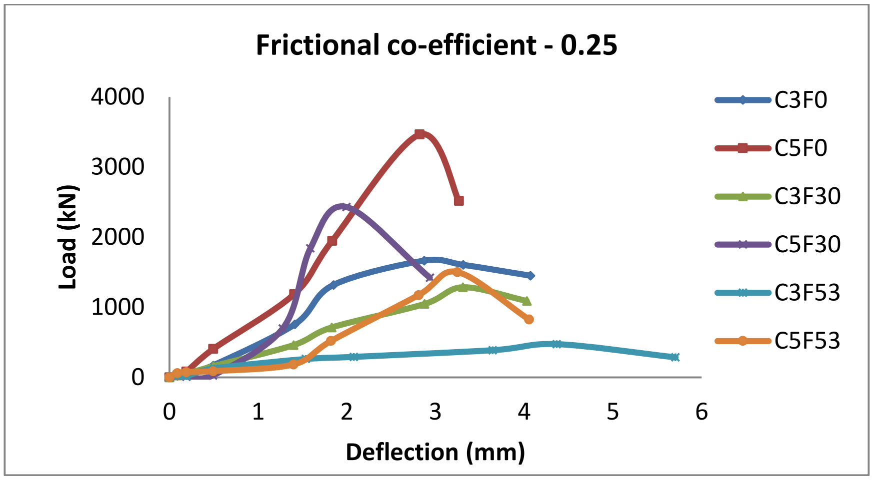


6(a)

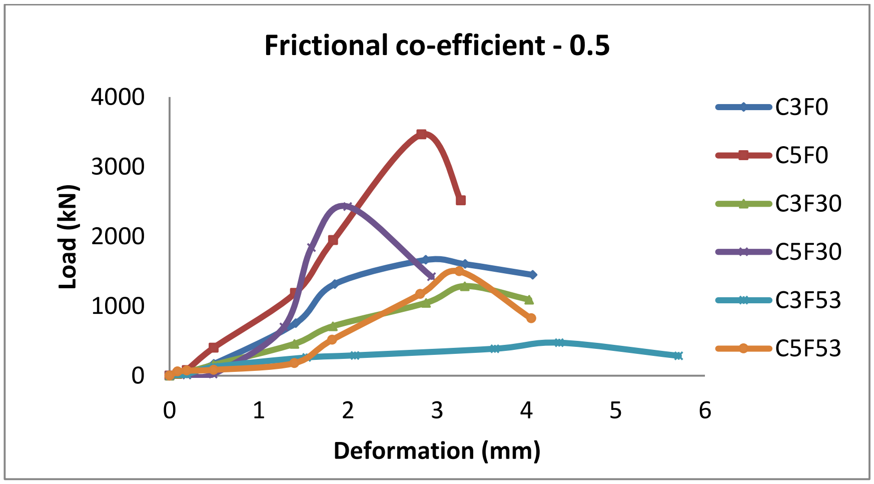


6(b)

Fig. 6 Effect of fiber orientation in 0^0, 30^0, and 53^0 specimens (a) 3mm, and (b) 5mm.



7(a)



7(b)

Fig. 7 Effect of Interfacial bonding in the specimens with (a) Frictional co-efficient – 0.25, and (b) Frictional co-efficient - 0.5.

CONCLUSION

Finite element analysis was performed on concrete in-filled FRP tubular columns in this study. Numerical parameters including thickness of the FRP tube, Fiber orientation and Interfacial bonding between the FRP tube and the confined concrete core were considered to examine the behaviour and failure modes of concrete in-filled FRP tubular columns. Based on this finite element modeling, the following conclusions can be drawn.

- The thickness of the shell has a significant effect on the load carrying capacity and corresponding deflection of the columns. Increasing the thickness of the shell can greatly increase the load carrying capacity and decrease the deflection of concrete in-filled FRP tubular columns.

- FRP tubular columns with lesser thickness exhibit better ductility compare to other columns.

- The load carrying capacity was observed to be maximum in the columns with fiber orientation by the hoop direction (0^0) than the other fiber orientation. The concrete in-filled FRP tubular column specimens with fiber orientation (0^0) withstands higher load carrying capacity than the columns with remaining fiber orientations (30^0 and 53^0). The column C5F0 exhibits higher load carrying capacity than other columns.

- By using the different co-efficient of friction (0.25, and 0.5) in the normal hard contact interactions between the surface of the FRP tube and concrete core in these concrete in-filled FRP tubular columns, there is very little effect in the load-deflection behaviour. The load carrying capacity of the columns with co-efficient of friction 0.25 was almost equal to the columns with co-efficient of friction 0.5.

- The behaviour and failure modes of concrete in-filled FRP tubular columns were closely simulated with this developed numerical model using Finite Element software.

Hence this finite element model can be used to simulate the real time behaviour of concrete in-filled FRP tubular columns under lateral cyclic loading.

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REFERENCES

[1] Sadeghian, Pedram & Rahai, Alireza & Ehsani, Mohammad. (2008). Numerical Modeling of Concrete Cylinders Confined with CFRP Composites. Journal of Reinforced Plastics and Composites. 27. 1309-1321. 10.1177/0731684407084212.

[2] ABAQUS standard user’s manual. Hibbitt. Karlsson and Sorensen. Inc., USA, 2008.

[3] Richart FE, Brandtzaeg A and Brown RL. A study of the failure of concrete under combined compressive stresses. Bulletin no. 185, Univ. of Illinois, Eng. Experimental Station, Champaign, 1928.

[4] Lam, Lik & Teng, J.G.. (2003). Design-Oriented Stress– Strain Model for FRP-Confined Concrete. Construction and Building Materials. 17. 471-489. 10.1016/S0950-0618(03)00045-X.

[5] ACI (American Concrete Institute). Building code requirements for structural concrete and commentary. ACI 318M-08, USA, 2008.

[6] Abdallah, Maha & Shazly, Mostafa & Mohamed, Hamdy & Masmoudi, Radhouane & Mousa, Ahmed. (2017). Nonlinear finite element analysis of short and long reinforced concrete columns confined with GFRP tubes. Journal of Reinforced Plastics and Composites. 36. 073168441769875. 10.1177/0731684417698758.

[7] Hashin, Z.: Failure criteria for unidirectional fiber composites. J. Appl. Mech. 47(2), 329–334 (1980).

[8] Hong, Won-Kee & Kim, Hee-Cheul. (2011). Behaviour of concrete columns confined by carbon composite tube. Canadian Journal of Civil Engineering. 31. 178-188. 10.1139/l03-078

[9] Hu, Hsuan-Teh & Asce, M & Huang, C. S. & Wu, Ming-Hsien & Wu, Yih-Min. (2003). Nonlinear Analysis of Axially Loaded Concrete-Filled Tube Columns with Confinement Effect. Journal of Structural Engineering-asce - J STRUCT ENG-ASCE. 129. 10.1061/(ASCE)0733-9445(2003)129:10(1322).

[10] ASCE (American Society of Civil Engineers). Task committee on concrete and masonry structure. state of the art report on finite element analysis of reinforced concrete. New York, 1982.

[11] Teng JG, Lam L. Behaviour and modeling of fiber reinforced polymer-confined concrete. J Struct Engng ASCE 2004;130(11):713-23.

[12] Parvin A, Jamwal AS. Effects of wrap thickness and ply configuration on composite-confined concrete cylinders. Compos Struct 2005;67(4):437–42.