FINITE ELEMENT ANALYSIS OF CIRCULAR CONCRETE-FILLED STEEL TUBE (CFST) UNDER VARIOUS LOADING CONDITION

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ABSTRACT

Extensive experimental studies about circular concrete-filled steel tubes (CFSTs) have been conducted for past decades. However experimental results alone are not sufficient to support the engineering of these components. Complementary advanced numerical models are needed to simulate the behavior of CFST to extend the experimental research and develop predictive tools required for design and evaluation of structural systems. In this study, a finite element model for CFST was developed. Firstly, this study provides a new modeling approach for finite element analysis of CFST. The majority of the prior CFST research has used a modified stress-strain relationship of the concrete to account for confinement. On the other hand, the proposed model employed unconfined concrete behavior, and the benefits of confinement were computed by the interface contact stress between the steel tube and concrete infill with concrete damaged plasticity model. This modeling produced a good representation of benefits of confinement and composite behavior of CFST. Then, the confinement effects, and behavior of CFST subjected various types of loading predicted by the proposed finite element model for CFST were verified by comparing with test results.

Keywords: Concrete-filled steel tube (CFST); Finite element analysis; Confinement effect.

1. INTRODUCTION

Circular concrete-filled steel tubes (CFSTs) are composite members, which consists of a steel tube and concrete infill. Relative to conventional structural steel and reinforced concrete components, CFSTs have several advantages. The steel tube serves as both reinforcement and formwork eliminating the need for both, and provides large tensile and compressive capacities; the concrete fill restrains buckling of the steel tube, which increases the strength, stiffness, and deformability of the section.

Extensive experimental researches have been conducted to investigate the behavior of CFST and the experiment results provide insight into the flexural behavior of CFST, however the experimental programs by their very nature must be limited and therefore it is hard to investigate the full range of important design parameters. Numerical modeling can complement and extend these results in part

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because they can simulate geometries, sizes, and demands that are difficult or even impossible to be simulated experimentally. Some prior studies have used fiber-based and macro-element models to simulate CFST beam, column, and beam-column (Hajjar and Gourley 1996; Han et al. 2001; Han 2004). The most important advantage of such models is efficiency in calculation. But these modeling approaches are not capable of simulating the composite action between concrete infill and steel tube or tube buckling and have not been adopted here. Another numerical method used in investigating CFST is the finite element method (FEM). FE modeling is generally more complex and time consuming, but permits more accurate investigation of composite action, concrete damage, as well as local and global instabilities (Moon et al. 2012; 2013). Prior researchers have used the FEM to investigate the behavior of CFST (Susantha et al. 2001; Hu et al. 2003; Han et al. 2007; Lu et al. 2009) and these results show that the FEM approach has promise to simulate the nonlinear response of CFST. However, prior research results have not achieved accurate simulation. In some cases, cracking in the tensile zone of concrete was not included or not modeled to a sufficient extent, which may compromise the accuracy of the nonlinear response. The choice of modeling approach for the confinement can also impact the model accuracy or limit its application. Typically, the confinement effects within the FE analysis are modeled using empirically established confined stress-strain relations. This may limit the applicability of the model if the confinement effects are generated by interface stress between the steel tube and concrete infill, which may not have been accurately modeled in smaller scale experimental results. A more direct approach is warranted.

The research program described herein was conducted with the objective of overcoming the challenges associate with prior FE analyses of CFST and developing modeling recommendations to accurately simulate the full nonlinear behavior of circular CFST components.

2. FINITE ELEMENT MODELING OF CFST

In this study, a general purpose structural analysis program ABAQUS (2009) was used to model the CFST. Figure 1 shows the configuration of the finite element model used to model a cantilever columns subjected to general combined loading. The model must accurately simulate the full response to axial and bending loads, including any relative movement between the steel shell and concrete fill. To enable this, three different types of elements were used to model the concrete fill, steel shell, and interface between the steel shell and concrete fill, as shown in Fig. 1(a). The 8-node solid element (C3D8R) was used to model the concrete, and the 4-node shell element (S4R) was used to model the steel shell. The GAP element in ABAQUS (2009) was used to simulate the interface between concrete infill and steel tube. GAP element has infinite stiffness for the compression and no stiffness in tension, which permitted simulation of slip by separation of two nodes. (Penetration of one node into an adjacent one was prevented.) The normal stresses in the GAP element results in confinement of the concrete, thus it permits explicit modeling of the confining effect of the tube. Shear stress transfer between the steel tube and the concrete infill is accomplished through friction, which was introduced to the model through a friction coefficient assigned to the GAP element. Thus, shear stress at interface is generated with pressure acting through the GAP element with specified value of friction coefficient. A friction coefficient of 0.47 was used based on validation from a prior study (Moon et al. 2012). Boundary and loading conditions are shown in Fig. 1(b). The nodes at the base of the CFT column model were fully restrained to model a fixed-base column. Distributed axial loads were applied uniformly at the top of the model to both the concrete and steel section. A monotonic lateral displacement history was applied at the top of the model. To ensure convergence, a mesh refinement study was conducted. Based on this study, a total of 20 elements is recommended to model the steel tube. This mesh was adopted for analysis as shown in Fig. 1(a).

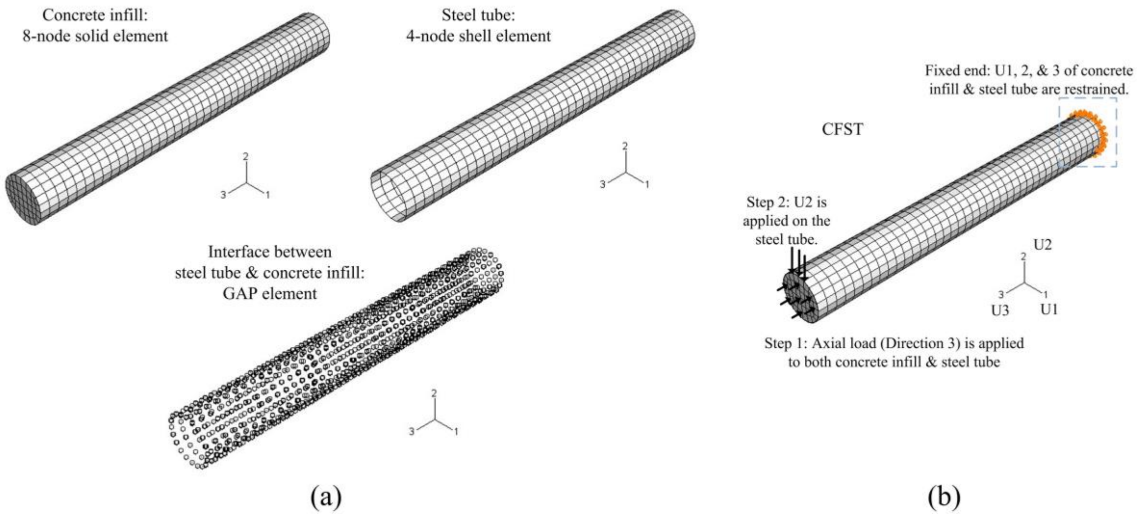

Figure 1: Finite Element Model of CFST for general combined loading: (a) Elements; and (b) BC and loading conditions.

The concrete was modeled using the available damaged plasticity model incorporated in ABAQUS (Lubliner et al. 1989; Lee and Fenves 1998). This constitutive model simulates triaxiality dependent plastic hardening. The uni-axial unconfined stress-strain relationship proposed by Saenz (1964) was employed, where it was assumed that the compressive stress-strain relation is linear up to a stress of $0.5f_c'$ and the maximum compressive strength, f_c', is achieved when compressive strain is 0.003. The modulus of elasticity of the concrete E_c was approximated as $4{,}700(f_c')^{0.5}$ MPa (ACI 2011). The tensile response of the concrete was modeled as follows: (1) the tensile stress increases linearly up to maximum tensile strength of the concrete, which is approximate as 0.09 f_c'. and (2) after this peak, the tensile stresses decrease linearly to zero at a strain equal to 10 times the strain at maximum tensile strength of the concrete, ε_{ct}.

The dilation angle, ψ, of the concrete is an important model parameter, which in part determines the plastic hardening of the concrete. It was approximated as 20° based on the results of prior research and parametric studies (Moon et al. 2012). For the steel tube and internal reinforcement, a tri-linear stress-strain relationship was used with an isotropic hardening plasticity rule. Young's modulus, E_s, was approximated as 200,000MPa; and Poisson's ratio, υ_s, was approximated as 0.3. The plastic plateau terminated when strain of the steel, ε_s, and was set equal to 10 times of yield strain of the steel ($10\varepsilon_{sy}$) and stress increase up to ultimate strength of the steel, f_u, which is achieved when the strain of the steel, ε_{su}, is 0.1. The measured stress-strain curve from the CFST tests was used to verify the analytical models when available.

3. VERIFICATION FOR VARIOUS LOADING CONDITION

3.1. Confinement effect

Uniaxial stress-strain relationship of the unconfined concrete was used with concrete damaged plasticity model, and in combination with the use of GAP element to simulate the concrete-filled steel tube interface, resulted in explicit modeling of the confinement effects. This approach provides a more rational and realistic simulation of the confinement effects because the confinement stresses that are generated in the steel tube transfer through the GAP elements placed at the interface and concrete infill undergoes tri-axial stress states. Experimental results were used to verify the modeling approach. Specifically, test results for CFST stub columns subjected to axial load only were compared with the FE analysis results. The results of specimens tested by Huang et al. (2002) and Schneider (1998) were used for this evaluation and are shown in Table 1.

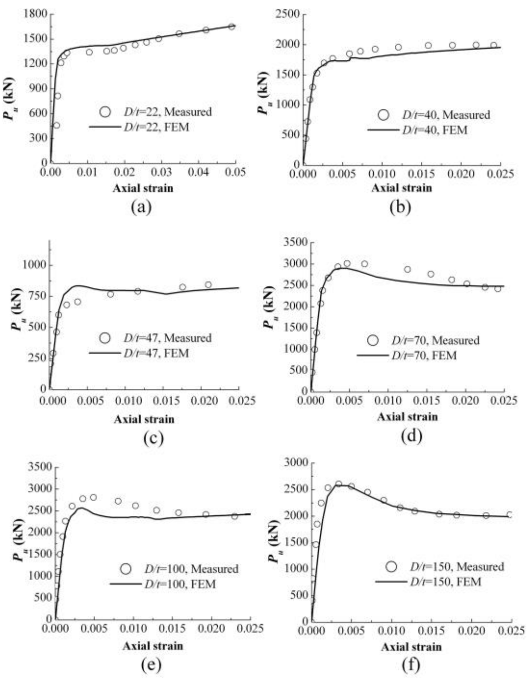

Figure 2: Comparison with test results: (a) *D/t*=22; (b) *D/t* =40; (c) *D/t* =47; (d) *D/t* =70; (e) *D/t* =100; and (f) *D/t* =150.

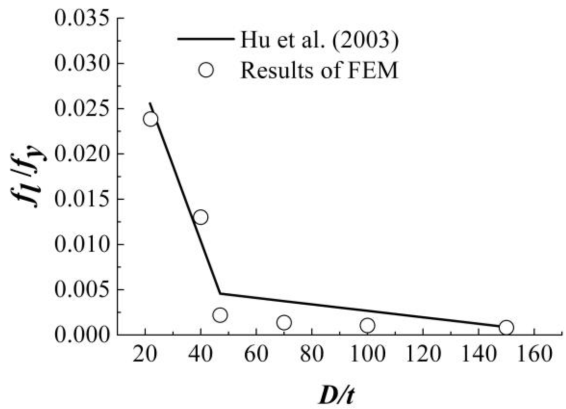

Figure 3: Comparison of confinement stress with results of Hu et al. (2003).

Figure 2 provides a comparison of the analytical and experimental axial loads as a function of axial strain. The analyses accurately predicted the measured results for all *D*/*t* ratios considered, where *D* is the diameter of the CFST, and *t* is the thickness of the steel tube. The maximum discrepancy between predicted and measured results was 8%.

Hu et al. (2003) proposed the equation to estimate the average confinement stress as a function of *D*/*t* ratio. In this research, the average confinement stresses were calculated from the analysis for models listed in Table 1 and compared with previous research results by Hu et al (2003) as shown in Fig. 3. Figure 3 shows the comparison of confinement stress predicted using the previously described modeling approach with GAP element and from the proposed equation of Hu et al. (2003) where f_l is the average confinement stress of CFST. The results demonstrate that the proposed modeling approach provides a reasonable confinement stresses.

Table 1: Test Specimens used to verify FE model for CFST under axial compression

Model	*D* (mm)	*t* (mm)	*D*/*t*	*L* (mm)	f_y (MPa)	f_c' (MPa)	Tested by
CU022	140	6.5	22	602	313	23.8	Schneider(1998)
CU040	200	5	40	840	265.8	27.15	Huang et al. (2002)
CU047	140	3	47	602	285	28.18	Schneider(1998)
CU070	280	4	70	840	272.6	31.2	Huang et al. (2002)
CU100	300	3	100	900	232	27.23	Schneider(1998)
CU150	300	2	150	840	341.7	27.2	Huang et al. (2002)

3.2. CFST under flexural, and general combined loading

The flexural behavior of CFT was verified herein. Three-point bending test results conducted by Thody (2006) were used to verify the finite element model for the CFT under flexural loading. The tests were simply supported components with a 5.49m span (*L*) and a single actuator located at mid-span to apply the cyclic lateral load. The steel tubes used for the test specimens were 508mm and 6.35mm in diameter and thickness, respectively. The measured compressive strength of the concrete, f_c', and yield stress of the steel tube, f_y, were 84.1MPa and 520.9MPa, respectively.

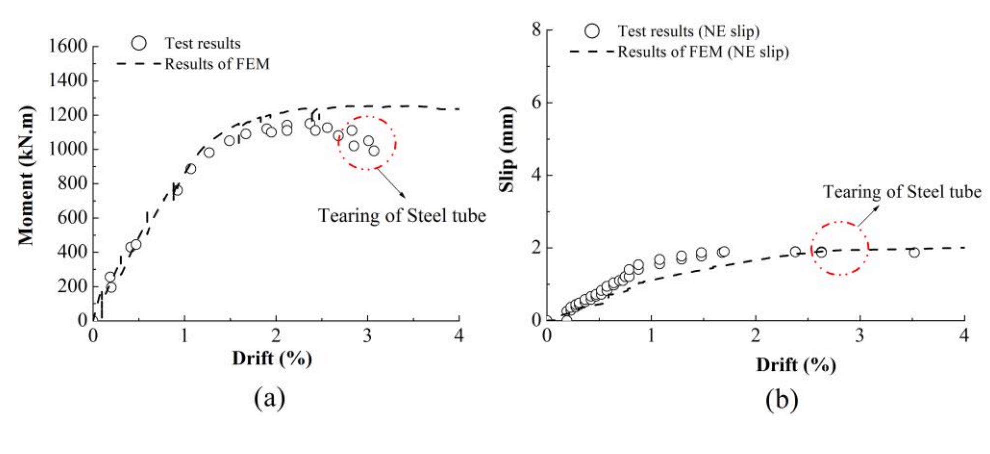

Figure 4. Comparison with test results (CFST under flexure, *D*/*t*=80): (a) Moment vs. Drift relationship; and (b) Slip vs. Drift relationship.

The simulated moment-drift and slip-drift relationships shown in Figs. 4(a) and (b) agree well with those from the test. On average, the analysis estimated a bending capacity approximately 6% smaller than that achieved in experiments. The computed maximum slip (slip was measured at the end of the CFST) was slightly larger than the experimentally measured slip.

The combined axial and bending test results of Marson and Bruneau (2004) were used to verify the finite element analysis models for CFT under general combined loading. Table 2 provides geometry and material properties for the four specimens simulated. The D/t ratio varied from 43.2 to 73.9 and axial load ratio ($P/P_{o,AISC}$) ranged from 0.13 to 0.32 where $P_{o,AISC}$ is the squash load calculated from AISC (2010).

Figure 5 compares the measured and simulated moment-drift relationship where the drift is defined as lateral displacement at the top of a specimen divided by the column length. The models provide good simulation of the measured stiffness, yield and maximum strengths. The average difference in the predicted and measured strengths was 7.3% and the FE proposed model was successfully verified.

Table 2: Specimen Properties and Predicted Results for CFT under Combined Loading.

Model	D (mm)	D/t	L/D	f_y (MPa)	f_c' (MPa)	$P/P_{o,AISC}$	$M_{u,Test}/M_{u,FEM}$
CFT34	323.9	43.2	6.8	415	40	0.32	1.07
CFT42	406.4	42.8	5.4	505	35	0.19	0.96
CFT51	323.9	58.9	6.8	405	35	0.33	1.15
CFT64	406.4	73.9	5.4	449	37	0.13	0.98

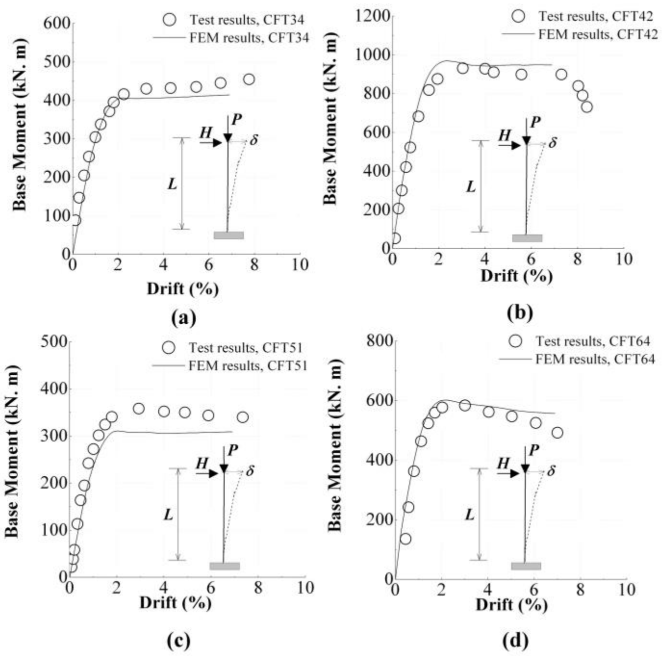

Figure 5. Verification of the FE model for CFT under combined loading:(a) CFT34; (b); CFT42; (C) CFT 51; and (d) CFT64 specimen.

4. CONCLUSIONS

This paper presents a nonlinear finite element analysis model for CFST under various loading. The proposed FE model provides good estimates of the observed global behavior such as moment-drift and moment-slip relationship. The proposed model employed unconfined concrete behavior, and the benefits of confinement were computed by the interface contact stress between the steel tube and concrete infill. This modeling produced a good representation of benefits of confinement and composite behavior of CFST, and successfully verified for various loading conditions.

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