NONLINEAR MODEL FOR CIRCULAR CONCRETE-FILLED STEEL TUBES UNDER MONOTONIC LOADING

Dionisios N. Serras
Ph.D. Student
School of Science and Technology, Hellenic Open University
Patras, GR-26335, Greece

Konstantinos A. Skalomenos
Specially Appointed Assistant Professor
Disaster Prevention Research Institute, Kyoto University
Gokasho, Uji, Kyoto, 611-0011, Japan

George D. Hatzigeorgiou
Associate Professor
School of Science and Technology, Hellenic Open University
Patras, GR-26335, Greece

Dimitri E. Beskos
Emeritus Professor
Institute of Structural Engineering
Department of Civil Engineering
University of Patras
Patras, GR-26500, Greece

Abstract: The response of circular concrete-filled steel tube (CFT) columns under monotonic loading is investigated in this study. Initially, accurate three-dimensional nonlinear finite element models of these columns are developed and validated by comparing their response results with those of experimental tests from the pertinent literature. Then, these models are used for an extensive parametric study that identifies the response to monotonic lateral loads of different circular CFT specimens with fairly broad values of diameter-to-thickness ratios (d/t), yield stress of steel tube (f_y), compressive strength of concrete core (f_c) for various axial load levels. Based on this response databank empirical expressions are developed aiming at estimating the force-displacement behavior of circular CFT columns under monotonic loading with simple yet reliable manner. The proposed empirical expressions are verified by comparing their results with those of experimental tests. It is found that the proposed expressions can describe with accuracy the force-displacement behavior and capacity of circular CFT columns under monotonic loading conditions.

Keywords: Inelastic behavior, monotonic loading, concrete-filled steel tubes, finite element method

1. INTRODUCTION

It is well-known that, combining the concrete and steel leads to efficient and cost-effective systems for resisting environmental loads. The behavior and strength of concrete-filled steel tubes (CFT columns) were examined firstly by Gardner and Jacobson [1] and Knowles and Park [2]. Then, numerous studies based on experimental and/or computational procedures have been conducted to examine the behavior and bearing capacity of CFT columns under pure axial loading and/or axial-lateral loads [3-8]. The review paper of Chacón [9] investigates the recent advances on the behavior of CFT columns for more details.

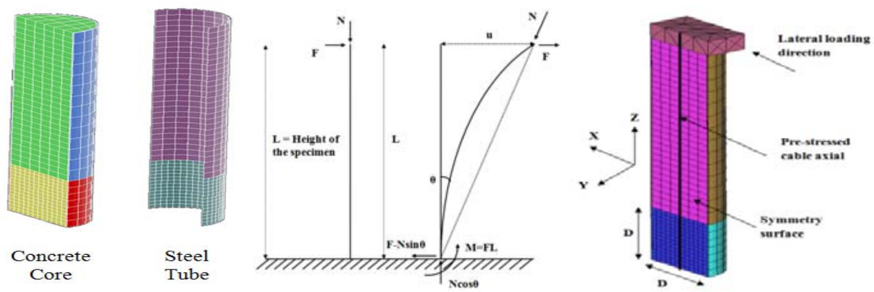
Recently, the authors Serras et al. [10] proposed a reliable computational approach where the behavior of circular concrete-filled steel tube columns is evaluated under lateral cyclic loading accurately using the finite element method (FEM). This approach enables one a further study which related with the seismic inelastic response of a composite frame consisting of steel beams and CFT columns.

The development of empirical expressions for the behavior of circular CFT columns under monotonic lateral loads, including or not axial loads, is considered one of the main objective of this study. Initially, circular CFT columns models are developed using ATENA program [11] and their analysis results are validated and compared with those of existing experimental tests form the pertinent literature. Then, extensive parametric analyses involve various numerical experiments under monotonic lateral loadings and include different geometrical characteristics, material properties and axial load levels ranging from 0% to 40% of the total axial load capacity. The produced response databank is used to determine the parameters of empirical expressions which describe the force-lateral displacement relation of circular concrete-filled steel tubes under monotonic lateral loads. The validity of this methodology is also established by comparing the proposed empirical equations with experimental results published in the pertinent literature.

2. FINITE ELEMENT MODELLING

In this section (3-D) three-dimensional non-linear finite element models are developed using the ATENA analysis program [11] to evaluate the actual behavior of circular CFT columns reliably. Because of the element type and mesh size are considered the most crucial parameters in order to determine the response of CFT columns within reasonable computational time, the concrete core and the steel tube are modeled by 20-node shell elements and 8-node solid elements, respectively. For a reliable simulation internal surface of steel tube and the external surface of concrete core come into contact, without to penetrate each other, contact pressure acts on these individual surfaces and friction stress occurs in the direction tangential to the contact surface. The concrete core exhibits a three-dimensional stress state due to combined axial-flexural loading as well as due to its confinement by the exterior steel tube.

Figure 1 shows a typical finite element discretization of concrete core and steel tube in the case of a circular CFT column where, due to symmetry, half of the total height of the test specimen and half of the member's section is examined and analyzed. The base of the developed finite element model is fixed and its top surface is free to deform, while the height of finite element models under consideration, L, is equal to 1.5 m. In this study, the steel tube modeling is based on the von-Mises plasticity theory and the hardening/softening plasticity model of Menétrey and Willam [12] is taken into account. The Poisson's ratio, v_s, and the elastic modulus E_s of steel are assumed to be 0.3 and 210 GPa, respectively, while the post-elastic (hardening) modulus ratio is assumed to be equal to 0.01. Additionally, the friction behavior is assumed to follow the Coulomb friction model with the friction coefficient between steel and concrete being equal to 0.47 [13] and it is maintained as long as the surfaces remain in contact and no tension strength exists between the two interfaces.



(a) (b)

Fig. 1 (a) Typical Finite Element Mesh (FEM) for circular concrete-filled steel tubular (CFT) columns and (b) Circular CFT column and finite element model structure.

3. VERIFICATION OF THE ANALYTICAL MODEL

The examined finite element models are verified via experimental results in Skalomenos et al. [8], Beheshti-Aval [14] and Inai et al. [15] pertaining to 3 specimens subjected to bending moment with or without axial force. Table 1 illustrates the basic data for these specimens, i.e., the steel tube external diameter *D*, the wall thickness *t* and the height (length) of specimen *L* in *mm*. Furthermore, the yield stress of steel tube, f_y, and the compressive strength of concrete, f_c, are expressed in *MPa*. As it can be seen from Fig 2, the developed finite element models can reliably simulate the monotonic behavior of CFT specimens providing in-detail information concerning their behavior and capacity.

Reference	Experiment ID	Dimensions				Material parameters		Axial load (KN) & Axial Load Ratio (N/N_{max})
		D (mm)	*t (mm)*	*L(mm)*	*D/t*	f_y *(MPa)*	f_c*(MPa)*	
Skalomenos et al. 2016	H-OC-2	150	6	1100	25	788	42.4	0.0/0.0
	H-25C-2	150	6	1100	25	788	82.3	831/0.25
Beheshti-Aval 2012	SI85-IV	100	2.20	300	45.455	384	20.9	130/0.46

Table 1 Geometry data and material parameters of test specimens.

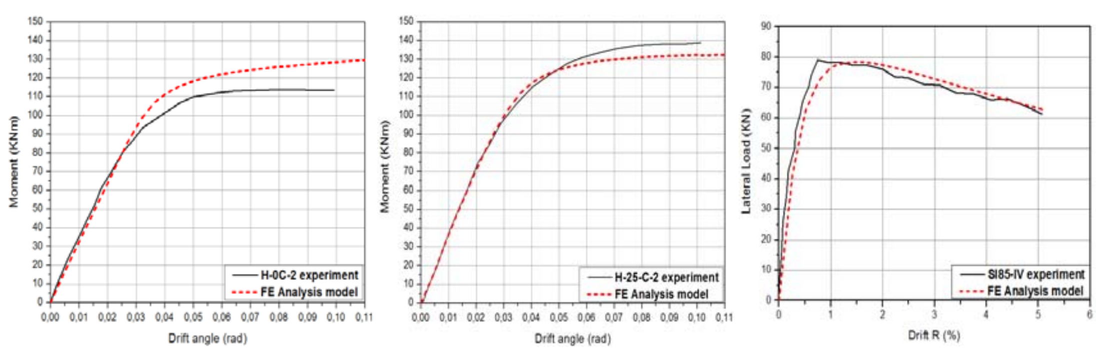


Fig. 2 Test specimens compared with finite element analysis using ATENA [14].

4. PARAMETRIC STUDY

Table 2 illustrates 2 circular CFT columns providing information for diameter-to-thickness ratios (*D/t*), yield stress of steel tube (f_y), compressive strength of concrete (f_c) under monotonic lateral load and constant axial force. The diameter, *D*, and the thickness, *t*, are expressed in *mm*, while the yield stress of steel tube (f_y) and the compressive strength of concrete core (f_c) in *MPa*. Additionally, the compressive strength of concrete is taken into account equal to 30 and 50 *MPa* and the yield stress of steel equal to 235, 275 and 460 *MPa*. It should be noted that, the finite element analysis of each specimen is carried out until the ratio of lateral displacement to the height of column (i.e., the interstorey drift ratio for building structures) becomes equal to 5.0%, which is the crucial value for collapse prevention, both for steel and concrete buildings according to FEMA-273 [16].

Specimen	Dimension			Material Properties	
S(D/t)-f_c-f_y	**D(mm)**	**t (mm)**	**D/t**	**f_y (MPa)**	**f_c (MPa)**
S59-30-235	355.6	6.00	59.267	235	30
S65-30-275	406.4	6.30	64.508	275	30
S43-50-460	610	14.20	42.958	460	50

Table 2 Geometry data and material parameters of specimens

The main objective in this study is the evaluation of the response of a circular CFT column under constant axial force and monotonic lateral loading conditions. This response can be simulated through the following empirical expression which describes the interrelation between the lateral force, *F*, and the lateral displacement, *u*, as

$$F(u) = \frac{M_{el}}{L}\left(a_1 u + a_2\sqrt{u} + a_3 u^2\right) \tag{1}$$

where, for a specific axial force, $F=F(u)$ is the lateral loading in *kN*, *u* the lateral top displacement of the column in *meters* and *L* the total height of the column, which is also expressed in *meters*. Furthermore, M_{el} is the "maximum elastic" bending moment, which has to do with the elastic section modulus of steel tube, W_s, yield stress of the steel tube, f_y, the elastic section modulus of concrete core, W_c, and compressive strength of concrete core, f_c, and is given by

$$M_{el} = aW_s f_y + bW_c f_c = a\left(\frac{\pi}{32}\frac{(D^4-(D-2t)^4)}{D}\right)f_y + b\left(\frac{\pi}{32}(D-2t)^3\right)f_c \tag{2}$$

where *a* and *b* are appropriate parameters taking here the values a=1.0 and b=0.6 considering the effective stiffness of the composite section [8,17]. Thus, Eq. (2) can be rewritten as,

$$M_{el} = \left(\frac{\pi}{32}\frac{(D^4-(D-2t)^4)}{D}\right)f_y + 0.6\left(\frac{\pi}{32}(D-2t)^3\right)f_c \tag{3}$$

Additionally, a_1, a_2 and a_3 in Eq. (1) are coefficients that have to do with the sectional dimensions, level of axial load and material parameters. Thus, taking into account the complete set of the examined finite element models and using their lateral load-lateral displacement response, the most appropriate coefficients are computed using a least-square approach, minimizing the error between the 'accurate' finite element models and analytical behavior from Eq.(1). The aforementioned coefficients can be expressed as

$$a_i = b_{i,1} + b_{i,2}\left(\frac{t}{D}\right) + b_{i,3}\left(\frac{f_c}{f_y}\right)^3 + b_{i,4}\left(\frac{N}{N_{max}}\right) + b_{i,5}\sqrt{\frac{N}{N_{max}}} \quad (4)$$

where the $b_{i,j}$ coefficients (i=1-3, j=1-5) are given in Table 3.

	j=1	j=2	j=3	j=4	j=5
i=1	-28.63	-741.15	-302.90	85.08	-86.59
i=2	11.87	209.49	42.66	-23.16	21.66
i=3	75.26	1271.77	400.86	-505.74	391.28

Table 3 $b_{i,j}$ coefficients of Eq. (4)

Figure 3 depicts the monotonic loading response for the examined circular CFT columns using the above proposed empirical relations (Eq. (1)) for the axial load capacity ratio N/N_{max} equal to 0.0, 0.20 and 0.40 where for comparison reasons, the results from finite element analysis are also provided.

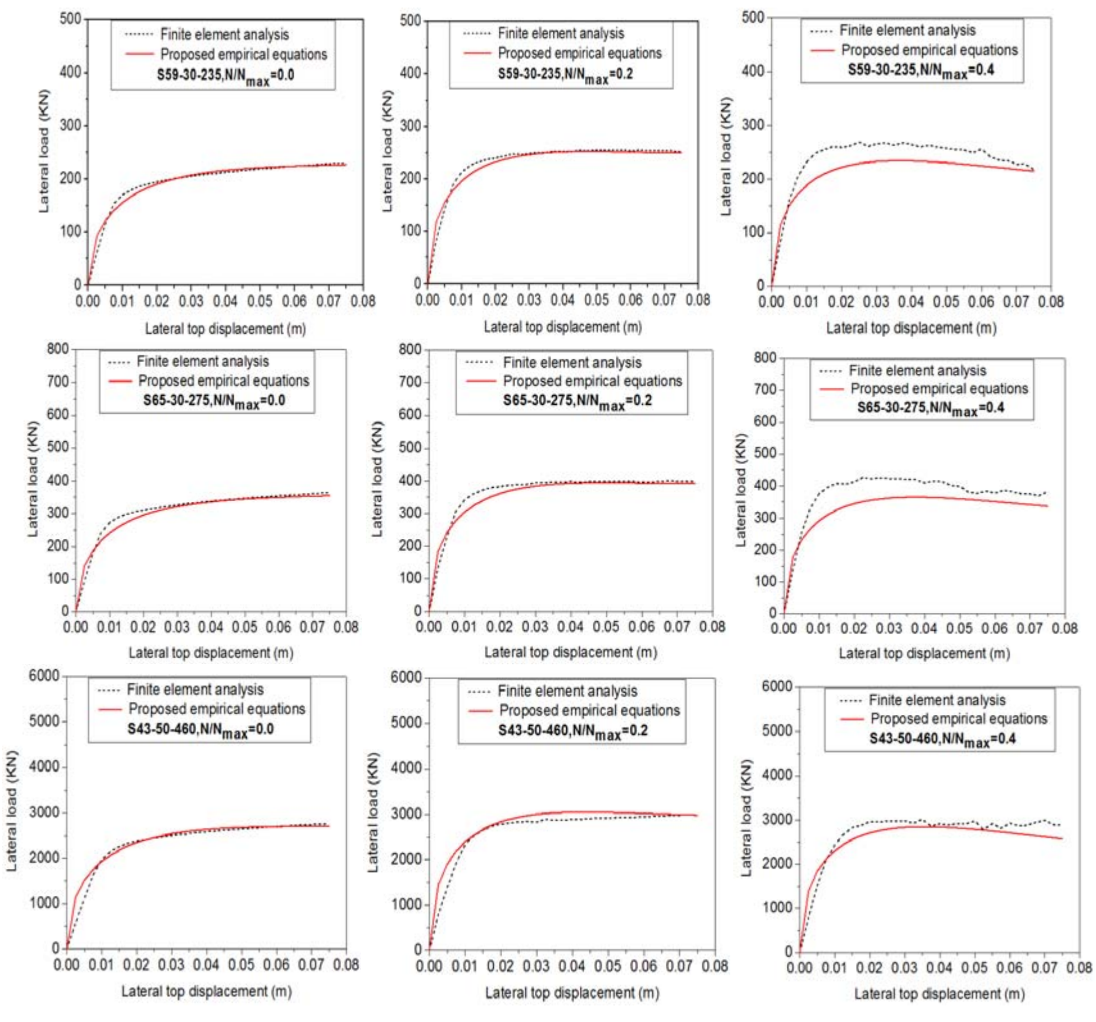


Fig. 3 Monotonic loading response of CFTs S59-30-235, S65-30-275 and S43-50-460 for various levels of axial force

Based on Fig 3, it is obvious that the proposed empirical expression (Eq. (1)) can successfully describe the monotonic lateral loading response of circular concrete-filled steel tubes under various levels of axial force, since it leads to similar results with those obtained by the more accurate finite element analysis using ATENA [11]. Examining the whole set of composite columns under consideration, the mean value for the ratio of lateral load between the proposed empirical relations and the finite element analysis, i.e., $mean[F(u)_{Eq.(1)}/F(u)_{FEA}]$, is equal to 1.001 (≅1.0), while the correlation coefficient between these different approaches is $R^2[_{Eq.(1)\sim FEA}]$=0.974=97.4%.

5. COMPARISON BETWEEN THE PROPOSED EMPIRICAL MODEL & EXPERIMENTAL TESTS

The accuracy of the proposed empirical expressions can be also confirmed by comparing this approach with experimental test results from the pertinent literature. The monotonic loading response by using the proposed method as well as by experimental procedures appears in Fig. 7. Based on the following Figure, it is evident that the proposed approach can accurately describe the lateral force-lateral displacement response of CFT columns under monotonic loading conditions.

Reference	**Experiment ID**	**Dimensions**				**Material parameters**		**Axial load (N) (KN) & axial load ratio (N/N_{max})**
		***D* (mm)**	***t* (mm)**	***L* (mm)**	***D/t***	**f_y (MPa)**	**f_c (MPa)**	
Han Lin-Hai et al. 2006	CB2-2	140	3.00	840	46.667	235	51.5	0.0/0.0
Inai et al. 2004	SC4-A-4-C	241	4.70	1446	51.276	338	40	1034/0.37
Skalomenos et al. 2016	C-25C-2	150	6	1100	25	387	79.0	559/0.25

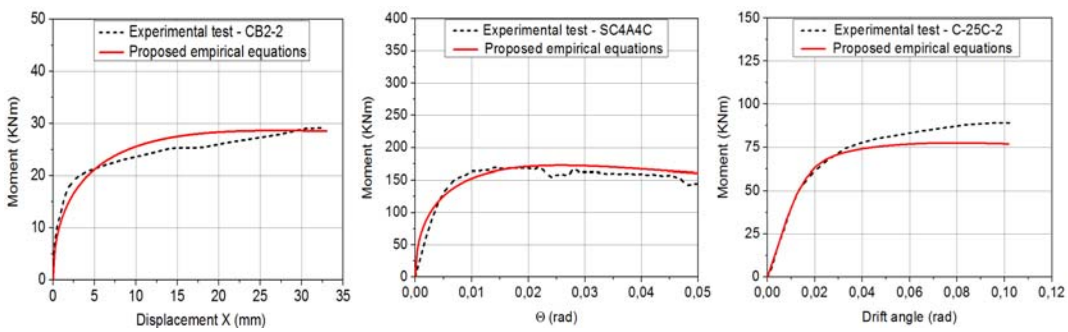


Fig. 7 Comparison between various experimental tests and proposed empirical equations

6. CONCLUSIONS

This study proposed a simple yet efficient method to simulate the inelastic behavior of circular concrete-filled steel tube columns under monotonic loading conditions. Thus, a parametric study was carried out, examining different circular concrete-filled steel tubes under constant axial load and monotonically varied lateral load. Furthermore, simple yet efficient empirical expressions were proposed to describe the behavior of composite members under monotonic loads. Comparing them with experimental results it was found that the finite element method is able to simulate the behavior of circular concrete-filled steel tube columns under monotonic loading conditions accurately for a fairly broad gamut of sectional dimensions, material parameters and levels of axial load.

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ΜΗ ΓΡΑΜΜΙΚΟ ΠΡΟΣΟΜΟΙΩΜΑ ΓΙΑ ΧΑΛΥΒΔΙΝΕΣ ΚΟΙΛΟΔΟΚΟΥΣ ΚΥΚΛΙΚΗΣ ΔΙΑΤΟΜΗΣ ΠΛΗΡΟΥΜΕΝΕΣ ΜΕ ΣΚΥΡΟΔΕΜΑ ΥΠΟ ΜΟΝΟΤΟΝΙΚΗ ΦΟΡΤΙΣΗ

Διονύσιος Ν. Σέρρας
Υποψήφιος Διδάκτορας
Σχολή Θετικών Επιστημών & Τεχνολογίας, Ελληνικό Ανοικτό Πανεπιστήμιο
Πάτρα, 26335, Ελλάδα

Κωνσταντίνος Α. Σκαλωμένος
Ειδικά Διορισμένος Επίκουρος Καθηγητής
Ινστιτούτο Έρευνας Πρόληψης Καταστροφών, Πανεπιστήμιο του Kyoto
Gokasho, Uji, Κιότο, 611-0011, Ιαπωνία

Γεώργιος Δ. Χατζηγεωργίου
Αναπληρωτής Καθηγητής
Σχολή Θετικών Επιστημών & Τεχνολογίας, Ελληνικό Ανοικτό Πανεπιστήμιο
Πάτρα, 26335, Ελλάδα

Δημήτριος Ε. Μπέσκος
Καθηγητής
Ινστιτούτο Αντισεισμικής Μηχανικής και Μείωση Καταστροφών, Τμήμα Πολιτικών Μηχανικών, Πανεπιστήμιο του Tongji
200092 Σανγκάη, Κίνα
&
Τμήμα Πολιτικών Μηχανικών
Πανεπιστήμιο Πατρών
Πάτρα, 26500, Ελλάδα

Περίληψη: Στην παρούσα εργασία αυτή γίνεται εκτεταμένη διερεύνηση της απόκρισης κυκλικών χαλύβδινων κοιλοδοκών πληρούμενων με σκυρόδεμα υπό μονοτονική φόρτωση. Αρχικά, αναπτύσσονται λεπτομερή τρισδιάστατα μη γραμμικά προσομοιώματα πεπερασμένων στοιχείων τέτοιων κυκλικών σύμμεικτων κοιλοδοκών, και τ΄ αποτελέσματα των αποκρίσεών τους συγκρίνονται με εκείνα των πειραματικών δοκιμών από τη σχετική βιβλιογραφία. Εν συνέχεια, αυτά τα προσομοιώματα χρησιμοποιούνται για μια εκτεταμένη παραμετρική διερεύνηση όπου προσδιορίζεται η απόκριση για μονοτονική πλευρική φόρτιση κυκλικών σύμμεικτων υποστυλωμάτων υιοθετώντας ένα ευρύ φάσμα τιμών του λόγου διαμέτρου προς πάχος της κοιλοδοκού, d/t, , του ορίου διαρροής του χάλυβα, f_y, και της θλιπτικής αντοχής του σκυροδέματος, f_c, για διάφορα επίπεδα του αξονικού επίβαλλόμενου φορτίου. Με βάση αυτή τη βάση δεδομένων απόκρισης, αναπτύσσονται εμπειρικές σχέσεις με στόχο την εκτίμηση της συμπεριφοράς δύναμης-μετατόπισης των κυκλικών σύμμεικτων κοιλοδοκών υπό μονοτονική φόρτωση με απλό και αξιόπιστο τρόπο. Οι προτεινόμενες εμπειρικές σχέσεις επαληθεύονται συγκρίνοντας τα αποτελέσματά τους με αυτά των πειραματικών δοκιμών. Διαπιστώνεται ότι οι προτεινόμενες σχέσεις μπορούν να περιγράψουν με ακρίβεια την συμπεριφορά δύναμης-μετατόπισης και την αντοχή των κυκλικών σύμμεικτων κοιλοδοκών υπό συνθήκες μονοτονικής φόρτισης.