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Nonlinear FEM analysis of inclined concrete-filled steel tube columns under vertical cyclic load

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Abstract. This article presents the nonlinear analysis of inclined Concrete-Filled Steel Tube columns (CFST) under vertical cyclic loading using the Finite Element Analysis. Fifteen analysis cases with three inclination angles were investigated. All the steel tube columns were 75x75 mm. square section with 500 mm. long. The thickness of the tube was varied as either 1.8 mm. or 3.0 mm. The infilled concrete was 23 MPa and 42 MPa. The internal contact surface between the infilled concrete and the steel tube was applied. The validation of the finite element model was made through comparison with the test results. From the analysis and the test results, the ultimate cyclic compressive strength decreases with the increase of the inclination angle. However, the decrease of the ultimate load with the inclination angle (from 0 to 9 degrees) is smaller with the presence of the infilled concrete. The buckle section is perpendicular to the inclined member axis.

1. Introduction

Concrete-filled Steel Tube Columns (CFST) has long been considered as a composite column which widely adopted in many high-rise building constructions. The main disadvantage of using the bare tube steel column of buckling is diminished by the restraining effect of the infilled concrete. Hence, the full ultimate capacity of the high strength steel can be utilized to resist the ultimate load. Furthermore, the buckling restraint also increases the deformation capacity and post-yield behavior of the column. The increase in fire resistance is also the merit of the presence of the infilled concrete, as indicated by many pieces of research, for example [1-2]. Likewise, the surrounding steel tube also increases the plain concrete performance. It not only increases the ultimate compressive capacity of the infilled concrete but also enhances the ductility significantly due to the lateral confining effect. Hence, the capacity and deformation performance of the composite CFST column is not just a straight-forward combination of individual strength superposition. Hence, there have been many research [3-7] emphasizing the investigation of the composite CFST column behaviors based on dependable variables eg. Cross-sectional dimension, Column Slenderness, Section-to-thickness D/t ratio, strength of the infilled concrete, Strength of the steel tube, Loading scheme etc.

The more complicated behavior can be seen when the CFST is subjected to combined axial and bending loading or when the loading is not aligned with the member axis. These situations can be easily found for an irregular structural arrangement in a building. Figure 1 shows a schematic view of the inclined CFST column application in buildings. Opened view, long span and unique style building can be achieved. However, only a few researches have discussed the loading capacity of the inclined CFST column. Therefore, this study aimed to investigate the behavior of the inclined CFST columns when subjected to cyclic loading. Fifteen CFST columns under vertical cyclic load until failure were simulated

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using the Finite Element Analysis. The applicability of the Finite Element Program used in this study was verified by comparing the analysis results with the experimental results performed by the authors in the previous works [8-9]. The effects of inclination angle, concrete compressive strength and the tube thickness on the loading capacity are discussed.

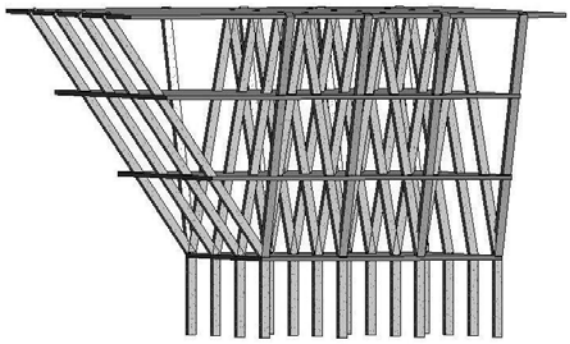

Figure 1. Example of application of the inclined column.

2. Finite element analysis

2.1. Analysis cases

Concrete compressive strength, tube thickness and inclination angle are the variable parameters in this study, as shown in Table1. The infilled concrete with the compressive strength of either 23 or 42 MPa was used, in addition to the no-fill concrete case. The tube thickness was 1.8 mm. or 3.0 mm. The inclination angle was 0, 4 or 9 degrees. With the variables, the total number of the analysis is 15 cases. For all the cases, the length of the column was 500 mm and the section was 75x75 mm. square. Yield strengths of the steel tubes were 264 MPa and 382 MPa for the 1.8 mm and 3.0 mm steel tube respectively. It is noted that the concrete compressive strength and the steel yield strength were from the test values.

Table 1. Analysis cases

Compressive strength, $f_c^{'}$ (MPa)	Thickness, t (mm)	Inclination angle (θ^o)	Case numbers
0	1.8	0, 4, 9	3
	3	0, 4, 9	3
23	1.8	0, 4, 9	3
	3	0, 4, 9	3
42	1.8	0, 4, 9	3
	Total analysis case		15

2.2. Finite element modelling

The finite element models were made resemble the tested columns in the laboratory [8,9], as shown in Figure 2. In the test, stiffener plates were added to the column ends to prevent the premature welding failure under the cyclic tensile load. The stiffeners were attached to two column faces at the center of the column width, in which the increase in bending resistance is minimized. LS-DYNA software package [10] was employed throughout the finite element (FE) analysis in the study. The steel tube, stiffeners, and bearing plates were modelled by 4-node (Belytschko-Tsay [11]) shell elements with 6 degree-of-freedom per node (3 translation and 3 rotation degree-of-freedom). The concrete core was modelled using three-dimensional 8-node brick elements with three translation degree of freedom at each node. The size of the shell element and the brick elements were approximately 10x10 mm. To

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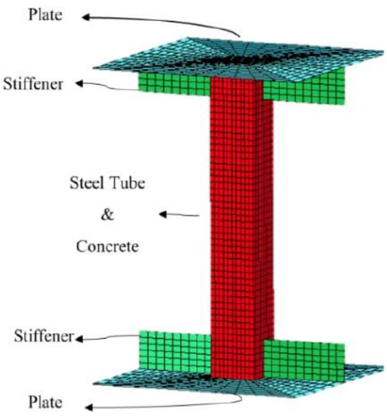
account for the friction between the concrete surface and the steel tube, as the specimens are stocky, the surface-based interaction with a friction coefficient of 0.40 was used. The coefficient between 0.1-0.5 was recommended by Lam et. al. [12].

Loading was applied in a displacement control mode at the top of a CFST column to simulate the vertical cyclic loading condition. The CFST column base was fixed against all degree of freedom. For the top end, the vertical displacement was allowed to induce vertical movement. The arranged loading and boundary configurations induce vertical load, horizontal shear and bending moment at the ends of the inclined column, as shown in Figure 3. This loading configuration is similar to an inclined column in a frame building. Figure 4 shows the applied cyclic vertical displacement at the top end. At the early loading, the expected elongation is less than the yielding point. The applied vertical displacement was cyclically applied with the increment of one-fourth of the yielding elongation (e_y). After that, the applied cyclic vertical displacement was increased incrementally to 2, 4, 6, 8 times the e_y (or until failure). The applied cyclic vertical displacement at this loading stage was repeated three times. To describe the stress-strain behavior of the steel tube, the piece-wise linear plasticity material was used. The Winfrith concrete model [13] providing plastic behavior including triaxial compression-tension and strain softening in tension was used to represent the confined concrete behavior.



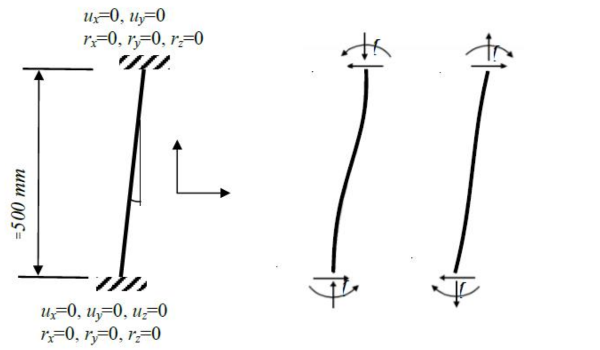


Figure 2. Finite element model. **Figure 3.** Boundary conditions and induced column forces.

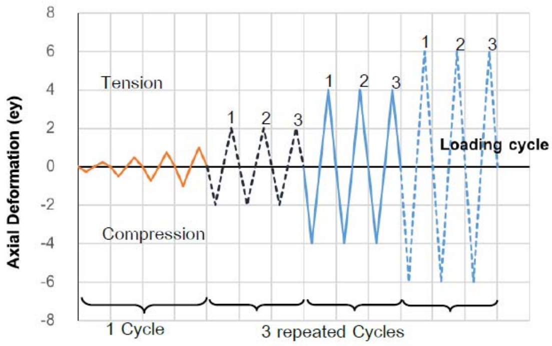
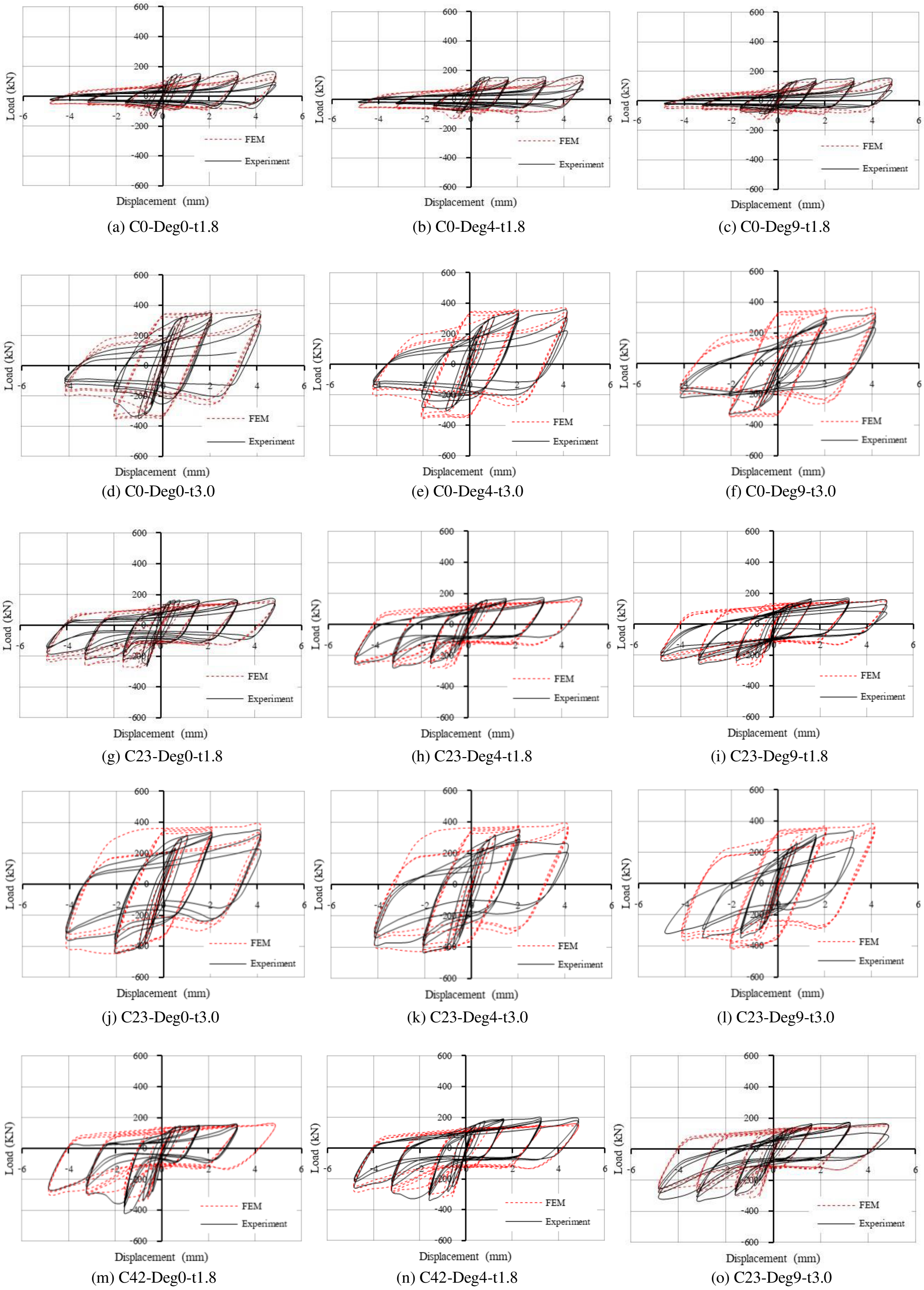


Figure 4. Cyclic Loading Scheme.



(a) C0-Deg0-t1.8 (b) C0-Deg4-t1.8 (c) C0-Deg9-t1.8

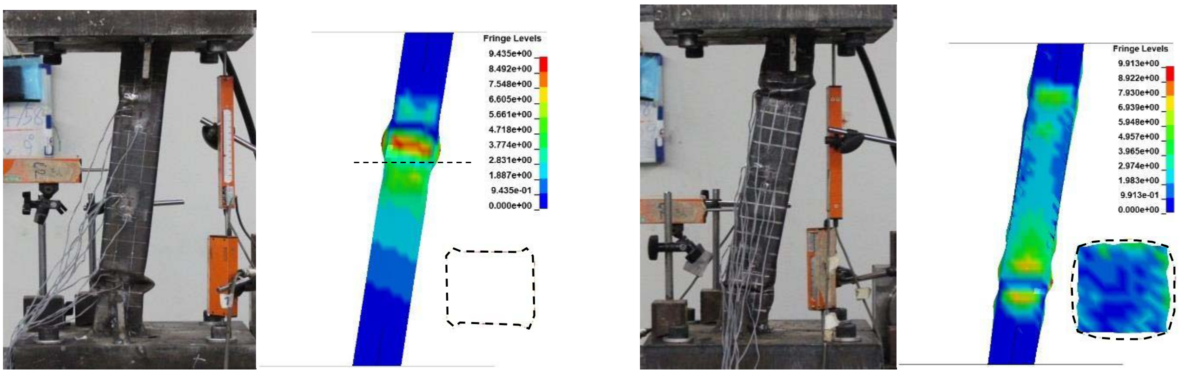
(d) C0-Deg0-t3.0 (e) C0-Deg4-t3.0 (f) C0-Deg9-t3.0

(g) C23-Deg0-t1.8 (h) C23-Deg4-t1.8 (i) C23-Deg9-t1.8

(j) C23-Deg0-t3.0 (k) C23-Deg4-t3.0 (l) C23-Deg9-t3.0

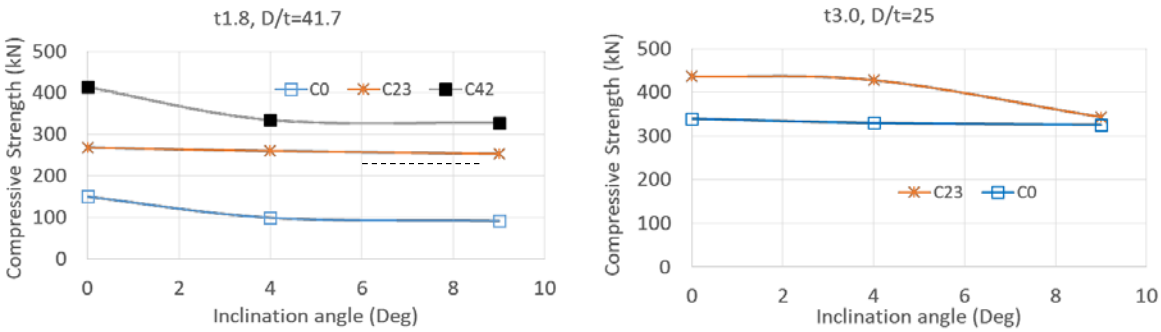
(m) C42-Deg0-t1.8 (n) C42-Deg4-t1.8 (o) C23-Deg9-t3.0

Figure 5. Hysteresis behaviour**.**



(a) C0-Deg.9-t1.8 (b) C23-Deg9-t1.8

Figure 6. Local Buckling of specimens C0-Deg.9-t1.8 and C23-Deg.9-t1.8.



(a) Thickness t= 1.8 mm. (D/t = 41.7) (b) Thickness t= 3.0 mm. (D/t = 25)

Figure 7. Effect of inclination angle on the compressive strength.

3. Results and discussion

The finite element analysis results are compared with the tested column results [8, 9]. Failure mode, Hysteresis behavior and the cyclic ultimate load are discussed as follow.

3.1. Hysteresis behavior

The Load-deformation relationships of the fifteen columns obtained from the analysis and test are shown in Figures5(a)-(o). The analysis and the test results agree quite well. At the early loading, the applied cyclic vertical displacement is lower than the yielding elongation, the relationships are linear. The hysteresis loops are narrow indicating no damage and no dissipated energy. However, with the increase of the applied vertical displacement, the local buckling of the steel column was observed and the stiffness was reduced. After the local bucking, the bare steel tube columns suddenly lost the capacity. However, the steel tube columns with the infilled concrete continued to carry more load. The failure of the infilled columns was first induced by yielding under tension and followed by the compressive steel buckling. The complete loss of the carrying capacity was after the beginning of the steel tube tearing. The buckling of the bare steel tubes was inward-outward mode. However, for the CFST columns, the buckling was outward-outward mode. The buckling plane inclined perpendicular to the member axis, as seen in Figure 6.

3.2. Cyclic ultimate load

The ultimate compression and tension loads obtained from the analysis and the test [8, 9] are shown in Table 2. The ratios of the two results are 1.05 and 0.95 respectively for the compression and tension. The infilled concrete substantially increases the compressive ultimate load but the enhancement is ignorable for the tensile strength. The effect of the inclination angle on the compressive load capacity for different thickness is presented in Figure 7. The inclination angle reduces the compressive strength especially for the thinner specimens without the infilled concrete (C0-t1.8). As seen in Table 2, the compressive strength of specimens C0-Deg4-t1.8 and C0-Deg9-t1.8 respectively were dropped by 34% and 39% compared with the specimen without inclination C0-Deg0-t1.8.

4. Conclusions

This paper presents the nonlinear finite element analysis of inclined Concrete-Filled Steel Tube columns (CFST) under vertical cyclic loading. The study parameters are the inclination angles, the thickness of the tube and the infilled concrete. To validate the finite element model, the analysis results are compared with the tested performed by the authors in the previous work [8,9]. The comparison of the two results in terms of the hysteresis curve of load-displacement relationships, failure mode, and ultimate capacity confirmed the accuracy of the model. From the study, the inclination angle significantly reduces the compressive loading capacity especially for the thinner tube (D/t = 41.7) and without the infilled concrete columns. The infilled concrete also significantly improves the compressive capacity and ductility. This is due to the buckle restraining of the infilled concrete and confinement of the steel tube. However, the compressive capacity of the inclined CFST columns infilled with higher strength concrete is highly affected by the inclination.

Table 2. Ultimate loads.

No	Specimen	t (mm)	D/t	f_c' (MPa)	Inclination angle (Deg)	Compression			Tension			Comparison	
						Experiment		FEM	Experiment		FEM	Comp.	Tension
						*P*Exp(kN)	Po/Pinc*	*PFEM*(kN)	*P*Exp (kN)	Po/Pinc*	*PFEM*(kN)	*PFEM/ PExp*	*PFEM/ PExp*
1	C0-Deg.0-t1.8	1.8	41.7	0	0	150.0	1.00	127.2	150.7	1.00	132.2	0.85	0.88
2	C0-Deg.4-t1.8	1.8	41.7	0	4	99.0	0.66	126.6	150.6	1.00	131.8	1.28	0.88
3	C0-Deg.9-t1.8	1.8	41.7	0	9	91.1	0.61	125.2	150.5	1.00	130.6	1.37	0.87
4	C23-Deg.0-t1.8	1.8	41.7	23	0	268.2	1.00	277.8	162.4	1.00	145.5	1.04	0.90
5	C23-Deg.4-t1.8	1.8	41.7	23	4	260.0	0.97	277.3	163.4	1.01	146.6	1.07	0.90
6	C23-Deg.9-t1.8	1.8	41.7	23	9	253.3	0.94	271.5	162.2	1.00	144.8	1.07	0.89
7	C42-Deg.0-t1.8	1.8	41.7	42	0	413.8	1.00	337.6	152.8	1.00	149.0	0.82	0.98
8	C42-Deg.4-t1.8	1.8	41.7	42	4	334.5	0.81	314.8	192.5	1.26	148.2	0.94	0.77
9	C42-Deg.9-t1.8	1.8	41.7	42	9	327.9	0.79	308.7	164.5	1.08	146.8	0.94	0.89
10	C0-Deg.0-t3.0	3.0	25.0	0	0	340.0	1.00	346.3	345.0	1.00	352.3	1.02	1.02
11	C0-Deg.4-t3.0	3.0	25.0	0	4	330.0	0.97	349.5	342.4	0.99	352.2	1.06	1.03
12	C0-Deg.9-t3.0	3.0	25.0	0	9	325.9	0.96	341.3	342.4	0.99	348.1	1.05	1.02
13	C23-Deg.0-t3.0	3.0	25.0	23	0	436.5	1.00	448.9	342.4	1.00	372.8	1.03	1.09
14	C23-Deg.4-t3.0	3.0	25.0	23	4	427.9	0.98	427.0	342.4	1.00	369.5	1.00	1.08
15	C23-Deg.9-t3.0	3.0	25.0	23	9	343.7	0.79	421.6	326.0	0.95	365.9	1.23	1.12
									Average			1.05	0.95
									Standard deviation			0.15	0.10

* P_o/P_{inc} is the ratio between the ultimate loads of the vertical column (P_o) and the inclined column (P_{inc}) for each group of the infilled concrete and the steel tube thickness.

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