Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (39) No. (2) April, 2017

Behaviour Of Concrete Filled Steel Tube Columns With Internal Steel Stiffeners Under Axial Load

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ملخص البحث

تستعرض الرسالة الاعمدة الحديدية ذات القطاع المفرغ المملوءة بالخرسانة باستخدام اعصاب تقوية تحت تاثير القوى المحورية وذلك باستخدام العناصر المحددة ببرنامج (ANSYS) ولتحديد دقة النموذج باستخدام العناصر المحددة يتم عمل مقارنة بين النتائج النظرية التى تم التوصل اليها مع مثيلتها من التجارب المعملية السابق تنفيذها بواسطة الاخرين. المتغيرات المختلفة التى تؤخذ فى الاعتبار تشمل ترتيب اعصاب التقوية وعددها, ومدى التباعد بينهم وعرضها وسمك قطاع الاعمدة الحديدية وكذلك مقاومة الخرسانة للضغط حيث يتم تقييم تاثير كل هذه المتغيرات على سلوك الاعمدة مع دراسة اشكال الانهيار للاعمدة. وبعد ذلك يتم عمل مقارنة بين القيمة القصوى للحمل المحورى للاعمدة التى تم التوصل اليها مع مثيلتها من الاكواد العالمية مثل الكود الاوربى (٢٠٠٤).

ABSTRACT

The behavior of concrete filled steel tube (CFST) columns with internal steel stiffeners under axial load is presented in this paper. The behavior of the columns is examined by the use of finite element software ANSYS. Results from nonlinear finite element analyses are compared with experimental tests carried out by other researchers which reveal the reasonable accuracy of the modeling. The columns are extensively developed considering three different special arrangements of the internal steel stiffeners with various number, spacing, and widths. Effects of the variables on the behavior of the columns are assessed. Failure modes of the columns are also illustrated. It is concluded that the variables have considerable effects on the behavior of the columns. Moreover, ultimate load capacities of the columns are predicted by the Egyptian code (ECP 2007), the American code (AISC 2005), and the Euro code (EC4 2004) .The obtained ultimate load capacities from the finite element analyses are compared with the predicted code values. It can be concluded that (ANSI/AISC 2005) approaches are conservative to estimate the ultimate capacities of the columns, (EC4 2004) approach overestimates the ultimate capacities of CFST columns for some models and are conservative for other models, and (ECP 2007) approach is conservative with respect to the ultimate capacities of the CFST columns.

KEYWORDS

Composite Column, Internal Stiffeners, Nonlinear Finite Element Analysis, Ultimate Load Capacity, Ductility.

1. Introduction

The Concrete Filled Steel tube structural system is a system based on filling steel tubes with high-strength concrete. CFST structures, a type of the composite steel-concrete structures consist of steel tube and concrete core inside it. Combining the advantages of both hollow steel and concrete filled steel tubes, such as high strength, high ductility and large energy absorption capacity.To date, several studies have been carried out on the CFST columns. The strength of concrete filled steel tubular columns (CFT) axially loaded in compression studied by Baig, M.N.,Jiansheng, F. and Jianguo,N. [2006]. An experimental behavior of concrete filled steel tubular columns is done by J. Zeghiche and K. Chaoui [2005]. Nonlinear analysis with and without stiffeners of hollow and concrete filled steel tube column was studied by Athiq Ulla Khanr, N.S.Kumar [2015]. However, no research works are available in the literature on the behaviour of the CFST columns with internal steel stiffeners adopted in this study. The current study investigates the behavior of concrete-filled steel tube (CFST) columns with internal steel stiffeners. The accuracy of the modeling is demonstrated by comparing the results of the experimental tests presented by other with those obtained from the proposed finite element modeling. Internal steel stiffeners are utilised in the columns of this study. The columns are numerously developed using three different arrangements of steel stiffeners with various numbers, spacings, widths of the stiffeners, and steel tube thicknesses. Different variables are considered including arrangement of the steel stiffeners (Cl, C2, and C3), number of the steel stiffeners (2 and 3), spacing of the steel stiffeners (50 mm and 100 mm), width of the steel stiffeners (50 mm, 75 mm, and 100 mm), steel thickness (2 mm, 2.5 mm, and 3 mm), and steel yield stress (240 MPa, 280 MPa and 345 MPa).Effects of these variables on the ultimate load capacity and ductility of the columns are assessed.Failure modes of the columns are evaluated. The obtained ultimate load capacities of the columns are thereafter compared with the predicted values by the the Egyptian code (ECP 2001), the American code (AISC 2005), and the euro code (EC4 2004).

1. Finite element modeling

Concrete-filled steel tube (CFST) columns which were experimentally tested by others were considered in this paper for the verification of the finite element modelling using the finite element software ANSYS. The cross sections of the columns with length (L) of 500 mm and steel tube thickness 2 mm are (80*80mm), (100*100mm), (120*120mm), (140*140mm), (160*160mm) and (200*200).

2.1 Material properties and constitutive models

Steel and concrete are the two main materials used in the numerical analysis of the columns in which their properties and constitutive models are presented below:

2.1.1 Steel

In the present research, modeling of steel was performed as an elastic-perfectly plastic material in both tension and compression. The material behavior provided by *ANSYS using* plastic option allows non- linear stress-strain curve to be defined. Strain-hardening stress-strain curve is used to describe the behavior of the steel for modeling the steel tube and the end plate as shown in figure (1). The main parameters for the curve are steel yield strength, F_y, steel ultimate strength, F_u, modulus of elasticity of steel, E_s, which is taken equal to 210000 MPa, and Poisson's ratio, γ_s, which is taken equal to 0.3.

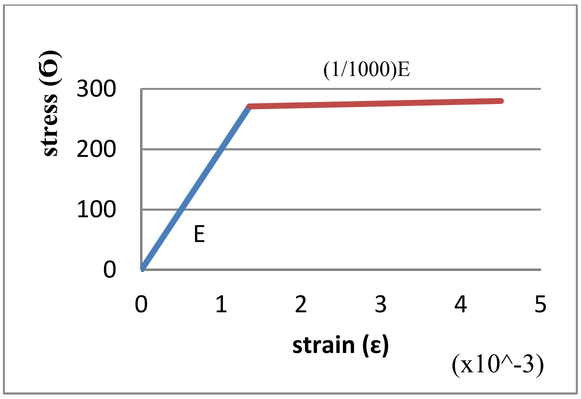


Figure (1): Stress-strain curve of steel used in the present research

2.1.2 Concrete

The concrete material model is developed to simulate conditions with uniaxial strain. The equivalent uniaxial stress-strain curves for concrete used in FEM in this study to model concrete, is illustrated in figure (2). The main parameters for the curve are the concrete compressive strength, f_c\`, and the modulus of elasticity of concrete, E_c. For undetermined data, the initial modulus of elasticity of concrete can be taken as $4400 f_{cu}^{0.5}$ or $4900 f_c'^{0.5}$ (Mpa). Concrete poison's ratio, υ_c, in the elastic part is taken equal to 0.2. The unconfined concrete cylinder compressive strength fc is equal to $0.8 f_{cu}$ in which f_{cu} is the unconfined concrete cube compressive strength. According to Hu et al. (2005), the corresponding unconfined strain ε_c is usually around the range of 0.002-0.003. They took ε_c as 0.002. When concrete is under laterally confining pressure, the confined compressive strength f_{cc} and the corresponding confined strain ε_{cc} are much larger than those of unconfined concrete f_{cc} and ε_{cc} can be respectively obtained by the use of equations (1) and (2), as recommended by Mander et al.(1988):

$$f_{cc} = f_c + k_1 f_l \qquad (1)$$

$$\varepsilon_{\alpha} = \varepsilon_c\,(1+k_2\, f_l/) \qquad (2)$$

Where f_l is the lateral confining pressure of steel on the concrete core. The approximate values reported by Hu et al. (1928) since f_l, k_1 and k_2 has been respectively taken as 4.1 and 20.5 according to richart et al. (1928). Since f_l, k_1 and k_2 are known, f_{cc} and ε_{cc} can be obtained using equations (1), (2).

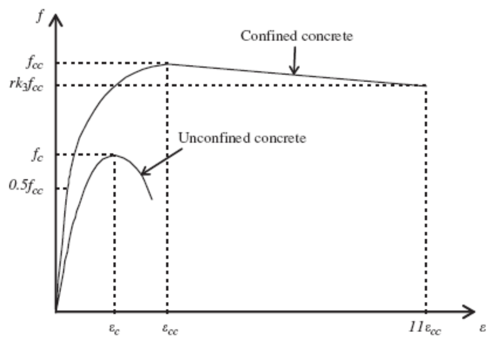


Figure (2): Equivalent uniaxial stress-strain curves for concrete

2.2 Finite element type, concrete-steel interface, boundary conditions, and load applications

The shell 181 was used for modeling of steel and end plates. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. Solid 65 is used to model the concrete in ANSYS. The solid element has eight nodes with three transitional degrees of freedom at each node and isotropic material properties.

To simulate the boundary conditions, the bottom surface of CFST column is restrained against translations degrees of freedom; Ux, Uy, Uz and the top surface of CFST column is restrained against translations degrees of freedom; Ux, Uz except for the displacement in the direction of the applied load, Uy.The compressive load is applied to the top surface in the Y direction through a rigid steel cap to distribute the load uniformly over the cross section. The load is applied in increments using the modified RIKS method with arc-length control available in ANSYS. Other nodes are free to displace or rotate in any direction.

2.3 Modelling accuracy and verification

In order to reveal the accuracy of the finite element modeling, the modeling results were compared and verified with the experimental test results presented by Matloub (2009). Table 1 shows a comparison between P_u and P_{FEM}. The good agreement achieved between both results for most specimens can be seen. As expected, the FEM shows results larger than experimental results for most specimens, as a result of no complete perfect conditions for the experiments.

Table (1) Comparison between test and FEM results (present research)

Column label	P_U EXP. (2009) (kN)	P_{FEM} Authors (2017) (kN)	P_{FEM}/P_U
SC80	294	302	1.03
SC100	384	390	1.02
SC120	490	498	1.02
SC140	589	620	1.05
SC160	723	770	1.07
SC200	1032	1100	1.07

- Table (1) show good agreement between the FEM results and the experimental work by others.

3. Numerical analysis

Because the proposed finite element modeling of this study was uncovered to be sufficiently accurate, the method was utilized for the nonlinear analysis of CFST columns of square cross sections (80x80x2mm) and (250x250x6mm) with length (L=500mm) with steel stiffeners. New steel stiffeners were utilized in the current study. Arrangements of the steel stiffeners in the CFST columns are shown in figure (3) which was analyzed by the use of nonlinear finite element method. According to the figure, three various special arrangements of the steel stiffeners namely C1, C2, and C3 were considered in this study. Also, different numbers (2 and 3), spacings (50mm and 100mm), and widths of the steel stiffeners (50mm, 75mm, and 100mm) were adopted in the analysis in which 4 typical elevations are illustrated in Figure 4 (a,b,c, and d).

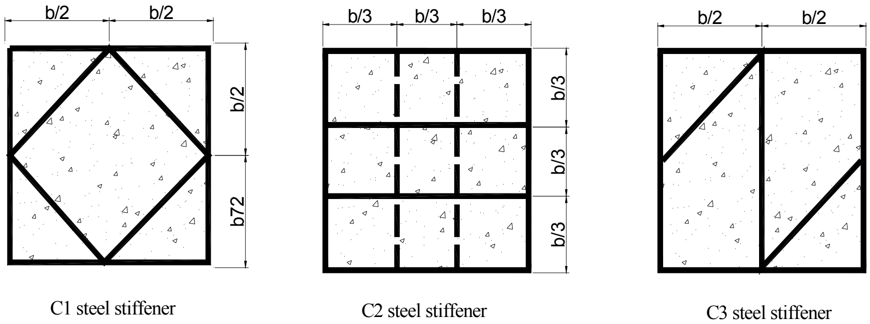


Figure (3): Arrangements of steel stiffeners in CFST columns

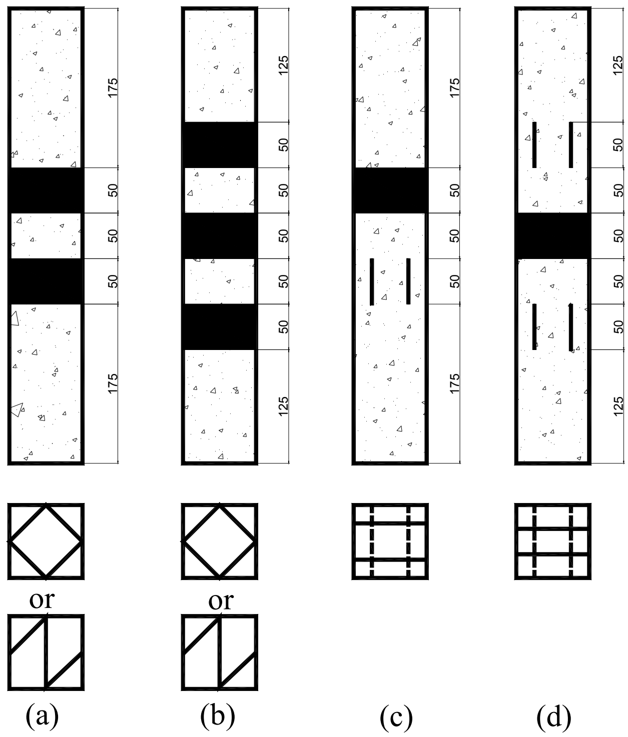


Figure (4): Typical elevations of stiffened CFST columns

4. Results and discussions

Tables (2) and (3) summarize the features and the obtained ultimate load capacities of the analyzed CFST columns. Different special arrangements of the steel stiffeners in the columns are represented by C1, C2 and C3 in the columns labels. The first fifth numbers following C1, C2, and C3 designate column width b (mm), the steel thickness t (mm), width of the steel stiffeners w (mm), steel yield stress F_y (MPa), and concrete cubic compressive strength F_{cu} (MPa) respectively . Also, the number before the parentheses in the columns labels is the number of steel stiffeners and the number in the parentheses represents the spacing S (mm) between the steel stiffeners, which can be presented as C1-b-t-w-F_y-F_{cu}-n(S). It needs to be noted that since the unstiffened CFST column does not have any kinds of the steel stiffeners, the number in the label corresponding to the steel stiffeners is zero. This point can be seen in the label of the unstiffened CFST column as C0-2-0-280-25-0. Effects of various parameters on the behavior of the columns are also presented in the following sub sections.

Table (2): Features and ultimate load capacities of the columns with square cross section 80x80 mm

Shape	No	Column label C-80-t-w-F_y-f_{cu}-n(S)	t (mm)	w (mm)	n	S	N_u (kN)
C1	1	C0-80-6-0-280-25-0	2	-	-	-	302
	2	C1-80-2-50-280-25-2(50)	2	50	2	50	330
	3	C1-80-2-50-280-25-3(50)	2	50	3	50	352
	4	C1-80-2-50-280-25-2(100)	2	50	2	100	315
	5	C1-80-2-75-280-25-2(50)	2	75	2	50	348
	6	C1-80-2-100-280-25-2(50)	2	100	2	50	382
	7	C1-80-2.5-50-280-25-2(50)	2.5	50	2	50	352
	8	C1-80-3-50-280-25-2(50)	3	50	2	50	397
C2	1	C0-80-6-0-280-25-0	2	-	-	-	302
	2	C2-80-2-50-280-25-2(50)	2	50	2	50	320
	3	C2-80-2-50-280-25-3(50)	2	50	3	50	335
	4	C2-80-2-50-280-25-2(100)	2	50	2	100	307
	5	C2-80-2-75-280-25-2(50)	2	75	2	50	333
	6	C2-80-2-100-280-25-2(50)	2	100	2	50	359
	7	C2-80-2.5-50-280-25-2(50)	2.5	50	2	50	340
	8	C2-80-3-50-280-25-2(50)	3	50	2	50	362
C3	1	C0-80-6-0-280-25-0	2	-	-	-	302
	2	C3-80-2-50-280-23-2(50)	2	50	2	50	326
	3	C3-80-2-50-280-23-3(50)	2	50	3	50	344
	4	C3-80-2-50-280-23-2(100)	2	50	2	100	312
	5	C3-80-2-75-280-23-2(50)	2	75	2	50	340
	6	C3-80-2-100-280-23-2(50)	2	100	2	50	365
	7	C3-80-2.5-50-280-23-2(50)	2.5	50	2	50	345
	8	C3-80-3-50-280-23-2(50)	3	50	2	50	370

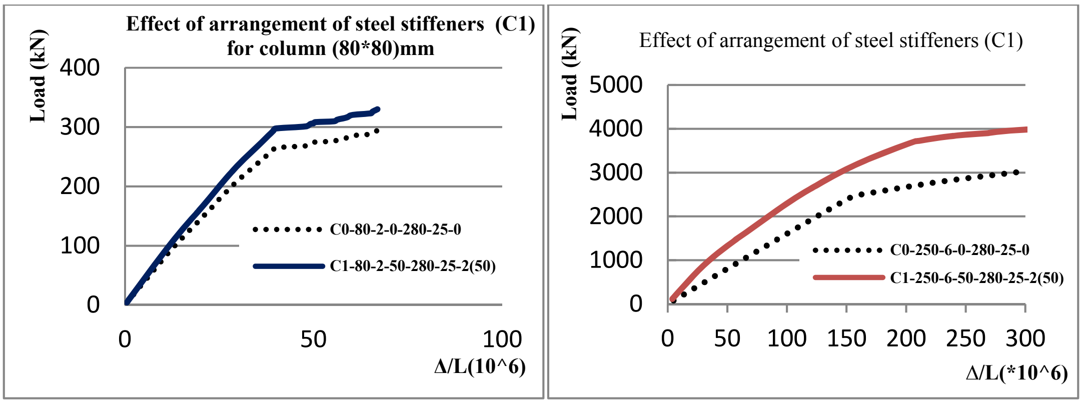
Table (3): Features and ultimate load capacities of the columns with cross section 250x250

Shape	No	Column label C-250-t-w-F_y-f_{cu}-n(S)	t (mm)	w (mm)	n	S	N_u (kN)
C1	1	C0-250-6-0-280-25-0	6	-	-	-	3000
	2	C1-250-6-50-280-25-2(50)	6	50	2	50	4000
	3	C1-250-6-50-280-25-3(50)	6	50	3	50	4320
	4	C1-250-6-50-280-25-2(100)	6	50	2	100	3500
	6	C1-250-6-75-280-25-2(50)	6	75	2	50	4300
	7	C1-250-6-100-280-25-2(50)	6	100	2	50	4400
	8	C1-250-8-50-280-25-2(50)	8	50	2	50	5440
	9	C1-250-9.5-50-280-25-2(50)	9.5	50	2	50	6320
C2	1	C0-250-6-0-280-25-0	6	-	-	-	3000
	2	C2-250-6-50-280-25-2(50)	6	50	2	50	3240
	3	C2-250-6-50-280-25-3(50)	6	50	3	50	3292
	4	C2-250-6-50-280-25-2(100)	6	50	2	100	3045
	6	C2-250-6-75-280-25-2(50)	6	75	2	50	3310
	7	C2-250-6-100-280-25-2(50)	6	100	2	50	3485
	8	C2-250-8-50-280-25-2(50)	8	50	2	50	4440
	9	C2-250-9.5-50-280-25-2(50)	9.5	50	2	50	4860
C3	1	C0-250-6-0-280-25-0	6	-	-	-	3000
	2	C3-250-6-50-280-23-2(50)	6	50	2	50	3780
	3	C3-250-6-50-280-23-3(50)	6	50	3	50	4200
	4	C3-250-6-50-280-23-2(100)	6	50	2	100	3086
	6	C3-250-6-75-280-23-2(50)	6	75	2	50	4150
	7	C3-250-6-100-280-23-2(50)	6	100	2	50	4300
	8	C3-250-8-50-280-23-2(50)	8	50	2	50	5280
	9	C3-250-9.5-50-280-23-2(50)	9.5	50	2	50	6020

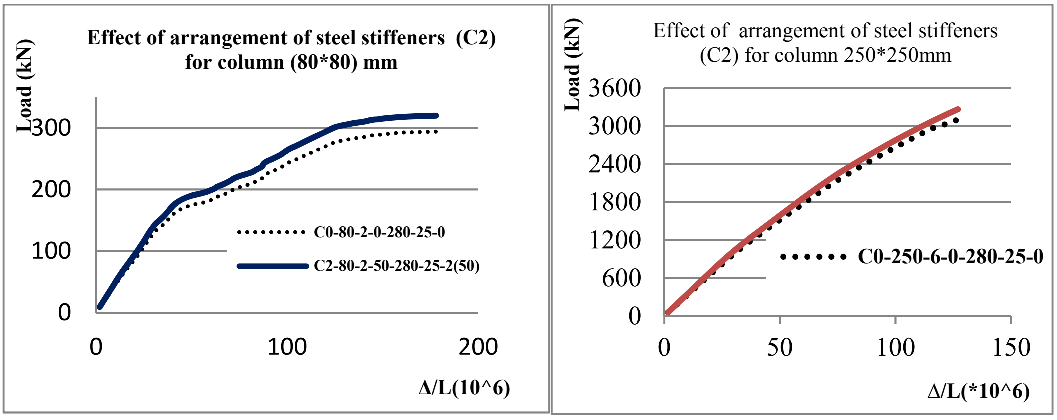
4.1 Effects of arrangement and number of steel stiffeners on ultimate load capacity

CFST columns with dimensions (80*80*2 mm) and (250x250*6 mm) are stiffened internally; as shown earlier in figures (3) and (4) with stiffener shape (C1), (C2) or (C3) for stiffener width of (50mm), number of stiffeners equals (2) and spacing between stiffeners equals (50mm).For sections (80*80*2)and(250x250x6 mm);the effect of arrangement of steel stiffeners on ultimate load capacity for stiffener shape (C1), (C2), and (C3) are shown in figure (5).

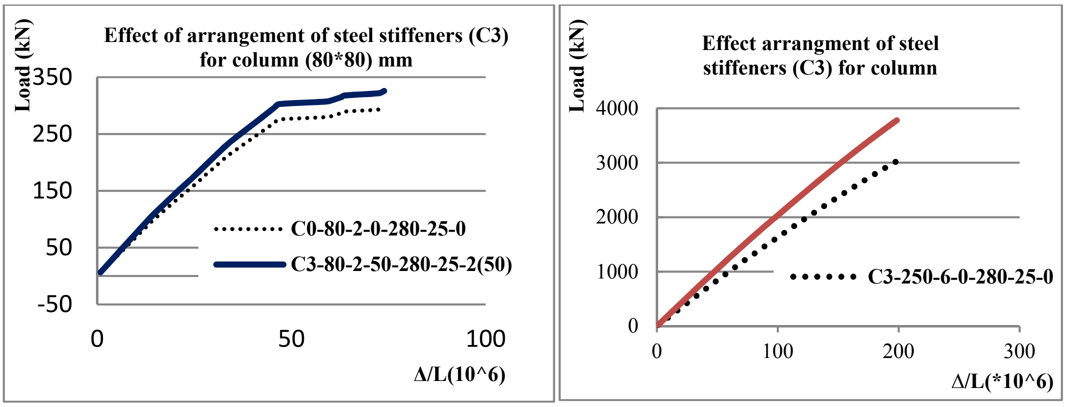
Different numbers of the steel stiffeners (2 and 3) were considered in the analyses of CFST columns to investigate their effects on the behavior of the columns. Figure (6) illustrates these effects on the ultimate load capacity and tables (2) and (3) summarize the corresponding ultimate load capacity values of the columns in accordance with the figures and the table. For section (80*80*2mm) for instance ;the ultimate load capacity of 2C1 steel stiffeners (C1-80-2-50-280-25-2(50)) is increased by the use of 3C1 steel stiffeners (C1-80-2-50-280-25-3(50)) from 330kN to352Kn. An improvement of 6.7% for the same steel stiffeners spacing of 50mm. For section (250*250*6), for instance; 2C1 steel stiffeners (C1-250-6-50-280-25-2(50)) is increased by the use of 3C1 steel stiffeners (C1-250-6-50-280-25-3(50)) from 4000kN to 4320kN; an improvement of 8% for the same steel stiffeners spacing of 50mm.



Steel stiffener shape (C1)



Steel stiffener shape (C2)



Steel stiffener shape (C3)

Figure (5): Effect of arrangement of steel stiffeners on ultimate load capacity for CFST columns

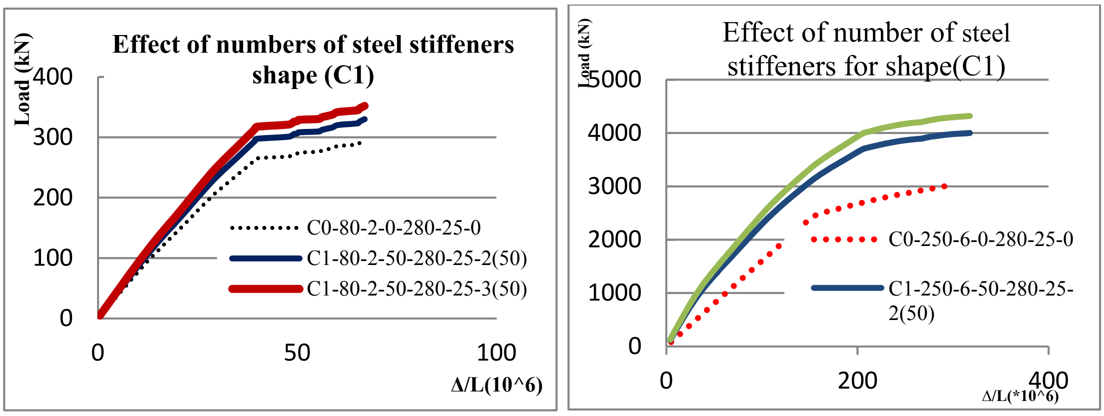


Figure (6): Effect of number of steel stiffeners shape (C1) on ultimate load capacity

4.2 Effect of spacing of steel stiffeners on ultimate load capacity

The effect of spacing of steel stiffeners on the behavior of the CFSC stub columns is investigated by considering two different steel stiffeners spacing of 50 mm and 100 mm in the analysis of the columns with Cl, C2, and C3 steel stiffeners.This effect on the ultimate load capacity of the columns is indicated in Figure (7). According the fig. (7) and Table (1), the decrease of the steel stiffeners spacing increases the ultimate load capacity.

For section 80*80: The ultimate load capacity of the column with the same number of C1 steel stiffeners improves from 315 kN (C1-2-50-280-25-3(100)) to 330 kN (C1-2-50-280-25-3(50)) respectively for the steel stiffeners spacing of 100 mm and 50 mm, an increase of 4.8%.

for section 250*250: The ultimate load capacity of the column with the same number of C1 steel stiffeners improves from 3500 kN (C1-250-6-50-280-25-3(100)) to 4000 kN (C1-250-6-50-280-25-3(50)) respectively for the steel stiffeners spacing of 100 mm and 50 mm, an increase of 14.3%.

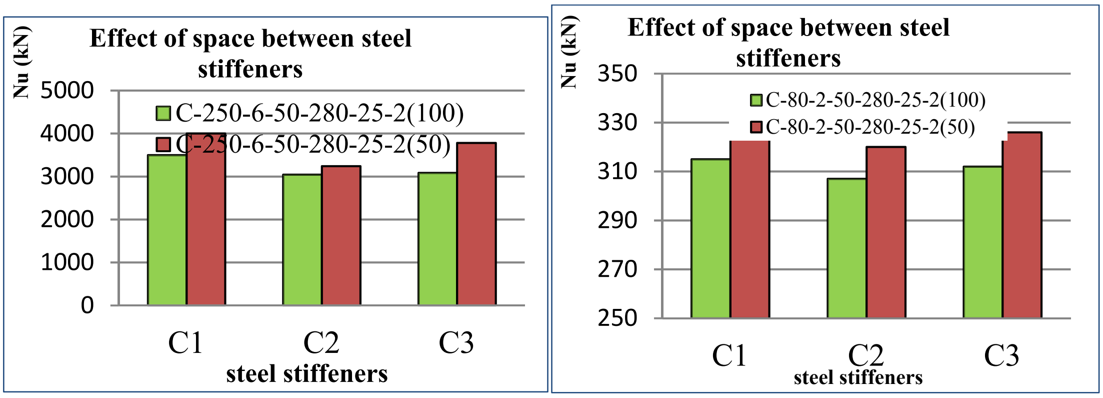


Figure (7): Effect of spacing of steel stiffeners on ultimate load capacity

4.3 Effect of width of steel stiffeners on ultimate load capacity

To assess the effect of width of steel stiffeners on the ultimate load capacity of the CFST columns, three different widths of the steel stiffeners (50mm, 75mm, and 100mm) were used in the analysis of the columns with 2C1,2C2, and 2C3 steel stiffeners. According to the obtained result in figure (8) for sections (80*80mm) and

(250*250mm) and their corresponding values in table (2); larger width of the steel stiffeners leads to higher ultimate load capacity.

For steel stiffener shape (C1),for section(80*80*2mm): enhancing the width of the steel stiffeners from 50mm [C1-80-2-50-280-25-2(50)] to 75mm [C1-80-2-75-280-25-2(50)] improves the ultimate load capacity from 330 kN to 348 kN with an increase of 5.5 %, and from 75mm [C1-80-2-75-280-25-2(50)] to 100mm [C1-80-2-100-280-25-2(50)]improves the ultimate load capacity from 348 kN to 382 kN with an increase of 9.8 %.

For section 250*250*6mm: for steel stiffener shape (C1), enhancing the width of the steel stiffeners from 50mm [C1-250-6-50-280-25-2(50)] to 75mm [C1-250-6-75-280-25-2(50)] improves the ultimate load capacity from 4000 kN to 4300 kN with an increase of 7.5 %, and from 75mm [C1-250-6-75-280-25-2(50)] to 100mm [C1-250-6-100-280-25-2(50)]improves the ultimate load capacity from 4300 kN to 4400 kN with an increase of 2.3 % .

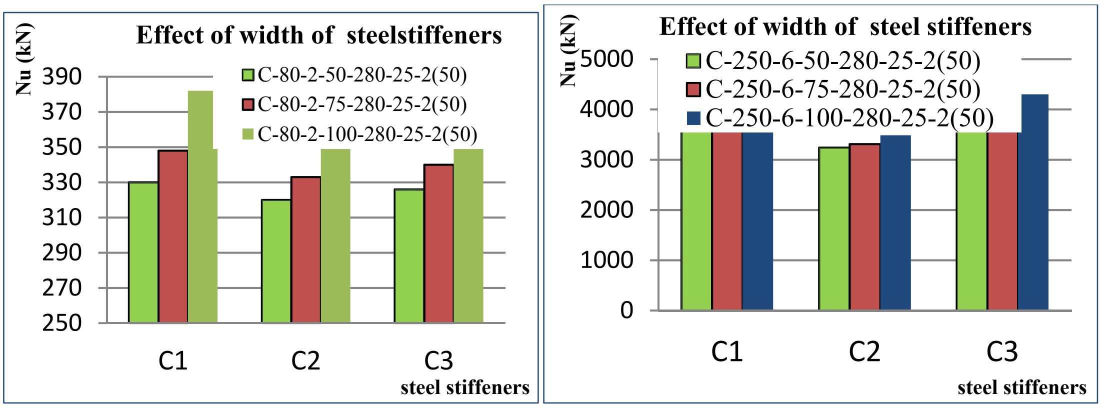


Figure (8): Effect of width of steel stiffeners on ultimate load capacity

4.4 Effect of steel thickness on ultimate load capacity

Three various steel thicknesses of 2 mm, 2.5mm, and 3 mm were considered in the analyzed CFST columns for section (80*80) ,with steel thickness of 6,8, and 9.5mm for section (250*250mm)with steel stiffeners to examine the effect of the steel thickness on the behavior of the columns. Consider steel stiffener shape (C1) for instance.

For section 80*80: for steel stiffener shape (C1), if the steel thickness enhances from 2 mm [C1-80-2-50-280-25-2(50)] to 2.5mm [C1-80-2.5-50-280-25-2(50)], the ultimate load capacity of the column is increased from 330 kN to 352 kN, an enhancement of 6.7%, and from 2.5 mm[C1-80-2.5-50-280-25-2(50)] to 3mm [C1-80-3-50-280-25-2(50)], the ultimate load capacity of the column is increased from 352 kN to 397 kN, an enhancement of 12.8% as shown in figure (9).

For section 250*250: for steel stiffener shape (C1), if the steel thickness enhances from 6 mm [C1-250-6-50-280-25-2(50)] to 8mm [C1-250-8-50-280-25-2(50)], the ultimate load capacity of the column is increased from 4000 kN to 5440 kN, an enhancement of 36%, and from 8 mm[C1-250-8-50-280-25-2(50)] to 9.5mm [C1-250-9.5-50-280-25-2(50)], the ultimate load capacity of the column is increased from 5440 kN to 6320 kN, an enhancement of 16.2%. Figure (9) illustrates the results for sections (80*80mm) and (250*250mm).

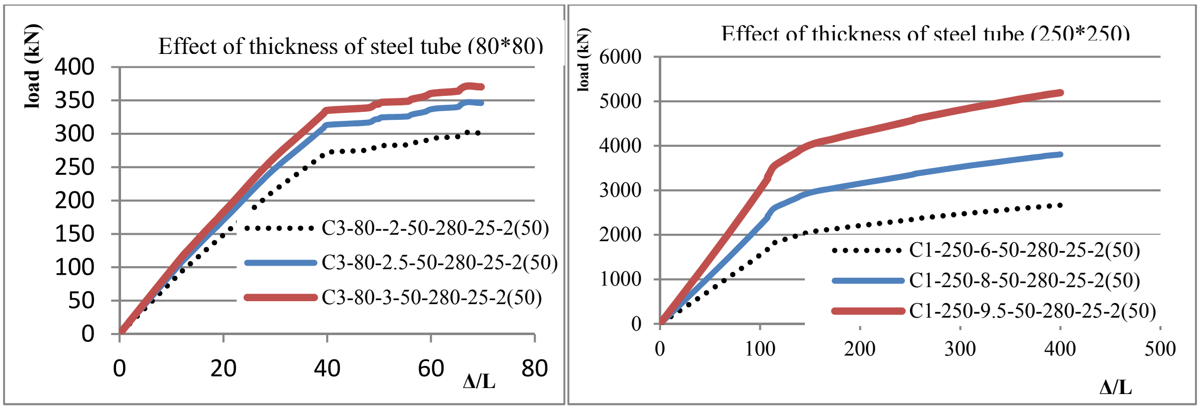


Figure (9): Effect of thickness of steel tube on ultimate load capacity

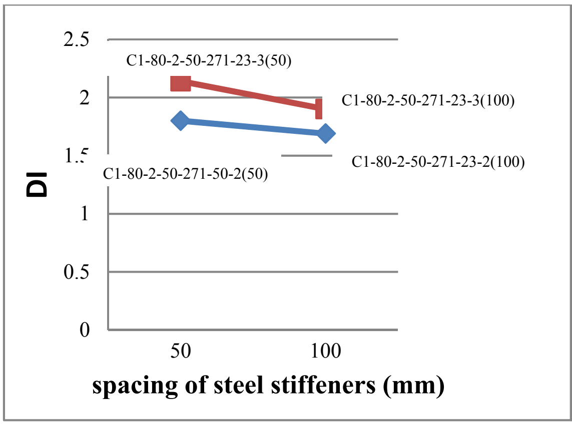
4.5 Effect of arrangement, number, and spacing of steel stiffeners on ductility

In order to evaluate the ductility of the columns, ductility index (DI) defined by Lin and Tsai (2001) has been utilized in this paper. Equation (3) expresses the ductility index:

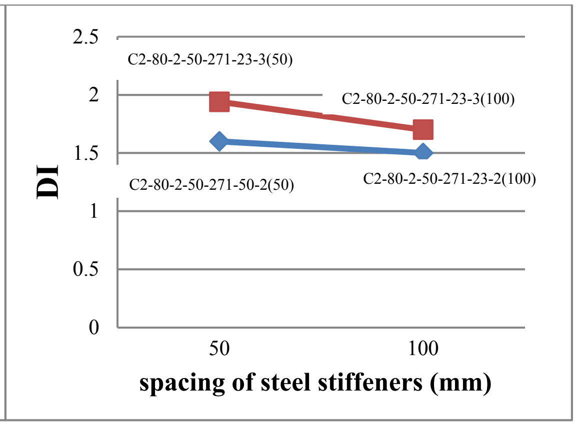
$$DI=\varepsilon_{85\%} / \varepsilon_y \quad (3)$$

in which $\varepsilon_{85\%}$ is the nominal axial shortening (Δ/L) corresponding to the load which falls within 85% of the ultimate load capacity and ε_y is $\varepsilon_{75\%}$ /0.75 in which $\varepsilon_{75\%}$ is the nominal axial shortening corresponding to the load that obtains 75% of the ultimate load capacity. The values of $\varepsilon_{85\%}$ and ε_y can be taken from figure (9) for section (80*80) and (250*250) respectively. Figure (10) illustrates effects of arrangement, number, and spacing of the steel stiffeners on the ductility.

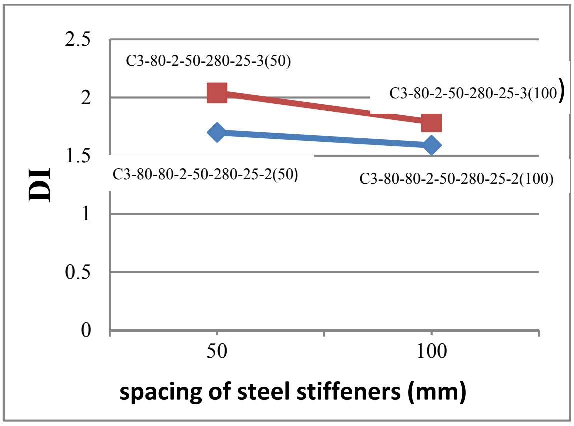
For section 80*80: According to figure (10), the use of the steel stiffeners improves the ductility of the columns. The ductility of the unstiffened column (C0-80-2-0-280-25-0) which can be obtained as 1.56 from figure (6) and using equation (3) increases to 2.14, 1.94 and 2.04 . The maximum ductility achieved respectively utilizing 3C1 steel stiffeners (C1-80-2-50-280-25-3(50)), 3C2 steel stiffeners (C2-80-2-50-280-25-3(50)), and 3C3 steel stiffeners (C3-80-2-50-280-25-3(50)) which denote enhancements of 37.2 %, 24.4 %, and 30.8 %, respectively. Therefore, the hierarchy of different arrangements of the steel stiffeners with the same steel thickness and same number and spacing of the steel stiffeners from the ductility view is C1, C3, and C2 which is the same hierarchy as that from the ultimate load capacity view, as discussed in section (4.1).As can be seen from figure (16), increasing the number of the steel stiffeners enhances the columns. As an example, for shape steel stiffener (C1), the ductility of the column (C1-80-2-50-280-25-2(50)) is 1.8 which is enhanced to 2.14 (C1-80-2-50-271-23-3(50)) respectively for 2 and 3 number of the steel stiffeners, an improvement of 19.9%.Moreover, reducing the steel stiffeners spacing increases the ductility of the columns figure (16). For example, by the reducing of the steel stiffeners spacing from 100mm (C1-80-2-50-280-25-3(100)) to 50mm (C1-80-2-50-280-25-3(50) for the same number of the steel stiffeners, the ductility enhances from 1.9 to 2.14, an enhancement of 12.6 %.



C1 steel stiffeners



C2 steel stiffeners



C3 steel stiffeners

Figure (10): Effects of arrangement, number, and spacing of steel stiffeners on ductility of CFST column for section (80*80)

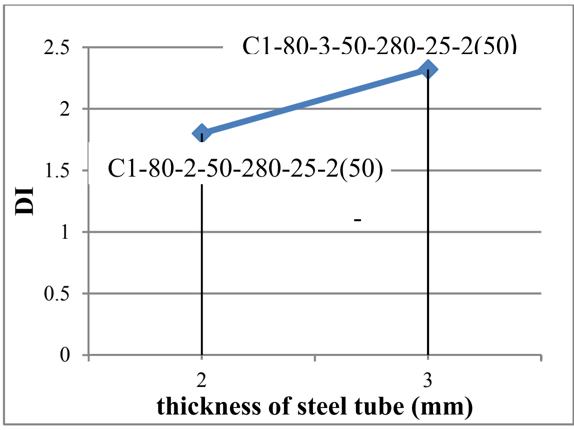
4.6 Effect of steel thickness of steel tube on ductility

The effect of steel thickness on the ductility of the columns is also examined by the use of equation (3). The values of $\varepsilon_{85\%}$ and ε_y in equation (3) can be determined from figure (9) for section (80*80). This effect on the ductility of the columns is shown in figure (11).The increase of steel thickness improves the ductility figure (11).

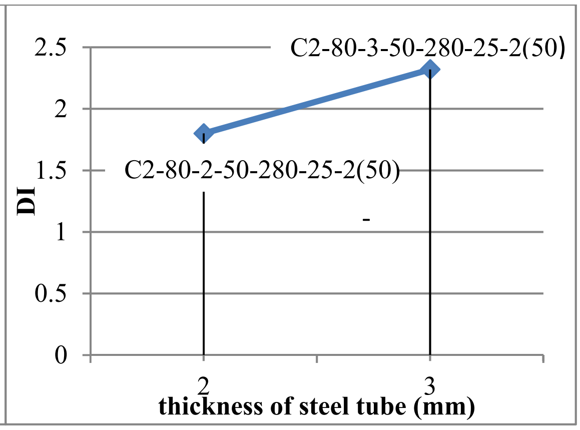
For steel stiffener shape (C1): enhancing the steel thickness from 2mm (C1-80-2-50-280-25-2(50)) to 3mm (C1-80-3-50-280-25-2(50)) increases the ductility of the columns from 1.8 to 2.32, an increase of 28.9%.

For steel stiffener shape (C2): enhancing the steel thickness from 2mm (C2-80-2-50-280-25-2(50)) to 3mm (C2-80-3-50-280-25-2(50)) increases the ductility of the columns from 1.65 to 2, an increase of 21.2%.

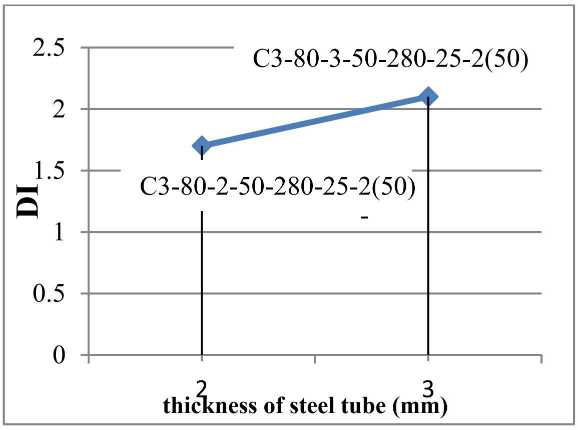
For steel stiffener shape (C3): enhancing the steel thickness from 2mm (C3-80-2-50-280-25-2(50)) to 3mm (C3-80-3-50-280-25-2(50)) increases the ductility of the columns from 1.7 to 2.1, an increase of 23.5%.



Steel stiffener shape (C1)



Steel stiffener shape (C2)



Steel stiffener shape (C3)

Figure (11): Effect of steel thickness on ductility

4.7 Effect of width of steel stiffeners on ductility

Equation (3) is also used to assess the effect of width of the steel stiffeners on the ductility of the columns. The values of $\varepsilon_{0.85}$ and ε_y in equation (3) can be obtained as mentioned previous. This effect of width of steel stiffeners on ductility of the columns can be observed from figure (12). It can be noticed from the figure that as a wider steel stiffener is used the ductility of the columns is enhanced.

For steel stiffener shape (C1): enhancing the steel stiffeners width from 50 mm (C1-80-2-50-280-25-2(50)) to 75mm (C1-80-2-75-280-25-2(50)) increases the ductility of the columns from 1.8 to 2, an increase of 11.1%, and from 75 mm (C1-80-2-75-280-25-2(50)) to 100mm (C1-80-2-100-280-25-2(50)) increases the ductility of the columns from 2 to 2.2, an increase of 10%.

For steel stiffener shape (C2): enhancing the steel stiffeners width from 50 mm (C2-80-2-50-280-25-2(50)) to 75mm (C2-80-2-75-280-25-2(50)) increases the ductility of the columns from 1.65 to 1.85, an increase of 12.1%, and from 75 mm (C2-80-2-75-280-25-2(50)) to 100mm (C2-80-2-100-280-25-2(50)) increases the ductility of the columns from 1.85 to 2.04, an increase of 10.3%.

For steel stiffener shape (C3): enhancing the steel stiffeners width from 50 mm (C3-80-2-50- 280-25-2(50)) to 75mm (C3-80-2-75-280-25-2(50)) increases the ductility of the columns from 1.7 to 1.9, an increase of 11.8%, and from 75mm (C3-80-2-75-280-25-2(50)) to 100mm (C3-80-2-100-280-25-2(50)) increases the ductility of the columns from 1.9 to 2.1, an increase of 10.5%.

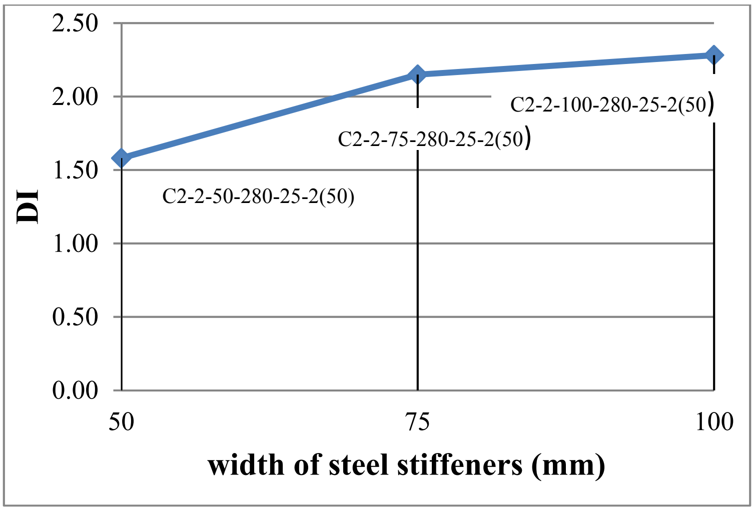
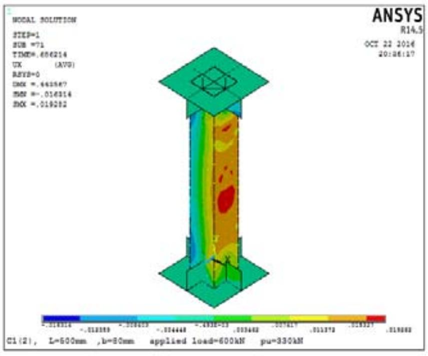
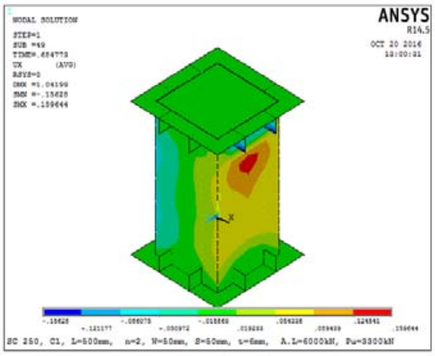


Figure (12): Effect of width of steel stiffeners on ductility

5. Failure modes

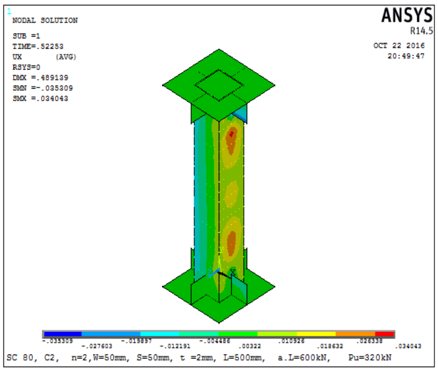
Typical failure modes of the stiffened CFST stub columns are shown in figure (13).As it obvious from the figures that the failure modes of the columns were characterized by crushing of the concrete core about their mid-height where local buckling of the steel wall. The infilled concrete prevented the steel wall from the buckling inward.As stated earlier, the use of the steel stiffeners, increasing number or width of the steel stiffeners, reduction of the steel stiffeners spacing, or increasing of the steel thickness lead to the improvement of the ultimate load capacity and ductility. This improvement is due to the increased confinement effect of steel on the concrete core due to each of the above-mentioned changes of the parameters. This increased confinement effect delays the local buckling of the steel wall which finally results in the enhancement of the ultimate load capacity and ductility.



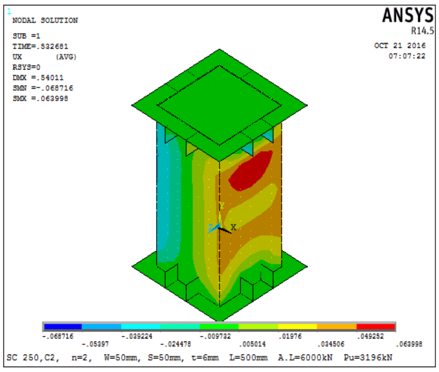


Section (80*80*2) **Section (250*250*6)**

(C1)

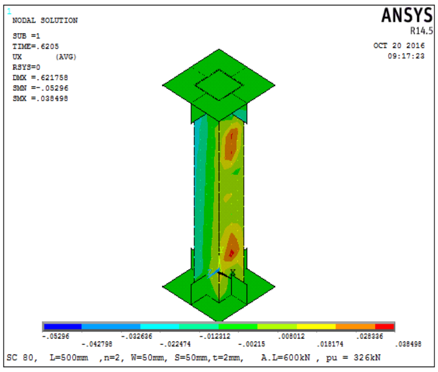


Section (80*80*2)

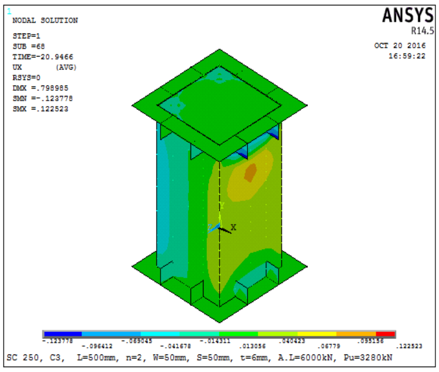


Section (250*250*6)

(C2)



Section (80*80*2)



Section (250*250*6)

(C3)

Figure (13): Typical finite element deformed meshes of the stiffened CFST columns

6. Predictions and comparisons of ultimate load capacity of unstiffened columns against various codes

6.1 Effect of flat width-to-thickness b/t ratio

The results of all the analyzed specimens are tabulated in Table (4) for b/t = 25, 35, and 45. The table contains the ultimate load resulting from the finite element analysis and those predicted by different codes of practice (EC4 2004), (ANSI/AISC 2005), and (ECP 2007).
The relationship between slenderness ratio b/t and P_{FEM}/P_u for different column cross sections SC100, SC150, SC200, SC250, and SC300 are shown in Figure (14).
The codes provisions specify flat width to-thickness ratio *b*/*t* limits for the square steel tubes. The slenderness ratios limit in different design codes are as follows:

For E_s = 200000 MPa, F_y = 280 MPa.
- The Eurocode 4 (2004) provisions limit the *b*/*t* ratio to:

$$\frac{b}{t} \leq 52 \text{ x } (235/F_y)^{0.5}$$

$$\frac{b}{t} \leq 52 \text{ x } (235/280)^{0.5} = 47.6$$

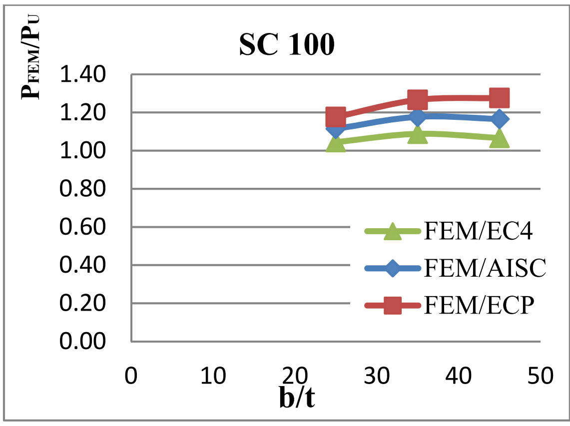
- The American AISC (2005) provisions limit the *b*/*t* ratio to:

$$\frac{b}{t} \leq 2.26 \text{ x } \sqrt{\frac{Es}{Fy}} = 60.4$$

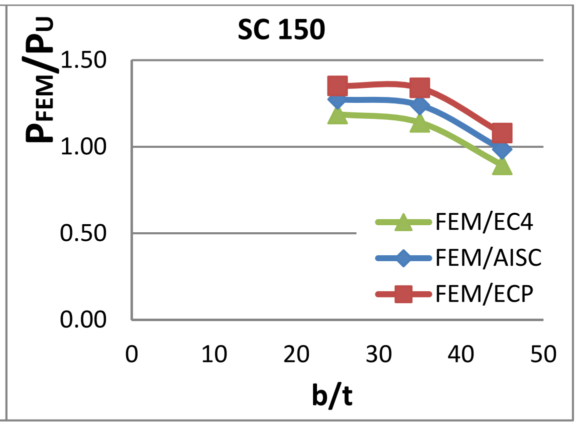
According to table (4) and figure (14) for models SC100,SC150,SC200,SC250, and SC300, it is concluded that the results of (EC4 2004) for some models predicts less ultimate load than the FEM results in the range of 2% to 27%, so it can be concluded that (EC4 2004) approach is conservative in estimating the ultimate capacities of the columns, for other models it predicts more ultimate load than the FEM results in the range of 3% to 14%. Thus it can be concluded that (EC4 2004) approache overestimates the ultimate capacities of the columns.

The (ANSI/AISC 2005) for some models predicts less ultimate load than the FEM results in the range of 3% to 41%, thus it can be concluded that (ANSI/AISC 2005) approach is conservative in estimating the ultimate capacities of the columns. For other models it predicts higher ultimate load than the FEM results in the range of 2% to 5%, so it can be concluded that (ANSI/AISC 2005) approache overestimates the ultimate capacities of the columns.

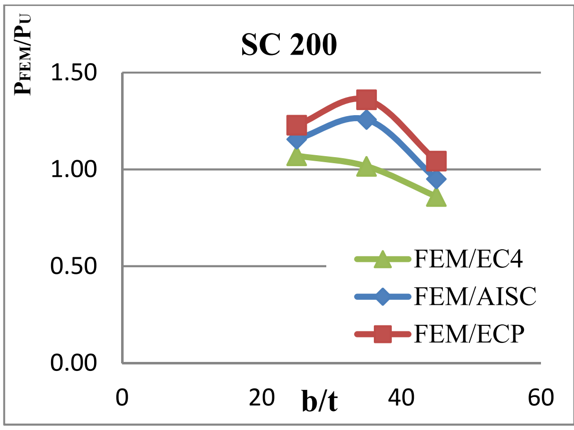
The ECP 2007 for models predicts less ultimate (failure) load than the FEM in the range of 4% to 54%, so it can be concluded that ECP 2007 approaches is conservative in estimating the ultimate capacities of the columns.



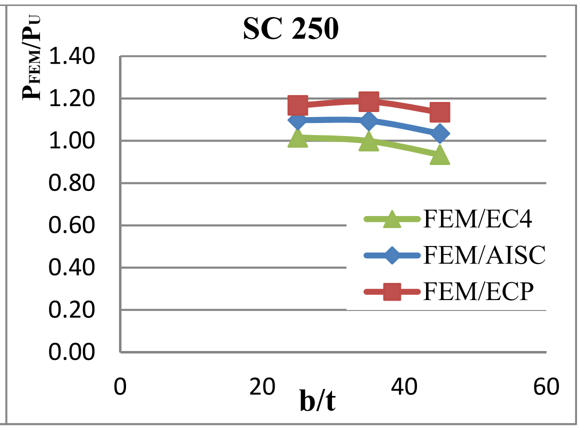
SC 100



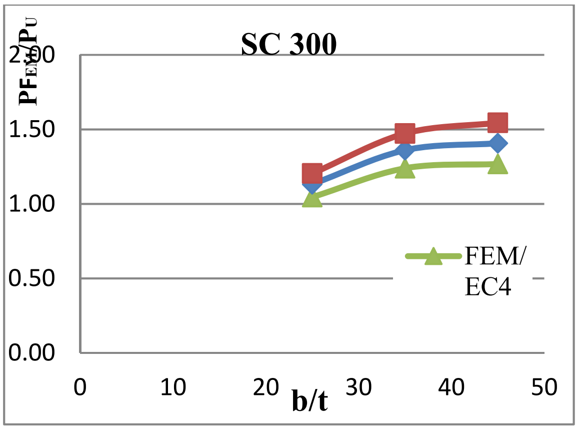
SC 150



SC 200



SC 250



SC 300

Figure (14): Relationships between *b*/*t* and P_{FEM} /P_u

Table (4) Comparison between ultimate load results from the FEM and those predicted by different codes

Specimen	b/t	Pu (kN)				P_{FEM}/P_{EC4}	P_{FEM}/P_{AISC}	P_{FEM}/P_{ECp}
		P_{FEM} (kN)	EC4 (2004)	AISC (2005)	ECP (2007)			
100	25	700	670	628	595	1.04	1.11	1.18
	35	604	555	513	477	1.09	1.18	1.27
	45	513	481	440	402	1.07	1.17	1.28
150	25	1825	1536	1433	1351	1.19	1.27	1.35
	35	1440	1263	1161	1075	1.14	1.24	1.34
	45	986	1102	1002	914	0.89	0.98	1.08
200	25	2960	2765	2560	2409	1.07	1.16	1.23
	35	2600	2558	2067	1911	1.02	1.26	1.36
	45	1700	1976	1788	1629	0.86	0.95	1.04
250	25	4400	4330	4008	3769	1.02	1.1	1.17
	35	3535	3539	3230	2983	1	1.09	1.19
	45	3000	3130	2827	2577	0.93	1.03	1.14
300	25	6540	6258	5779	5432	1.05	1.13	1.2
	35	6368	5140	4682	4325	1.24	1.36	1.47
	45	5725	4516	4069	3707	1.27	1.41	1.54

7. STIFFENED COMPOSITE COLUMN

The verified finite element model is used to study the effect of different parameters on the ultimate capacity and failure modes of CFST columns with internal stiffeners. eleven stiffened composite columns specimens for stiffener shape (C1) with the same dimensions (250×250×6) mm and changing numbers of stiffeners (2 and 3), width of stiffeners (50, 75 and 100mm) , spacing between stiffeners (50 and 100 mm), thickness of steel tube (6,8 and 9.5mm), steel yield strength (240,280 and 360MPa) and concrete compressive strength (20,25 and 30MPa).

The results of all specimens are tabulated in Table (5) .The table contains the ultimate load of the resulting from the finite element analysis P_{FEM} and those predicted by different codes of practice P_u [EC42004,e ANSI/AISC 2005 and ECP 2007].

Table (5): Comparison between ultimate load results from the FEM and those predicted by different codes

NO.	Specimen	P_u (kN)				P_{FEM}/P_{EC4}	P_{FEM}/P_{AISC}	P_{FEM}/P_{ECP}
		P_{FEM}	P_{EC4} (2004)	P_{AISC} (2005)	P_{ECP} (2007)			
1	C1-250-6-50-280-25-**2**(50)	4000	3239	2934	2685	1.23	1.36	1.49
2	C1-250-6-50-280-25-**3**(50)	4320	3239	2934	2685	1.33	1.47	1.61
3	C1-250-6-**75**-280-25-3(50)	4300	3239	2934	2685	1.33	1.47	1.60
4	C1-250-6-**100**-280-25-3(50)	4380	3239	2934	2685	1.35	1.49	1.63
5	C1-250-6-100-280-25-3(**100**)	3500	3239	2934	2685	1.08	1.19	1.30
6	C1-250-6-100-**240**-25-3(100)	3800	2996	2696	2446	1.27	1.41	1.55
7	C1-250-6-100-**360**-25-3(100)	4700	3724	3410	3162	1.26	1.38	1.49
8	C1-250-6-100-360-**20**-3(100)	3000	2937	2683	2484	1.02	1.12	1.21
9	C1-250-6-100-360-**30**-3(100)	4740	3541	3185	2886	1.34	1.49	1.64
10	C1-250-**8**-100-360-30-3(100)	5400	3785	3471	3227	1.43	1.56	1.67
11	C1-250-**9.5-**100-360-30-3(100)	6300	4194	3874	3634	1.50	1.63	1.73

Finally, the obtained ultimate load capacities of the columns from the nonlinear analyses were compared with the predicted values by EC4 (2004), (ANSI/AISC 2005) and (ECP 2007) which uncovered that EC4 (2004) predicts the ultimate load capacity of the columns more conservatively than the (ANSI/AISC 2005) and (ECP 2007).

8. CONCLLUTIONS

This study has widely investigated the concrete-filled steel composite (CFST) columns with steel stiffeners using the finite element software ANSYS. The existing experimental test results were used to compare with the results of the nonlinear analyses to verify the modeling. It was clearly demonstrated that the proposed finite element modeling was reasonably accurate to predict the behavior of the columns herein. Internal steel stiffeners were used in the columns. The columns were extensively developed incorporating different special arrangement, number, spacing, and widths of the steel stiffeners with various steel thickness. Effects of the variables on the behavior of the columns were also examined. It was shown that using C1, C2, and C3 steel stiffeners increases the ultimate load capacity and ductility of the columns. Increasing the number or width of the steel stiffeners or steel thickness improves the ultimate load capacity and ductility. Reducing the steel stiffeners spacing enhances the ultimate load capacity and ductility. The hierarchy of different arrangements of the steel stiffeners with same steel thickness and same number and spacing of the steel stiffeners from the ultimate load capacity and ductility views is C1, C3, and C2. As the concrete compressive strength increases the ultimate load capacity improves. Furthermore, the ultimate load capacity increases if the steel yield stress is increased. In addition, the failure modes of the columns were recognized as concrete crushing of the columns about their mid-height with local buckling of the steel wall. Meanwhile, the obtained ultimate load capacities of the columns from the nonlinear analysis were compared with the predicted values by ECP (2007), AISC (2005), and EC4 (2004). EC4 (2004) predicts the ultimate load capacity of the columns more conservatively than the ECP (2007) and AISC (2005).

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