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The behavior of Hollow/ Filled steel tubular sections (CFT/CFSt) under axial compression

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In this study, compressive strength, modulus of elasticity and steel tensile coupon tests are performed to determine material properties. Sixteen hollow cold formed steel tubes and 48 concrete filled steel tube specimens are used for axial compression tests. The effects of width/thickness ratio (b/t), the compressive strength of concrete and geometrical shape of cross section parameters on ultimate loads, axial stress, ductility and buckling behavior are investigated. Circular, hexagonal, rectangular and square sections, 18.75, 30.00, 50.00, 100.00 b/t ratio values and 13, 26, 35 MPa concrete compressive strength values are chosen for the experimental procedure. Circular specimens are the most effective samples according to both axial stress and ductility values. The concrete in tubes has experienced considerable amount of deformations which is not expected from such a brittle material in certain cases. The results provide an innovative perspective on using cold formed steel and concrete together as a composite material.

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1. Introduction

Tension and compression stresses occur at different regions according to the loads and load conditions in structural members. It can be seen that the optimum resisting section against these stresses in the same member is the reinforced concrete which has had a composite structure since the 1850s. However, recent studies concerning concrete filled steel tubes (CFST) have become important in the area of structural engineering.

Structural members have enough bearing capacity against internal forces according to dead loads and live loads caused by external effects in normal conditions. However, extra shear forces and moments created by seismic movements or dynamic vibrations during earthquakes force the capacities of members. Conventional reinforced cross sections might be of higher dimensions than required during the design stage because of this. Concrete filled steel tubes have a high ductility and bearing capacity. This system provides for rapid construction without removing any formwork. Steel members prevent lateral expansion of concrete as seen with stirrups. Steel tube performs both longitudinal and lateral reinforcement as well as it is used in formwork. A concrete core resists axial force, at the same time preventing the buckling of steel in an inward direction on a tube. The main design criteria of Turkish Earthquake Codes, based on the human life sustainability during earthquakes, can be easily provided by the ductility behavior of CFST members easily. The use of steel walled composite cross sections is becoming widespread in civil engineering.

The main purpose of using CFST members is to provide maximum bearing capacity prior to possible buckling modes. Local buckling is expected in the case of the inadequate confinement effects by steel tube or inadequate concrete core strength in a composite section. The confinement effect is called the radial pressure created by steel tubes. It operates in the same manner as stirrups and alters the buckling mode. Slenderness is also an important effect on the buckling mode determined using the dimensions of members.

Most researchers have focused on the strength, ductility, deformation, buckling and confinement effects created by the change of cross section areas and shape, the interaction of composite materials, the strength of materials, strengthening bars,

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and member lengths and width (or diameter)/thickness ratios (b/t) under normal load or bending moment conditions. Hu et al. [1] investigated the confinement effects on 24 circular, square and strengthened square sectioned specimens with a range of 17–150 b/t ratio under compression. The maximum confinement effects were seen on circular specimens (b/to40). Little confinement effects were observed on square sections (b/t430). Other experimental tests were performed on composite stub columns produced with b/t ratio values between 15 and 59. The results indicate that circular shaped specimens produced three dimensional inclusive confinement effects on core concrete (Knowles and Park [2]). An experimental study was performed on elliptical concrete filled tubular specimens with a range of 69–160 b/t ratio under centric loading (Uenaka [3]). They showed that the axial load capacity of elliptical CFST columns can be estimated by the equation including confinement effect of smaller diameter direction. Gupta et al. [4] showed that lower b/t ratios provide higher confinement effects on the test results of 81 specimens having the ratios of between 25 and 39. Hu et al. [5] investigated the interaction and confinement effects on CFT columns under a combination of axial compression and bending moment. More lateral confinement pressure was observed in strengthened circular specimens with an increasing axial loading ratio. The behavior of stub CFT column under concentric loading on 11 specimens was studied by Sakino et al. [6]. Chitawadagi et al. [7] demonstrated that the most effective parameter is the diameter of a steel tube related with the ultimate axial load and axial shortening on highly slender CFTs. Elchalakani et al. [8] performed a series of bending tests on circular hollow sections. They showed that the effects of nonlinear bending properties and the regulation of existing slenderness criteria are required for circular hollow sections. Yang et al. [9] investigated the ultimate bearing capacity and buckling mechanisms on 28 cold formed steel specimens having the high tensile strength (550 MPa) and the b/t range between 13 and 119. An approximate six percent difference between the experimental and the analytical results was observed according to the finite element model. The buckling and ultimate strength behavior of cold formed steel mid-length columns was investigated on 16 innovative specimens by Narayanan and Mahendran [10].

Table 1
Amount of materials for 1 m^3 concrete mix design.

Material	Estimated compressive strength values of concrete		
	10 MPa	20 MPa	30 MPa
Cement (kg)	240.0	313.0	400.0
Water (kg)	238.6	237.1	236.9
0–5 mm aggregate (kg)	808.9	781.6	749.1
5–15 mm aggregate (kg)	529.7	511.8	490.6
15–22 mm aggregate (kg)	441.3	426.3	408.6

Fig. 1. Concrete compression test equipment.

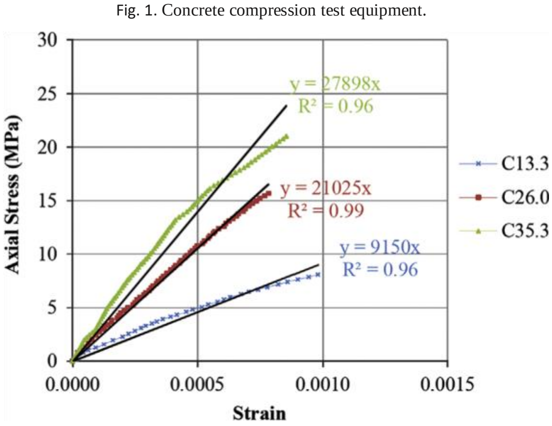


Fig. 2. Modulus of elasticity results for concrete specimens.

Ductility behavior and buckling behavior are the other results of this study. Ductility is the total deformation capacity measurement up to an ultimate point. Serious deformation might occur when the strength of the material is approximately constant throughout the ductile structure. Ductility is an important parameter for the dissipation of energy during earthquakes or blasting

Fig. 3. Steel tension coupon test equipment.

(Celep and Kumbasar [11]). Ductility or strength of specimens will otherwise suffer sudden decrement if any type of buckling occurs. Three different types of buckling behavior are possible for steel members. First of all, the wide part of the member surface becomes unstable and buckles, then lateral buckling also occurs.

If a loaded point ruptures or deflects in the opposite direction of the near points' curvature, it is called local buckling. A member buckling individually under axial compression is called member buckling (Al Nageim and MacGinley [12]). Compression members produced from fairly thin material might collapse with local

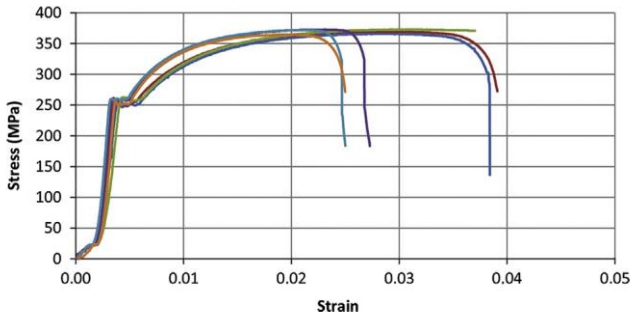


Fig. 4. Tension coupon test results for cold formed steel.

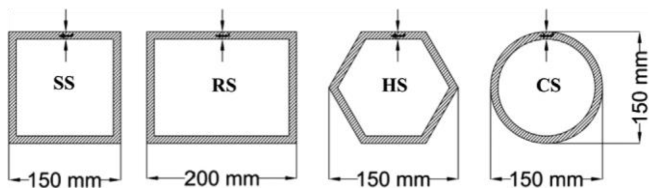


Fig. 5. Shapes of specimens.

buckling and is generally called crippling. If a cross section weakens against the twisting, twist-torsion will occur. A twisttorsion mode is rarely observed for tubular sections (Bresler and Lin [13]). Buckling of walls was observed on the square and rectangular specimens according to Schneider [14]. An experimental study was performed on rectangular and square hollow specimens by Goggins et al. [15] under monolithical and cyclic axial loading. They showed that ductility capacity is in direct proportion with slenderness. Broderick et al. [16] showed that concrete filled sections prevent local buckling and increase ductility capacity under compressive strength. O'Shea and Bridge [17] proved that the reduction in strength and ductility depends on an increase in of b/t value. Fujimoto et al. [18] showed that high strength concrete decreases the strain of concrete filled tubes.

Investigation of changes in b/t ratio, concrete compressive strength and cross section shape in the same test procedure is a unique aspect of this study. Load–displacement, axial stress, ductility and buckling characteristics are also studied.

2. Experimental investigations

Sixty four specimens were used in the experiment. Each was of 400 mm height and variable 'b/t' ratios. The letter 'b' refers to the diameter or width of specimen and 't' refers to the thickness of

Table 2 Testing specimens.

Specimen	Width/thickness Ratio (b/t)	f_{cc}[a] (MPa)	Specimen	Width/thickness ratio (b/t)	f_{cc}[a] (MPa)
SS1500	100.00	Hollow	HS1500	100.00	Hollow
SS1510	100.00	13.3	HS1510	100.00	13.3
SS1520	100.00	26.0	HS1520	100.00	26.0
SS1530	100.00	35.3	HS1530	100.00	35.3
SS3000	50.00	Hollow	HS3000	50.00	Hollow
SS3010	50.00	13.3	HS3010	50.00	13.3
SS3020	50.00	26.0	HS3020	50.00	26.0
SS3030	50.00	35.3	HS3030	50.00	35.3
SS5000	30.00	Hollow	HS5000	30.00	Hollow
SS5010	30.00	13.3	HS5010	30.00	13.3
SS5020	30.00	26.0	HS5020	30.00	26.0
SS5030	30.00	35.3	HS5030	30.00	35.3
SS8000	18.75	Hollow	HS8000	18.75	Hollow
SS8010	18.75	13.3	HS8010	18.75	13,3
SS8020	18.75	26.0	HS8020	18.75	26.0
SS8030	18.75	35.3	HS8030	18.75	35.3
RS1500	100.00	Hollow	CS1500	100.00	Hollow
RS1510	100.00	13.3	CS1510	100.00	13.3
RS1520	100.00	26.0	CS1520	100.00	26.0
RS1530	100.00	35.3	CS1530	100.00	35.3
RS3000	50.00	Hollow	CS3000	50.00	Hollow
RS3010	50.00	13.3	CS3010	50.00	13.3
RS3020	50.00	26.0	CS3020	50.00	26.0
RS3030	50.00	35.3	CS3030	50.00	35.3
RS5000	30.00	Hollow	CS5000	30.00	Hollow
RS5010	30.00	13.3	CS5010	30.00	13.3
RS5020	30.00	26.0	CS5020	30.00	26.0
RS5030	30.00	35.3	CS5030	30.00	35.3
RS8000	18.75	Hollow	CS8000	18.75	Hollow
RS8010	18.75	13.3	CS8010	18.75	13.3
RS8020	18.75	26.0	CS8020	18.75	26.0
RS8030	18.75	35.3	CS8030	18.75	35.3

[a] f_{cc} is the average 28-day compressive strength values of the core concrete.

steel plate. Thickness values of 1.5, 3.0, 5.0, 8.0 mm were used providing b/t ratios of 18.75, 30.00, 50.00 and 100.00 for the purpose of determining the effects of duplicated values according to the general literature ranges.

2.1. Material properties

The mechanical properties of concrete and steel coupon specimens are examined, having the same strength values as core concrete and tubes. Compressive strength values were chosen within the scope of obtaining the effects of double and triple increased compressive strength values on focused parameters. Concrete mix designs were performed on 27 cylindrical and cubic concrete specimens in total for compressive strength. Seven and 28 days approximate concrete compressive strength values are obtained on the trial samples. The amounts of cement, water and aggregate used during the pour of concrete into the steel tubes are given in Table 1.

Compressive strength values are obtained as 13.3, 26.0 and 35.3 MPa after crushing the samples using a compression test machine given in Fig. 1.

Modulus of elasticity values were determined as 9150, 21000 and 28000 MPa for concrete specimens using linear interpolation according to the FEMA356 [19] given in Fig. 2.

Steel tensile coupon tests were performed on six specimens to determine the mechanical parameters of steel given in Fig. 3.

Modulus of elasticity, yield strength, ultimate strength and elongation ratio values were given as 200000 MPa, 255 MPa, 370 MPa and 32.12%, respectively, relating to the average results of tests in Fig. 4. Steel tubes were produced using standard industrial steel plates. Circular tubes were shaped using cylindrical rollers in cold state monolithically and others were spanned using an industrial steel spinning machine. Square, rectangular and hexagonal cross sectional tubes were vertically produced in two equal parts. All twin steel parts and spanned circular sections were welded along the cutting surfaces using an argon welding machine with a minimum 420 MPa yield strength and a minimum 500–640 MPa tensile strength during the welding process. Steel plates of 3 mm thickness and 160 mm by 160 mm or 160 mm by 210 mm dimensions were welded at the top and at the bottom ends as a cap.

2.2. Test specimens

Systematic denotation was used for the geometrical shape of the horizontal cross section of the specimen, wall thickness of steel and compressive strength of core concrete. For example, an SS1500 expression indicates a hollow square specimen with a 1.5 mm wall thickness. The shapes and dimensions of four different models are given in Fig. 5 (SS: square section, RS: rectangular section, HS: hexagonal section, CS: circular section). All the model heights were kept constant at 400 mm. In total, 64 specimens were used to determine the effect of the domain parameters given in Table 2.

A circular hole with a 42 mm diameter was bored at the center of the top cap for pouring and vibration of the concrete. A minimum 28-day curing time was applied to gain a standard concrete compressive strength of the core concrete specimens after pouring of concrete into the steel tubes. All the sides of the specimens were covered by hydrated lime to observe possible cracks during the test.

2.3. Test setup and instrumentation

Intense labor and time were required for the experimental studies. This study consists of producing specimens, providing materials, designing and placing of concrete, preparing experimental setups, realizing experiments and evaluation of test results.

Thirty channeled TDS303 type TML data logger was used to obtain a time dependent load versus displacement curve at the same loading steps. Displacement gauges named Linear Variable Differential Transducer (LVDT) were used to measure elongation and shortening along a working axis. Two TML-CDP25 type 2.5 mm capacity LVDTs were used during the tests. A strain gauge was the unit deformation measurement apparatus which worked the electrical output values of the elongation and shortening phenomena placed along the longitudinal direction according to the electrical resistance. The LVDT equipment measured the change in the overall height; with strain gauges measuring the point change. In total, 384 pieces of FLA-6-11-5L type TML of 6 mm length strain gauge equipment was used during testing. The measurement resistance of the strain gauges had to be at 12070.5 Ω range and the bypass of cables had to be prevented. In total, four strain gauges and two

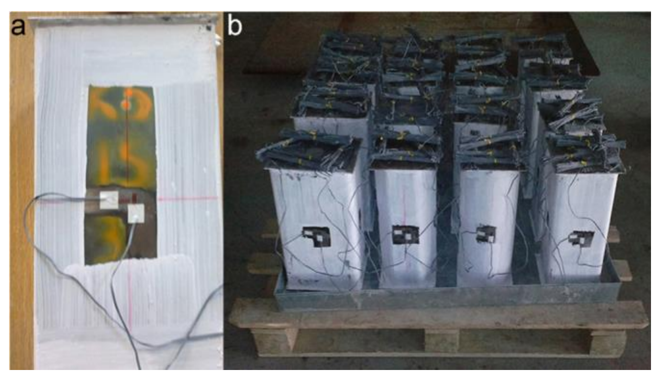
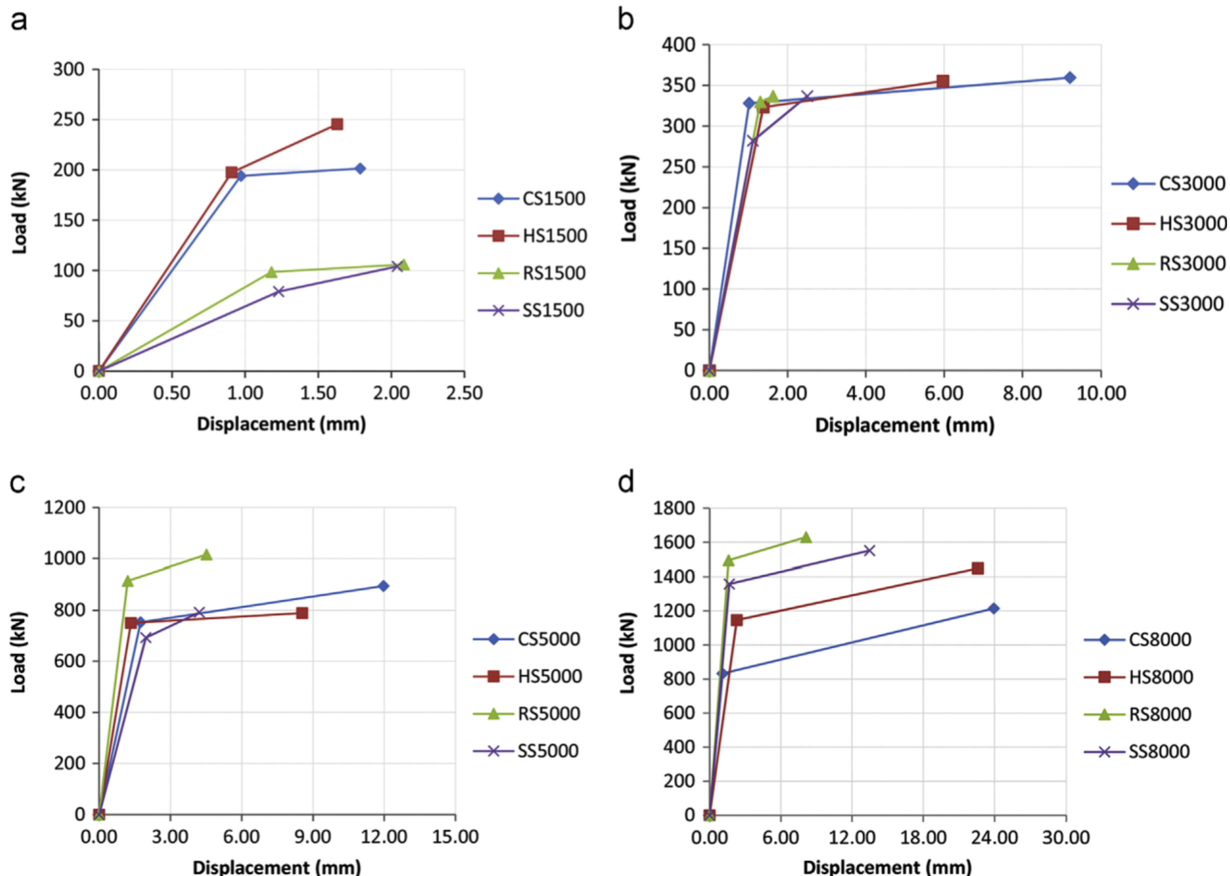


Fig. 6. (a) Location of strain gauges and (b) final position of CFST specimens before tests.



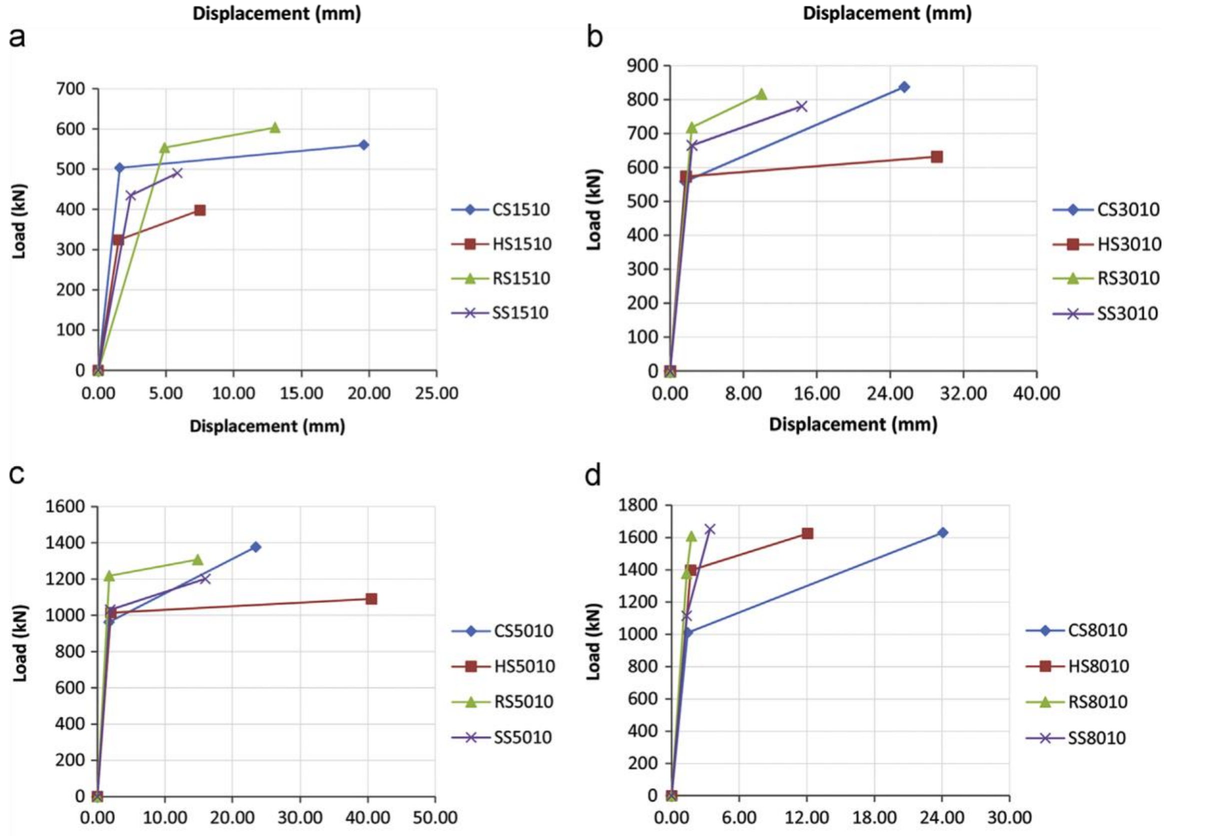


Fig. 7. Load displacement curves for hollow specimens.

Fig. 8. Load displacement curves of 13.3 MPa concrete filled tube specimens.

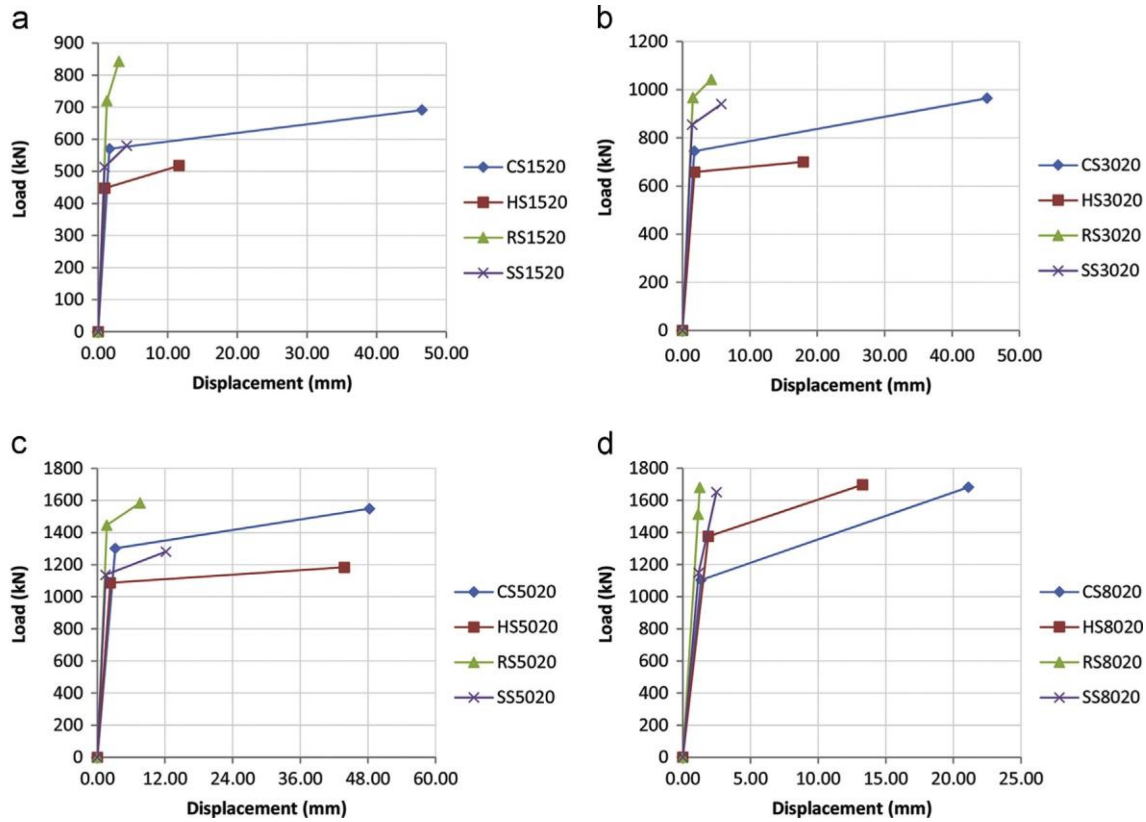


Fig. 9. Load displacement curves of 26.0 MPa for concrete filled tube specimens.

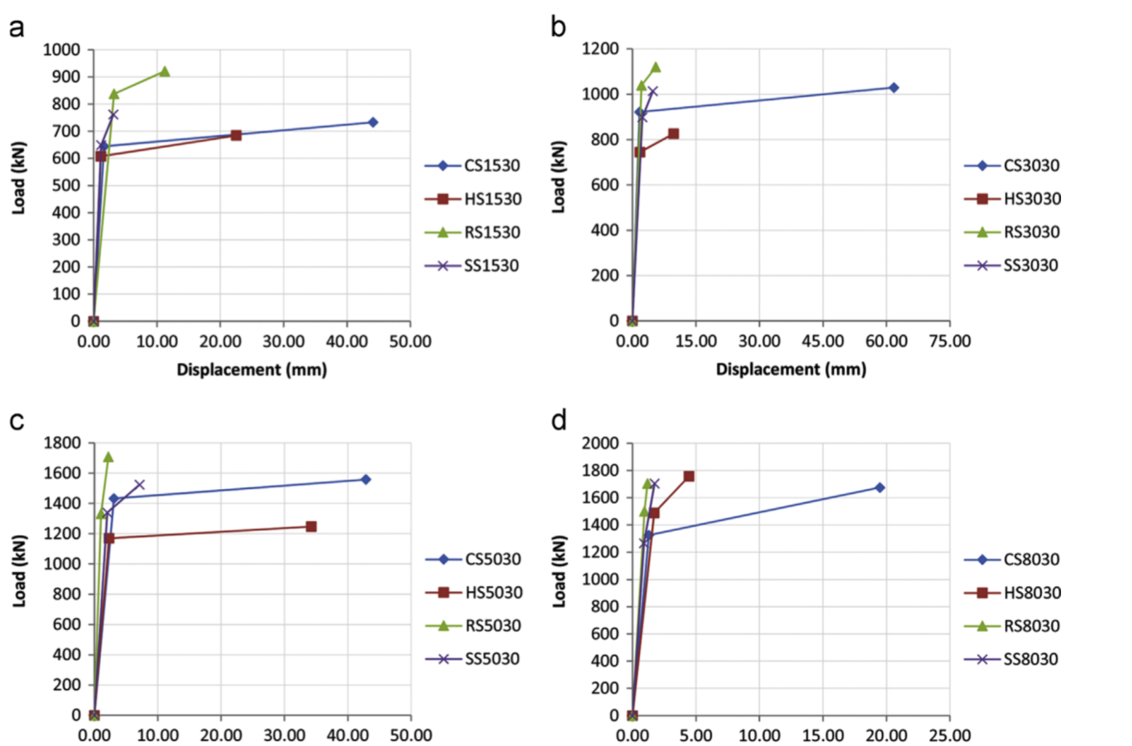


Fig. 10. Load displacement curves of 35.3 MPa for concrete filled tube specimens.

LVDTs were used for each CFST specimen. Two strain gauges were glued at the front and at the rear sides of the specimens, vertically as shown in Fig. 6. Two other strain gauges were glued to the other sides, vertically.

Experiments were performed only under the effect of an axial compression load assumption. Possible shear force and bending moment values caused by eccentric loading and deformation during the test process were ignored. The top and bottom ends were assumed to be roller supports that permit only axial force transition.

3. Results

The average values of results from two LVDTs and four vertical strain gauges were calculated for each specimen. After this, the average values of these two parameters were bilinearized according to the FEMA356 [19] to obtain the closest realistic estimation of a load displacement curve.

3.1. Load–displacement characteristics

The increment of ultimate load capacity and displacement of circular and hexagonal hollow specimens were higher than those of square and rectangular specimens as shown in Fig. 8. Circular and hexagonal hollow specimens had two to three times more displacement than the square and rectangular sections according to the confinement effect caused by the composite sections in 13.3 MPa concrete filled steel tube specimens shown in Fig. 9.

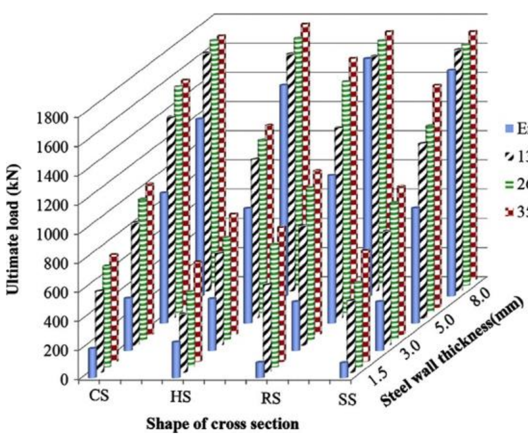


Fig. 11. The change in ultimate load values according to the domain parameters.

In general, deformation values are increased as a result of the elimination of the buckling of steel tube in an inward direction according to the increment of the core concrete compressive strength values.

Minimum load can be seen on hexagonal specimens. In addition, circular specimens showed maximum displacement values of 26.0 MPa and 35.3 MPa for concrete filled steel tubes. Square and rectangular specimens carried more load, while they indicated less displacement according to the effective areas of resistance against the load related to the results in Figs. 10 and 11.

The changes in ultimate load capacity values are given in Fig. 12 with respect to the cross sectional shape, steel wall thickness and concrete compressive strength. Ultimate load capacity values are also increased according to the increment of concrete compressive strength and steel wall thickness. The ultimate load capacity of composite sections are considerably increased in comparison with the unconfined compressive strength values of concrete and ultimate load capacity values of hollow steel tubes. Some of the specimens with 80 mm steel wall thickness reached the maximum capacity of the compression machine. The ratio of the stress capacity for Filled to Hollow was found minimum for the RS cross section, where the failure stress was found about 591MPa when the applied displacement is 1 mm.

The increment ratio of ultimate stress capacities of the CFST members, with respect to the initial unconfined concrete compressive strength, are compared according to all the domain parameters given in Table 3. These are average values for each variable. This is one of the main results of this paper. If the steel wall thickness increases, the increment ratio of axial stress values also increases. Despite the decrement in the area of the core concrete, the stress values increase according to the confinement effect increment caused by the steel wall thickness. Maximum axial stress increments are also observed in circular sections for this reason. They have higher values than square and rectangular specimens. Therefore, the axial stress increment ratio of the CFST members decreases with the increment of compressive strength of the core concrete.

3.2. Ductility characteristics

The circular specimens have maximum ductility behavior when ductility values were analyzed. Ductility values were calculated as a ratio between the maximum deformation at the ultimate load point and the deformation at the elastic limit. All concrete filled specimens have higher ductility than related hollow specimens. The ductility values of 19.8, 11.6, 4.0 and 3.1 are circular, hexagonal, square and rectangular specimens, respectively, as shown in

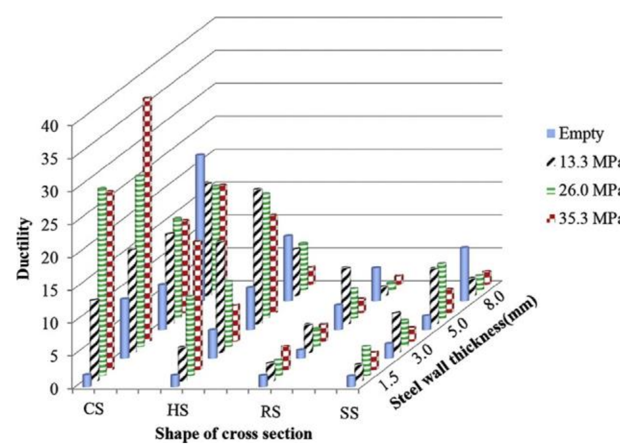


Fig. 12. The variation of ductility values of CFST specimens.

4. Conclusions

In this paper, both experimental and finite element analyses of 64 CFST stub columns with three different domain parameters in total have been analyzed. The change of mechanical properties, such as ultimate load, ultimate stress, ductility and buckling values are presented in the paper with respect to the domain parameters. Based on the results, the following conclusions may be drawn.

Core concrete prevents the buckling of steel tube in an inward direction and steel tube provides a confinement effect for axially loaded CFST stub columns at the same time. Axial strength values increased at CFST columns when these were compared with the unconfined compressive strength of core concrete. Maximum increment ratios are seen in the circular sections at 167.8%. The increment ratio is enhanced with respect to both the thickening of steel tube and a decrease of compressive strength of the concrete. This behavior also consists of a confinement effect along all lateral directions on rounded specimens.

Average ductility values were calculated as 19.8, 11.6, 4.0 and 3.1 for the circular, hexagonal, square and rectangular specimens respectively. It can be clearly seen that rounded specimens have higher ductility than angular specimens.

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