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Buckling performance of thin-walled filled steel columns

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Abstract

Concrete-filled composite elements have recently gained popularity as beams and columns all over the world. They have advantages similar to reinforced concrete elements, such as the moulding process and the lack of maintenance of the filled concrete, as well as advantages similar to hollow steel elements, such as enhancing compressive strength and bending capacity by using smaller sections. In this paper, the buckling behaviour of thin-walled steel columns with circular cross-section and different filling materials was investigated under uniaxial load. Six different materials (concrete produced using normal aggregate, concrete produced using waste aggregate, waste fine aggregate, waste coarse aggregate, waste iron dust and polyurethane) were used as filling. Filled columns were compared experimentally with hollow thin-walled steel columns that had the same height and diameter. All specimens had the same length (750 mm), same diameter (60.3mm) and the same wall thickness (3mm). Experimental results were compared with analytical results obtained from a calculation done using the national steel design code, Design, Calculation and Construction Principles of Steel Structures 2016. Additionally, columns specimens were modelled in Abaqus software. Conservative and consistent results were obtained from comparing experimental, analytical, and numerical results.

1. Introduction

Concrete and structural steel are the most used materials in construction sector today. If the mechanical properties of these two materials are examined, it is seen that the concrete has high compressive strength with very low flexural capacity. On the other hand, structural steel has both, high flexural capacity and high compressive strength but has a great weakness against fire and buckling problem. To overcome the weakness of these two materials, they are both used together as concrete-filled composite members (CFST) [1]. CFST members have been used widely, recently. Concrete-steel composite columns have numerous advantages and are an interesting alternative for columns made of steel or reinforced concrete. CFST members are more fire resistant than steel structures, additionally, local buckling occurs in steel members, where this problem is mostly prevented in CFSTs [2-6]. CFST columns have higher axial load capacity than reinforced concrete columns [7-8].

1.1. Literature Review

CFST members has been investigated experimentally by some researchers. For example, Han investigated the flexural behaviour of 16 concrete-filled steel beams with a length of 1100 mm and a cross-section of square and rectangular. The beams had the width/depth ratio varying between 1 - 2 and the depth/thickness ratio varying between 20 and 50. Additionally, Han compared experimental results with different standards and codes [9]. Zeghiche and Chaoui investigated 27 concrete-filled steel tubular columns. The main objective of the study was to demonstrate the influence of column slenderness, loading type and compressive strength of the infill concrete on the strength and behaviour of concrete-filled steel tubular columns [10]. Abramski examined 30 CFST columns. In this study, different parameters such as column slenderness factor, various tube thickness, loading type and bond strength between steel and concrete was used [11]. Essopjee and Dundu investigated

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double-skin CFST columns under axial compression until failure. The parameters of this study are the lengths, diameters and strength of the steel tube. Additionally, results obtained from the experimental investigation were compared with international standards and codes such as the South African Standard (SANS) and Eurocode 4 (EC4). Furthermore, experimental results had good agreement with analytical results [12]. Ibanez et al. [13] investigated different cross-sectional shapes CFST stub columns which filled normal and high strength concrete. The test specimens' cross-sections were circular, rectangular and square and also all specimens had equivalent cross-sectional area. Experimental test results compared with Eurocode 4, American, Australian and Chinese codes.

CFST members has been studied theoretically. For instance, Liang and Fragomeni investigated the nonlinear inelastic behaviour of concrete-filled short columns under axial load. The theoretical results obtained from the study were compared with the results obtained from the experimental studies available in the literature [14]. The axial load capacity of CFST columns subjected to concentric and eccentric loads was established by Tan and Nichols. The extent of the experimentally recorded compressive strength increase for the filled concrete owing to steel confinement is proportional to the ratio of steel to a concrete area, according to the findings. As the eccentricity to radius ratio rises, the columns load-carrying capacity and maximum strain drop if the slenderness ratio remains constant [15]. Roader et al. calculated the stiffness and resistance of circular CFST using combined axial and flexural loads. For the evaluation, 122 test specimens were collected from literature observations. The plastic stress method, according to the results, is an effective method for predicting the combined load capacities of circular CFST columns. Furthermore, data shows that current provisions produce ineffective results. The presented models allow for accurate stiffness and resistance predictions [16].

CFST members has been studied numerically using finite element analysis. Abed et al. investigated compressive behavior of CFST's columns subjected to axial load. Three different diameters to thickness ratios and two different compressive strength were used in this investigation as parameters. Axial load capacities obtained from the test were compared with different international codes and standards [17]. Duarte et al. numerically examined short CFST columns filled with rubberized concrete, including rubber particles, in terms of ductility and strength. Short CFST columns with rubberized concrete were compared with same size CFST columns filled with normal concrete. Moreover, columns were modelled numerically to include two types of concrete. Ultimate strengths, load-displacement curves and failure modes were found numerically. Numerical results were compared with experimental results. Furthermore, the results showed good agreement [18]. Hassanein et al. numerically investigated the octagonal cross-sections CFST columns. Finite element model parameters were diameter-wall thickness ratios of steel tube varying from 40 to 200 and compressive strength of filled concrete ranging from 40 to 100 MPa. Finite element analysis results were compared with existing design codes and standards. Results obtained from numerical analysis were conservative with existing provisions [19]. Al-Ani investigated the axial load capacity of circular CFST stub columns numerically and analytically using finite element analysis via Abaqus software. Finite element analysis results were compared with experimental results in terms of failure load and load-displacement curves. The finite element model and analytical model were consistency with experimental data [20]. Saleh and Al-abboodi numerically investigated CFST stub columns under axial compression using Abaqus software. Investigation parameters for the study were the effects of the concrete grade, steel grade, wall thickness of the steel tube and the cross-sectional shape [21].

In this study, the buckling performance of thin-walled steel columns was experimentally investigated. A total of 13 columns with circular cross-section were used. 2 of 13 specimens were cast as hollow columns and used as reference specimens. The rest were filled with different materials. As filling 6 different materials consisting of waste fine aggregate, waste coarse aggregate, waste iron dust, polyurethane and two types of concrete which, one was produced using normal aggregate and the second one with waste aggregate were used. The main objectives of this study were threefold: first, the investigation of the buckling performance of the thin-walled columns filled with different materials; second, to see the convergence of Turkish national steel design code with axial load capacity obtained from the experimental study [22]. Final, to demonstrate the modelling of concrete-filled composite columns in the Abaqus software that performs Finite Element Analysis (FEA).

2. Materials

2.1. Aggregates

In study, two types (waste and normal) of aggregates have been used in two ways. First as a filling material and second as component of concrete. Sieve analysis has been done to classify the aggregates size. For both types of aggregates, grain diameters were determined as 1-4 mm (fine) and 4-16 mm (coarse). Fine aggregate water absorption rate was calculated as 10.64%, and coarse aggregate water absorption rate was 4.62%. The specific gravity values of fine and coarse aggregates are 2.2 gr/cm^3 and 2 gr/cm^3, respectively. Summary of aggregate usage details in this study is given in Table 1 and Figure 1.

2.2. Concrete

The mix proportions of the concrete used in the study are described in Table 1. Concrete was produced from both normal aggregate and waste aggregate. Three-cylinder samples were cast from each of the produced concrete. The samples cast were subjected to a compressive strength test after 28 days of curing. According to the test results, the 28-day cubic compressive strength was about 37 MPa. So cylindrical compressive strength can be calculated about 30 MPa

(Figure 2). The slump values were obtained from the slump test and the slump value for both types of concrete were approximately 70 mm.

Figure 1. 1-4 mm (fine) and 4-16 mm (coarse) aggregate

Figure 2. Cubic concrete specimens and compressive test

Table 1. Mix proportions of concrete

Concrete Compressive Strength Type	Cement (%)	Aggregates (%)		Water (%)	Chemical Additives (%)
		Fine	Coarse		
Normal Strength	28.6	14.3	43	13.8	0.3

2.3. Polyurethane foam

The mechanical properties of the polyurethane were obtained from the manufacturer notes. It has a deformation capacity of up to 10% of the total thickness of the material. The average compressive strength shown in the thickness of the material used in the test was 0.516 MPa. The young modulus of polyurethane was between 3-5 MPa.

2.4. Structural steel

The same mechanical properties are expected in each location on the surface of steel columns. Therefore, 2 thin-walled steel profiles used in the experiment were obtained from the same manufacturer. Column specimens were obtained by dividing the profiles at 750 mm. The structural steel had a diameter of 60.3 mm, a wall thickness of 3 mm and a characteristic yield strength of about 235 MPa (Figure 3).

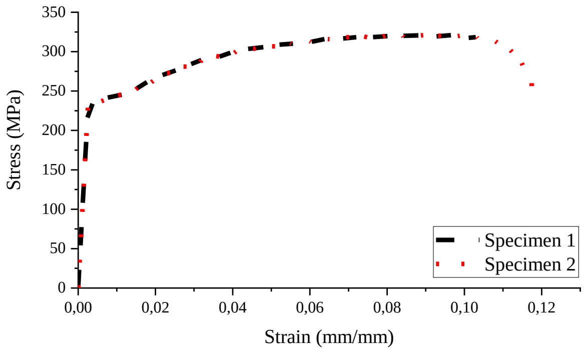


Figure 3. Tensile test results for the steel tube

2.5. Filled columns specimens

In the experimental part of this study a total of 13 CFST column specimens with an identical height and circular cross-section of 750 mm and 60.3 mm were casted in the laboratory. 2 of 13 specimens were consider as reference and cast as hollow columns. From the remaining 11 specimens 2 were filled with concrete produced from normal aggregate, 2 filled with concrete produced from waste aggregate, 2 filled with waste fine aggregate, 2 filled with waste coarse aggregate, 2 filled with polyurethane foam and 1 was filled with waste iron dust. The steel columns were cleaned before filling. Steel plates which had 3 mm thickness were welded under the specimens with fillings, to prevent the discharge of filling materials. In order to place the filling materials homogeneously and without any gaps, the vibration process was applied for 15 seconds. A brief specification of test samples is given in Table 2.

3. Methods

3.1. Experimental study

In this study, thin-walled steel columns filled with different materials were subjected to uniaxial compressive load. In the experiments, a hydraulic press with a capacity of 3000 kN was used to apply the uniaxial load. The applied load and deformations were measured by load-cell and linear variable displacement transducers (LVDT) respectively, which then the data was transferred to a computer by using a data logger. The rotation of specimens was prevented at the supports, and their movement was restricted in the longitudinal and transverse directions. The specimens were capped on both ends with rigid steel caps to distribute the applied load uniformly over the concrete and steel cross-section. A total of 5 LVDTs were used to measure the horizontal and vertical displacements of the columns under the uniaxial load. One LVDT was used to measure the vertical displacement, and the rest were used to measure horizontal displacements. The experimental setup is shown in Figure 4.

Table 2. Specimen labels and material properties

No	Specimens	D (mm)	t (mm)	L (mm)	Infill Materials
1	C-H1	60.3	3	750	-
2	C-H2	60.3	3	750	-
3	C-NC1	60.3	3	750	concrete produced from normal agg.
4	C-NC2	60.3	3	750	concrete produced from normal agg.
5	C-RC1	60.3	3	750	concrete produced from waste agg.
6	C-RC2	60.3	3	750	concrete produced from waste agg.
7	C-RFA1	60.3	3	750	waste fine agg.
8	C-RFA2	60.3	3	750	waste fine agg.
9	C-RCA1	60.3	3	750	waste coarse agg.
10	C-RCA2	60.3	3	750	waste coarse agg.
11	C-P1	60.3	3	750	polyurethane
12	C-P2	60.3	3	750	polyurethane
13	C-ID1	60.3	3	750	iron dust

4. Methods

4.1. Experimental study

In this study, thin-walled steel columns filled with different materials were subjected to uniaxial compressive load. In the experiments, a hydraulic press with a capacity of 3000 kN was used to apply the uniaxial load. The applied load and deformations were measured by load-cell and linear variable displacement transducers (LVDT) respectively, which then the data was transferred to a computer by using a data logger. The rotation of specimens was prevented at the supports, and their movement was restricted in the longitudinal and transverse directions. The specimens were capped on both ends with rigid steel caps to distribute the applied load uniformly over the concrete and steel cross-section. A total of 5 LVDTs were used to measure the horizontal and vertical displacements of the columns under the uniaxial load. One LVDT was used to measure the vertical displacement, and the rest were used to measure horizontal displacements. The experimental setup is shown in Figure 4.

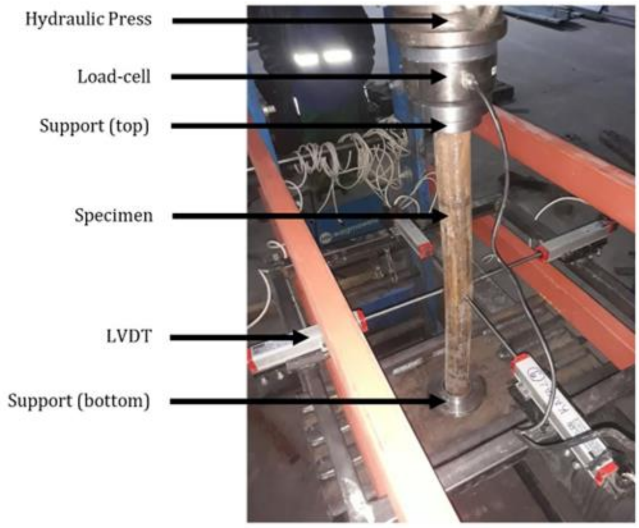


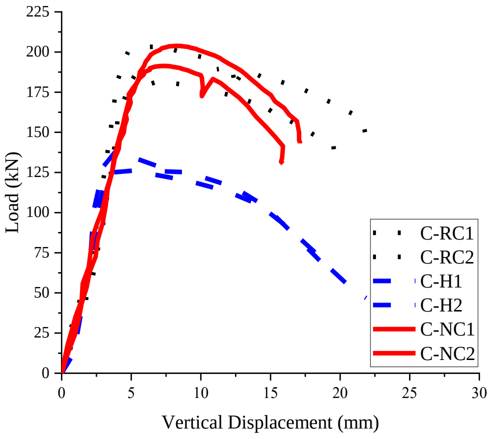
Figure 4. Test setup and instrumentation

In order to consider the behaviour of the filled steel column, 13 specimens were tested with various infill materials and same wall thickness. 60.3 mm diameter circular hollow section (CHS) with 3 mm wall thickness were used for the tests. All the tests have been carried out at the KTO Karatay University Structural Mechanics Laboratory.

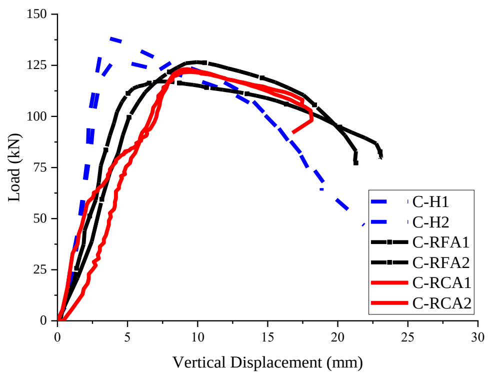
The specimens were loaded at 5 kN intervals during the test period. Uniaxial loading was operated manually. All the readings were recorded when both load and displacements had been stabilized. After the failure of the specimen due to local buckling, the loading was not stopped, and the test continued as the vertical displacement reached about 25 mm. Load – displacement curves obtained from the experiment are shown in Figure 6.

All test specimens of experimental investigations after buckling are given in Figure 5.

Figure 5. Test specimens after buckling



(a)



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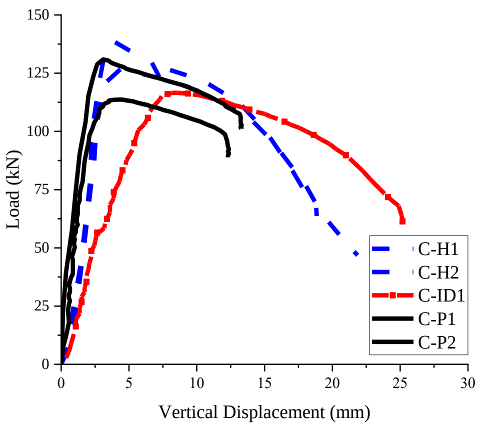

(c)

Figure 6. Experimental test results

4.2. Analytical study

According to [22] section 12, for the plastic stress distribution method, the nominal strength shall be computed assuming that steel components have reached stress of F_y in compression, and concrete components in compression due to axial force have reached stress of 0.85 f_{ck}. For a circular cross-section filled with concrete, the stress of 0.95 f_{ck} is permitted to be used for concrete components in compression due to axial force to account for the effects of concrete confinement.

DCCPSS – 2016 [22] has determined material limits for concrete-filled composite sections that can be used. For the determination of the available strength, concrete shall have a compressive strength (f_{ck}) of not less than 20 MPa nor more than 70 MPa for normal-weight concrete. The specified minimum yield stress of structural steel used in strength calculation of the composite members shall not exceed 460 MPa. The concrete compressive strength used in the study was 30 MPa and the characteristic yield strength of the structural steel element was determined as 235 MPa.

CFST columns need to be classified for local buckling. The cross-section used in the test was in compact class according to the λ_p limit value given in DCCPSS - 2016 Table 12.1A.

DCCPSS - 2016 Table 12.5 was obtained based on the interaction diagram. According to this table, the axial force formula is given in Equation 1.

$$M_A = 0 \,;\; P_A = A_S F_y + 0.95 f_{ck} A_C \qquad (1)$$

where F_y was the yield strength of the structural steel and f_{ck} was compressive strength of the concrete. A_S and A_C were the cross-section areas of steel and concrete, respectively.

4.3. Numerical study

Numerical studies are straightforward and rapid than experimental studies. However, the materials must be defined conveniently to obtain realistic results. There are many programs based on finite element method that can be used to evaluate the numerical analysis of load bearing elements. Abaqus is one of these programs which any structural element can be analyzed numerically in this software [23].

In this paper, Abaqus software was used for concrete-filled column design and analysis. Solid element (C3D8R) in the Abaqus was used to define both the concrete core and the structural steel. Rigid steel caps were modelled with discrete rigid shell elements. These caps were used to distribute the applied load uniformly over the concrete and steel. Concrete-filled column model is illustrated in Figure 7.

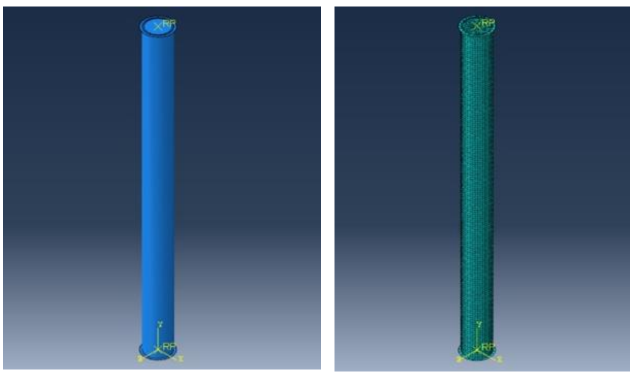

Figure 7. CFST column model in Abaqus

Young modulus was taken as 26600 MPa, and Poisson's ratio of concrete was assumed to be 0.2, in the elastic properties of concrete. To define the plastic properties of concrete "Concrete Damage Plasticity" was used. The compressive and tensile behavior values of concrete were utilized from [24]. To define the elastic properties of steel, Young modulus was taken as 200 GPa and Poisson's ratio of steel was assumed to be 0.3. The plastic properties of steel were modeled where the yield stress was taken as 235 MPa and the plastic strain was defined as "0" at yielding point. Additionally, ultimate stress and strain was defined as 360 MPa and 0.1, respectively. The properties of materials are shown in Table 3. The interface between the concrete core and steel tube of CFST was modelled in the tangential and normal directions. The friction coefficient was taken 0.3 between steel and concrete (F. H. Abed et al., 2018).

Table 3. Material properties

Elastic/ Plastic	Material parameters	Concrete core	Structural steel
Elastic	Young modulus (MPa)	26600	200000
	Poisson's ratio	0.2	0.3
Plastic	Dilation Angle	31	-
	Eccentricity	0.1	-
	fb0/fc0	1.16	-
	K	0.67	-
	Viscosity parameter	0.0005	-

The numerical study was done with displacement control. The deflection was increased until the vertical displacement reached to 25 mm. Load – displacement curves obtained from the analysis is shown in Figure 8.

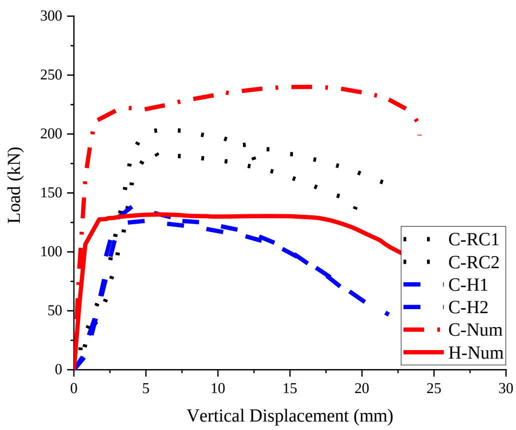

Figure 8. Numerical results

5. Results

To evaluate and compare the obtained results, the mean values of reference specimens have been taken into consideration. Comparing the mean value (C-H1 and (C-H2) and C-NC1 and C-NC2, the axial load capacity had increased by approximately 49%, and the vertical displacement was increase around 79%. Similarly comparing the mean value (C-H1 and (C-H2) and C-RC1 and C-RC2, the axial load capacity had increased by approximately 47% and the vertical displacement increment was around 27%. In the comparison of the reference columns with columns which filled with different aggregates, the axial load capacity had no increments. However, vertical displacement increased by approximately 122% for C-RFA1 and C-RFA2 and 117% for C-RCA1 and C-RCA2. Similarly, the axial load capacity of C-ID1 did not increase but its vertical displacement was increased by about 135%. Unlike other results, neither the axial load capacity nor the vertical displacement value of the C-P1 and C-P2 specimens increased. The results obtained from the experimental study performed as described in the previous sections are summarized in Table 4.

Experimental and analytical results were compared. And, for hollow columns, the prediction success ratio was 96%. Similarly, for C-NC1 and C-NC2, this ratio was 98% and for C-RC1 and C-RC2 was 99%. The prediction success ratio for concrete-filled specimens was 98.6%. Comparisons results are summarized in Table 5.

Numerical results were compared with experimental results. According to comparison, for hollow columns, the ratio of numerical results to experimental results was in the range of 0.959, at the yield point. Similarly, the ratio was 1.110 for concrete-filled columns produced from normal aggregate. Comparisons results are given in Table 6.

Table 4. Results obtained from the experiment

Specimens	P_{EXP} (kN)	Vertical Displacement (mm)	Increase in Axial Load Capacity (%)	Increase in Vertical Displacement (%)
C-H1	138.601	4.245	-	-
C-H2	126.730	4.388	-	-
Mean Value (C-H1 and C-H2)	**132.666**	**4.317**	**-**	**-**
C-NC1	191.350	7.266	44.23	68.31
C-NC2	203.836	8.201	53.65	89.97
C-RC1	185.580	5.252	39.89	21.66
C-RC2	203.302	5.683	53.24	31.64
C-RFA1	117.128	9.266	No Increments	114.64
C-RFA2	126.556	9.928	No Increments	129.97
C-RCA1	121.735	9.424	No Increments	118.30
C-RCA2	123.138	9.281	No Increments	114.98
C-P1	130.901	3.094	No Increments	No Increments
C-P2	113.683	4,388	No Increments	No Increments
C-ID1	116.607	10.144	No Increments	134.98

Table 5. Comparisons between experimental and analytical results

Specimens	P_{EXP} (kN)	$P_{ÇYTHYE}$ (kN)	$P_{ÇYTHYE}/P_{EXP}$
C-H1	138.601	126.909	0.915
C-H2	126.730	126.909	1.001
Mean Value (C-H1 and C-H2)	132.666	126.909	0.956
C-NC1	191.350	192.908	1.008
C-NC2	203.836	192.908	0.946
C-RC1	185.580	192.908	1.039
C-RC2	203.302	192.908	0.949
C-RFA1	117.128	-	-
C-RFA2	126.556	-	-
C-RCA1	121.735	-	-
C-RCA2	123.138	-	-
C-P1	130.901	-	-
C-P2	113.683	-	-
C-ID1	116.607	-	-
Mean Value (Filled Specimens)			0.986
Mean Value (All Specimens)			0.971

Table 6. Comparisons between experimental and numerical results

Specimens	P_{EXP} (kN)	P_{NUM} (kN)	P_{NUM}/P_{EXP}
C-H1	138.601	127.250	0.918
C-H2	126.730	127.250	1.004
Mean Value (C-H1 and C-H2)	132.666	127.250	0.959
C-NC1	191.350	219.018	1.145
C-NC2	203.836	219.018	1.075
Mean Value (Filled Specimens)			1.110
Mean Value (All Specimens)			1.035

6. Conclusion

In this study, the axial load capacity of CFST columns with circular cross-section and filled with different materials (concrete produced from normal aggregate, concrete produced from waste aggregate, waste fine aggregate, waste coarse aggregate, polyurethane foam and waste iron dust) were determined experimentally. And the results were compared with analytical and numerical models. The main results obtained from limited number of test specimens are listed below:

(1) CFST columns have more load-carrying capacities than hollow and filled with different materials columns.
(2) Vertical displacement increased in CFSTs compared with hollow columns. Load-carrying capacities had no increased infilled with different materials columns compared with hollow columns however vertical displacement increased considerably, except filled with polyurethane.
(3) Compared experimental and analytical results for CFSTs and hollow columns, ÇYTHYE is successful in prediction of load-carrying capacity (approximately 97%).
(4) Compared experimental and numerical results for CFSTs and hollow columns, Abaqus software is successful in modelling, analyzing, and predicting.
(5) All results compared with each other, results are conservatively and successfully.

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Author contributions

Abdulkerim İlgün: Investigation, supervision, methodology, funding acquisition. **Ahmad Javid Zia:** Investigation, supervision, writing - original draft writing - review & editing. **Sadrettin Sancıoğlu:** Conceptualisation, methodology, investigation, writing - original draft writing - review & editing. **Hasan Furkan Soydoğan:** Methodology, investigation, writing. **Münife Hanım Köklü:** Investigation, analyzing, writing. **Semih Arıbaş:** Investigation, writing, funding acquisition. **Berna Bayram:** Investigation, writing.

Conflicts of interest

The authors declare no conflicts of interest.

Abbreviations

CFST	Concrete-filled steel tubes
CHS	Circular hollow section
DCCPSS	Design, Calculation and Construction Principles of Steel Structures
FEA	Finite element analysis
LVDT	Linear variable displacement transducers
A_C	Cross-section area of concrete
A_S	Cross-section area of steel
f_{ck}	Compressive strength of the concrete
F_y	Yield strength of the structural steel
P	Axial load capacity

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