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EXPERIMENTAL TESTING OF AXIAL LOAD CAPACITY AND STABILITY OF CIRCULAR CFT COLUMNS

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Abstract:

The paper presents the experimental testing of the axial capacity and stability of short, moderately slender and slender circular CFT columns. For the purpose of sample testing a special set of hydraulic presses was constructed. In order to achieve centric loading of the load, a device calotte was used. With the help of the dosing and gauges placed at the top of the column, force and vertical displacement were measured continuously. The test was carried out on two short columns 0.5 m and 1.0 m long, and four moderately slender and slender columns with a length of 4.0 m with different boundary support conditions. In the short CFT columns the confinement effect was taken into account as well and loss of bearing capacity occurred due to the steel profile yield strength. In moderately slender and slender columns, the loss of stability occurs before the loss of the load capacity of the column. The obtained results of the experimental tests were then compared with the valid regulations: EC4, ACI, AS and AISC. It can be concluded that EC4 gives the most approximate results to the experiment.

Key words: circular CFT columns, experimental testing, load capacity and stability

1. Introduction

CFT columns are concrete filled steel tube columns. Calculation of the load capacity and stability are both based on the limit states design methods. Due to geometry imperfections, non-linear characteristics of concrete and steel materials, residual stresses in the steel profile, history of the load and its eccentricity, second order theory, etc., determination of load capacity of CFT columns is a complex process.

The loss of stability of the structural element is demonstrated with loss of the designed position and shape of the column followed by large deformations and the plastic release of the material until the new equilibrium state is reached. Since the deformations are large, the force balances are set on the deformed configuration and so the superposition principle cannot be applied. And finally, taking into account nonlinear stress strain relationship, determining the critical load becomes not only geometric and static, but also material non-linear problem.

According to design codes such as: EC4 (Eurocode 4) [1], ACI (American Concrete Institute) [2], AS (Australian Standard) [3, 4], AISC (American Institute of Steel Construction) [5] the load capacity of the composite CFT column can be calculated with adequate accuracy.

The length of the CFT column has a significant effect on its load capacity [6, 7, 8, 9]. In case of short and moderately slender column, the load capacity loss can occur due to fracture of the concrete or due to the yield strength of steel tubes. However, the loss of load capacity of slender columns is based on the problem of stability. In slender columns, the fracture is caused by the buckling in the elastic area, while in moderately slender columns, the buckling happens in the plastic area.

2. Experimental testing of axial capacity and stability of CFT columns

The paper presents the experimental testing of the axial load capacity of CFT short columns, the stability of CFT moderately slender and slender columns with different boundary conditions: simple support on top and simple or fixed support at the bottom.

For the purpose of carrying out the test, a special set is constructed as in Figure 1. The set consists of an outer fixed steel frame 2300 mm · 900 mm · 900 mm with two hydraulic presses diameter Ø200 mm, as well as an internal mobile steel frame 2400 mm·600 mm ·600 mm. The outer steel frame is ballast, while the internal steel frame is used to apply pressure force to the sample. The stroke length is 40 cm. The hydraulic presses are powered by two electric motors (power 7 kW and 10kW) with two hydraulic pumps (for lower and higher pressure). The capacity of the press is 300 bars, which makes possible to achieve a force of intensity of about 1885 kN. At the end of each working stroke of the hydraulic presses the pressure on the gauge is measured and it is registered in the work chart. The relationship between the pressure shown on the gauge and the force is linear.

Fig.1. Set for sample testing with hydraulic presses

All CFT column samples have compressive strength of concrete tested first. The mean values obtained are f_c'=30.50 MPa for short columns and f_c'= 26.70 MPa for moderately slender and slender columns which correspond to C30/37 or C25/30 concrete class respectfully.

In order to achieve centric loading of the columns a special device-calotte was applied. The loading for each sample was applied in increments of 5 bar, corresponding to a force of 31.42 kN. Applying the load until fracture took about 3 minutes for each sample tested, so the load can be considered to be short-lived. In order to apply the load to the steel profile and the concrete core simultaneously, concrete core was made to be several centimetres longer than the steel profile. Finally, on the day of testing, the upper and lower surfaces of the column were finely aligned with concrete grinder.

Fig.2. Device-calotte

2.1 Testing of axial load capacity of short CFT columns

The load is applied incrementally over a rigid plate which is welded at the upper end of the steel column and the CFT column.

Force is measured continuously with a C6A2MN dosing device that can measure a force of up to 2000 kN with an accuracy of ± 0.1 kN. The shortening od the column is measured continuously as well by using the W100 type gauge (Inductive Standard Displacement Transducers), which allows measuring of shortening or vertical displacements of the column with an accuracy of ± 0.01 mm. Fracture of samples *C1* and *C2* was caused by reaching yield strength of the steel profile. Figure 3 shows the tested samples.

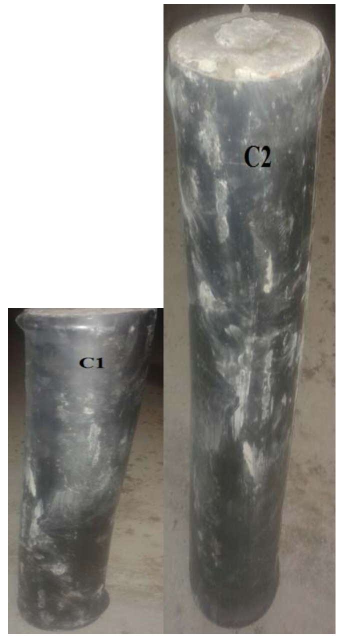

Fig. 3. Tested samples *C1* and *C2*

2.2 Testing of stability of moderately slender and slender CFT columns

The stability of four samples *C3*, C4, *C5* and *C6* all 4.0 m long was tested. The samples *C3* and *C4* are composite CFT columns fixed on the bottom into the steel plate of dimensions 450 mm · 450 mm · 30 mm. Top of the samples has horizontal displacement prevented while rotation and vertical displacement are permitted, which corresponds to the movable support. Samples *C5* and *C6* are composite CFT columns with simple supports on both ends.

The ratio of the outer diameter and wall thickness of the steel profile for the sample *C3* is D/t = 101.6 mm/2.7 mm, while for the sample *C4* it is D/t = 114.3 mm/2.7 mm. Steel quality is S355. The concrete fill in the steel tubes is class C25/30, while the mean value of the tested compressive concrete strength is f_c '=26.70 MPa.

As previously described, load and vertical displacements or shortening of the columns were measured at the top of the columns continuously. The gauges set which are placed at 0.35·L from the top of the sample columns *C3* and *C4*, or to 0.50·L for samples *C5* and *C6* measured the horizontal displacement. The accuracy of ± 01 kN for force and 0.01 mm for vertical and horizontal displacement was achieved in these testing as well.

3. Presentation and processing of experimental test's results

This chapter presents the results of experimental tests of samples *C1* and *C2*. Diagram in Figure 4 shows the dependence of the axial load capacity N on the engineering strain ε=ΔL/L for the CFT column L=0.50 m (sample *C1*), while the diagram in Figure 5 shows the dependence of the axial load capacity N on the strain ε for the CFT column L=1.00 m (sample *C2*).

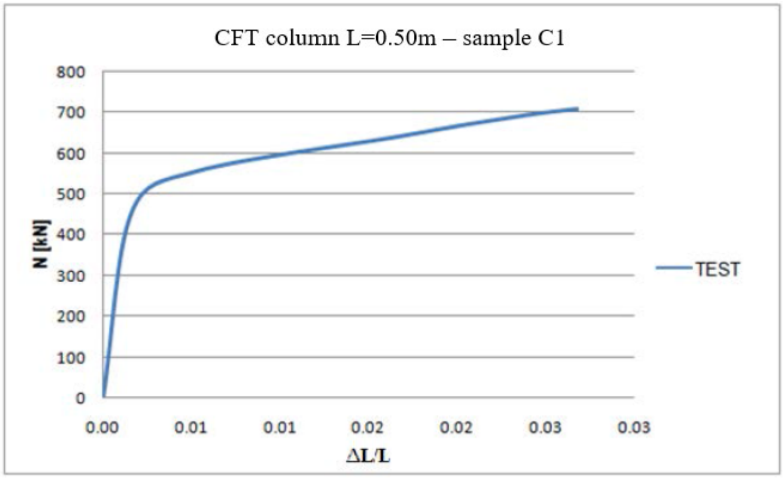

Fig.4. Diagram N-ΔL/L of sample *C1*

The diagram shows almost linear increasing of the axial force until N=400 kN and strain of about 0.0025. Further increase of axial force causes the plastic material behaviour with hardening.

If the length of the column is increased to 1.00 m (sample *C2*), the non-elastic behaviour of the material starts significantly earlier, at about 200 kN for the force and about 0.001 for the strain (Figure 5).

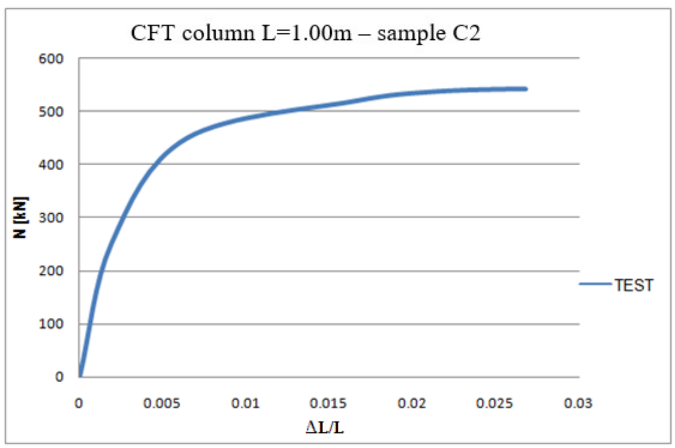

Fig.5. Diagram N-ΔL/L of sample *C2*

Based on the obtained results, it can be concluded that the axial load capacity of the CFT column significantly depends on the length of the column. Increase in length of the column from 0.50 m to 1.00 m results in 1.26 times smaller axial load capacity of the CFT column.

The second part of the experimental testing includes a stability analysis of 4 meters long CFT columns. Figure 6 shows the dependence of the critical buckling force N on the engineering strain $\varepsilon = \Delta L/L$ for the sample *C3*. The loss of stability of the CFT column is realized at a force of 327.7 kN, while the maximum horizontal displacement on 0.35L from the top of the column was 41.24 mm.

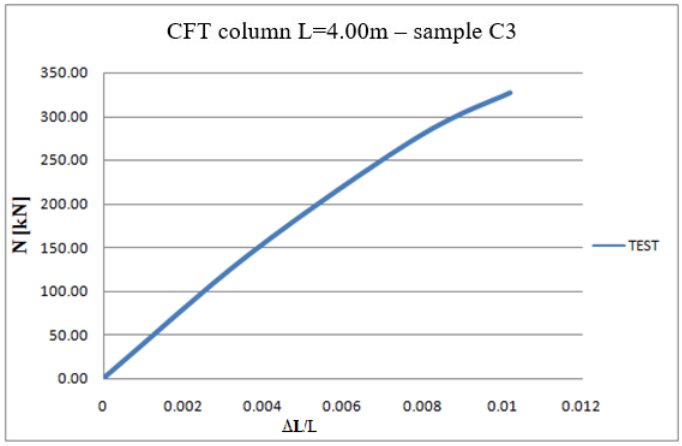

Fig.6. Diagram N-ΔL/L of sample *C3*

Diagram in the Figure 7 shows the dependence of the buckling force on the engineering strain for the sample *C4*. The loss of stability of the CFT column is realized at a force of 489.1 kN, while the measured maximum horizontal displacement on 0.35·L from top of the column was 43.27 mm.

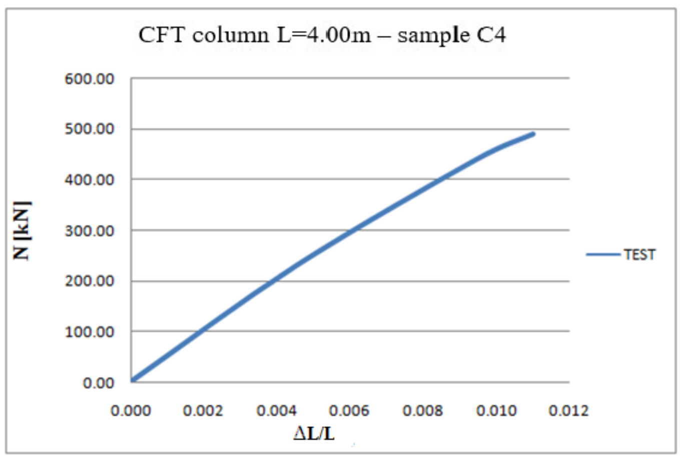

Fig.7. Diagram N-ΔL/L of sample *C4*

Based on the shape of the diagram, it can be concluded that the behaviour of the samples *C3* and *C4* is approximately elastic. However, in certain part of the cross section the yield strength of steel tubes has occurred.

The Figure 8 shows dependence of the buckling force on the engineering strain for the sample *C5*. The loss of stability of the CFT column is realized at a force of 226.0 kN, while the measured maximum horizontal displacement on 0.5·L from top of the column was 32.93 mm.

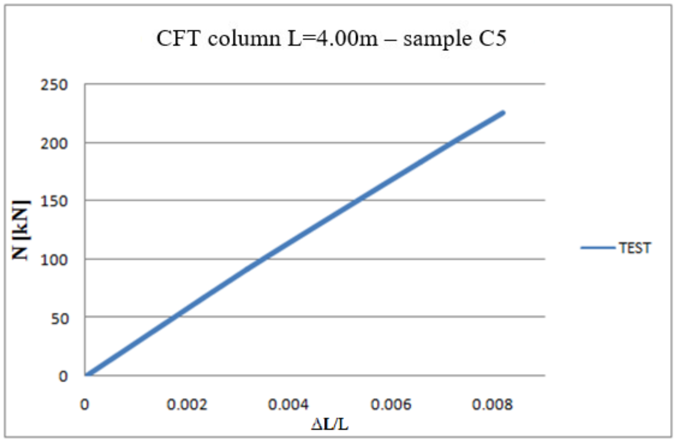

Fig.8. Diagram N-ΔL/L of sample *C5*

The Figure 9 shows dependence of the buckling force on the engineering strain for the sample *C6*. The loss of stability of the CFT column is realized at a force of 319.0 kN, while the measured maximum horizontal displacement on 0.5·L from top of the column was 36.45 mm.

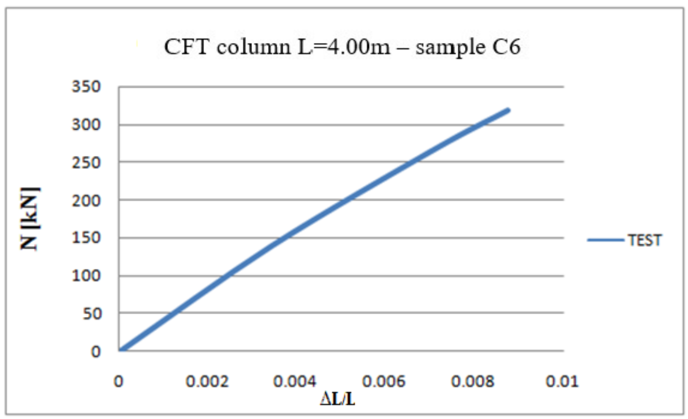

Fig.9. Diagram N-ΔL/L for sample *C6*

Based on the shape of the diagrams, it can be concluded that the behaviour of samples *C5* and *C6* is elastic, thus the loss of stability of these CFT columns has occurred in an elastic region. The elastic behaviour of the *C5* and *C6* samples could have been expected, since these samples were slender columns.

4. Verification of the results

In order to verify the obtained test results, a comparison to the designed guide was made.

According to Eurocode 4 [1], the load capacity of a fully-plastified circular cross-section of the CFT column at compression $N_{pl,Rd}$ can be calculated as follows:

$$N_{pl,Rd} = A_a \cdot f_{yd} + A_c \cdot f_{cd} + A_s \cdot f_{sd} \tag{1}$$

where A_a, A_c and A_s are the surfaces of the cross section of the steel profile, concrete and reinforcement, and $f_{yd}=f_y/\gamma_a$, $f_{sd}=f_{sk}/\gamma_s$, $f_{cd}=f_{ck}/\gamma_c$ are the corresponding yield strengths for steel and reinforcement, and compressive strength for concrete; f_y, f_{sk}, f_{ck} are their respective characteristic values; γ_M=1.0, γ_c=1.5, γ_s=1.15 are recommended values of the partial safety coefficients for the corresponding materials according to EC2 [10] and EC3 [11].

According to EC4 for concrete-filled steel tube columns, it is possible to take into account the increase of compressive concrete strength due to the confinement effect if the following conditions are met [1]:

relative slenderness $\overline{\lambda} \leq 0.5$, e / D <0.1, where e is the load eccentricity, while D is the external diameter of the CFT column.

In this case, fully-plastified circular cross-section of the CFT column under compression can be calculated as follows:

$$N_{pl,Rd} = \eta_a \cdot A_a \cdot f_{yd} + A_c \cdot f_{cd} \cdot \left[1 + \eta_c \cdot \frac{t}{D} \cdot \frac{fy}{fck}\right] + A_s \cdot f_{sd} \quad (2)$$

The confinement effect is taken into account by using coefficients η_c and η_a which depend on relative slenderness $\overline{\lambda}$ and e/D ratio.

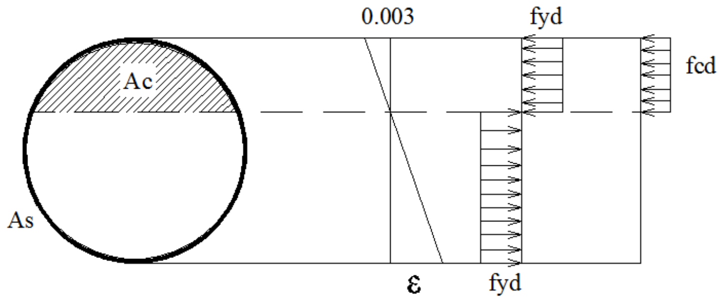

Fig. 10. Stress and strain distribution in cross section according to EC4 method

According to ACI [2] and AS [3], the axial load capacity of the fully-plastified cross-section of the CFT column is calculated without the corresponding material safety coefficients (unfactored axial load) and is given by the following formula:

$$N_{ACI,AS} = A_a \cdot f_y + 0.85 \cdot A_c \cdot f_{ck} \quad (3)$$

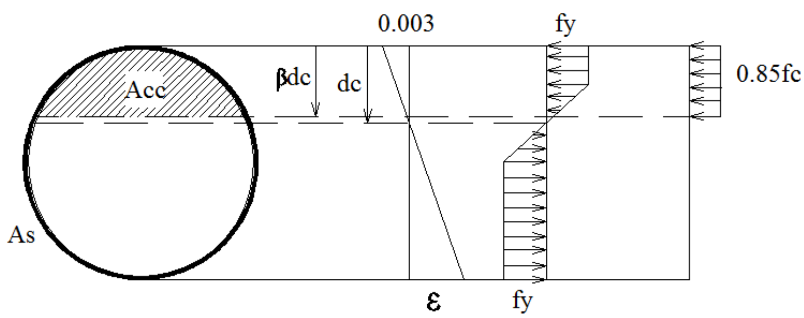

Fig.11. Stress and strain distribution in cross section according to ACI/AS method

According to AISC [4, 5] the axial load capacity of the fully-plastified cross-section of the CFT column is calculated by the following formula:

$$N_{0,AISC} = A_a \cdot f_y + C_2 \cdot A_c \quad (4)$$

where C2 is the concrete strength factor for concrete and for circular CFT columns equals $0.95 \cdot f_{ck}$.

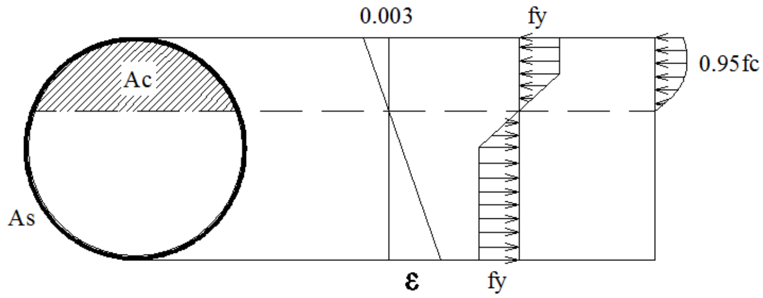

Fig. 12 Stress and strain distribution in cross section according to AISC method

The results of experimental testing of the axial load capacity of CFT columns for samples *C1* and *C2* and the axial capacity of cross-sections of the CFT column calculated using: EC4, EC4 including confinement effect, ACI, AS and AICS respectively, are shown in Tables 1 and 2 below.

N_{TEST} [kN]	N_{TEST}/N_{EC4}	$N_{TEST}/N_{EC4,confined}$	$N_{TEST}/N_{ACI/AS}$	N_{TEST}/N_{AISC}
701.7	1.351	1.049	1.443	1.380

Table1. Axial load capacity of CFT column L=0.50 m

N_{TEST} [kN]	N_{TEST}/N_{EC4}	$N_{TEST}/N_{EC4,confined}$	$N_{TEST}/N_{ACI/AS}$	N_{TEST}/N_{AISC}
555.6	1.069	0.946	1.143	1.093

Table2. Axial load capacity of CFT column L=1.00 m

It can be concluded that for the CFT column L=0.50 m, EC4 including confinement effect provides the most approximate results to the results obtained by experimental testing. On the other hand, the ACI/AS rule provides the most conservative results.

In case of CFT column L=1.00 m, the confinement effect is significantly lower due to increase in slenderness of the column. Consequently, the critical axial force obtained by experimental testing is lower than the value proposed by EC4 including confinement effect. Relative slenderness in this case equals to 0.453 which is very close to the value recommended in the EC4 [1] when the increase in the compressive strength of the concrete could be taken into account. Although not on the safety side, calculation by EC4 including confinement effect is the most approximate to the results of the experimental testing, while the ACI/AS deliver more conservative results.

Tables 3, 4, 5, and 6 show the results of experimental testing of critical buckling forces for the *C3*, *C4*, *C5*, and *C6* samples compared to the values calculated using above listed design rules.

N_{TEST} [kN]	$N_{TEST}/N_{EC4,I}$	$N_{TEST}/N_{EC4,II}$	$N_{TEST}/N_{ACI/AS}$	N_{TEST}/N_{AISC}
327.7	0.879	1.023	1.074	1.318

Table 3.The critical buckling force of C3 CFT column sample

N_{TEST} [kN]	$N_{TEST}/N_{EC4,I}$	$N_{TEST}/N_{EC4,II}$	$N_{TEST}/N_{ACI/AS}$	N_{TEST}/N_{AISC}
489.1	0.879	1.028	1.098	1.194

Table 4.The critical buckling force of C4 CFT column sample

N_{TEST} [kN]	$N_{TEST}/N_{EC4,I}$	$N_{TEST}/N_{EC4,II}$	$N_{TEST}/N_{ACI/AS}$	N_{TEST}/N_{AISC}
226.0	0.966	1.108	1.106	0.988

Table 5.The critical buckling force of C5 CFT column sample

N_{TEST} [kN]	$N_{TEST}/N_{EC4,I}$	$N_{TEST}/N_{EC4,II}$	$N_{TEST}/N_{ACI/AS}$	N_{TEST}/N_{AISC}
319.0	0.918	1.058	1.070	0.955

Table 6.The critical buckling force of C6 CFT column sample

Based on the obtained results, it can be concluded that the EC4 guide the most favorable results when compared to the results of the experimental testing, with the effective bending rigidity calculated according to the second-order theory [1]. Alternatively, if effective bending rigidity is calculated according to the first-order theory, the values of critical forces are not on the safe side.

On the other hand, by applying the AISC rule for samples *C5* and *C6* the buckling forces are very close to the experimental test values but are not on the safety side as well.

5. Conclusions

The paper compares the results of our own experimental testing with the results calculated by designed guides: EC4, AS, ACI and AISC. Generally, the EC4 gives the most approximate results to the results obtained by experimental testing for all CFT column types considered. For the axial load capacity of short columns it is necessary to take into account the confinement effect, while for stability of slender and moderately slender columns the effective bending rigidity should be calculated according to the second-order theory.

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