2018 2nd International Workshop on Renewable Energy and Development (IWRED 2018) IOP Publishing
IOP Conf. Series: Earth and Environmental Science **153** (2018) 032020 doi:10.1088/1755-1315/153/3/032020

Experimental study on short steel-reinforced concrete columns under long-term axial loads

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Abstract. Steel-reinforced concrete (SRC) columns have been widely used over the past few decades. This paper presents the results of an experimental study on short SRC columns under sustained axial loading. Long-term axial deformations due to shrinkage and creep of the concrete were recorded. The ultimate strengths of the columns after long-term loading were also determined, and the results showed that the sustained axial loads had no significant effect on the axial compressive strength of the SRC columns.

1. Introduction

A steel-reinforced concrete (SRC) column is a combination of concrete, structural steel and reinforcing steel that provides adequate load-carrying capacity of the member. SRC columns combine the rigidity of reinforced concrete and the strength of structural steel to produce an economic structural component. For concrete-encased SRC columns, an additional advantage is that the concrete used to encase the structural steel not only increases its stiffness but also protects it from fire damage and local buckling failure. Due to these advantages, SRC columns have become popular in tall building construction. Because of the widespread use of SRC columns, experimental investigations and analytical studies on SRC columns have been conducted by many researchers. An extensive review of most of these studies was conducted by Shanmugam and Lakshmi [1]. While much attention has been focused on the study of aspects of SRC columns such as their ultimate strength, bond strength, seismic loading and so on, little is known about the time-dependent behavior of SRC columns caused by creep and shrinkage under long-term loading.

This paper describes an experimental study on long-term axial deformations due to shrinkage and creep of the concrete in short SRC columns under sustained axial loading and a further test of their ultimate axial capacity.

2. Experimental Program

2.1. Specimens design and materials properties

Six short SRC columns were tested. The characteristics of the specimens are listed in Table 1 and their cross section details are illustrated in Figure 1. All columns had a cross section of 160×160 mm and a height of 410 mm. We select this size is to meet the loading capacity of the long-term loading device used in the test, which has the maximum axial loading capacity of 600 kN. Three of the specimens (S1-N0, S1-N1, and S1-N2) had structural steel I-shape sections of 80×50×4 mm (width× depth× flange and web thickness) encased in concrete, while the other three (S2-N0-1, S2-N0-2, and S2-N1) had structural steel I-shape sections of 80×50×7.8 mm. All of the columns were reinforced with 12-mm-diameter deformed bars at their four corners, and 8-mm-diameter smooth round bars were used as stirrups spaced 100 mm apart.

Table 1. Properties of long-term test specimens and their axial load capacity

Specimen	S1-N0	S1-N1	S1-N2	S2-N1	S2-N0-1	S2-N0-2
Steel area ratio (%)	2.7	2.7	2.7	5.0	5.0	5.0
Nominal sustained load ratio	0	0.32	0.43	0.31	0	0
Sustained load duration (days)	0	202	202	202	0	0
$N_{u,exp}$(kN)	1136.2	1080.2	1271.5	1163.2	1238.2	1336.9
$N_{u,pred}$ (kN)	1063.8	1063.8	1063.8	1196.4	1196.4	1196.4
$N_{u,exp}$ /$N_{u,pred}$	1.07	1.02	1.2	0.97	1.03	1.12

The specimens were all cast from the same batch of concrete. The concrete mix proportions (cement: water: sand: gravel) were 1.00:0.43:1.11:2.15 by weight. A gravel with a maximum size of 10 mm was used as coarse aggregate. The 150-mm cube strength of the concrete at 28 days was f_{cu}=39.1 MPa, and the modulus of elasticity was E_c=21,000 MPa. The two types of steel I-shape sections used in the columns were fabricated from steel plates with thicknesses of 4 mm and 7.8 mm by cutting and welding. The measured yield strengths and elastic moduli were F_{ys}=279 MPa and E_s=204,000 MPa for the 4-mm-thick plate, F_{ys} =266 MPa and E_s =205,500 MPa for the 7.8-mm-thick plate, F_{yr} =436 MPa and E_{sr} =201,000 MPa for the 12-mm-diameter deformed bars, and F_{yh} =325 MPa and E_{sh} =200,000 MPa for the 8-mm-diameter smooth round bars.

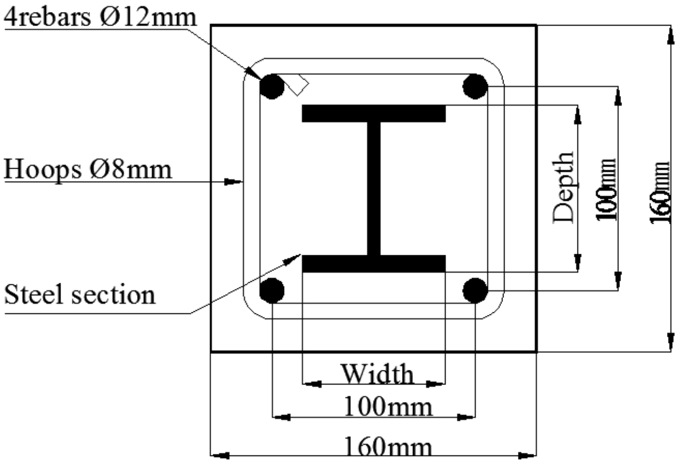

Figure 1.Cross section of test specimens.

2.2. *Long-term service load test*

Long-term load tests were carried out for specimens S1-N1, S2-N1, and S1-N2 when the concrete reached an age of 28 days after casting. Column axial loads equal to 345 kN and 375 kN were selected for specimens S1-N1 and S2-N1, respectively, representing approximately 30% of the nominal ultimate strength of the columns under axial compression at 28 days. This level of stress was selected because it is likely to be experienced under service conditions in the columns of a building. For specimen S1-N2, an axial load equal to 460 kN, approximately 40% of the nominal ultimate strength of the column under axial compression at 28 days, was chosen to study the influence of axial load magnitude on long-term column behavior.

Strain measurements were obtained from length changes measured between metal targets cast into the concrete at spacing of 150 mm. The length changes were measured using a micrometer dial indicator fixed to one of the metal targets. Two strain readings for each column were obtained on the opposing column faces. The temperature and humidity in the laboratory where the experiments were carried out were measured by a temperature and humidity data logger. The readings indicated that the temperature did not fluctuate much during the time period over which the tests were conducted, so its influence on the tests can be ignored. The humidity changed with the seasons. The average relative humidity in the test period of 202 days was 60%.

2.3. Static ultimate load tests

When the long-term service load tests completed, after a load duration of 202 days, all specimens were removed from the long-term loading devices and tested to failure under axial compression. The specimens that were not subjected to long-term loading were also tested for comparison. The cube strength of the concrete on the day of the static ultimate load tests was f_{cu} =46.9 MPa.

The load was applied by an electro-hydraulic servo compression testing machine. The axial shortening of the columns was measured using displacement transducers that were located on two opposing sides of the specimens. Ten strain gauges were mounted to the reinforcing bars and to the steel web and flanges in the mid-height region of the column. Four strain gauges were mounted on the concrete surface along the longitudinal axis. Prior to loading, the alignment of the columns was checked. The columns were loaded up to failure using load control, with each load step nearly one tenth of the estimated load capacity.

3. Experimental results

3.1. Strain measurements in long-term load specimens

The strains measured during the long-term load tests are shown in Figure 2 for specimens S1-N1, S2-N1, and S1-N2, which were loaded for 202 days. Total strains are shown as the sum of the initial elastic strain and time-dependent strains in the concrete. As Figure 3 shows, the long-term deformations during the sustained load tests were large, with the final strains being 1.93, 2.22 and 2.73 times larger than the initial elastic strains in specimens S2-N1, S1-N1 and S1-N2, respectively.

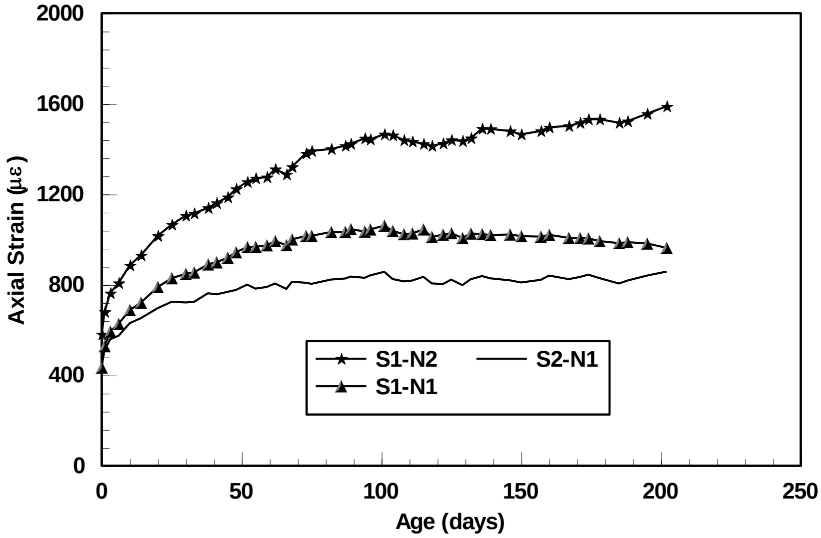

Figure 2. Long-term strains during sustained load tests.

In the long-term load tests, as shown in Table 1, experimental variables included the magnitude of the axial load and the amount of steel reinforcement. A comparison between specimens S1-N1 and S2-N1, which had the same long-term axial load ratio (the ratio of the long-term axial load to the nominal ultimate strength of the column under axial compression) but different steel area ratios (the ratio of the cross-sectional area of the encased steel to the total cross-sectional area of the column), shows that the long-term deformation of the columns increased as the steel area ratio decreased. Specimens S1-N1 and S1-N2, on the other hand, had the same steel area ratio but different long-term axial load ratios. The comparison between them indicates that the long-term deformation of the columns increased with increasing long-term axial load ratio. It is easy to understand why the creep is highly dependent on the stress level in the concrete. The detail time analysis of the SRC columns under sustained axial loads were given in another paper [2].

3.2. Ultimate load test results

The experimental axial load–deformation diagrams for all specimens are presented in Figure 3. The maximum loads obtained in the tests are summarized in Table 1. The failures of all of the columns were characterized by concrete crushing. As Figure 5 shows, the sustained axial load had no significant effect on the axial compressive strength of the SRC columns.

The equation proposed by ACI 318 [3] for calculating the ultimate load N_u for composite columns with encased steel cores, which is essentially the same as that for reinforced concrete columns, is the following:

$$N_u = 0.85 A_c f_c' + A_s F_{ys} + A_r F_{yr} \quad (1)$$

where A_c =the area of the concrete, f_c'=the concrete compressive strength (note that the compressive strength of 150×300-mm cylinders used here was estimated from the measured 150-mm cube strength by multiplying by a correction factor of 0.83 [4]), A_s = the cross-sectional area of the structural steel, F_{ys} = the yield strength of the structural steel, A_r = the cross-sectional area of the reinforcing bars, and F_{yr} = the yield strength of the reinforcing bars.

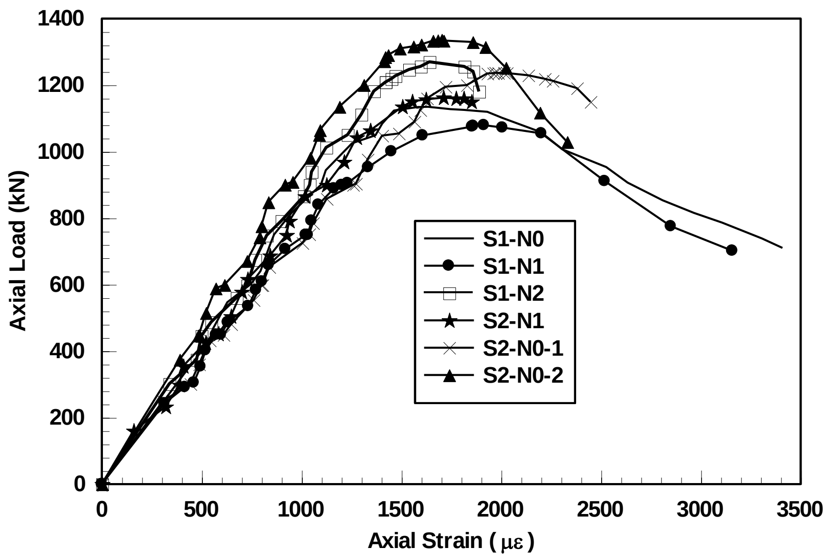

Figure 3.Axial load–deformation response

The predicted loads $N_{u,pred}$ in Table 1 for all specimens are in good agreement with the experimental values $N_{u,exp}$,confirming the negligible influence of the sustained axial load on the axial capacity of the SRC columns.

4. Conclusions

Experimental tests involving both long-term and ultimate loading of steel-reinforced concrete columns was carried out in this study. The following observations and conclusions can be drawn from this study:

(1)The long-term deformations of the columns during the sustained load tests were large. At the end of a 202-day loading period, the final axial strains of the columns were 1.93, 2.22 and 2.73 times larger than the initial elastic strains in specimens S2-N1, S1-N1 and S1-N2, respectively. The long-term deformations of the columns increased as the long-term axial load ratio increased, and decreased as the steel area ratio increased.

(2)The failure mode, characterized by concrete crushing, of the columns with long-term loading histories was the same as for those columns without long-term loading histories in the ultimate load tests. The ultimate capacities of comparable specimens with and without long-term loading histories were also very close to each other. An existing equation for the computation of the ultimate axial load yielded good predictions for all columns, confirming the negligible influence of the sustained axial load on the axial capacity of the SRC columns.

Acknowledgments

This work was supported by the Structural Dynamics Experimental Teaching Platform Construction funding from Yantai XTD test technology co., LTD.

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