Strength of preliminary compressed concrete-filled steel tubular columns with square cross-section

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Abstract. The strength of CFST columns with a square cross-section at axial and eccentric compression operation with small eccentricities is noticeably lower, if compared with similar circular cross section columns. The paper suggests increasing the strength of CFST columns with square section by preliminary compressed concrete core implementation. The compression is carried out by a long pressing of the concrete mixes after column molding process completion. This paper’s objective is to determine the efficiency of preliminary compression of the concrete core of CFST columns with a square cross-section, based on the strength experimental research. In order to test the effect on preliminary compression of concrete CFST, 4 series of laboratory column samples were manufactured and tested for the central compression with a short-term load. The samples of different series, varied in the original concrete class (C40 or C80), as well as the availability or lack of preliminary compression of the concrete core. The experimental research showed a gain in the strength of samples made of C40-class concrete by 13%, C80-class concrete – 20% and a significant increase of the fixture effect, due to the core preliminary compression.

1. Introduction

In recent years, the Compressed Concrete-Filled Steel Tubular (CFST) Elements are increasingly frequently used in the construction of high-rise buildings and long-span bridges [1-10]. Also these elements are used in the construction of multi-storey frame buildings with an enlarged grid of columns in Japan and Southeastern Asia countries [11]. In addition, preference is given mainly to columns of circular cross section due to a number of circumstances [12]. The main reason is a much greater fixture effect occurring under operation of a compressed CFST element with a circular cross section. Consequently, the strength of the concrete core increases significantly. As a result, the strength of CFST columns with circular cross section is noticeably higher for the same material consumption [13].

Moreover, CFST with square cross section have own advantages. For instance, CFST with square cross section are often more effective at eccentric compression operation [14]. In addition, the prismatic surface of the structures simplifies the interfacing nodes with the load carrying structure of the building slabs. Finally, the CFST columns with a square cross section can be more fully in line with the architect's intentions under the project development of a particular object. Not without reason, the scopes of researches of the power resistance of CFST columns with square and rectangular cross sections have recently increased [15-19].
In connection therewith, the task of strengthening the CFST columns with square cross section is actual. We propose to solve this problem by preliminary compression of the concrete during the column manufacturing process. That constructive solution will make columns equally effective compared to elements of the circular cross section and at compressed operation in the area of random and small eccentricities. However, little research has been undertaken on this issue. In respect thereof, the experimental researches of the strength of compressed CFST elements with square cross section with a preliminary compressed concrete core should be recognized as highly relevant.

2. The method of columns preliminary compressed samples production
Initially, the manufacture of laboratory column samples was necessary. The preliminary tensile stresses in the outer steel shell and concrete core compression were artificially created during the manufacture of preliminary compressed samples. The long pressing method of a reinforced concrete mix was used. Pressing was carried out by sequenced pushing of steel pipes with different diameters into concrete mix along the guide pin. The connection diagram of the preliminary compression is shown in Figure 1.

The long pressing technology has been developed earlier for the manufacture of preliminary compressed columns with circular cross section. The technology's essence reduces to the following. Through the opening in the upper end closure of the sample, three steel tubes with matching diameters of the cross sections are pressed into the molded concrete mix. The pin pre-installed coaxially to the steel shell of the sample serves as a guide for the first tube. The first and second tubes serve as guides for the second and third tubes, respectively.

The first two tubes have perforated walls. The concrete mix pressing is the result of tubes pushing. The excess fluid from concrete mix is pressed out through the openings in the walls of the tubes. The initial water-to-cement ratio of the high-flow concrete mix decreases by approximately 0.03-0.06. There are no openings in last tube walls. When last tube is pressed, the pressing pressure is transferred to the inner surface of the steel shell, creating tensile stresses of the circumferential direction in it. After the element manufacturing, this tube remains as an inner pin, and the guide pin and tubes with perforated walls are removed and used to preliminary compression of the following structure.

The use of concrete mix long-compression under this technology, allows improving the structure of the concrete core. During pressing, the cement layer thickness between the filler grains decreases and fine-grained structure of a cement stone has a better quality with significantly smaller pore sizes. The result is the best quality of preliminary compressed concrete, with fewer pores and greater strength. In
the experiments, the compressive pressure was in the order of 2 MPa, and the concrete strength increased about 40-50%.

3. Technique of experimental research

The experimental researches of laboratory samples of CFST columns with square cross section were made to test the effect of preliminary concrete compression of such structures at central compression operation by short-term load. For visual reference of the preliminary compression effectiveness, similar uncompressed samples were formed simultaneously using a concrete mix of same batch. In total, 4 series of samples were manufactured and tested:

- **C40** series – the concrete-filled steel tubular samples from C40-class heavy concrete, enclosed in a steel tube of square cross section;
- **C80** series – the samples similar to the C40 series, but made of C80-class concrete;
- **PC40** series – the samples similar to the C40 series with preliminary compressed concrete core;
- **PC80** series – the samples similar to the PC40 series, but made of C80-class concrete.

The basis of each series was 3 twin-samples. The length of all the samples was 580 mm. The outer shells were made of steel curved locked profiles of square cross section with dimensions of 140×140×4 mm. The tubes are made of steel with point of yielding \( \sigma_{yp} = 285 \text{ MPa} \). The metal sheets 10 mm thick were fixed at the ends of the laboratory samples. Figure 2 shows the design of laboratory samples.

The samples were tested in an upright position of concrete strength at 28 days on a 500-ton hydraulic press 2PG-500 with a short-time compressive load. The load was transferred simultaneously to the concrete core and the steel shell. The Hinged Support of the Ends was adopted. The Standard Test Methodology was adopted.

The strain-gauge method was mainly used to study the stress-strain state of the tested laboratory samples. The strain-gages with a base of 20 mm are glued to the outer steel shell in vertical and horizontal directions. The Aistov's mechanical strain-gages and electronic indicators graduated in 0.001 mm, duplicated the readings of longitudinal steel deformation measurements.

![Figure 2. The laboratory sample design.](image-url)
4. Results of experimental researches
The key test results of the tested samples are presented in Table 1. The values of the initial concrete prism strength \( f_c \), the load corresponding to the completion of the sample elastic behavior \( N^\text{exp}_{el} \), the fracture load \( N^\text{exp}_{u} \) and the theoretical force \( N^\text{th}_{cp} \) equal to the sum of the maximum efforts in the concrete core and the steel shell under the assumption of uniaxial compression operation are reported here. The relative level of sample elastic behavior was calculated for clear assessment of the impact of preliminary concrete compression to the CFST operation nature – \( n_{el} = \frac{N^\text{exp}_{el}}{N^\text{exp}_{el}} \). The coefficient \( m_c = N^\text{exp}_{u} / N^\text{th}_{cp} \) is presented for a quantitative assessment of the impact of fixture effect determined by the outer steel shell availability.

The data in Table 1 indicate a positive effect of the preliminary compression of the concrete core on the strength of the laboratory samples under study. The average value of the increase in strength due to preliminary compression was:
- 13% for samples made of C40-class concrete;
- 20% for samples made of C80-class concrete.

| Series, sample | \( f_c \), (MPa) | \( N^\text{exp}_{el} \), (kN) | \( N^\text{exp}_{u} \), (kN) | \( N^\text{th}_{cp} \), (kN) | \( n_{el} \) | \( m_c \) |
|---------------|-----------------|-----------------|-----------------|-----------------|------|------|
| C40-1         | 40.5            | 800             | 1470            | 1316            | 0.54 | 1.12 |
| C40-2         | 43.0            | 900             | 1600            | 1359            | 0.56 | 1.18 |
| C40-3         | 42.2            | 900             | 1533            | 1345            | 0.59 | 1.14 |
| PC40-1        | 40.5            | 1050            | 1650            | 1316            | 0.64 | 1.25 |
| PC40-2        | 43.0            | 1100            | 1800            | 1359            | 0.61 | 1.32 |
| PC40-3        | 42.2            | 1100            | 1733            | 1345            | 0.63 | 1.29 |
| C80-1         | 84.4            | 1250            | 2167            | 2082            | 0.58 | 1.04 |
| C80-2         | 81.7            | 1200            | 1867            | 2035            | 0.64 | 0.92 |
| C80-3         | 82.7            | 1250            | 2083            | 2053            | 0.60 | 1.01 |
| PC80-1        | 84.4            | 1550            | 2467            | 2082            | 0.63 | 1.18 |
| PC80-2        | 81.7            | 1600            | 2467            | 2035            | 0.65 | 1.21 |
| PC80-3        | 82.7            | 1600            | 2400            | 2053            | 0.67 | 1.17 |

Even more significantly, the preliminary compression has affected the increase in effort corresponding to the completion of the structure's sample elastic behavior. The relative level of elastic behavior \( n_{el} \) in C40-class concrete samples increased by 11 %, and high-strength concrete samples – by 13%. At the same time, the absolute effort value \( N^\text{exp}_{el} \) increased on average by:
- 25% for samples made of C40-class concrete;
- 28% for samples made of C80-class concrete.

A correlation of the reported values of the coefficient \( m_c \) indicates a greater demonstration of the fixture effect in preliminary compressed samples. For PC40 series samples, the average coefficient value \( m_c \) is 1.29, which is noticeably higher compared to \( m_c = 1.15 \) for the C40 series. The corresponding coefficients, in preliminary compressed and uncompressed samples of high-strength concrete, were found to be equal – 0.99 and 1.19, respectively.

The fracture pattern of samples of the C40 and PC40 series was plastic. The riffsles were formed at the fracture point on side faces of steel shell, at about the same height of the element. The concrete disintegration was observed in the secondary buckling places of the shell (after removal). The fracture of samples of the C80 and PC80 series resulted from the shear of the concrete core and was of a feeble nature. The slope of the shearing section to the vertical axis of the sample was at an angle of about 33°-35°. The riffsles were formed in the connection points between the upper and lower areas of the
shearing section and a steel shell. The axial deformations of the samples reached 0.6±1% by the fracture point.

5. Discussion
The power resistance features and the fracture pattern laboratory samples detected in experiments indicate a three-dimensional stress state of concrete core. In this case, the structures with a preliminary compressed concrete core had a higher strength and an even greater elastic behavior limit compared to uncompressed ones.

These results are mainly attributable to a significant increase of concrete strength as a result of long-pressing [20,21]. In addition, the utilization efficiency of a steel shell exercising a function of fixture increases in the preliminary compressed samples. During the manufacture thereof a low shell prestressing in cross direction is created. During the axial compression this leads to the additional side pressure from the shell side to the concrete, first of all, in the structure's corner areas. As a result, the strength of the volumetrically compressed concrete and the entire sample increases.

In our experiments, with the assumed value of the preliminary compression (about 2 MPa), the concrete side pressure from the outer shell side was preserved even at low loading levels. In samples without preliminary compression, the reactive concrete side pressure from the shell side generated only after the beginning of the micro-fracturing. At low loading levels, the concrete core was in uniaxial compression. Because of this, in the preliminary compressed samples the elastic behavior limit turned out to be much higher.

With a rise of concrete prismatic strength $f_c$, both in preliminary compressed and uncompressed samples, the coefficient $m_c$, reflecting the efficiency of the steel shell, was reduced. This occurs due to the following reason. The steel shell of the samples was manufactured from a single tube batch with virtually the same point of yielding. During the loading of samples to the fracture load, it created a similar side pressure $\sigma_{cr}$, both for regular strength concrete and high-strength concrete. At the same time, the relative pressure $\sigma_{cr}/f_c$, directly affecting the strength of volumetrically compressed concrete [20], in high-strength concrete samples was much lower.

In the samples of the PC40 series, the initial compression pressure had a positive impact increasing both the relative side pressure and the concrete core strength.

6. Conclusions
The results of the experimental studies reflect the favorable effect of concrete preliminary compression on the strength properties of CFST columns. We managed to increase the strength of laboratory samples made from C40-class concrete by 13%, and C80-class concrete – by 20% and significantly increase the fixture effect due to preliminary compression. CFST columns with square cross section with a preliminary compressed core may well be considered as an alternative to columns circular cross section.

References
[1] Chen B C 2008 New Development of Long Span CFST Arch Bridges in China Proc. Chinese-Croatian Joint Colloquium “Long arch bridges” (Brijuni Islands) pp 357–367
[2] Tsai Shaokhuai 2001 The latest case history of using tube confined concrete in the P. R. China Concrete and Tube Confined Concrete 3 20–24
[3] Han L H, Li W and Bjorhovde R 2014 Developments and advanced applications of concrete filled steel tubular (CFST) structures J. of Constructional Steel Research 100 211–28
[4] Jayasooriya R, Thambiratnam D P and Perera N J 2014 Blast response and safety evaluation of a composite column for use as key element in structural systems Engineering Structures 61 (1) 31–43
[5] Krishan A L, Krishan M A and Sabirov R R 2014 The future of application of concrete-filled steel tubular columns at construction sites in Russia The Bulletin of the Nosov Magnitogorsk State Technical University 1 (45) 137–40

[6] Ma T L, Xu Y, He T and Chen K 2001 China's First Concrete-filled Steel Tube (CFST) Arch Railway Bridge: The Beipanjiang Long Span Bridge on the Shuicheng-Baiguo Line Proc., Third International Conference on Arch Bridges (Paris, France) pp 877–882

[7] Mu T M, Fan B K, Zheng X F, Zheng Y H and Xie B Z 2007 Wuxia Yangtze River Bridge in Wushan, China Proc. Fifth International Conference on Arch Bridge (Madeira, Portugal) pp 911–918

[8] Popkova O M 1992 Concrete-filled steel tube columns of high-rise buildings made of high-strength concrete in the USA J. Concrete and Reinforced Concrete 1 29–30

[9] Zhang W Z, Chen B C and Huang W J 2004 Design of the Second Highway Bridge over Yellow River in Zhengzhou, China Proc. Fourth International Conf. on Arch Bridge (Barcelona, Spain) pp 531–537

[10] Yang Y L and Chen B C 2007 Rigid-frame Tied through Arch Bridge with Concrete Filled Steel Tubular Ribs Proc. Fifth International Conference on Arch Bridge (Madeira, Portugal) pp 863–868

[11] Nishiyama I, Morino S, Sakino K and Nakahara H 2002 Summary of Research on Concrete-Filled Structural Steel Tube Column System Carried out under the US-JAPAN Cooperative Research Program on Composite and Hybrid Structures (Japan) p 176

[12] Krishan A L and Melnichuk A S 2013 The Strength of Concrete-filled Steel Tubular Columns with Square Cross Section (Magnitogorsk: Novos Magnitogorsk State Technical University Publ.) p 105

[13] Han L H and An Y H 2014 Performans of concrete-encased CFST stub columns under axial compression J. of Constructions Steel Research 93 92–6

[14] Krishan A L, Sabirov R R and Surovtsov M M 2014 The Concrete-Filled Steel Tubular Columns with Circular, Annular and Square Cross Section (Magnitogorsk: Novos Magnitogorsk State Technical University Publ.) p 209

[15] Hamidian M R, Jumaat M Z and Alengaram U J 2016 Pitch Spacing effect on the axial compressive behavior of spirally reinforced concrete-filled steel tube (SRCFT) J. of Thin-Walled Structures 100 213–23

[16] Liu D 2006 Behaviour of eccentrically loaded high strength rectangular concrete-filled steel tubular columns J. of Constructional Steel Research 62 839–46

[17] Masoudnia R, Amiri S and WanBadaruzzaman W H 2011 An analytical model of short steel box columns with concrete in-fill (part I) Australian J. of Basic and Applied Sciences 5 1715–21

[18] Nacej M, Bali M, Nacej M R and Amir J V 2013 Prediction of lateral confinement coefficient in reinforced concrete columns using M5’ machine learning method J. of Civil Engineering 17 (7) 1714–19

[19] Yu T and Teng J G 2013 Behavior of hybrid FRP-concrete-steel double-skin tubular columns with a square outer tube and a circular inner tube subjected to axial compression J. of Composites for Construction 17 271–79

[20] Krishan A L, Astafeva M A and Sabirov R R 2016 The Calculation and Construction of Concrete-Filled Steel Tubular Columns (Saarbrucken, Deutschland: Palmarium Academic Publishing) p 261

[21] Murashkin G V 1984 About the role of the pressure application duration in the physical and chemical processes of hardening concrete Reinforced concrete constructions pp 5–20

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