Compressed Concrete Filled Steel Tube Elements with Confinement Reinforcement of Concrete Core

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Abstract. The purpose of this paper is to study the main features of power resistance of compressed concrete filled steel tube elements (CFSTE) with spiral reinforcement. The spiral reinforcement of a concrete core makes it possible to increase the load-bearing capacity of such structures significantly. Based on the results of performed experiments, the coefficient of indirect reinforcement efficiency among CFSTE with spiral reinforcement made 1.48 to 1.62, depending on initial concrete class. This coefficient was in the range from 1.23 to 1.33 in similar samples without spiral reinforcement. The experiments showed that a high efficiency of these structures is maintained when high-strength concrete is used in them.

1. Introduction

In recent years, concrete filled steel tube elements have been widely used in the construction of buildings and structures. Most often they are used as vertical bearing structures of high-rise buildings [1-3], multi-storey buildings with an enlarged grid of columns [4, 5] and bridge structures [6-8]. This is facilitated by their numerous positive qualities [2, 9, 10], among which we can especially note the reduction of material consumption and the cost of the constructed facilities during the provision of the necessary bearing capacity, safety and survivability.

Due to the fact that CFSTE is mainly used as heavily loaded columns or supports, it is desirable to look for new ways to increase their bearing capacity. The use of high-strength concrete is promoted to the solution of this problem. This path should be considered a promising one, but it has its limitations.

Another option to increase the load-bearing capacity of compressed CFSTE is the development of a more rational design solution. To do this, its concrete core is proposed to be supplied with a reinforcing cage. The main working armature of a frame is spiral one, wound along longitudinal rods. Longitudinal reinforcement is also working. It can have both normal and high strength. The experiments recently carried out in Malaysia and China [11, 12] has proved a high efficiency of such designs.

The purpose of this work is to study the features of compressed CFSTE power resistance with a spiral reinforcement.

2. Experimental study technique
In order to achieve this goal, the experimental studies of centrally compressed CFSTE strength of circular cross-section with a spiral reinforcement have been performed. In order to demonstrate their effectiveness, reinforced concrete samples with spiral reinforcement and CFSTE without a concrete core reinforcement were studied simultaneously. 8 series of laboratory samples with different parameters were manufactured and tested in total. The basis of each series made 3 twin samples. The basic geometric and structural parameters of the samples are presented in Table 1. The length of all the samples made 1000 mm. They were made of two classes of concrete – C40 and C80. R2.40 and R2.80 series, as well as TR1.40, TR1.80 and TR2.40 had a confinement reinforcement in the form of a spiral. The parameters of the used frames with a spiral armature are given in Table 2.

The tests of CFSTE samples were carried out at the age of 28 days on a 500-ton hydraulic press 2PG-500 with a short-time compressive load. The transfer of the load to the samples was carried out over the entire cross section.

### Table 1. Geometric and Structural Parameters of Laboratory Samples

| Series | Section diameter, [mm] | Section dimensions, [mm] | Steel case | Yield strength, [MPa] | Spiral presence | Concrete prism strength, [MPa] |
|--------|------------------------|--------------------------|------------|-----------------------|-----------------|-----------------------------|
| R2.40  | 209                    | 112×1.2                  | +          | 41.1                  |                 |                             |
| R2.80  | 209                    | 112×1.2                  | -          | 82.9                  |                 |                             |
| T1.40  | 112                    | 112×1.2                  | -          | 43.8                  |                 |                             |
| T1.80  | 112                    | 112×1.2                  | -          | 83.4                  |                 |                             |
| T2.40  | 219                    | 219×5.0                  | +          | 42.0                  |                 |                             |
| TR1.40 | 112                    | 112×1.2                  | +          | 43.8                  |                 |                             |
| TR1.80 | 112                    | 112×1.2                  | +          | 83.4                  |                 |                             |
| TR2.40 | 219                    | 219×5.0                  | +          | 41.7                  |                 |                             |

### Table 2. Parameters of Spiral and Longitudinal Frame Reinforcement

| Series | Spiral diameter, [mm] | Diameter of rods, [mm] | Coil step, [mm] | Armature class | Rod diameter, [mm] | Number of rods | Armature class |
|--------|-----------------------|-------------------------|-----------------|---------------|-------------------|----------------|---------------|
| TR1.40 | 90                    | 3                       | 20              | B500          | 3                 | 4              | B500          |
| TR1.80 | 90                    | 3                       | 20              | B500          | 3                 | 4              | B500          |
| R2.40  | 185                   | 5                       | 30              | B500          | 6                 | 4              | A500          |
| R2.80  | 185                   | 5                       | 30              | B500          | 6                 | 4              | A500          |
| TR2.40 | 185                   | 5                       | 30              | B500          | 6                 | 4              | A500          |

### 3. Experimental study results

The main test results, containing the data on the carrying capacity and deformability of the studied laboratory specimens averaged within each series, are presented in Table 3. The experimental values of the bearing capacity $N_u^{exp}$ and relative longitudinal strains of the samples when the maximum load $\varepsilon_{cc1}^{exp}$ are compared with their theoretical values $N_u^{th}$ and $\varepsilon_{cc1}^{th}$. The formulas for the calculation of these quantities are given in [13, 14].

The table also shows the total percentage of indirect reinforcement $\mu_c$ of samples, which is calculated by the following formula

$$\mu_c = \mu_p + \mu_{sc},$$

(1)
where $\mu_p$ and $\mu_{sc}$ are the reinforcement percentage of an outer shell and spiral reinforcement, which are calculated by the following formulas

$$\mu_p = \left( \frac{A_p}{A} \right) \cdot 100\%;$$

(2)

$$\mu_{sc} = \left( \frac{2A_{sc}}{d_{ef}s} \right) \cdot 100\%.$$  

(3)

Table 3. Main Results of Performed Studies

| Series    | $\mu_{sc}$ [%] | Destructive loading, $N_u^{exp}$ [kN] | $N_u^{th}$ | $N_u^{exp}$ | $N_u^{th}$ | $m_c$ | Deformations $\times 10^5$ | $\varepsilon_{cel}^{exp}$ | $\varepsilon_{cel}^{th}$ | $\varepsilon_{cel}^{exp}$ | $\varepsilon_{cel}^{th}$ |
|-----------|----------------|---------------------------------------|------------|-------------|------------|-------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| R2.40     | 0.7            | 2167                                  | 1975       | 1.10        | 1.11       | 690   | 757                      | 0.91                     |                          |                          |                          |
| R2.80     | 0.7            | 3233                                  | 3368       | 0.96        | 1.10       | 670   | 567                      | 1.18                     |                          |                          |                          |
| T1.40     | 4.2            | 650                                   | 563        | 1.15        | 1.31       | 520   | 595                      | 0.87                     |                          |                          |                          |
| T1.80     | 4.2            | 933                                   | 866        | 1.08        | 1.23       | 510   | 459                      | 1.11                     |                          |                          |                          |
| T2.40     | 8.9            | 3217                                  | 3125       | 1.03        | 1.33       | 1150  | 897                      | 1.28                     |                          |                          |                          |
| TR1.40    | 5.0            | 700                                   | 733        | 0.95        | 1.60       | 1010  | 1191                     | 0.85                     |                          |                          |                          |
| TR1.80    | 5.0            | 1200                                  | 1103       | 1.08        | 1.48       | 930   | 808                      | 1.15                     |                          |                          |                          |
| TR2.40    | 9.6            | 4200                                  | 3914       | 1.07        | 1.62       | 1520  | 1779                     | 0.85                     |                          |                          |                          |

In formulas (2) and (3) $A$, $A_p$, and $A_{sc}$ are the cross-sectional areas of a concrete core, a steel shell and a spiral reinforcement; $d_{ef}$ is a spiral diameter; $s$ is a spiral coil step.

In order to quantify the influence of a confinement reinforcement effect the coefficient $m_c$ was calculated. It is equal to the ratio $N_u^{th}$ to the sum of the maximum forces in a concrete core and a steel shell under the assumption of their work on uniaxial compression. For the samples of T1.40, T1.80, TR1.40 and TR1.80 series this calculation was made taking into account their flexibility [13].

The data in Table 3 show that the samples of all series have a confinement reinforcement effect. Its value depends on the presence of spiral reinforcement, a steel pipe, as well as on the percentage of confinement reinforcement and the strength of initial concrete. The lowest coefficient $m_c$ are among reinforced concrete samples with a spiral reinforcement (R2.40 and R2.80 series), which is explained by a small percentage of reinforcement. The concrete filled steel tube samples without a spiral (T1.40, T1.80 and T2.40 series), have a higher percentage of reinforcement. Here, the efficiency of a confinement reinforcement is much higher.

For the samples of TR1.40, TR1.80 and TR2.40 series, which have both a steel shell and a spiral reinforcement, the coefficient $m_c$ is the largest one as compared to all others and it is reached 1.6. The average strength of the samples of the series TR2.40 is determined from the experiment results, which was 1.3 times higher in comparison with the samples of T2.40 series and 1.9 times higher in comparison with the samples of R2.40 series.

Thus, it has been experimentally proven that an additional reinforcement CFSTE with a spiral reinforcement can significantly increase their bearing capacity and efficiency. With the increase of concrete strength, the effect of a clip, although becomes somewhat weaker, nevertheless it remains significant.

The nature of studied sample destruction was mainly dependent on the presence of an outer steel shell. The destruction of samples of R2.40 and R2.80 series began with the detachment of concrete protective layer (Figure 1, a). With further load increase, their concrete core was crushed. The samples of all series
with a steel shell, had a similar character of destruction. By the moment of the ultimate load reaching, they had the folds on a steel shell surface due to the loss of adhesion with the crumbling concrete along the perimeter of its cut surface (Fig. 1, b and 1, c). And right up to the stage of destruction the joint work of a concrete core, a longitudinal and a confinement reinforcement (if any), as well as a steel shell, were not violated. The process of destruction was flexible.

Figure 1. The nature of the samples destruction of the following series: R2.40 (a), T1.80 (b) and TR2.40 (c)

4. Discussion

The performed studies showed that the spiral reinforcement of a concrete core of CFSTE can significantly increase their bearing capacity and efficiency. When an outer steel shell is not operated (for example, during a fire), the confinement reinforcement effect can still be quite noticeable. Its magnitude is largely determined by the percentage of spiral reinforcement and is regulated by the structural parameters of a spiral armature.

The performed studies clearly demonstrated another important advantage of the columns with a steel shell and a spiral reinforcement of a concrete core. A large deformability of the prototypes with a high strength implies that a much larger amount of energy is required to destroy them in comparison with traditional reinforced concrete structures. This CFSTE property allows you to increase significantly the survivability of the building frames during earthquakes. This is very important to consider when you build buildings and structures in seismically active areas.

It should also be noted that the samples with a confinement reinforcement have an opportunity for an effective use of high-strength longitudinal reinforcement. For reinforced concrete structures in which concrete operates under uniaxial compression, the design resistance of the reinforcement is limited to 500 MPa. This value is conditioned by the deformability of the compressed concrete at the top of the deformation diagram ($\varepsilon_{ct} = 0.2\div 0.25\%$). In the studies carried out, the samples of T1.40 and T1.80 series showed the least deformability ($\varepsilon_{ct} \approx 0.5\%$). But even with such longitudinal deformations of a concrete core, it is possible to achieve 100% use of compressed reinforcement of A800 class and above. Taking into account a very high deformability of CFSTE with a spiral reinforcement, it can be concluded that there is almost no restriction for them in the use of high-strength longitudinal reinforcement. Here there is a good opportunity and economic expediency to reduce the expense of steel, and thus to achieve the reduction of design cost.
5. Conclusions
The obtained experimental and calculated data confirm the efficiency of spiral reinforcement use for CFSTE concrete core. Due to the spiral reinforcement, there is a real possibility of fire resistance significant increase for such elements without the use of flame retardant coatings. A high efficiency of these structures is maintained when high-strength concrete is used in them. The next step in improving the CFSTE design may be changing the cross-section shape of the samples and spiral reinforcements, replacing the metal shell and spiral reinforcements with a fiberglass shell, reinforcing bars and spiral reinforcements. The relative tests are scheduled in the foreseeable future.

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