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Compressed Concrete-Filled Steel Tube Elements with Indirect Reinforcement of the Concrete Core

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Abstract. The purpose hereof is to study the specifics of the force resistance and to experimentally identify the reinforcement effect of short square-section concrete-filled steel tube elements (CFSTE) with spiral reinforcement. Analysis of the laboratory samples of concrete-filled steel tube columns shows that spiral reinforcement makes them stronger by 18÷43% depending on the source concrete class. Maximum recorded longitudinal deformation in spiral-reinforced samples is 1.7÷2 times larger. Using a relatively small amount of spiral reinforcement (about 1%) has resulted in a mean 23% stronger reinforcement effect in the studied structures. Such structures remain efficient when using high-strength concrete.

1. Introduction

Compressed concrete-filled steel tube elements of square or rectangular section are becoming more popular in the construction industry. [1-5] They are especially in demand in the construction of multi-story frame buildings with enlarged column grids. [6] The vertical supports of such buildings have to bear relatively high loads. They thus require high-strength, economic, and safe-to-use columns. Global experience shows that concrete-filled steel tube elements are appropriate for that. [7-10]

In reality, CFSTE are mostly of circular cross-section. The main reason is that the reinforcement effect is much less prominent in square- or rectangular-section structures. The reinforcement effect of such elements is often neglected as this issue has not been well studied yet.

However, when designing such a structure it should be borne in mind that the prismatic surface simplifies the use of such structures as columns in multi-story buildings. There are no additional complications in designing the joints between columns and the supporting elements of floor slabs. Another advantage of such elements is that frames can be erected very fast, while the steel shell allows using CFSTE of any cross-section shape. [11-12]

All of this proves relevant any and all research into improving the reinforcement effect of square-section CFSTE. The reinforcement effect can be improved by spiral reinforcement of the concrete core. The purpose hereof is to study the specifics of the force resistance and to experimentally identify the reinforcement effect of short square-section concrete-filled steel tube elements (CFSTE) with spiral reinforcement of the concrete core.

2. Experiment Methodology

To attain the goal, we have experimentally studied the strength of compressed laboratory samples of various designs. All in all, we made and tested 5 sample series:

- series T consisted of steel samples made of square-shaped 140×4-mm tubes;
- series CT.40 consisted of concrete-filled steel tubes made of C40 heavy concrete in 140×4-mm steel tubes;
- series CT.80 was similar to CT.40 must used C80 concrete;
- RCT.40 was similar to CT.40 but had spiral reinforcement;
- series RCT.80 was similar to RCT.40 must used C80 concrete.

Each series was based on three twin samples. Each sample was 560 mm long. Outer shells were made of 140×140×4-mm bent closed squared steel sections. The steel of the tubes had a yield strength of $\sigma_{yp} = 285$ MPa. 10-mm thick metal plates were attached to the butt ends of laboratory samples.

Prior to forming, reinforcement cages were placed inside the RCT.40 and RCT.80 samples, see *Figure 1*. Spiral reinforcements for the cages were made of ∅ 5 Bp500 wire with a winding pitch of 30 mm. The spiral diameter was 120 mm. Longitudinal cage rods were made of 4 ∅ 6 A500C rebar. In order to preserve the design shape, longitudinal and spiral reinforcements were fastened with a knitting wire. Yield strength was $\sigma_{ys} = 552$ MPa for the reinforcement wire and $\sigma_{ys} = 548$ MPA for the rebars.

28 days old laboratory samples were placed vertically on a 2ПГ-500 500-ton hydraulic press to be tested by short-term compressive load. Butt ends were hinge-supported. Load was applied to the entire cross-section of each sample. Since stress is usually concentrated near the butt ends, bandages were tied in these areas before tests; the height of each bandage was half the outer cross-section size of the sample, see *Figure 2*. We used a standard test procedure.

The stress-strain state of these samples was mainly studied by strain gaging. Strain gauges were glued to the outer steel shell vertically and horizontally as well as to the longitudinal and spiral reinforcements of the cage, if any. Shell gauges had a 20-mm base while the reinforcement gauges had a 5-mm base.

Longitudinal deformation measurements were supplemented with redundant readings of Aistov strain gauges and electronic indicators of a 0.001-mm readability.

Figure 1. Reinforcement cage placement in RCT.40 samples

Figure 2. Laboratory sample before testing

Table 1. Strength and deformability of the studied samples

Series, sample	f_c, *MPa*	$N_u^{\exp}$, kN	N_{cp}, kN	m_c	$\varepsilon_u^{\exp}$, %	ε_{c1}^{th}, %	$\varepsilon_u^{\exp}/\varepsilon_{c1}^{th}$
T-1	-	623	-	-	0.17	0.142	1.19
T-2	-	632	-	-	0.16	0.142	1.13
T-3	-	650	-	-	0.16	0.142	1.16
CT.40-1	40.2	1,570	1,310	1.20	0.53	0.22	2.41
CT.40-2	42.3	1,733	1,347	1.27	0.55	0.22	2.50
CT.40-3	43.5	1,683	1,368	1.23	0.51	0.22	2.32
CT.80-1	84.4	2,167	2,082	1.04	0.42	0.26	1.60
CT.80-2	81.7	1,867	2,035	0.92	0.55	0.26	2.11
CT.80-3	82.7	2,083	2,083	1.01	0.40	0.26	1.52
RCT.40-1	40.2	2,017	1,404	1.43	1.12	0.22	5.68
RCT.40-2	42.3	1,900	1,441	1.32	1.32	0.22	6.04
RCT.40-3	43.5	1,933	1,462	1.32	0.87	0.22	3.95
RCT.80-1	84.4	2,733	2,176	1.26	0.66	0.26	2.52
RCT.80-2	81.7	2,967	2,129	1.39	0.77	0.26	2.96
RCT.80-3	82.7	3,033	2,146	1.41	0.88	0.26	3.38

3. Experiment Results

Table 1 presents the main results of laboratory tests. It specifies the strength $N_u^{\exp}$ and relative longitudinal deformation of samples when reaching the maximum load $\varepsilon_u^{\exp}$. To quantify the indirect-reinforcement effect, we introduce the coefficient m_c calculated as follows

$$m_c = N_u^{\exp} / N_{cp}, \tag{1}$$

where N_{cp} is the force found as the sum of maximum forces in the concrete core, the steel shell, and the longitudinal reinforcement (if any) assuming that the forces in all three components are directed to provide uniaxial compression.

The formula for calculating N_{cp} is written as follows:

$$N_{cp} = f_c A + f_{yp} A_p + f_{ys} A_s, \tag{2}$$

where f_c is the prism strength of the source concrete; f_{yp} and f_{ys} are the yield strength values for the outer shell and the longitudinal reinforcement; A, A_p and A_s are the cross-section areas of: the concrete core, the steel shell (pipe), and the longitudinal reinforcement.

Apparently, CFSTE is considerably stronger than steel structures. Direct series-against-series comparison illustrates the advantage of spiral reinforcements. For instance, CT.40 and CT.80 samples were respectively 2.5 times and 3.4 times stronger than steel samples. Use of spiral reinforcements in CFSTE resulted in a considerable increase in strength. RCT.40 and RCT.80 samples were respectively 3 and 4.7 times stronger than T samples. Compared to CT.40 and CT.80, RCT.40 and RCT.80 samples were 18% and 43% stronger, respectively.

Interestingly, use of spiral reinforcements was more efficient for B80 concrete. This is due to a greater contribution of the volume-stressed high-strength concrete core to the CFSTE strength.

The values of m_c indicate that without spiral reinforcement, high-strength CFSTE manifest virtually no reinforcement effect. The mean value of m_c CT.40 samples equaled 1.23, which is rather significant. At the same time, the measured shortening deformations were more significant than what is usually observed in uniaxial compression, even in CT.80 samples (0.4 to 0.55%). For clarity, the Table gives theoretically calculated deformation values of concrete subjected to uniaxial compression at the maximum stress ε_{c1}^{th}. These deformations are determined using the formula:

$$\varepsilon_{c1} = 0{,}0012 + 0{,}00016\sqrt{f_{ck,cube}}\,, \qquad (3)$$

where $f_{ck,cube}$ is the concrete class by compressive strength, 15 to 105 MPa.

For the T-series steel samples, the ε_{c1}^{th} was calculated using Hooke's law.

The mean ratio of $\varepsilon_u^{\exp}/\varepsilon_{c1}^{th}$ for CT.80 samples equaled 1.74. For other series, this ratio is more significant. That is, the identified deformations suggest the concrete of all the CFSTE was subjected to volumetric compression.

The low efficiency of the steel reinforcement in CT.80 samples was due to its complicated stress state. Lateral pressure of the concrete exposes the tube walls to bending and tensile force. As a result, the tube takes a considerably lesser compressive force in the longitudinal direction as compared to T samples, which mostly have compressive stresses occurring in their walls. At the same time, CT.80 steel tubes take an even lesser force as the high-strength concrete core generates greater lateral pressure. Besides, for a higher-class concrete, the strength gains are smaller. This explains why the coefficient m_c in the CT.80 samples was so low.

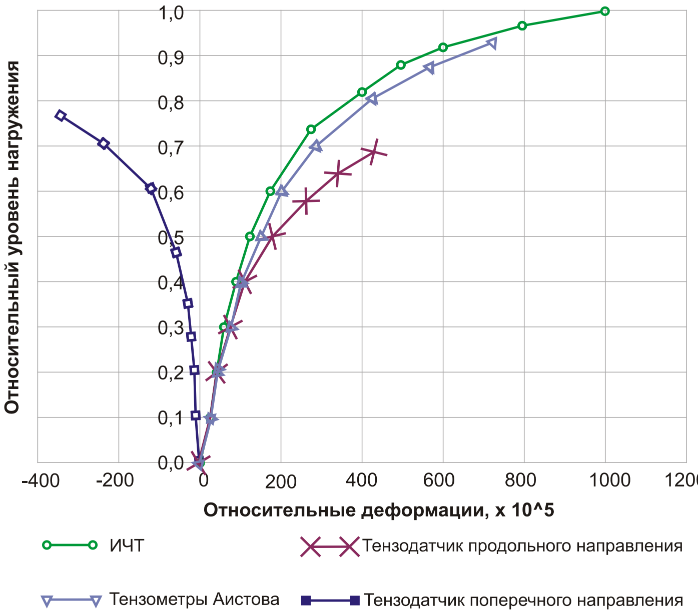

Figure 3. Load and strain correlations for RCT.40-1 sample. **Legend:** bold type (left to right) – relative load level, relative deformation, x 10^5; left to right, top to bottom – IchT furnace, longitudinal strain gauges, Aistov strain gauges, transverse strain gauges

Figure 4. Destruction of CFSTE samples

Use of spiral reinforcement in RCT.40 and RCT.80 samples did make them more efficient despite rather low reinforcement percentage (about 1%). The mean value of m_c was 1.36 for C40 concrete samples and 1.35 for high-strength concrete samples.

Based on the relative steel-shell deformation measurements, we have the dependency $n-\varepsilon$ for RCT.40 and RCT.80 reinforcement, where $n = N/N_u$ is the relative load and ε are the sample deformations in longitudinal or transverse direction. *Figure 3* presents the characteristic features of the RDT.04-1. Their analysis highlights 3 main CFSTE operation stages. Stage 1: quasi-flexible element operation air until $n = 0.45 \div 0.55$. We then moved one to the elastoplastic stage. Microscopic cracks were appearing ever more intensely in the large concrete core, as it is connected to the spiral reinforcement. The steel shell pipe entered a yield state. Laboratory samples were destroyed at the final stage.

CT.40, CT.80, RCT.40, and RCT.80 were destroyed similarly; their destruction was plastic, see *Figure 4*. By the time maximum load was reached, the steel shell had already had buckled. This was preceded by the fragmentation of the concrete (reinforced-concrete) core in the buckling area, resulting in the disconnection of concrete from the steel shell. In such cases, concrete could not prevent the steel shell from local destabilization.

Maximum recorded longitudinal deformations in CFSTE samples depended on both the source concrete class but even more so on whether spiral reinforcement was used. In RCT.40 samples, the mean value of $\varepsilon_u^{\exp}$ reached 1%, which was approximately twice as much as for CT.40 samples. When destroying CT.80 samples, longitudinal deformation amounted to 0.45% on average, being 1.7 times larger for RCT.80 samples.

4. Discussion

Experiments have shown that compressed concrete-filled steel tube structures can be quite efficient. Spiral reinforcement of the concrete core of short compressed square-section CFSTE did considerably increase their strength. This was mainly due to a considerable increase in the indirect-reinforcement efficiency. Experiments showed that a rather small amount of spiral reinforcements (about 1%) increased the coefficient m_c by 23% on average. Such a considerable increase in the efficiency of RCT.40 and RCT.80 samples was due to a substantial increase in the strength of the volume-compressed concrete provided by the spiral reinforcement. Maximum recorded pre-destruction deformation levels were also considerably higher.

The improvement in strength and deformability makes spiral-reinforced samples more durable in case of, for example, seismic activity, as they will absorb much more energy before being destroyed. This has to be taken into account when designing a real building.

5. Conclusion

Experiment results prove that compressed square-section CFSTE with spiral reinforcements feature high strength and deformability. Using a relatively small amount of spiral reinforcement (about 1%) has resulted in a mean 23% stronger reinforcement effect in the studied structures. Such structures remain efficient when using high-strength concrete.

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