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Improving strength and deformation characteristics of concrete-filled steel tubular elements in bending

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Abstract: The article is devoted to the investigation of the type of monolithic reinforced concrete structures, known as Concrete-Filled Steel Tubular (CFST) elements. They are mostly used in compression and rarely in bending, due to their high deformability. However, there is still a trend in the development of CFST structures with both compressed and bent elements. While bending the reactive lateral pressure transmits from the steel tube to the concrete core creating a favorable condition - volumetric stresses in the concrete, which increases the flexural strength of the material significantly.

Experimental studies have been carried out to determine the bearing capacity and deformability of steel-reinforced concrete (composite) structures filled with fiber-reinforced concrete (FRC) of different compositions. The optimal composition of the concrete core for CFST elements in bending was selected, it helped to increase the strength and deformation characteristics of the element. To choose this optimal composition of the concrete core among others, a series of specimens were prepared and tested in compression, tensile and bending tests, and together with that, the modulus of elasticity and adhesion between the concrete core and the metal casing were studied. As the optimal solution for the concrete core – a mixture of concrete modifier (CM) and metal fibers were selected, due to an increase in the adhesion between the concrete core and the metal casing.

As a result, of experimental studies, graphs of load-deflection dependencies were built and presented. The research results proved that with an increase in the physical and mechanical properties of concrete together with the degree of its adhesion to steel, transverse deformations decrease. For further research development, numerical modeling might be created to describe and foresee the behavior of such elements with different parameters in more detail, which will lead to a better understanding of the combined operation of the tube and core.

Keywords: concrete-filled steel tube, concrete core, steel casing, fiber-reinforced concrete, bending, physical and mechanical properties, specimens, experimental studies, strength, deformability.

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1. Introduction

Nowadays, the main challenges of the construction industry are reducing the weight of buildings and material consumption, as well as reducing load-bearing elements volume and labor costs. This challenge cannot be solved with the use of traditional methods and materials; the issues of creating effective materials and structures of high reliability and minimum weight are raised. To solve these issues, it is necessary to introduce new technologies and high-strength materials.

Worldwide, such type of monolithic reinforced concrete structures as Concrete-Filled Steel Tubular (CFST) structures has become widespread, its use makes it possible to increase the stability of buildings by several times while reducing the material consumption, labor intensity and overall cost of the building.

There are a number of advantages of CFST structures: simplification of the manufacturing process; no formwork, additional reinforcement, or embedded parts are needed; immediately after installation, the structure can withstand significant loads. Assembly of such structures is carried out in the same way as for steel structures; the steel tube works as a longitudinal and transverse reinforcement. Concrete, due to the volumetric stress state inside the tube, perceives stresses that significantly exceed its prism strength, which makes it possible to achieve savings in steel and concrete.

In most cases, CFST elements are used in compression; it is practically not used in bending, due to the high deformability. One of the perspective trends in the development of CFST structures is their use as bent elements. At high loads, the deformation of concrete and steel is different, due to different coefficients of transverse deformation. Therefore, the longer the steel tube will work as a single solid element, the greater load the structure itself can withstand.

2. Object and subject of research

Structures made of CFST elements have been appreciated and are increasingly being used in world construction practice. CFST elements subjected to bending have an exceptionally high bearing capacity with relatively small cross-sections, being an example of a successful combination of the most valuable properties of steel and concrete. While bending CFST element, the reactive lateral pressure transmits from the steel tube to the concrete core creating a favorable condition for the concrete as a material - volumetric stress. As a result, the flexural strength of concrete increases significantly. The steel tube, in turn, is protected from the loss of local stability due to the favorable effect of the internal pressure of the solid material inside.

CFST elements in bending, even those that have a core filled with high-strength concrete, are distinguished by the plastic nature of work in the limit state, which eliminates the risk of sudden failure of both: a separate structure and the entire building as a whole.

3. Target of research

The target of this study is to determine the bearing capacity and deformability of steel-reinforced concrete (composite) structures filled with fiber-reinforced concrete (FRC) of a special composition.

To achieve this target, the following tasks were set:

- to analyze the existing knowledge of using and designing such elements;
- to choose the optimal composition of the concrete core (using various modifiers and fibers) for the CFST beam, in order to achieve the increase in strength, deformation and adhesive properties;

- to experimentally investigate the bearing capacity and deformability of the bent elements of a square steel tube filled with fiber-reinforced concrete;

4. Literature analysis

Back in 1903, O. Consider carried out the first studies of reinforced concrete structures with indirect reinforcement, as a result, it was discovered that concrete in the shell has completely new, better physical and mechanical properties. The search for various methods of reinforcement led to the idea of using a shell tube instead of bar reinforcement.

Over the past decade, active scientific research on CFST structures has been carried out in Ukraine. To date, peculiarities of operation of cylindrical cross-section CFST elements depending on their geometrical characteristics, physical and mechanical properties of concrete core and shell material, stress-strain state, load application methods and their duration have been studied quite thoroughly. On the other hand, CFST elements working in bending are insufficiently investigated.

A significant contribution to theoretical and experimental studies of CFST elements, working both in compression and in bending, was made by local scientists: A.A. Gvozdev, V.A. Rosnovsky, O.A. Dolzhenko, L.K. Luksha, R.S. Sanzharovsky, L.I. Storozhenko, E.D. Chikhladze, O. I. Kikin and others. Studies were also conducted by foreign scientists: Y. Hunaiti, L. Han, R. Gopal, D. Manoharan [1-8].

Many researchers in the field of CFST structures noted that the tube begins to work like a clip only at the stage close to the destruction of concrete, before that the tube works only like a formwork, in case it is not included in the structural work.

5. Research methods

To determine the optimal composition of the concrete core, a series of specimens were made for compression, tensile and bending tests, as well as for the determination of the modulus of elasticity and adhesion to the metal casing.

A concrete modifier (CM) and various fibers were used to increase the adhesion between the concrete core and the steel tube casing. The modifier for concrete was obtained from industrial waste product - dried sludge from the wet gas treatment of ferrosilicon production and superplasticizer (SP) [9-10].

Four concrete compositions were selected:

1 - control composition;

2 - composition of 0.1% basalt fiber from the total mass of the concrete mixture;

3 - composition of 1.5% metal fiber of the total mass of the concrete mixture;

4 - composition of 15% modifier by weight of cement and 1.5% of metal fiber by weight of the total concrete mixture.

From each composition, 4 prisms with a section of 10x10x40mm and 4 "dog-bone" were made. The samples were tested in compression, and the modulus of elasticity and prismatic strength were determined.

The process and results of the research are shown in Figure 1 and in Table 1.

During the initial stage of research, part of the compositions was eliminated because of unsatisfactory results.

Figure 1. Specimens testing process.

Table 1. Optimal core test results

No. specimen	Cubical strength, $f_{cm,cube}$, MPa	Prism strength, $f_{cm\ prism}$, MPa	Ratio $\frac{f_{cm,prism}}{f_{cm,cube}}$	Tensile strength, f_{ctk}, MPa	Initial modulus of elasticity, E_{cm}, MPa
1	27,5	22,8	0,83	1,7	26500
2	33,3	27,97	0,84	2,7	31300
3	34,8	29,23	0,84	3,2	38000
4	52,6	45,76	0,87	4,9	54700

Further experimental studies of CFST elements in bending were carried out on samples No. 1, 4 and 6.

In the next step of the research, a corresponding experiment was developed: it includes 4 series of experimental samples (12 specimens), having an external cross-sectional dimension of steel tube of 100x100mm, tube wall thickness t=3mm and length L=1300mm.

Tubular samples were filled with a concrete mixture of three compositions.

B1 - steel tube without concrete;

B2 - steel tube filled with a control composition of class C16/20 concrete;

B3 - steel tube filled with concrete with the addition of 1.5% metal fiber of the total mass of the concrete mixture;

B4 - steel tube filled with concrete with the addition of 15% of the modifier by weight of cement and 1.5% of metal fiber by weight of the total concrete mixture.

The scheme of experimental studies and the test of CFST elements in bending are shown in Figures 2-3.

Testing for bearing capacity and deformability of CFST elements was carried out on the UIM-50M press [11-12]. The maximum distance between the supports allowed for this press is 1200mm. The loading was carried out using a traverse with a distance between the applied forces of 400 mm. The tested beam was loaded in thirds of the span (pure bending zone). A general view of the specimen being tested is shown in Figure 2. The specimen was loaded stepwise, with a load of 200kg up to a load of 2000kg, then the step was increased to 500kg.

The test results are shown in Figures 4-5.

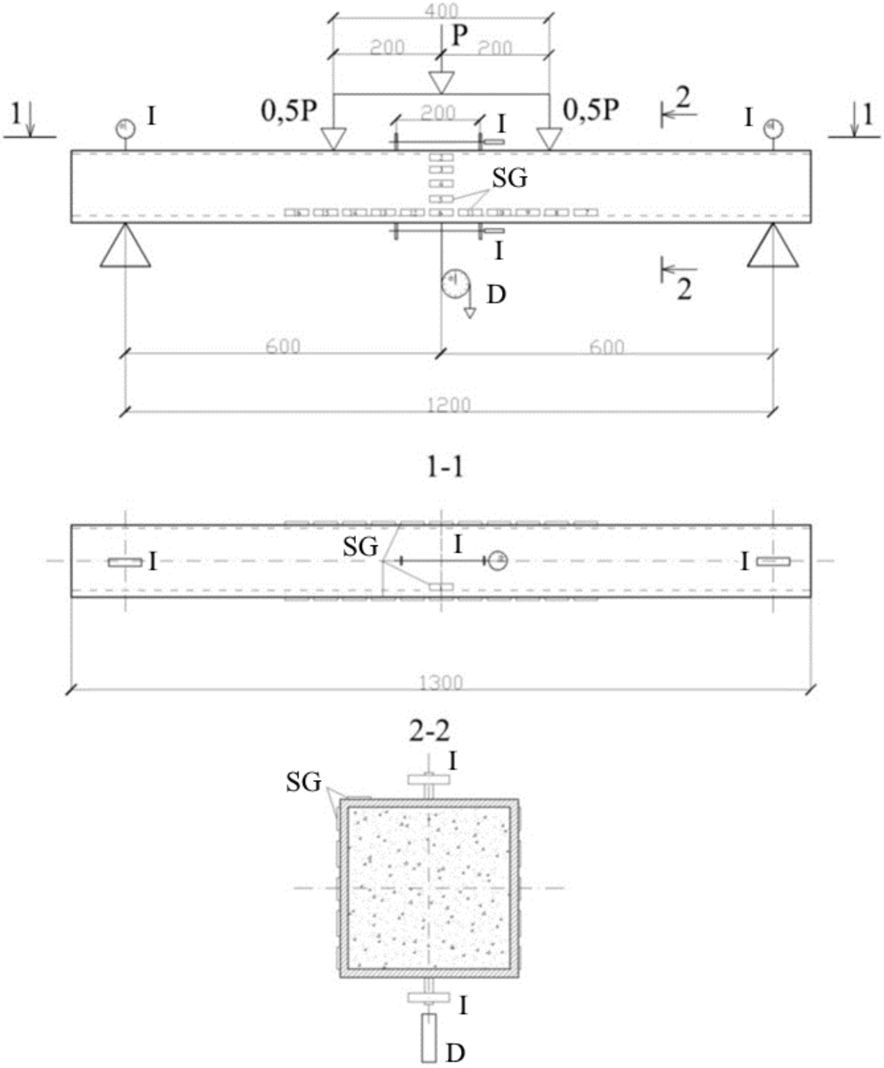

Figure 2. General view of the bending element and layout of measuring instruments: D - deflectometer; I - clock type indicators; SG - strain gauges

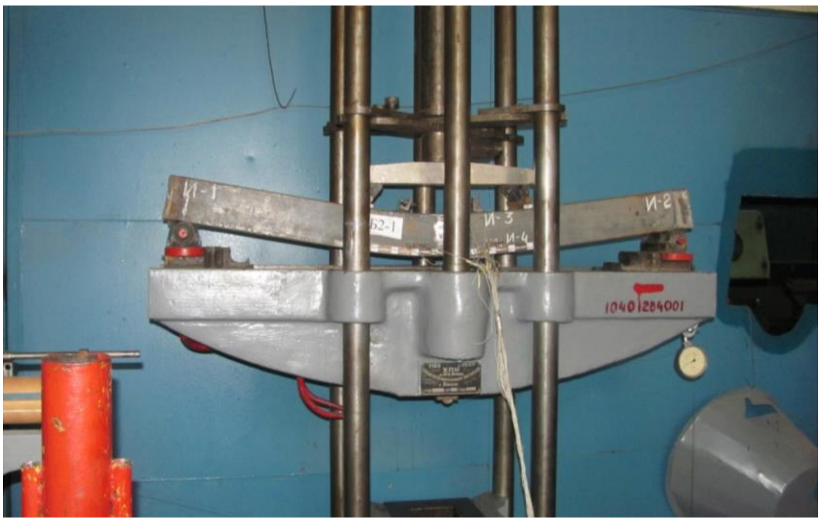

Figure 3. CFST element bent during the test

6. Research results

Table 1 shows that the addition of metal fiber and SP fibers to the concrete matrix significantly increases the main deformation and strength characteristics of concrete.

An important factor in the performance of the CFST structures is the adhesion between the core and the tube.

According to the research carried out by the authors [9], the adhesion strength of cement stone with aggregate grains, fibers and the inner surface of the tube casing depends on many factors, in particular:

- the nature of the surface of aggregate grains, the shape of the fiber and the degree of its purity; foreign particles located on the surface of the aggregates. For example, clay impurities sharply reduce the strength of adhesion;
- the chemical and mineralogical composition of aggregate grains;
- the strength of the cement stone; with an increase in the strength of the cement stone, all other things being equal, the adhesion strength increases;
- from the moisture content of concrete at the time of testing; with an increasing moisture content of concrete, all other things being equal, the strength of adhesion of cement stone decreases. The use of SP as an additive to concrete, in turn, affects this parameter.

During bending tests of elements, an important factor is its deformability, both longitudinal and transverse, as well as displacements (deflections).

Figure 4 shows the results of strain measurements in the compressed and stretched zones by means of clock-type indicators I-3 and I-4, respectively.

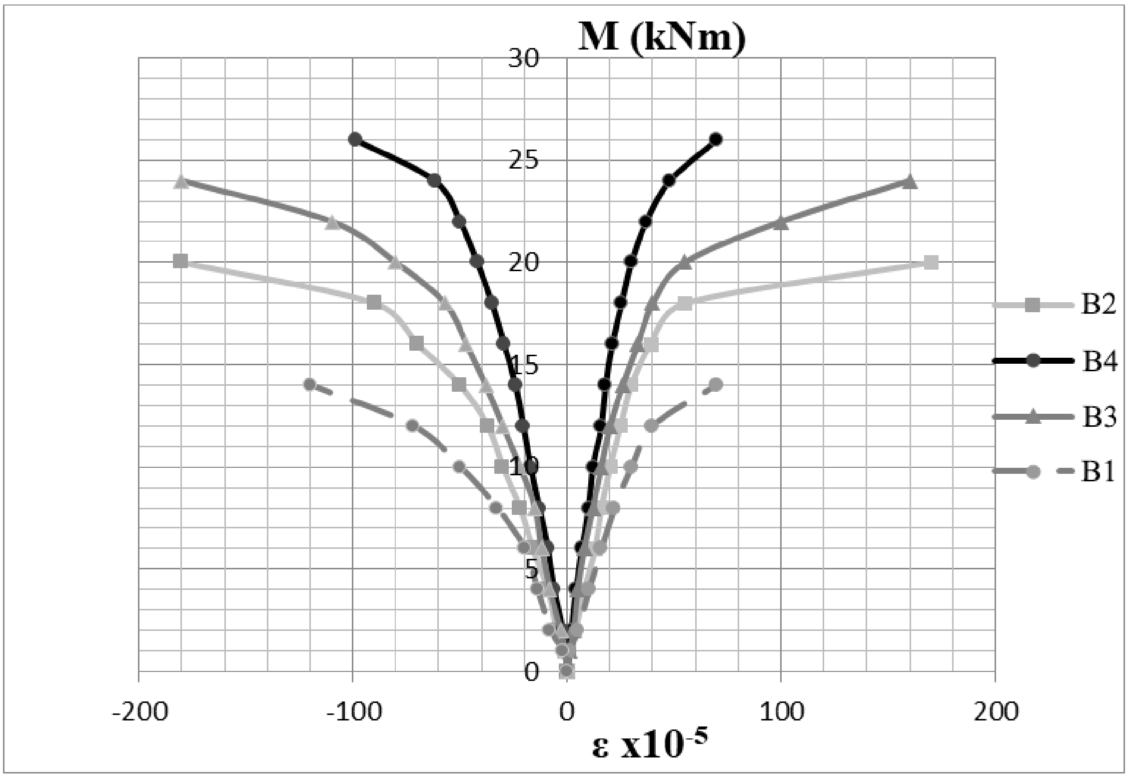

Figure 4. Dependence of longitudinal deformations for different compositions of concrete core

In experimental studies, the buckling of the support zone of the beam was determined. The buckling was determined using clock-type indicators I-1 and I-2. The results of the deformation of the support zone are shown in Figure 5.

As can be seen from the graphs, with an increase in the physical and mechanical properties of concrete and the degree of its adhesion to steel, transverse deformations decrease. An empty tube has the least rigidity, hence the greatest deformability. As can be seen from the graphs, up to a certain bending moment, the longitudinal deformations in the support zone develop linearly.

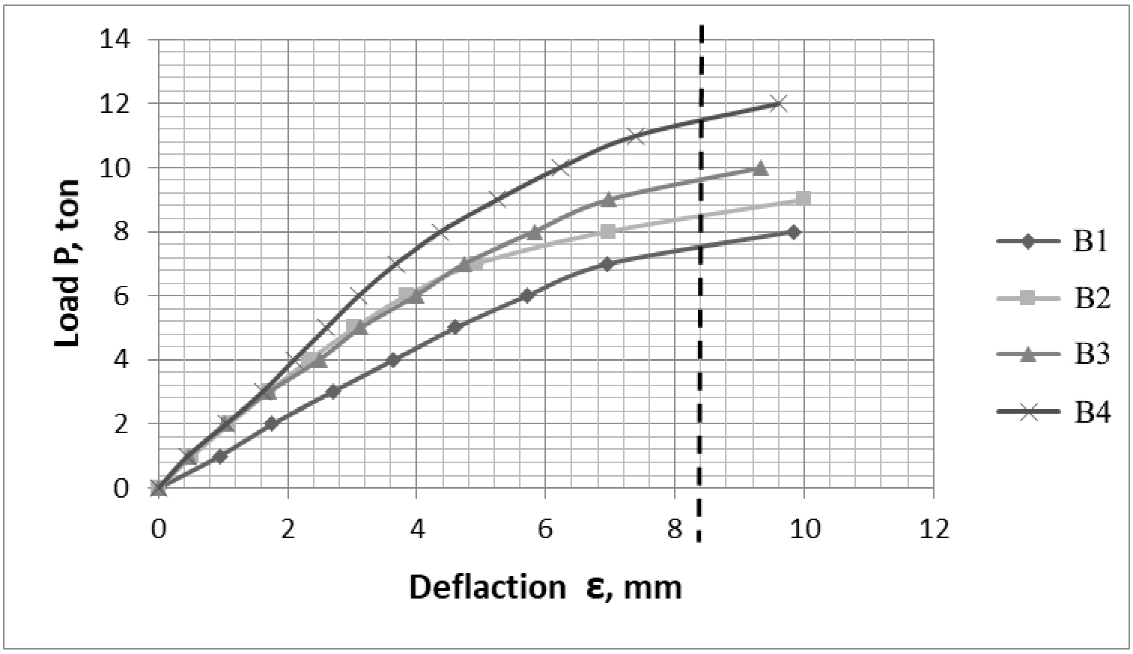

Figure 5. Dependence of transverse deformations in the support zone for different compositions of concrete core

These experimental studies reveal the influence of various types of concrete core compositions of CFST elements on their deflections in bending. It is known that CFST bendable elements are able to withstand significant loads, but at the same time, the structure will have significant transverse deformations (deflections). In the building codes and standards, there are restrictions on the maximum deflection of bent elements. For tested elements, the maximum allowable deflection was 8mm. The maximum deflection for the used loading scheme is reached in the middle of the span, the deflectometer was installed there.

7. Prospects for further research development

The results of the research have established the effectiveness of the proposed design. The proposed design methods for CFST beam elements can be used in load-bearing structures. A new design approach for CFST beams in bending that has high physical and mechanical characteristics can be proposed for implementation in modern construction, primarily for reconstruction.

Modern calculation software can describe and foresee the behavior of similar structures with different parameters in an even more detailed way, which will lead to the possibility of numerical modeling of the combined operation of the tube and core. In our opinion, this approach is promising for further research development.

8. Conclusions

In this research, the optimal composition of the concrete core for CFST elements in bending was selected, which makes it possible to increase the strength and deformation characteristics of the structure. Experimental studies of CFST elements in bending have been carried out.

It was experimentally established that the characteristics of concrete with the addition of 15% SP from the weight of cement and 1.5% of metal fiber, compared with the control composition increased by more than 90% (compressive and flexural strength), and the axial tensile strength is more than 2 times.

Experimental studies of the deformability of CFST elements in bending showed that the proposed concrete core composition reduces the deformability of the beam by 35%, and increases the bearing capacity by 1.3 times.

Moreover, there was one peculiarity of the obtained experimental results as it showed that CFST beams continued to bare the load even at abnormal, as for concrete, deflections.

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