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Load-bearing capacity of concrete elements reinforced with steel and composite coatings

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Abstract. In the article, the compressive strength of steel-concrete structures defined as CFST (Concrete Filled Steel Tubular) has been checked. The steel elements used in CFST columns have high tensile strength and ductility while the concrete elements have high compressive strength and stiffness. Therefore, CFST elements have a large range of applications in construction. The analysis included 8 examples of elements consisting of a steel tube filled with a concrete core. The examples differed in the thickness of the steel coating and the compressive strength of the concrete core. Analytical calculations and experimental studies for them were carried out. The analytical calculations were based on the author's method of assessing the load-bearing capacity of concrete-filled steel tubes. In experimental verification, CFST samples were subjected to a static compression test. The calculation method was also used to calculate the load capacity when composites reinforcement is the outer coating for the concrete core. Three types of composites were analysed. The obtained results show a large influence of the steel coating thickness on the compressive strength for the CFST elements. The load-bearing capacity of the elements depends on the appropriate ratio of the surface of the steel coating to the concrete coating.

1. Introduction

The idea of filling steel tubes with concrete is mainly used in load-bearing structures of high-rise buildings and bridges. The combination of a steel tube with a concrete core is defined as CFST (Concrete Filled Steel Tubular) structures and is characterized by high bearing capacity, stiffness, resistance to seismic and mechanical loads as well as weathering. This structural elements also have a high fire resistance which increases the possibility of application. Columns made of steel tubess filled with concrete have a higher class of the fire resistance the load capacity of the CFST column in fire conditions increases several times. This was proven by the authors of publications [1], [2].

Another important aspect in CFST constructions is the strength of the connection between steel and concrete. The authors of the work [3] in their research have checked for which type of steel and concrete CFST elements have the highest load capacity as well as

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the best strength of the connection between steel and concrete. Based on their research results, the best solution is to use carbon steel tubes and expansive concrete to fill. This is also confirmed by the authors of the papers [4], [5]. Therefore, R35 carbon steel and expansive concrete of various strengths were used for the analysis.

Interesting research was carried out by the authors in [6] who proposed using a corrugated steel tube as the outer shell. The working mechanism of such an element is similar to the model CFST but corrugated steel tube has better corrosion resistance and higher lateral stiffness than the classic smooth tube.

Researchers also checked for which geometrical section the best values of strength and stiffness will be obtained. Experimental results presented in [7], suggest that circular tubes offer substantial post-yield strength and stiffness, not available in most square or rectangular cross sections.

The design of tube-concrete elements is a very complex process, which is why there are many calculation procedures. The algorithms can be found in European standards [8] or in American [9], [10]. The authors in [11-14] compared the calculation methods for steel pipes filled with concrete. Depending on the calculation method used, for the same material assumptions for steel and concrete, different load-bearing or strength results were obtained. In this article, the analytical method based on the theory contained in [15] was used.

Currently, concrete constructions are often reinforced with composite materials glued to their surfaces. It is an alternative to the traditional reinforcement of steel elements. The composites are characterized by very high tensile strength and the value of boundary distortions. At the same time, they are resistant to corrosion and allow the application of a composite layer on elements of more irregular shapes in difficult conditions. In the works [16], [17] the authors demonstrated the validity of using composites such as carbon or glass fibers in concrete constructions. The conversion of the steel coating in the tube-concrete elements to the composite coating is proposed in the article.

2. Analytical method

Analysis of the mechanical work of CFST (Concrete Filled Steel Tubular) structures is a complex issue. Therefore, some analytical assumptions should be determined at the beginning.
In order to solve the problem, it was assumed that:

- the pipe-concrete element is loaded with short-term static force,
- the axial compressive force is applied to the core,
- the core material (concrete) is a brittle and isotropic,
- the relationship between stresses and strains, according to Hooke's generalized law, is used for the steel coating as well as for the concrete core,
- in the limit state before destruction of the element, the concrete core pressures on the surface of the steel coating as well as counteracts the axial loading,
- in the limit state before destruction of the element, the steel coating acts on the concrete core and carries axial loads,
- the reaction of the steel coating is directed towards the concrete core and therefore the core is in the triaxial state of compressive stresses.

Figure 1 presents the distribution of boundary stress for individual layers of the analyzed structure. In the limit state, it was assumed that:

- the external steel coating (Fig.1.a), is loaded with a circumferential tensile stress $\sigma_{\Theta ce} = \sigma_1$, axial compressive stress $\sigma_{zs} = -\sigma_3$, and radial stress $\sigma_0 = \sigma_2$;
- concrete core (Fig. 1b), is loaded to axial stress $\sigma_{zb} = -\sigma_1$ and lateral radial stress $-\sigma_0 = \sigma_2$;

- radial stresses act on the concrete core with the same value. Compressive stresses were taken as positive.

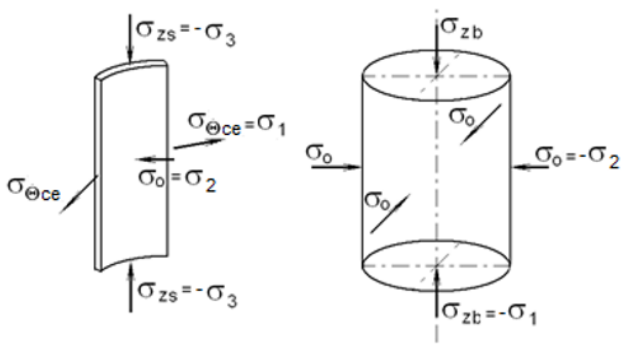

Fig. 1. Limit stresses in the element layers: a) in the outer steel shell, b) in the inner concrete core

The calculation algorithm developed by L. Łuksza at work [15] was adopted to solve the problem. The algorithm used a description of the strength of concrete derived from the hypothesis of brittle materials effort in which the boundary surface has the shape of a non-rotatable hyperboloid, and with the Lode parameter μ = -1 it takes the following form:

$$f_{ccc} = \varphi\sigma_\rho + 0{,}5(f_c - f_t) + [(\varphi^2 + \varphi - 2)\sigma_\rho^2 + (2+\varphi)(f_c - f_t)\sigma_\rho + 0{,}25(f_c + f_t)^2]^{\frac{1}{2}} \quad (1)$$

where:

f_{ccc} – concrete strength with triaxial compression

f_c – concrete strength with uniaxial compression

f_t – strength of the steel shell

σ_ρ – circumferential stresses

φ- strength parameter determined by the formula:

$$\varphi = \frac{2(3\kappa - m)}{3\kappa + m} \quad (2)$$

where:

m – material class index, equal to 2 for ordinary concretes

κ – brittleness material index, determined by the formula:

$$\kappa = \frac{f_c}{f_t} \quad (3)$$

Finally, for the calculations was used the dependence of:

$$f_{ccc} = f_c + K\sigma_0 \quad (4)$$

for:

$$K = -\frac{100\sigma_0}{f_c + 15\sigma_0} \quad (5)$$

where:

K – coefficient of lateral load impact for the concrete core

σ_0 – concrete pressure on the steel coating

According to the author of the work [15], the load-bearing capacity of a short tube-concrete element loaded over the entire cross-sectional area is as follows:

$$N = (f_c + K\sigma_0)A_c + f_s A_s \tag{6}$$

where:

A_c – cross-sectional surface of the concrete core

A_s – cross-sectional surface of the steel coating

f_c – concrete strength with uniaxial compression

f_s – the yield point of steel

The concrete pressure σ_0 on the steel coating was calculated using the following formulas:

$$\sigma_0 = \frac{f_s + \alpha f_c}{\alpha(K - 2\nu_c) - 1}\left(1 - \beta_r^{\frac{-[\alpha(K - 2\nu_c) - 1]}{1 + \nu_a}}\right) \tag{7}$$

$$\beta_r = \frac{r + d}{r} \qquad \alpha = \frac{E_k}{E_{cm}} \tag{8}$$

$$\sigma_z = f_y - \sigma_0 \frac{\beta_r}{\beta_r - 1} \geq 0 \tag{9}$$

gdzie:

υ_a, υ_c, – Poisson's ratio for steel and concrete

E_a – modulus of elasticity of steel

E_{cm} – secant modulus of elasticity of concrete

r, R - outer and inner radius of the steel tube

The basic formula for the load-bearing capacity of a stocky tube-concrete column is a function of many factors affecting on the work of such an element. The parameter *m* defines the ratio of the CFST element bearing capacity resulting from tests when the tube starts to plasticize (N), to the load capacity of this element, calculated by summing the load capacity of steel pipe and concrete without considering their cooperation $f_c A_c + f_s A_s$:

$$m = \frac{N}{f_c A_c + f_s A_s} \tag{10}$$

gdzie:

f_s – the yield point of steel

f_c – compressive strength of concrete

The value of parameter m can be saved as a function depending on:

$$m = f\left(\mu, \frac{f_s}{f_c}\right) \tag{11}$$

where:

$$\mu = \beta_r^{\ 2} - 1 \tag{12}$$

μ- reinforcement factor, which is a function of the wall thickness of the tube.

Figure 2 shows the distribution of the effectiveness of a tube-concrete element depending on the value of parameter m.The distribution was created after the results of the study from work [18]. Based on it, it can be concluded that the expression (11) approaches the maximum values for tube-concrete element when:

$$1 \leq \mu, \frac{f_s}{f_c} \leq 3 \tag{13}$$

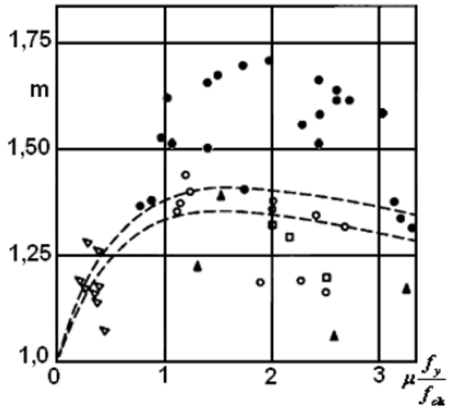

Fig. 2. Distribution of the effectiveness for concrete [18]

In the used calculation method, one of the most important factors is the lateral pressure factor. Simplifying the calculation of this factor gives K = 4. The points in fig. 2 show the results of research from work [18]. The two curved lines describe the function graphs from the expression (11) for two values of the Poisson's ratio: upper for $\upsilon_c = 0{,}5$ and lower for $\upsilon_c = 0.2$, both for the factor K = 4. These graphs do not overlap with a large number of points. The curve lines would be more similar to the test results if the K parameter values were more varied. Part of the test results were determined visually, i.e. the point indicating the beginning of plasticizing of the steel pipe was visually determined.

These calculation method for the 8 types tube-concrete elements (samples R1 ÷ R8) was used. The samples were differed in the wall thickness of the steel tube and the compressive strength value for concrete. A constant value of the external radius R of the sample and the height of all samples equal to 0.29 m were assumed. Steel pipes made of carbon steel grade R35 (steel P235TR1) and a concrete core of expansive concretes with a strength of 25 MPa and 50 MPa were adopted.

Table 1 contains material properties for tube-concrete elements.

Table 1. Material data [19], [20]

Propoerties Material	Density ρ [kg/m³]	Young's modul E [GPa]	Poisson's ratio υ [-]	Yield strength R_e[MPa]
Expansive concrete	2200	30	0.20	variable
Steel R35	7850	210	0.30	210

3. Concrete elements reinforced with a composite coating

The calculation method described above for the analysis of the load-bearing capacity of cylindrical concrete elements with a composite coating has been applied. The load bearing capacity of the external coating was assumed to be zero.

$$N = (f_c + K\sigma_0)A_c \tag{14}$$

gdzie:

A_c – cross-sectional surface of the concrete core

f_c – concrete strength with uniaxial compression

K – coefficient of lateral load impact for the concrete core

σ_0 – concrete pressure on the composite coating

where according to the expressions (7) and (8) the pressure σ_0 should be calculated from the formulas:

$$\sigma_0 = \frac{f_y + \alpha f_c}{\alpha(K - 2\nu_c) - 1}\left(1 - \beta_r^{\frac{-[\alpha(K-2\nu_c)-1]}{1+\nu_k}}\right) \tag{15}$$

$$\beta_r = \frac{r+d}{r} \qquad \alpha = \frac{E_k}{E_{cm}} \tag{16}$$

gdzie:

υ_k, υ_c, – Poisson's ratio for composite and concrete,
E_k – modulus of elasticity of the composite along the fibers,
E_{cm} – secant modulus of elasticity of concrete,
R – outer radius of the concrete core,
d – thickness of the composite coating
f_y – tensile strength of the composite fibers.

The analysis of the strength of cylindrical concrete elements reinforced with a composite coating was carried out for three constructional solutions:

- core + polymer construction composite UD glass-epoxy,
- core + polymer construction composite UD carbon-epoxy,
- core + PBO fibers together with a special mortar of the Ruredil X Mesch Gold System.

In UD polymer structural composites, glass and carbon fibers are oriented one-way and have high strength and stiffness in the direction of the fibers.The third composite coating is the Ruredil X Mesch Gold System consists of a Polyparaphenylene benzobisoxazole (PBO) mesh and a stabilised inorganic matrix designed to connect the mesh with the concrete substrate. This system increases the strength of concrete elements to stresses caused by stretching during bending and shearing. For each composite variant eight types of concrete cores were adopted. The geometric dimensions of the core and compressive strength values for concrete were the same as for the analysis of the tube-concrete samples.

Table 2 shows the material properties of the used composites.

Table 2. Material data for composites [18], [21]

Propoerties Material	**thickness of the composite coating d [mm]]**	**Young's modul E [GPa]**	**Poisson's ratio υ [-]**	**Tensile strength f_y [GPa]**
glass-epoxy composite UD	0.05	39	0.25	1.20
carbon-epoxy composite UD	0.25	134	0.263	2.04
fibers PBO	0.0455	270	0.25	5.80

4. Analysis of the results

Load capacity results for steel-concrete tubes and concrete samples reinforced with a composite coating are shown in Table 3.The geometrical dimensions for each sample and the compressive strength of the concrete are also given. For tube-concrete elements, results from laboratory tests from work [11] were included.

Table 3. Comparison of the results of laboratory measurements with analytical calculations

L.p.	Sample	Parameters of samples				N	N values - analytical calculations			
		D_s	t_s	r	f_c	the result of experimental studies	Steel coating	glass-epoxy composite UD	carbon-epoxy composite UD	fibers PBO
		[mm]	[mm]	[mm]	[Mpa]	[kN]	[kN]	[kN]	[kN]	[kN]
1.	R1	106	3.00	50.0	26.9	616.0	604.1	667.4	409.0	528.9
2.	R2	106	3.00	50.0	27.1	620.0	606.5	669.4	409.1	531.0
3.	R3	106	4.00	49.0	26.9	786.0	668.0	648.9	395.6	512.9
4.	R4	106	4.00	49.0	27.1	795.0	671.0	653.7	397.6	514.9
5.	R5	106	3.00	50.0	41.9	751.0	785.7	747.1	554.0	685.3
6.	R6	106	3.00	50.0	42.4	768.0	791.7	753.0	558.8	690.4
7.	R7	106	4.00	49.0	41.9	924.0	846.8	723.1	535.3	663.3
8.	R8	106	4.00	49.0	42.4	945.0	852.7	728.8	539.9	668.3

where:

– D_s – outside diameter of the steel tube

– t_s – wall thickness of the steel tube

– r – radius of the concrete core

– f_c – compressive strength of concrete - determined experimentally

Based on the analyzes carried out, large differences between the values of the load capacity from analytical calculations and laboratory tests for samples where the wall thickness of the steel tube was 4 mm can be noticed. For samples R3 and R4 is 118 kN and 124 kN respectively, for R7 and R8 it is 77 kN and 92 kN. In addition, a change in the wall thickness of a steel pipe by 1 mm for the same strength of concrete resulted in an increase of the load capacity of the elements by an average of 25% for laboratory tests and more than 9% for results from analytical calculations. This means that the steel element has, in fact, a much greater impact on the final load capacity of the tube-concrete element than the calculation method adopted. In 75% of the samples, higher values of load capacity were obtained in laboratory tests, while for samples R5 and R6 these values were higher for analytical calculations.

However, for geometrically the same tube-concrete element, the change of the strength class for concrete caused an increase of the load capacity by approx. 20% for the experimental samples and 28.6% for the samples from analytical calculations.

For the concrete elements in which a composite coating was placed instead of the steel coating, the best load capacity values were obtained for the glass-fiber composite and the lowest for the composite with carbon fibers. At the same time, the change of the strength class of the concrete had the least impact on glass fiber samples (increase by approx. 12%) and the largest for samples with carbon fiber (increase by approx. 35%).

5. Conclusions

Based on the results of computational analyses and experimental tests, it can be concluded that:

- the wall thickness of a steel pipe in structures such as CFST has a significant effect on the load capacity of the element;
- change of the concrete strength class for the inner core, both in elements with steel and composite coating, has a similar effect on the load capacity of the element,
- the best load capacity results can be obtained by determining the appropriate surface ratio of the steel coating to the surface of the concrete core,
- the load capacity of concrete elements with a composite coating is not much smaller than elements with a steel coating. This combination of concrete and composites can be used where it is impossible to use a steel coating for structural reasons or access to the element.

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