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Analysis of local stability of the rectangular tubes filled with concrete

Анализ местной устойчивости трубобетонных конструкций прямоугольного сечения

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Abstract. The use of rectangular steel tubes filled with concrete allows combining the advantages of concrete (reinforced concrete) and steel structures with reciprocal compensation of their disadvantages. Building code Eurocode 4 is used for the design of such structures in the European Union, but the main disadvantage of this standard is its limitations for use of the class 4 rectangular steel cross-sections (classification according to standard EN 1993-1-1) filled with concrete. Therefore, the study of local stability of such structures and the impact of friction between the components of the composite section on it is relevant. The analysis of the influence of friction between the steel shell and the concrete core on the local buckling of composite structures was carried out using the ABAQUS computational-graphics software. The models of behavior of axial compressed rectangular cross-section samples with different coefficients of friction between the shell and the core were created for this. The load on the samples was applied in two variants: a) simultaneously through the steel section and the concrete core; b) only through the steel section. The variants with different fixing conditions of loaded edges of the steel section were also considered. Based on this research, the basic laws of development of local buckling deformation of the structures under study were analyzed. The influence of the conditions of fixing the loaded edges of the steel section to local buckling deformation of the composite structure was determined. The dependence of the friction effect between the components of steel-concrete section on the local stability of rectangular tube was shown.

Аннотация. Применение стальных прямоугольных труб, заполненных бетоном, позволяет использовать и сочетать преимущества бетонных (железобетонных) и стальных конструкций с взаимной компенсацией их недостатков. Для проектирования таких конструкций на территории Европейского Союза уже существует строительная норма Еврокод 4. Но основным недостатком данной нормы является ограничение в использовании стальных прямоугольных сечений 4-го класса (классификация согласно EN 1993-1-1), заполненных бетоном. Следовательно, на сегодняшний день являются актуальными исследования потери местной устойчивости данных конструкций и влияния на неё трения между составными частями композитного сечения. Анализ влияния трения между стальной оболочкой и бетонным ядром на местную устойчивость композитных конструкций проводился в расчетно-графическом комплексе ABAQUS. Для этого были созданы модели поведения центрально-сжатых образцов прямоугольного сечения с разными значениями коэффициентов трения между оболочкой и ядром. Нагрузка на образцы прикладывалась в двух вариантах: а) одновременно на стальную оболочку и бетонное ядро; б) только на стальную оболочку. Также были рассмотрены варианты с различными условиями закрепления нагруженных граней стальной части сечения. На основании проведенного исследования были проанализированы основные закономерности проявления деформаций при потере местной устойчивости исследуемых конструкций. Установлено влияние условий закрепления нагруженных граней стальной части сечения на деформации локального выпучивания композитной конструкции. Показана зависимость влияния трения между составными частями сталебетонного сечения на местную устойчивость прямоугольной трубы.

Introduction

A characteristic feature of modern building is a divergence from the legacy of constructive solutions of buildings, engineering structures, and the search for new technology of building objects. In these cases, the need for engineers is to design structural elements, which combine the advantages of concrete and steel materials with a mutual compensation of their disadvantages. These structural elements are steel-concrete structures.

Steel-concrete (composite) structures are constructions, in which the steel and concrete parts of the cross-section have their own bending stiffness, and contact areas are interconnected by means of friction forces. The main difference between composite and reinforced concrete structures is that flexural rigidity of steel reinforcement of reinforced concrete structures can be neglected before complete hardening of concrete.

Composite columns are a very important part of composite structures, and are widely used in the erection of high-rise buildings and bridge constructions, in places with high compressive loads with relatively small bending moments [1]. One type of composite columns are rectangular concrete-filled steel tubes (CFSTs). As noted in [2–10], these structures have their advantages in comparison with an empty steel pipe, but one main preference is a significant resistance to loss of local and global stability, which greatly reduces the cross-section of the element.

Review of literature

World standards described in [11–14] exist for the design of the above mentioned structures. However, these standards have limitations in practice, such as mechanical properties of materials or the slenderness of steel elements of composite cross-sections etc. Authors, such as Mouli [15], Uy [16–18], Krishan [19], in their scientific works, devoted to enhancing validity of these standards, investigated the ultimate strength, stability and ductility characteristics of rectangular CFSTs subject to axial compression using high performance steels and lightweight concrete aggregates. Experimental tests, conducted by Lee [20] and Storozhenko [21] on high-strength concrete-infilled steel tube columns subject to eccentric loads, showed the influence of width-to-thickness ratio, buckling length-sectional width ratio and eccentricity ratio on the behavior of these structures. Patel *et al.* [22] proposed a multiscale numerical model for simulating the interaction of local and global buckling behavior of eccentrically loaded high strength rectangular CFSTs with large depth-to-thickness ratios. Yang and Han [23] presented the research aimed at the experimental investigation of the behavior of rectangular CFSTs loaded axially on a partially stressed cross-sectional area. The research conducted by Nethercot [24] and Bradford [25] was devoted to the problem of the loss of the local stability effect on the strength of thin-walled tubes filled with concrete.

Currently, the European Union uses EN 1994-1-1 (Eurocode 4) to design rectangular CFSTs [26]. The basic disadvantage of the standard is its limitations regarding the slenderness of the web of the rectangular cross-section. The design of more efficient composite structures is conducting research on class 4 hollow steel cross-sections, according to EN 1993-1-1 (Eurocode 3) [27], filled with concrete, which already lie beyond the validity of Eurocode 4. Since it is impossible to use connecting elements between the steel shell and the concrete core in such structures, the interaction or bond between the two materials is achieved by natural connection. Consequently, the problem of the impact of changes in friction between the two materials on the local buckling of the composite structure is a relevant topic.

Formulation of the problem

The object of this research is a welded cold-formed hollow profile of rectangular cross-section RHS 200/100/3 (standard EN 10219 [28]), filled with concrete.

The objective of this work is to study the behavior of the compressed composite profile, which lies beyond the validity of Eurocode 4, and to analyze the changes of the natural connection characteristics between the steel shell and the concrete core on the local stability of the composite structure.

To achieve this objective, the following tasks were set:

- 1) Analytical review of scientific and technical material on local buckling of the steel-concrete element and the interaction between steel and concrete parts of the composite cross-section.
- 2) Modelling of the axially compressed composite element behavior using ABAQUS computer-graphics software.

3) Analysis of the impact in friction changes between the components of the composite section on the local stability of rectangular CFST.

Local stability of the axially compressed rectangular tubes

According to the standard EN 1993–1–1, class 4 cross-section is the section in which the loss of local stability occurs up to the yield stress in one or several parts of the section. The sections of this class are calculated according to the technique, specified in standard EN 1993–1–5 (Eurocode 3 part 1–5) [29]. This technique is based on adducing a full cross-section of the welded cold-formed hollow profile to the effective (reduced) one. The effective cross-section is a profile in which the eliminated from calculations parts of the webs of the rectangular cross-section are due to local buckling. The reduction of the section allows taking into account the effect of local buckling and loss of cross-sectional shapes on the load-bearing capacity of the compressed tube.

The basic principles of designing class 4 cross-sections were stipulated by Bryan [30], who offered a critical analysis of the elastic stress σ_{cr} for local buckling of long right-angled wall elements with simple (hinge) supports on all the edges acting under the influence of a uniform pressure load. The term “stress” includes various boundary conditions and distribution of forces over the element with the aid of the coefficient of critical stress k_{σ} :

$$\sigma_{cr} = k_{\sigma} \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2 \tag{1}$$

The minimum values of the coefficient of critical stress k_{σ} are stipulated in EN 1993-1-5. In the case of internally compressed cross-sections (rectangular tube wall), this coefficient varies from $k_{\sigma} = 4$ for pure pressure to $k_{\sigma} = 23.9$ for the combination of compression and bending. The coefficient can be used for hollow rectangular tubes. When the tube is filled with concrete, the standard does not provide the k_{σ} value.

In the research by prof. Timoshenko [31], devoted to the stability of right-angled walls with simple (hinge) supports, a differential equation was presented for a slender wall with length a , and width b (Fig. 1a), which is simply supported around its perimeter:

$$C \left(\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) + P \frac{\partial^2 w}{\partial x^2} = 0 \tag{2}$$

where w is the deflection of slender walls, m;

P is the compression force, N.

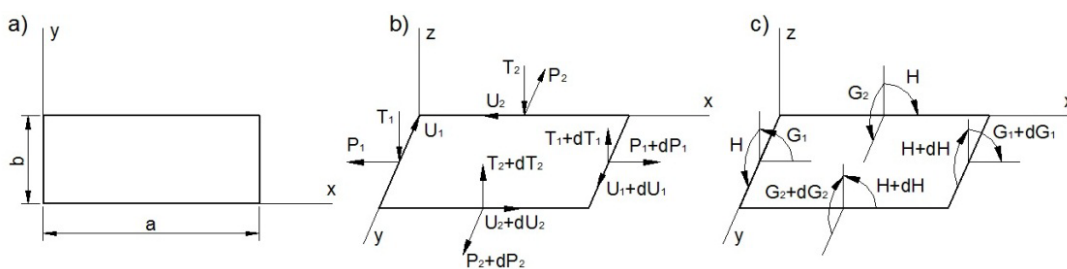


Figure 1. Mathematical model of a slender wall:
a) location of walls in the coordinate axes; b) components force in a unit element of the wall;
c) components of the bending moment in a unit element of the wall.

The cylindrical wall stiffness C :

$$C = \frac{Et^3}{12(1-\nu^2)} \tag{3}$$

where E is the modulus of elasticity of steel, MPa;

t is the wall thickness, m;

ν is the Poisson ratio.

A particular solution to the differential equation (2) represents the balance of forces in one of the possible buckling forms of its walls:

$$w = A \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \quad (4)$$

The given solution satisfies the boundary conditions (Fig. 1b,c): for $x=0$ and $x=a \rightarrow w=0$ a $G_1=0$; for $y=0$ and $y=b \rightarrow w=0$ a $G_2=0$. The following conditions are fulfilled for stress: $P_1=-P$; $U_1=U_2=P_2=0$.

The compressive force P can be determined by substituting the expression (4) for equation (2):

$$P = C\pi^2 \frac{\left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right)^2}{\frac{m^2}{a^2}} \quad (5)$$

where m and n are half-waves along the length and across the width of the wall.

Of all the possible buckling forms of the force balance in the cross-section of the wall, we need to find one where the value of the force P will be minimal. This will be achieved if $n=1$ and the value m according to [31] is expressed by equation (6). From the above relationship, it follows that the limit value for the length a , at which the wall reaches its first buckling form, comprises the m half-waves.

$$a = b\sqrt{m(m+1)} \quad (6)$$

If we consider that $P = P_{cr}$ and $P_{cr}/t = \sigma_{cr}$, where σ_{cr} is the value of the critical compressive stress, i.e. formula (5) adjustments for $n=1$ and the cylinder wall stiffness are taken as:

$$\sigma_{cr} = \left(m \frac{b}{a} + \frac{1}{m} \frac{a}{b}\right)^2 \frac{\pi^2 E t^2}{12(1-\nu^2) b^2} \quad (7)$$

According to EN 1993-1-5, expression (7) is the value of the elastic critical stress of the wall $\sigma_{cr} = k_{\sigma} \sigma_{E_s}$, and the first factor of this expression is the coefficient of the elastic critical stress k_{σ} .

Interaction of steel shell and concrete core when loading composite columns in high-rise buildings

The load in frames with hinged columns (Fig. 2a) is introduced into the columns at the top, in frames with continuous columns (Fig. 2b) through column-beam joints at each floor level.

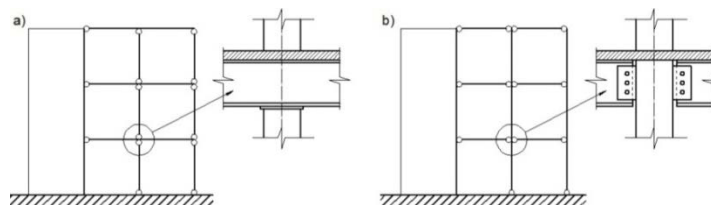


Figure 2. Load introduction:
a) hinged columns; b) continuous columns

The load at the top of a hinged column may be introduced as follows:

- a) simultaneously through the steel section and the concrete core;
- b) only through the steel section;
- c) only through the concrete core.

The total interaction between steel and concrete elements of the composite cross-section is due to the natural bond of the two materials which includes: adhesion, interlock due to surface unevenness, and friction.

Adhesion or adhesive bond is considered to be elastic-brittle and it is activated mainly at the initial loading stage. The maximum shear strength detected according to [3] is 0.1 MPa. In steel-concrete Kanishchev R.A. Analysis of local stability of the rectangular tubes filled with concrete. *Magazine of Civil Engineering*. 2016. No. 4. Pp. 59–68. doi: 10.5862/MCE.64.6

composite columns this component of shear transfer may be neglected, since the shear resistance is excessive at the value of the slip smaller than 0.01 mm and concrete shrinkage diminishes the effect of such connection.

Interlock due to surface unevenness occurs as a result of concrete leakage and its hardening in troughs on the surface of a steel element. This method of interaction is effective only when steel and concrete elements are connected perpendicularly to the shear flow. The interlocking of the two materials due to their surface unevenness contributes to the initial stiffness of a column. Shear connection disappears when relative deformation/strain of the concrete in the contact area reaches 0.035 %. Similar to adhesion, concrete shrinkage has a negative impact on the effectiveness of this connection.

Shear transfer by friction is closely related to interlock due to surface unevenness and it depends on the normal force in the contact area and the relevant coefficient of friction μ . Friction is a resistance force acting against separation of composite elements or their sliding against each other. This type of interaction between physical bodies consists of two components: normal and tangential ones. The normal component is hard contact acting perpendicularly to a steel section that allows individual movements of steel and concrete under some specific loading conditions. However, the tangential component acts against these movements and it depends on a number of factors such as surface structure, roughness of the material used, temperature, and humidity.

The overview of research works shows that the coefficient of friction μ varies from 0 (when a steel surface is painted) to 0.7 (when a steel surface is unfinished/unpainted). Rabbat and Russell [32] have tested 15 specimens and concluded that the value of this coefficient was within the range between 0.57 and 0.70. Baltay and Gjelsvik [33] have specified the mean value of the friction coefficient as 0.47. Evirgen and Tunçan [34] have empirically detected in their experiments that the coefficient of friction was 0.55, while it weakly correlated to the compressive strength of concrete.

The design shear strength τ_{Rd} is lower than the tensile strength of concrete and it depends on the type of section. It is dependent on the friction produced between steel and concrete elements; therefore, the values $0.29 \div 0.35$ MPa calculated according to [34] and 0.4 MPa, given in standard EN 1994-1-1, are applicable only to an unfinished steel surface with no coat or paint, free from oil, grease, loose scale or rust. The design values of shear strength can be used only if there is no separation between the surface areas. The influence of "pressing" concrete to a steel element/creep on the design shear strength manifests itself more in circular concrete-filled hollow sections than rectangular ones.

FEM modelling of the concrete-filled rectangular tubes

A test with 36 "short" specimens was modelled using the ABAQUS 6.13-4 software application to analyze the impact of friction between the steel shell and concrete core on the local stability of rectangular CFSTs. The behavior of rectangular tubes (steel part of composite cross-section) with a section of RHS 200x100x3 (according to EN 10219) was investigated. The test specimens were divided into 3 groups by length: a) 200 mm (4 specimens); b) 400 mm (4 specimens); c) 600 mm (4 specimens). The length of the specimens in each group is selected according to expression (6) based on occurring the estimated number of half-waves (from 1 to 3 half-waves) along the length of an element.

When modelling steel cross-sections, the material characteristics defined by EN 1993-1-1: steel class S235, elastic modulus $E = 210\,000$ MPa, the Poisson's ratio in the elastic state $\nu = 0.3$, were used. The behavior of the material was modelled as an elastic-plastic with hardening, according to the norm EN 1993-1-5. The core of the composite section was modelled as concrete class C20/25 with elastic modulus $E = 30\,000$ MPa and the Poisson's ratio in elastic state $\nu = 0.2$, according to the standard EN 1992-1-1 (Eurocode 2) [35].

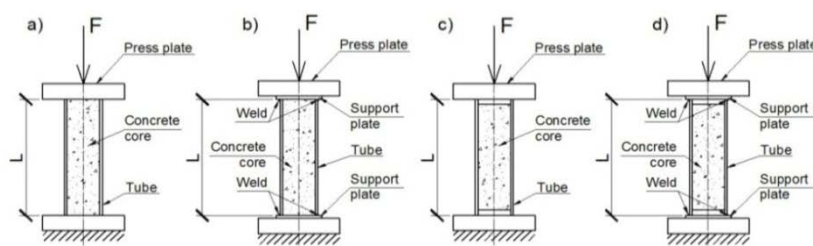


Figure 3. Scheme of loading steel-concrete specimens:
a) on the steel tube and the concrete core;
b) on the steel tube and concrete core through the welded support plate;
c) on the steel tube; d) on the steel tube through the welded support plate

The library of ABAQUS elements [36] was used for the modelling: the steel section was made of «shell-type» S4R elements and the concrete core of “solid-type” C3D8 elements. The maximum mesh size of finite elements is 10 mm. The interaction of steel and concrete materials was modelled by means of two components: the «normal» one as compression of concrete on the steel section and the “tangential” one as shear resistance at the steel-concrete interface. To determine the impact of friction on the local stability of rectangular CFSTs, the coefficients of friction μ were taken 0; 0.35 and 0.7.

The loading of elements was simulated with a type of hinged columns (see Fig. 2a): a) simultaneously on a steel tube and concrete core (Fig. 3a,b); b) only on the steel tube (Fig. 3c,d). The fixation of loaded edges of the steel tube walls was modelled in two versions: simply supported (Fig. 3a,c) and clamped (Fig. 3b,d). In reality it can be achieved by welding the support plates at the ends of the column. The loading of columns was modelled as short-term, rising steadily at a constant rate, introduced through the plate of a hydraulic press. The process of loading is stopped after a pronounced buckling deformation. The critical compressive stresses were recorded in the places of local buckling of the greater wall of the rectangular steel tube (Fig. 4 ÷ Fig. 6).

Discussion of the results

As a result of modelling the behavior of the short composite columns under axial compression using ABAQUS computational-graphics software, it can be stated that deformation of the buckling of the steel tube (loss of local stability) for various boundary conditions of loaded edges of the steel section has a different character.

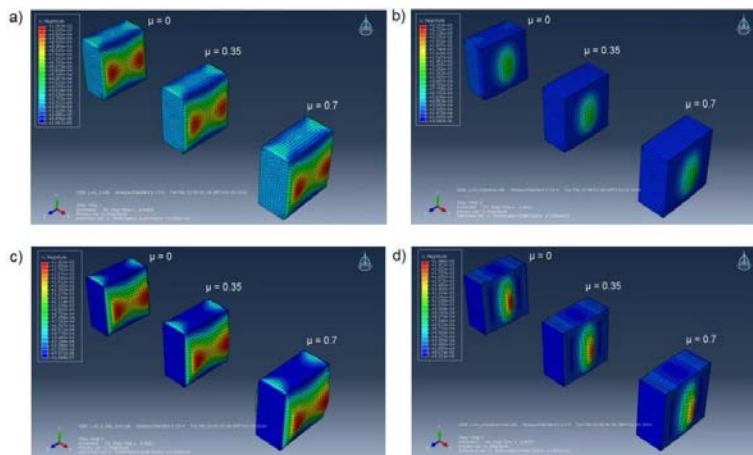


Figure 4. Local buckling deformations of the specimens with length $L = 200$ mm and loading:
 a) simultaneously on the simply supported steel tube and concrete core;
 b) simultaneously on the clamped steel tube and concrete core;
 c) on the simply supported steel tube; d) on the clamped steel tube

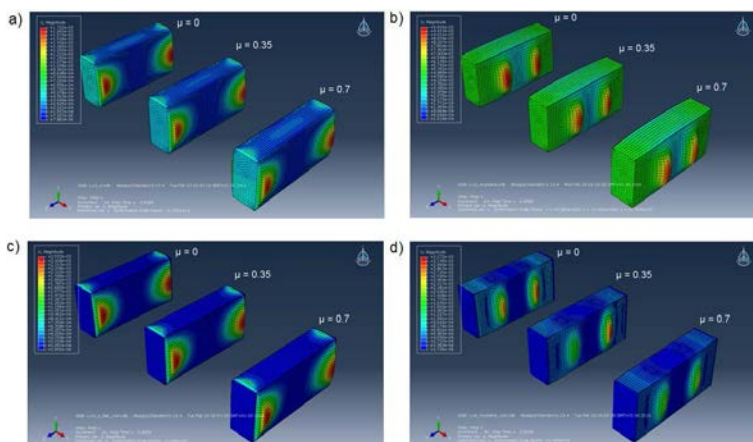


Figure 5. Local buckling deformations of the specimens with length $L = 400$ mm and loading:
 a) simultaneously on the simply supported steel tube and concrete core;
 b) simultaneously on the clamped steel tube and concrete core;
 c) on the simply supported steel tube; d) on the clamped steel tube

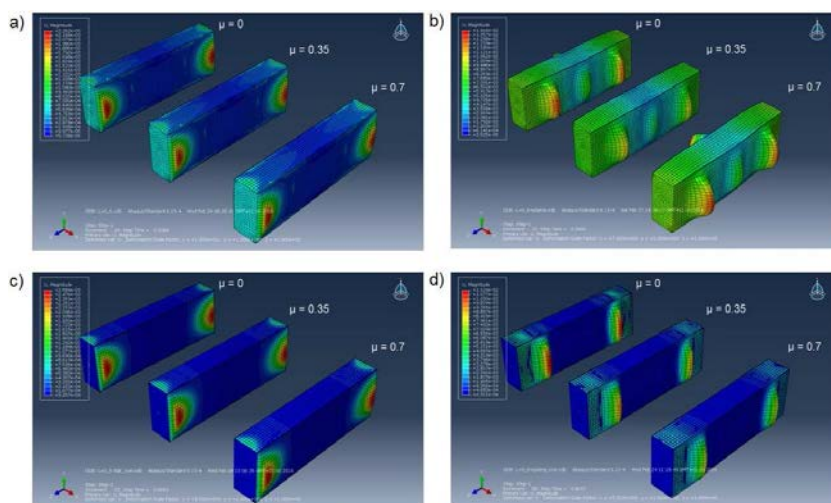


Figure 6. Local buckling deformations of the specimens with length $L = 600$ mm and loading:
 a) simultaneously on the simply supported steel tube and concrete core;
 b) simultaneously on the clamped steel tube and concrete core;
 c) on the simply supported steel tube; d) on the clamped steel tube

In the case of compression of the specimen without a welded plate, the development of buckling deformation of the tubes is shown close to the ends of the test specimens (Fig. 4a,c ÷ 6a,c). In specimens with clamped end edges of the tube, these deformations tend to occur at the middle of the specimen length (Fig. 4b,d ÷ 6 b,d).

Table 1. Results of modelling

Coefficient of friction μ	Compression of the composite cross-section		Compression of the composite cross-section through the welded support plate		Compression of steel part of the composite cross-section		Compression of steel part of the composite cross-section through the welded support plate	
	σ , [MPa]	k_{σ}	σ_{cr} , [MPa]	k_{σ}	σ , [MPa]	k_{σ}	σ_{cr} , [MPa]	k_{σ}
L=200 mm								
0	269.441	-	216.977	4,71	240.295	-	224.443	4,88
0.35	269.442	-	217.117	4,72	240.554	-	224.891	4,89
0.7	269.457	-	218.344	4,74	240.556	-	226.997	4,93
L=400 mm								
0	268.393	-	223.393	4,85	255.037	-	230.647	5,01
0.35	268.397	-	223.891	4,86	255.312	-	230.648	5,01
0.7	268.418	-	223.81	4,86	255.574	-	230.847	5,02
L=600 mm								
0	271.922	-	225.120	4,89	242.743	-	227.653	4,95
0.35	271.927	-	225.058	4,89	242.453	-	227.748	4,95
0.7	272.039	-	224.954	4,89	242.239	-	227.840	4,95

When compressing the specimens without end support plates during buckling deformation of the walls, the magnitude of compressive stress lies beyond the elastic stage of the work material, which is limited in this case, the yield strength is equal to 235 MPa (Tab. 1). For this reason, the coefficients of elastic critical stresses were not calculated. In the specimens with end support plates, the magnitude of critical compressive stress σ_{cr} lies in the elastic stage of steel material functioning and coefficients of the elastic critical stress exceeds the standard value $k_{\sigma} = 4$, specified in the standard EN 1993-1-5 for the walls of hollow tubes. This indicates that filling hollow cross-sections with concrete increases their local stability. As seen from Table 1, the values of this coefficient under compression only the steel part of the composite section is higher than in the case of compressing the whole of cross-section. In these specimens, the excess is negligible and has the maximum value of 3.5 %. The reason for different values of the critical compression stress is that the concrete core is deformed in the transverse direction in the

specimens, in which a compressive load is applied to both parts of the section. It promotes early development of the local buckling of the tube at a lower value of compressive stresses. But in terms of bearing capacity of the considered columns, the load imposed on the whole cross-sections is more advantageous.

From the viewpoint of the influence of friction between the components of the composite cross-section on the local stability of a rectangular tube, it must be emphasized that the maximum difference between the values of the compressive stress at $\mu = 0$ and $\mu = 0.7$ is 1.1 % (see Tab. 1) in all cases of fixation conditions of loaded edges of the walls, the lengths of the specimens, and methods of introducing the loading.

Conclusion

General conclusions and results of the research are the following:

1. One of the basic types of composite sections in the form of a rectangular steel tube with a profile of RHS 200x100x3 (EN 10219), filled with concrete, which lies beyond the validity of European construction standard Eurocode 4, was investigated.

2. Based on modelling the specimens' behavior under axial compression using ABAQUS computational-graphics software, it was shown that the development of the local buckling of the steel part of the composite cross-section occurs at a higher value of the coefficient of the elastic critical stress in comparison with normative data EN 1993-1-5 for tubes not filled with concrete. The lack of welded support plates in the investigated composite columns leads to plastic deformation of the local buckling of the rectangular tube walls, which indicates the impossibility and classified as a steel cross-section class 4, according to standard EN 1993-1-1.

3. Analysis of the influence of friction between the components of the composite section on the local stability of the steel-concrete element showed that the change of the friction coefficient has a negligible effect on the critical stresses.

4. Based on the results of this work, it can be stated that in studying the local stability of axial compressed composite structures with a cross-section in the form of rectangular tubes filled with concrete, there is no necessity of «push out» test to establish the natural bond parameters, because they have a negligible influence on the result.

References

1. Ovchinnikov I.I., Ovchinnikov I.G., Chesnokov G.V., Mihal'dykin E.S. O probleme rascheta trubobetonnih konstrukcij s obolochkoj iz raznyh materialov. Chast 1. Opyt primeneniya trubobetona s metallicheskoj obolochkoj [About the problem of calculating the pipe-concrete structures with a shell made of different materials. Part 1. Experience of use the pipe-concrete with a metal shell]. *Online Magazine "Naukovedenie"*. 2015. Vol. 7 No. 4. [Electronic resource]. System requirements: AdobeAcrobatReader. URL: <http://naukovedenie.ru/PDF/95TVN415.pdf> (date of application: 14.12.2015). (rus)
2. Kanishchev R., Kvocak V. Spriahnuté ocelobetónové tlačené prúty a stĺpy vyplnene betónom [Composite steel and concrete compression bars and columns filled with concrete]. *Vedecko-výskumná činnosť UIS 2013* [Research activities UIS 2013]. UVZ TU Herľany: TUKE, SvF, UIS, Kosice, 2014. Pp. 107–116. (sk)
3. Kvocak V., Varga G., Vargova R. Composite steel concrete filled tubes. *Procedia Engineering*. 2012. Vol. 40. Pp. 469–474.
4. Duricova A., Rovnak M. *Navrhovanie ocelovo – betónových konštrukcii* [Design of steel – concrete structures]. Bratislava: VEDA, 2008. 264 p. (sk)
5. Kozak J., Gramblička S., Lapos J. *Spriahnuté a kombinované ocelobetónové konštrukcie pozemných stavieb* [Composite and combined steel and concrete structures in civil engineering]. Bratislava: Jaga, 2000. 161 p. (sk)
6. Kikin A.I., Sanzharovskiy R.S., Trul V.A. *Konstrukcii iz stalnyh trub, zapolnennyh betonom* [Construction of steel tubes filled with concrete]. Moscow: Stroyizdat, 1974. 144 p. (rus)
7. Storozhenko L. I., Plachotnyj P. I., Černyj A.Y. *Raschet Kanishchev R.A. Analysis of local stability of the rectangular tubes filled with concrete. Magazine of Civil Engineering*. 2016. No. 4. Pp. 59–68. doi: 10.5862/MCE.64.6

Литература

1. Овчинников И.И., Овчинников И.Г., Чесноков Г.В., Михалдыкин Е.С. О проблеме расчета трубобетонных конструкций с оболочкой из разных материалов. Часть 1. Опыт применения трубобетона с металлической оболочкой // Интернет-журнал «НАУКОВЕДЕНИЕ». 2015. Том 7, №4. [Электронный ресурс]. Систем. требования: AdobeAcrobatReader. URL: <http://naukovedenie.ru/PDF/95TVN415.pdf> (дата обращения: 14.12.2015).
2. Kanishchev R., Kvočák V. Spriahnuté ocelobetónové tlačené prúty a stĺpy vyplnene betónom // *Vedecko-výskumná činnosť UIS 2013*. UVZ TU Herľany: TUKE, SvF, UIS, Košice, 2014. Pp. 107–116.
3. Kvocak V., Varga G., Vargova R. Composite steel concrete filled tubes // *Procedia Engineering*. 2012. Vol. 40. Pp. 469–474.
4. Ďuricová A., Rovňák M. *Navrhovanie ocelovo - betónových konštrukcii*. Bratislava: VEDA, 2008. 264 p.
5. Kozák J., Gramblička Š., Lapos J. *Spriahnuté a kombinované ocelobetónové konštrukcie pozemných stavieb*. Bratislava: Jaga, 2000. 161 p.
6. Кикин А.И., Санжаровский Р.С., Труль В.А. *Конструкции из стальных труб, заполненных бетоном*. М.: Стройиздат, 1974. 144 с.
7. Стороженко Л.И., Плахотный П.И., Черный А.Я. *Расчёт трубобетонных конструкций*. К: Будивелник, 1991. 120 с.
8. Онищенко О.Г., Пичугін С.Ф., Онищенко В.О., Семко, О.В., Стороженко Л.И., Емельянова І.А., Ландар О.М. *Високоєфективні технології та комплексні конструкції в будівництві*. Полтава: Форміка, 2009. 404 с.
9. Garanzha I., Vatin N. Analytical methods for determination

- trubobetonnyh konstrukcij* [Calculation of steel tubes filled with concrete]. Kiev: Budivelnik, 1991. 120 p. (ua)
8. Onishchenko O.G., Pichugin S.F., Onishchenko V.O., Semko O.V., Storozhenko L.I., Emelanova I.A., Landar O.V. *Visokoeffektivni tehnologii ta kompleksni konstrukcii v budivnictvi* [High-technology and complex construction in buildings]. Poltava: Formika, 2009. 404 p. (ua)
 9. Garanzha I., Vatin N. Analytical methods for determination a load capacity of concrete-filled tubes under axial compression. *Applied Mechanics and Materials*. 2014. No. 633–634. Pp. 965–971.
 10. Duvanova I.A., Salmanov I.D. Trubobetonnye kolonny v stroitelstve visotnyh zdaniy i sooruzhenij [Pipe-concrete columns in the construction of tall buildings and structures]. *Construction of Unique Buildings and Structures*. 2014. No. 6(21). Pp. 89–103.
 11. Kanishchev R., Kvocak V. Effects of Stability on the Resistance of Composite Concrete-Filled Rectangular Steel Pipes According to World Standards. *Elegance in Structures*. Zurich: IABSE, 2015. Pp. 1–8.
 12. Kang W.-H., Uy B., Tao Z., Hicks S. Design strength of concrete-filled steel columns. *Advanced Steel Construction*. 2015. No. 11(2). Pp. 165–184.
 13. Ovchinnikov I.I., Ovchinnikov I.G., Chesnokov G.V., Mihaldykin E.S. O probleme rascheta trubobetonnyh konstrukcij s obolochkoj iz raznyh materialov. Chast 2. Raschet trubobetonnyh konstrukcij s metallicheskoj obolochkoj [About the problem of calculating the pipe-concrete structures with a shell made of different materials. Part 2. Calculation of pipe-concrete structure with the metal shell]. *Online Magazine "Naukovedenie"*. 2015. Vol. 7 No. 4. [Electronic resource]. System requirements: AdobeAcrobatReader. URL: <http://naukovedenie.ru/PDF/112TVN415.pdf> (date of application: 14.12.2015). (rus)
 14. Nesvetaev G.V., Revzan I.V. Ocenka prochnosti trubobetona [Evaluation of pipe-concrete strength]. *Technical sciences*. 2011. No. 12–13. Pp. 580–583. (rus)
 15. Mouli M., Khelafi H. Strength of short composite rectangular hollow section columns filled with lightweight aggregate concrete. *Engineering Structures*. 2007. Vol. 29. Pp. 1791–1797.
 16. Uy B. Stability and ductility of high performance steel sections with concrete infill. *Journal of Constructional Steel research*. 2008. Vol. 64. Pp. 748–754.
 17. Uy B. Local and post-local buckling of concrete filled steel welded box columns. *Journal of Construction Steel research*. 1998. No. 47. Pp. 47–72.
 18. Uy B., Bradford M. A. Local buckling of composite steel-concrete rectangular columns. *Fifth international conference on steel structures*. Jakarta: 1994. Pp. 313–322.
 19. Krishan A.N., Melnichuk A.S. Prochnost trubobetonnyh kolonn kvadratnogo sechenia pri osevom szhatii [The strength of pipe-concrete square columns under axial compression] *Vestnik magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G.I. Nosova* [Bulletin of the Nosov magnitogorsk state technical university]. Magnitogorsk: MGTU, 2012. No. 3. Pp. 51–54. (rus)
 20. Lee S. Capacity and the moment-curvature relationship of high-strength concrete filled steel tube columns under eccentric loads. *Steel and Composite Structures*. 2007. Vol. 7. No. 2. Pp. 135–160.
 21. Storozhenko L.I., Ermolenko D.A., Demchenko O.V. Rabota pod nagruzkoy szhatyh trubobetonnyh elementov s usilennymi jadrami [The work under load of compressed pipe-concrete elements with strengthened nuclei]. *Resursoehnergoeffektivnye tekhnologii v stroitelnom komplekse regiona* [Efficiency of resource energy of technology in the construction industry of region]. Poltava: PNTU, 2014. No. 4. Pp. 288–292. (rus)
 22. Patel V. I., Liang Q. Q., Hadi M. Inelastic stability analysis of high strength rectangular concrete-filled steel tubular a load capacity of concrete-filled tubes under axial compression // *Applied Mechanics and Materials*. 2014. № 633–634. Pp. 965–971.
 23. Дуванова И.А., Сальманов И.Д. Трубобетонные колонны в строительстве высотных зданий и сооружений // *Строительство уникальных зданий и сооружений*. 2014. №6(21). С. 89-103.
 24. Kanishchev R., Kvocak V. Effects of Stability on the Resistance of Composite Concrete-Filled Rectangular Steel Pipes According to World Standards // *Elegance in Structures*. Zurich: IABSE, 2015. Pp. 1–8.
 25. Kang W.-H., Uy B., Tao Z., Hicks S. Design strength of concrete-filled steel columns // *Advanced Steel Construction*. 2015. № 11(2). Pp. 165–184.
 26. Овчинников И.И., Овчинников И.Г., Чесноков Г.В., Михалдыкин Е.С. О проблеме расчета трубобетонных конструкций с оболочкой из разных материалов. Часть 2. Расчет трубобетонных конструкций с металлической оболочкой // Интернет-журнал «НАУКОВЕДЕНИЕ». 2015. Том 7, №4. [Электронный ресурс]. Систем. требования: AdobeAcrobatReader. URL: <http://naukovedenie.ru/PDF/112TVN415.pdf> (дата обращения: 14.12.2015).
 27. Несветаев Г.В., Резван И.В. Оценка прочности трубобетона // *Фундаментальные исследования*. 2011. № 12-3. С. 580–583.
 28. Mouli M., Khelafi H. Strength of short composite rectangular hollow section columns filled with lightweight aggregate concrete // *Engineering Structures*. 2007. Vol. 29. Pp. 1791–1797.
 29. Uy B. Stability and ductility of high performance steel sections with concrete infill // *Journal of Constructional Steel research*. 2008. Vol. 64. Pp. 748–754.
 30. Uy B. Local and post-local buckling of concrete filled steel welded box columns // *Journal of Construction Steel research*. 1998. № 47. Pp. 47–72.
 31. Uy B., Bradford M. A. Local buckling of composite steel-concrete rectangular columns // *Fifth international conference on steel structures*. Jakarta: 1994. Pp. 313–322.
 32. Кришан А.Н., Мельничук А.С. Прочность трубобетонных колонн квадратного сечения при осевом сжатии // *Вестник магнитогорского государственного технического университета им. Г.И. Носова*. Магнитогорск: МГТУ, 2012. № 3. С. 51–54.
 33. Lee S. Capacity and the moment-curvature relationship of high-strength concrete filled steel tube columns under eccentric loads // *Steel and Composite Structures*. 2007. Vol. 7. № 2. Pp. 135–160.
 34. Storozhenko L.I., Ermolenko D.A., Demchenko O.V. Работа под нагрузкой сжатых трубобетонных элементов с усиленными ядрами // *Ресурсоэнергоэффективные технологии в строительном комплексе региона*. Полтава: ПНТУ, 2014. № 4. С. 288–292.
 35. Patel V. I., Liang Q. Q., Hadi M. Inelastic stability analysis of high strength rectangular concrete-filled steel tubular slender beam-columns // *Interaction and Multiscale Mechanics*. 2012. Vol. 5. № 2. Pp. 91–104.
 36. Yang Y., Han L. Experiments on rectangular concrete-filled steel tubes loaded axially on a partially stressed cross-sectional area // *Journal of Constructional Steel Research*. 2009. Vol. 65. Pp. 1617–1630.
 37. Nethercot D. A. Composite construction. New York: Spon press, 2004. 242 p.
 38. Bradford M. A., Oelhers D.J. Composite steel and concrete structural members. Fundamental behaviour. London: Pergamon, 1995. 536 p.
 39. EN 1994–1–1: 2004. Eurocode 4. Design of composite steel and concrete structures. Part 1-1: General rules and rules for buildings. Brussels: CEN, 2004. 120 p.
 40. EN 1993–1–1: 2005. Eurocode 3. Design of steel structures. Part 1–1: General rules and rules for buildings.

- slender beam-columns. *Interaction and Multiscale Mechanics*. 2012. Vol. 5. No. 2. Pp. 91–104.
23. Yang Y., Han L. Experiments on rectangular concrete-filled steel tubes loaded axially on a partially stressed cross-sectional area. *Journal of Constructional Steel Research*. 2009. Vol. 65. Pp. 1617–1630.
 24. Nethercot D. A. *Composite construction*. New York: Spon press, 2004. 242 p.
 25. Bradford M. A., Oelhers D.J. *Composite steel and concrete structural members. Fundamental behaviour*. London: Pergamon, 1995. 536 p.
 26. EN 1994-1-1: 2004. *Eurocode 4. Design of composite steel and concrete structures. Part 1-1: General rules and rules for buildings*. Brussels: CEN, 2004. 120 p.
 27. EN 1993-1-1: 2005. *Eurocode 3. Design of steel structures. Part 1-1: General rules and rules for buildings*. Brussels: CEN, 2005. 92 p.
 28. EN 10219-2: 2006. *Cold formed welded structural hollow sections of non-alloy and fine grain steels. Part 2. Tolerances, dimensions and sectional properties*. Brussels: CEN, 2006. 40 p.
 29. EN 1993-1-5: 2006. *Eurocode 3. Design of steel structures. Part 1-5: General rules – Plated structural elements*. Brussels: CEN, 2006. 56 p.
 30. Bryan G.H. On the stability of a plane plate under trusts in its own plane, with applications to the “buckling” of the sides of a ship // *Proceedings of the London Mathematical Society*. 1891. Vol. 22. Pp. 54–67.
 31. Тимошенко С. П. Устойчивость стержней, пластин и оболочек. М.: Наука, 1971. 807 с.
 32. Rabbat B. G., Russell H. G. Friction coefficients of steel on concrete or grout // *ASCE, Journal of Structural Engineering*. 1985. Vol. 111. Pp. 505–515.
 33. Baltay P., Gjelsvik A. Coefficient of friction for steel on concrete at high normal stress // *ASCE, Journal of Materials in Civil Engineering*. 1990. Vol. 2. Pp. 46–49.
 34. Evirgen B., Tuncan A. Determination of frictional behaviour between concrete and steel tube interaction // *EUROSTEEL 2014, September 10-12*. Brussels: ECCS, 2014. Pp. 419–425.
 35. EN 1992-1-1: 2005. *Eurocode 2. Design of concrete structures. Part 1-1: General rules and rules for buildings*. Brussels: CEN, 2005. 200 p.
 36. Simulia. *Abaqus 6.13: Analysis Users Guide. Volume I*. Dassault Systems, 2013. 840 p.

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