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ПРО ПІДХОДИ ДО РОЗРАХУНКУ ТРУБОБЕТОННИХ КОНСТРУКЦІЙ В УКРАЇНІ ТА ЗА КОРДОНОМ

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Анотація. У статті визначене місце використання трубобетону як будівельних конструкцій. Розглянуто чотири існуючі аналітичні методики для визначення несучої здатності трубобетонних конструкцій круглого перерізу при центральному стиску, які використовуються в Україні та за кордоном. Проаналізовані підходи до питання розрахунків граничного стискального навантаження (несучої здатності), яке здатне витримати трубобетонний елемент. Виділені принципові відмінні риси і подібності, розглянутих методик, а також їх недоліки, що впливають на точність результатів при розрахунках показників міцності і стійкості трубобетонних конструкцій. На конкретному прикладі виконане чисельне порівняння результатів визначення несучої здатності за чотирма методиками і визначена різниця, яка варіюється (у відносних одиницях) у межах 1,08...1,38.

Ключові слова: трубобетонні конструкції, аналітичні методи розрахунку, сумісна робота, осьовий стиск, міцність й стійкість конструкцій, знижена жорсткість, контакт між матеріалами.

О ПОДХОДАХ К РАСЧЕТУ ТРУБОБЕТОННЫХ КОНСТРУКЦИЙ В УКРАИНЕ И ЗА РУБЕЖОМ

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Аннотация. В статье определена область применения трубобетона в качестве строительных конструкций. Рассмотрены четыре существующих аналитических методики для определения несущей способности трубобетонных конструкций круглого сечения при центральном сжатии, которые используются в Украине и за рубежом. Проанализированы подходы к вопросу расчета предельной сжимающей нагрузки (несущей способности), которую способен выдержать трубобетонный элемент. Выделены принципиальные отличительные особенности и сходства, рассмотренных методик, а также их недостатки, влияющие на точность результатов при расчете показателей прочности и устойчивости трубобетонных конструкций. На конкретном примере выполнено численное сравнение результатов определения несущей способности по четырем методикам и определена разница, которая варьируется (в относительных единицах) в пределах 1,08...1,38.

Ключевые слова: трубобетонные конструкции, аналитические методы расчета, совместная работа, осевое сжатие, прочность и устойчивость конструкций, пониженная жесткость, контакт между материалами.

ABOUT APPROACHES TO THE CALCULATION OF COMPOSITE TUBES IN UKRAINE AND ABROAD

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Abstract. In a paper are determinated an area of using composite tubes as structures. Considered four existing analytical methods for determination a load capacity of composite tubes with circular cross-section under axial compression are using in Ukraine and abroad. Analyzed approaches to the questions of a limit compression load (load capacity) calculation are able to withstand a composite element. Highlighted the fundamental features and similarities of discussed methods, and also their shortcomings affecting to the accuracy of the strength and stability computing results for composite tubes. On the particular example performed a results comparison of determining the load capacity by the four methods and determinated a difference which is varies (in relative units) within 1,08...1.38.

Keywords: composite tubes, analytical methods of calculation, joint work, axial compression, load capacity, strength and stability of structures, reduced flexibility, contact between materials.

Introduction

Composite steel and concrete structures (concrete-filled tubes in particular), as species of composite elements, taking its origins since the 40-ies of the last century, already acquired enough popularity in a building practice worldwide and widely used as carrying structures for various industry objects, namely (fig. 1) [1–3, 9–11]:

- residential and civil buildings (including high-rise);
- tower structures (supports of overhear transmission power lines (OHPL), antenna supports of mobile communication, lighting masts, TV and radio towers, etc.);
- supports of bridges and overpasses;
- structural elements of a cover (beams, arches, trusses);
- foundations of tower structures.

Nowadays concrete-filled structures can be manufactured not only based on circular tubes. As a basis is possible to use steel polygonal cold-formed tubes with different number of sides that are already fully approbated as structures [4–8]. This is a new and promising modifications allowing extend the types of the design solutions composite structures (for example, to create fairly wide range of the OHPL supports, especially those located in urban areas) and to increase its aesthetic qualities [9–11].

A quality of its design and manufacturing, certainly, depend of several aspects (availability or a adequate normative base, accumulated experience in creating designs of this structural type, the level of knowledge of concrete-filled structures under load, qualifications of designer, etc.), each of which makes a significant contribution to the smooth functioning of the concrete-filled tubes structures. Separately necessary highlight the issue of the analytical approach to the determination of its load capacity, especially when they are considered as rods working under axial compression (possibly jointly with a bend), excluding triaxial stress state, which in real conditions concrete-filled structures are testing. This approach may be using for light tower structures, for single-column OHPL supports and its foundations, where defining are vertical loads, causing compression and volumetric stress state of the composite material may be neglected (for example, for preliminary calculations at pre-design stage or checking calculations for comparison with finite-element modeling).

Consequently, necessary to perform an analyze of features of the approaches set out in the existing domestic and foreign techniques to determine load capacity the considered structures and perform a comparison of results obtained on

Figure 1. Examples of existing composite tubes: a) Saint-Petersburg Plaza; b) residential complex, Moscow; c) apartment house, Dnepropetrovsk, Ukraine; d) railway bridge, Khabarovsk, Russian Federation.

the particular example. It will form the basis for further research related to the study of the real work of concrete-filled tubes (as a structural material) under load, and also its physical and operational reliability, which will significantly expand the range of concrete-filled structures.

Existing methods of calculation the concrete-filled tubes under axial compression

Nowadays are existing four main analytical methods which is allowing to determinate the load capacity of concrete-filled tube elements:

1) **the «unified» method** proposed by Chinese scientists Min Yu, Xiaoxiong Zha, Jianqiao Ye, Yuting Li for calculating the strength and stability of concrete-filled tubes of various structural performance (including the «hollow») (fig. 2) under axial compression [12];

2) **the method of Min Yu, Xiaoxiong Zha, Jianqiao Ye, Chunyan She** for calculating the strength and stability of concrete-filled tubes with a circular cross-section [13];

3) **the method of L. I. Storozhenko** (Poltava national technical university named of Yuri Kondratyk) for determination of load capacity of circular concrete-filled tubes under axial and unaxial compression (the last stress state in this paper don't consider) [1—3]. This method is included to the relevant standart of Ukraine [6];

4) **the method of EN 1994 Eurocode 4** «Design of composite steel and concrete structures» [15].

In consequence defined features of the above methods of approach to the determination the load capacity of concrete-filled structures, at the example of circular cross-section tube with concrete compressive class B20 and steel mark S235, with the following geometric parameters: diameter D = 200 mm, height H = 500 mm, wall thickness of the steel tube t = 3 mm.

In subsections 1.1...1.4 listed the general positions of calculation the concrete-filled tubes under axial compression according to the above methods.

The «unified» method of Min Yu, Xiaoxiong Zha, Jianqiao Ye, Yuting Li

This method represents two mathematical equations for calculating the critical compressive forces N_0 (1) and N_{st} (2), which determine the load capacity of the structure prior to the point of losing the strength and stability, respectively. Its main

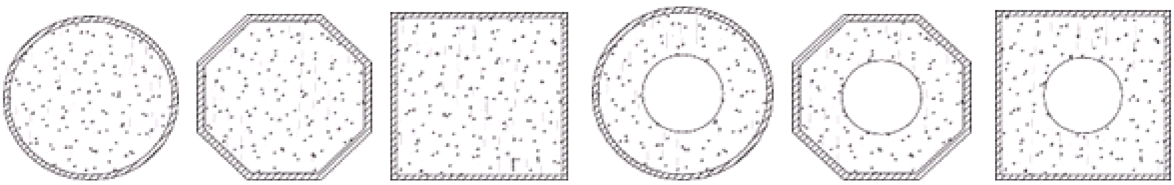

Figure 2. Varieties of the concrete-filled tubes cross-sections.

feature is applicable not only for structures with circular cross-section, but also for concrete-filled polygonal tubes (including structures based on square tubes). According to the considered method of load capacity for axial compressive strength is defined as follows (1):

$$N_0 = (1+\eta)(f_y A_s + f_c A_{ck}), \quad (1)$$

where η – a coefficient of strength increase by tube compression of concrete (fig. 3), depending to number of sides n, characteristics of materials, and also to the «hollow» ratio ψ (in case of design the «hollow» concrete-filled tubes). When using the equation (1) for calculating the circular concrete-filled structures parameter η is taken equal to ∞.

In this case, characteristics f_y и $f_c = f_{ск}$ [16, 17], are considering only for elastic stage of the steel and concrete work respectively, as members of the composite structure. It remains unclear is it possible to use the expression (1) for construction work beyond the elastic stage, ie when is necessary to use in the calculation temporary resistance for steel f_u, and for concrete – compressive resistance of confined concrete by steel shell (tube) f_{cc} [20].

The method experimentally confirmed on basis of the mechanical tests results of square and 8-sided concrete-filled elements [4].

The load capacity by stability under axial compression is determinating by equation (2):

$$N_{st} = \varphi_{st} N_0, \quad (2)$$

where φ_{sc} — the stability factor (the buckling-coefficient), which is depend of sides number n

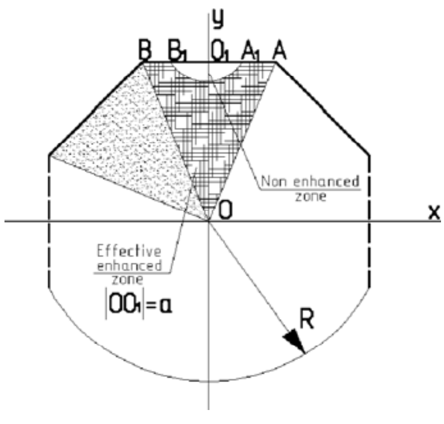

Figure 3. The area of increase strength through the efficient compression of concrete by steel tube (for polygonal tubes).

(in case of using circular cross-sections $n = \infty$), characteristics of using materials, and also to reduced flexibility λ_{sc} and to the flexural rigidity of the total concrete-filled tude section (3):

$$E_{sc} I_{sc} = E_c I_c + E_s I_s \,. \quad (3)$$

Method of Min Yu, Xiaoxiong Zha, Jianqiao Ye, Chunyan She for the circular cross-section structures

This method in calculation don't consider number of sides, respectively, can be using for calculation only for circular cross-sections. The order of the using this method is following:

– determination of the yield strength of the concrete-filled element f_{sc} by equation (4):

$$f_{sc} = \left[1 + \frac{\Omega \xi_{sc}}{\left[2\Omega + 0.05\xi_{sc} + (0.2\frac{f_{ck}}{f_y} - 0.05)\xi_{sc}\Omega \right](\Omega + \xi_{sc})} \right], \quad (4)$$

where $\Omega = \frac{A_c}{A_c + A_k}$ — ratio between area of the concrete core and the total section area, closed by steel tube (A_c+$A_к$). For solid concrete-filled elements the parameter Ω =1, for «hollow» structures (see fig. 2) – Ω =1-ψ (ψ – «hollow» ratio of cross-section [13]);

$\xi_{sc} = \frac{A_s \cdot f_s}{A_c \cdot f_{ck}}$ — limiting coefficient for solid structure, which equal to ratio of load capacities of steel and concrete;

f_s и f_{ck} – the yield strength of steel and the prism compressive strength of concrete respectively [16,17].

– calculation of the limit load to element (the load capacity of strength conditions) by equation (5):

$$N_0 = f_{sc} A_{sc}, \quad (5)$$

where A_{sc} – the cross-section area of concrete-filled element;

– determination of the stability factor (the buckling coefficient) φ_{sc} by equation (6):

$$\varphi_{sc} = \frac{1}{2\overline{\lambda_{sc}}^2} \cdot \left[\overline{\lambda_{sc}}^2 + 0.25\beta\overline{\lambda_{sc}}^2 + 1 - \sqrt{(\overline{\lambda_{sc}}^2 + 0.25\beta\overline{\lambda_{sc}}^2 + 1)^2 - 4\overline{\lambda_{sc}}^2} \right], \quad (6)$$

where $\overline{\lambda_{sc}}$ — the reduced flexibility of concrete-filled cross-section;

$\beta = \frac{A_s}{A_{sc}}$ — ratio of the steel cross-section area to the total area of concrete-filled section.

– calculation of the limit compression load to the element (the load capacity of stability conditions) by equation (7):

$$N_{st} = \varphi_{sc} f_{sc} A_{sc} . \quad (7)$$

This method has passed the experimental confirmation based on results of mechanical tests series of «hollow» и «solid» models with circular cross-sections [13].

The method of L. Storozhenko (DBN V.2.6-160:2010 «Composite steel and concrete structures. Main rules»)

As an alternative to foreign methods for determining load capacity of concrete-filled structures under compression is the Ukrainian method of L. I. Storozhenko, which allows to determine the limit load of concrete-filled at the axial compression. This method can be use only for structures with the circular cross-section and has expounded in equations (7), (8):

– determining of the concrete resistance in the circular tube:

$$R_b^* = 0.65 \cdot B \cdot (1 + 16.1 \mu_{pb} \beta), \quad (8)$$

where $\mu_{pb} = (\frac{D}{D-2t})^2 - 1$ — the concrete-filled tube reinforcement coefficient (the main parameter, which consider ratio between tube thickness and the outside diameter of the structure);

– determining of the load capacity (the limit compression load, is able to withstand the composite element):

$$N_{stb} = \gamma_{bs} \cdot (R_b^* A_b + \gamma_{s2} R_y A_{st}), \quad (9)$$

where γ_{bs} и γ_{s2} – coefficients, which are considering the joint work features of the concrete and steel tube.

In this method are traced fundamental differences. For the first, unlike the others, here as a defining of the load capacity of the concrete-filled element is not used calculating resistance of the total cross-section, and the resistance of the confined concrete into the steel tube. For the second, for calculation of the limit compression load are using not only mechanical characteristics of materials and geometrical characteristics of cross-sections, but and clarifying coefficients, which is considering the maim moments, inherent to the joint work under the load, for two materials with different properties and structure. The method of L. I. Storozhenko is empirical, i.e. the results obtained from its use are experimentally confirmed.

The method of EN 1994 Eurocode 4 «Design of composite steel and concrete structures»

The method of Eurocode 4 for calculation the concrete-fillet elements under axial compression in relation to other methods is considered one important distinctive feature the structural load load capacity primarily depend of its flexibility, which defines the way of calculating the limit load to the concrete-filled element. Pre-determine the numerical values reduced flexibility section $\overline{\lambda}$ by equation (10), can to calculate the required value of the limit compression load $N_{pl,Rd}$ (which is the main index of the load capacity) according to conditions, are expounded in (11), (12):

$$\lambda = \sqrt{\frac{N_{Pl,\mathrm{Rk}}}{N_{cr}}}, \quad (10)$$

where $N_{pl,Rk}$ – normative compressive resistance of the considered cross-section; N_{cr} – the critical compressive force, determined by Eiler or Yasinskiy, depend of the element flexibility [18, 19].

Then:

$$N_{Pl,Rd} = A_a \cdot f_{yd} + A_c \cdot f_{cd}, \text{ if } \overline{\lambda} > 0{,}5 , \quad (11)$$

$$N_{Pl,Rd} = \eta_a A_a \cdot f_{yd} + A_c \cdot f_{cd}(1 + \eta_c \cdot \frac{t}{D} \cdot \frac{f_y}{f_{ck}}),$$
$$\text{if } \overline{\lambda} \le 0{,}5 . \quad (12)$$

The numerical comparison of calculation results of the strength by four methods

In this section представлено the numerical comparison the results of determination the load capacity used a shot concrete-filled model based on the circular tube (fig. 4), produced by the all aforementioned methods.

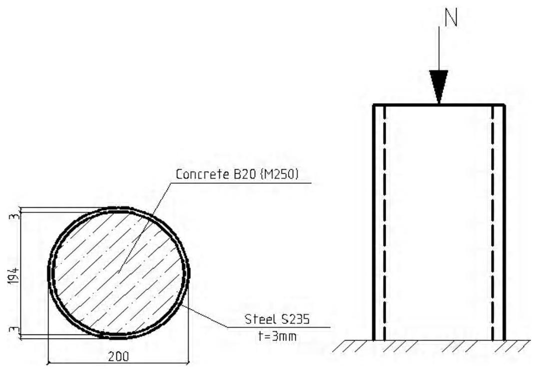

Figure 4. A computational model of the circular concrete-filled element.

The computational model has the following parameters and materials:

– high H = 500 mm;
– diameter D = 200 mm;
– tube wall thickness t = 3 mm;
– steel mark C235;
– class of concrete B20 (mark M250).

In table 1 showed the results of calculation for the short composite model by four methods. In table 2 contains the difference between them, both in absolute units [kN], and relative (dimensionless).

Conclusions

1) Despite the experimental approbation all without an exception of the considered methods for determining the load capacity of concrete-filled elements under the axial compression results obtained with their using significantly differing (difference reaches ≈ 40 %). The maximum strength to the calculation model gives the «unified» Chinese method, the minimal – the method of L. I. Storozhenko.

2) The common negative feature of foreign analytical techniques is that from all geometric characteristics for calculation used only the area of the cross-section, and ignored the tube wall thickness ***t***, the outside diameter of the structure ***D***, and also its ratio ***t / D***, which has a fundamentally important effect to the load capacity.

3) According to the «unified» method, the equivalent cross-section by area, regardless of its geometric shapes and sizes, will have the same load capacity that is absolutely untrue.

4) Any of the methods do not considers contact (adhesion) between the materials, thereby probably significantly reduced accuracy of determining the value of the limit load, which is capable of supporting element.

5) The above methods require further experimental verification, detailed search for reasons discrepancies in obtained results, also considering in the calculation all conditions of the joint work between two materials, which will significantly improve the accuracy of calculations, and possibly to get the only correct method for concrete-filled structures.

Table 1. The limit compression load to the computational model

Method [1]	**1**	**2**	**3**	**4**
N, [kH]	1128	980	815	1045

[1] under the numbers 1...4 are considered the methods in order of its appearance under subsection 1.1...1.4.

Table 2. Comparison of the results for the computational model

Δ	**Δ(1/2)**	**Δ(1/3)**	**Δ(1/4)**	**Δ(1-2), кH**	**Δ(1-3), кH**	**Δ(1-4), кH**
Value	1,15	1,38	1,08	147	312	83

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