Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2020.54.2266

UDC 624.012.35

Strength analysis of reinforced concrete in a closed space of a metal pipe

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The concrete strengthening coefficient calculating method of concrete-filled steel tubular members at axial compression based on the plasticity theories by Saint-Venant and Huber-Mises-Genk. This method is used for calculating values taking into account the concrete meridional pressure on the pipe and axial stresses in it. The following tubular concrete element strength equation is obtained, where the stresses in the pipe reach the limit values at the element destruction moment, that is the materials strength is used completely. An calculation example is given and the strengthening coefficient calculation results are compared according to both theories. For determining the proposed method accuracy it is planned to compare the results of the calculation with experimental data.

Keywords: concrete, pipe, plasticity, steel, strength.

Аналіз міцності залізобетону в замкнутому просторі металевої труби

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На сьогодні проєктування стиснутих трубобетонних елементів являє собою досить складний процес, причиною чого є відсутність розрахункових залежностей, які б враховували явище збільшення несучої здатності елемента за рахунок роботи бетону в умовах об'ємного напружено-деформованого стану, що обумовлює одержання розрахункових значень міцності нормального перерізу трубобетонного елемента, які будуть недовикористані. Можливість розв'язання існуючої проблеми полягає в подальшому дослідженні теорії розрахунків міцності трубобетонних елементів на основі впроваджуваних сучасних поглядів на роботу бетону в поєднанні з арматурою та сталевою оболонкою. Тож було розроблено методику аналізу міцності з використанням коефіцієнта зміцнення бетону трубобетонних елементів при осьовому стисненні для обчислення значень з урахуванням меридіонального тиску бетону на трубу й осьових напружень у ньому на основі теорій пластичності Сен-Венана та Губера – Мізеса – Генкі. Критерієм руйнування трубобетонного елемента обрано його граничний стан при досягненні в сталі труби напружень текучості, завдяки чому отримано таке рівняння міцності трубобетонного елемента, в якому напруження в стінці труби в момент руйнування елемента приймаються граничними, тобто міцність матеріалів використовується повністю. Наведено приклад виконання розрахунку та здійснено порівняння результатів розрахунку міцності з використанням коефіцієнта «зміцнення» за обома теоріями як у табличній формі, так і шляхом побудови графіків залежності значень міцності трубобетонного елемента й коефіцієнта зміцнення бетону від його класу. Відмічено суттєве зростання коефіцієнта зміцнення для низьких класів бетону при відповідному збільшенні товщини стінки труби за обома теоріями, що може свідчити про суттєві резерви міцності та потребує подальшого теоретичного й експериментального дослідження.

Ключові слова: залізобетон, сталь, труба, міцність, пластичність.

Introduction

Currently, many experimental and theoretical studies have been conducted on the composite elements resistance with concrete-filled circular steel pipe sections to longitudinal (axial) compression. The occurrence of the strengthening phenomenon arising in concrete, which filled the pipe, was proved by the studies results. This is mainly due to the deformation limiting artificially created conditions by the outer tube-shell. Also, a way of applying an external load to the concrete-filled steel pipes has not gone unnoticed by researchers in this aspect. The first case is the load application to the pipe and concrete at the same time [1] and as the second case is considered the situation when the load is applied only to the concrete [2, 3]. The adhesion level of the contact "tube – concrete" was taken into consideration as well as the destruction criteria (the first – for the yield stress achievement in the pipe, the second – the state of concrete element complete destruction).

It is known that much research has been done on these issues, but despite this, there is still a wide contradictions range in ideas about the pipe and concrete core joint work. Obviously, the proposed analyzing methods of composite steel and concrete elements strength are significantly affected by these contradictions directly.

Review of the research sources and publications

In this study, as the criterion for the destruction of the composite steel and concrete member the second operation state is adopted. This ultimate limit state is declared the main one in the norms [4, 5]. Widespread introduction in the modern analysis methods of building structures of the ultimate state concept based on the manifestations of composite materials plastic properties [6, 7] sufficiently substantiates the non-availability of need to use the first condition (criterion) for calculating the concrete-filled steel tubular members strength. The number of different methods is constantly increasing, in particular it is observed in the norms of the USA [8, 9], Canada [10], England [11], and Europe [12].

Therefore, this article presents a possible solution to the existing problem in the analysis the composite members strength theory, which is based on the introduced modern views on the concrete work in combination with reinforcement and steel shell [13 – 18].

Definition of unsolved aspects of the problem

From the above contradictions follows an important composite steel and concrete elements designing problem, it is the structural dependencies lack, in terms of concrete volumetric stress-strain state would clearly distinguish the strengthening component. A large number of empirical methods for analyzing the compressed concrete-filled steel tubular members strength have been proposed to eliminate this gap. Unfortunately, their main imperfection is the empiricism accumulation, which does not contribute to a deep understanding of the tubular concrete elements composites complex work.

Problem statement

The aim of this paper is to obtain an analytical expression for the concrete strengthening coefficient calculation of the concrete-filled steel tubular member core at the complete destruction moment and the element strength equation, where the stresses in the pipe would reach the limit values at the element destruction time, in case the materials strength completely using.

Basic material and results

Under the action of axial compression, the normal cross section strength of a cylindrical concrete-filled steel element, taking into account the concrete meridional pressure p on the tube (shell) and the meridional (axial) stresses σ_{s1} in it, will be ensured if condition (1) is fulfilled (figure 1).

$$N_{Ed} \le N_{Rd} = A_c\left(f_c + 4\cdot p\right) + A_s\sigma_{s1}, \qquad (1)$$

where A_c is the concrete cross-sectional area in the pipe, A_s is the pipe cross-sectional area, f_c is the limit stress value in the concrete at its destruction.

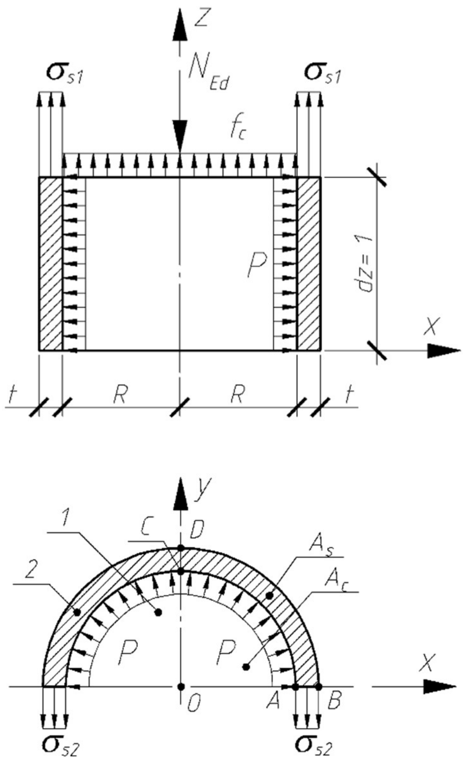

Figure 1 – Design diagram of concrete-filled steel tubular member deformation mode:
1 – concrete; 2 – tube (shell)

The right equation side (1) is a well-known expression [6], which only partially takes into account the shell operation in the boundary state in the axial direction, so the calculated normal cross section values of tubular concrete elements do not allow to use materials completely. Thus, the stress values σ_{s1} in equation (1) can be much less than the stress limit value of the concrete-filled steel tubular element steel pipe f_y in its ultimate state. The calculations' consequence with such in-accuracy is insufficient use of the concrete-filled element normal cross section strength calculated value. Therefore, the purpose of this article is to eliminate calculations shortcoming, namely to obtain the reinforced concrete steel tubular element strength equation, which would allow the materials complete strength.

To obtain the tubular concrete element strength equation, which would allow to obtain the materials strength value, which is used in full, consider the tubular concrete element part with thickness $dz = 1$ (Fig. 1). It should be borne in mind that the circular force inside the layer of the shell with a thickness $dz = 1$ (Fig. 1) from the meridional pressure p of concrete can be found from the equation $\sigma_{s2} \cdot t \cdot dz = p \cdot R \cdot dz$, whence

$$p = \frac{\sigma_{s2} \cdot t}{R} . \quad (2)$$

If expression (2) is substituted in the right equation part (1), then the result of this action will be such a dependence as:

$$N_{Rd} = A_c \left(f_c + 4 \frac{\sigma_{s2} \cdot t}{R} \right) + A_s \cdot \sigma_{s1} . \quad (3)$$

Given that for equation (3) the values of $A_s = 2\pi R t$ and $A_c = \pi R^2$, their ratio was obtained as:

$$\frac{t}{R} = \frac{A_s}{2A_c} . \quad (4)$$

After obtaining equation (4), the next step in mathematical transformations will show us expression (3) in the following form:

$$N_{Rd} = A_c f_c + 2\sigma_{s2} \cdot A_s + A_s \cdot \sigma_{s1} . \quad (5)$$

Now, to represent expression (5) in a more perfect view, it was introduced the notation:

$$\frac{\sigma_{s2}}{\sigma_{s1}} = k \Rightarrow \sigma_{s1} = \frac{\sigma_{s2}}{k} , \ \sigma_{s2} = k\sigma_{s1} . \quad (6)$$

from (1) it becomes clear that

$$N_{Rd} = A_c f_c + (2k+1) \cdot A_s \cdot \sigma_{s1} . \quad (7)$$

The above expression (7) has two unknown quantities σ_{s1} (or axial stresses σ_{s1} and meridional stresses σ_{s2}) and k. The first of them, for example σ_{s2}, can be easily determined from the condition of compatibility and shell deformation uniformity and concrete in the radial direction. Given this deformation feature of the tubular concrete element layer dz, it can be determined that at point A the displacement of concrete u_c and the steel shell u_s displacement are equal, i.e.

$$u_s = u_c . \quad (8)$$

Each of the displacements given in equation (8) can be calculated from the expressions obtained during the study. In particular

$$u_c = \varepsilon_c \cdot R = \left(\frac{p}{E_c} \right) R. \quad (9)$$

On the other hand, the displacement u_c in equation (9) can be expressed in terms of the circular stresses σ_{s2} unknown value with the using dependence (2). In this context:

$$u_c = \left(\frac{\sigma_{s2}}{E_c} \frac{t}{R} \right) R, \quad (10)$$

where E_c is the concrete deformation modulus;

t is the thickness of the shell; R is the shell inner radius.

The next step is to express the displacement u_s from equation (8) due to the unknown value of the circular stress σ_{s2}. For this action, it is assumed that all points of the inner ring of the shell (including points A and C) due to the pressure p have a radial displacement. As a consequence of this process, the inner ring expanded by $2\pi (R + u_s) - 2\pi R = 2\pi \times u_s$, and the relative value of this elongation in the circular direction, in its turn, was $\varepsilon_s = 2\pi \times u_s / 2\pi R = u_s / R$. However, considering that the relative radial displacement value u_s is also the value of u_s / R, it must be noted that the relative shell displacements in the radial and circular directions are the same. If this proof of the shell relative displacements (deformations) equality in the radial and circular directions was chosen as a basis, that

$$u_s = \varepsilon_s R . \quad (11)$$

The relative shell deformation in the radial direction can be found from the dependences based on Hooke's Law [15 – 17], if the calculation basis is the shell relative displacements equality in the radial and circular directions in case of concrete-filled steel tubular element deformation. Taking into account these dependencies, it becomes clear that

$$\varepsilon_s = \frac{\sigma_{s2} - \nu\sigma_{s1}}{E_s}, \quad (12)$$

here ν is the Poisson's ratio.

From expression (11) the tube shell radial displacement, taking into account equation (12) will take the following form

$$u_s = \left(\frac{\sigma_{s2} - \nu\sigma_{s1}}{E_s} \right) R. \quad (13)$$

In turn, the unknown value of σ_{s2} from equation (7) can be determined from the dependence, which will be obtained by replacing in equation (8) each of the quantities by its corresponding expressions (10), (13) and after performing certain mathematical transformations. This dependence is given below as expression (14).

$$\sigma_{s2} = \frac{\nu}{1 - \frac{E_s}{E_c} \frac{t}{R}} \sigma_{s1} = \frac{\nu}{1 - 2\alpha_s \frac{t}{D}} \sigma_{s1}, \quad (14)$$

here $D = 2R$ is the inner diameter of the shell.

Applying relation (6) and equation (14) at the same time, it can be reasonably noted like a

$$k = \frac{\nu}{1 - \frac{2E_s}{E_c} \frac{t}{D}} = \frac{\nu}{1 - 2\alpha_s \frac{t}{D}} . \quad (15)$$

If expression (15) will chosen as a basis, then the dependence (7), which makes it possible to determine the strength of the concrete-filled steel tubular element normal cross section, will be appropriately presented in the following form:

$$N_{Rd} = A_c f_c + \left(\frac{2\nu}{1 - 2\alpha_s \frac{t}{D}} + 1 \right) A_s \sigma_{s1}. \qquad (16)$$

Using equation (7) or (16) with the expression of displacements through stress in order to check the strength of the cylindrical tubular concrete element under central compression normal cross section, it is necessary to make an additional equation to calculate the meridional stresses σ_{s1}. Such an equation can be reduced to a form in which it would become the Saint-Venant (17) or Huber-Mises-Genk (18) plasticity theory condition, and would occur as follows:

$$\sigma_{s1} + \sigma_{s2} = f_y, \qquad (17)$$

$$\sigma_{s1}^2 - \sigma_{s1}\sigma_{s2} + \sigma_{s2}^2 = f_y^2. \qquad (18)$$

When (17) and (18) are used together with (6) and (7), it is possible to obtain the final expression form to determine the tubular concrete element under central compression bearing capacity:

$$N_{Rd} = k_{cs} A_c f_c + A_s f_y. \qquad (19)$$

According to the Saint-Venant plasticity theory, in expression (19) the concrete strengthening coefficient will be determined from equation (20)

$$k_{cs} = 1 + \frac{4k}{k+1} \frac{f_y}{f_c} \frac{t}{D}, \qquad (20)$$

where

$$k = \frac{\nu}{1 - \frac{2E_s}{E_c} \frac{t}{D}} = \frac{\nu}{1 - 2\alpha_s \frac{t}{D}}, \qquad (21)$$

based on relation (6) and knowing that

$$\sigma_{s2} = \frac{\nu}{1 - \frac{E_s}{E_c} \frac{t}{R}} \sigma_{s1} = \frac{\nu}{1 - 2\alpha_s \frac{t}{D}} \sigma_{s1}.$$

If the theory of Huber-Mises-Genka plasticity is applied to (19), then to determine the concrete strengthening coefficient the following dependence become obtained:

$$k_{cs} = 1 + 4\left(\frac{2k+1}{\sqrt{k^2 + k + 1}} - 1 \right) \frac{f_y}{f_c} \frac{t}{D}. \qquad (22)$$

As for the equations for determining the tubular concrete element bearing capacity, after substituting in expression (19) the equations for calculating the value of the concrete strengthening coefficient according to both the above plasticity theories (20, 22) dependencies become obtained by which it becomes possible to calculate the tubular concrete element bearing capacity values by applying the Saint-Venant (23) and Huber-Mises-Genk plasticity theories(24).

$$N_{Rd} = \left(1 + \frac{4k}{k+1} \frac{f_y}{f_c} \frac{t}{D} \right) A_c f_c + A_s f_y, \qquad (23)$$

$$N_{Rd} = \left(1 + 4\left(\frac{2k+1}{\sqrt{k^2 + k + 1}} - 1 \right) \frac{f_y}{f_c} \frac{t}{D} \right) A_c f_c + A_s f_y. \qquad (24)$$

***Example of calculation*.** Determine the steel tube concrete-filled steel column bearing capacity with a diameter D = 102 mm and a wall thickness t = 3 mm. The steel yield strength stresses value f_y = 287 MPa (E_s = 210000 MPa, ν = 0,3). The tube is filled with concrete with the characteristics: f_c = 13,5 MPa, E_c = 25600 MPa.

The element bearing capacity is determined based on Saint-Venant's theory by expression (23) and based on the Huber-Mises-Genk theory by expression (24) by the following method.

1. Find the parameter k value the using expression (15):

$$k = \frac{\nu_s}{1 - \frac{2E_s}{E_c} \frac{t}{D}} = \frac{\nu_s}{1 - 2\alpha_s \frac{t}{D}} = \frac{0,3}{1 - 2 \times 8,203 \times \frac{3,0}{102}} = 0,580,$$

given that in this equation

$$\frac{E_s}{E_c} = \frac{210000}{25600} = 8,203.$$

2. The concrete k_{cs} strengthening coefficient when applying the Saint-Venant plasticity theory by expression (20) is established:

$$k_{cs} = 1 + \frac{4k}{k+1} \frac{f_y}{f_c} \frac{t}{D} = 1 + \frac{4 \times 0,580}{0,580 + 1} \times \frac{287}{13,5} \times \frac{3}{102} = 1,918.$$

The value of the strengthening k_{cs} coefficient by applying the of Huber-Mises-Genk plasticity theory by expression (22):

$$k_{cs} = 1 + 4\left(\frac{2k+1}{\sqrt{k^2 + k + 1}} - 1 \right) \frac{f_y}{f_c} \frac{t}{D} =$$

$$= 1 + 4\left(\frac{2 \times 0,580 + 1}{\sqrt{0,580^2 + 0,580 + 1}} - 1 \right) \frac{287}{13,5} \times \frac{3}{102} = 2,231.$$

3. The tubular concrete element bearing capacity the is calculated taking into account theSaint-Venant plasticity theory by expression (23) as:

$$N_{Rd} = k_{cs} A_c f_c + A_s f_y = (1,918 \times 7238,2 \times 13,5 +$$

$$+ 933,1 \times 287) \times 10^{-3} = 455,2\ kN,$$

given that in this equation A_c = 7238.2 mm^2, A_s = 933.1 mm^2 .

The tubular concrete element bearing capacity according to expression (24) when applying the Huber-Mises-Genk plasticity theory is calculated as follows:

$$N_{Rd} = k_{cs} A_c f_c + A_s f_y = (2,231 \times 7238,2 \times 13,5 +$$

$$+ 933,1 \times 287) \times 10^{-3} = 485,8\ kN.$$

To identify the nature of the change in the concrete strengthening coefficient value depending on various parameters, it was calculated in the range of all concrete classes [19]. For comparison, 2 sections of pipes with a diameter of 102 mm with a wall thickness of 3 mm and 1 mm, respectively, were used. The steel characteristics were taken from the calculation example. The calculations results are shown in Table 1.

Table 1 − The concrete strengthening coefficient values for tubular concrete elements with different pipe wall thickness of the pipe

No.	Concrete class	A wall thickness t = 3 mm			A wall thickness t = 1 mm		
		k_{cs} by (20)	k_{cs} by (22)	$\frac{k_{cs}^{(22)}-k_{cs}^{(20)}}{k_{cs}^{(22)}}$,%	k_{cs} by (20)	k_{cs} by (22)	$\frac{k_{cs}^{(22)}-k_{cs}^{(20)}}{k_{cs}^{(22)}}$,%
1	C12/15	3,198	4,139	22,73	1,379	1,586	13,05
2	C16/20	2,291	2,933	21,89	1,268	1,415	10,39
3	C20/25	1,916	2,389	19,80	1,208	1,321	8,55
4	C25/30	1,739	2,127	18,24	1,175	1,27	7,48
5	C30/35	1,617	1,943	16,78	1,151	1,233	6,65
6	C32/40	1,531	1,814	15,60	1,133	1,205	5,98
7	C35/45	1,453	1,695	14,28	1,116	1,179	5,34
8	C40/50	1,403	1,619	13,34	1,105	1,162	4,91
9	C45/55	1,365	1,561	12,56	1,096	1,148	4,53
10	C50/60	1,328	1,504	11,70	1,087	1,134	4,14

As can be seen from table 1, if the concrete strengthening coefficient values deviation according to two different plasticity theories is analyzed, given as a percentage for each case of different pipe wall thickness, it can be concluded that for samples with a wall thickness of 1 mm in most cases it will be smaller than with a wall thickness of 3 mm.

The calculated concrete strengthening coefficient values, which were obtained on the basis of Saint-Venant and Huber-Mises-Genk plasticity theories, were compared by plotting the concrete values strengthening coefficient dependence on the concrete class (Fig. 2).

According to the same initial data for the same cases of tubular concrete elements pipe wall thicknesses taking into account the obtained concrete strengthening coefficient values, that were given in Table 1, then calculate the bearing capacity value and enter the calculations results in Table 2. Also in this table the error value of the concrete-filled steel tubular elements bearing capacity values, which were calculated on the basis of Saint-Venant plasticity theories by expression (23) and Huber-Mises-Genk expression (24), in percent to facilitate the results and clarity analysis.

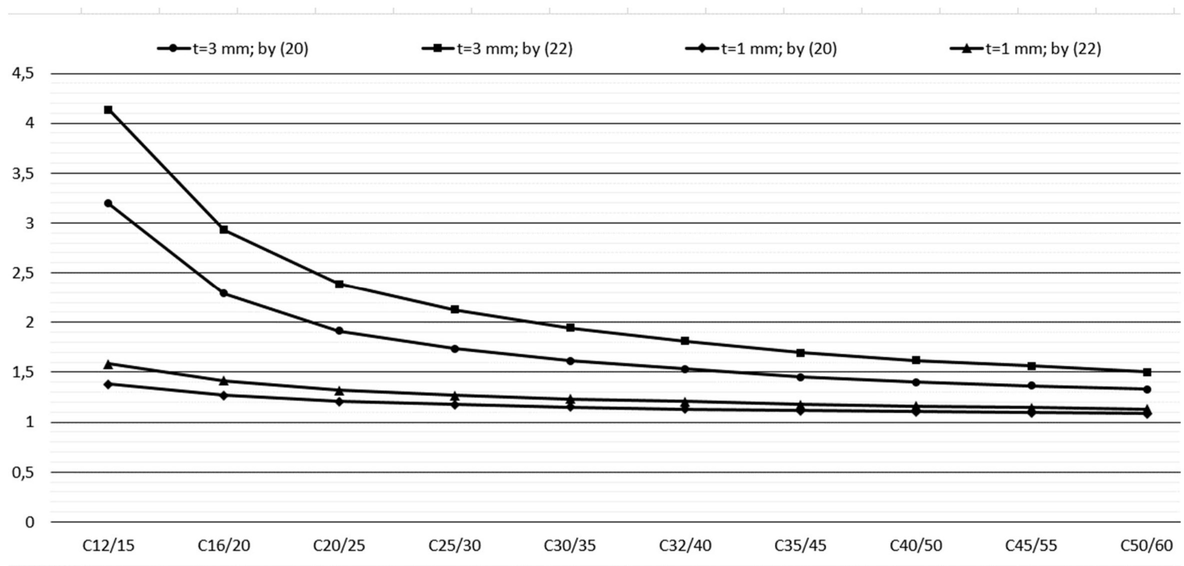

Figure 2 – Graphs of concrete strengthening coefficient values dependence on a concrete class for pipes with the set parameters

Table 2 − The bearing capacity values of the concrete-filled steel tubular elements with different pipe wall thickness of the pipe

No.	Concrete class	A wall thickness t = 3 mm			A wall thickness t = 1 mm		
		N_{Rd} by (23), kN	N_{Rd} by (24), kN	$\frac{N_{Rd}^{(24)} - N_{Rd}^{(23)}}{N_{Rd}^{(24)}}$, %	N_{Rd} by (23), kN	N_{Rd} by (24), kN	$\frac{N_{Rd}^{(24)} - N_{Rd}^{(23)}}{N_{Rd}^{(24)}}$, %
1	C12/15	464,6	522,5	11,08	352,6	365,4	3,49
2	C16/20	458,5	511,9	10,44	373,3	385,6	3,17
3	C20/25	468,9	518,5	9,57	394,6	406,4	2,92
4	C25/30	481,8	529,5	9,02	412,4	424,1	2,76
5	C30/35	496,0	542,0	8,49	430,3	441,8	2,62
6	C32/40	511,6	556,7	8,10	448,2	459,7	2,49
7	C35/45	530,7	574,5	7,62	469,7	481,1	2,37
8	C40/50	547,1	590,1	7,29	487,8	499,1	2,27
9	C45/55	564,2	606,8	7,01	505,8	517,1	2,18
10	C50/60	585,0	627,0	6,70	527,4	538,7	2,08

In general, the data in Table 2, firstly, is a clear proof of the obtaining the elements bearing capacity value possibility according to the above calculation method and, secondly, demonstrate that the bearing capacity values obtained from the same source data, i.e. calculated for one case, but given the different plasticity theories application, do not differ significantly. Due to the direct influence of the concrete strengthening coefficient value on the elements bearing capacity value, based on this table, it is concluded that the obtained values discrepancy according to different plasticity theories decreases with decreasing wall thickness.

Graphs of the bearing capacity value dependence on the prototype concrete class were compiled to better understand the calculations results. These graphs are shown in Figure 3.

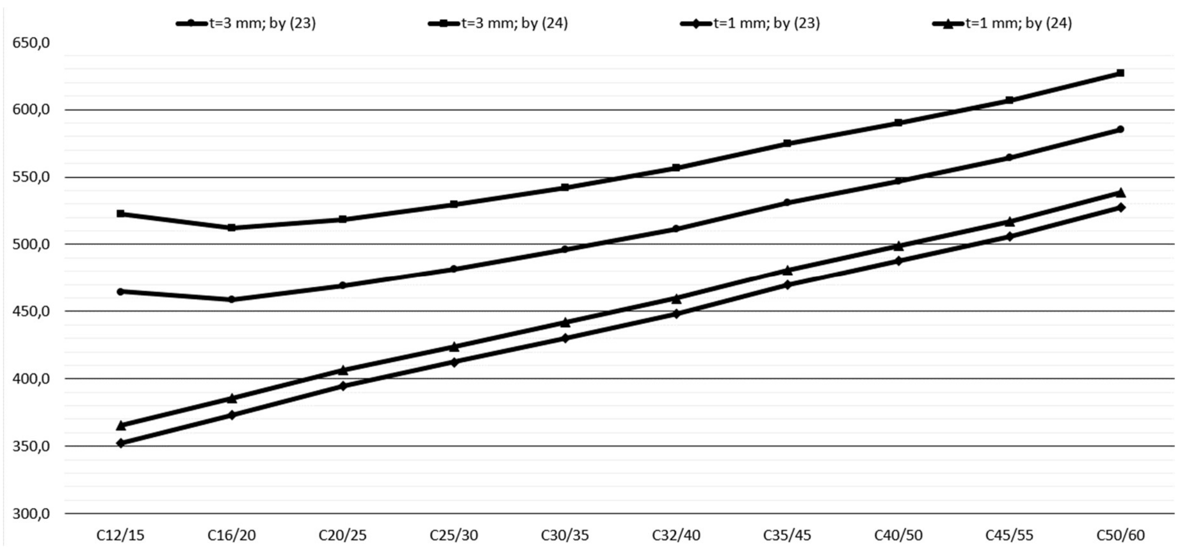

Figure 3 – Graphs of dependence of values of bearing capacity on a class of concrete

Conclusions

Based on the Saint-Venant and Huber-Mises-Genk plasticity theories application, analytical expressions are obtained to calculate the concrete reinforcement coefficient of a tubular concrete element core in the limit state and the strength equation of a tubular concrete element, which allows to use full strength. Calculations were made according to the given expressions and comparison of the coefficient strengthening values, obtained on the basis of the both presented plasticity theories application. To determine the proposed method accuracy, it is planned to compare the calculation results with experimental data.

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