MATEC Web of Conferences **278**, 03003 (2019) https://doi.org/10.1051/matecconf/201927803003
ICBMM 2018

Accounting for the Scale Factor in Determining the Compressed Concrete Strength of Concrete-Filled Steel Tube Elements

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Abstract. The published experimental data on the influence of the concrete samples dimensions on their strength under axial compression had been analyzed in the article. The mechanism of this influence is revealed from the positions of strength statistical theories. The known dependences are given and a new formula is proposed for taking into account the scale factor in determining the strength of compressed concrete. An algorithm for calculating the strength of centrally compressed concrete-filled steel tube elements (CFSTE) with a circular cross-section taking into account the scale factor is shown.

1 Introduction

According to the current regulations of the Russian Federation, the effect accounting of the working section dimensions of concrete and reinforced concrete structures on the concrete strength in axial compression is not provided in their calculation. However, according to the published experimental data, such an influence exists. For example, the US irrigation bureau carried out special experiments to determine the influence of the specimen dimensions on the compression temporary resistance of concrete in connection with the construction of the Boulder dam. The results of the performed tests were published in [1]. Similar data of Japanese researchers are also noted here [2].

These experiments have established that the compressive strength of concrete decreases with increasing of sample sizes. Moreover, the degree of strength reduction is practically independent on the concrete mix composition.

Currently, heavily loaded reinforced concrete columns are increasingly used [3-6]. Such columns perceive colossal loads in high-rise buildings. The cross-sectional dimensions of such columns often reach 1÷1.5 m, and sometimes even more. Concrete-filled steel tube columns with a cross-section dimensions of 3×3 m were used in the construction of famous skyscrapers in Malaysia – twin towers “Petronas”.

It is necessary to investigate more thoroughly the influence of structural dimensions on the concrete strength in such a situation. The influence of concrete structure affects the choice of control samples sizes (i.e. homogeneous elements). Concrete control samples with cross-sectional dimensions of 150×150 mm are accepted as reference in the existing standards of the Russian Federation. It is necessary to take into account the effect of the scale factor for section sizes that differ from the reference.

2 Main part

The effect mechanism of structural dimensions on the concrete strength is revealed in the strength statistical theories by V.V. Bolotin [2], M.M. Kholmyanskiy [7], V.D. Harlab [8], etc. According to these theories the scale factor is always evident in the fractured bodies. A large spread of defects in the form of internal cracks in volume is inherent for such bodies. It should be noted that the main factor - the determining effect of internal cracks on the materials strength – is correctly represented in statistical theories.

Non-scale calculation models of concrete do not exist from the modern positions of solid-state mechanics [9]. The destruction of the concrete sample is almost always accompanied by the development of cracks in its structure. These cracks are scattered throughout the volume in the form of internal defects. It is known that the scale factor is always manifested in fractured bodies.

Not only the presence of inhomogeneous components of the structure, but also the inhomogeneous stress-strain state have a significant impact on the internal cracks growth in the concrete. This state is always manifested in a certain scale of the sample volume.

The actual stresses in the concrete sample are usually replaced by smooth stresses in practical calculations, and these stresses are continuous functions of the section coordinates. The smoothing process is performed in determining the strength characteristics of concrete by the results of control samples tests (cubes, prisms, cylinders),

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which are conditionally considered to be made of a continuous homogeneous material. The stresses in such a material act as the smoothed stresses of the samples from the real material. In this case, the smoothing procedure is reduced to averaging over the working areas of the control samples sections. The concrete strength is based on the test results of control samples, and then it is used in the calculation of real structures.

In deterministic models of concrete with averaged characteristics of a structurally inhomogeneous material it is possible to adopt the statistical theory of V.D. Harlab [8] to take into account the scale factor. He took as a basis the Weibull distribution law, and associated the probability of a dangerous crack with the sample volume – in a small volume this probability is less. In the accepted formulation, we have a smooth strength reduction as the dimensions of the concrete section increases.

The regularity of this decrease can be described by analytical dependencies. It is most convenient to take into account the scale factor using the appropriate coefficient γ_c, which should be multiplied by the calculated resistance of concrete compression, taken in accordance with the current design standards.

In work [10] the following formula is proposed for determination of this coefficient

$$\gamma_c = 1.67 \cdot d_b^{-0.112}, \qquad (1)$$

where d_b is the characteristic size of concrete normal section of the calculated reinforced concrete element.

This formula has two main drawbacks. First, it was obtained for the cross-sectional dimension of the concrete reference control sample of 100 mm. In the norms of the Russian Federation the size of the reference cube edge is taken equal to 150 mm. Secondly, the formula (1) gives an underestimated values of the coefficient that takes into account the influence of the scale factor for samples with cross section sizes over 900 mm.

In [11] it is proposed to take the coefficient values that takes into account the scale factor, taking into account the data of Table 1.

Intermediate values are calculated using linear interpolation. Values of coefficient γ_c are allowed to accept by linear extrapolation, but not less than γ_c =0.8 with diameters of the concrete core over 630 mm.

In work [12] the following formula is offered

$$\gamma_c = 0.7 + 0.3\left(\frac{d_0}{d_b}\right)^{0.5}, \qquad (2)$$

where d_0 is the diameter of the reference cylinder, taken equal to 0.15 m.

Table 1. Values of the coefficient that takes into account the scale factor

Diameter of concrete core, [mm]	150	300	400	630
Values of the coefficient γ_c	1	0.907	0.873	0.838

Formula (2) is devoid of the drawbacks noted above. But when it was received, only the results of the work [2] were taken into account. Therefore, the results are not always obtained with acceptable accuracy for practical purposes.

Statistical processing of the data given in [1] and [2] was carried out for the purpose of receiving a more reliable formula. The result of this treatment (after rounding) is the following formula for determining the coefficient that takes into account the influence of the scale factor on the concrete strength

$$\gamma_c = 0.8 + 0.2\left(\frac{d_0}{d_b}\right)^{0.5}. \qquad (3)$$

It is recommended to use this formula for $d_b \geq 100$ mm (at $d_b = 100$ mm $\gamma_c \approx 1.05$, which corresponds to the position of the current norms). The restriction of the minimum value of the coefficient that takes into account the influence of the scale factor is practically not required, since the value of γ_c asymptotically approaches 0.8 even at sufficiently large values of d_b, which is usually confirmed by the corresponding experiments. For example, for $d_b = 3000$ mm $\gamma_c \approx 0.81$.

The design resistance to uniaxial compression of the concrete core of the concrete-filled steel tube element f_{bc} taking into account the scale factor is recommended to be determined as follows

$$f_{bc} = \gamma_c f_c, \qquad (4)$$

where f_c is the design resistance of concrete under uniaxial compression, determined according to the current design standards.

Previously, the vast majority of researchers used a fairly simple relationship to find the strength of the concrete core at a triaxial compression f_{cc} with a uniform lateral compression of concrete-filled steel tube columns with stresses $|\sigma_r| < |\sigma_{cz}|$. This dependence is essentially a condition of the Coulomb-Mohr strength

$$f_{cc} = f_c + k\sigma_r, \qquad (5)$$

where f_c is the concrete strength at uniaxial compression; k is the coefficient of lateral pressure; σ_r is the lateral pressure on the concrete core in the limiting state of CFSTE.

The value of the coefficient k in this formula was usually assumed constant − k = 4.1 or k = 4.0, taking into account experimental studies.

This formula was proposed by American researchers F. Rihart, A. Brattsaeg and R. Brown in the first half of the 20th century. It is widely used by many scientists and now, including for the calculation of columns with a steel cage.

However, in recent years, many experts use more accurate dependencies to determine the strength of a volume-compressed concrete. The formula of J. Mander is used more often than others [13]

$$\frac{f_{cc}}{f_c} = 2.254\sqrt{1+7.94\frac{\sigma_r}{f_c}} - 2\frac{\sigma_r}{f_c} - 1.254. \qquad (6)$$

This formula has its drawbacks. It should be noted that the lateral pressure on the concrete core in the limiting state σ_r is initially unknown for concrete-filled steel tube columns. Its value depends on the geometric and structural parameters of the calculated column. Therefore, it is difficult to find the stress reliable value at the top of the concrete core deformation diagram "$\sigma_{cz} - \varepsilon_{cz}$" by the formula (6).

In addition, verification of the calculations accuracy based on the comparison results of the theoretical values obtained with the tests experimental data of concrete-filled steel tube elements indicates a noticeable understatement of the concrete core strength thus calculated at relatively low levels of lateral compression.

We accept a theoretically grounded solution of the strength characteristic function of the volume-compressed concrete at the suggestion of N.I. Karpenko [14] for a more accurate solution of the task. In the particular case of uniform lateral compression, a result of this solution is the equation (5), but with a variable value of k, which depends on the level of lateral compression $m = \sigma_r / f_{cc}$ and the type of concrete. For its determination a formula is recommended

$$k = \frac{1 + a - am}{b + (f - b)m}, \qquad (7)$$

where *a*, *b* are the material coefficients determined on the basis of experiments; f is a parameter determining the nature of strength surface in the area of all-around compression (for a dense concrete core, the strength surface is open and $f = 1$).

The researchers of our scientific group [11-12, 15-16] have revealed that coefficient k varies in a fairly wide range (from 2.5 to 7) for the CFSTE concrete core. Since the lateral pressure σ_r can reach 15÷20 MPa or more before the destruction of concrete, even minor inaccuracies in the definition of k can lead to significant errors in determining the concrete strength f_{cc} and the bearing capacity of the calculated element.

Comparison of calculated values with numerous experimental data performed in [9] indicates that the values of b = 0.118 and a = 0.5b correspond to a certain lower limit of the strength of volume-compressed heavy concretes. The values of b = 0.096 and a = 0.5b correspond to the average strength values of volume-compressed dense concretes (with a reliability of 0.5). It is known that fine-grained concrete is slightly worse resist volumetric compression. According to our calculations, the coefficients b = 0.16 and a = 0.5b correspond to the average experimental values f_{cc} of fine-grained concrete. Thus, application of the formula (7) allows to consider the influence of not only the lateral pressure level, but also the structure specifications of concrete itself on the strength of volumetrically loaded concrete core, which is important for obtaining more valid solutions using various types of concrete.

The analysis of the dependence (7) shows that with high levels of lateral compression ($m \to 1$), the value of the lateral pressure coefficient is $k \to 1$. In such cases, concrete destruction will be of shear nature, according to Coulomb's law. With the above-mentioned coefficients k = 2.5÷7, volumetrically loaded concrete destruction occurs due to combinations of break and shear, which corresponds to numerous experimental data [11].

It is necessary to obtain a dependence that allows to determine the strength of the CFSTE volume-compressed concrete core, since the level of lateral compression $m = \sigma_r / f_{cc}$ in the limiting stage of the CFSTE operation before the calculation is unknown. Inserting the equation (7) into the formula (5) and performing some transformations, we will obtain for heavy concrete

$$f_{cc} = f_{bc}\left[1 + \left(0{,}5\bar{\sigma} + \frac{\bar{\sigma} - 2}{4} + \sqrt{\left(\frac{\bar{\sigma} - 2}{4}\right)^2 + \frac{\bar{\sigma}}{b}}\right)\right], \qquad (8)$$

where $\bar{\sigma}$ is the relative value of the lateral pressure from the steel shell on the concrete core in the limiting state $\bar{\sigma} = \sigma_r / f_{bc}$.

We write down the dependence for calculation of the normal section strength of the central compressed short CFSTE in which there is no reinforcement of the concrete core

$$N = f_{cc}A + \sigma_{pz}A_p, \qquad (9)$$

where σ_{pz} is the compressive stress of the axial direction in the steel shell in the CFSTE limiting state; A_p is the cross-sectional area of steel pipe; A is the cross-sectional area of the concrete core.

It is known that the lateral pressure exerts a significant influence not only on the concrete core strength of the structure, but also on the value of the axial direction stress in the steel shell σ_{pz}. This stress is expressed from the Genki-Mises condition for a flat stress state in the limiting stage of the centrally compressed CFSTE

$$\sigma_{pz} = \sqrt{f_y^2 - 0.75\sigma_{p\tau}^2} - 0.5\sigma_{p\tau}, \qquad (10)$$

where f_y is a yield stress of the CFSTE steel shell; $\sigma_{p\tau}$ is the stress of the circumferential (tangential) direction of the steel pipe in the limiting state.

Note that formula (10) is valid for thin-walled pipes (at $d/\delta \geq 40$, where d and δ are the diameter and wall thickness of the pipe). It is these pipes are mainly used as steel shells for CFSTE.

The thickness-averaged tangential stresses in the steel shell for thin-walled pipes can be expressed through the lateral pressure with sufficient accuracy for practical calculations by using the dependence

$$\sigma_{p\tau} = -2\sigma_r \frac{A}{A_p}. \tag{11}$$

Next, we use the value of the constructive coefficient of CFSTE, calculated by the formula

$$\xi = \frac{f_y A_p}{f_c A}. \tag{12}$$

The formula for calculating the stress in the steel shell σ_{pzu} can be written taking into account the dependencies (11) and (12) in the form of

$$\sigma_{pzu} = \sqrt{\xi^2 f_{bc}^2 \frac{A^2}{A_p^2} - 3\sigma_r^2 \frac{A^2}{A_p^2}} - \sigma_r \frac{A}{A_p}. \tag{13}$$

After small transformations we have the following formula for finding σ_{pz}

$$\sigma_{pzu} = f_{bc}\left(\sqrt{\xi^2 - 3\bar{\sigma}^2} - \bar{\sigma}\right)\frac{A}{A_p}. \tag{14}$$

First, we express through this parameter the right-hand side of formula (9) for determining the value of $\bar{\sigma}$. The longitudinal force, perceived by concrete, with account of formula (8), is represented as expression

$$N_b = f_{bc}A\left[1 + \left(0{,}5\bar{\sigma} + \frac{\bar{\sigma}-2}{4} + \sqrt{\left(\frac{\bar{\sigma}-2}{4}\right)^2 + \frac{\bar{\sigma}}{b}}\right)\right]. \tag{15}$$

The longitudinal compressive force perceived by the steel shell, taking into account the dependence (14) is determined by the formula

$$N_p = f_{bc}A\left(\sqrt{\xi^2 - 3\bar{\sigma}^2} - \bar{\sigma}\right). \tag{16}$$

Then the dependence to determine the limit load for a short centrally compressed CFSTE can be presented in the following form

$$N = f_{bc}A\left[1 + \left(\frac{\bar{\sigma}-2}{4} + \sqrt{\left(\frac{\bar{\sigma}-2}{4}\right)^2 + \frac{\bar{\sigma}}{b}} - \frac{\bar{\sigma}}{2} + \sqrt{\xi^2 - 3\bar{\sigma}^2}\right)\right]. \tag{17}$$

Note that the total longitudinal force, perceived by concrete and steel in the normal section, depends only on the relative lateral pressure $\bar{\sigma}$ at fixed values of geometric and structural parameters (f_c, f_y, A, A_p, b).

The following condition corresponds to the maximum value of the longitudinal force

$$\frac{dN}{d\bar{\sigma}} = 0. \tag{18}$$

We obtain the following equation after determining the derivative of expression (18)

$$\left(\frac{b(\bar{\sigma}-2)+8}{\sqrt{b}\sqrt{b(\bar{\sigma}-2)^2 + 16\bar{\sigma}}} - \frac{12\bar{\sigma}}{\sqrt{\xi^2 - 3\bar{\sigma}^2}} - 1\right) = 0. \tag{19}$$

We obtain a formula for determining the relative lateral pressure of the steel shell on the concrete core in the limiting state of the CFSTE from the equation solution (19)

$$\bar{\sigma} = 0.48e^{-(a+b)}\xi^{0.8}. \tag{20}$$

The found parameter $\bar{\sigma}$ and the obtained dependence for taking into account the scale factor (4) allows to determine the strength of centrally compressed concrete-filled steel tube elements of circular cross-section, as well as the stress f_{cc} at the top of the concrete core deformation diagram.

3 Summary

The obtained dependence for taking into account the scale factor in determining the concrete core strength of the concrete-filled steel tube elements is characterized by the simplicity of writing and the accuracy that is acceptable for practical calculations. The data of the Japanese researchers noted above are very well correlated with calculations using the proposed formula.

Acknowledgments

This article was prepared by results of implementation of the scientific project within the state task of the Ministry of Education and Science of the Russian Federation No. 7.3379.2017/4.6.

References

1. V.A. Bushkov. *Reinforced concrete structures. Part 1* (Moscow, State publishing house of building literature, 1940)
2. V.V. Bolotin. *Mechanics of multilayer structures* (Moscow, 1986)
3. M. Abramski. *In. Archives of Civil and Mechanical Engineering* **18 (3)** (2018). http://doi.org/10.1016/j.acme.2018.01.002
4. S. Jayalekshmi, J.S.S. Jegadesh, A. Goel. J. Inst. Eng. India Ser. A **99**, 257-268 (2018). http://doi.org/10.1007/s40030-018-0291-x

5. E. Farajpourbonab, S.Y. Kute, V.M. Inamdar. Int J Adv Struct Eng **10**, 61-72 (2018). http://doi.org/10.1007/s40091-018-0186-0
6. J. Wang, Q. Sun. *12th International Conference on Advances in Steel-Concrete Composite Structures (ASCCS 2018)* (Universitat Politècnica de València, València, Spain, 2018). http://dx.doi.org/10.4995/ASCCS2018.2018.7287
7. M.M. Kholmyanskiy, E.I. Shifrin. Physical and technical problems of mining **3**, 52-61 (1981)
8. V.D. Kharlab. Mechanics of rod systems and solid mediums **11**, 150-152 (1987)
9. N.I. Karpenko. *General Models of Steel Concrete Mechanics* (Moscow, Stroyizdat, 1996)
10. I. Nishiyama, S. Morino, K. Sakino, H. Nakahara. *Summary of Research on Concrete-Filled Structural Steel Tube Column System Carried Out Under The US-JAPAN Cooperative Research Program on Composite and Hybrid Structures* (Japan, 2002)
11. A.L. Krishan. *Concrete-Filled Tubular Columns with Preliminarily Confined Core* (Rostov-on-Don, Rostov State Construction University, 2011)
12. A.L. Krishan, M.A. Astafyeva, R.R. Sabirov. *Calculation and designing of concrete filled steel tube columns* (Saarbrucken, Deutschland, Palmarium Academic Publishing, 2016)
13. J.B. Mander, M.J.N. Priestley, R. Park. Journal of Structural Engineering, ASCE **114 (8)**, 1804-1826 (1988)
14. N.I. Karpenko. Structural Mechanics and Analysis of Constructions **2**, 33-36 (1982)
15. A.L. Krishan, V.V. Remnev. Journal Industrial and Constructional Engineering **10**, 22-24 (2009)
16. A.L. Krishan, V.I. Rimshin, A.I. Sagadatov. Byulleten' stroitel'noj tehniki **6**, 13-21 (2016)