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Durability and Concrete Strain Capacity of Concrete Filled Steel Tube Columns with Hooped Reinforcement

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Abstract: Definition matters of strength and strain capacity properties of the concrete filled steel tube columns with hooped reinforcement are considered. Theoretical approach to consideration of power resistance of concrete filled steel tube columns with hooped reinforcement in the form of grids allowed receiving new dependences for determination of durability and limiting deformation of volume compressed concrete. Practical use of these dependences will allow increasing the bearing ability calculations accuracy for the concrete filled steel tube columns with hooped reinforcement.

Key words: Concrete filled steel tube columns, hooped reinforcement, bearing ability, volume compression, concrete durability, strain capacity

INTRODUCTION

Hooped reinforcement of concrete filled steel tube columns allows increasing at the same time durability and strain capacity of concrete that leads to significant increase in the energy necessary for their destruction. As a result during earthquakes survivability of the buildings built of such columns significantly increases. Therefore, concrete filled steel tube columns with hooped reinforcement are especially demanded at construction in the territories which are in zones of high seismic activity (Liang and Samuel, 2012; Krishan *et al*., 2014a, b) now. Many scientists pay much attention to researches of features of their power resistance (Fattah, 2012; Kotsovos, 2007; Krishan *et al*., 2014; Mander *et al*., 1988; Masoudnia *et al*., 2011; Naeej *et al*., 2013; Attard and Setunge, 1996; Rastorguyev and Vanus, 2009; Waston *et al*., 1994; Krishan, 2014; Karpenko, 1996).

However, the made analysis of the offered methods of durability calculation of the compressed elements with hooped reinforcement demonstrates that all of them are based on experimental dependences and have a limited scope. In this regard development of a universal method of the durability calculation of the compressed elements with hooped reinforcement which is adequately considering the main features of their constructive decision and the intense deformed state is represented urgent.

Design features of the compressed elements with hooped reinforcement assume performance of durability calculation of their normal sections on the basis of nonlinear deformation model. This model allows considering fully the main features of power resistance of reinforced concrete elements including their physical and geometrical nonlinearity and also the difficult nature of tension.

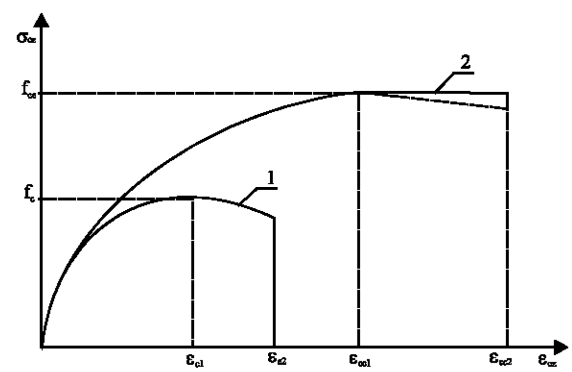

Fig. 1: Charts of deformation for single-axis compressed 1 and volume compressed 2 concrete

Initial base for calculations for nonlinear deformation model are charts of deformation of concrete and fittings. These charts have to reflect real work of materials most precisely. At the same time the main problem consists in reliable determination of durability at compression and limit deformations of shortening of volume and intense concrete.

A form of the chart of deformation of concrete "σ_{cz}-ε_{cz}" is recommended to be taken curvilinear with the falling site (Fig. 1). The main parametrical point of this

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chart is its top with coordinates f_{cc} ε_{cc1}. Limit relative deformation is designated as ε_{cc2}. Thus, it is necessary to refer determination of coordinate of top of the chart to the main objective of calculation "σ_{cz}-ε_{cz}".

In this research theoretical aspects of power resistance of the compressed reinforced concrete elements with hooped reinforcement by steel grids are considered. At the same time the offered approach can be used for any options of hooped reinforcement (Karpenko, 1996).

DETERMINATION OF DURABILITY OF CONCRETE

At an element loading with hooped reinforcement along a longitudinal axis of "z" it is central by the applied squeezing force in a concrete kernel there is both longitudinal tension σ_{cz} and side tension σ_{cx} and σ_{cy} (Fig. 2). And side tension, as well as longitudinal is squeezing and is caused by operation of hooped reinforcement on stretching. In grid cores with cross-sectional areas A_{sx} A_{sy} there are also stretching efforts, respectively $\sigma_{sx}A_{sx}$ and $\sigma_{sy}A_{sy}$. Therefore, concrete of a kernel is in conditions of three-axis compression and hooped reinforcement in the conditions of monoaxial stretching.

As an example we will consider the column of square section the sizes $x_c = y_c$ reinforced by the grid which also have a square cell with a size x_s. For ensuring noticeable effect of hooped reinforcement a step of grids S and distance between cores x_s y_s are also accepted by rather small. Therefore with a small error it is possible to accept tension σ_{cx} and σ_{cy} evenly distributed on a side surface of a column.

From equality to zero sum of projections of internal efforts in the stretched cores of fittings and in the compressed concrete on an axis X for the considered fragment thickness S, we receive the equation:

$$\psi_c \sum \sigma_{sx} A_{sx} + \sigma_{cx} x_c S = 0 \quad (1)$$

in which ψ_c the coefficient considering unevenness of side sinking of concrete owing to a discrete arrangement of hooped reinforcement both on cross section and on column section height. For prismatic elements it is recommended to accept $\psi_c = 0.75$ for cylindrical $\psi_c = 0.95$ (Waston *et al*., 1994).

Then the average value of side pressure upon concrete caused by existence of hooped reinforcement by grids is determined by a equation:

$$\sigma_{cx} = -\frac{0.75 \sum \sigma_{sx} A_{sx}}{x_c S} = -\frac{0.75 \times \sigma_{sx} A_{sx}}{x_s S} \quad (2)$$

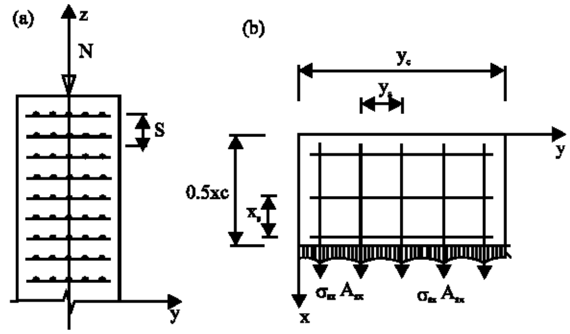

Fig. 2: Reinforced concrete element with mesh reinforcing: a) Side view; b) The scheme of efforts in the considered fragment

Taking into account that in a destruction stage tension in hooped reinforcement reaches a fluidity limit f_{yh} a Eq. 2 it is possible to present in the form:

$$\sigma_{cx} = -0.375 \rho_{sl} f_{yl} \quad (3)$$

where $\rho_{sl} = 2A_{sx}/(x_s S)$ coefficient of hooped reinforcement. In it is central the compressed reinforced concrete elements with hooped reinforcement at which any point there is uniform side pressure, durability of volume compressed concrete f_{cc} can be calculated on the formula received theoretically by Karpenko (1996) and Chistyakov (1988):

$$f_{cc} = f_c + k\sigma_{cx} \quad (4)$$

in which f_c concrete durability at monoaxial compression; k the coefficient of side pressure depending on the level of side sinking $m = \sigma_{cx}/f_{cc}$ and for concrete of dense structure determined by a equation:

$$k = \frac{1 + a - am}{b + (1 - b)m} \quad (5)$$

where a, b the material coefficients established on the basis of experiences (for heavy concrete b = 0.118, a = 0.5 b).

From the joint solution of the Eq. 4 and 5, taking into account dependence 3 for determination of durability of volume compressed concrete f_{cc}, we receive the following equation:

$$f_{cc} = \alpha_c f_c \quad (6)$$

in which:

$$\alpha_c = 0.5 + 0.75\xi + 0.25\sqrt{(2 - \xi)^2 + 16\xi / b} \quad (7)$$

Table 1: Comparison of experimental and settlement data of the bearing ability and a strain capacity of columns to hooped reinforcement

Column codes	Prismatic durability of concrete (MPa)	Longitudinal reinforcing f_y (Mπa)	Longitudinal reinforcing ρ_{sl} (%)	Hooped reinforcement f_{yl}(Mπa)	Hooped reinforcement ρ_{sl} (%)	Bearing ability (kN) N_u^{exp}	N_u^{th}	N_u^{exp}/N_u^{th}	Relative deformation×10[5] ε_{ccl}^{exp}	No. 9/ε_{ccl}^{9}	No. 13/ε_{ccl}^{12}	$\varepsilon_{ccl}^{exp}/\varepsilon_{ccl}^{9}$	$\varepsilon_{ccl}^{exp}/\varepsilon_{ccl}^{13}$
Kc-12-1	41.2	-	0	430	1.55	4360	4235	1.30	425	481	446	0.88	0.95
Kc-12-2	48.8	-	0	430	1.55	4900	4819	1.02	425	462	420	0.92	1.01
Kc-13-1	42.2	-	0	430	3.49	4800	5438	0.88	650	760	695	0.85	0.94
Kc-13-2	42.2	-	0	430	3.49	4800	5438	0.88	650	760	695	0.85	0.94
Kc-16-1	40.0	-	0	430	3.10	5200	5047	1.03	600	720	666	0.83	0.90
Kc-16-2	47.5	-	0	430	1.86	5300	4931	1.07	550	508	460	1.08	1.20
Kc-16-3	40.0	-	0	430	4.00	5660	5495	1.03	800	853	792	0.94	1.01
Kc-1-1	42.0	413	1.63	430	1.55	4950	4885	1.01	430	479	443	0.90	0.97
Kc-1-2	42.9	455	1.63	430	1.55	5300	5026	1.05	430	476	439	0.90	0.98
Kc-1-3	42.9	455	1.66	430	1.55	5300	5026	1.05	430	476	439	0.90	0.98
Kc-2-1	42.0	412	2.68	430	1.55	5300	5261	1.01	450	479	443	0.94	1.02
Kc-2-2	46.8	400	2.74	430	1.55	5640	5623	1.00	450	467	426	0.96	1.06
Kc-2-3	46.8	400	2.74	430	1.55	5640	5623	1.00	450	467	426	0.96	1.06

Test results of short columns 1200 mm long with overall dimensions of cross section 300×300 mm and in distances between extreme grid cores of hooped reinforcement 270×270 mm are given in the table

where ξ the constructive coefficient of mesh reinforcing calculated on a equation:

$$\xi = 0.375\rho_{sl}\frac{f_{yl}}{f_c} \tag{8}$$

The received formulas can be applied to heavy and fine-grained concrete. Table 1 comparison of the calculated theoretically bearing ability of columns to hooped reinforcement by grids N_u^{th} with the bearing ability received in experiences N_u^{exp} (Alacali *et al*., 2011) is executed $N_u^{th}N_u^{exp}$. Theoretical data are determined by a method of extreme efforts that for short is central the compressed elements are quite admissible. At the same time durability of the concrete kernel concluded within hooped reinforcement was determined by Eq. 6 and 7.

Skilled data are obtained in large-scale experiments with concrete filled steel tube columns of the natural sizes executed in NIIZB under the leadership of Chistyakov, (1988). They cause high degree of trust. Results of the executed comparison demonstrate good coincidence of the theory to practice. The maximum divergence between the theory and experience made 12%, coefficient of a variation of a vector of mistakes 6%.

DEFINITION OF CONCRETE STRAIN CAPACITY PROPERTIES

Other coordinate of top of the chart of deformation "σ_{cz}-ε_{cz}" is relative deformation of shortening of concrete in the axial direction ε_{cc1}. Value of this deformation also should be found taking into account work of concrete in the conditions of volume compression.

For calculation ε_{cc1} there are many various offers (Imran and Pantazopoulou, 1996; Mendis *et al*., 2000; Subramanian, 2011; Hamidian *et al*., 2016; Han and An, 2014; Krishan, 2014) calculation ε_{cc1} there are many various offers (Imran and Pantazopoulou, 1996; Mendis *et al*., 2000; Subramanian, 2011; Hamidian *et al*., 2016; Han and An, 2014; Krishan *et al*., 2014a, b). All of them are received by results of processing of experimental data. In practice of design rather simple dependence recommended in EN 1992-1-1 is most often applied. Eurocode 2; design of concrete structures and having the following appearance:

$$\varepsilon_{cc1} = \varepsilon_{c1}\left(\frac{f_{cc}}{f_c}\right)^2 \tag{9}$$

where ε_{c1} relative deformation in top of the chart of deformation single-axis the compressed concrete. For the purpose of assessment of accuracy of a Eq. 9 comparison of the sizes calculated on it ε_{cc1} to experimental data of work is executed ε_{c1} (Alacali *et al*., 2011). Results of this comparison are given in Table 1. They demonstrate quite satisfactory coincidence of the theory to practice. The maximum divergence between the theory and experience made 17%, coefficient of a variation of a vector of mistakes 11%. However, the fact that the Eq. 9 is received in the empirical way limits the field of its use. For example, it will be not clear what its accuracy when using high-strength or fine-grained concrete. Besides in 12 cases from 13 compared results this formula overestimates the size of deformations ε_{c1} that testifies to a probable system error.

Therefore, receiving the universal formula based on phenomenological approach is represented urgent. For this purpose we will consider curve deformations "σ_{cz}-ε_{cz}" for single-axis and volume compressed concrete (Fig. 3). It is obvious that at small levels of axial tension σ_{cz} the side pressure upon concrete σ_{cx} is absent. In this case

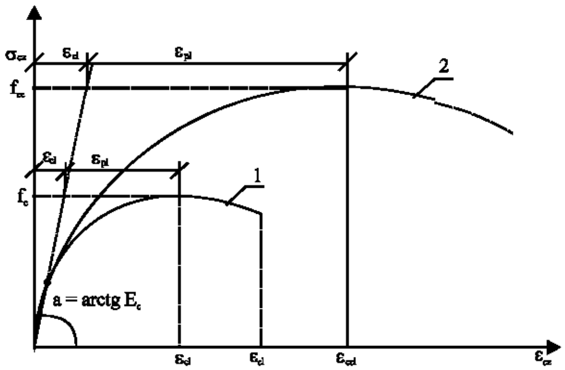

Fig. 3: Schedules of deformation for single-axis compressed 1 and volume compressed 2 concrete kernels

column concrete works with hooped reinforcement in the conditions of monoaxial compression. That is dependences 1 and 2 in Fig. 2 in an initial stage of deformation coincide. Then the initial module of elasticity for both dependences can be accepted identical and equal E_c.

Full deformations of concrete at any level of tension can be presented as the sum of elastic and inelastic deformations. Taking into account the accepted equality of modules of elasticity the following communication between elastic deformations volume compressed ε_{el} and single-axis the compressed ε_{el} concrete is fair ε_{el} ε_{el}.

$$\varepsilon_{el} = \varepsilon_{el}\frac{f_{cc}}{f_c} \quad (10)$$

On the other hand, it is logical to assume that inelastic parts of the general deformation in tops of the considered schedules also depend on a ratio f_{cc}/f_c, i.e.:

$$\varepsilon_{pl} = \varepsilon_{pl}\left(\frac{f_{cc}}{f_c}\right)^m \quad (11)$$

where m exponent>1. From here it is possible to write down a Eq. 12:

$$\varepsilon'_{pl} = \left(\varepsilon_{cl} - \frac{f_c}{E_c}\right)\left(\frac{f_{cc}}{f_c}\right)^m \quad (12)$$

The made statistical analysis showed that to the best coincidence to experimental data there corresponds m = 2.5 value. Then relative deformation of shortening in top of the chart of deformation of volume compressed concrete can be calculated on a equation:

$$\varepsilon_{cc1} = \varepsilon_{c1}\alpha_c^{2,5}\left[1 - \frac{f_c}{\varepsilon_{cl}E_c}\left(1 - \alpha_c^{-1,5}\right)\right] \quad (13)$$

For determination of sizes ε_{cl} and E_c it is convenient to use their dependences on a concrete class at compression $f_{ck,\ cube}$ received earlier 22. Relative deformation single-axis of the compressed concrete can be found on a equation:

$$\varepsilon_{c1} = 1.2 + 0.16\sqrt{f_{ck,\ cube}} \quad (14)$$

Value E_c (MPa) can be calculated on a Eq. 15:

$$E_c = \beta_{c\alpha}\left(17000 + 2600\sqrt{f_{ck,\ cube}}\right) \quad (15)$$

in which the coefficient $\beta_{c\alpha}$ considers influence on the size of the initial module of elasticity of concrete of a type of large filler and is accepted by equal:

$\beta_{c\alpha}$ = 1.0 at granite filler,
$\beta_{c\alpha}$ = 1.2 at basalt filler,
$\beta_{c\alpha}$ = 0.9 at filler from limestone,
$\beta_{c\alpha}$ = 0.7 at filler from sandstone

The analysis of a Eq. 13 shows that the size of deformation ε_{cc1} depends not only on the size of growth of durability of concrete at three-axis compression but also on durability at compression and deformation characteristics of the compressed concrete initial single-axis that is quite logical.

Adequacy to the received dependence is checked by results of comparison of skilled and calculated values of deformations ε_{cc1} which is executed in Table 1. The analysis of these results demonstrates that the Eq. 13 allows much more precisely dependence of EN 1992-1-1 to determine the size of relative deformation of shortening in chart top "σ_{cz}-ε_{cz}" concrete with hooped reinforcement. Though the maximum divergence between the theory and experience in one case made 20%, the coefficient of a variation of a vector of mistakes appeared equal 7.5%. In need of definition of limit relative deformation at the end of the chart of volume compressed concrete kernel ε_{cc2} it is possible to use the known dependence:

$$\varepsilon_{cc2} = \varepsilon_{c2}\frac{\varepsilon_{cc1}}{\varepsilon_{c1}} \quad (16)$$

in which ε_{c2} = 0.0035 relative deformation at the end of the chart of deformation single-axis the compressed concrete.

CONCLUSION

On the basis of the known provisions for mechanics of a solid body formulas for determining the extreme tension and relative deformation of shortening in chart "σ_{cz}-ε_{cz}" concrete with hooped reinforcement are received "σ_{cz}-ε_{cz}". Advantage of these formulas in comparison with earlier offered consists that they are received in the phenomenological way and therefore truly reflect influence of all major factors on durability and a strain capacity of concrete. Their practical use will allow increasing the accuracy and reliability of calculations of the bearing ability is non-central the compressed concrete filled steel tube columns with hooped reinforcement on nonlinear deformation model. Formulas for calculation of the initial module of elasticity of concrete E_c and deformation single-axis of the compressed concrete ε_{cl} simplify calculation for the actual strength and deformation characteristics accepted according to experiments.

All offered equations can successfully be applied also to calculation of the compressed designs with other options of hooped reinforcement.

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