Deformability of Volume-Compressed Concrete Core of Concrete Filled Steel Tube Columns

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Abstract. The application scale related to concrete filled steel tube columns is gradually expanding. Therefore, increasingly greater attention is given to their structural improvement. In particular, concrete filled steel tube columns can be manufactured with precompressed concrete core in order to improve the efficiency. However, known relationships used to calculate axial deformations of concrete filled steel tube structures are obtained empirically and unsuitable for precompressed elements. The formula for defining axial deformations of volume-compressed concrete core of concrete filled steel tube columns when achieving its strength is obtained in this study based on phenomenological approach. This formula allows carrying out accurate calculations when using structures both with precompressed and uncompressed concrete.

1. Introduction
Concrete filled steel tube columns (CFSTC) have good perspectives for expanding their practical application boundaries. They often resist high compressive forces resulting from external loads more effectively when compared to steel and reinforced concrete structures, providing remarkable material and financial resource savings [1-5]. Therefore, greater focus must be placed on the issues related to improving the structural concept of CFSTC and the methods of calculating their load-bearing capacity.

2. Relevance
Currently applied methods of calculating CFSTC load-bearing capacity have a number of significant disadvantages [6-10]. They are based on empirical relationships and, generally, have no way of considering any structural changes in CFSTC when they are improved. For example, transversely precompressed CFSTC are well known [11]. Precompression is achieved due to long-term pressing of concrete mix, which makes it possible to considerably increase the strength of the concrete core. This fact must be taken into account when performing calculations. For this purpose, more universal calculation methods relying on the main features of structural force resistance must be developed. The conducted analysis showed that the deformation model could serve as theoretical basis for such calculations [12]. Deformation calculations are based on material deformation diagrams. Once these diagrams can adequately represent the performance of structures, it becomes possible to describe their
stress strain behavior quite accurately at any stages of loading. The most complex challenge in this case is the analytical construction of the deformation diagram for volume-compressed concrete core of CFSTC, including the precompressed core. Since the actual concrete deformation diagram is curvilinear with ascending and descending sections, first of all it is necessary to pursue the more accurate calculation of its vertex coordinates. The problem of theoretical definition of volume-compressed concrete strength is successfully solved [13]. In this regard, the reliable determination of concrete core deformation at maximum stress is quite important.

3. Statement of the problem
Fairly large number of relationships was proposed to determine deformations of the concrete core of CFSTC $\varepsilon_{cc1}$ at the vertex of its deformation diagram [14-19]. One of the most reliable formulas proposed in the study [20] following the results of computerized finite element analysis of force resistance of compressed CFST elements appears as follows:

$$
\varepsilon_{cc1} = \varepsilon_{c1} \cdot 0.94 \exp \left( 3.9 \xi_p \right),
$$

where $\varepsilon_{c1}$ is the deformation of uniaxially compressed concrete at the vertex of deformation diagram; $\xi_p$ is the structural coefficient calculated using the following formula:

$$
\xi_p = \frac{f_y A_p}{f_c A + f_y A_p},
$$

where $f_c$ is the strength of uniaxially compressed concrete; $f_y$ is the yield strength of the steel shell; $A$ and $A_p$ are the cross-section areas of concrete core and steel shell.

The analysis of reported relationships testifies that they are all obtained based on the processing of experimental data. However, empirical formulas represent specific conditions of conducted research. For this reason, their application scope is limited. For precompressed CFSTC, as an example, their own empirical relationships need to be obtained.

The purpose of this study is to obtain a universal relationship for determining deformation at the vertex of the volume-compressed concrete deformation diagram. This relationship must take into account the basic principles of structural force resistance and ensure high accuracy of calculations when using both precompressed and uncompressed concrete.

4. Theoretical part
The formula for defining deformation $\varepsilon_{cc1}$ at the vertex of the volume-compressed concrete deformation diagram can be obtained following the comparison between this diagram and the corresponding “$\sigma - \varepsilon$” curvilinear relationship for uniaxially compressed concrete (figure 1). When using pressed concrete, the coordinates $f_{cp}$ and $\varepsilon_{cp}$ of its deformation diagram vertex for uniaxial compression conditions are calculated first. According to the proposals made in the study [21], the following relationships are used for this purpose:

$$
f_{cp} = f_c (1 + 0.3 \alpha \sqrt{\rho});
$$

$$
\varepsilon_{cp} = 0.0012 + 0.00016 \sqrt{f_{cp}},
$$

where $f_c$ is the compressive strength of original (unpressed) concrete; $\alpha \leq 1$ is the coefficient depending on concrete composition;
$P$ is the value of effective compression pressure.

$P$ and $f_{cp}$ values are substituted in formulas (3) and (4) in MPa.

![Deformation curve](image)

**Figure 1.** Deformation curves for uniaxially compressed original concrete (1), pressed concrete (2) and volume-compressed (3) concrete core.

The study [11] shows that there is no pressure applied by the steel shell to the concrete core of CFST when the loading levels are low. In this case, equal tangent modulus of elasticity is assumed for curves 2 and 3 represented in figure 1, which is calculated using the following formula:

$$E_{cp} = \beta_c \left( 56000 - 122000 \sqrt{f_{cp}} \right),$$

where $\beta_c$ is the adjustment coefficient taking into account the influence of the coarse aggregate type [12] (for crushed stone concretes $\beta_c = 1$).

Total deformation $\varepsilon_{cp}$ can be represented as the sum of elastic $\varepsilon_{el}$ and plastic $\varepsilon_{pl}$ components:

$$\varepsilon_{cp} = \varepsilon_{el} + \varepsilon_{pl}. \quad (6)$$

The elastic component represents a function of volume-compressed concrete strength $f_{cp}$ and its tangent modulus of elasticity $E_{cp}$:

$$\varepsilon_{el} = f_{cp} / E_{cp}. \quad (7)$$

Apparently, the elastic components of total deformations for uniaxially and volume-compressed concrete depend on the corresponding strengths in direct proportion. It is logical to assume that the plastic deformation component of volume-compressed concrete $\varepsilon_{pl}$ is associated with equivalent deformation of uniaxially compressed concrete $\varepsilon_{pl}'$ based on the following relationship:

$$\varepsilon_{pl} = \varepsilon_{pl}' \left( \frac{f_{cp}}{f_{cp}'} \right)^m, \quad (8)$$

where the exponent of power $m > 1$. 


Plastic deformation component $\varepsilon_{pl}$ at the diagram vertex for uniaxially compressed concrete is determined from the following formula:

$$\varepsilon_{pl} = \varepsilon_{cp1} - \varepsilon_{el}.$$  

(9)

Based on relationships (6), (7) and (9), we obtain the following formula:

$$\varepsilon_{cp} = \frac{f_{cp}}{E_{cp}} + \left( \varepsilon_{cp1} - \frac{f_{cp}}{E_{cp}} \right) \left( \frac{f_{cp}}{f_{cp}} \right)^m.$$  

(10)

The performed statistical analysis showed that the value of $m \approx 2.5$ represented the best agreement with experimental data.

Strength of volume-compressed pressed concrete can be calculated using the formula obtained in the study [11]:

$$f_{cp} = f_{cp} \left\{ 1 + 0.5\sigma \bar{\sigma} + \frac{\bar{\sigma} - 2}{4} + \left[ \frac{\bar{\sigma} - 2}{4} + B\sigma \right]^{1/2} \right\},$$  

(11)

where $\bar{\sigma}$ is the relative value of radial stress in the concrete core in the limit state of CFSTC $\bar{\sigma} = \sigma_{cr} / f_{cp}$;

$B$ is the experimentally determined material coefficient ($B = 10.4$ and $7.7$ for heavyweight and fine-grained concrete, respectively).

The following formula for determining the relative value of radial stress is theoretically obtained:

$$\bar{\sigma} = 0.48\exp(-1.5/B)\xi^{0.8},$$  

(12)

where $\xi$ is the structural coefficient calculated using the formula:

$$\xi = \frac{f_{cp} A_p}{f_{cp} A}.$$  

(13)

5. Comparison of theory with experiments

Experimental deformation values $\varepsilon_{exp}^{(1)}$ of short centrally compressed CFSTC are compared with calculated values $\varepsilon_{exp}^{(1)}$ and $\varepsilon_{exp}^{(10)}$ determined from formulas (1) and (10), as shown in the table 1. Steel shell diameter and wall thickness for laboratory samples are presented in table column $d \times \delta$.

Experimental data are assumed based on the results of the study [11].

The results of this comparison indicate that the accuracy obtained by calculating concrete core deformations using the formula (10) is perfectly acceptable for practical purposes. The average value of $\varepsilon_{exp} / \varepsilon_{exp}^{th}$ for 10 series of experimental samples (each series includes 3 samples) is 0.98. The mean square deviation $\sigma$ equals 0.12, which should be accepted as a good result when comparing experimental and theoretical deformations. It should be noted that the proposed formulas were also used for samples without precompression assuming that $P = 0$. When using the formula (1), the comparison results are notably worse. For precompressed samples, the comparison result is unsatisfactory. However, even without taking precompressed samples into account, the average value of $\varepsilon_{exp} / \varepsilon_{exp}^{th}$ equals 0.94 when $\sigma = 0.26$. 


### Table 1. Comparison between calculated and experimental deformations of CFSTC concrete core.

| № | Series | $d \times \delta$ (mm) | $f_c$ (MPa) | $P$ (MPa) | $f_{yp}$ (MPa) | $N_u$ (kN) | $\varepsilon_{exp} \times 10^5$ | $\varepsilon_{exp} / \varepsilon_{(1)}$ | $\varepsilon_{exp} / \varepsilon_{(10)}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | H1.0 | 150x1.5 | 23.4 | 0 | 295 | 950 | 810 | 1.21 | 1.04 |
| 2 | H2.0 | 153x3 | 22.7 | 0 | 295 | 1473 | 1500 | 1.11 | 1.11 |
| 3 | H3.0 | 159x6 | 25.1 | 0 | 295 | 2040 | 1700 | 0.67 | 1.04 |
| 4 | H4.0 | 219x6 | 23.7 | 0 | 290 | 3020 | 1450 | 0.77 | 1.12 |
| 5 | O1.3 | 150x1.5 | 23.4 | 3.0 | 295 | 1282 | 1900 | 3.64 | 1.05 |
| 6 | O2.1 | 153x3 | 21.3 | 1.2 | 295 | 1200 | 2100 | 1.85 | 0.88 |
| 7 | O2.2 | 153x3 | 25.1 | 1.8 | 295 | 1400 | 2450 | 2.54 | 1.06 |
| 8 | O2.3 | 153x3 | 22.7 | 3.0 | 295 | 1410 | 2400 | 2.45 | 0.83 |
| 9 | O3.3 | 159x6 | 25.1 | 2.9 | 295 | 2200 | 2600 | 1.38 | 0.80 |
| 10 | O4.3 | 219x6 | 23.7 | 2.9 | 290 | 3288 | 2550 | 1.85 | 0.89 |

**Average value**

| | | | | | | | $\sigma$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1.75 | 0.98 | 0.92 | 0.12 |

### 6. Conclusions

Based on phenomenological approach, formula for calculating axial deformations of volume-compressed concrete core of CFSTC when achieving its strength is obtained. This formula allows carrying out accurate calculations when using structures both with precompressed and uncompressed concrete.

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