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EXPERIMENTAL ESTIMATION OF LOAD-CARRYING CAPACITY OF CIRCULAR, SQUARE AND RECTANGULAR CFTS COLUMNS

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ЕКСПЕРИМЕНТАЛЬНА ОЦІНКА НЕСУЧОЇ ЗДАТНОСТІ КРУГЛИХ, КВАДРАТНИХ І ПРЯМОКУТНИХ СТАЛЕБЕТОННИХ КОЛОН

Purpose. Determining the nature of deformation developing inside the concrete core and on the surface of steel casing at different loading stages using the strain measurement method. Studying features of strain-stress behavior of concrete-filled steel tube columns (CFST) of different cross-sections under axial compression; comparison of theoretical and experimental data of concrete-filled steel tube columns by their load-carrying capacity.

Methodology. The method is based on detection of contact interaction between the concrete core performing under 3D stress and the casing of the steel concrete element at short-term static loading.

Findings. Strength and load-carrying capacity of CFST elements are assessed. The obtained results allow beginning experimental studies on CFST constructions of various lengths and cross-sections using not only exterior, but also interior gauges in order to access the strain-stress behavior of constructions.

Originality. New experimental data on the regularities of performance and destruction of CFST columns of various cross-sections were obtained.

Practical value. The proposed methods for structural design enable both producing efficient composite structures that perform under compression and bending and designing load-carrying elements for industrial facilities.

Keywords: *concrete-filled steel tube columns (CFST), load carrying capacity, axial compression, concrete core, steel case, the 3D depth gauge rosette, deep strain measurement method*

Introduction. At present, there are a number of recognized approaches for estimation of the load-carrying capacity of CFST structures under axial compression, each being based on the initial assumptions underlying the estimation formulas. S. Morino [1] evaluated the compressive strength of short square CFST columns and identified the dependence of the size and shape of the cross-section on the load-carrying capacity. D. Petrenko [2] provided the comparative analysis of existing methods for CFST load-carrying capacity calculation under axial compression proposed by domestic and foreign researches. G. Vatulia [3] described the method of CFST column load-carrying capacity calculation with consideration of physical nonlinearity of materials, geometric nonlinearity of the confinement and the effect of the gain in core strengthening. The method uses a step iteration algorithm, which involves analytical dependencies and the ultimate element simulation method. G. Litivinskyi [4] considered three different types of stress-strain state of CFST elements, and determined conditions of the limit state approach for each type. A. Krishan [5] presented the results of the FEM analysis of CFST columns with square cross-section and various tube thicknesses. R. Kanishchev [6] analyzed the influence of friction between the steel shell and the concrete core on the local buckling of composite structures using the ABAQUS software. The purpose of experimental studies is investigation of the nature of deformations developing inside the concrete core and on the surface of the steel casing at different loading stages using the depth strain measurement method.

Analysis of the recent research and publications. Today, there are a few recognized approaches to estimation of the load-carrying capacity of CFST structures under axial compression. However, lack of the shared opinion on the methods for designing and strength analysis under force impact prevents the large-scale implementation of the CFST structures in the domestic construction practice.

Earlier, a method was developed for estimation of axial compression strength for CFST elements of a rectangular cross-section, based on the opening of the contact between the casing and the core performing under 3D stress with field-variable deformation parameters [2]. It was proved that the contact interaction between the casing and the core at the corners of cross-sections can be taken into account for evaluation of the load carrying capacity. The most effective width-to-length ratios of the cross-sections and casing thickness for the most efficient performance of concrete were found. The consistency of the experimental findings and theoretical data is shown. It is noted that reinforcement of concrete with the outer casing increases its strength, creates better performance conditions under load, improves the resistance of concrete to the action of aggressive media, and reduces shrinkage and creep strains.

Objective of the study is investigation of the features of the stress-strain state of CFST columns of various cross-sections under axial compression; comparison of theoretical and experimental data of their load-carrying capacity; assessment of the consistency of the obtained findings with the results of other authors.

In accordance with the approved experimental procedure, three sample series were manufactured, namely:

- circular CFST – concrete-filled steel tube, C16/20 concrete, yield strength of the casing $\sigma_y = 330$ MPa, geometrical dimensions $D = 102$ mm, $t = 3$ mm, $h = 500$ mm;
- square CFST – concrete-filled steel column of the square cross-section, C16/20 concrete, yield strength of the casing $\sigma_y = 220$ MPa, geometrical dimensions $a =$ 100 mm, $t = 2$ mm, $h = 500$ mm;
- rectangular CFST – concrete-filled steel column of the rectangular cross-section, C16/20 concrete, yield strength of the casing $\sigma_y = 220$ MPA, geometrical dimensions $a = 100$ mm, $b = 150$ mm, $t = 2$ mm, $h = 500$ mm.

Measuring equipment and its positioning. A 3D depth gauge rosette was installed inside the samples for more detailed investigation of longitudinal and lateral deformations developing in the concrete core, concrete destruction mechanism, as well as for taking into account the squeeze reduction effect caused by performance of the steel casing. The depth sensor was placed into the casing during concreting.

The depth strain gauges were manufactured according to the procedure as follows. A 2 mm thick layer of the jointing compound was deposited into the dismountable metal mold (Fig. 1, *a*), with a cell for manufacturing of each gauge 50×10×4 mm lubricated with grease. The jointing compound consisted of the mixture of BF-2 glue with cement at the ratio 1:2. After curing (within 24 hours), BX120-20AA-X strain gauges were glued onto it (Fig. 1, *b*), on which, in its turn, another layer of the jointing compound was applied. Only the gauge heads with leadouts remained free. After the wires were soldered to the leadouts, this part of the gauge was polished as well. After complete curing of the jointing compound within 24 hours, the gauges were removed from the mold (Fig. 1, *c*). Then a 3D depth gauge rosette was manufactured (Fig. 1, *d*). The sequence for manufacturing a depth gauge rosette is shown in Fig. 1 [7].

The wires form the gauges were led out through the top of the columns or through the apertures on the sides of the columns made at a distance of $^1/_4$ of height. The diameter of the circular apertures was $2t$ (Figs. 2, *a, b*), the transverse apertures had the width t and length $2t$ (Figs. 2, *c, d*), the general view of the apertures is shown in Fig. 2.

The apertures had no material effect on the load-carrying capacity of the CFST columns. However, it should be noted that circular apertures proved to be more appropriate for leading the wires out, since they did not change their geometrical shape at every loading stage, while the transverse slits squeezed the wire causing the

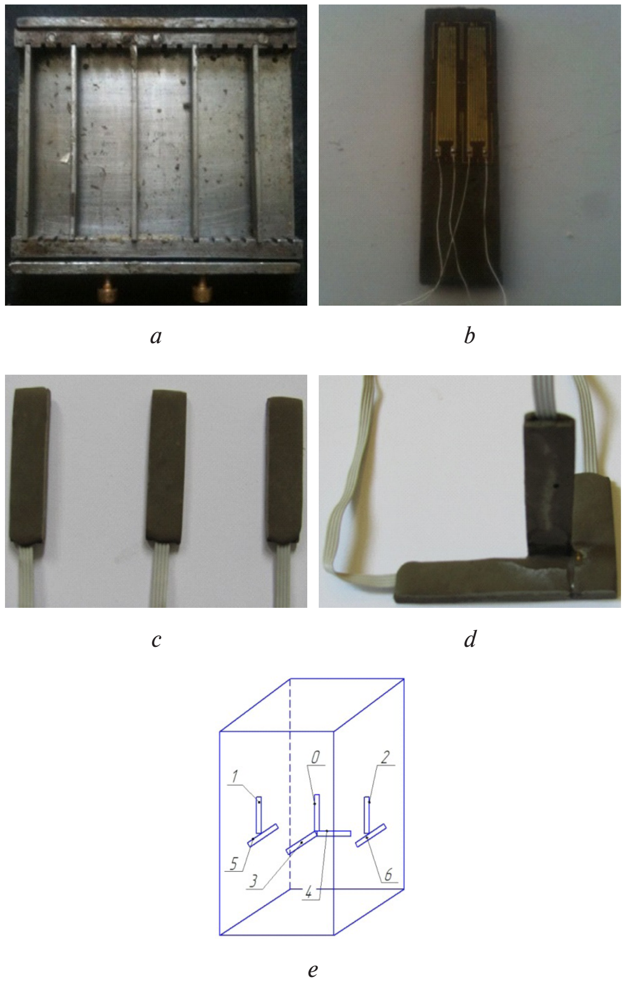


Fig. 1. Sequence for manufacturing a depth gauge rosette and the gauge layout in the CFST columns:
a – gauge casing; b – resistive strain gauges; c – depth gauge; d – depth gauge rosette; e – gauge layout

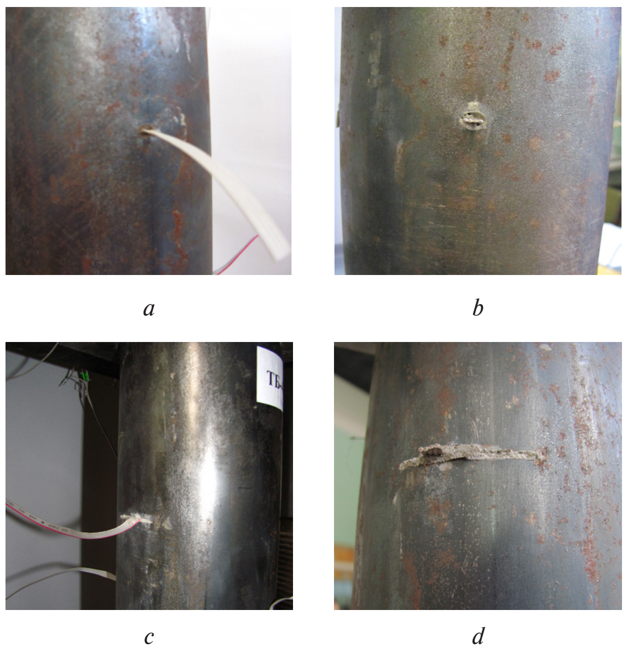


Fig. 2. General view of the apertures for wire lead off:
a, b – circular apertures; c, d – rectangular apertures

loss of the signal from the gauge at the final loading stages. The choice of the shape, size and location of the apertures along the height of the CFST column was based on the findings of the experiments presented in [8].

Experimental study. The CFST columns were tested at IP-2000 hydraulic press in the laboratory of the Structural Mechanics and Hydraulics Department of the Ukrainian State University of Railway Transport.

Geometrical parameters were determined for the tested samples before the experiment. For the columns of the circular cross-section, the reduced axial moment of inertia $I_{red} = 146$ cm^4, the reduced cross-section area A_{red} = 14.81 cm^2, the reduced flexibility $\lambda_{red} = 17$ were determined. For the columns of the square cross-section they were: $I_{red} = 214$ cm^4, $A_{red} = 19.36$ cm^2, $\lambda_{red} = 16$. Respectively, for the columns of the rectangular cross-section they were: $I_{red} = 634$ cm^4, $A_{red} = 27.36$ cm^2, $\lambda_{red} = 11$. Due to the structural features, the base plates of the hydraulic press provided the hinge support of the columns.

Axial loading on the combined cross-section was applied to the samples. During the test, longitudinal and transverse deformations were measured. For this purpose, BX120-10AA-X strain gauges were glued on the sides of the columns in the longitudinal and transverse directions. Depth gauges in the form of a 3D rosette were installed in the samples during concreting. The gauge layout is shown in Fig. 1, *e* [8].

The strain gauge readings were recorded using VNP-8 strain gauge scanner recorder. The load was applied in 20 kN increments within the range from 0 to 0.9 × $N_{pl,Rd}$, each loading stage lasting at least 5 min. $N_{pl,Rd}$, is an estimated value of the load-carrying capacity of the CFST column along the axial compression force at the plastic stage which is determined using the formula

$$N_{pl,Rd} = \eta_a A_a f_{yd} + A_c f_{cd}\left(1 + \eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right), \qquad (1)$$

where η_a, η_c are coefficients for squeeze reduction of concrete; A_c, A_a are cross-sectional areas of concrete and the steel casing; f_{yd} is design value of the yield strength of structural steel; f_{cd} is design value of cylinder compressive strength of concrete; d is diameter of the steel casing; t is wall thickness of the steel pipe; f_{ck} is characteristic value of cylinder compressive strength of 28 days old concrete; f_y is rated value of the yield strength of structural steel.

The metering readings were recorded at every loading stage. All samples were brought to destruction. The exterior of the CFST columns before testing is shown in Fig. 3.

During the experiment, two forces, which correspond to different criteria of the loss of load-carrying capacity, were recorded. The first force (N_1) corresponded to reaching the yield strength limit of the casing steel, while the second force (N_2) was the maximum load value which the sample could stand. According to the regulatory documents, the design of constructions should be based on the limit states of the first and second groups. Different criteria of suitability for use of the construction can be used depending on the construction type and purpose. In most cases, operation of CFST columns is limited with

a *b* *c*

Fig. 3. The exterior of the CFST columns before testing: a – circular CFST; b – square CFST; c – rectangular CFST

the force N_1. Quite significant difference between forces N_1 and N_2 suggests high reliability of the CFST elements.

The experience of the previous studies shows that a complicated correlation between the steel casing and the concrete core occurs in the CFST element during loading. Use of the 3D rosette of the depth gauge enabled comparison of the value and nature of development of deformations inside the concrete core and outside the steel casing. According to the findings of the experiments, the difference between the deformations inside and outside the CFST column is insignificant at the initial loading stages. The dependencies of longitudinal and transverse deformations on the load are practically linear or close to such. Therefore, a conclusion can be made on the joint performance of the steel casing the concrete core. Further, the linearity is broken at load of (0.4–0.5) × $N_{pl,Rd}$. The intermediate stage of performance of the CFST element begins, at which the identical longitudinal deformations ensure the joint performance of two components. Under load of 0.8 × $N_{pl,Rd}$ longitudinal and transverse deformations are developing intensively both inside and outside the CFST column. More intense transverse extension of the concrete core begins at this stage. As the core extends it begins to compress the casing walls, causing the significant change in performance of the components of the CFST element. Since the steel casing prevents the excessive concrete extension, the casing effect occurs. The concrete core is under 3D pressure; as a result, it can accept increased loads.

The CFST columns after the test are shown in Fig. 4. It should be noted that the test samples did not lose their load-carrying capacity instantaneously. Although considerable deformations were caused to them, they sustained the load for a long time.

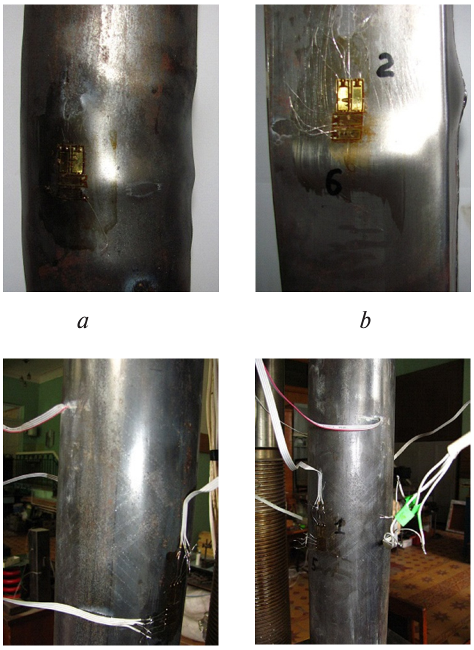
Such behavior of the samples is associated with the transition to the plastic stage of performance. At this stage, intensive cracking occurs in the concrete core.

In the places of destruction of the concrete core, a local loss of stability of the casing wall takes place together with the appearance of buckles. The irreversible destruction of the concrete core and further increase in the load on the column leads to the appearance of significant radial stresses in the column casing. Further expansion of the concrete core leads to emergence of a critical internal lateral pressure. As a result, the maximal tangential (tensile) stresses occur in the case. It causes the longitudinal rupture of the casing.

Test findings. Occurrence of the Chernov-Luders lines on the steel casing, which indicate the beginning of the steel fluidity, is also a characteristic phenomenon at the last stage of performance of the CFST element. During the experiment, the occurrence of the Chernov-Luders lines was recorded only for circular steel columns (Figs. 5, *c, d*). The appearance of buckles in the middle section of the columns (Figs. 5, *a, b*) indicates a partial (local) destruction of the concrete core and, as a result, the local loss of stability of the casing.

a *b* *c*

Fig. 4. Concrete-filled steel tube columns after testing:
a – circular CFST; b – square CFST; c – rectangular CFST



a *b*

c *d*

Fig. 5. The nature of destruction of the samples:
a, b – buckles in the columns of the experimental series; c, d – Chernov-Luders lines, circular CFST

After disassembly of the casing of the CFST columns, the nature of destruction of the concrete core was analyzed. The appearance of the concrete core and steel casing after disassembly is shown in Fig. 6. The figure shows that in the places of partial (local) destruction of the concrete core, the concrete is detached from the casing, at this time stress is critically redistributed between the components of the CFST element, eventually causing the lost of stability of the steel casing and appearance of buckles.

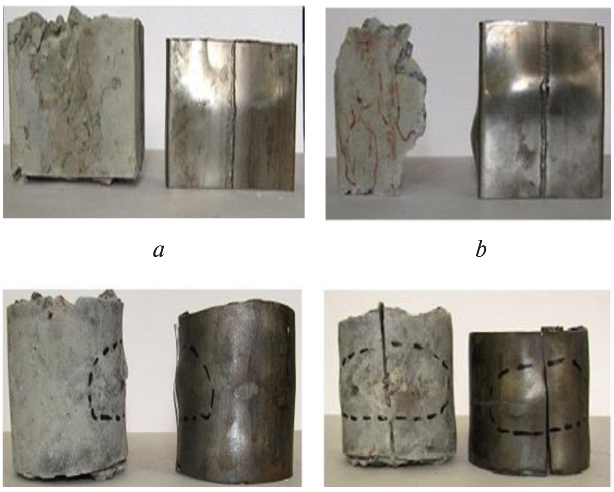
The tests of the CFST columns provided the data about the nature of the development of longitudinal and transverse deformations on the surface of the steel casing and inside the concrete core at various loading stages. The experimental studies have revealed the effect of the geometric dimensions and the physical and mechanical properties of the materials used on the load-carrying capacity and deformability of the CFST columns.

A 3D strain gauge rosette was designed that allows measuring deformations in three mutually perpendicular planes to reveal the deformation mechanisms of CFST structures at every loading stage. The obtained data on the relative deformations confirm the theory of the joint performance of the concrete core and the steel casing.

The performed experimental studies confirm that the obtained design of a depth sensor can be used to reveal the deformation mechanisms of concrete structures at every loading stage.

The obtained results enable to proceed to experimental studies on CFST structures of different lengths and cross-sectional shapes using not only external, but also depth sensors for estimating the stress-strain state of structures, which is necessary for further optimization of cross-sections of combined constructions.

Verification of the obtained findings. After the experiment was carried out, the obtained values of the load carrying capacity of the CFST columns were verified by comparing the findings with the data of theoretical estima-



a *b*

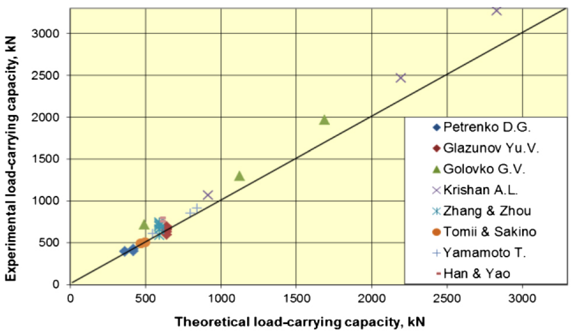
c *d*

Fig. 6. The appearance of the concrete core and steel casing after disassembly of the columns:
a – rectangular CFST; b –square CFST; c, d – circular CFST

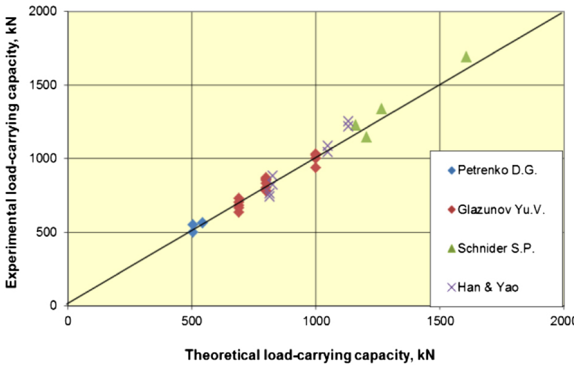
tion using the existing methods [2]. The results of comparison of the experimental findings with the data of estimation using the method suggested by the Ukrainian State University of Railway Transport are shown in Fig. 7. The performed analysis suggests that the assessment of the load carrying capacity based on the opening of the contact between the casing and the core performing under 3D stress state with field-variable deformation parameters describes relevantly the stress-strain state of a CFST element. The empirically obtained values are not used to determine the load carrying capacity.

Conclusions. The experimental and theoretical studies described in the article enabled to draw the following conclusions:

1. A 3D strain gauge rosette has been designed that allows measuring deformations in three mutually perpendicular planes to reveal the deformation mechanisms of CFST structures at every loading stage.



a



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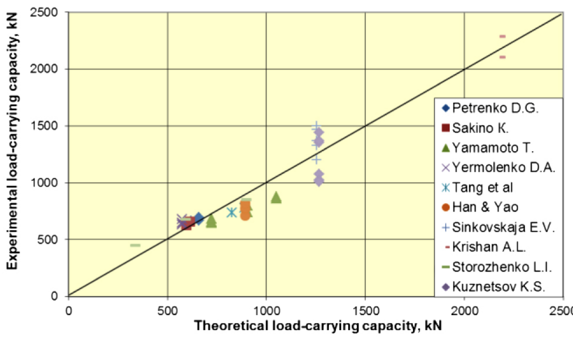

c

Fig. 7. The results of comparison of the experimental studies with the considered methods:
a – square CFST; b – rectangular CFST; c – circular CFST

2. It is found that the preferred aperture for wire output from the measuring devices is circular. The circular aperture retains its original shape at every loading stage, unlike the rectangular cross slits, which close at the final loading stages squeezing the wires and causing the loss of the signal from the sensor.

3. The consistency of the experimental findings and the data of theoretical study was checked by comparison of the results. The maximum error does not exceed 10%.

4. The results of comparison of our experimental findings with the results of estimation using the methods of other authors showed good convergence, within 10%. The proposed method for assessment of the stress-strain state of a CFST structure can be used for columns of different cross-sections.

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Мета. Встановлення характеру розвитку деформацій всередині бетонного ядра й на поверхні сталевої оболонки на різних етапах навантаження з використанням методу тензометрії. Вивчення особливостей напружено-деформованого стану сталебетонних колон різного поперечного перерізу при осьовому стисненні, зіставлення теоретичних і експериментальних даних сталебетонних колон по несучій здатності.

Методика. Заснована на розкритті контактної взаємодії між бетонним ядром, що працює в умовах об'ємного напруженого стану, та обоймою сталебетонного елементу при короткочасному статичному навантаженні.

Результати. Дана оцінка потенціалу міцності й несучої здатності сталебетонних елементів. Отримані результати дозволяють перейти до експериментальних досліджень сталебетонних конструкцій різної довжини та форми поперечного перерізу з використанням не тільки зовнішніх, але й глибинних датчиків для оцінки напружено-деформованого стану конструкцій.

Наукова новизна. Отримані нові експериментальні дані закономірностей роботи й руйнування сталебетонних колон різного поперечного перерізу.

Практична значимість. Запропоновані методики розрахунку опорних конструкцій забезпечують можливість створення ефективних сталебетонних конструкцій, що працюють на стиснення та згин, та дозволяють виконувати проектування несучих елементів споруд промислового призначення.

Ключові слова: *сталебетонні колони, несуча здатність, осьове стиснення, бетонне ядро, сталева обойма, тривимірна розетка глибинного датчика, метод глибинної тензометрії*

Цель. Установление характера развития деформаций внутри бетонного ядра и на поверхности стальной оболочки на разных этапах нагружения с использованием метода тензометрии. Изучение особенностей напряженно-деформированного состояния сталебетонных колонн различного поперечного сечения при осевом сжатии, сопоставление теоретических и экспериментальных данных сталебетонных колонн по несущей способности.

Методика. Основана на раскрытии контактного взаимодействия между бетонным ядром, которое работает в условиях объемного напряженного состояния, и обоймой сталебетонного элемента при кратковременном статическом нагружении.

Результаты. Дана оценка потенциала прочности и несущей способности сталебетонных элементов. Полученные результаты позволяют перейти к экспериментальным исследованиям сталебетонных конструкций различной длины и формы поперечного сечения с использованием не только наружных, но и глубинных датчиков для оценки напряженно-деформированного состояния конструкций.

Научная новизна. Получены новые экспериментальные данные закономерностей работы и разрушения сталебетонных колонн различного поперечного сечения.

Практическая значимость. Предложенные методики расчета опорных конструкций обеспечивают возможность создания эффективных сталебетонных конструкций, которые работают на сжатие и изгиб, и позволяют выполнять проектирование несущих элементов сооружений промышленного назначения.

Ключевые слова: *сталебетонные колонны, несущая способность, осевое сжатие, бетонное ядро, стальная обойма, трехмерная розетка глубинного датчика, метод глубинной тензометрии*

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