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THE STIFFNESS OF STEEL-PLATE COMPOSITE STRUCTURES FOR SHORT-TERM LOADS

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Abstract: The features of the behavior of steel-plate composite walls for static short-term loads are considered. Based on the analysis of modern technical and regulatory documentation, the rationale for the chosen research topic is given. A review of the literature is performed, and the features of development are noted. Description and features of the experimental structures are presented. Analytical and numerical calculations of structures for central compression have been performed. A description of the calculation complex is presented; a description of numerical models, features of their construction and calculation are given. Calculation results are presented – features of changes in structural rigidity during load application. The general types of experimental models tested for central compression are presented, and the destruction pattern is shown. The analysis of the experimental data obtained and their comparison with analytical and numerical calculations are performed. An assessment of the features of modeling steel-plate composite structures in software complexes is given.

Keywords: concrete, steel, reinforced concrete, composite steel and concrete structure, steel-plate reinforcement, steel-plate composite (SC) walls, adhesion, stud

ЖЕСТКОСТЬ СТАЛЕЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ С ЛИСТОВЫМ АРМИРОВАНИЕМ ПРИ ДЕЙСТВИИ КРАТКОВРЕМЕННЫХ НАГРУЗОК

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Аннотация: Рассмотрены особенности работы сталежелезобетонных конструкций с листовым армированием при воздействии кратковременных нагрузок. Дано обоснование выбранной темы исследования на основе анализа современной технической и нормативной документации. Выполнен обзор литературы, отмечены особенности развития вопроса. Представлено подробное описание и особенности исследуемых конструкций. Выполнены аналитические и численные расчеты конструкций на центральное сжатие. Представлено описание расчетного комплекса; дано описание численных моделей, особенности их построения и расчета, приведены результаты расчетов – характер изменения жесткости конструкций в процессе приложения нагрузки. Представлены общие виды экспериментальных моделей, испытанных на центральное сжатие, приведена картина разрушения. Выполнен анализ полученных экспериментальных данных, их сравнение с аналитическими и численными расчетами. Дана оценка особенностей моделирования сталежелезобетонных конструкций с листовым армированием в программных комплексах.

Ключевые слова: бетон, сталь, железобетон, сталежелезобетонная конструкция, листовое армирование, композитные стены с листовым армированием, сцепление, анкерное устройство

INTRODUCTION

It is essential to properly determine longitudinal deformations and stiffnesses of the elements in the walls of high-rise buildings, where the elements are subjected to significant compression forces under the action of long-term and short-term loads. The influence of longitudinal deformations in multi-storey and high-rise buildings can affect the drift of the frame cells, which should have deformations no greater than those specified in SP 20.13330 and clause 8.2.4.16 of SP 267.1325800 “High rise buildings and complexes. Design rules” which allow displacements of 1/300 of the height of this building.

Cell drift is calculated by the formula $f_1/h_s + f_2/l$, where f_1 and f_2 are the horizontal and vertical displacement, respectively, and h_s and l are the height of the cell and its span (Figure E.3 in SP 20.13330 "Loads and actions"). Since there is no experimentally and theoretically substantiated methodology for calculating the stiffness of steel-reinforced concrete (composite) structures with sheet reinforcement, as well as the actual experience of building construction using such systems, it is practically impossible to reliably determine the values of controlled vertical and horizontal deformations of the entire building frame and its individual elements that are permissible for a particular structure.

The papers [1, 2] present the results of tests of eccentrically compressed steel-reinforced concrete elements with a percentage of longitudinal reinforcement from 3 to 20, made with concrete of compressive strength class up to B90 and fiber concretes. These articles, as well as in [3], provide the results of tests and calculations for the first group of limit states in detail. The paper [4] analyzes domestic and foreign experience in studying the performance of steel-reinforced concrete structures in eccentric compression. The issues of structural performance in compression are also considered in [5, 6].

Extensive studies of steel-reinforced concrete structures with sheet reinforcement have been carried out by foreign authors in Japan [7, 8], South Korea [9...14] and China [15...17]. In these studies, a comprehensive assessment of the performance of structures with sheet reinforcement was performed, as well as experimental and theoretical results and design recommendations were given.

There is an important description of the features of modeling and calculation of the considered structures in the software complexes [18] in addition to the available experimental and theoretical information on the operation of structures, discussed above. In calculations of the frames of unique buildings and structures involving steel-reinforced concrete components, certified software packages that implement the finite element method are used. Composite columns and walls, as a rule, are modeled by beam and shell finite elements of reduced stiffness, less often - by solid finite elements for separate nodes. The capability of such an approach requires a certain justification, which is presented in this paper based on the experimental study of R&D “Experimental and numerical studies for the development of recommendations for the calculation, design, construction and erection of steel-reinforced concrete structures with external sheet reinforcement...”. The results of studies devoted to the assessment of stiffness and deformability of high-strength concrete [19, 20] were taken into account when analyzing the obtained data.

The presented experimental and theoretical data were obtained for structures with the percentage of reinforcement - 2.5...5.0 % and are correct provided that the design requirements for sheet reinforcement and stad-bolts are met.

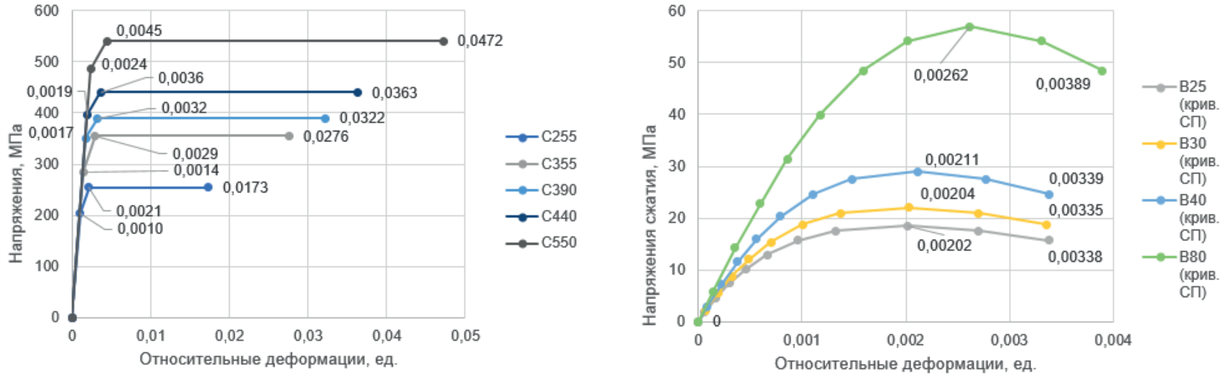
METHODS

Large-scale tests of steel-reinforced concrete structures for central and eccentric compression have been carried out in the laboratories of the V.A. Kucherenko Central Research Institute of Steel and Concrete Structures. Detailed test results are given in [1, 2].

The paper [21] presents a methodology for calculating the strength of steel reinforced concrete compressed-bending elements (columns) using a nonlinear deformation model, which corresponds to the modern norms for the calculation of reinforced concrete structures - SP 63.13330. The limit state of the structure is determined by reaching the limit longitudinal deformations of concrete, reinforcement and rigid reinforcing steel. The limiting value of longitudinal strains of concrete $\varepsilon_{b,ult}$ is taken depending on the ratio of concrete edge strains $\varepsilon_1$and ε_2 by linear interpolation from -0.002 at $\varepsilon_1/\varepsilon_2 = 1$ to -0.0035 at $\varepsilon_1/\varepsilon_2 \leq 0$ (where ε_2 is the concrete strain at the most compressed edge with the minus sign). In this case, the resistance of the tensile concrete is not taken into account in the calculation. The limit value of the strain of the core steel and tensile reinforcement is assumed to be 0.025.

In current standards for the calculation of steel structures SP 16.13330 “Steel Structures”, a generalized diagram of steel deformation under load action is given for various steels. Figure 1 a, b shows the dependences “stress-relative strain” for steels from C255 to C550 in accordance with the characterisitic parameters. The ultimate strain of the steel should be taken corresponding to the end of the yield point. For steels with yield point from 255 to 550 MPa, the value of ultimate strain will vary from 0.017 to 0.047 respectively. From the above, it is obvious that it is incorrect to take the ultimate strain as 0.025 (as for rebar), irrespective of the yield strength of the steel. Since for steels C235, C245, C255 this value will correspond to the steel performance in the self-strengthening section (above the yield strength), and for steels C355 and above - will not be fully utilized plastic properties of steel.

For proper accounting of concrete strains in steel-reinforced concrete structures, it is possible to adopt several variants of diagrams of its work under load. In modern standards it is allowed to use two- and three-line diagrams (clauses 6.1.19...6.1.21 in SP 63.13330), as well as curvilinear diagram of concrete deformation (Appendix D in SP 63.13330), which is developed on the basis of the studies summarized in the monograph by Academician N.I. Karpenko [22...24]. Also, Prof. G.V. Murashkin and co-authors developed and presented in [25, 26] an exponential variant of the concrete deformation diagram. In addition to the above mentioned, it is possible to use the curvilinear diagram given in the European Union standards (Eurocode 2). In this paper, we will limit ourselves to the consideration of the three-linear (Figure 1 c) and curvilinear (Figure 1 d) diagrams, since by now they are reflected in the normative documents (SP 266.1325800.2014 “Composite steel and concrete structures. Design rules”, SP 63.13330.2018 ”Concrete and reinforced concrete structures. General provisions"), implemented in finite element software systems, tested by a large amount of experimental data and many years of experience in the design and operation of real buildings and structures.



a)

b)

Figure 1. Deformation diagrams of steel and concrete: a - for steel, b - curvilinear for concrete

The theoretical stiffness of a structure subjected to compression is calculated as follows: the reduction coefficients of reinforcement and sheet steel to concrete are calculated, and then the area of the reduced cross-section A_{red} is determined.

$$\alpha_{st} = \frac{E_{st}}{E_b}, \alpha_s = \frac{E_s}{E_b}, \tag{1}$$

$$A_{red} = A_b + A_{st}\alpha_{st} + A_s\alpha_s \tag{2}$$

where A_b, A_{st}, A_s are the areas of concrete, sheet and bar reinforcement, respectively.

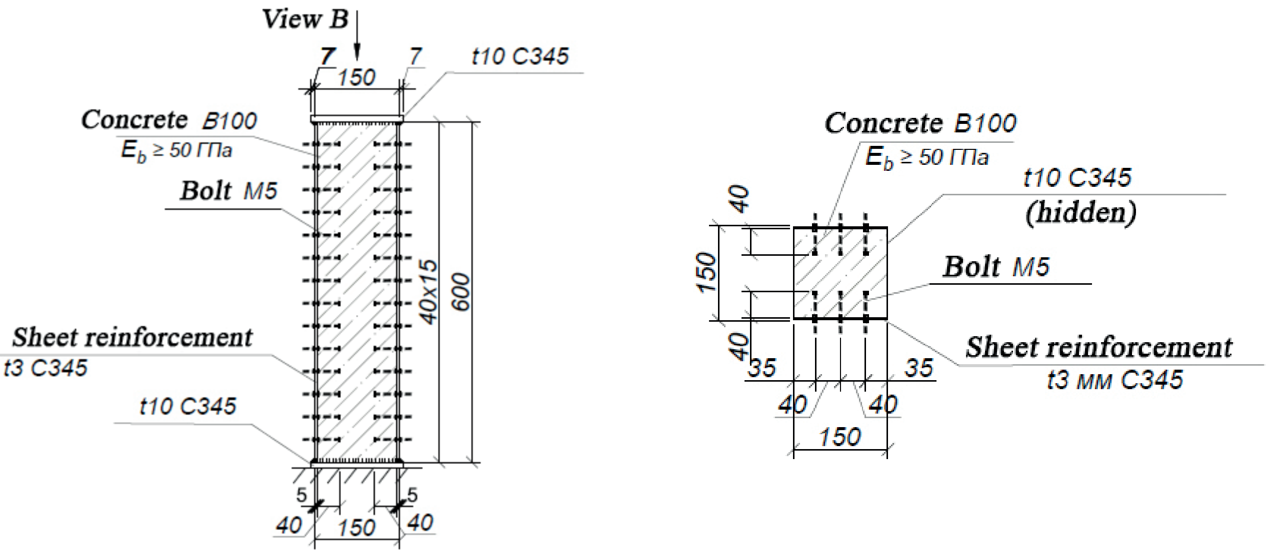
The longitudinal stiffness of the reduced section D_a is calculated by the formula:

$$D_a = E_b A_{red} \tag{3}$$

Calculations using the above formulas allow us to estimate the value of shortening in compression and compare it with the corresponding results of numerical modeling and experimental data.

To verify the solution of the problem, the results of central compression tests of steel reinforced concrete columns with sheet reinforcement are considered. The models are prisms of 600 mm height, the cross-section is square of 150x150 mm. The material of sheet reinforcement is C345 steel. Concrete of the models has different compressive strength of class B100, B60, B30. Concrete mix of class B30, B60 is made on basalt crushed stone with increased deformation characteristics (relative to the normative indicators). Concrete of compressive strength class B100 has an increased modulus of elasticity - not less than 50 GPa. Longitudinal reinforcement is A500C class, transverse reinforcement is A500C class.

To ensure that the sheet reinforcement cooperates with concrete, the installation of restraints in the form of bolts with a spacing of 40 mm is provided. A general view of the steel core and the location of the restraints is shown in Figure 2. Characteristics of the tested models are given in Table 1.

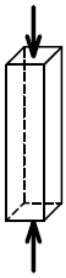


a) General view

b) cross-section

Figure 2. General view of the tested experimental models

Table 1. Characteristics of the experimental models

No	Quantity, pcs	Scheme	μ, % reinforcement ratio	Steel class of sheets	Concrete compressive strength class	h, cm	b, cm	L, cm
1	3		4,67	C345	B30	15	15	60
2	3		4,67	C345	B60	15	15	60
3	3		4,67	C345	B100 ($E_b \geq$ 50 GPa)	15	15	60

Note:
μ is the reinforcement ratio, equal to the ratio of the area of steel in the cross-section to the area of concrete; h,b are the dimensions of the cross-section of the concrete part, L is the length of the model, along the axis of which the external load is transferred.

The tests were carried out on a calibrated hydraulic press MAN1000 (Germany), simulating axial load up to 1000 tf (10 MN) in V.A. Kucherenko Central Research Institute for Structural Engineering. Loading was carried out according to GOST 8829-2018 "Prefabricated construction concrete and reinforced concrete products. Load testing methods. Rules for assessment of strength, rigidity and crack resistance" in stages of not more than 10% of the failure load. "Central" compression of the model was ensured by centering the column model relative to the markings on the press tabletops, as well as by controlling the readings of sensors at the first stages of loading. If a significant difference in deformations was revealed, the model was additionally leveled relative to the press table. During testing of models under stepwise application of compressive load, the magnitude of applied load, vertical absolute shortening of models (by means of displacement sensors) were recorded at each step. The presented models were tested within the framework of R&D "Experimental and numerical studies for the development of recommendations on calculation, design, construction and erection of steel-reinforced concrete structures with external sheet reinforcement...". It is important to note that in order to confirm the correctness of the calculation of the total stiffness of the steel-reinforced concrete element, it is necessary to accurately measure its longitudinal deformations at all stages of loading. In this case, it is necessary to exclude random factors of non-uniform load transfer, non-uniform load absorption by steel and concrete. Therefore, to investigate the stiffness, we analyzed models that are equipped with accurate strain gauges with the possibility of averaging values over the cross section, as well as those tested under "accurate" central compression with spherical press table supports to exclude "clamping" of individual fibers of the structure.

Numerical modeling by the finite element method was performed in the ATENA software package for models similar in size and material properties, taking into account the nonlinear performance of materials: a curvilinear diagram for concrete and a three-linear diagram for steel. The number of steps and mesh size for each model was also selected individually. The minimum number of loading steps was at least 20 and the mesh size was about 20 mm. The Fracture-Plastic Constitutive Model (CC3DCementitious2) material model, which is based on the combination of the tensile fracture model with the compressive fracture model of the material, was used to describe the performance of the concrete. The characteristics of the FE models fully replicated the experimental specimens and were consistent with the data shown in Figure 2 and Table 1. Structures with contact interaction between steel and concrete were also modeled. It was found that for models with small or zero eccentricities, the presence of finite contact interaction at the steel-concrete joint has little or no effect on the longitudinal strain results. The general view of numerical models and some results of calculations for models made of high-strength concrete are shown in Figures 3, 4. The general view and characteristic failure of the experimental models are shown in Figure 5.

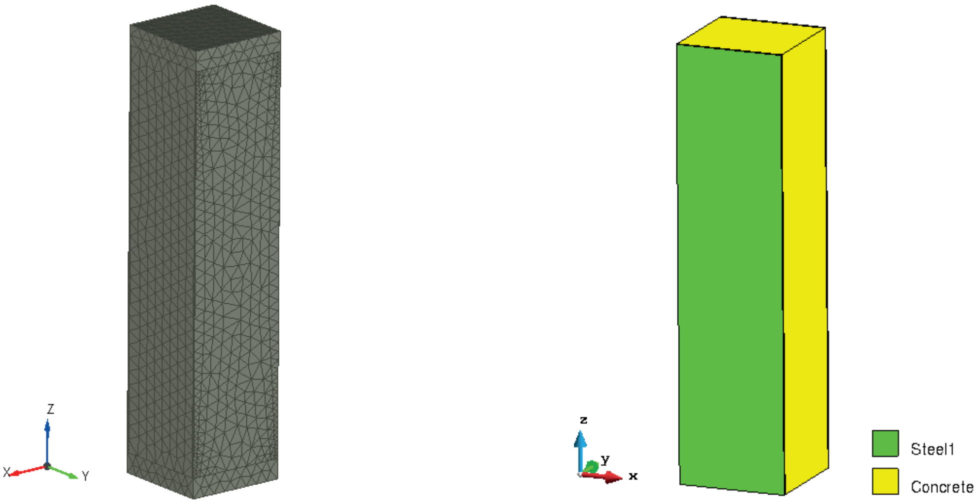
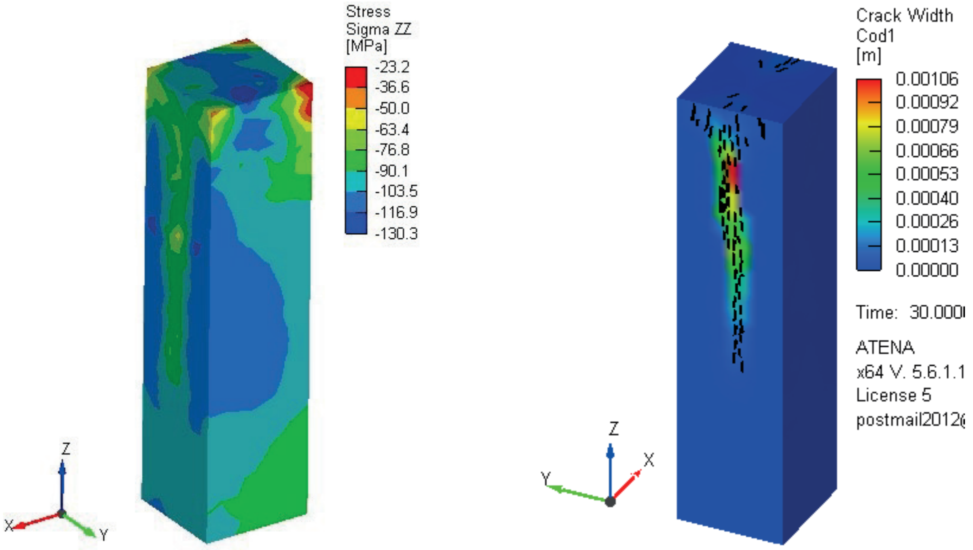


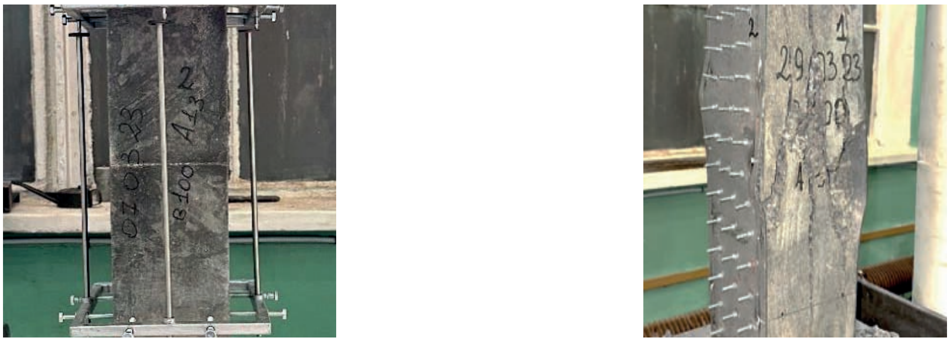
Figure 3. General view of numerical models



a) stresses in concrete models along Z axis, MPa

b) deformed structure with cracks, crack opening width, m

Figure 4. Calculation results



a) general view of the model *b) characteristic failure*

Figure 5. General view and characteristic failure of the model made of high-strength concrete

3 RESULTS AND ANALYSIS

The results of comparison of theoretical, numerical calculations and experimental data for the changes in longitudinal stiffness of centrally compressed structures are shown in Figure 6. The stiffness of the structures was determined taking into account the short-term action of loads according to SP 63.13330, the concrete deformation modulus was assumed to be E_{b1}=0.85E_b. Comparison of models was performed in dimensionless coordinate by force, as it is required to compare theoretical calculation, in which characteristic values of strength and deformation properties of materials are utilized. The experimental data, in which values of actual failure loads are overestimated in relation to characteristic values. That is, one of the coordinates of the graphs was the value N/N_u, where N is the current compressive load during tests or calculations, and N_u is the ultimate design compressive load, which is calculated by the formula:

$$N_u = R_b A_b + R_y A_{st} + R_s A_s \,, \qquad (6)$$

where $R_b, R_y,\ R_s$ are the design values of concrete compressive strength, steel strength, design strength of reinforcement, respectively.

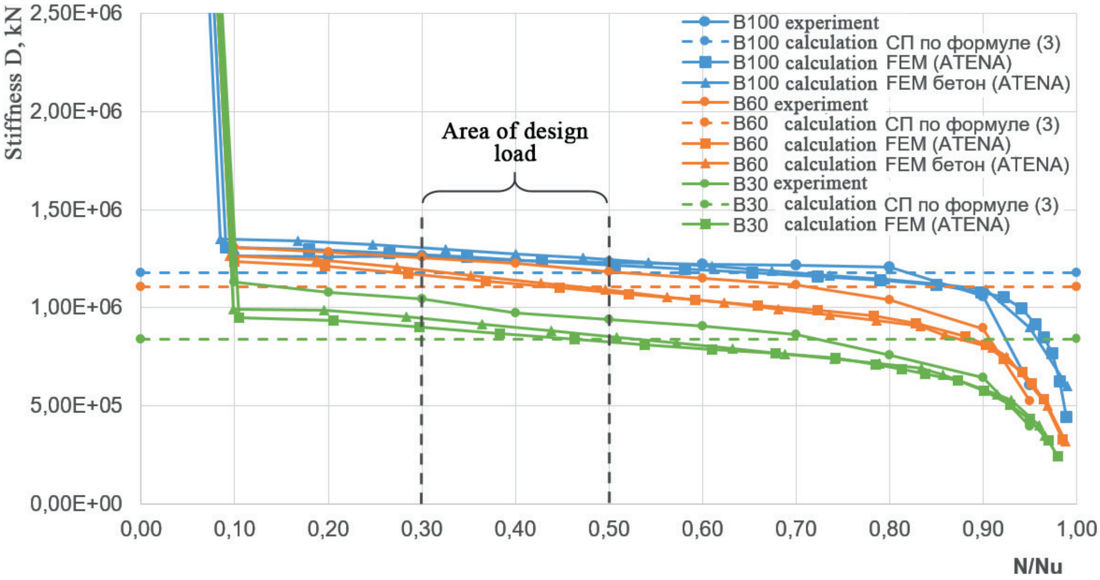


Figure 6. Changes in column stiffness during loading (for all types of specimens and concrete classes)

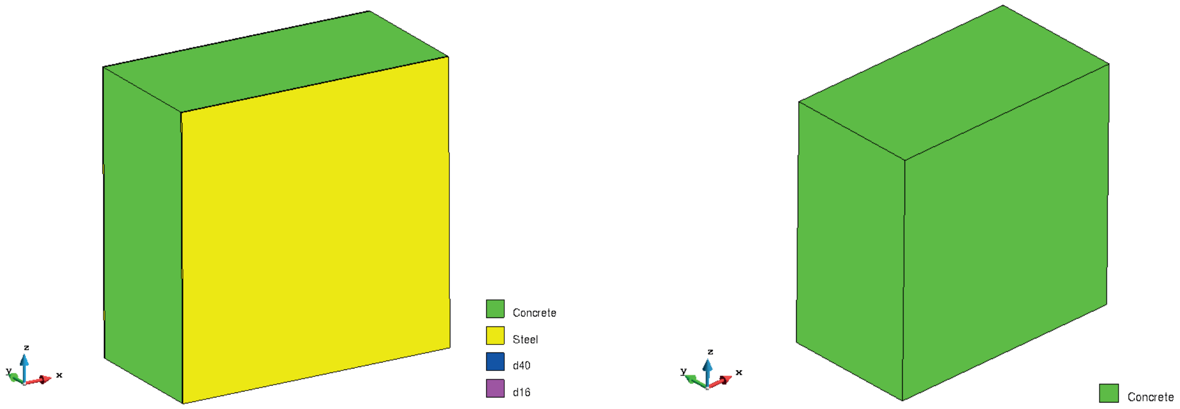
Figure 6 clearly shows the trend of stiffness drop as the structure approaches failure, and at the last stage of loading the stiffness tends to zero. It can also be noted that the stiffness drops as the compressive strength class of concrete decreases, which can be explained by a similar decrease in the elastic modulus of the material. A significant drop in stiffness for all the studied specimens was observed at loads above 80% of the failure load. Moreover, for low-strength concrete, stiffness starts to decrease somewhat earlier than for high-strength concrete as it approaches failure. Experimental data coincide well with numerical calculations. For high-strength concrete, the difference in stiffnesses is within 1.5%. Comparison of experimental and calculated data for the studied specimens is given in Table 2. The calculated characteristic stiffnesses of the structures (dashed lines in Figure 6) have a satisfactory coincidence with the stiffnesses obtained experimentally and numerically, and the characterisric stiffness curves are slightly underestimated. This can be explained by the use of non-standard concrete with moduli of elasticity different from the characteristic ones.

Table 2. Comparison of experimental and calculated data for the studied specimens

Parameter	Experiment	Numerical calculation	Difference, %
Prisms, concrete B100			
Stiffness at design loads	1229381,4	1220861,9	0,69
Reduced stiffness at design loads	1229381,4	1244345,7	1,2
Prisms, concrete B60			
Stiffness at design loads	1184924,8	1079326,9	9,7
Reduced stiffness at design loads	1184924,8	1090418,4	8,6
Prisms, concrete B30			
Stiffness at design loads	938902,3	826346,6	13,6
Reduced stiffness at design loads	938902,3	854559,3	9,8

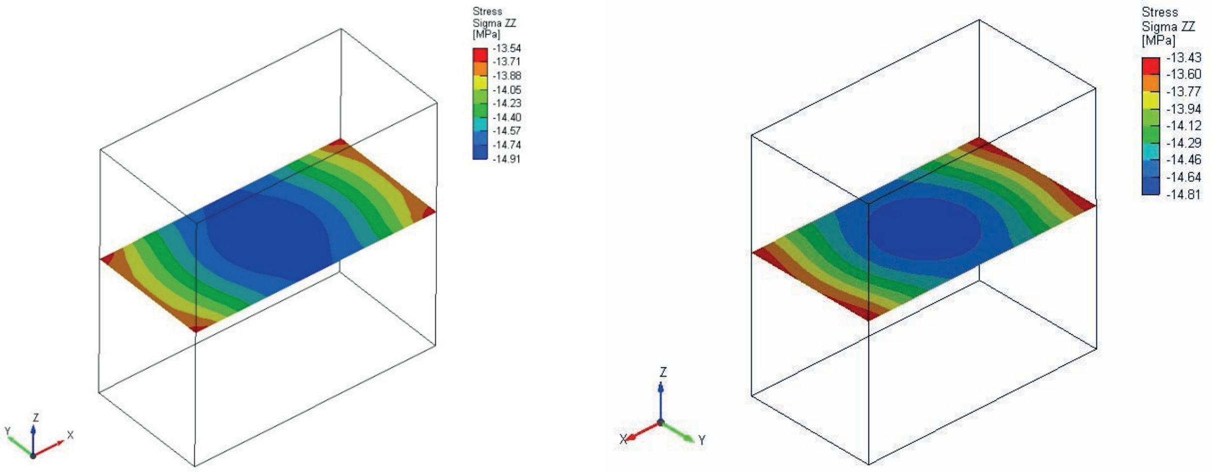
To illustrate the possibility of using the approach implemented in SP63.13330 and SP 266.1325800 to determine the stiffness, where the characteristics of the cross-section of the element are introduced into the calculation, a computational comparison was performed. A structure completely similar to the experimental model was modeled, including concrete and steel cladding sheets on both sides. The calculations were performed in the solid formulation using the finite element method, taking into account the nonlinear performance of materials. A similar calculation was also performed for the structure with reduced concrete performance. Comparing the results of the calculation for the actual structure and the structure with the reduced characteristics, a complete match was obtained (see Figure 9).

Having a good confirmation of the possibility to use in the calculations of real steel and reinforced concrete structures with sheet reinforcement the reduced cross-sectional characteristics, the calculation of a section of a real structure the wall of the stiffening core with a thickness of 2 m, made of high-strength concrete of compressive strength class B100 was performed. The calculation was also performed in two variants: for the actual element, taking into account the presence of sheet and bar reinforcement, studs and stad bolts, and for the equivalent cross-section reduced to concrete. The general view of the numerical models and individual calculation results are shown in Figures 7, 8. Calculation results as a comparison of graphs of change in longitudinal stiffness of structures in dimensionless coordinates by load are presented in Figure 9.



a) model similar to the physical structures *b) specified model*

Figure 7. General view of numerical models



a) stresses in concrete models along Z axis, MPa *b) stresses in concrete models along Z axis, MPa*

Figure 8. Results of calculations

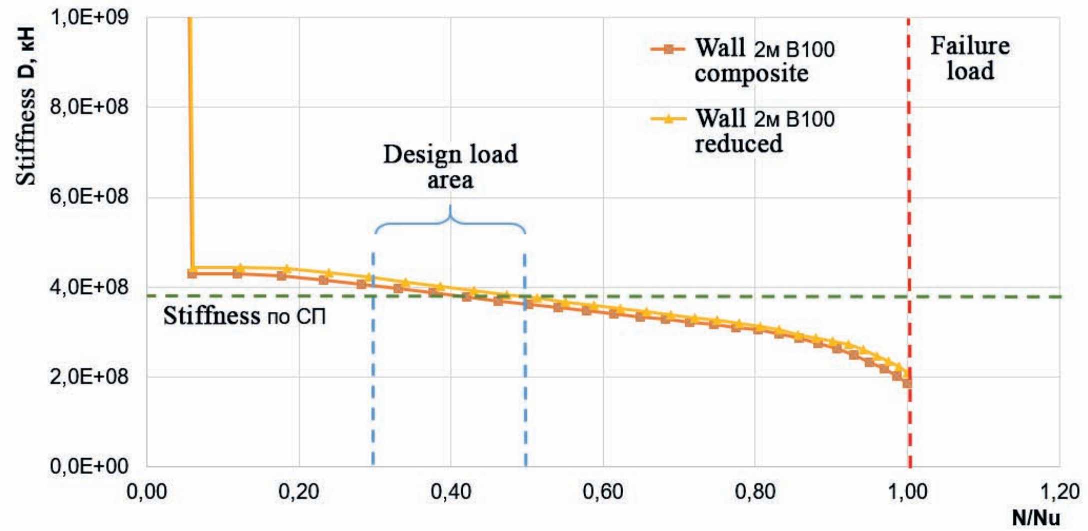


Figure 9. Variation of stiffness of steel-reinforced concrete wall with sheet reinforcement during loading process

Analysis of the obtained results, presented in Figure 12, has shown a good convergence of the calculated data with a difference of 5%. The insignificant difference can be explained by the presence of the volumetric stress state when the material performs in a complex massive structure. Summarizing the performed experimental, theoretical and numerical studies, it is possible to note the validity of the existing normative calculation methods in relation to the considered steel-reinforced concrete structures with sheet reinforcement. Performing complex calculation schemes with a large number of finite elements, it is possible to recommend the introduction of the reduced stiffness characteristics of structures into the calculation. As it was shown above, such an assumption does not introduce a significant error when analyzing the calculation results.

CONCLUSIONS

1. The peculiarities of stiffness changes in structures with sheet reinforcement under short-term loads have been evaluated. The presented experimental and theoretical data are obtained for structures with the percentage of reinforcement - 2.5...5.0 % and are valid under the condition of compliance with the design requirements for sheet reinforcement and stud-bolts..
2. A comparison has been made of “experiment - FE model - formulaic calculation” for the tested models and “verified FE model of a real wall from a building structure with nonlinear materials - FE model with reduced to concrete characteristics” for a real designed wall. The comparison results show that the numerical and experimental models have almost the same load-stiffness diagrams. The difference of stiffness values obtained by formula (3) for high-strength concrete according to the experimental and FE models is not more than 8% in the load range of 0.4-0.5 N/Nu (which corresponds to the design load range).
3. Good agreement of the experimental data with the results of numerical and theoretical calculations is ensured, among other things, due to the uniform inclusion in the operation of the sheet reinforcement located at the opposite edges of the cross-section, by installing a sufficient number of flexible stops (stad-bolts) and compliance with the structural requirements in the design of experimental models.
4. The use of reduced cross-sectional characteristics in the stress region, which corresponds to the design stresses, gives the same deformation results as those obtained by solid FE calculations with nonlinear material characteristics.
5. The possibility of simplified modeling of steel-reinforced concrete structures with sheet reinforcement (only concrete section with the given characteristics) in the general calculation of the building without compromising the accuracy of the deformation calculation of the whole structure is confirmed.

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