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CALCULATION OF STEEL-REINFORCED CONCRETE STRUCTURES OF THE BUILDING OF THE NATIONAL LIBRARY OF THE REPUBLIC OF BELARUS

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Abstract

The unique building of the National Library of the Republic of Belarus includes not only urban planning, architectural, technological modern solutions, but also structural ones. One of such modern structural solutions is the use of composite (steel-concrete) structural elements. The advantages of steel-reinforced concrete structures are manifested in the possibility of placing steel profiles of large cross-sectional area in their cross-section and protecting them from corrosion and high temperatures with concrete; the use of rigid reinforcement as load-bearing elements or formwork during their construction. The article presents the results of applying a nonlinear analysis to obtaining of the parameters of the stress-strain state (normal stresses, strains) at any stage of behavior under loading, including the construction stage, as well as the strength, deformability of complexly loaded composite elements under the condition of joint operation of rigid steel sections and reinforced concrete. The resolving system of equations of the nonlinear deformation model includes the conditions of equilibrium of internal forces in the cross-section, the condition of distribution of relative deformations along the height of the cross-section in accordance with the hypothesis of a flat section, as well as approximations of the deformation diagrams of concrete and rigid reinforcement in the form of rolled sections under tension-compression. A criterion for assessment the internal force corresponding to the resistance of a composite steel element, which does not require standardization of the ultimate compressibility of concrete and allows taking into account a high degree of redistribution of forces between the components in the cross section of the composite steel element is proposed. The advantages of the nonlinear design method are demonstrated with usage of the examples of calculating composite steel structures of the building of the National Library of the Republic of Belarus.

Keywords: steel-reinforced concrete structure, nonlinear deformation model, material deformation diagrams, plane section hypothesis, stress-strain state, concrete shrinkage, stages of work under load, failure criterion.

РАСЧЕТ СТАЛЕЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ЗДАНИЯ НАЦИОНАЛЬНОЙ БИБЛИОТЕКИ РЕСПУБЛИКИ БЕЛАРУСЬ

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Реферат

Уникальное здание Национальной библиотеки Республики Беларусь включает в себя не только градостроительные, архитектурные, технологические современные решения, но и конструкционные. Одним из таких современных конструкционных решений является применение сталежелезобетонных конструкций. Преимущества сталежелезобетонных конструкций проявляются в возможности размещения в их поперечном сечении стальных профилей большой площади сечения и их защитой против коррозии и высоких температур бетоном, использовании при их возведении жесткой арматуры в качестве несущих элементов или опалубки. В статье представлены результаты применения нелинейного расчета для определения параметров напряженно-деформированного состояния (нормальных напряжений, относительных деформаций) на любой стадии работы под нагрузкой, включая стадию возведения, а также прочности, деформативности сложно нагруженных сталежелезобетонных элементов при условии совместной работы жестких стальных профилей и железобетона. Разрешающая система уравнений нелинейной деформационной модели включает в себя условия равновесия внутренних усилий в поперечном сечении, условие распределения относительных деформаций по высоте поперечного сечения в соответствии с гипотезой плоского сечения, а также аппроксимации диаграмм деформирования бетона и жесткой арматуры в виде прокатных профилей при растяжении-сжатии. Предложен критерий вычисления внутреннего усилия, соответствующего прочности сталежелезобетонного элемента, не требующий нормирования предельной сжимаемости бетона и позволяющий учитывать высокую степень перераспределения усилий между составляющими в поперечном сечении сталежелезобетонного элемента. Преимущества нелинейного метода расчета продемонстрированы на примерах расчета сталежелезобетонных конструкций здания Национальной библиотеки Республики Беларусь.

Ключевые слова: сталежелезобетонная конструкция, нелинейная деформационная модель, диаграммы деформирования материалов, гипотеза плоских сечений, напряженно-деформированное состояние, усадка бетона, стадии работы под нагрузкой, критерий разрушения.

Introduction

At the present stage of construction industry development, composite steel structures are widely used in the construction of frame buildings and structures with heavily loaded elements experiencing a complex stress-strain state under eccentric compression-tension and bending. The advantages of composite steel structures are manifested in the possibility of placing in their cross-section, in addition to steel bar flexible reinforcement, steel profiles (rigid reinforcement) with high physical and mechanical characteristics (compared to concrete) of a large cross-sectional area and their protection against corrosion and high temperatures by concrete; the use of rigid reinforcement as load-bearing elements or formwork during their construction [1–6].

The joint work of steel elements having a larger contact surface area with concrete than flexible reinforcement of a round cross-section, with concrete is ensured by the device of various transverse projections in the form of rigid anchor stops or flexible stud bolts, reinforcement rods welded at one end to the profile. This allows to exclude their mutual shift under load up to the ultimate stage of strength of steel-reinforced concrete elements [7–15].

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Approaches to the design of steel-reinforced concrete elements as a composite structure have historically evolved from the method of allowable stresses for a reduced cross-section working elastically (steel structures) to the method of ultimate forces with plastic behaviour of concrete (rectangular block of normal stresses in concrete of the compressed zone) and limited plastic work of steel (reinforced concrete structures). Further development of the ultimate force method led to the method of ultimate states, which is used in regulatory and advisory documents on the calculation of steel-reinforced concrete elements to this day [7–15].

Advances in the development of computer –based design have made it possible to apply in practice the deformation approach to the calculation of cross-sections of steel-reinforced concrete elements, which allows obtaining the parameters of their stress-strain state (SSS) for a cross-section of any shape, with any distribution of rigid and flexible reinforcement across the cross-section, at any stage of their deformation under load [16–22], taking into account the actual nonlinearity of the work of materials in the cross-section, the phenomena of shrinkage and creep of concrete [23], and the monotonic stage-by-stage loading [24–26]. The proposed deformation approach to the design of composite elements is based on the usage of material stress-strain diagrams and the linear distribution of strains in the cross-section (the hypothesis of plain sections), which is valid for composite elements in the absence of slippage between rigid steel reinforcement and surrounding concrete [16].

One of the positive examples of the use of composite elements was the construction of the unique building of the National Library of the Republic of Belarus. The building of the National Library consists of two main volumes: a high-rise book depository building and a 2–4-story stylobate located around it, where the rooms provided for by the library technology are located. The height of the book depository building is 72.6 m, and the height of the stylobate is 17.5 m [27]. The book depository itself begins at the +12.6 m mark. The lobby and the central entrance are located in the building up to this mark. The round stylobate building has a diameter of 167.5 m [28, 29]. The stylobate is separated from the high-rise book depository by a fireproof monolithic reinforced concrete wall. The main, most interesting part of the design concept is the high-rise book depository. It is a volumetric "symmetrical crystal" with the geometric shape of a rhombicuboctahedron with maximum dimensions of 30 x 60 x 60 m. In the lower inclined part of the structure, additional rod elements of the external contour are provided, which significantly increased the rigidity and stability of the building. Increased requirements for the rigidity of the structural scheme of the book depository building, in addition to the standard ones, are explained by its continuous cladding with decorative glass.

Additional elements that increase the rigidity and stability of the book depository building frame are steel-reinforced concrete struts resting on the support ring and taking the load from the frame columns located between the reinforced concrete diaphragms. In this case, the vertical component of the forces in the inclined steel-reinforced concrete struts is transferred to additional reinforced concrete columns at the point of support of the struts along the perimeter of the ring. The use of composite elements simplified the technology of concreting in suspended formwork with their negative angle of inclination and the installation of supporting circles.

The aim of this study is to apply a nonlinear approach based on concrete stress-strain diagrams, rigid and flexible reinforcement, taking into account the loading stages of the steel and reinforced concrete parts of the element, to the calculation of composite elements of the book depository building of the National Library of the Republic of Belarus.

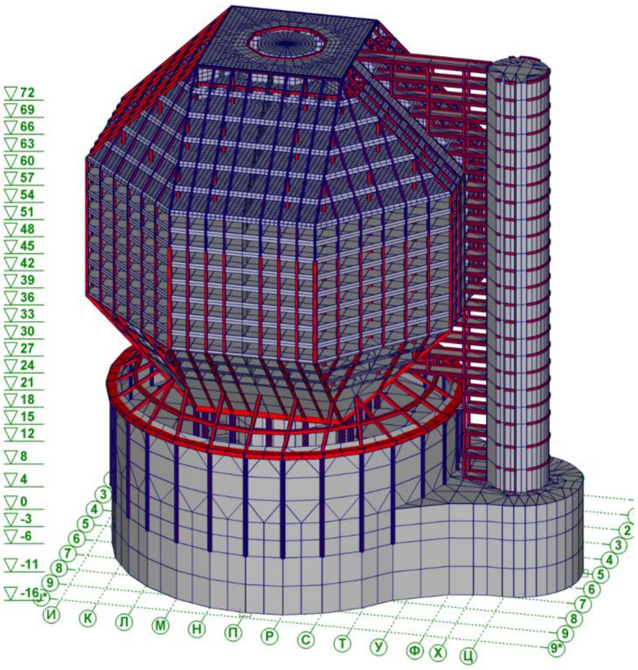


Figure 1 – Structural diagram of the building of the National Library of the Republic of Belarus

Nonlinear deformation model (NDM) for composite elements

According to the section method for NDM, the cross-section of a composite element consisting of concrete, rigid and flexible reinforcement is considered as a set of elementary areas with uniformly distributed compression-tensile stresses, the value of which depends on the strain in the center of gravity of the elementary area according to the material diagrams. The distribution of strain over the cross-section of the composite element obeys the Bernoulli hypothesis of a plain section.

The design stress-strain diagram of concrete under compression and tension, establishing the relationship between stresses and strains, is taken in the form of a parabolic curve with a descending branch, recommended by the European Concrete Committee (ECC-FIP) [30, 31], without limiting its length by deformations under compression in order to obtain a complete redistribution of forces between the components of the cross-section of the steel-reinforced concrete element.

The design stress-strain diagram of rigid and flexible reinforcement under compression and tension is taken to be bilinear (Prandtl diagram) with a limitation of strain of elongation at break. For flexible reinforcement of class S500, the stress-strain diagram according to [31] is taken with an inclined branch, the angle of inclination of which depends on the class of deformability (plasticity) of the reinforcement.

The system of NDM equations in the general case of loading for the composite cross-section of a element under the action of a longitudinal force N with eccentricities along the *x* and *y* axes relative to the center of gravity of the element section and bending moments M_x and M_y has the form:

$$\begin{cases} \sum\sigma_c(\varepsilon_c(x_c,y_c))A_c(x_c,y_c)(x_c-x_0)+\sum\sigma_s(\varepsilon_s(x_s,y_s))A_s(x_s,y_s)(x_s-x_0)-M_x-N\cdot e_{0,x}=0 \\ \sum\sigma_c(\varepsilon_c(x_c,y_c))A_c(x_c,y_c)(y_c-y_0)+\sum\sigma_s(\varepsilon_s(x_s,y_s))A_s(x_s,y_s)(y_s-y_0)-M_y-N\cdot e_{0,y}=0 \\ \sum\sigma_c(\varepsilon_c(x_c,y_c))A_c(x_c,y_c)+\sum\sigma_s(\varepsilon_s(x_s,y_s))A_s(x_s,y_s)-N=0 \\ \varepsilon_c(x_c,y_c)=\varepsilon_{c,II}+\varepsilon_z+{}^{1}\!/_{r_x}(x_c-x_0)+{}^{1}\!/_{r_y}(y_c-y_0) \\ \varepsilon_s(x_s,y_s)=\varepsilon_{s,II}+\varepsilon_z+{}^{1}\!/_{r_x}(x_s-x_0)+{}^{1}\!/_{r_y}(y_s-y_0) \end{cases}, \quad (1)$$

where $\sigma(x, y)$, $\varepsilon(x, y)$ – normal stresses, strains in an elementary area of concrete, rigid or flexible reinforcement with coordinates (x, y);

$A_c(x_c, y_c)$, $A_s(x_s, y_s)$ – cross-sectional area of an elementary area of concrete, rigid or flexible reinforcement with coordinates (x, y);

(x_0, y_0) – coordinates of the center of gravity of the cross-section of the composite concrete element;

$1/r_x$, $1/r_y$ – curvature of the longitudinal axis of the composite concrete element in the plane of the x, y axes, respectively;

Strain ε_z at the center of gravity of the cross-section of the composite element is equal to:

$$\varepsilon_z = \frac{N}{\sum E_c A_c + \sum E_s A_s}. \tag{2}$$

The influence of longitudinal bending when calculating the parameters of the stress-strain state (SSS) of an eccentrically compressed composite element at any stage of its loading, including the ultimate strength, is produced by the coefficient η according to the formula [7, 30, 31]:

$$e_0 = \left(\sqrt{e_{0,x}^2 + e_{0,y}^2}\right) \cdot \eta, \tag{3}$$

where

$$\eta = \frac{1}{1 - N/N_{crit}}; \tag{4}$$

$$N_{crit} = \frac{\pi^2 \cdot (EI)}{l_0^2}; \tag{5}$$

l_0 – design effective length of the composite element; (EI) – the rigidity of the composite element at the calculated stage of its deformation.

$$EI = \frac{\sqrt{\left(N \cdot e_{0,x} + M_x\right)^2 + \left(N \cdot e_{0,y} + M_y\right)^2}}{\sqrt{\left(\frac{1}{r_x}\right)^2 + \left(\frac{1}{r_y}\right)^2}}. \tag{6}$$

The criterion for the formation of normal tensile cracks in a composite element is the achievement by concrete of the extreme tensile strain in relation to the neutral line of the elementary area. The failure criterion of the composite element is the maximum value of the internal force from external effects that the element perceives. The maximum value of the internal force $N(M)$, at which the process of successive approximations in the numerical solution of the system of equations (1) converges (the equilibrium conditions and the condition of strain compatibility are met), corresponds to the resistance of the composite concrete element. The advantage of the proposed failure criterion is the absence of the need to standardize the ultimate compressive strain of concrete and to take into account the high degree of redistribution of forces between the components in the cross section of the composite concrete element.

During the construction process, the rigid reinforcement of the composite elements is subject to the effects of its own weight and the weight of other precast elements supported by rigid sections, monolithic concrete and flexible reinforcement, and self-weight. This causes the appearance of an initial stress-strain state in the rigid reinforcement. The stage-by-stage construction process of composite elements [24–26] in the NDM is taken into account by summing the strains of each elementary area of the rigid reinforcement of the calculated cross-section with the strains $\varepsilon_{s,I}$, calculated at the first stage from the equations (7):

$$\begin{cases} \sum \sigma_s(\varepsilon_s(x_s,y_s)) A_s(x_s,y_s)(x_s - x_0) - M_{x,I} - N_I \cdot e_{0,x} = 0 \\ \sum \sigma_s(\varepsilon_s(x_s,y_s)) A_s(x_s,y_s)(y_s - y_0) - M_{y,I} - N_I \cdot e_{0,y} = 0 \\ \sum \sigma_s(\varepsilon_s(x_s,y_s)) A_s(x_s,y_s) - N_I = 0 \\ \varepsilon_{s,I}(x_s,y_s) = \varepsilon_{z,I} + 1/r_{x,I}\,(x_s - x_0) + 1/r_{y,I}\,(y_s - y_0) \end{cases}. \tag{7}$$

In addition, during concreting of composite structures and hardening of concrete, shrinkage strains appear, which are restrained by steel sections with a large contact surface and by the flexible reinforcement. For the given the high degree of deformation restraint composite elements, there is a risk of shrinkage cracking. Under the action of shrinkage deformations, compression deformations appear in rigid and flexible reinforcement, and tensile deformations in concrete.

In order to taking into account the shrinkage strain of concrete during its hardening at the second stage of design, the cross-section of the steel-reinforced concrete element is modeled without increasing the external load, compared to the first stage of the initial loading of rigid reinforcement. The value of the shrinkage strain of concrete $\varepsilon_{cs}(t, t_s)$ at time t, having an age of t_s at the time of the start of air-dry curing, is calculated using in accordance with [31]:

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cbs}(t) + \varepsilon_{cds}(t,t_s), \tag{8}$$

where $\varepsilon_{cbs}(t)$ – is the base shrinkage strain of concrete;

$\varepsilon_{cds}(t,t_s)$ – is the drying shrinkage strain of concrete.

The system of equations for calculating the stress-strain state parameters of the composite element at the second stage of the design is transformed to:

$$\begin{cases} \sum \sigma_{c,II}(\varepsilon_{c,II}(x_c,y_c)) A_c(x_c,y_c)(x_c - x_0) + \sum \sigma_{s,II}(\varepsilon_{s,II}(x_s,y_s)) A_s(x_s,y_s)(x_s - x_0) - M_{x,I} - N_I \cdot e_{0,x} = 0 \\ \sum \sigma_{c,II}(\varepsilon_{c,II}(x_c,y_c)) A_c(x_c,y_c)(y_c - y_0) + \sum \sigma_{s,II}(\varepsilon_{s,II}(x_s,y_s)) A_s(x_s,y_s)(y_s - y_0) - M_{y,I} - N_I \cdot e_{0,y} = 0 \\ \sum \sigma_{c,II}(\varepsilon_{c,II}(x_c,y_c)) A_c(x_c,y_c) + \sum \sigma_{s,II}(\varepsilon_{s,II}(x_s,y_s)) A_s(x_s,y_s) - N_I = 0 \\ \varepsilon_{c,II}(x_c,y_c) = \varepsilon_{z,I} + 1/r_x\,(x_c - x_0) + 1/r_y\,(y_c - y_0) + \varepsilon_{cs}(t,t_s) \\ \varepsilon_{s,II}(x_s,y_s) = \varepsilon_{s,I} + 1/r_x\,(x_s - x_0) + 1/r_y\,(y_s - y_0) + \varepsilon_{cs}(t,t_s) \end{cases}. \tag{9}$$

The strains distribution in the composite element sections obtained at the second stage of calculation will be the input ones at subsequent stages of its response under load (system of equations (1)).

Calculation of composite concrete elements according to NDM

The composite concrete elements of the book depository building of the National Library of the Republic of Belarus are: support ring (ОК) with a radius of 27650 mm; inclined elements (НЭ1…НЭ3), supporting, cantilevering, bordering reinforced concrete floor beams, with a total length of 25400 mm and a calculated length (taking into account bracing along the length by floor beams) of l_0 = 4240 mm; braces (ПК), resting with one end on the composite concrete ring (ОК), and the other on the inclined elements НЭ at the point of their connection with the bordering floor beams at the 18.600 m mark, with a length of 12100 mm (l_0 = 6050 mm) (Figure2). The steel-reinforced concrete element of the support ring experiences tension (+) with bending under the action of assembly forces, its own weight and internal forces from the acting loads, the other steel-reinforced concrete elements experience compression (–) with bending. The calculated forces in the composite elements under consideration at the time of their concreting (N_l, M_l) and from the calculated values of design effects of action (N, M) are given in Table 1.

Table 1 – Design values of the internal forces in composite elements

Element	N_l, kN	M_l, kN ·m	η_l	N, kN	M, kN ·m	η	N_u, kN	M_u kN ·m	η_u
ОК	+4250	168	–	+5285	280	–	+26823	1393	–
НЭ1	–43	26	1,000	–220	150	1,001	–2152	1498	1,027
НЭ2			1,000			1,001	–1743	1208	1,026
НЭ3			1,001			1,001	–1777	1226	1,018
ПК	–1364	18	1.000	–3560	21	1,001	–13587	461	2,679

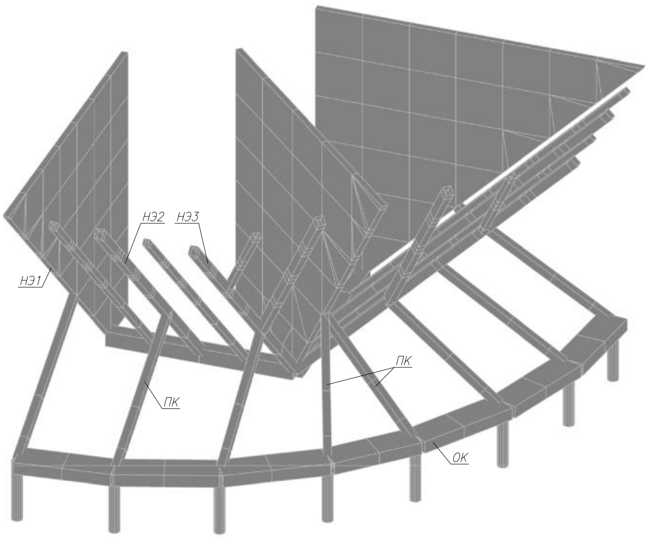


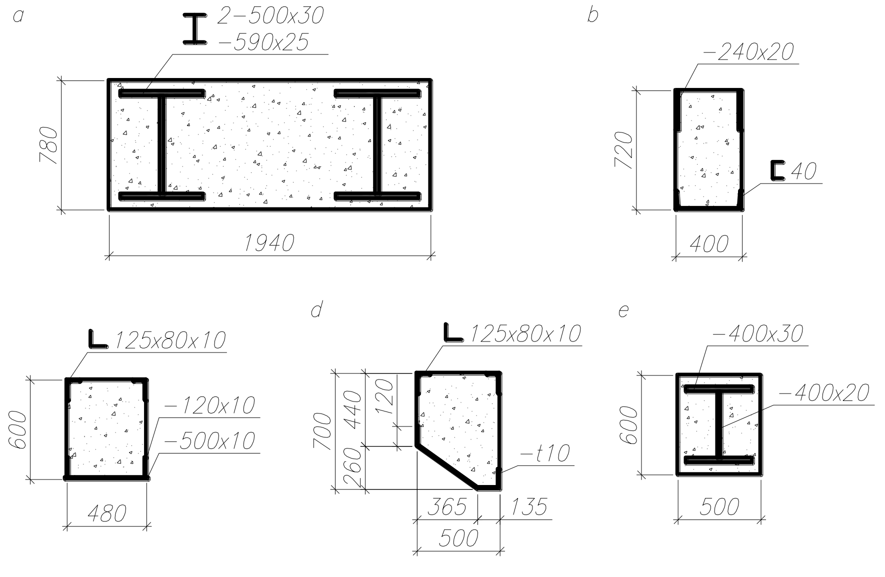
Figure 2 – Composite elements disposition in book depository building

The cross-sections of the considered composite elements with rigid reinforcement made of rolled and welded profiles are shown in Figure 3. All steel sections of the composite elements are made of steel C345, with the exception of inclined elements НЭ1…НЭ3, which are made of steel C245. Concrete class C25/30 is adopted for concreting all composite structural elements.

An example of calculating the parameters of the stress-strain state of the composite element using the proposed method for the support ring (ОК) under the tensile force and bending moment is shown in Figure 4.

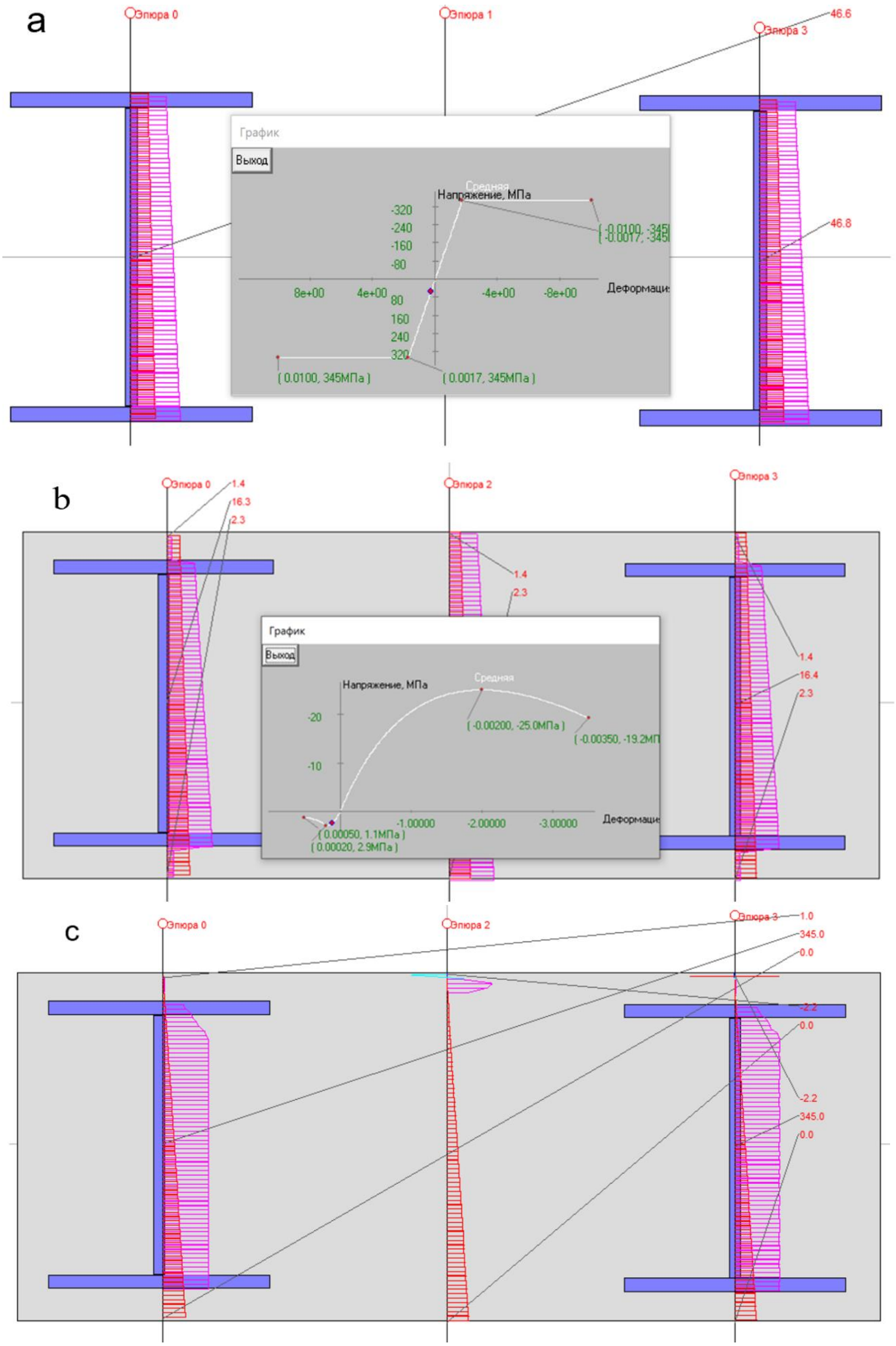
The analysis of the calculation results shown that the shrinkage strain of concrete $\varepsilon_{cs}(t,t_s)$ = 0.00025 caused the tensile stresses in concrete, and compressive stresses in rigid profile reinforcement, partially damping the tensile stresses from external effects. Under the design load, there are no flexural cracks in the concrete of the support ring. In the ultimate limit state, the support ring is loaded under tension with bending, but only rigid reinforcement, carry out effects of loading.

The strains and stresses distribution along the height of the cross-section of eccentrically compressed composite steel elements, taking into account their longitudinal bending, the initial stress-strain state at the time of concreting and the imposed shrinkage strain of the hardening concrete in the ultimate strength state, is shown in Figure 5. The results of calculating the ultimate forces (N_u, M_u) of the composite steel elements under consideration are given in Table 1.



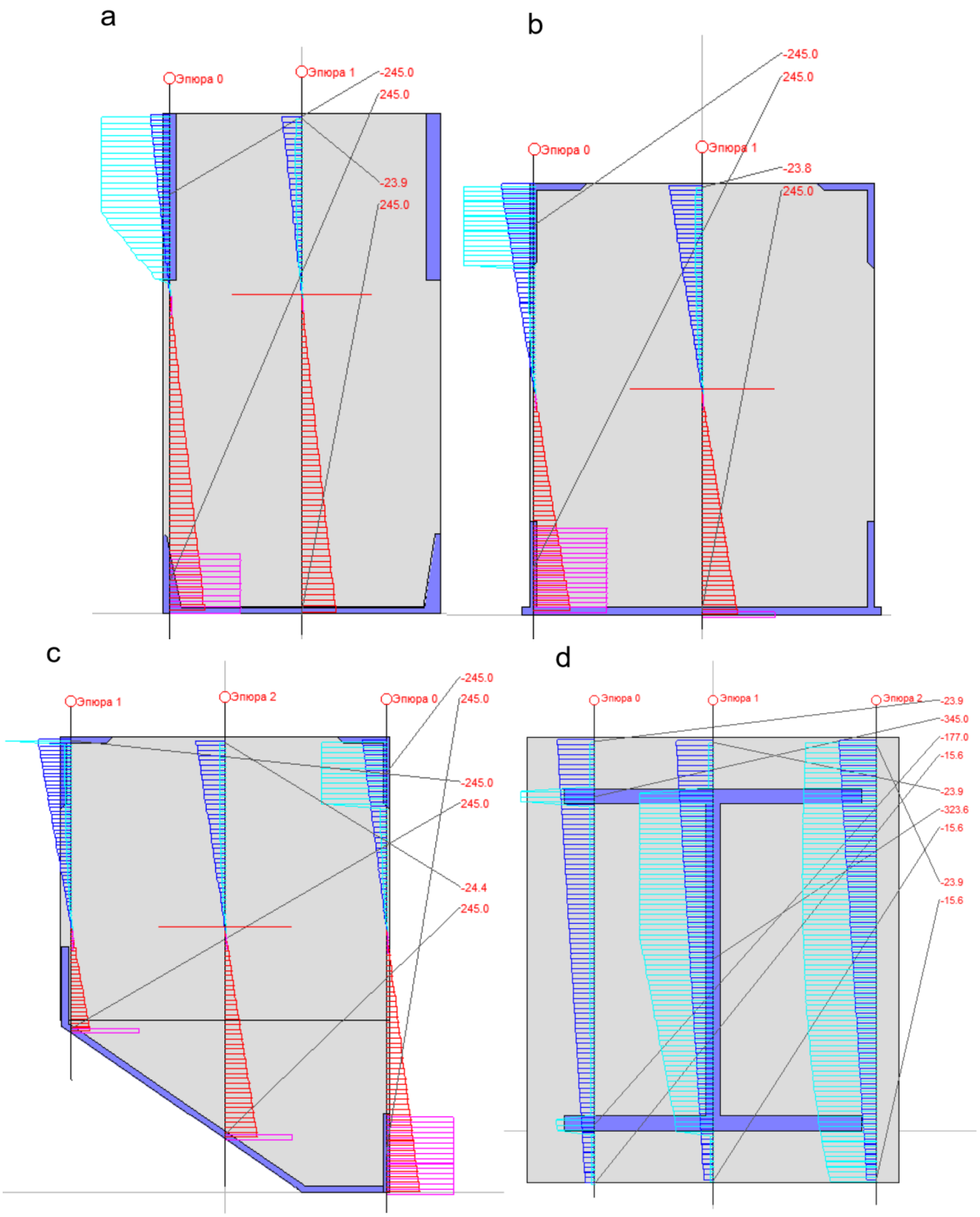
a – support ring OK; b – inclined element NE1; c – inclined element NE2; d – inclined element NE3; e – struts PK

Figure 3 – Cross-sections of composite elements with rigid reinforcement



a – under the action of a tensile longitudinal force N_l = 4251 kN and a bending moment $M_{Sd,l}$ = 168 kN· m before concreting; b – the same, with the same internal forces and forces as a result of concrete shrinkage after its hardening; c – under the ultimate tensile longitudinal force N_u = 26823 kN and a bending moment Mu = 1393 kN·m (the numbers in red to the right of the cross-section are normal stresses in MPa)

Figure 4 – Results of calculating the distribution of strains and stresses across the cross-section of the composite element of the support ring OK



a – НЭ1; b – НЭ2; c – НЭ3; d – ПК (numbers in red to the right of the cross-section are normal stresses in MPa)

Figure 5 – Results of calculating the distribution of strains and stresses in the cross-section of compressed-bending composite elements in Ultimate Limit State (ULS)

The calculation of the maximum values of internal forces (effect of action) in the composite elements of the National Library of the Republic of Belarus shows a significant margin of safety when the resistance of the compressed concrete is taking into account.

Conclusion

Using the example of compressed (tensioned) with bending composite elements of the National Library of the Republic of Belarus, the applicability of a nonlinear deformation model for calculating their stress-strain state parameters at the stage of their construction is demonstrated, taking into account the effect of actions and imposed forces developed by concrete shrinkage during curing, when working under load, including the ultimate load**.**

Taking into account concrete shrinkage allows to increase the reliability of calculating the parameters of the stress-strain state of composite elements and to foresee the possibility of shrinkage cracks appearing at the stage of their concreting and curing.

The criterion for calculating internal forces corresponding to the resistance of element without the ultimate strain of concrete limiting and rigid reinforcement under compression makes it possible to take into account the redistribution of forces in the cross-section between rigid reinforcement and compressed concrete.

References

1. Vasil'ev, A. P. ZHelezobeton s zhestkoj armaturoj / A. P. Vasil'ev ; Narodnyj komissariat po stroitel'stvu. Tekhn. upr. Central'nyj nauchno-issledovatel'skij institut promyshlennyh sooruzhenij – CNIPS. – Moskva ; Leningrad : Gosudarstvennoe izdatel'stvo stroitel'noj literatury, 1941. – 123 s.
2. Raschet stalezhelezobetonnoj kolonny vysotnogo doma na kosoe vnecentrennoe szhatie / A. M. Desyatkin, D. V. Konin, A. S. Martirosyan, V. I. Travush // ZHilishchnoe stroitel'stvo. – 2015. – S. 92–95.
3. Tamrazyan, A. G. Istoriya razvitiya teorii zhelezobetona: biograficheskij ocherk / A. G. Tamrazyan, A. F. Lolejt. – M. : MGSU, 2018. – 184 s.
4. Babalich, V. S. Stalezhelezobetonnye konstrukcii i perspektiva ih primeneniya v stroitel'noj praktike Rossii / V. S. Babalich, E. N. Androsov // Uspekhi sovremennoj nauki. – 2017. – T. 4, № 4. – S. 205–208.
5. Kibireva, YU. A. Primenenie konstrukcij iz stalezhelezobetona / YU. A. Kibireva, N. S. Astaf'eva // Ekologiya i stroitel'stvo. – 2018. – № 2. – S. 27–34. – DOI: 10.24411/2413-8452-2018-10004.
6. Vinogradova, N. A. Issledovaniya stalezhelezobetonnyh izgibaemyh konstrukcij (obzor) / N. A. Vinogradova, G. A. SHvec // Vestnik inzhenernoj shkoly DVFU. – 2020. – № 1(42). – S. 114–127.
7. Konstrukcii stalezhelezobetonnye. Pravila proektirovaniya : SP 266.1325800.2016. – M., 2017.
8. Konstrukcii stalezhelezobetonnye pokrytij i perekrytij. Pravila proektirovaniya : TKP 45-5.03-16-2005 (02250) / Ministerstvo arhitektury i stroitel'stva Respubliki Belarus'. –Minsk, 2006. – 71 s.
9. Metodicheskie rekomendacii po raschetu i proektirovaniyu stalezhelezobetonnyh perekrytij. – M. : Federal'nyj centr normirovaniya, standartizacii i ocenki sootvetstviya v stroitel'stve, 2018. – 62 s.
10. Metodicheskoe posobie po raschetu i proektirovaniyu stalezhelezobetonnyh konstrukcij s zhestkoj armaturoj. – M. : Federal'nyj centr normirovaniya, standartizacii i ocenki sootvetstviya v stroitel'stve, 2018. – 49 s.
11. Tonkih, G. P. Eksperimental'noe issledovanie sdvigovogo soedineniya monolitnyh stalezhelezobetonnyh perekrytij na ugolkovyh ankernyh uporah / G. P. Tonkih, D. A. CHesnokov // Vestnik MGSU. – 2021. – №2. – S. 144–152. – DOI: 10.22227/1997-0935.2021.2.144-152.
12. Semenov, V. A. Stalezhelezobetonnye konstrukcij. Oblast' primeneniya i osnovnye polozheniya SP 266.1325800.2016 «Konstrukcii stalezhelezobetonnye. Pravila proektirovaniya». Preimushchestva stalezhelezobetonnyh konstrukcij po sravneniyu s tradicionnymi resheniyami. Modelirovanie stalezhelezobetonnyh konstrukcij s pomoshch'yu sovremennogo inzhenernogo PO dlya proektirovshchikov / V. A. Semenov // Prezentaciya: Associaciya razvitiya stal'nogo stroitel'stva (ARSS). – URL: https://steel-fabrication.ru/mediatsentr/5_Vladimir%20Semenov_Tekhsoft.pdf (data obrashcheniya: 01.07.2024).
13. Rukovodstvo po proektirovaniyu zhelezobetonnyh konstrukcij s zhestkoj armaturoj. – M. : Strojizdat, 1978. – 57 s.
14. Proektirovanie stalezhelezobetonnyh konstrukcij : EN 1994-1-1:2005. Evrokod 4. – CH. 1. Obshchie pravila dlya zdanij i sooruzhenij. – M., 2011. – 123 s.
15. Proektirovanie stalezhelezobetonnyh konstrukcij : Rukovodstvo dlya proektirovshchikov k Evrokodu 4 EN 1994-1-1. – M., 2013. – 414 s.
16. Muhamediev, T. A. Raschet prochnosti stalezhelezobetonnyh kolonn s ispol'zovaniem deformacionnoj modeli / T. A. Muhamediev, O. I. Starchikova // Beton i zhelezobeton. – 2006. – № 4 (541). – S. 18–20.
17. Karpenko, N. I. K raschyotu prochnosti, zhyostkosti i treshchinostojkosti vnecentrenno szhatyh zhelezobetonnyh elementov s primeneniem nelinejnoj deformacionnoj modeli / N. I. Karpenko, B. S. Sokolov, O. V. Radajkin // Izvestiya Kazanskogo gosudarstvennogo arhitekturno-stroitel'nogo universiteta. – 2013. – № 4(26). – S. 113–120.
18. Kudinov, O. V. Novyj podhod k ocenke prochnosti stalezhelezobetonnyh perekrytij / O. V. Kudinov // Beton i zhelezobeton. – 2010. – № 2(563). – S. 14–16.
19. Arleninov, P. D. Sovremennoe sostoyanie nelinejnyh raschetov zhelezobetonnyh konstrukcij / P. D. Arleninov, S. B. Krylov // Sejsmostojkoe stroitel'stvo. Bezopasnost' sooruzhenij. – 2017. – № 3. – S. 50–53.
20. Gholamhoseini, A. Long-Term Behavior of Continuous Composite Concrete Slabs with Steel Decking / A. Gholamhoseini, R. I. Gilbert, M. Bradford // ACI Structural Journal. – 2018. – № 115. – P. 439–449.
21. Karpenko, N. I. Iskhodnye i transformirovannye diagrammy deformirovaniya betona i armatury / N. I. Karpenko, T. A. Muhamediev, A. N. Petrov // Napryazhenno-deformirovannoe sostoyanie betonnyh i zhelezobetonnyh konstrukcij. – M. : NIIZHB, 1988. – C. 7–25.
22. Bondarenko, V. M. Inzhenernye metody nelinejnoj teorii zhelezobetona / V. M. Bondarenko, S. V. Bondarenko. – M. : Strojizdat, 1982. – 287 s.
23. Uchet polzuchesti i usadki betona po SP 5.03.01-2020 pri raschete zhelezobetonnyh konstrukcij na osnove deformacionnoj raschetnoj modeli / D. N. Lazovskij, V. V. Tur, D. O. Gluhov, E. D. Lazovskij // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2021. – № 2(125). – S. 7–12. – DOI: 10.36773/1818-1212-2021-125-2-7-12.
24. Lazovskij, D. N. Usilenie zhelezobetonnyh konstrukcij ekspluatiruemyh stroitel'nyh sooruzhenij / D. N. Lazovskij. – Novopolock : Polockij gosudarstvennyj universitet, 1998. – 240 s.
25. Nelinejnyj raschet izgibaemyh stalezhelezobetonnyh elementov / D. N. Lazovskij, D. O. Gluhov, A. M. Hatkevich [i dr.] // Vestnik Polockogo gosudarstvennogo universiteta. Seriya F. Stroitel'stvo. Prikladnye nauki. – 2024. – № 2(37). – S. 9-23. – DOI: 10.52928/2070-1683-2024-37-2-9-23.
26. Lazovskij, D. N. Deformacionnyj podhod k raschetu soprotivleniya szhatiyu stalezhelezobetonnyh elementov / D. N. Lazovskij, A. I. Gil', D. O. Gluhov // Vestnik MGSU. – 2024. – T. 19. Vyp. 9. – S. 1469–1483. – DOI: 10.22227/1997- 0935.2024.9.1469-1483.
27. Arhitekturno-konstruktivnye resheniya unikal'nogo zdaniya Nacional'noj biblioteki Belarusi / M. K. Vinogradov, V. V. Kramarenko, L. M. SHohina [i dr.] // Stroitel'naya nauka i tekhnika. – 2005. – № 1. – S. 8–13.
28. SHohina, L. M. Konstruktivnye resheniya novogo zdaniya biblioteki / L. M. SHohina // Arhitektura i stroitel'stvo. – 2003. – № 2. – S. 2–3.
29. Konstruktivnye resheniya vysotnogo zdaniya knigohranilishcha Nacional'noj biblioteki Belarusi / D. N. Lazovskij, A. V. Popravko, T. M. Pecol'd, L. M. SHohina // Vestnik Polockogo gosudarstvennogo universiteta. Seriya B: Prikladnye nauki. – 2006. – № 9. – S. 2–7.
30. Fib Model Code for Concrete Structures 2010. – Germany. – 402 p.
31. Betonnye i zhelezobetonnye konstrukcii : SP 5.03.01-2020 / RUP «Strojtekhnorm». – Minsk : Ministerstvo arhitektury i stroitel'stva Respubliki Belarus', 2020. – 236 s.

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