DOI:10.22337/2587-9618-2023-19-2-150-160

CALCULATION MODEL OF A MULTI-STOREY REINFORCED CONCRETE FRAME WITH COMPLEXLY STRESSED BEAMS UNDER ACCIDENTAL IMPACT

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Annotation. A computational model is presented for determining deformations in complexly stressed beams of a structurally non-linear reinforced concrete frame in a transcendental state caused by a special emergency action in the form of a sudden removal of one of the structural elements. The determination of the stress-strain state after the formation of spatial cracks in the reinforced concrete elements of the frame was carried out using the calculated spatial section. At the same time, dynamic additional loads in the design section of the reinforced concrete frame element from a special impact are determined on an energy basis using the "bending moment-curvature" and "torque-angle of rotation" diagrams. The considered calculation algorithm includes the determination of forces in compressed concrete, longitudinal and transverse reinforcement for primary and secondary design schemes and verification of special limit state criteria. The results of a numerical analysis of the effect of cracking, the ratio of torque and bending moment on the stress state in transverse and longitudinal reinforcement and on the dissipative properties of a frame structural system are presented.

Keywords: reinforced concrete frame, cracks, dynamic additional loads, complex resistance, spatial section

РАСЧЕТНАЯ МОДЕЛЬ МНОГОЭТАЖНОЙ ЖЕЛЕЗОБЕТОННОЙ РАМЫ СО СЛОЖНОНАПРЯЖЕННЫМИ РИГЕЛЯМИ В ЗАПРЕДЕЛЬНОМ СОСТОЯНИИ

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Аннотация. Приведена расчетная модель для определения деформаций в сложнонапряженных ригелях железобетонной конструктивно нелинейной рамы в запредельном состоянии, вызванном особым аварийным воздействием в виде внезапного удаления одного из конструктивных элементов. Определение напряженно деформированного состояния после образования пространственных трещин в железобетонных элементах рамы выполнено с использованием расчетного пространственного сечения. При этом динамические догружения в расчетном сечении железобетонного элемента рамы от особого воздействия определены на энергетической основе с использованием диаграмм «изгибающий момент-кривизна» и «крутящий момент -угол поворота». Рассмотренный алгоритм расчета включает определение усилий в сжатом бетоне, продольной и поперечной арматуре для первичной и вторичной расчетных схем и проверку критериев особого предельного состояния. Приведены результаты численного анализа влияния трещинообразования, соотношения крутящего и изгибающего момента на напряженное состояние в поперечной и продольной арматуре и на диссипативные свойства рамной конструктивной системы.

Ключевые слова: железобетонная рама, трещины, динамические догружения, сложное сопротивление, пространственное сечение

INTRODUCTION

The problem of ensuring the safety of structural systems always remains the main priority of scientific, design and construction activities. In recent decades, due to the constant growth in the types and intensity of various impacts on buildings and structures, there is a constant need to improve ways to protect structural systems from such impacts, including the so-called special and emergency ones. This caused the appearance in Russia and some other countries of new regulations aimed at providing such protection, in particular, Russian State Standard GOST 27751-2014 with Amendment No. 1, SP 385.1325800.2018 with Amendments No. 1, 2, 3, SP 296.1325800.2017. These documents contain general provisions regarding the consideration of special effects, the scope of the provisions given in these standards, ways to protect different types of structural systems during their design. However, many of the provisions presented here look like criteria requirements without detailing how to ensure these requirements in the design. At the same time, as shown in [1-3], these criterion requirements remain within the framework of the traditional approach of the limit states method. At the same time, the concepts of “special impact”, “special limit state” and “criteria for a special limit state” introduced in these documents for the calculated parameters do not adequately reflect the physical essence of the deformation of structural systems made of various materials under various stress states at the stages of deformation that go beyond limits of criteria for limit states established experimentally [4-14]. For example, in [1, 15] it is shown that the coefficient of dynamic additional loads and the parameter of survivability of a structural system depend on the material, the topology of the structure, the stage of deformation, and other factors. But this is not taken into account in the requirements of the norms and most studies and publications in the field under consideration. The change in the dissipative properties of the material depending on the load level at which the system is dynamically additionally loaded by a special emergency effect is also not taken into account. The article under consideration presents a computational model, algorithm and results of numerical studies of static-dynamic deformation of reinforced concrete elements of a multi-storey reinforced concrete frame with complexly stressed crossbars in a transcendental state with an analysis of its dissipative properties depending on the type and level of stress state.

METHODS

The solution of the considered problem of computational analysis of the parameters of deformation of a reinforced concrete frame in the limiting and translimiting states is carried out in relation to a fragment of a reinforced concrete frame-rod structural system of the frame of a multi-storey building with a complex stress state in the crossbars under the combined action of torsional and bending moments from the forces Pi applied to the crossbars of the first floor with eccentricity e (Fig. 1 a, b). The calculation scheme of the frame is adopted in two versions: primary - at given loads before the application of a special impact and secondary - under the action of the same loads on the frame, but with the application of a special impact in the form of a sudden removal of one of the columns of the first floor of the frame.

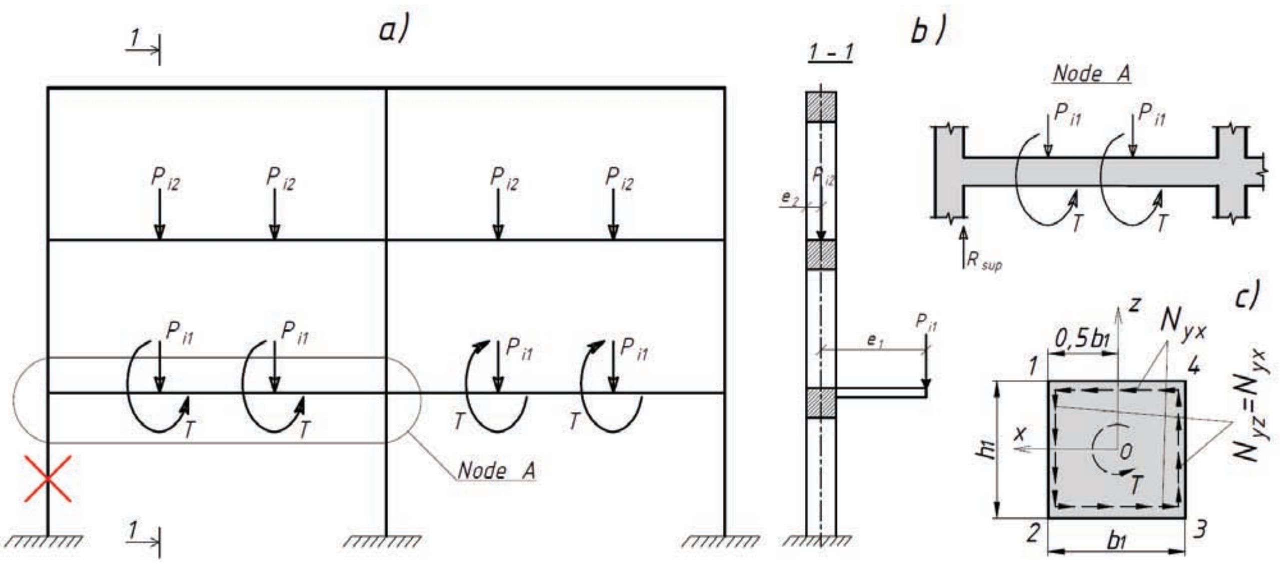


Figure 1. *Scheme of application of loads (a, b) and scheme of flows of tangential forces from the action of torque along the design contour of a box section 1-2-3-4 (c)*

Reinforcement of the frame structure is made as follows (Fig. 2). The crossbar is reinforced in the upper and lower zones with symmetrical longitudinal reinforcement from reinforcing bars, determined by the calculation for a given load and a special effect. The transverse reinforcement of the crossbar is adopted in the form of closed clamps designed for the combined action of the transverse force, torsional and bending moments. The step of the clamps is different in the support zone in the areas of the joint action of the torques of the bending moments and in the middle part of the span of the crossbars.

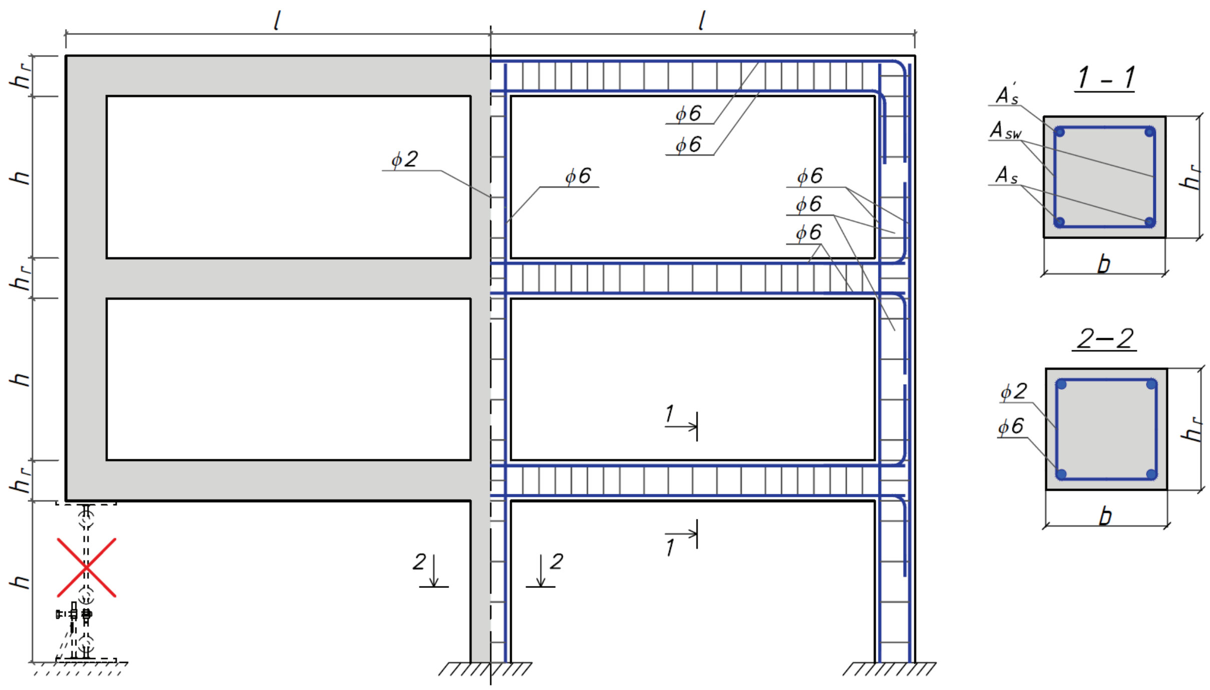
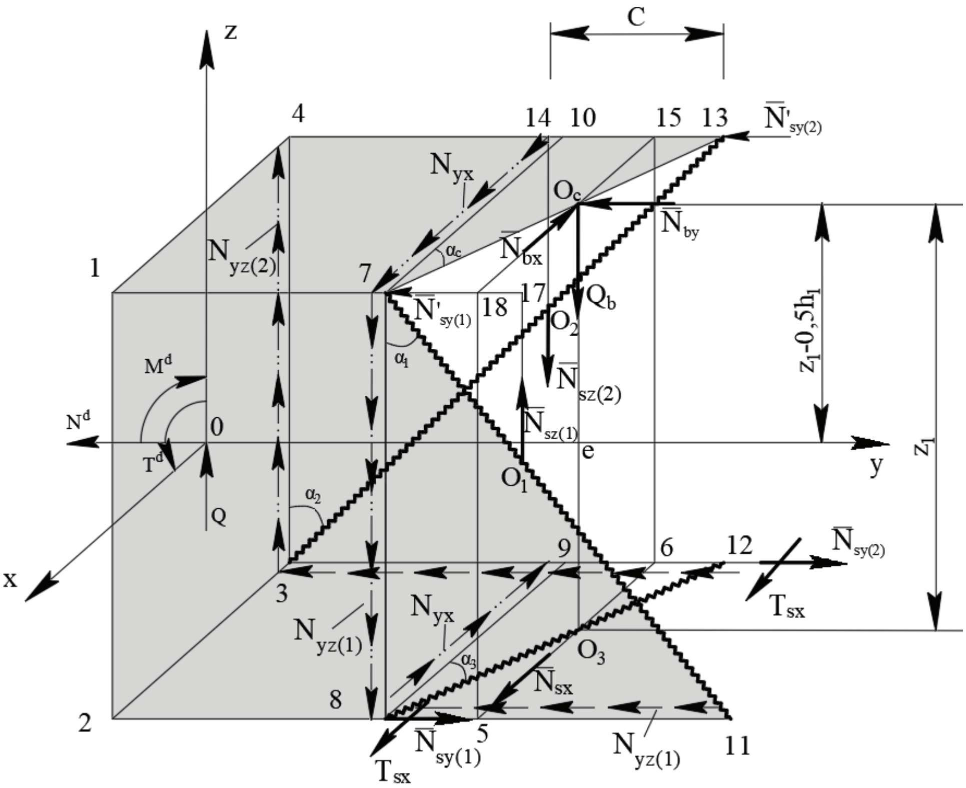


Figure 2. *Scheme of formwork and reinforcement of a reinforced concrete frame*

The calculation scheme for determining the stress-strain state in the section after the formation of spatial cracks in the crossbars of the frame was adopted on the basis of the hypotheses and main provisions of the deformation model proposed in [16, 17]. In the calculation, the given rectangular section of the crossbar is modeled by a box-shaped section. At the same time, an additional hypothesis is introduced that the scheme of the calculated spatial section in the limiting and transcendental states (Fig. 3) does not change after the application of a special impact. Depending on the ratio of torque and bending moment T/M and, accordingly, the nature of the stress state of the element, the angles of inclination of the spatial crack can change α.

The algorithm for calculating the frame according to the primary and secondary design schemes includes the following steps.

1. In the primary design scheme for given design loads P_i applied to the frame with eccentricity e and the initial stiffness of the sections of the frame elements B_0, the forces in the crossbars are determined and the condition for the formation of a spatial crack from these forces is checked.
2. If a spatial crack formed in the most stressed section of the crossbar, the stiffness of the crossbar section is calculated taking into account cracks B_1 [18] and the frame is recalculated under the same load.
3. One of the structural elements is removed from the primary design scheme of the frame, for example, the rack of the first floor of the frame, and the reaction in this rack, determined from the calculation according to the primary design scheme, is applied to the secondary design scheme thus obtained in the direction of the axis of the remote rack with the opposite sign.



<u>Figure 3.</u> Calculation scheme of the crossbar section after the formation of a spatial crack with the joint application of torsional and bending moments in the limiting and transcendental states

4. Using the analytical dependence to determine the increment of dynamic forces and dynamic deformations obtained in the frame system under the considered influences [19], dynamic forces, dynamic curvatures and dynamic angles of rotation in the considered spatial section of the crossbar with a crack are calculated.
5. A diagram of the calculated spatial section is built (see Fig. 3) and for this section, the shear longitudinal $\bar{N}_{by}$ and transverse $\bar{N}_{by}$ forces in compressed concrete, the forces in the transverse reinforcement located on the left $\bar{N}_{sz(1)}$ and right $\bar{N}_{sz(2)}$ sides of the element section, the forces in the longitudinal tensile reinforcement located on the left $\bar{N}_{sx(1)}$ are calculated and on the right $\bar{N}_{sz(2)}$ at the lower edge of the crossbar section according to the formulas obtained from the conditions of statics, physical and deformation relations for the considered design section.
The value of the transverse force perceived by the concrete of the compressed zone, with some approximation, can be determined by the formula (1):

$$Q_b \approx \frac{\phi_{b2} R_{bt} bh_0^2}{C} \cdot \beta_Q \qquad (1)$$

where, φ_{b2}–is a coefficient taken equal to 1.5; R_{bt} - design resistance of concrete to axial tension; b - crossbar width; h_0 - working height of the crossbar; C - the length of the horizontal projection of the most dangerous inclined section (cut span).
The value of the longitudinal shear force in compressed concrete:

$$\bar{N}_{bx} = N_{yx} b_1 = \frac{Tb_1}{2(b_1+Z_1)}, \qquad (2)$$

where, $\bar{N}_{bx}$ - tangential force from torque T; b_1 – is the horizontal distance between the rods; Z_1 - the distance from the tensile reinforcement $2F_s$ to the center of gravity of the concrete of the compressed zone.
The value of the longitudinal force in compressed concrete:

$$\bar{N}_{by} = \frac{M}{Z_1} - \left(\frac{T}{4(b_1+Z_1)} - \frac{(Q-Q_b)}{4Z_1}\right)(Z_1 \mathrm{tg}\alpha_1 - \\ - b_1 \mathrm{tg}\alpha_c) - \left(\frac{T}{4(b_1+Z_1)} + \frac{(Q-Q_b)}{4Z_1}\right) * \\ * (Z_1 \mathrm{tg}\alpha_2 - b_1 \mathrm{tg}\alpha_c) - \frac{Tb_1(\mathrm{tg}\alpha_3 - \mathrm{tg}\alpha_c)}{4(b_1+Z_1)} \qquad (3)$$

where, M – is the bending moment in the crossbar; α_c – is the slope angle of the compressed zone line; Q_b – transverse force perceived by the concrete of the compressed zone.
The total forces in the clamps are equal to:

$$\left.\begin{aligned} \bar{N}_{sz(1)} &= N_{yz(1)} Z_1 = \frac{TZ_1}{2(b_1+Z_1)} - \frac{(Q-Q_b)}{2}, \\ \bar{N}_{sz(2)} &= N_{yz(2)} Z_1 = \frac{TZ_1}{2(b_1+Z_1)} + \frac{(Q-Q_b)}{2} \end{aligned}\right\}, \qquad (4)$$

where, $N_{yz(1)}, N_{yz(2)}$ – shear forces in clamps located on the left and right sides of the cross section; Z_1 – the distance from the tension reinforcement $2F_s$ to the center of gravity of the concrete of the compressed zone of the concrete; T – torque; Q_b – transverse force perceived by the concrete of the compressed zone.

$$\begin{cases} N_{sy(1)} = 0.5N_{by} + t_{yz(1)} d_1 \cdot \mathrm{tg}\alpha_1 + 0.5N \\ N_{sy(2)} = 0.5N_{by} + t_{yz(1)} d_1 \cdot \mathrm{tg}\alpha_2 + 0.5N \end{cases} \qquad (5)$$

When calculating forces in longitudinal and transverse reinforcement and compressed concrete of a three-dimensional section, the values of torque T_{n-1}^d and bending moment M_{n-1}^d obtained from the calculation according to the secondary design scheme are used, taking into account dynamic additional loads from special effects.
6. The criteria for a special limit state established by the requirements are checked (SP 385.1325800.2018 "Protection of buildings and structures against progressive collapse" with Amendments No. 1, 2, 3) for the values of curvatures and angles of rotation and limiting longitudinal and transverse deformations for compressed concrete of the section and

stretched longitudinal and transverse reinforcement.

Numerical studies and analysis of results

To evaluate the effectiveness of the proposed calculation model, a calculation of a reinforced concrete frame was carried out, the test results of which are given in publications [20, 21]. In accordance with the above algorithm, the static calculation of the frame according to the primary and secondary design schemes was performed with the following initial data: frame span l = 1050 mm, storey height h = 450 mm, crossbar section height hr =100 mm, crossbar section width b = 100 mm. Reinforcement of the crossbar and above the first floor A_s and A_s' is taken from rods with a diameter of 6 mm. The transverse reinforcement is adopted in the form of closed clamps made of wire with a strength equivalent to A240 with a diameter of 2 mm. The pitch of the transverse reinforcement on the supporting sections is 40 mm in a span of 60 mm. Frame construction concrete adopted B15.

In accordance with the algorithm, dynamic curvatures and dynamic angles of rotation were calculated using the formulas given in [19] for two variants of the stress state: option 1 - under the load Pi when there are no cracks in the frame crossbars and option 2 - under the load Pi at which inclined spatial cracks. As a result of the calculation for these options, the values of bending and torque moments were calculated in the original n-fold statically indeterminate frame, in the frame with the left post removed according to the secondary design scheme and the moments calculated according to the secondary design scheme, but taking into account the dynamic additional loading from the considered special impact (Fig. 4). The values of the coefficient of dynamic additional loading were determined as the ratio of the dynamic moment in the n-1 system to the static moments in the same system according to the formula:

$$\theta = \frac{M_{n-1}^{d}}{M_{n-1}^{st}}. \tag{6}$$

According to formulas (4)-(5), the stress values in the longitudinal and transverse working reinforcement located on the left and right in the design section were calculated (see Fig. 3).

a) b)

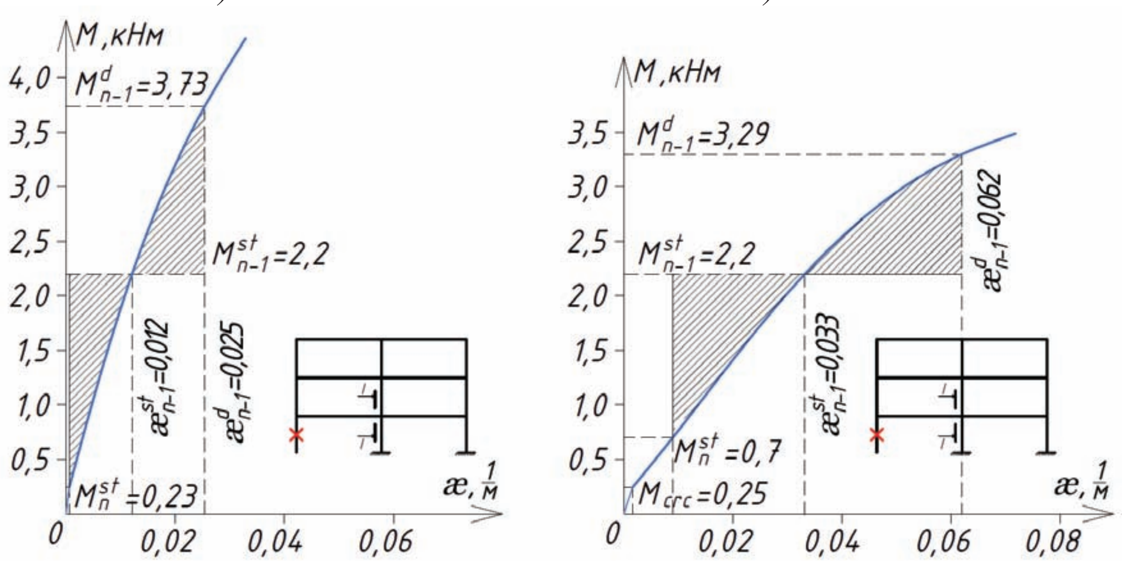
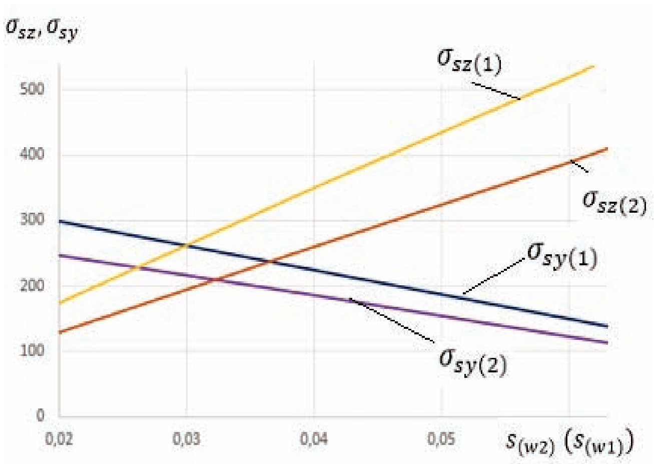


Figure 4. Diagrams of static-dynamic deformation of section 1-1 after an emergency impact when it is applied to a frame without cracks from the action of loads Pi (a) and in a frame with cracks (b)

Analyzing the results obtained (Fig. 5 a), it can be seen that with an increase in the ratio of torque to bending moment (ξ), the stress state in the clamps of the crossbar located to the left and right of the calculated section increases. The stresses in the longitudinal reinforcement located on the left and right at the lower edge of the section, on the contrary, decrease.

From a comparison of the obtained dependences for stresses in longitudinal and transverse reinforcement according to the results of calculation for the first and second options (without cracks - dependence 1 and with cracks - dependence 2 in Figure 5b in crossbars when design loads Pi are applied at the first stage of loading), it can be seen that the stress state in the transverse and longitudinal reinforcement under loading of a frame with cracks is significantly greater by a special effect than when the frame is loaded when there are no cracks in it under the design load. It follows from this that the dissipative properties of reinforced concrete frames with cracks under operational load are higher than in structures without cracks. The same applies to the stressed state: the dissipative properties of the crossbar loaded with torque and bending moment increase with increasing ratio ξ (Fig. 5b).

a)



b)

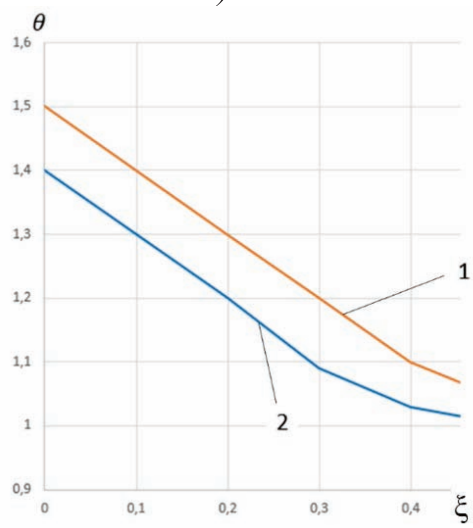


Figure 5. Dependences for stresses in the clamps «$\sigma_{sz}-s_{w2}$» and stresses in the longitudinal working reinforcement «$\sigma_{sy}-s_{w1}$» (a) and the dependence of the coefficient of dynamic additional loads θ on the ratio of torque to bending moment ξ in the design cross section of the crossbar (b): 1- when applying a special effect to the frame without cracks; 2- the same, to the frame with cracks

CONCLUSIONS

The parameters of the stress-strain state in the complexly stressed design section of the crossbar under the considered loading mode are determined based on the model of the spatial section passing through the spatial crack. The limiting state of the calculated section is determined by the deformation criteria for concrete and reinforcement.

1. A deformation model and an algorithm for calculating a multi-storey reinforced concrete frame with complexly stressed crossbars, in a transcendental state caused by a special emergency impact, are built.
2. The determination of dynamic forces in complexly stressed crossbars under the combined action of bending and torsional moments, loaded with an operational static load and dynamic additional loading in the form of a

sudden removal of one of the structures from the frame structural system, was performed on an energy basis using deformation diagrams of the design section "bending moment - curvature" and "torque - angle of rotation".

3. The parameters of the stress-strain state in the complexly stressed design section of the crossbar under the considered loading mode are determined based on the model of the spatial section passing through the spatial crack. The limiting state of the calculated section is determined by the deformation criteria for concrete and reinforcement.

4. The proposed model of static-dynamic deformation of complexly stressed reinforced concrete elements can be used in the design of protection of reinforced concrete frames of multi-storey buildings from progressive collapse.

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