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Deformation criteria for reinforced concrete frames under accidental actions

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Abstract. A review of scientific research on survivability and protection of buildings from progressive collapse showed that despite the researchers' increasing interest in the problem, many tasks in this area are waiting to be solved. The subject of the study in this work was the study of the parameters of the capacity curves of cross-sections of reinforced concrete elements of constructive systems of building frames under their static-dynamic loading conditions. This paper presents a methodology for determining the parameters of "load-deflection" curves and the deformation criterion for accidental limit state of a reinforced concrete element of statically indeterminate frame-rod constructive systems under an accidental action caused by removing one of the load-bearing elements from the constructive system. Two stages of loading such systems are considered: static loading to a specified design level and additional dynamic loading caused by a sudden structural rearrangement of the constructive system from the mentioned action. At the first stage of loading, the relative parametric load of cracking in an arbitrary cross-section of the reinforced concrete element of the constructive system and the sequence of formation of plastic hinges in this element is determined using an extraordinary version of the mixed method of structural mechanics of rod systems. At the second stage, the limit value of the relative parametric load is determined on an energy basis without using the structural dynamics apparatus. An algorithm for calculating parameters of the capacity curve of cross-sections of reinforced concrete elements of constructive systems under the considered actions and calculation results of the "relative parametric load-deflection" curve for the most stressed cross-section of the reinforced concrete frame when a middle column is removed from it are presented. The calculated values of the deforming cross-section parameters are compared with experimental data. It is shown that the use of parametric load in the proposed calculated dependencies for analyzing the sequence of formation of plastic hinges in the constructive system is in satisfactory agreement with the test results of such constructive systems under the considered loading regimes.

1. Introduction

Currently, in the regulatory documents of many countries, when designing constructive systems of buildings, an analysis must be performed to protect against progressive collapse, in particular, to check the criteria for an accidental limit state for elements of a constructive system when one of the supporting structures, for example, one of the columns of the first floor of a building, is suddenly removed from it. And despite the fact that scientific research in this area around the world has been intensively conducted since the end of the last century, after the well-known event with the Ronan Point tower in London [1], answers to many scientific questions about this problem have not yet been received. And if the term "progressive (disproportionate) collapse" is clearly understood by scientists in various countries as a sequential (chain) failure of load-bearing building structures, leading to the collapse of the entire structure or its parts due to

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a sudden local failure [2–5], the criteria for protection against such failure are understood and accepted far from unambiguous. Moreover, even terminologically, these criteria are designated differently: limit state criteria [6–9], beyond limit state criteria [2, 3], accidental limit state criteria [10, 11]. In the most rapidly developing algorithms for numerical modeling of these processes, for example [12, 13], traditional physical models of material deformation are laid, without taking into account the specifics and mechanisms of the considered loading regime of structures, and despite the fact that such models are the most representative and can be relatively universal, the practical recommendations for designing that follow from these models are not confirmed experimentally are of a particular nature and are often questionable. Moreover, such models are very demanding in terms of computational capabilities (see, for example, [14]), which, taking into account the requirements for the qualification of the constructor, allows them to be used in design practice only in special cases.

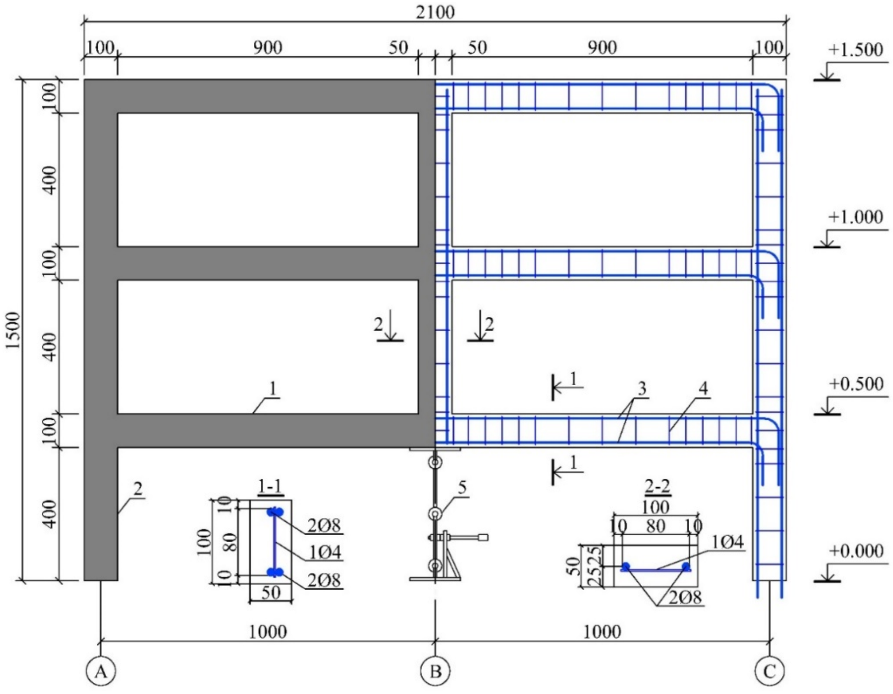
There are also known alternative approaches to solving problems of considered class, focused on analytical and semi-analytical methods of analysis using the concept of the so-called " alternate load path" and structural level models for these problems [5, 15, 16]. In these solutions, the physical side of deformation is associated with the mechanisms of progressive collapse development, followed by the available experimental studies results. Assessment of dynamic forces arising in this case in cross-sections of constructive system elements is most often made on an energy basis, the idea of which was first expressed still a quarter of a century ago by prof. G.A. Geniev [17] and which is currently used in many researches, for example [16, 18, 19]. At the same time, the material stress–strain curves in these researches are accepted as for the regime of one-stage static loading, without taking into account the time of removal of the supporting structure and the features of cross–section deformation under high-speed loading (impact), see, for example, the research [6, 10, 20–22]. And this, as established by experimental studies [23–25], significantly affects the ultimate strains and strength properties of structural materials and, accordingly, the deformation or strength criteria of an accidental limit state accepted for analysis.

One of the criteria for the accidental limit state of reinforced concrete elements of statically indeterminate constructive systems of buildings in scientific publications [3, 7, 11, 20, 26] and current regulatory documents is the condition for limiting the ultimate deflections of the structure after removing one of the constructive elements, the excess of which is taken as the exhaustion of the load-bearing capacity of the constructive system. At the same time, the analysis of deflections of reinforced concrete elements of the considered structures using traditional "moment-curvature" curves, especially static capacity curves, can be performed to the load level, when the reinforced concrete element is crushed by compressed zone, divided into separate blocks and turns into a hanging system. Such a solution for the simplest structurally nonlinear statically indeterminate beam was considered, for example, in [27, 28]. But this solution is limited to the first two criteria of failure, defined by limiting the ultimate strains of concrete or rebar. There are very few works devoted to the study of deformation of reinforced concrete constructive systems during their transformation from rigid to flexible hanging systems, and the available solutions, even such detailed ones as [18–22], also use diagrams of static deformation of concrete and reinforcement.

This work aimed to determine the parameters of static-dynamic capacity curves and strain criteria for concrete frames with their structural rearrangement from rigid systems in hanging when the sudden removal of constructive systems of one of the bearing structures. The main investigated parameters were the relative load levels at which cracks and plastic hinges formed in the frame elements during static load increase and their subsequent dynamic additional loading after removal of one of the columns, and the deformation criteria for failure of the constructive system under the considered static-dynamic loading regime.

2. Methods

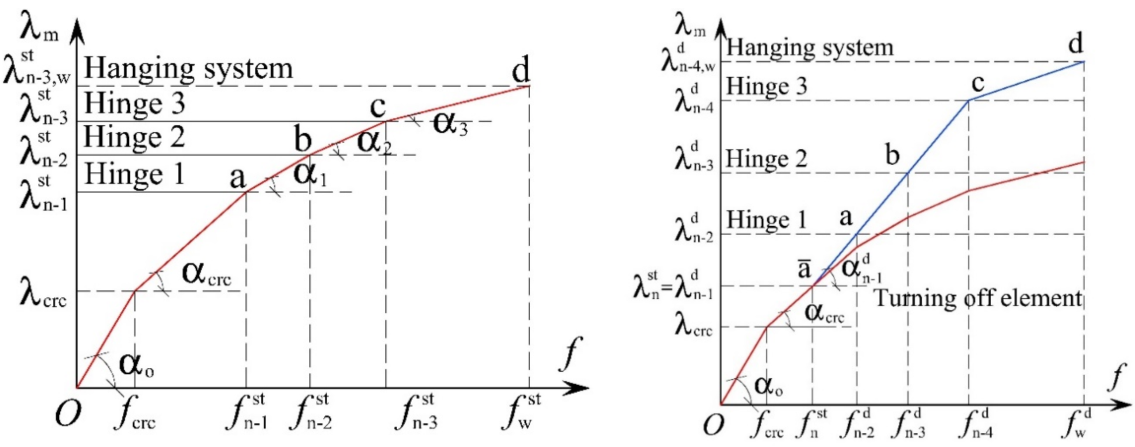
Consider the frame-rod constructive system of a reinforced concrete building, the beams of which are reinforced symmetrically with reinforcing bars in the upper and lower zones (Fig. 1). Such reinforcement and reliable anchoring of reinforcing bars of beams with their lead into the body of the column are aimed at ensuring the work of the loaded system under accidental limit state caused by removing one of the columns, and the sudden redistribution of force flows in the frame system.



a **b**

Figure 1. The formwork scheme (a) and the reinforcement scheme (b) of the frame structure: 1 – beam; 2 – column; 3 – longitudinal reinforcement; 4 – transverse reinforcement; 5 – equipment modeling loss of column.

The "parametric load-deflection" curve $(\lambda_m - f)$ of the cross-section of the reinforced concrete element of a constructively non-linear system at all levels of its deformation under static and static-dynamic loading in a general form can be represented by graphs in Fig. 2.



a **b**

Figure 2. "Relative parametric load – deflection $(\lambda_m - f)$" curves of a cross-section of a reinforced concrete element of a physical and constructive nonlinear system: a – under static loading; b – under static loading and dynamic additional loading.

We define the characteristic points of these graphs. Let a statically indeterminate frame-rod constructive system be given, loaded with forces λP_i applied at arbitrarily given points at distances $al_1,\ al_2$ from the supports along the length of the span of each beam (Figure 3). Moreover, the load on the beam is accepted as parametric, and their change occurs in proportion to a certain parameter λ. Cross-sections $C_1, C_2, ..., C_k$ where it is possible to turn off connection (the formation of plastic hinges or brittle failure of a cross-section on compressed concrete) as the parameter λ increase are known: these are nodes of the frame-rod system, points of application of concentrated forces, points of change in the stiffness of the rod system.

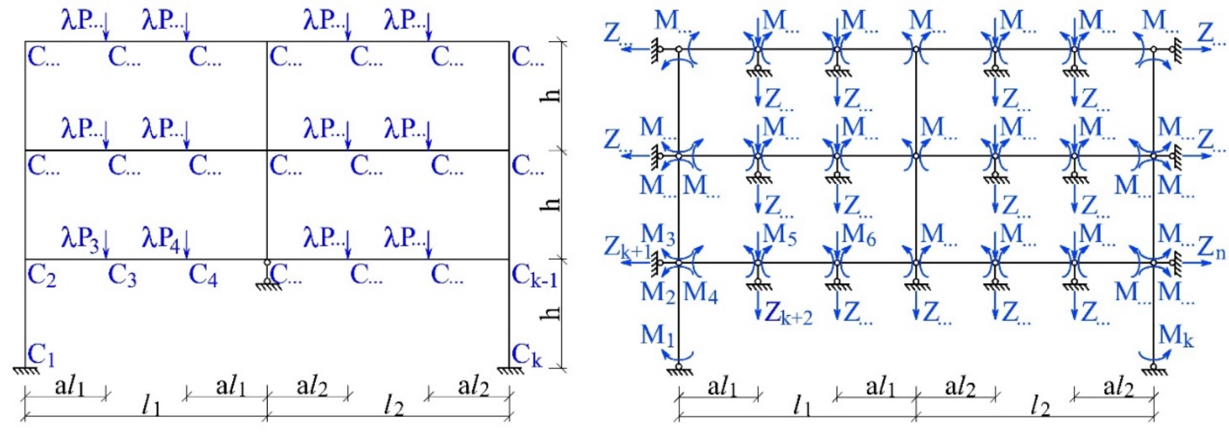
As the frame-rod system is loaded to the level $\lambda_{crc}P_i$ (see Figure 2a), cracking begins in the most stressed cross-section of one of the elements of the constructive system. Accordingly, the stiffness of the considered cross-section changes from the initial stiffness $B_0 = tg\alpha_0$ to the stiffness of the element with cracks $B_{crc} = tg\alpha_{crc}$. The calculation of this stiffness is performed according to the dependences known in the theory of reinforced concrete, for example, the formulas of [29].

With further loading of the constructive system with a static load in the frame structure, the process of cracking in the considered and other frame elements continues. At a certain level of load $\lambda_1 P_i$, in one of the cross-sections of the most stressed element, the first plastic hinge is formed, and its rigidity will accordingly decrease to a value $B_1 = tg\alpha_1$. A further increase in the load to levels $\lambda_2 P_i$ and $\lambda_3 P_i$ will lead to the formation of a second and then a third plastic hinge in the beam and the element under consideration turns from rigid to flexible. The reinforcement begins to work in tension as a cable.

After an accidental action is imposed on the loaded constructive system in the form of a sudden column removal from the frame system, its static indeterminacy decreases, and the force flows are redistributed from the structural rearrangement of the constructive system. Accordingly, the forces M_j in the cross-sections of the beams of the frame change, and the loading regime of the beam changes from static to dynamic. The determination of forces M_j in a constructive system after such an action can be performed using an extraordinary version of the mixed method [30]. The essence of the method is that the mixed calculation method's main system is selected in the form of a hinged-rod polygon with the connections removed at the places of possible switching off and replacing them with unknown ones M_j $(j = 1, 2, ..., k)$ (Figure 3a, b). If a geometrically variable main system is formed when the connections are removed, then additional connections are superimposed Z_i $(i = k+1, k+2, ..., n)$.

In this case, the stage of static loading with initial stiffness to the level $\lambda_{crc}P_i$ remains unchanged. Then, upon further loading of the *n*-times static indeterminate constructive system to the level of the given static load λ_n^{st} (see Figure 2b), the cross-section of the beam is deformed as in the case of static loading of the initial *n*-times statically indeterminate frame.

Using the main system selected as described, the relative parametric load $\lambda_m P_i$ can be determined at which one of the criteria for an accidental limiting state is achieved in the most stressed cross-section of the beam under static-dynamic loading of the frame. As with static loading, the index *m* determines the level of relative load $\lambda_m P_i$ at which, after the imposition of accidental action in the form of removing one of the columns of the frame in one of the cross-sections of the most loaded beam adjacent to the removed column, the ultimate moment is reached, i.e., the first plastic hinge is formed. Then, as the dynamic load increases, the second and third hinges are formed (on the curve, the hinges' formation is indicated by points $\lambda_{n-2}^d, \lambda_{n-3}^d, \lambda_{n-4}^d$, respectively). If, after the formation of the third plastic hinge, the deformation of the reinforcement does not reach the limiting values and its anchoring in the support cross-sections of the beam is not violated, then the construction of the continuous beam from a rigid beam turns into a variable cable system, which only resists tension. On the graphs "$\lambda_m - f$" this relative load is indicated by $\lambda_{n-4,w}^d$. In this case, the third criterion for the accidental limiting state is checked - the criterion for the maximum allowable deflection of the structure f_w^d.



a b

Figure 3. The specified (a) and main (b) system of the mixed method for determining the parametric load.

Analyzing the capacity curve of the cross-section of the reinforced concrete element can be noted that the segment of the successive formation of plastic hinges «$\bar{a}-a-b-c$» in the static-dynamic capacity curve differs from the analogous segment in the static capacity curve of the cross-section in that it does not have turning point caused by the reduced and manifest in the time of bending stiffness of the beam cross-sections. The absence of these turning points in the segment of the dynamic capacity curve «$\bar{a}-a-b-c$» of the beam cross-section is explained by the adopted two-element model of high-speed dynamic deformation of reinforced concrete [16, 31] according to which the work of a purely viscous element (Kelvin-Voigt) ends at a very small value of time *t*, reported from the moment of the beginning of dynamic loading, having, according to experimental data [3, 29, 32, 33] the order of tenths and even hundredths of a second. However, over this interval of time, the viscous element in the two-element model contributes to the inhibition of the development of strains initiated in the elastic element and, consequently, to an instantaneous increase in the cross-section stiffness on the segments of dynamic deformation "$\bar{a}-a-b-c$" equal to $B_{n-1}^{d} = tg\alpha_{n-1}^{d}$ (see Fig. 2b).

The parameters of the presented static-dynamic capacity curve “relative parametric load-deflection” for an arbitrary cross-section of the frame-rod system can be calculated using a specially constructed system of canonical equations of an extraordinary version of the mixed method (see Fig. 3), in which the load coefficients are presented in the form two terms [30].

$$\left.\begin{aligned} A\cdot\vec{M}+B\cdot\vec{Z}+\vec{\Delta}_q+\vec{\delta}_p\cdot\lambda=0 \\ C\cdot\vec{M}+D\cdot\vec{Z}+\vec{R}_q+\vec{r}_p\cdot\lambda=0 \end{aligned}\right\}, \tag{1}$$

where $A, B, \vec{\Delta}_q, C, D, \vec{R}_q$ are the matrix coefficients of unknowns mixed method; $\vec{\delta}_p$ is the matrix of displacements in the direction of remote connections from an external parametric load P_i at $\lambda=1$; $\vec{r}_p$ is the reaction matrix in superimposed connections of the main system from an external parametric load at $\lambda=1$.

Given the properties of the canonical equations of the mixed method $C=-B^T$, where the index "T" means the transpose operation, we rewrite the system of equations in the form:

$$\begin{Vmatrix} A & B \\ -B^T & 0 \end{Vmatrix}\cdot\begin{Vmatrix} \vec{M} \\ \vec{Z} \end{Vmatrix}+\begin{Vmatrix} \vec{\Delta}_q \\ \vec{R}_q \end{Vmatrix}+\begin{Vmatrix} 0 \\ \vec{r}_p \end{Vmatrix}\cdot\lambda=0. \tag{2}$$

The solution to this system is:

$$\begin{Vmatrix} \vec{M} \\ \vec{Z} \end{Vmatrix}=\begin{Vmatrix} \vec{M}_q \\ \vec{Z}_q \end{Vmatrix}+\begin{Vmatrix} \vec{m}_p \\ \vec{z}_p \end{Vmatrix}\cdot\lambda \tag{3}$$

where

$$\begin{Vmatrix} \vec{M}_q \\ \vec{Z}_q \end{Vmatrix} = -\begin{Vmatrix} A & B \\ -B^T & 0 \end{Vmatrix}^{-1} \cdot \begin{Vmatrix} \vec{\Delta}_q \\ \vec{R}_q \end{Vmatrix}; \begin{Vmatrix} \vec{m}_p \\ \vec{z}_p \end{Vmatrix} = -\begin{Vmatrix} A & B \\ -B^T & 0 \end{Vmatrix}^{-1} \cdot \begin{Vmatrix} 0 \\ \vec{r}_p \end{Vmatrix}. \quad (4)$$

The value of the forces in the turned off connections of the constructive system from the total action of the given and parametric loads are calculated by the formulas:

$$M_j = M_{jq} + m_{jp} \cdot \lambda, \left(j = 1, 2, ..., k \right), \quad (5)$$

where M_{jq} and m_{jq} are the column matrix elements $\vec{M}_p$ and $\vec{m}_p$.

Criteria verification of survivability[1] of a physical and constructive nonlinear system under accidental action is performed based on the calculation of the parameters of capacity curve “ $\lambda_m - f$ ”. Turning off the moment connection (the formation of a plastic hinge with a limited deformation branch) in one of the elements of the frame system after removing one of the columns will occur in the case when, at the ultimate moment $M^d_{j,ult}$ in compressed concrete or tensile reinforcement, ultimate deformations are reached. Then, for all forces in turning off moment connections, the system of inequalities must be satisfied:

$$\left| M_j \right| = \left| M_{jq} + m_{jp} \cdot \lambda \right| \le M^d_{j,ult}, \left(j = 1, 2, ..., k \right), \quad (6)$$

where $M^d_{j,ult}$ is the ultimate value of the dynamic forces in the turned off connection.

On the left side of the system of inequalities (6), M_j is taken in absolute value, since the presence of a negative sign of M_j indicates that the direction of this force is opposite to the ultimate value of the force accepted in the main system.

The minimum value of the parametric load λ_m $(m = 1, 2, 3)$ at which the maximum value of the moment is reached in the most loaded cross-section of the beam C_j under the considered accidental action can be determined by the formula:

$$\lambda_m = \min \left(\frac{M^d_{j,ult} \pm \left| M_{jq} \right|}{m_{jp}} \right), \left(j = 1, 2, ..., k \right). \quad (7)$$

The “minus” sign in the numerator is accepted if M_{jq} and m_{jp} match and vice versa.

The end of the beam's deformation stage as an invariable structure $\lambda = \lambda^d_m$ $(m = n-2, n-3, n-4)$ occurs when the ultimate values of the moments are reached in the three cross-sections of the beam, and the cross-sections undergo local failure in compressed concrete at $\varepsilon_b = \varepsilon_{bu}$ (Figure 4a).

Up to this moment, the displacements (deflections) of cross-sections where the ultimate deformations of concrete $\varepsilon_b = \varepsilon_{bu}$ are achieved occur as in a rigid-plastic body from bending and turning cross-sections. If the reinforcement deformations do not reach the limiting values $\varepsilon_s < \varepsilon_{su}$, then the work of the beam construction passes from the stage of elastic-rigid-plastic deformation to the stage of work as a hanging system, when the reinforcement A_s and $A_s^{'}$ acts as tensile cables(Figure 4b). Rigid concrete blocks "hang" on reinforcing bars (cables). The limit value of the deflection of the beam at this stage is determined as for a cable system by the known dependencies of structural mechanics. In this case, the criterion of an accidental limiting state becomes the maximum deflection $f = f^d_w$ determined by calculation as for a hanging system. The experimental data on the relative value of this deflection before the rupture of the

[1] Here, the term "verification of survivability" refers to modeling the progressive collapse resistance of the constructive system of a building, which boils down to finding an initial local failure in one of the most stressed cross-sections of the system and sequentially propagating this failure (the sequence for turning off new connections), taking into account a decrease in the degree of static indeterminateness of the system, and also the dynamic effect caused by the sudden turning off the first and subsequent connections.

reinforcement in the tests of different authors vary significantly and range from 1/30 span in the studies [23, 25, 34] to 1/20 and even 1/10 in the study [35–37]. As a standardized value in Russian Standards SP 385.1325800.2018, carefully, for all types of reinforcement, the value 1/50 of the span is taken.

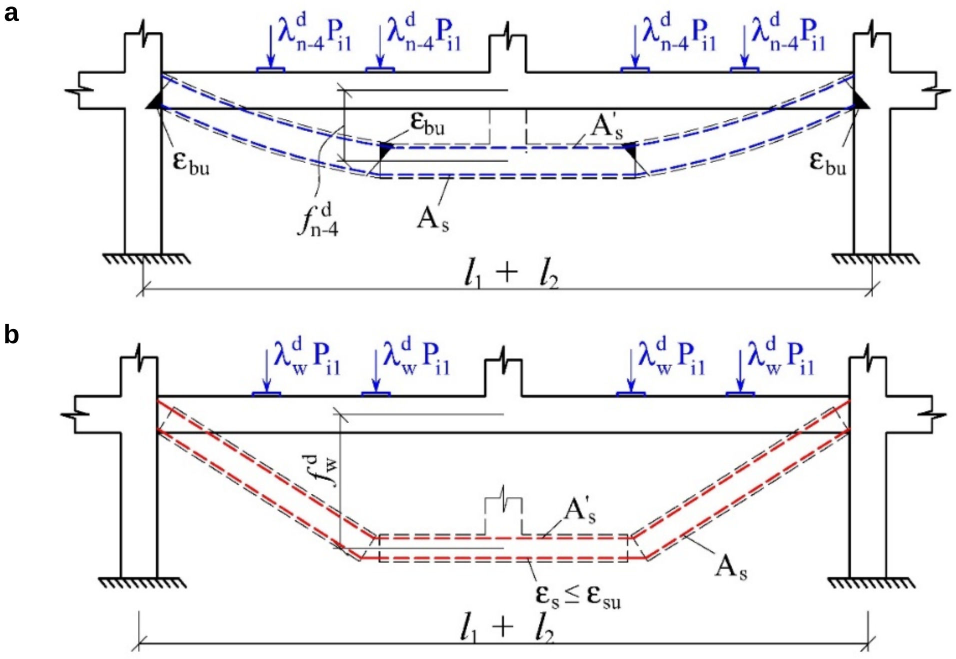


Figure 4. The scheme of displacement in the considered double-span beam substructure as an elastic-rigid-plastic body (a) and as a cable (b).

3. Results and Discussion

The reliability of the proposed model was evaluated by comparing the experimental results conducted by the author and other scientists.

3.1. Static-dynamic tests

For analysis, experimental studies of the static-dynamic frame test carried out in [29] are considered. In the experimental structure of a two-span three-story frame of the third series, the beams' reinforcement is symmetrical in the upper and lower zones by two rods with a diameter of 8 mm of class A500. The reinforcement scheme of the experimental structure is shown in Fig. 1. The beams' transverse reinforcement is adopted from a wire with a diameter of 2 mm in increments of 50 mm and 100 mm. The construction is made of fine-grained concrete of class B40.

When calculating the experimental frame structure, a two-stage regime of its loading is considered. At the first stage, the structure was loaded with concentrated forces λP_i according to the scheme of Figure 3a, symmetrically applied by two forces to each beam to the level of relative value $\lambda = 1$. The value of the relative load corresponding to the formation of cracks λ^{st}_{crc} was 0.44. The actual value of the load at the first stage of loading was $\lambda P = 2.64$ kN. At the second stage of loading, an accidental action was applied to the loaded structure with the load of the first stage in the form of the sudden removal of the central column.

The parameters of the "relative load-deflection" curve for the most strained cross-section of the beam 1-1 above the first floor of the frame (see figure 1) were calculated using the considered algorithm and the Matlab program for solving the system of equations (3). The cross-sectional stiffness of the beam B_{crc}, B^d_{n-1} respectively determined by crack formation during loading of the constructive system and its structural rearrangement after removal of the central column, were calculated using the formulas of [29]. At the same time, an increase in the dynamic stiffness of the considered cross-section caused by high-speed loading of constructive system elements under accidental action was taken into account in the segment $\overline{a} - c$ of the static-dynamic capacity curve (Figure 5).

The obtained parametric "relative load-deflection" ("$\lambda_m - f$") curve allows us to analyze the nature of nonlinear deformation of the frame-rod constructive system taking into account crack formation in the cross-sections of the beams (λ_{crc}^{st}) at the first loading stage $0-\bar{a}$, to determine the beginning of the structural rearrangement of the system ($\lambda_n^{st} = \lambda_{n-1}^{d} = 1$) the formation sequence of the first and second plastic hinges in the beam ($\lambda_{n-2}^{d} = \lambda_{n-3}^{d} = 1.22$ and $\lambda_{n-4}^{d} = 1.84$), as well as the beginning of the failure of the considered structure of the beam ($\lambda_{n-4,w}^{d}$) due to the formation of a third plastic hinge and the transformation of the beam into the hanging system.

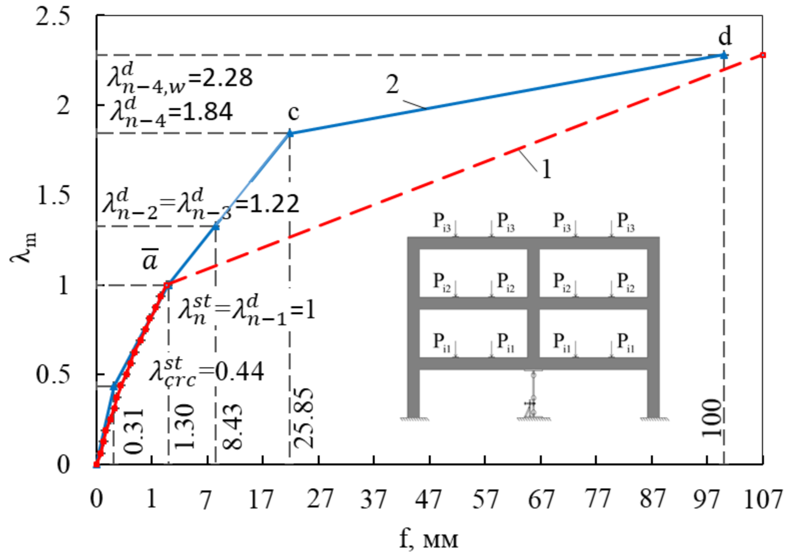


Figure 5. Capacity curves of static-dynamic loading "$\lambda_m - f$" of cross-section 1-1 of the beam of a physical and constructive nonlinear frame of the third series [29]: experiment (1); calculation (2).

A comparison of the experimental and calculated curves of static and static-dynamic deformation of the studied reinforced concrete frame-rod system (curves 1 and 2) indicates the acceptability of using the presented analytical dependences to calculate the main parametric points of the "parametric load-deflection" capacity curve graph describing the deformation of physical and constructive nonlinear frame rod systems under accidental actions caused by sudden structural rearrangement in such systems.

3.2. Quasi-static tests

The test results of the double-span beam substructures given by Jun Yu and Kang Hai Tan in [23] are also considered for analysis. The loading regime of the substructures in the first and second stages was static. Fig. 6 shows the "relative parametric load-deflection" curve for the structures of two experimental series. Substructures differed among themselves in the percentage of reinforcement of cross-sections.

The following conclusions can be drawn from the analysis of Figure 6. The calculated capacity curves satisfactorily describe the key points of the experimental curves: $\lambda_{n-1}^{st}, \lambda_{n-2}^{st}, \lambda_{n-3}^{st}, \lambda_{n-3,w}^{st}$. The theoretical ratio $\lambda_{n-3}^{st} / \lambda_{n-1}^{st} = 1.4$ agrees well with the experimental data and confirms the significant influence of constructive nonlinearity established in experiments on the survivability of the structure. An increase in the reinforcement ratio of a structure significantly increases its bearing capacity at the stage of work as a hanging system ($\lambda_{n-3,w}^{st} = 2.88$ at $\mu = 1.87\%$ and $\lambda_{n-3,w}^{st} = 2.1$ at $\mu = 1.24\%$). The ultimate deflection of the structure at the stage of work as a hanging system was 1/30-1/10 of the span, which is in good agreement with the data obtained in similar studies under static loading regimes of constructive nonlinear systems [28, 32, 35, 36].

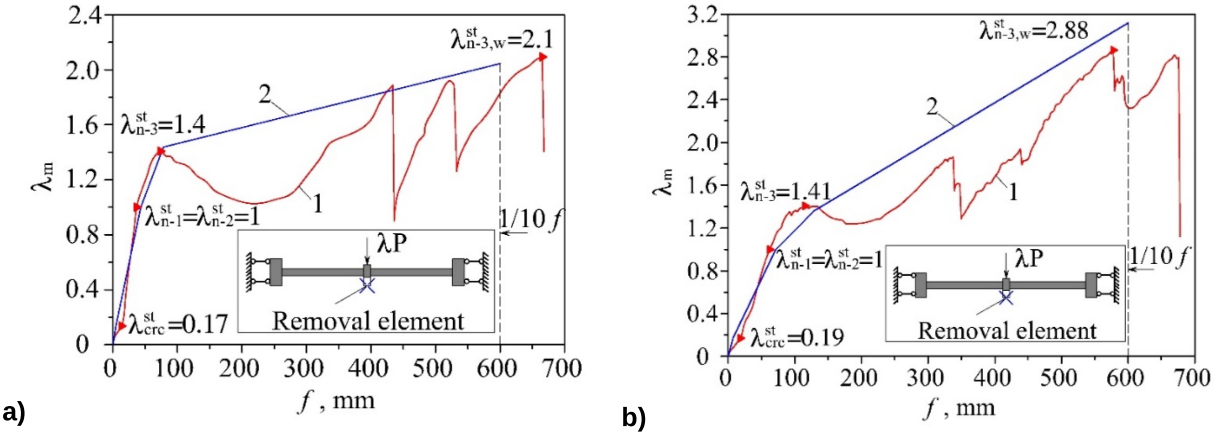


Figure 6. Capacity curves under quasi-static loading " $\lambda_m - f$ " for the structure of beams with different percentages of reinforcement (μ): a- at $\mu = 1.24\%$, b- at $\mu = 1.87\%$; experiment (1), calculation (2).

4. Conclusions

1. The presented methodology and algorithm make it possible to calculate the parameters of the "relative load-deflection" curve of the cross-sections of reinforced concrete elements of constructive systems under static loading and their subsequent dynamic additional loading, taking into account physical and constructive nonlinearity.

2. To determine the calculated parameters of the capacity curve of reinforced concrete elements the constructed system of canonical equations of an extraordinary version of the mixed method is proposed in a special way, which allows one to calculate the parametric load at which ultimate forces are reached in the cross-sections of the constructive system elements, accordingly, the degree of static indeterminacy of the constructive system changes and its survivability is exhausted.

3. The proposed algorithm for calculating the parameters of the “parametric load-deflection” curves for physical and constructive non-linear reinforced concrete frame-rod constructive systems can be used in designing the protection of building and structures frames from progressive collapse under accidental actions.

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