Progressive collapse behaviour of compressed-bent rods of RC moment frames at sudden column removal

Sergey Savin

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia

E-mail: savinsyu@mgsu.ru

Abstract. Due to the increasing incidence of disproportionate destruction of structural elements after the sudden removal of any supporting element, the number of studies of the resistance of structural systems to progressive collapse has grown significantly. However, among the research results presented in the scientific literature, there are practically no such studies in which an analysis of the resistance of compressed and compressed-curved reinforced concrete elements to disproportionate destruction would be performed. Therefore, in this paper, using the step-iteration method (Lira-CAD software) and non-linear stability analysis, we analyzed the behavior of the frame model when the column of the outer row was suddenly removed. In order to solve this problem, the analytical dependences are obtained for evaluating the stiffness of sections of compressed and compressed-curved elements. It has been established that the disproportionate fracture mechanism of compressed-bent elements of frame model is associated with a loss of stability.

1. Introduction

The growth rate of construction over the past decades has led, among other things, to an increase in the number of cases of sudden failures of structural elements of structural systems. A number of accidents at capital construction sites that have occurred in the world since the 1960s have shown that the sudden failure of one load-bearing element of a structural system can lead to a disproportionate failure of the surviving elements of the structural system [1]. In this regard, studies of the resistance of structural systems to progressive collapse during the removal of one of the load-bearing elements have been actively developed in the theory of structures.

A significant number of scientific publications in this field are devoted to the study of resistance to progressive destruction of bent or stretched elements of structural systems [1–8]. In this case, the issues of resistance of compressed-bent structural elements, which include columns, pylons and prestressed girders, are not given due attention in the scientific literature. A few works in this direction are mainly devoted to studies of the resistance of steel moment frames [9–11]. In relation to reinforced concrete, these works are even scarcer [12–14]. Moreover, all the noted works are linked with the numerical modeling of the deformation and destruction of structural systems under emergency impacts. One of the most frequently used calculation methods for such a numerical analysis is the step-iteration method, taking into account physical and geometric nonlinearity. However, when using the step-iteration method, the calculation uses a slightly overestimated value of the deformation modulus. This circumstance does not lead to large discrepancies in solving the problems of
determining deformations; however, in this connection, the question of a possible loss of stability, which may be accompanied by a sharp change in the deformation mode of the structural system, remains unexplored. In this regard, the subject of this study is the resistance to progressive collapse of compressed-bent structural elements of a reinforced concrete moment frame during the redistribution of power flows associated with the sudden removal of the outer column.

2. Models and methods
In order to identify the features of deformation and fracture of compressed-curved elements of a reinforced concrete structural system, a numerical analysis of the resistance to progressive destruction of the physical model of a reinforced concrete frame (scale 1:8), prepared for full-scale tests, was performed. The frame under consideration is under the action of a load from its own weight and concentrated forces statically applied in the upper nodes of the frame. The material of the frame is concrete - B20, the reinforcement of the uprights and crossbars is a spatial framework with a longitudinal class A400 and transverse reinforcement B500. A distinctive feature of the frame under consideration is that the columns of the second floor have significant flexibility in excess of 20 (Figure 1, a). Considering that the effective dimensions of the cross sections of the columns will decrease during deformation due to the development of plastic deformations in concrete and crack formation, the value of flexibility during loading will increase. In the case of additional loading caused by the redistribution of power flows in the structural system when one of the load-bearing elements is removed, the flexibility can reach a critical value at which there will be a loss of stability of the deformed state of the structure, and then its destruction.

Consider an emergency situation in which the outer column of the first floor suddenly turns off from the power resistance of the structural system (Figure 1, b). To analyse the resistance of the considered structural system, the quasi static method is used, in the form first proposed in the works of G.A. Geniyev [15, 16]. The approach proposed by him is based on the condition of constancy of the total specific strain energy of a structural element:

$$\Phi(\epsilon^*_n) - \Phi(\epsilon^*_s) = \sigma^*_n(\epsilon^*_n - \epsilon^*_s) \quad \sigma^*_n = 2\sigma^*_{n-1} - \sigma^*_s, \quad N^*_n = 2N^*_{n-1} - N^*_s,$$  \hspace{1cm} (1)

where $\sigma^*_n$, $\sigma^*_s$, $\epsilon^*_n$, $\epsilon^*_s$, $\epsilon^*_u$ – accordingly, stresses and relative strains in the n-1 system (secondary design with rejected coupling) under dynamic (d) and static (s) loading and in the n system under static loading; $\Phi(\epsilon^*_n)$, $\Phi(\epsilon^*_s)$ – accordingly, the potential energy of deformation under dynamic and static loading in systems n-1 and n.

When using this method, instead of the force acting at the stage of normal operation in the “removed” element of the primary calculation scheme (system “n”), a secondary calculation scheme (system “n-1”) is applied with equal in magnitude and opposite in sign generalized force at the place of discarded communication (Figure 1, c).

In connection with the use of idealized two- or three-line diagrams of reinforced concrete deformation, this approach will give somewhat overestimated forces in the elements of the “n - 1” system, since kinetic energy losses associated with the development of inelastic deformations and the viscous resistance of the material will not be taken into account. However, this excess does not negatively affect the bearing capacity of the structure.

In order to obtain the most complete understanding of the nature of the deformation of the reinforced concrete frame under consideration when the first floor column was suddenly removed, two calculation options were used: a static calculation based on a nonlinear deformation model using the finite element method in the Lira-CAD software and a nonlinear stability analysis of the deformed states of the structural system. When calculating according to the nonlinear deformation model by the stepwise method, the tangent deformation modulus by iteration j-1 was used as a parameter characterizing the deformability of reinforced concrete, the use of which in the stability analysis will give a somewhat overestimated value of the critical force (Figure 2).
In the second case, when calculating the stability of the deformed states of the structural system, the tangential modulus of elasticity is used for the final deformed state of the system, which is more consistent with the specifics of the problem of stability loss. In this case, the reduced geometric characteristic of the resistance of the cross sections, which is understood here, as the resistance of the cross sections to deformation from the increment of forces, is a function of the deformations of the edge fibers (Figure 3) [14]:

$$J_{red,0} = J_{red,01} - A_{red,0} \theta_0^2,$$

(2)
\[ J_{\text{red,}0} = \frac{E_s}{E_0} A_y \cdot a^2 + \frac{E_s}{E_0} A_y' (h - a')^2 + b \int_{h-\theta}^{h} \left( 1 - \frac{\varepsilon}{\varepsilon_{bs}} \right) y^2 dy + b \int_{h-\theta}^{h} \left( 1 - \frac{\varepsilon}{\varepsilon_b} \right) y^2 dy, \]  
\[ a_0 = S_{\text{red,}0} / A_{\text{red,}0}, \]  
\[ S_{\text{red,}0} = \frac{E_s}{E_0} \left[ A_y \cdot a + A_y' (h - a') \right] + b \int_{h-\theta}^{h} \left( 1 - \frac{\varepsilon}{\varepsilon_{bs}} \right) y dy + b \int_{h-\theta}^{h} \left( 1 - \frac{\varepsilon}{\varepsilon_b} \right) y dy, \]  
\[ A_{\text{red,}0} = b \int_{h-\theta}^{h} \left( 1 - \frac{\varepsilon}{\varepsilon_{bs}} \right) dy + b \int_{h-\theta}^{h} \left( 1 - \frac{\varepsilon}{\varepsilon_b} \right) y dy + A_{s,\text{tot}} E_s / E_0, \]

where \( J_{\text{red,}0} \) – the moment of inertia of the cross section given with respect to the tangent modulus relative to its own center of gravity;  
\( J_{\text{red,}0} \) - the moment of inertia of the cross section given along the tangent modulus relative to the center of gravity of the undeformed cross section;  
\( A_{\text{red,}} \) - the cross-sectional area given by the tangent modulus;  
\( S_{\text{red,}0} \) – static moment of the tangential modulus of the cross section;  
\( a_0 \) – the coordinate of the center of gravity of the section tangent to the module, measured from the axis relative to which \( S_{\text{red,}0} \);  
\( x \) – compressed area height;  
\( b, h \) – width and cross-sectional height, respectively;  
\( A_y, A_y' \) – area of compressed and stretched (least compressed) reinforcement, respectively;  
\( h_{crc} \) – the depth of the crack formed in the cross section;  
\( E_s, E_0 \) – modulus of elasticity of steel and initial modulus of elasticity of concrete, respectively;  
\( \varepsilon, \varepsilon_{bs} \) – deformations of compressed and stretched concrete, corresponding to the normative resistance to compression and stretching of concrete. In the considered problem, these values were adopted according to Building Code of Russian Federation SP 63.13330.2018, Appendix G.

Figure 2. Scheme for calculating the shape stability for a deformed state

Deformations of edge fibers are calculated for sections of reinforced concrete elements according to the results of calculating a structural system using a nonlinear deformation model using the step method or the method of variable elastic parameters (Figure 3).
Figure 3. Scheme for determining the parameters of the stress-strain state of a compressed-bent reinforced concrete element to solve the problem of buckling

For a special case of central compression of a reinforced concrete element, assuming that concrete and reinforcement are deformed together, we write the expression for the total longitudinal force in the element:

$$\varepsilon \left( \frac{E_i}{E_0} A_i + \left( 1 - \frac{\varepsilon}{2\varepsilon_b} \right) A_b \right) = \frac{N}{E_0}.$$  \hspace{1cm} (7)

Solving equation (7) with respect to deformations and limiting the range of possible solutions to the physical meaning of the problem, we obtain:

$$\varepsilon = \frac{\dot{\varepsilon}_b A_{b,red}}{A_b} - \frac{\dot{\varepsilon}_b A_{b,red}}{A_b} \frac{2\varepsilon_b N}{E_0 A_b},$$  \hspace{1cm} (8)

Taking into account expression (8), the value of the tangential modulus of deformations and bending stiffness can be obtained with an infinitely small increment of force (resistance), which will be $E_t J_{red}$ Here $E_t$ – tangent module, $J_{red}$ – moment of inertia of the reduced section in the undeformed state.

3. Results and Discussion

The results of calculating the model of a reinforced concrete frame for a special emergency action by the nonlinear deformation model in the Lira-CAD software (first approach) and the results of a nonlinear stability analysis of its deformed state (second approach), preceding failure according to the calculation by the first method, are presented in the form of bending moment diagrams and longitudinal forces, as well as forms of buckling. An analysis of the results of a nonlinear deformation calculation shows that in the considered model of a structural system with a given ratio of its geometric and physical parameters, the loading of the support cross sections of the crossbars and the preserved columns of the extreme rows caused by the sudden shutdown of the extreme row column on the first floor leads to the fact that the data bearing capacity sections is exhausted according to the criteria of strength (Figure 2, a, b). As a result of a nonlinear stability analysis of the deformed state of the frame corresponding to step j-1 of the nonlinear deformation calculation, where j is the nonlinear deformation calculation step corresponding to the exhaustion of the cross section strength, the stability margin coefficient turned out to be 0.983 (Figure 4 (c), (d)). In this case, a similarity of the form of loss of stability and the deformed state of the system is observed (Figure 4). These data are in good agreement with the results of previously performed numerical studies [15] for a prefabricated-monolithic structural system of panel-frame elements. Attention should be paid to the fact that despite the high convergence of the calculation...
results for compressed-curved elements of the structural system model by the two approaches used in this study, the mechanisms and modes of deformation are fundamentally different.

![Image of graphs and diagrams](image_url)

Figure 4. Results of a numerical analysis of deformation and buckling: longitudinal force diagram (a), bending moment diagram (b), equivalent frame, section sizes of which are given by the tangent modulus (c), form of buckling of the deformed state (d)

An analysis of the nature of the redistribution of forces in compressed reinforcement and compressed concrete of a compressed-bent element on the basis of dependence (8) shows that as the values of stresses in concrete approach its standard compressive strength $R_{b,cr}$, the concrete deformation modulus tends to zero. In this case, concrete cannot independently perceive the forces that are redistributed to the reinforcement. As the stress level in the reinforcement of the columns approaches its physical yield point, the cross section pressure will tend to zero, which will lead to a loss of bearing capacity according to stability criteria.

Due to the lack of test results in the world scientific literature on the stability of deformed states of compressed-bent elements of frame structural systems made of composite materials with an elastic-brittle-plastic matrix (concrete) under static-dynamic loading conditions to obtain unambiguous answers to questions about the features of deformation, loss of stability and destruction of compressed-curved elements of reinforced concrete structural systems with the considered form of
impacts, it is advisable to conduct a series of tests representations frames on a model similar to that considered in this paper.

4. Conclusions

Based on a numerical study of the deformation of a model of a reinforced concrete frame and analysis of the analytical dependences for the geometric characteristics of the resistance of compressed and compressed-bent elements, it is established that the mechanism of the disproportionate response of the structural system to the sudden removal of the first floor column can be associated with a loss of stability.

In order to obtain unambiguous answers to questions about the features of deformation, loss of stability, and fracture of compressed-curved elements of reinforced concrete structural systems under considered type of action, it is necessary to conduct a series of tests on physical models of reinforced concrete frames.

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