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The dynamic effect in a structural adjustment of reinforced concrete structural system

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Abstract. Results of experimental and theoretical studies of the dynamic effect of reinforced concrete structural system of building in case of its sudden structural adjustment caused by special accident action in the form of hypothetical removal of one of bearing structures are given. A zone of possible local failure of the structural system is modeled by a fragment of the structural system adjacent to that zone. For such a fragment called a substructure, an analytical solution of the problem for determining the time of dynamic loading of fragment elements is obtained. Evaluation of theoretical solution for determination of dynamic parameters of frame structural system at the considered action is performed by comparison of theoretical results with data of experimental studies of the fragment of a reinforced concrete multistory frame.

1. Introduction

In Russian norms [1], as in the normative documents of several other countries on protection of buildings and structures from progressive collapse [2-6], when calculating structural systems of buildings for special action, such a concept is used as "zone of local failure," defined by some fragment of the building, structural elements of which are adjacent to the structure to be removed during calculation. The purpose of selecting such the most stressed fragments is to assess the stress-strain state of structures included in such a fragment from the positions of the criteria of the special limit state. The experience of such analysis of buildings and structures of the first and second levels of responsibility [7-10] has shown that even with the application of modern PCs it requires a long time of calculation and high qualification of engineers.

One of the tasks of analysis of zones of local failure of structural systems is determination of time of dynamic loading from the beginning of column removal to transfer of force to adjacent structural elements of the system. The considered work provides an analytical solution to the problem of evaluating the dynamic effect of sudden removal of one of the load-bearing structures from the



structural system in comparison with the results of experimental studies of a fragment of reinforced concrete multistory frame.

2. Research methods

The reinforced concrete structural system in the form of a frame of a multistory building loaded with operational load and special action in the form of hypothetical removal of one of the load-bearing structures - a column of the first floor (figure 1) is considered.

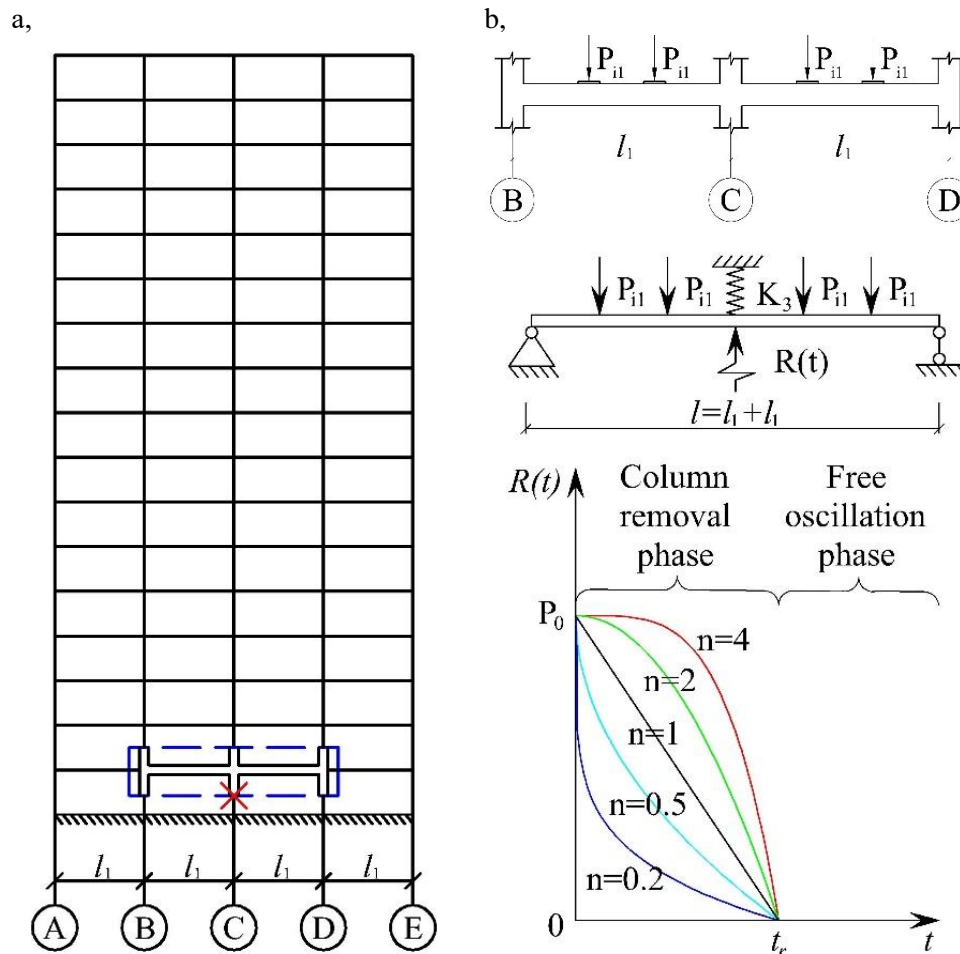


Figure 1. Diagram of the structural system model of the building (a) and the area of possible local failure (b).

It should be noted that the current rules [1] establish a requirement to take into account the dynamic effect in the calculated analysis of the structural system for the special action, but do not provide information on the parameters of such action and, above all, on the duration of the special action. As shown by the experimental studies carried out [11-13], the failure time of the load-bearing structure removed directly determines parameters of dynamic effect in the structural system under such action and dynamic strength of the material of structural elements.

In the first approximation, the area of possible local failure can be modeled by a substructure in the form of a two-span reinforced concrete beam with an operational load of P_{il} (figure 1, b). The sudden removal of the middle support column in the zone of possible local failure is expressed by the reduction of the internal force $R(t)$ in this column from P_0 to zero for some short time t_r . Here P_0 is the

force in the column to be removed was determined when calculating the structural system using the primary design diagram for the entire building frame (figure 1, a).

The force $R(t)$ as a function of time is written by the following expression:

$$R(t) = \begin{cases} P_0 \left[1 - \left(\frac{t}{t_r} \right)^n \right] & \text{if } 0 < t \leq t_r \\ 0 & \text{if } t > t_r, \end{cases} \quad (1)$$

where t_r - is the time of column failure depending on the nature of the special action [14-17], n is a positive exponent describing the rate of column failure (figure 1, b).

The force $R(t)$ in time can be represented as the sum of the two-component forces: P_0 causing the initial static stress-strain state of the substructure and the internal force $P(t)$ causing the movement of the system:

$$R(t) = P_0 - P(t) \quad (2)$$

Thus, static-dynamic deformation of the considered substructure is represented by the sum of two stages: stage 1 - static loading of the substructure to the given operational load, at which the internal force in the removed column reaches the value of P_0 and stage 2 - dynamic loading by force $P(t)$ causing the system movement.

From the schedules of figure 1, it can be seen that the value of $n = 1$ can be considered as an average value for estimating the rate of removal of the column. Accepting $n = 1$, the dynamic loading of the elements of the considered substructure has two phases: a phase of removal of a column at $0 < t \leq t_r$, and a phase of steady oscillation of a substructure with a removed column at $t > t_r$.

To determine dynamic parameters of the substructure, it is necessary to calculate its total stiffness [18], which will be determined by the load causing unit displacement of the substructure in the direction of spring K_3 . The total stiffness of the considered reinforced concrete substructure depends on the boundary conditions, as well as on the presence of cracks in it (figure 2). The diagram of figure 2: C_1 , C_2 - nodal stiffness in the elastic flexible node determined by the displacement method at single angular displacement $\varphi = 1$; the value K_3 is determined from the condition that the displacement of a single-story building and a multistory building is equal when a unit load is applied.

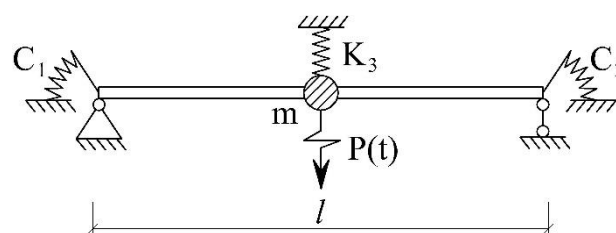


Figure 2. The calculated scheme of the substructure under elastic restraint.

The equation of motion of the substructure in question with one degree of freedom is written as [19-20]:

$$m \cdot \ddot{u}(t) + c \cdot \dot{u}(t) + K \cdot u(t) = P(t) \quad (3)$$

or

$$\ddot{u}(t) + 2\zeta\omega_n \cdot \dot{u}(t) + \omega_n^2 \cdot u(t) = \frac{P(t)}{m} \quad (4)$$

where: $u(t)$, $\dot{u}(t)$, $\ddot{u}(t)$ corresponding displacement, speed and acceleration of the point of application of concentrated mass; $\omega_n = \sqrt{\frac{K}{m}}$ - frequency of natural oscillations of the system without taking into account energy dissipation; $\zeta = \frac{c}{2m\omega_n}$ - damping factor.

The solution of equation (4) is:

$$u(t) = (u_{st})_0 \left[\frac{t}{t_r} - \frac{1-2\zeta^2}{t_r\omega_D} e^{-\zeta\omega_n t} \sin \omega_D t - \frac{2\zeta}{t_r\omega_n} (1 - e^{-\zeta\omega_n t} \cos \omega_D t) \right] \quad \text{if } 0 \leq t \leq t_r;$$

$$u(t) = (u_{st})_0 \left\{ 1 + \frac{2\zeta}{t_r\omega_n} \left[e^{-\zeta\omega_n t} \cos \omega_D t - e^{-\zeta\omega_n(t-t_r)} \cos \omega_D(t-t_r) \right] - \frac{1-2\zeta^2}{t_r\omega_D} \left[e^{-\zeta\omega_n t} \sin \omega_D t - e^{-\zeta\omega_n(t-t_r)} \sin \omega_D(t-t_r) \right] \right\} \quad \text{if } t > t_r,$$
(5)

where $(u_{st})_0 = \frac{P_0}{m\omega_n^2}$ - static deflection of substructure; $\omega_D = \omega_n \sqrt{1-\zeta^2}$ - frequency of natural oscillations of the system taking into account energy dissipation.

3. The results of the study and their analysis

Since damping affects only the amplitude of oscillations, and does not affect the value of the time of dynamic loading of the design t_d , without violating the generality of the definition and solution of the problem by definition t_d [21], consider the case $\zeta = 0$. Then equations (5) are written as:

$$u(t) = \begin{cases} (u_{st})_0 \left(\frac{t}{t_r} - \frac{\sin \omega_n t}{\omega_n t_r} \right) & \text{if } 0 \leq t \leq t_r, \\ (u_{st})_0 \left\{ 1 - \frac{1}{\omega_n t_r} [\sin \omega_n t - \sin \omega_n(t-t_r)] \right\} & \text{if } t > t_r, \end{cases} \quad (6)$$

Based on equation (6), a graph can be constructed describing the effect of the failure time t_r on the dynamic response of the substructure (figure 3).

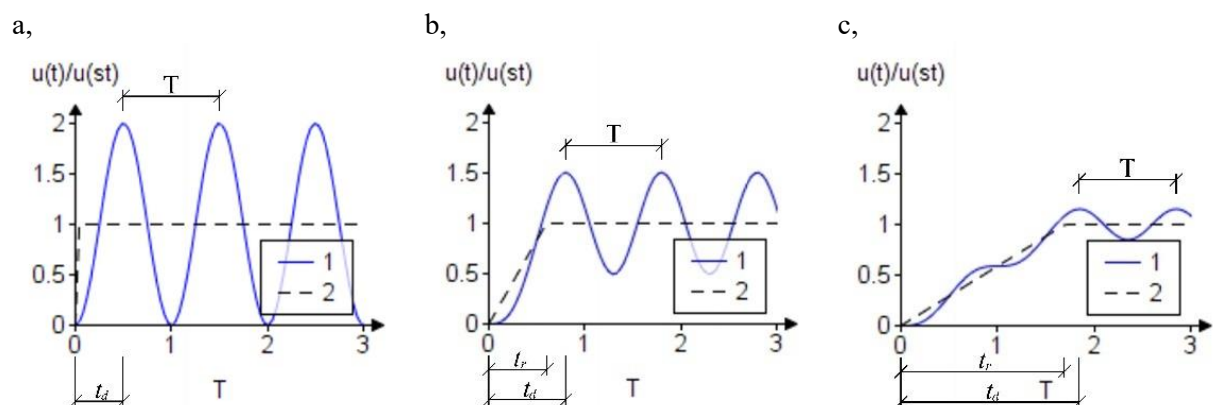


Figure 3. Graphs of the dynamic response of the substructure at different values of the column failure time and without taking into account energy dissipation: a - at $t_r = 0$; b - at $t_r = 0.6T$; c - at $t_r = 1.7T$; 1, 2- dynamic and static column removal respectively.

The evaluation of the obtained theoretical solution of the definition of the dynamic effect during structural adjustment of the frame reinforced concrete structural system will be carried out by comparing it with the results of experimental studies of the fragment of the reinforced concrete multistory frame. During the tests of the fragment of the monolithic reinforced concrete frame [22], the time of failure of the removed middle column $t = t_r$ and the time of dynamic loading $t = t_d$ of the structural system was determined using a high-speed digital camera. The general picture of the step-by-step static-dynamic deformation of the reinforced concrete frame structure is shown in figure 4, and the change of relative displacements of the frame beam in the cross-section above the removed column at the considered loading mode in figure 5.

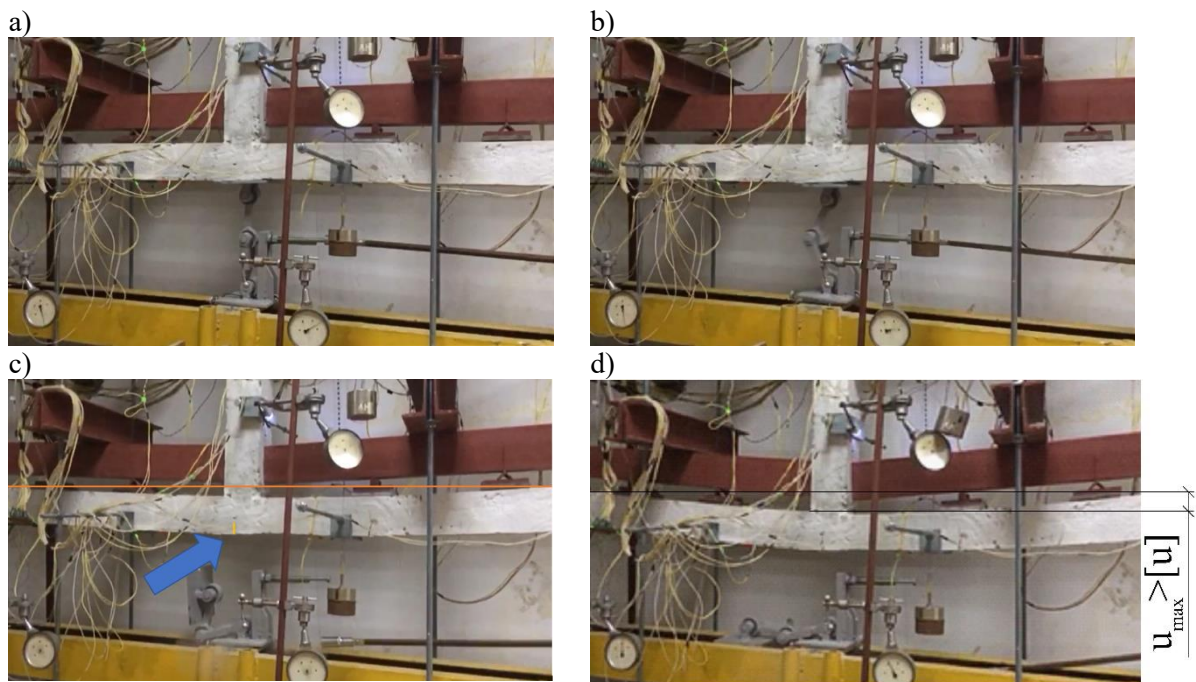


Figure 4. Stages of static-dynamic deformation of reinforced concrete frame structure: a - state before removing the middle support ($t = 0$); b - state after removing the supporting reaction ($R = 0$, $t = t_r = 0.08$ s); c - state of maximum dynamic loading ($t = t_d = 1.12$ s); d - achieving a specific displacement limit $u_{\max} > [u]$ or $(f/l > 1/26)$.

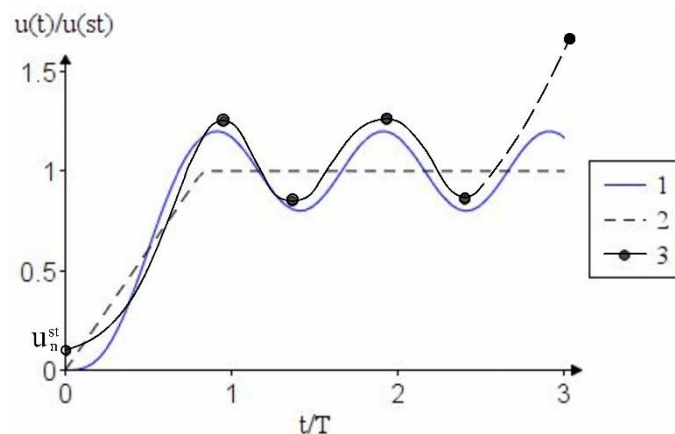


Figure 5. Relative displacements of the beam of the test frame in cross-section above the removed column in case of dynamic effect: 1, 2- the calculated value of dynamic and static deflections; 3- experimental values.

Analyzing the above results, it can be seen that the stiffness of the substructure, which models a fragment of the zone of possible progressive failure, significantly affects the parameters of its dynamic response of the structure. With a reduced failure time of the structural element from the structural system, the dynamic loading of the substructure increases (figure 4). The time of dynamic loading of frame beams from the moment of removal of the column to maximum displacements of beams adjacent to the remote support was 1.12 sec. The theoretical and experimental values of relative displacements of the frame during the removal of the middle column (figure 5) are satisfactorily consistent with each other. Therefore, the proposed analytical dependencies for determining the dynamic response of the structural system can be used to evaluate the deformation of reinforced concrete frames of multistory buildings under the considered actions.

4. Conclusions

The proposed calculated scheme of substructure for simulation of a zone of possible local failure of the reinforced concrete frame structural system of a multistory building at special accident action makes it possible to determine parameters of dynamic loading of such system at its sudden structural adjustment caused by the removal of one of bearing elements from the system.

Obtained analytical dependencies for determination of parameters of the dynamic response of frame structural system can be used for the determination of criteria of special limit state in the calculation of protection of buildings against a progressive collapse in case of accident actions.

Acknowledgments

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