Deformation and Failure of a Monolithic Reinforced Concrete Frame under Accidental Actions

V I Kolcunov¹, Vu Ngoc Tuyen² and P A Korenkov³

¹Moscow State University of Civil Engineering (National Research University), 26 Yaroslavskoe shosse, Moscow, 129337, Russian Federation
²South-West State University, street 50 let Oktyabrya, 94, Kursk, 305040, Russia
³V.I.Vernadsky Crimean Federal University, 4 Academic Vernadsky Avenue, Simferopol, 295007, Russian Federation

E-mail: ngoctuyenmdnd91@gmail.com

Abstract. The results of experimental and theoretical studies of deformation and failure of monolithic reinforced concrete (RC) frames under accidental action caused by the sudden removal of one of the columns are suggested. Experimental studies have been conducted on the model of structures of RC frames designed from fine-grained concrete class B40 with reinforcement class A500. Loading of experimental structures of frames was realized by gravitational method using a specially designed lever loading device. Accidental actions in the form of sudden removal of the central columns of the frame were modeled using a special designed device in the form of switch-off columns. The calculation of the experimental frame structures is executed on by an analytical method on an energy basis using level calculation schemes. Comparison of the calculation results with the test data on the parameters of deformation of structural elements and strength criteria of frames under the considered actions showed their satisfactory agreement.

1. Introduction

In connection with the adoption in some countries of the world of new legislative and regulatory documents on the protection of buildings and structures from progressive collapse [1-4], it is necessary to specify the design and structural protection requirements for different types of structural systems and, in particular, the specification of the load-bearing capacity criteria for the considered special accidental condition. Many scientists have conducted a number of experimental studies to examine the behavior of structures in limiting and prohibitive states [5-9]. Based on the experimental results, a number of computational models based on quasi-static or dynamic methods were proposed [10-16]. In scientific publications [17-19] in relation to monolithic RC frames, as a criterion of a special limit state of sections of elements of monolithic frames the restriction of deformation of compressed concrete with the limit value and the value of the limit stresses equal to were formulated. For tensile reinforcement also introduced criteria of ultimate strain and ultimate stress equal to . With an additional coefficient of the operating conditions of RC elements is introduced in the calculation of stability against progressive collapse.

In structural systems of RC frames of buildings with floor structures subjected to bending moment, it is appropriate to formulate a more general criterion of the special limit state using the calculated
parameters of the diagram "moment-curvature". Such criteria is of interest not only from the point of convenience of practical application in the design of RC structures, above all - from a position of view of the unity of requirements for assessing the deformation of the entire section of the RC element.

2. Models and methods

For the convenience of direct comparison of theoretical and experimental results, as a subject of theoretical research was considered a model of monolithic RC frame, which was tested in the laboratory of the Department of building structures of the Academy of construction and architecture of the V. I. Vernadsky Crimean Federal University (Figure 1).

![Figure 1](image.png)

**Figure 1.** Scheme of experimental design of frames of the first series: a - formwork, b – reinforcement.

For pilot studies experimental designs of two-span three-storied RC monolithic frames of two series were designed and produced. Specimens of experimental designs of these series differed by their longitudinal reinforcement of the beams of the frame structure. The first series of frames (figure 1) was designed under the designation РЖ-2Ф8(б) with reinforcement two bars 8mm diameter in the stretched zone cross section, and one bar with a diameter of 4mm A500 in the compressed zone of the cross section (over-reinforced section \( \xi > \xi_R \)). Reinforcement is assigned in such a way that when the central column of the experimental frame structure is turned off, brittle failure of the beams along the compressed concrete occurs from reaching the limit deformations in the compressed zone and there is a rupture of the longitudinal reinforcement in the stretched zone on the supporting sections of the beams at the central column at the moment of sudden removal of this column.

The second series is a normally reinforced construction of beams \( (\xi \leq \xi_R) \) with one bar 8mm diameter A500, so that when the central column is turned off, the failure occurs due to the fluidity of
the longitudinal reinforcement. Since the ultimate strain of reinforcement, specified in [4], much higher than the ultimate strain of concrete ($\varepsilon_{s2}/\varepsilon_{b2}=0.025/0.0035\approx7$ times), so after the onset of yield strength of reinforcement, strain of compressed concrete has also sharply increased and beam according to [4] is considered to be exhausted bearing capacity, when deformation in it reaches values $\varepsilon_{b2}$ [4]. The deformations in the longitudinal reinforcement are in the range $\varepsilon_{b2}[4]<\varepsilon_{b2}\le\varepsilon_{s2}$ (figure 2). The failure of frame at such variant of reinforcement carries plastic character with a maximum curvature, significantly exceeding the limit curvature for the frames of the first series with the criterion of brittle fracture on concrete.

![Figure 2](image_url). Scheme of the deformation of RC cross section with fragile (a) and plastic (b) failure.

In relation to RC elements of structural systems as failure criteria, standards [4] introduced the restriction of the deflection, which must not exceed 1/50 of the span. Therefore, for this case, the criteria for the parameters of the moment-curvature diagram become decisive.

For the calculation of the considered frame structure on the primary and secondary design schemes (terminology adopted by [4]) used diagram method [21, 22]. With the aim of obtaining analytical expressions for the calculation of limiting dynamic curvatures, a simplified analytical dependence proposed in [22, 23] is used, the dependence is based on the assumption that after the formation of cracks in the bending element, the curvature increment is practically proportional to the increment of moments (figure 3):

$w = \frac{M - M_1}{B_1}$  

where the stiffness of the element in the static area of deformation of the element after the formation of cracks, determined by the expression:

$B_1 = \frac{\varphi_1 E_s A_s h_0^2}{\mu \cdot \alpha}$  

The value of the moment $M_1$ is determined by the cutoff continuation of the line a-e in the diagram "moment-curvature" under static loading of the element (see figure 3):

$M_1 = \frac{z}{h_0} = \frac{\varphi_2 bh^2 R_{bt,ser}}{1.25 + \frac{\Psi h \cdot \mu \cdot \alpha}{v \cdot \varphi + \xi}}$  

$\varphi_2 = \frac{\varphi_{is} \cdot \left[0.292 + 0.75 \cdot (\gamma_1 + 2 \cdot \mu_1 \cdot \alpha) + 0.075 \cdot (\gamma_1 + 2 \cdot \mu_1 \cdot \alpha)\right]}{1.25 + \frac{\Psi h \cdot \mu \cdot \alpha}{v \cdot \varphi + \xi}}$  

Other designations in formulas (2)-(5) are accepted same as well as in norms [20-21]. Determination of dynamic curvature at static-dynamic deformation of RC element is feasible on the energy basis [24]. In accordance with the adopted dependence, the level of potential energy in the structural system after structural rearrangement for an arbitrarily loaded section of the element is determined by the expression:
Then, in the dynamic deformation of the section of the RC element, the work of external (internal) forces on the corresponding displacements is defined as the product of the force on the corresponding movement, the condition of the constancy of the total energy leads to the following analytical expression:

$$F(\omega) \, d\omega = \int_0^a M(\omega) \, d\omega = \int_0^a (M_1 + \omega B_1) \, d\omega = \frac{B_1}{2} \omega^2 + M_1 \omega$$  \hspace{1cm} (6)

As on the examined area of deformation $M > M_{\text{cr}}$ connection of " M-\omega " concordantly (1) carries linear character, a dynamic moment can be found from the condition of equality of areas of the shaded triangles $\omega_1 \omega_2 \omega_3 \omega_4$ (see figure 3):

$$M_{n-1}^d = 2M_{n-1}^c - M_n^c$$  \hspace{1cm} (8)

Putting (6) in (7) we will get

$$B_1 \left(\frac{M_{n-1}^d}{M_{n-1}^c} \right)^2 + M_1 \omega_{n-1}^d - \left(\frac{B_1}{2} \left(\omega_n^c\right)^2 + M_1 \omega_n^c\right) = M_{n-1}^c \left(\omega_{n-1}^c - \omega_n^c\right)$$  \hspace{1cm} (9)

Solving the quadratic equation (9) we find the required value of the dynamic curvature in the section of the loaded RC element:

$$\omega_n^d = \frac{M_{n-1}^c - M_1 + \sqrt{(M_{n-1}^c - M_1)^2 + B_1^2 (\omega_n^c)^2 - 2B_1 \omega_n^c (M_{n-1}^c - M_1)}}{B_1}$$  \hspace{1cm} (10)

Figure 3. Calculation diagram "moment-curvature" of static-dynamic deformation of the section of RC element.

3. Results and discussion
The analysis of the obtained data of the tested structural frames of both series showed that the deformation, crack formation and failure of the studied structures under the considered action has a number of features.

Experimental deformations of compressed concrete in the supporting cross section 1-1 of the frame of the first series (figure 4a) had a character close to bilinear. The maximum deformations of the compressed zone of concrete on the first linear section before crack formation of the considered sections at approximately $1.1 \cdot 10^{-4}$ (curve 1). In the second section of concrete deformation after crack formation deformation of compressed concrete to loading the frame total load $\Sigma P_i = 31.5 \text{kN}$ in the supporting section 1-1 were $(4.17 - 4.61) \cdot 10^{-4}$. Experimental diagrams "load-deformation" of
reinforcement in the same sections (figure 4b) had almost the same character as for compressed concrete. The values of deformations of tensile reinforcement at cracking load was $(0.73 - 1.63) \times 10^{-4}$, at the limit value of the static load in the system $n \varepsilon_s = 5.32 \times 10^{-3}$. Under dynamic loading the frame after turning off the central column ruptured tensile reinforcement (section 3-3) in the center column of the frame.

![Figure 4](image1.png)

**Figure 4.** Diagrams of deformation of the compressed concrete (a) and stretched reinforcement (b) in section 1-1 of the frame of the first series: 1 - experimental, 2 - theoretical under static deformation.

According to the obtained experimental values of the deformations of concrete and reinforcement was defined curvature in cross section 1-1 in different stages of the static deformation of the cross section (figure 5).

![Figure 5](image2.png)

**Figure 5.** Character of distribution of experience deformations in section 1-1 before (a) and after (b) crack formation.

Experimental values of the dynamic curvatures in a supporting section 1-1 with undisturbed reinforcing bar anchorage were determined by the values of deformation of compressed concrete and tensile reinforcement strains. While experimental values of the ultimate strain of reinforcement on the dynamic section of deformation $\varepsilon_{ult}$ were calculated according to the measured increments of the crack width in the section under dynamic loading frame.
In the structures of the first series (figure 6a) up to the moment of cracking ($M_{crx} = 0.39$ kNm), the dependence $M_{a}$ was almost linear (curve 1 section "o-a"), determined by the initial stiffness of the cross section of the frame structures $B_0$. After the formation of normal cracks in the upper zone, there was a significant increase in curvature with almost minor changes in the load and increase to the level of static application to the frame in the original $n$-system, causing by the moment $M_{n}^{st} = 0.86$ kNm in the section 1-1. After the beyond-design action and instantaneous transformation of the initial $n$-system into the $n$-1 system (switching off the middle column), there was also a practically linear growth of curvature in the considered supporting section up to its failure (section b-c).

Comparison of the experimental diagram (curve 1) with the theoretical one (curve 2) shows that the calculated dependences for the determination of dynamic curvatures describe the experimental deformation curves quite satisfactorily.

Figure 6. Experimental and calculated diagrams "moment - curvature" in section 1-1 for frames of the first (a) and second (b) series.

Comparing the calculated diagram 2 of the dynamic deformation of section 1-1 with the diagram 3 of its static deformation, we can see a significant increase in stiffness ($R_{d} = \tan \alpha_{d} = 1.1 \cdot B_{s}$, see Fig.3) of the cross section of the element under dynamic deformation due to the dynamic hardening of concrete and reinforcement under high-speed loading of the secondary structural system $n$-1 at a speed $t_{d} = 0.019$ sec. The experimental value of $t_{d}$ was obtained by a high-speed video camera Nikon 1J5 with a measurement frequency of 600 frames per second.

Similar features of the diagrams "moment-curvature" of static-dynamic deformation of sections are observed for the experimental design of the frame of the second series (figure 6b). Moreover, for the experimental diagram "$M_{a}$" of this series, a more pronounced area of nonlinear deformation after the crack formation was observed.

4. Conclusions

Experimental studies of a fragment of a monolithic RC frame of the building studied the features of static-dynamic deformation and failure of such a structural system under accidental actions. The results of dynamic loading and typical failures after a sudden removal of the central column in the bending elements of the structural system of each series depending on the percentage of longitudinal reinforcement are obtained and analyzed. Comparison of the test results on the parameters of deformation of structural elements and strength criteria of frames with the results of analytical calculation showed their satisfactory agreement. The formulated criterion of the special limit state for
the bending RC elements on the basis of the parameters of the diagram "moment-curvature" can be used in the design practice to protect the buildings and structures from progressive collapse.

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