Experimental research methodology for the deformation of RC frame under instantaneous loss of column

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Abstract. In recent years, numerous experimental and especially numerical studies have been conducted in order to study the mechanisms of the resistance of reinforced concrete building frames to progressive collapse during the instantaneous removal of one of the columns. Analysis of these researches shows that almost all study deals with strength performance of RC structural elements under quasi static or instantaneous loss of column. At the same time, a number of numerical and analytical studies of the progressive collapse behaviour of steel moment frames as well as fragments of RC moment frames indicates that loss of bearing capacity of structures can be associated with buckling behaviour. Therefore, using the theory of functional similarity, a physical model of the reinforced concrete frame of a multi-storey building and a methodology for experimental studies of the buckling and fracture of this structural system under instantaneous loss of the corner column are proposed.

1. Introduction

During the entire service life, reinforced concrete constructions of buildings and structures are subject to power and environmental influences of various nature and intensity. In some cases, such effects can lead to loss of load bearing capacity of the elements of the reinforced concrete building frames. In turn, it can lead to a disproportionate failure of the entire structural system that is known as progressive collapse. Major accidents that occurred at building facilities, such as the collapse of a section of a multistory residential building Ronan Point (London, 1968), Sampoong Department Store (Seoul, 1995), Transvaal Park (Moscow, 2004), the World Trade Center building (New York, 2011) and others, clearly demonstrated the relevance of this problem. In this regard, the requirements for structural analysis against collapse under instantaneous loss of a structural element of the building frame were included in the regulatory documents of the USA, Great Britain, the EU, China, Australia, Russia [1–6].

G.V. Gudmundsson and B.A. Izzuddin [7] confirmed the validity of this approach by numerical studies of the deformation of building frames dynamic impacts associated with an explosion and under instantaneous loss of column scenario. Their study shown that dynamic deflections at an instantaneous removal of the first floor column form an upper boundary for dynamic deflections caused by explosive action, in which the column is destroyed according to a non-shear scenario. If the explosion causes the
shear failure of the column, the instantaneous loss of the column scenario gives similar values of
dynamic deformations.

In recent years, numerous experimental and especially numerical studies have been conducted in
order to study the mechanisms of the resistance of reinforced concrete building frames to progressive
collapse during the instantaneous removal of one of the columns. The most common way to
experimentally study the mechanisms of resistance to disproportionate failure and the nature of the
deformation of structural elements during the redistribution of power flows is to carry out quasi static
tests on substructures decomposed from the building frame. Such studies include, for example, the
works of Yu Jun and Tan Kang Hai [8], Kang Shao-Bo et al. [9], Forquin Pascal and Chen Wen [10],
Han Qinghua et al. [11]. In these researches, hydraulic jacks were used to simulate the removal of the
interior column at a controlled speed of the jack piston.

Another approach to investigate the resistance mechanisms to progressive collapse is testing of two
or three story and two or three span flat or spatial scale models of building frames. The validity of the
number of storeys and spans of such scale models was proven by non-linear dynamic analysis
conducted by M. Botez, L. Bredean, A.M. Ioani [12]. They carried out structural analysis for the entire
building frame, for two spans and for one span under sudden loss of column scenario. The results of
this numerical analysis showed that is enough to consider no more than two spans adjacent to location
of failed column in order to assess the stresses and deformations in the building frame under such
impact. Similar experimental approach was applied by Wang et al. [13], Anil Özgür and Altin Sinan
[14], Li Shuang et al. [15], Fedorova N.V. and Ngoe Vu Tuyen [16], Kolchunov V.I. et al. [17],
Fedorova N.V. and Korenkov P.A. [18]. The listed works can be divided into two groups depending
on the method of modeling column removal: quasi static based on application of hydraulic jacks;
dynamic based on application of gravitational loading.

The approach based on scale model testing allows accurate simulation of redistribution of power
flows through alternate load paths and identification of resistance mechanisms to progressive collapse
depending on the topology of the structural system. The main advantage from application of hydraulic
loading devices is that allows testing of scale models close in their geometrical dimensions to real
structures. However, it almost does not take in account the inertia forces arising at the instantaneous
loss of column scenario. In contrast, the use of the gravitational-lever loading system makes it possible
simulation of such dynamic effects in the tested scale models, however one imposes restrictions on the
scale of the experimental models. In addition, this approach requires a sufficiently rigorous analysis
and selection of structural materials based on the theory of similarity and dimensions [19-21] in order
to provide equivalence of scale models and full-scale structures, especially for such complex material
as reinforced concrete.

In this regard, a separate group consists of studies performed on the reinforced concrete building
frames of real buildings to be demolished, for example, studies of progressive collapse resistance of
hotel San Diego conducted by Sasani et al. [22]. Undoubtedly, such studies are of the greatest value,
however, for obvious reasons that is extremely costly and difficult to implement. Therefore, results
obtained in some studies cannot be processed statistically.

Analysis of the most common methods of experimental testing of the RC models for progressive
collapse behavior shows that almost all the above researches study the strength performance of bent
and compressed-bent crossbars, as well as stretched and eccentrically stretched RC structural elements
under quasi static or instantaneous loss of column. However, some numerical and analytical studies of
the progressive collapse behavior of steel moment frames carried out by Pantidis P. and Gerasimidis S.
[23,24], as well as fragments of RC moment frames and frame-braced structures conducted in the
papers [25-27] indicate that loss of bearing capacity of structures can be associated with buckling of
compressed-bent elements, if some rods are slender or damaged by corrosion.

Apparently, tests of models of RC frames or substructures in order to investigate the buckling
performance of their elements under the static-dynamic loading mode that is characteristic for
instantaneous loss of column scenario have not been carried out to date. The results of buckling tests
presented in the scientific literature relate to rod specimens of concrete or reinforced concrete [28-30],
which are tested, as a rule, under the static loading mode. The studies of the static-dynamic deformation of specimens are extremely few [31]. As for the testing of frames, such tests were carried out mainly for steel or duralumin small-scale models of substructures under quasi static loading [32-34]. However, reinforced concrete structures have a number of special properties, among them are the low resistance to tensile stresses, the brittle fracture of the concrete matrix under compression and stretching, plastic performance and creep already at the initial stages of loading. All these factors affect to the dissipation of the strain energy under dynamic impacts.

Therefore, the aim of this paper is developing and substantiation of a methodology for experimental testing of RC moment frame scale models under instantaneous loss of column in order to establish the features of buckling and fracture of structural elements of the models.

2. The constructive solution of the experimental model of the RC frame

In order to identify the buckling and fracture performance of compressed-bent slender columns of RC moment frames under accidental impacts associated with the instantaneous loss of the column, we propose performing a series of tests of physical models of RC moment frames made in scale of 1:8. The geometric dimensions and reinforcement scheme of such a reinforced concrete frame are shown in Figure 1. In contrast to the previously tested models considered in the papers [16, 18], the topology of the proposed frames was changed by increasing the ratio between the height of the column of the second floor and the span of the crossbars. Accordingly, the slenderness ratio of these columns has been increased. Frames are made in two series, which differ from each other by the class of concrete for compression. The materials of the frames of the first series are following: concrete of compression strength class B25, for which the standard compression resistance is \( R_{b,n} = 18.5 \text{ MPa} \), and the initial elastic modulus is \( E_0 = 30000 \text{ MPa} \). The columns and crossbars are reinforced by spatial reinforcement cages with axial steel wire of class Bp500 (\( R_{s,n} = 500 \text{ MPa} \)) and transverse steel rods of class \( \text{A}300 \) (\( R_{s,n} = 300 \text{ MPa} \)). The second series of the frames are made of concrete of the compressive strength class B100, for which the standard compression resistance is \( R_{b,n} = 71 \text{ MPa} \), and the initial elastic modulus is \( E_0 = 43000 \text{ MPa} \). The second floor columns of these scale models are slender with slenderness ratio at the undeformed state \( \mu (l/h) = 1.2 \) (940/50) = 22.6, where \( \mu = 1.2 \) is the effective length factor for restrains accepted at the column ends. Since the effective dimensions of the column cross sections decreases because of the development of plastic deformations in concrete and crack formation, then slenderness ratio increases too. In the case of additional loading caused by the redistribution of power flows in the structural system under instantaneous loss of column, the slenderness can reach a critical value at which structure loss of stability, and then fracture. Varying the class of concrete, we assume to evaluate the effectiveness of high-strength concrete as a way to protect against progressive collapse.

3. Numerical and analytical proven of the experimental research methodology

3.1. Simulation of loads and impacts acting on the RC frame

Figure 2 shows the reinforced concrete frame considered in the section 2, which is loaded with evenly distributed dead load and concentrated loads applied to the upper nodes of the frame and simulating the dead and live loads from the overlying floors of the building.

As an emergency design situation, the instantaneous loss of the corner column on the ground floor was considered. Such an approach corresponds to requirements in the regulatory documents of the USA, EU, and Russia [1–3,5].

In order to determinate efforts in structural elements of the scale model under impact under consideration we used two approaches: linear dynamic analysis and quasi static in formulation proposed by G.A. Geniev [35,36].
3.2. Linear dynamic analysis

In order to assess the nature of the dynamic redistribution of power flows between the structural elements of the secondary design scheme of the scale model under instantaneous removal of the column, a linear dynamic analysis has been performed. For these purposes, the impact was simulated using substitution of the failed structural element by reaction and opposite generalized force $P$, linearly increasing from 0 to 4 kN over a time interval from 0 to 0.01 seconds. During the time interval from 0.01 to 0.5 seconds, the load $P$ remained constant. According to the results of linear dynamic analysis, the maximum deflection of the frame node adjacent to the removed column was achieved at
time $t = 0.274$ seconds from the start of the impact. The obtained values of the internal forces in the structure at this time are shown in Figure 3.

![Figure 3](image1.png)

**Figure 3.** Internal efforts in the secondary scheme at the time $t = 0.274$ seconds after instantaneous loss of column: axial forces, kN (a) and bending moment, kNm (b).

### 3.3. Non-linear static analysis

Nonlinear static analysis has been performed using the FEM (Lira-CAD software), taking into account physical and geometric nonlinearity. In this paper, the geometrical nonlinearity means a change in the calculation scheme during loading that is modeled using a combination of the increment method and the "Installation" tool of software. The deformation diagrams of concrete and steel have been approximated with exponential curves. At the stage of normal operation, concentrated forces $P_1 = 4$ kN, $P_2 = 20$ kN, $P_3 = 16$ kN have been applied to the upper nodes of the frame as it is shown in Figure 2. The dynamic effect arises in the structure through the time $t = T/4$ after loss of the corner column on the ground floor, where $T$ is the period of forced vibrations secondary structural system. Such an effect was modeled by a static force $P = 4$ kN applied instead lost column in opposite direction as it is shown in figure 2 (b). Besides, we calculated stress-strain state of the frame model at time $t = T/8$, when the reaction in the lost column is null. Figure 4 present the results of such a calculation in the form of diagrams of bending moments and longitudinal forces.

The results of the nonlinear static analysis (NSA) slightly differs from data of linear dynamic analysis. This can be explained by accounting the plastic behavior of structure at nonlinear analysis.

### 3.4. Solution to stability problem for the deformed 2D reinforced concrete frame

In addition to the results of linear dynamic and nonlinear static analysis, we performed stability analysis of the reinforced concrete frame under sudden loss of corner column at time $t = T/8$ taking into account elastic and plastic behavior of materials under loading [25,26].

As a result, a safety factor by critical force for this frame model took value $k = 0.98$ indicating a change in the equilibrium state of the frame under accidental impact (Figure 5). The most sensitive structural element to the buckling was the column on the second floor in the far corner from the location of initial fracture. This result good coincides with the data of nonlinear static analysis, in which the destruction of this structural element occurred in the time interval from $T/8$ to $T/4$ from the beginning of the impact.
Figure 4. Results of non-linear static analysis of the frame of the first series under instantaneous loss of the corner column: axial forces, kN (a) and bending moments, kNm (b) at $t = T/8$; axial forces, kN (c) and bending moments, kNm (d) at $t = T/4$.

Figure 5. Results of stability analysis of the frame at the time $t = T/8$ from the beginning of the accidental impact: equivalent elastic frame adopted by deformation modulus (a), buckling mode of the frame (b).

4. Methodology of experimental investigation of buckling and fracture of the RC frame

Numerical analysis conducted in section 3 allowed us to develop a test scheme in order to investigate buckling and fracture of the scale model experimentally. Figure 6 presents such a test scheme of the
reinforced concrete frame, the design of which is described in section 2 of the paper. A comparative analysis of modeling conditions by similarity type [19-21] performed with a computational model made it possible to recommend the use of a functionally similar physical model for which the following conditions are satisfied:

- physical phenomena in the considered physical and mathematical objects are of the same nature;
- the physical model and the investigated natural fragment of the building have the same calculation model;
- the number of defining similarity criteria for the model and the full-scale structure is the same, although their numerical values may not be equal;
- physical and mechanical characteristics in the initial data for the calculation model and facility should have the same properties;
- the loads acting on the model are not similar, but the nature of the stress-strain state caused by them is identical.

Figure 6. The arrangement of the optical-mechanical measuring devices (a) and the general view of the test bench (b) for testing the experimental design of the reinforced concrete frame: 1 - power frame; 2 - steel strands; 3 - beam; 4 - lever; 5 - strain gauge on concrete; 6 - strain gauge on the steel reinforcement; 7 - device modeling instantaneous loss of column, 8 - reinforced concrete frame, 9 - optical indicator, 10 - beacon with graduated scale, 11 - high-frequency video camera.

At the second stage, a patented test method [37] is used to simulate the instantaneous removal of the corner column on the first floor of the scale model of the reinforced concrete frame [37]. For these purposes, the special device [38] consisting of a three-hinged rack and a rigid support is installed instead of the corner column on the first floor. When using this device, the three-hinged rack turns into an instantly changeable system that is equivalent to instantaneous loss of the structural element.

Deformations of concrete and steel reinforcement in the most loaded sections of the experimental frame are measured by the method of electrotensometry. The arrangement of strain gages on compressed concrete and on tensile steel reinforcement is shown in Figure 6.

During the test, the horizontal deflections of the end sections of the columns and the vertical deflection of the girders in the areas with the greatest dynamic deflections (see Figure 6) are also controlled by the P1 - P7 deflection meters located according to the results of numerical simulation obtained in section 3 of this paper.
In order to measure dynamic displacements in the tested experimental RC frame under sudden loss of the corner column on the first floor, laser optical indicators are installed in the characteristic nodes of this structure. The light signals of the lasers are fixed on the graded surfaces of the fixed beacons installed separately from the power frame and RC frame under testing using digital video cameras with a shooting frequency of at least 200 frames per second.

In addition, oscilloscope controls frequency, period as well as parameters characterizing the process of damping of forced vibrations of the experimental structure under accidental impact.

5. Discussion
Due to the fact that the use of physical models applied to verify and evaluate computational and mathematical models at such a complex phenomenon as a disproportionate failure of a full-scale structural system is associated with large resource costs, and it often becomes impossible that can be seen from the analysis of various methods of experimental studies given in section 1 of this paper. In this regard, we propose a relatively mild modeling method called the functional similarity method when creating physical models. This method is advisable to apply exclusively in combination with the calculation models of various level of complexity.

The use of functionally similar physical models should be considered as a way of verifying the adequacy of design models of physically and structurally nonlinear reinforced concrete structural systems under complex loading modes. For this purpose, physical models are developed on the basis of full functional similarity with the fulfillment of all the conditions described in the paper.

In this case, physical models similar to ones given in Section 2 of this paper are used to confirm the adequacy of the calculation models of the substructures included in the object of study. At the same time the stiffness and strength parameters of structural elements and nodes are determined using a simple or extended similarity [19-21]. Experimental physical models are built on the principle of mixed similarity. In order to determine the ductility of the frame nodes before and after crack formation, the model of the structural system is functionally similar to real structure. And modeling of the structural elements and their joints is based on the principle of simple similarity to real structures that includes similarity in all coordinates, similarity of boundary conditions, equality of scale factors, equality of the number of determining factors for the model and the original, identity to the materials of the model, invariance of similarity criteria in magnitude, qualitative and quantitative similarity of effects, etc.

6. Conclusion
In accordance with the numerical simulation of the instantaneous loss of the corner column of the reinforced concrete frame, it is established that the buckling can precede the exhaustion of the strength of the sections of the compressively-bent elements of the structural system.

Using the theory of functional similarity, a physical model of the reinforced concrete frame of a multistory building and a methodology for experimental studies of the buckling and fracture of this structural system under instantaneous loss of the corner column are proposed.

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