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Failure simulation of a RC multi-storey building frame with prestressed girders

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Keywords: reinforced concrete, precast and cast-in–place structures, building frame, prestressing, progressive collapse, numerical analysis, accidental actions, Vierendeel truss

Abstract. In recent decades, more and more attention has been paid to studying the mechanisms of resistance to the progressive collapse of various types of buildings and structures. Wherein, one of the most common types of structural systems of multi-storey residential and public buildings is a reinforced concrete frame or reinforced concrete frame-braced system. The scientific literature contains the following mechanisms of resistance of such structural systems to progressive collapse: arch, catenary or Vierendeel truss. However, currently there is not strict correspondence between the type of structural system, the nature of the accidental impact and the resistance mechanisms to progressive collapse. A similar situation exists in the field of developing effective ways to ensure the structural safety of such frames in case of accidental impacts. Therefore, a multi-storey reinforced concrete frame braced structural system with prestressed girders was selected as the object of study in this work. The purpose of the study is thus to establish the resistance mechanism of the reinforced concrete frame with prestressed girders at the failure of an outer column on the ground floor of the building. For the purpose of this study, using the decomposition method, the substructure in the form of two-story two-span reinforced concrete frame has been cut from the 3D model of the structure under consideration and has been performed a nonlinear quasi static analysis of the finite element model of this substructure. As a result of nonlinear numerical analysis, the diagrams of the axial forces and moments and schemes of destruction have been obtained for different values of prestressing in the girders. It has been established that over failed outer column the reinforced concrete frame under consideration transforms to Vierendeel truss. Change of the level of prestressing in the girders of the frame allows varying the stress-strain state and ensures load-bearing capacity of its elements under accidental impacts.

1. Introduction

A large number of investigation on behavior of structures in resisting progressive collapse of building and structures permanently growths especially in the last decades [1]. As a result, an experience accumulated in this field allowed to create and introduce building codes and regulatory documents in design practice. Advanced analysis of these documents is given, for example, in the works [1–3]. However, in a row of cases these regulatory documents do not contain unambiguous and explicit answers for many questions linked with features of design of a protection against progressive collapse and do not take into account the static-dynamic properties of deforming under accidental actions.

A significant number of research articles devoted to assessment resistance of buildings and structures to progressive collapse considers exhaustion of strength of the material as a criterion of failure [4–9]. A significantly less number of investigations deals with the stability problem of compressed and compressed-bent rods of structural systems when some element of the structural system collapsed [10–15].

Analysis of publications on protection of RC frames of buildings and structures against non-proportional failure shows that the resistance mechanism may be different in regard with a number of the floors in the

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Колчунов В.И., Федорова Н.В., Савин С.Ю., Ковалев В.В., Ильющенко Т.А. Моделирование разрушения железобетонного каркаса многоэтажного здания с предварительно напряженными ригелями // Инженерно-строительный журнал. 2019. № 8(92). С. 155–162. DOI: 10.18720/MCE.92.13

building frame. In particular, the works [16–18] show that the mechanism of alternate load path takes the following forms: arch, catenary or Vierendeel truss. L. Shan, F. Petrone, S. Kunnath, X.H.C. He, W.J. Yi and X.X. Yuan noted that tall building resists to progressive collapse better due to redistribution of power flows. The arch effect may be implemented, if a structural element, for example a column, collapses slowly without dynamic effects. If a number of storeys of a building frame is less than ten ones and first floor column collapses quickly with dynamic effects then resisting mechanism is catenary. However, if a number of storeys is more than ten at the same parameters of accidental impact then behavior of the building frame in resisting to progressive collapse is Vierendeel truss. Similar results were obtained by Y. Li, X. Lu, H. Guan and P. Ren who investigated behavior of the multi-storey RC building frame depending on storey where the column was removed [19].

The works mentioned above deal with investigation of resistance to progressive collapse of cast-in-place multi-storey RC building frames. However, issues on ensuring alternate load path of precast - cast-in-place RC building frames were investigated worse [20–22]. An instrument protecting such a structural system usually is installation of additional links, which redistribute power flows into structural elements at accidental action such as sudden removal of a load bearing element [21].

Therefore this paper is devoted to investigation of behavior of the multi-storey RC building frame made of precast panel-frame elements [22–24]. As additional instrument protecting such a structure against progressive collapse, we proposed applying of continuous pre-stressed reinforcement in girders along the whole length of the building frame or its parts.

2. Methods

Constructive decisions. Load bearing building frame presented in Figure 1 consists of reinforced concrete precast elements (panel-frames) – 1; hollow-core slabs – 2 and continuously prestressed external girders – 3. Here 4 is up and down reinforcement, 5 is a hole for heat insulation and 6 is external multi-layer wall. Steel links between wall panels are marked number 7. The girders of the frame consist of precast and cast-in-place parts the shear resistance of which ensured by transverse reinforcing bars – 8. Conjunction node between column and girder is made of cast-in-place. Outer parts of the reinforcing bars – 9 of the precast hollow-core slabs are involved into cast-in-place part of the girder. Outer parts of the reinforcing bars - 9, 10 jutting from the precast hollow-core slabs and columns are immersed into cast-in-place part of the girder. Steel rods 11 work as anchors. Plugs 12 are installed in holes of hollow-core slabs and separate cast-in-place part of the girder 13. Prestressed reinforcing bars 14 are installed into cast-in-place part of girder along the whole width of the building or its part.

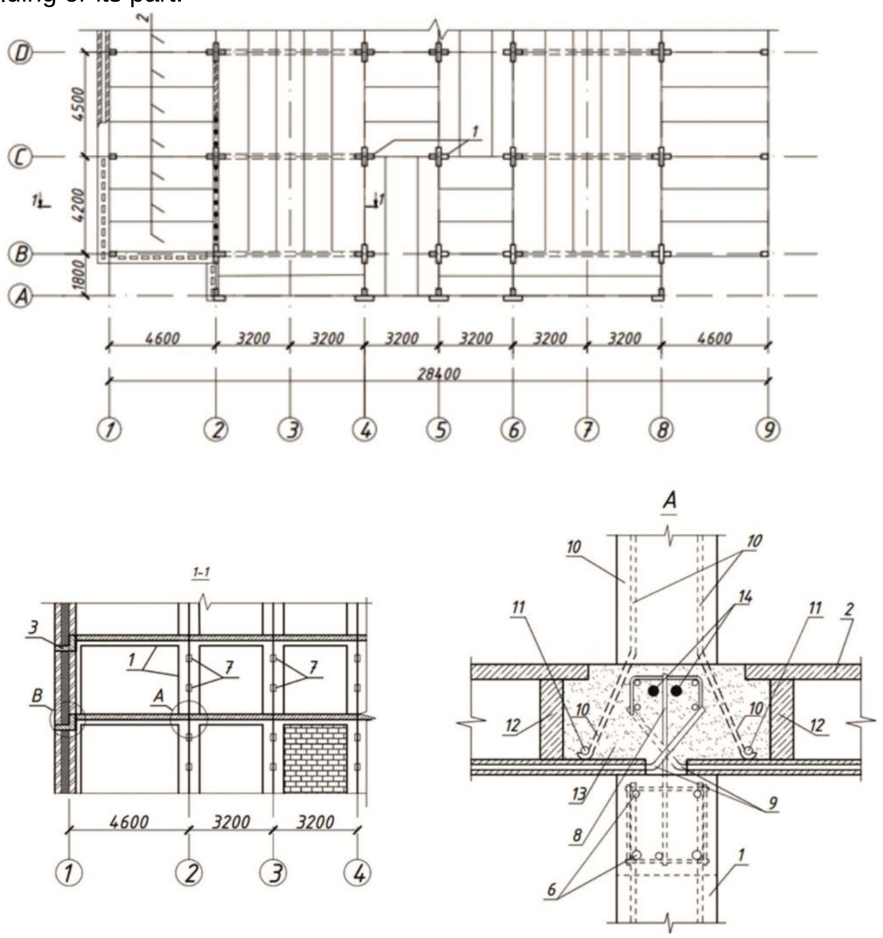

Figure 1. Multi-storey building made of RC panel-frames.

In contrast to earlier constructive decisions of similar building frames [22–24], this one contains prestressed reinforcing bars installed in cast-in-place part of girders along the whole length or width of building or its part. External parts of rebars jutting from the column are introduced into cast-in-place part of the girder. In the upper part of hollow-core slabs, the concrete keys are performed to ensure shear resistance. Moreover, additional steel rods connect slabs with cast-in-place part of girders.

Such decisions provide robustness of building frame both under operational impacts as well as under accidental impact, caused by sudden failure of a column.

Description of model and method. In order to evaluate effectiveness of the suggested protective decisions, we have conducted nonlinear structural analysis of the finite element model cut from the 3D model of building frame using the decomposition method (Figure 2).

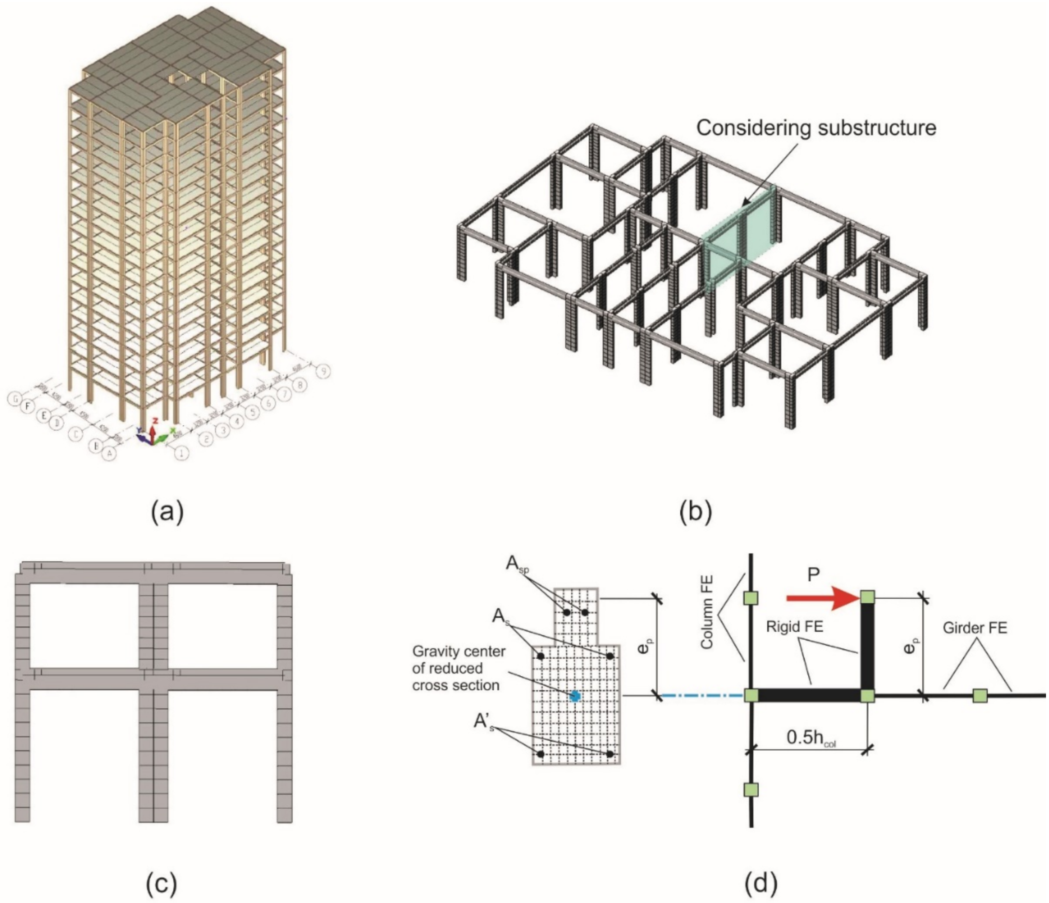

Figure 2. Finite element calculation model of multi-storey RC building frame: first level model (a) second level model (b), substructure for performance simulation (c), scheme for simulating of prestressed girder (d).

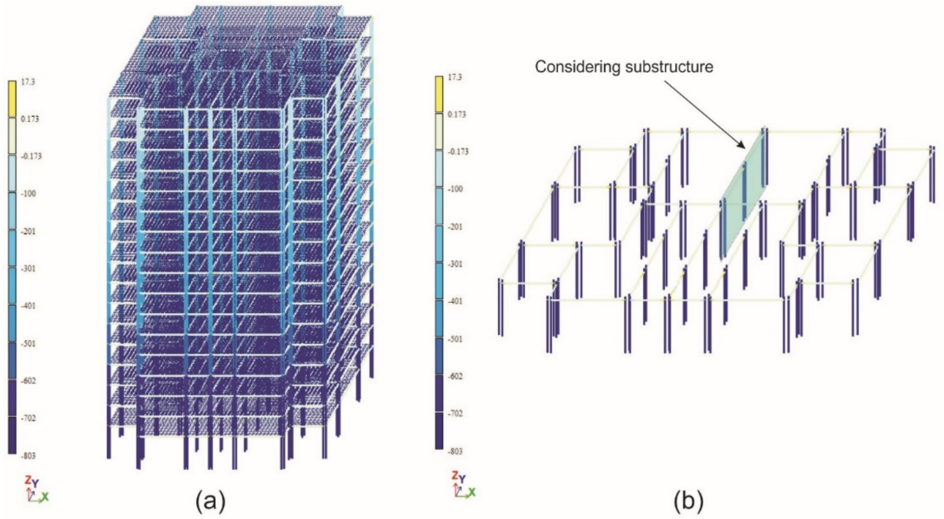

Figure 3. Mosaic of axial forces N (kN) in the structural elements of multi-storey RC building frame (a), mosaic of axial forces N (kN) in the first floor columns of considering building under design combination of loads (b).

At the first stage, we have performed structural analysis of entire reinforced concrete building frame using the finite element method by Lira-CAD program. A calculation scheme of the first level (Figure 2, a) was spatial plate-rod model of whole building, in which elements of frame were simulated by universal rod finite elements (FE), and hollow-core slabs of overlaps are simulated by universal 4-nodes shell elements. Hinge conjunction between girders and hollow-core slabs was simulated using coupled degree of freedom (DOF) X, Y, Z in respective nodes. In order to decrease common laboriousness of calculation and make results clearer from engineering position, we did not take in account non-linear behavior of multi-storey RC building frame at this step. The result of such numerical analysis was diagrams of forces and moments caused by design combination of loads (Figure 3).

In order to provide detailed assessment of stress-strain state of reinforced concrete structural elements of the building frame, we have chosen a substructure (building frame fragment) in the zone of possible local failure of the building frame. Correctness of algorithm suggested here is proved by row of experimental researches, for example, [6, 20], which had established that dynamic effect, caused by sudden structural transformation under accidental action, quickly damping with distance from the place of the local damage.

As example, we have considered the most loaded substructure in the form of two-span two-storey flat frame (Figure 2, b), for which a calculation scheme of the second level have been built (Figure 2, c). Initial data for advanced numerical analysis of behavior of structural elements of this substructure have been obtained from results of numerical analysis for the calculation scheme of the first level. At the same time structural elements of the second level calculation scheme have been simulated by universal physically non-linear rod finite elements with exponential strain - stress dependencies for concrete C60 and steel reinforcement A500.

Slabs of the multi-storey building have been replaced by evenly distributed load in the calculation model of the second level. The stiffness of the building frame part excluded from consideration have been substituted by one-node finite element of elastic spring, which makes the model equivalent to the first level calculation scheme by deformations. In order to take in account prestressing force and its eccentricity ep, we have introduced rigid rod finite elements (Figure 2, d), in the upper nodes of which prestressing forces P have been attached.

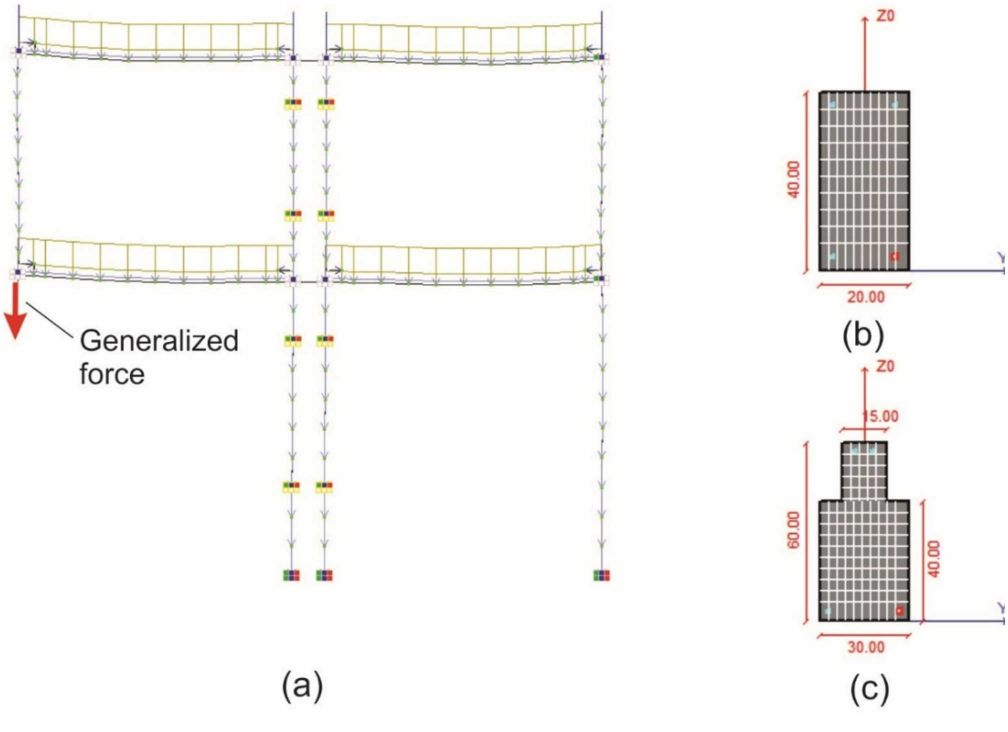

Figure 4. Secondary calculation scheme of second level at the stage of the outer column removal: quasi-static model of substructure in place of local failure (a), calculation cross section of column (b), calculation cross section of girder (c).

Numerical modeling of behavior of the substructure (calculation scheme of the second level) in resisting to progressive collapse have been conducted using step-iterative method. At the same time, we took in account static mode of loading during operational stage and dynamic mode at accidental impact caused by sudden removal of the first floor column. Increment of dynamic force into the secondary second level scheme have been simulated quasi-statically, assuming that removal of the column leads to appearing of the generalized force in the corresponding node of the girder. This force equals to axial force in the collapsed column at the stage of normal operation but change its direction in comparison with operational stage (Figure 4).

3. Results and Discussion

In order to evaluate how prestressing of girders affects to behavior of the substructure under consideration in resisting to progressive collapse, we have performed comparative numerical analysis of robustness for three variants of calculation schemes: without prestressing, when prestressing force equals $0.6 \cdot R_{s,ser} \cdot A_s$ and when prestressing force equals $0.9 \cdot R_{s,ser} \cdot A_s$.

Figure 5 presents results of such calculation in the form of mosaic of bending moments and axial forces and failure schemes. Analysis of results presented in the figure 5 allowed concluding the following.

Installation of prestressed rebars into cast-in-place part of girders of the first floor overlap and connection of these girders with columns of upper floor using steel links provides alternate load paths for redistribution of power flows at accidental impact. Such a decision may serve as a protection against progressive collapse. As a result, structural system under consideration becomes the truss-diaphragm similar to Vierendeel truss. This is consistent with results obtained in the works [16, 17, 19] for cast-in-place reinforced concrete multi-storey building frames.

Thus, we can varies stress-strain state in the zones of a possible local failure of precast-cast-in-place reinforced concrete building frame changing placement of prestressed rebars through the height of girders. It allows us provide bearing capacity of these local zones in accordance with criteria of the special limit state.

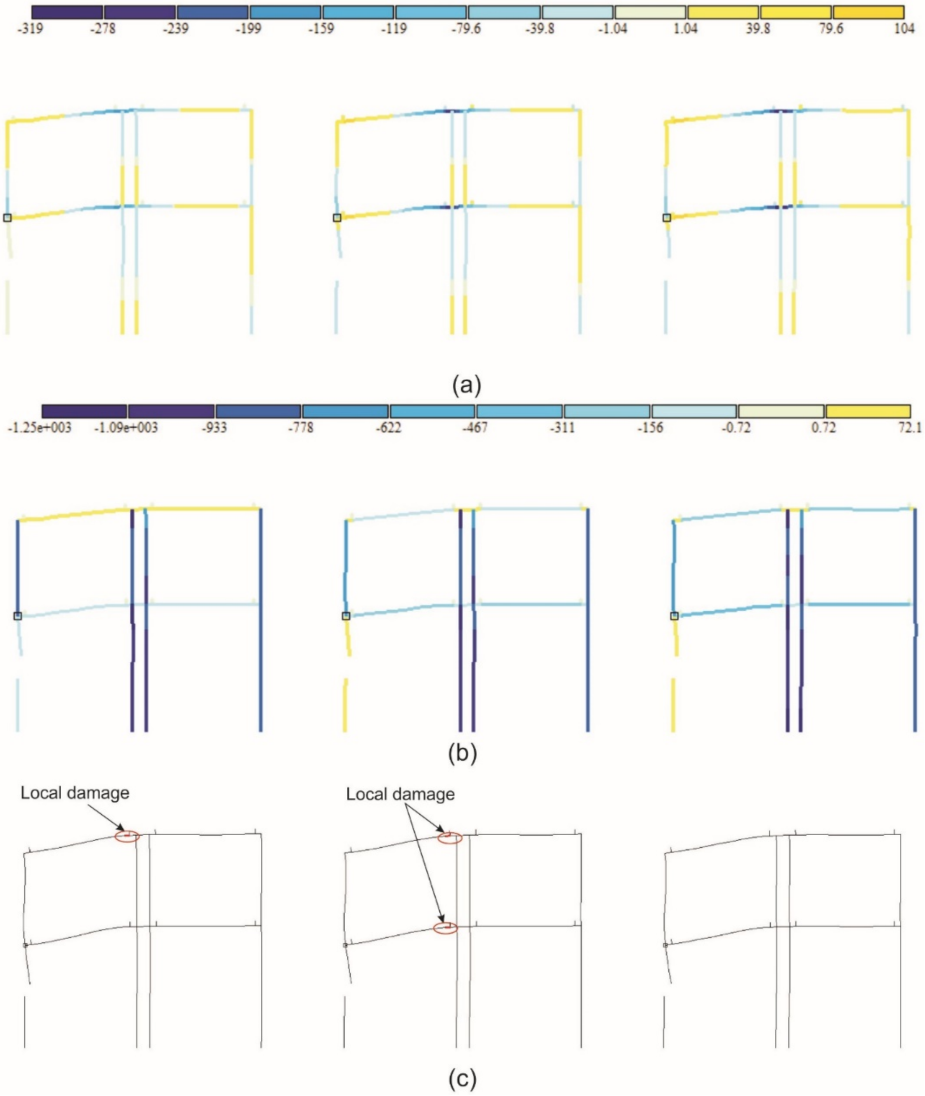

Figure 5. Calculation results for substructure robustness to progressive collapse: moments, kN·m (a), axial forces, kN (b), failure schemes (c). Here accepted: without prestressing (left column), prestressing force equals $0.6 \cdot R_{s,ser} \cdot A_s$ (middle column) and prestressing force equals $0.9 \cdot R_{s,ser} \cdot A_s$ (right column).

At the same time, constructive decision considered above leads to moment increasing into posts. According to this feature, it is necessary to provide additional control of strength and stability of columns as compressed-bent elements [22], as well as carried out reliability control of anchoring of reinforcing bars into connection nodes of posts and girders.

4. Conclusions

1. It is established that reinforced concrete building frame made of precast panel-frame elements with prestressed girders transforms to truss-diaphragm system similar to Vierendeel truss if outer column of the first floor was collapsed.

2. Changing placement of prestressed rebars through the height of girders allows us varying stress-strain state into the danger zones of precast-cast-in-place building frames made of panel-frame elements and provides load bearing capacity of such structures under accidental impacts.

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Моделирование разрушения железобетонного каркаса многоэтажного здания с предварительно напряженными ригелями

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Ключевые слова: моделирование, железобетонный сборно-монолитный каркас, расчетная схема, преднапряжение, аварийные воздействия, численный анализ

Аннотация. В последние десятилетия в области структурного анализа стало все больше внимания уделяться изучению механизмов сопротивления прогрессирующему разрушению различных типов конструктивных систем зданий и сооружений при аварийных воздействиях. Одним из наиболее распространенных типов конструктивных систем многоэтажных жилых и общественных зданий в настоящее время является рамный или рамно-связевой железобетонный каркас. В качестве механизмов его сопротивления прогрессирующему сопротивлению в научной литературе, как правило, выделяются следующие: арочный, вантовый, ферма Виренделя. Однако к настоящему времени не установлено строгого соответствия между типом конструктивной системы, характером аварийного воздействия и механизмами сопротивления прогрессирующему обрушению в зависимости от первых двух факторов. Аналогичная ситуация складывается и в области разработки эффективных способов обеспечения конструктивной безопасности таких каркасов при аварийных воздействиях. Поэтому в качестве объекта исследования в данной работе был выбран многоэтажный железобетонный рамно-связевой каркас с предварительно напряженными ригелями, подверженный аварийному воздействию в виде внезапного удаления колонны крайнего ряда на первом этаже здания. Целью исследования являлось установление механизма сопротивления железобетонного каркаса с предварительно напряженными ригелями при рассматриваемом типе воздействия. Для достижения целей исследования с помощью метода конечных элементов был выполнен нелинейный квазистатический анализ деформирования и разрушения подконструкции в виде двухэтажной двухпролетной рамы, выделенной из каркаса здания методом декомпозиции. По результатам нелинейного численного анализа были получены значения внутренних усилий в элементах подконструкции и схемы ее разрушения в зависимости от величины предварительного напряжения в ригелях. Установлено, что при удалении колонны крайнего ряда в рассматриваемом железобетонном каркасе с предварительно напряженными ригелями над зоной локального разрушения реализуется механизм сопротивления по типу фермы Виренделя. Показано, что изменение уровня усилия предварительного обжатия в ригелях позволяет варьировать НДС статически неопределимой стержневой системы и обеспечивать ее несущую способность при аварийных воздействиях.

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