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ANALYSIS OF EXPERIMENTAL STUDIES OF FRAGMENTS OF BUILDING STRUCTURES FOR PROGRESSIVE COLLAPSE

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Abstract. The article examines the history of the problem of buildings and structures assessment of resistance to progressive collapse. The main prerequisites for the beginning of the study on the prevention of progressive collapse in Russia, the United States and the European Union countries have been identified. The analysis of pilot research of fragments of building structures for progressive collapse has been carried out. Foreign and domestic approaches to the methods of pilot research of fragments of building structures are considered, and their main features are revealed. Based on the analysis of recent studies and publications, it has been concluded that with an increase in static uncertainty and structural instability, resistance to progressive collapse increases, and dynamic overloading occurs in the surviving structural elements with a sudden application of load. It is also noted that dynamic overloading of the entire system is more dangerous than switching off the carrier element. Theoretical and experimental studies of the protection of structures from progressive collapse are necessary for a more detailed study of the behavior of structures under the influence of special loads.

Keywords: progressive collapse, emergency impact, local collapse, stress-strain state.

АНАЛИЗ ЭКСПЕРИМЕНТАЛЬНЫХ ИССЛЕДОВАНИЙ ФРАГМЕНТОВ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ НА ПРОГРЕССИРУЮЩЕЕ ОБРУШЕНИЕ

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Аннотация. В статье рассмотрена история возникновения проблемы оценки устойчивости зданий и сооружений к прогрессирующему обрушению. Выявлены основные предпосылки начала исследования предотвращения прогрессирующего обрушения в России, США и стран Евросоюза. Выполнен анализ экспериментальных исследований фрагментов строительных конструкций на прогрессирующее обрушение. Рассмотрены зарубежные и отечественные подходы к методикам экспериментальных исследований фрагментов строительных конструкций, и выявлены их основные особенности. На основе анализа последних исследований и публикаций сделаны выводы, что с увеличением статической неопределённости и неразрезности конструкции увеличивается сопротивление прогрессирующему обрушению, при внезапном приложении нагрузки в уцелевших элементах конструкции возникают динамическое догружение. Также отмечено, что большую опасность представляет динамическое догружение всей системы, чем выключение несущего элемента. Теоретические и экспериментальные исследования защиты конструкций от прогрессирующего обрушения необходимы для более детального изучения поведения конструкций при воздействии особых нагрузок.

Ключевые слова: прогрессирующее обрушение, аварийное воздействие, локальное обрушение, напряжено-деформированное состояние.

Problem statement

Progressive collapse is a local collapse that leads to the spread of damage of building elements until its complete or partial destruction. This phenomenon gained the main publicity in the society in 1968, after the accident of Ronan Point building. An explosion of household gas occurred in the task, which resulted in successive destruction (figure 1).

This tragedy forced to make changes to the building regulatory framework in England. In «Standards for the prevention of progressive collapse in large-panel structures» published in 1968, the terms accidental (unforeseen) load and alternative load path were first noticed. Already in 1970, the «Standards for the prevention of progressive collapse in large-panel structures» became an obligatory part of British building codes.

In the normative documents of the USSR, the requirement for prevention of progressive collapse was first recorded in VSN 32-77 «Instructions for the design of structures of panel buildings» [23]. A more detailed formulation of the requirements was formulated and considered in the «Handbook on the design of residential buildings. Issue 3 Constructions of residential buildings (to SNiP 2.08.010-85)» [9].

The following decades saw an increase in scientific research on progressive collapse among the global community in the construction industry, associated with new cases of this phenomenon. The tragic events of September 11, 2001, which occurred in New York (USA) with the towers of the World Trade Center, forced us to bring research and methods of protection against such destruction to the most pressing problems of the construction industry.

Accidents with the effect of progressive collapse have also occurred in the Russian Federation. One such example is the collapse of the load-bearing structures of the Transvaal Water Park (figure 2).

The above-mentioned tragedies point to the urgent need to study the problem of survivability of buildings in the case of emergency impacts. It is especially important to prevent the progressive collapse at the design stage by maintaining the overall integrity of the building a case of the local damage, at least until complete evacuation of people.

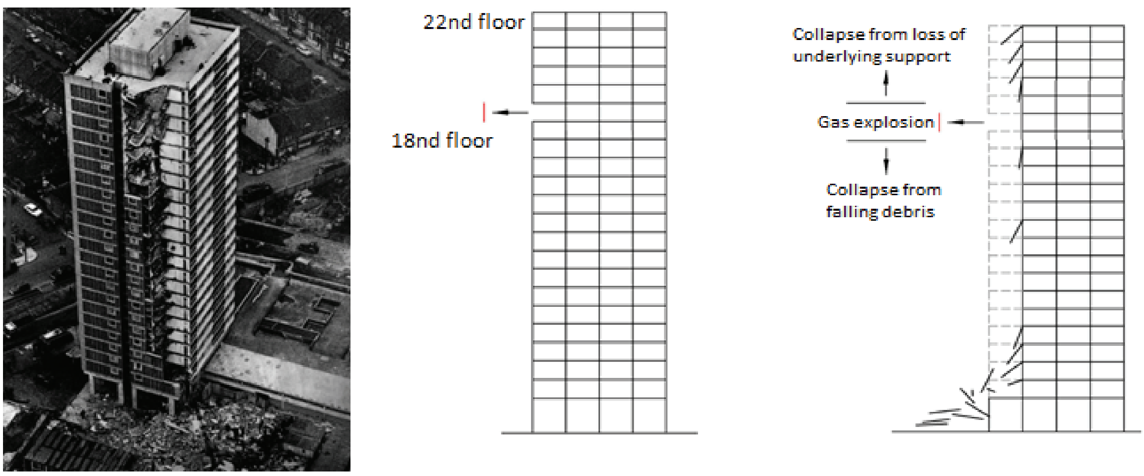

Figure 1 – The collapse of the part of the facade of the large-panel Ronan Point building. England, 1968.

a) b)

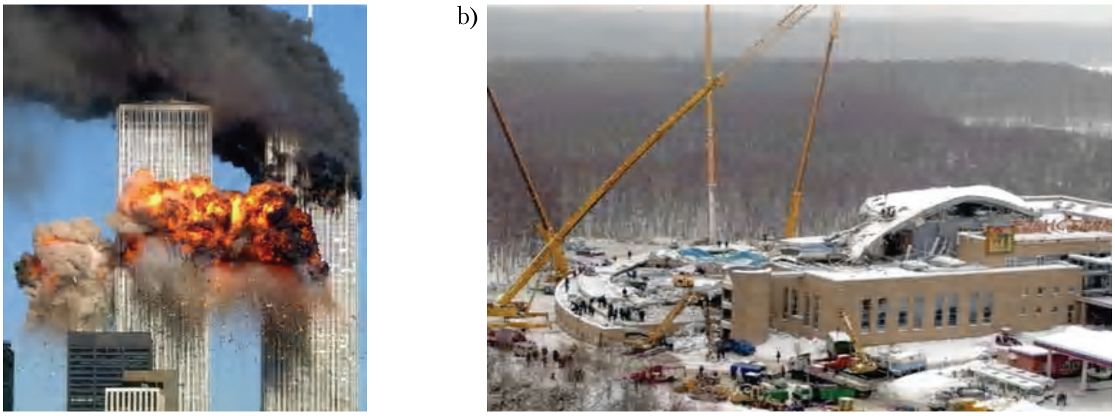

Figure 2 – Historical examples of buildings that have undergone progressive collapse: a) The Towers of the World Trade Center, 2001 the USA (after the terrorist attacks); b) The Transvaal Water Park, 2004 (Russia, design error).

Analysis of the latest research and publication

In the process of studying experimental studies, the works of the author were studied: J. Yu and K. H. Tan [26, 27], H. Jian [10], W. J. Yi [25], V. M. Bondarenko [1], G. A. Geniev [7], V. A. Gordon [8], V. I. Kolchunov, N. V. Fedorova, O. A. Vetrova, K. A. Shuvalov, P. A. Korenkov, N. T. Vu [22, 11, 14, 12, 6, 15, 13, 5, 16], P. G. Yeremeyev [24].

The main part

To achieve the goals of preventing the progressive collapse, the global scientific community in the field of construction has focused on creating new design principles that will increase the building's resistance to progressive collapse and control the expansion of damage from local destruction. Some of the most important principles were formulated in Britain after the events with the Ronan Point multi-apartment panel building in London [2] and in the Eurocode [3] and American norms that appeared after the collapse of the World Trade Center in 2001 [17, 21].

For the first time in the Russian standards, requirements for calculating stability against progressive collapse for buildings and structures of an increased level of responsibility were introduced into Federal Law № 384-FZ «Technical Regulations on the Safety of Buildings and Structures» on December 30, 2009 [4]. As a result, SP 296.1325800.2017 «Buildings and structures». Special effects» [18], SP 385.1325800.2018 «Protection of buildings and structures from progressive collapse. Design rules. The main provisions» [19].

Over the past twenty years, experimental studies have been intensively conducted on the behavior of reinforced concrete structures subjected to progressive collapse when the load-bearing element is removed. Many design options: combinations of beams and columns, beams and slabs, flat frames and large-scale buildings have been studied.

J. Yu and K. H. Tan [26, 27] investigated the behavior of two-span reinforced concrete beams when removing the middle columns (figure 3, a). The experiment included testing beams with various reinforcements and cross-section sizes. Beams with and without prestressed reinforcement were also tested.

H. Jian [10] and colleagues tested the operation of plates and crossbars when modeling the local destruction of the extreme column (figure 3, b). The authors of the experiments concluded that plates significantly increase resistance to progressive collapse, redistribution of forces and rigidity of structures.

W. J. Yi [25] and colleagues conducted experimental studies on four-span three-story reinforced concrete frames gradually destroying the middle column (figure 3, c).

The experimental data allowed us to draw several conclusions:

– the arch effect increases the bending capacity of the beam;
– with an increase in the ratio of width to height and a decrease in the percentage of reinforcement, the arch effect is stronger;
– the percentage of reinforcement significantly affects the bearing capacity of the structure, especially during its operation as a hanging system;
– prestressing increases the arch effect.

The results obtained indicate that with an increase in static indeterminacy and the continuity of the structure, the resistance to progressive collapse increases.

In Russia, over the past two decades, a number of experimental studies have been carried out in this direction, including the works of V. M. Bondarenko [1], G. A. Geniev [7], V. A. Gordon [8], V. I. Kolchunov, N. V. Fedorova, O. A. Vetrova, K. A. Shuvalov, N. V. Klyueva, P. A. Korenkov, N. T. Vu [22, 11, 14, 12, 6, 15, 13, 5, 16], D. V. Kudrina [24]. These studies are aimed at investigation of the behavior of the structure under static-dynamic loading, which distinguishes them from foreign ones. The authors focused on the study of the principles of force resistance of reinforced concrete structures during a sudden failure of load-bearing elements in extreme conditions.

Thanks to the structural systems prepared for field experiments (figure 4 – figure 7), the strength characteristics, deformability and fracture patterns and survivability parameters of structures in extreme conditions were analyzed.

a)

b)

c)

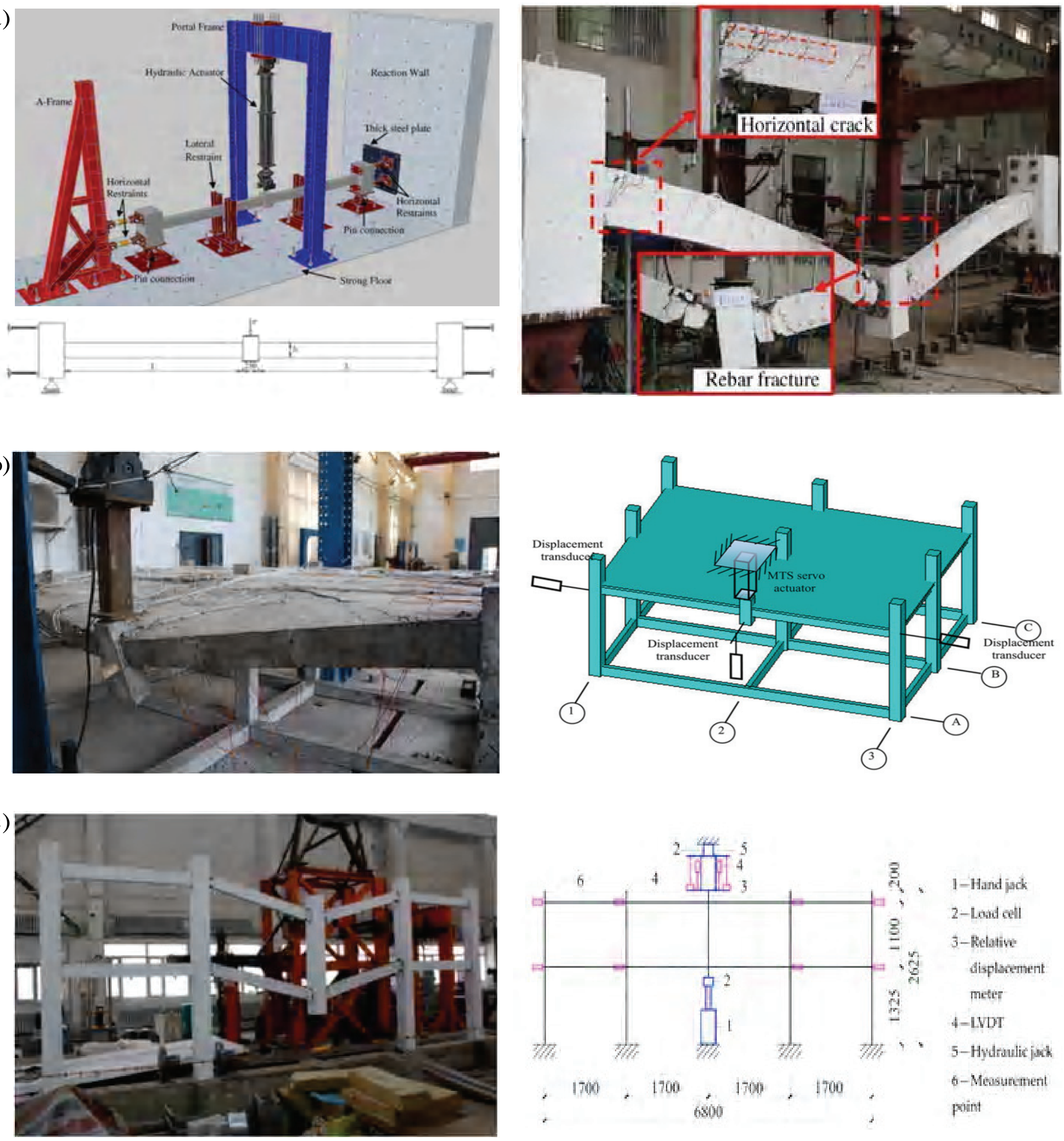

Figure 3 – Schemes of test installations: a) J. Yu and K. H. Tan; b) H. Jian ; c) W. J. Yi.

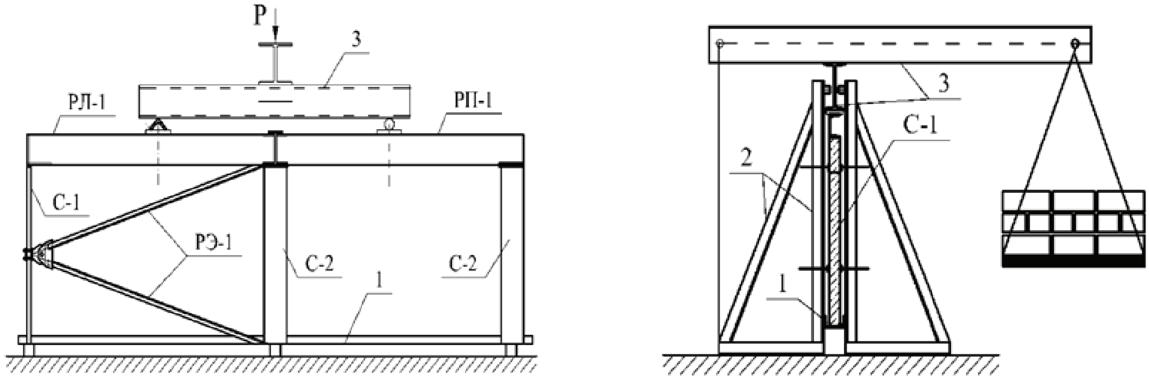

Figure 4 – Flat frame of solid or composite section, without or with prestressing in a case of sudden disconnection of the torque connection of the left rack with the crossbar: 1 – support beam, 2 – struts with guides, 3 – lever loading system.

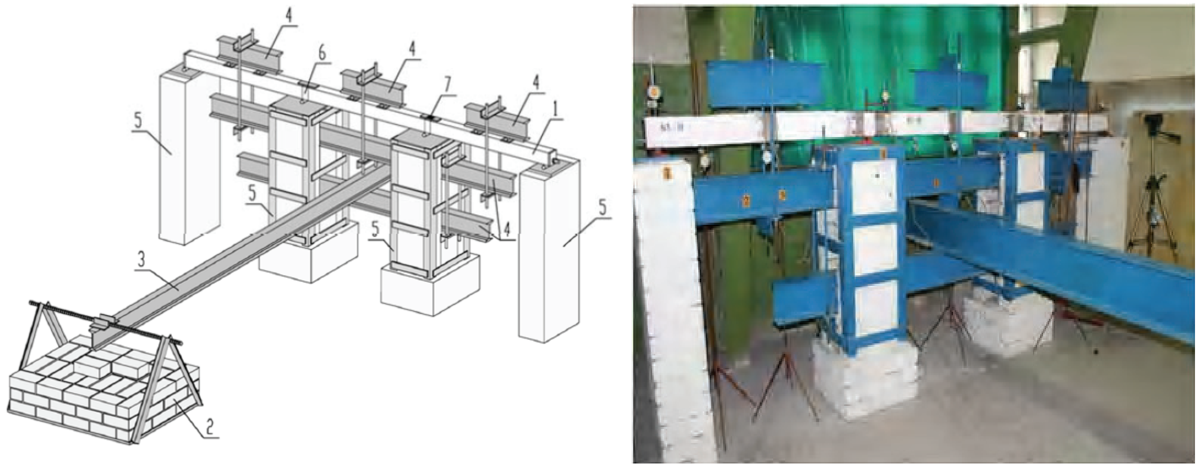

Figure 5 – Three-span beam of solid or composite section, without or with prestressing in a case of sudden disconnection of the torque coupling in the section above the support: 1 – experimental beam design; 2 – loading platform with loads; 3 – lever; 4 – switchgear; 5 – supports; 6 – over-bearing connecting part; 7 – calibrated connecting part.

Figure 6 – A flat two-span three-story frame with a sudden shutdown of the middle or extreme pillar of the first floor.

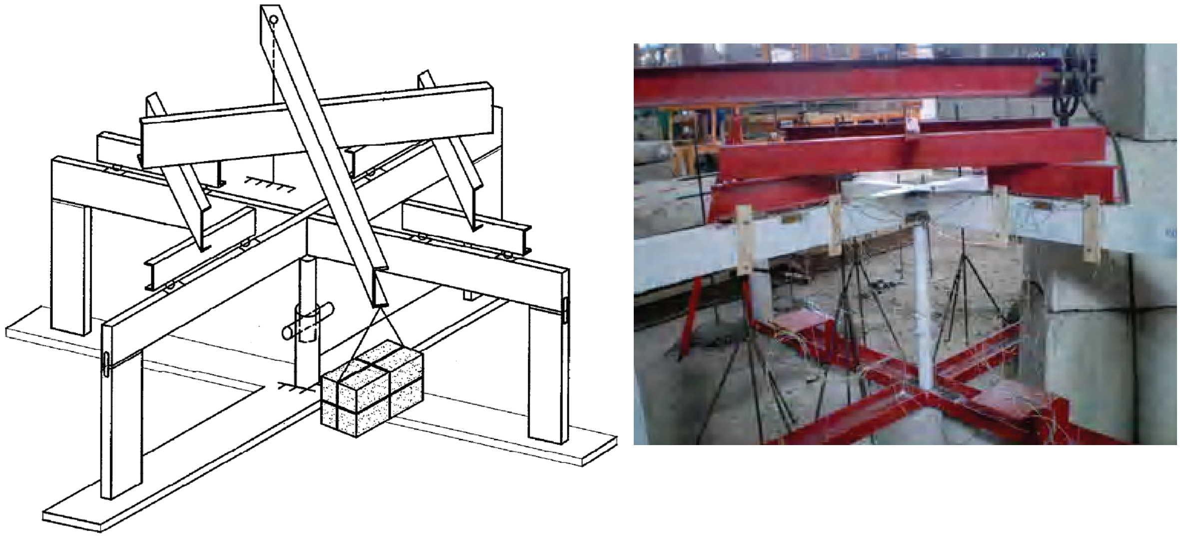

Figure 7 – A spatial frame of a solid or composite section with a sudden shutdown of the linear connection – the central telescopic rack.

Conclusions

After analyzing the research results, the main conclusions can be highlighted. It is revealed that with the instantaneous application of a load, dynamic additional loading (added stress) occurs in the surviving elements of a statically indeterminate structure. The peak of overloading occurs at a time equal to a quarter of the oscillation period. The amount of overloading is influenced by the nature of structural failure and the magnitude of applied loads, the conditions for fixing elements and the percentage of reinforcement [22, 12].

Also, the magnitude of the increment of dynamic overloading in reinforced concrete elements depends on the level of load [12], the speed of emergency impact application [11] of prestressing the reinforcement and its level, the class of concrete and reinforcement [22, 20].

It is worth noting, based on the results of the experiments, the greatest danger is precisely the dynamic overloading of the entire system, and not only the shutdown of the carrier element. The development of such a scenario may lead to a local or complete progressive collapse.

In [14], a methodology for assessing survivability is presented by introducing a quantitative parameter equal to the magnitude of the load, at which kinetic processes occur that initiate the transition of a constructive system to a variable one [1]. Thus, it is possible to record the nature of changes in the structural system during its destruction.

At the moment, most studies on the protection of structures from the progressive collapse are carried out on monolithic reinforced concrete, steel and composite structures. Experimental research directly affects the development of regulatory documents regulating the structural safety of buildings and structures. Further theoretical and experimental research in this area is necessary for a more detailed study of the redistribution of forces in the structural system and the stress-strain state of structures under special loads.

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