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PROGRESSIVE COLLAPSE RESISTANCE OF FACILITIES EXPERIENCED TO LOCALIZED STRUCTURAL DAMAGE - AN ANALYTICAL REVIEW

Abstract. *During the entire life cycle, the facilities are experienced to force and environmental actions of various nature and intensity. In some cases, such influences can lead to a loss of the bearing capacity of the structural elements of a building, which in turn can lead to a disproportionate failure of the entire structural system. Such phenomenon was called progressive collapse. Major accidents at facilities, such as the collapse of a section of the Ronan Point high-rise residential building (London, 1968), the Sampoong department store (Seoul, 1995), the Transvaal Park pavement (Moscow, 2004), the World Trade Center (New York, 2011) and others, clearly demonstrated the urgency of this problem. In this regard, the regulatory documents of the USA, Great Britain, EU, China, Australia, Russia and other countries established requirements for the need to calculate structural systems of buildings for resist to progressive collapse after sudden localized structural damage. However, the steady increase in the number of new publications on the problem of progressive collapse observed in the world scientific literature indicates that the results of such studies do not yet provide exhaustive answers to all questions related to this phenomenon. In this regard, the proposed review article is aimed at systematizing, generalizing and analyzing new research results on resistance to progressive collapse of facilities, identifying new trends and proposing new research directions and tasks to improve the level of structural safety of design solutions for buildings and structures. In order to achieve this goal, the following aspects were considered: the nature of the impacts leading to progressive collapse; features of modeling the progressive collapse of structural systems of buildings and structures; mechanisms of resistance to progressive collapse and criteria for evaluation of a progressive collapse resistance.*

Particular attention in the scientific review is paid to the analysis of works related to a new direction of research in the area under consideration, associated with the assessment of the bearing capacity of eccentrically compressed elements of structural systems, the effect on their resistance to progressive collapse of the parameters of the loading mode, degradation of material properties and the topology of the structural system.

The significance of the proposed scientific review is that, along with the well-known and new results presented in the English-language scientific literature, it summarizes and analyzes the original approaches, methods and research results published in Russian-language scientific publications, primarily included in the RSCI Web of Science.

Keywords: *analytical review, structural safety, progressive collapse, progressive collapse resistance, ultimate limit state, buckling failure, shear failure, flexural failure*

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АНАЛИЗ ОСОБЕННОСТЕЙ СОПРОТИВЛЕНИЯ ПРОГРЕССИРУЮЩЕМУ ОБРУШЕНИЮ КОНСТРУКТИВНЫХ СИСТЕМ ЗДАНИЙ И СООРУЖЕНИЙ ПРИ ВНЕЗАПНЫХ СТРУКТУРНЫХ ПЕРЕСТРОЙКАХ: АНАЛИТИЧЕСКИЙ ОБЗОР НАУЧНЫХ ИССЛЕДОВАНИЙ

Аннотация. *В течение всего срока службы конструкции зданий и сооружений подвержены силовым и средовым воздействиям различной природы и интенсивности. В отдельных случаях такие воздействия могут приводить к потере несущей способности конструктивных элементов здания, что в свою очередь может привести к непропорциональному отказу всей конструктивной системы – ее прогрессирующему обрушению. Крупные аварии, произошедшие на объектах капитального строительства, такие как обрушение секции многоэтажного жилого здания Ронан Пойнт (Лондон, 1968), торгового центра Сампун (Сеул, 1995), покрытия Трансвааль-Парка (Москва, 2004), здания ВТЦ (Нью Йорк, 2011) и др., наглядно продемонстрировали актуальность этой проблемы. В связи с этим в нормативных документах США, Великобритании, ЕС, Китая, Австралии, России и других стран были установлены требования о необходимости расчета конструктивных систем зданий на прогрессирующее обрушение при внезапных структурных перестройках, вызванных удалением одного из несущих элементов. Однако наблюдаемый в мировой научной литературе устойчивый рост числа новых публикаций по проблеме прогрессирующего обрушения указывает на то, что результаты таких исследований пока не дают исчерпывающих ответов на все вопросы, связанные с этим явлением. В этой связи предлагаемая обзорная статья направлена на систематизацию, обобщение и анализ новых результатов исследований по вопросам сопротивления прогрессирующему обрушению конструктивных систем зданий и сооружений, выявление новых тенденций и предложение новых направлений и задач исследований для повышения уровня конструктивной безопасности проектных решений зданий и сооружений. Для достижения указанной цели рассмотрены: природа воздействий, приводящих к прогрессирующему обрушению; особенности моделирования прогрессирующего обрушения конструктивных систем зданий и сооружений; механизмы сопротивления прогрессирующему обрушению и критерии особого предельного состояния.*

Особое внимание в научном обзоре уделено анализу работ, относящихся к новому направлению исследований в рассматриваемой области, связанному с оценкой несущей способности сжатых и сжато изогнутых элементов конструктивных систем, влияния на их сопротивление прогрессирующему обрушению параметров режима нагружения, деградации свойств материалов и топологии конструктивной системы.

Значимость предлагаемого научного обзора состоит в том, что в нем наряду с известными и новыми результатами, представленными в англоязычной научной литературе, обобщены и проанализированы оригинальные подходы, методики и результаты исследований, опубликованные в русскоязычных научных изданиях, прежде всего входящих в RSCI Web of Science.

Ключевые слова: *конструктивная безопасность, конструктивная система, прогрессирующее обрушение, особое предельное состояние, механизмы сопротивления разрушению, критерии особого предельного состояния*

1 Introduction

It is believed that since the partial collapse of the Ronan Point building on May 16, 1968 in London [1], which occurred as a result of a gas explosion on the 18th floor of this 25-story building, scientists and design engineers have paid closer attention to the problem of ensuring the safety of supporting systems buildings and structures under accidental impacts caused by emergencies of various nature. An additional impetus to the development of this relatively new direction in the field of theory of structures and structural analysis was given by a series of collapses of buildings caused by terrorist attacks [2], [3]. Thus, most of the victims of the terrorist attacks on the buildings of Alfred Murray in Oklahoma City (USA) in 1995, residential buildings in Moscow on September 8 and 13, 1999 were caused by the collapse of parts of the buildings that followed powerful explosions, and not a direct result of the blast wave. Fires following the collision of aircraft with the South and North Towers of the World Trade Center in New York on September 11, 2001 [4] led to the complete collapse of these structures and thousands of lives. These collapse cases clearly demonstrated that an emergency failure can be implemented for any element of the supporting system.

Subsequent studies of the problem of progressive collapse showed that the nature of the failure of a structural element of a building or structure can vary from a relatively mild scenario of failure associated with bending, for example, in mechanical collisions of vehicles moving at low speeds, to a shear [5], characterized by the absence of significant deflections of the structure immediately before destruction and the transfer of the reaction from the destroyed element to the remaining part of the bearing system for a period of time, calculated from tenths to hundredths of a second. Analysis of experimental and numerical studies [5–8], modeling such a character of the initial local destruction of the bearing element of the structural system of a building, makes it possible to ascertain the emergence of additional inertial forces in the elements of the frames of buildings and structures. Due to a wide range of impacts that differ both in their physical nature and in the intensity and likelihood of occurrence during the life of the structure, the enumeration of design situations covering all the assumed cases is ineffective. Therefore, to substantiate constructive measures to protect against progressive collapse, most researchers, and subsequently in the regulatory documents of many countries [2,9–11], [12], adopted a situational approach to modeling the design situation. In this case, the most unfavorable scenario is considered as a scenario for the development of an emergency, leading to the emergence of additional dynamic additional loading. Despite the currently emerging dominance of the situational approach to modeling emergency design situations for analyzing the stability of bearing systems of buildings and structures to progressive collapse, it is an important scientific and technical task to analyze the mechanisms of initial local destruction and the corresponding modes of deformation of structural systems to formulate sound recommendations for modeling the effects in the secondary design diagrams of structures that are formed after the initial local destruction.

The authors of the reviews of studies of progressive collapse presented in the scientific literature, as a rule, focus on the mechanisms of destruction of elements of the secondary design scheme [13–15], analysis of experimental and numerical studies of the problem of progressive collapse, while taking a situational approach as a postulate. However, the list of loads and actions adopted in the current regulatory documents of various countries, which are used for the design justification of protection against progressive collapse, has some differences. For example, in UFC 4-023-03, a non-linear static analysis for floors above a removed structural member takes a load:

$$G_N = \Omega_N\,(1.2D + (0.5L \text{ or } 0.2S)),$$

where Ω_N is a normative dynamic amplification factor, D is a death load; L is a live load; S is a snow load.

In a numerical study by Byfield and Paramasivam [16] of the explosion-induced collapse of the supporting system of the federal building by Alfred Murray (Oklahoma City, USA, 1995), the convergence of the simulation results with the real picture of destruction was achieved with a combination of loads:

$$G = 1.05D + 0.25L.$$

In Building Code of Russian Federation SP 385.1325800.2018, as in UFC 4-023-03, a combination of constant and long-term loads is accepted:

$$C_s = P_d + P_l + P_s,$$

where P_d is death load, P_l is live long-term load, P_s is a load associated with the dynamic effect in the load-bearing system under the sudden removal of the load-bearing member. All loads, including death ones, are taken according to their nominal value.

In the Eurocode EN 1991-1-7, the issue of normalization of loads for the calculation of disproportionate destruction is included in national annexes, however, in contrast to the above-mentioned regulatory documents, recommendations are given for assessing the risk of emergencies.

Analysis of these documents also indicates differences in approaches to accounting for the dynamic effects of removing an element. UFC 4-023-03 unambiguously adopted the dynamic nature of the removal of an element, while with a static method of calculating an accident in the form of a failure of a bearing element for elastically deformable systems, the dynamic factor is taken equal to 2 for all loads applied to the floors above the removed element. And for systems that allow the development of plastic deformations, it accepts with a reduction factor that takes into account the features of the structural system. In the Building Codes of Russian Federation for reconstructed buildings built before the entry into force of SP 385.1325800.2018, in order to ensure the requirements of protection against progressive collapse, it is allowed to perform calculations for a statically applied impact, and for newly erected buildings, a “slow” quasi-static or sudden dynamic scenario of the transfer of forces can be considered. from the item to be removed. However, the document lacks criteria for differentiating these design situations for specific types of buildings and structures. Although this aspect is not reflected in the main text of Eurocode EN 1991-1-7, as noted by Paolo Formichi [17], it is common practice to apply a dynamic amplification factor of 2 for structures above the localized failure zone.

An analysis of regulatory documents and review and analytical scientific articles on the issue of progressive collapse shows that in order to answer the questions related to taking into account the initial local destruction in the supporting system of a building or structure, it is necessary to return to considering the possible causes of such local destruction. In this direction, one can note the informative report of Ellingwood B.R. et al. [18] and an article by Kiakojouri et al. [3], in which one of the sections is devoted to a brief analysis of the impacts that cause the progressive destruction of the load-bearing systems of buildings. As such, Kiakojouri et al. following Ellingwood B.R. et al. emit explosions, fires, shock and seismic effects, as well as combinations of these and other factors. However, Kiakojouri et al. as well as in the above-considered analytical reviews, the quantitative and qualitative parameters of such impacts are not highlighted, their assessment is not given in terms of the impact on the propagation of damage in the bearing system and the nature of such damage.

In addition, since the publication of the review articles discussed above, such as [13–15], new publications have been published on the issue of progressive collapse, and a number of non-English-language research articles of the past (primarily those belonging to authors from the CIS countries) have remained outside the border consideration of these works. Therefore, this analytical review is intended to fill this gap.

2. The nature of the impacts leading to progressive collapse. Loading modes

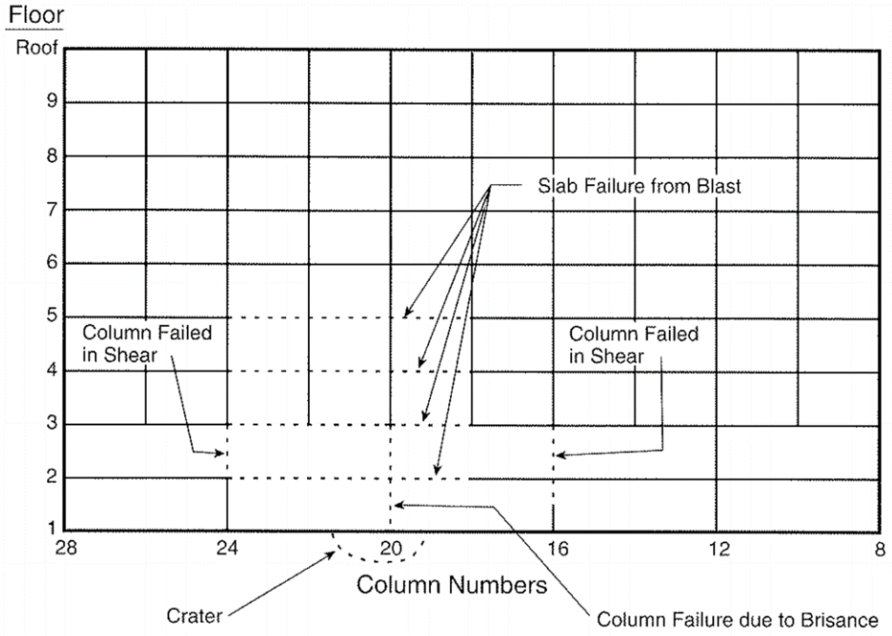
2.1. Explosions

The collapse of part of the Ronan Point building due to a natural gas explosion on May 16, 1968 in London [1], served as a trigger for a more intensive study of the phenomena associated with the progressive destruction of the bearing systems of buildings and structures in order to reduce the possible damage from some initial local destruction in constructive system.

At present, many researchers [3–5, 13, 19] consider explosions as one of the main threats to the occurrence of initial local destruction, since it is precisely with such influences that the mechanism of initial shear destruction is possible [5], characterized by a rapid transfer of forces from the destroyed element on the preserved structures and the emergence of significant forces of inertia.

Explosive effects are extremely diverse. These include explosions of natural gas in residential premises and inside industrial buildings and structures, terrorist attacks. In the listed cases, the loading mode and the load application pattern will differ. In the scientific literature, as a rule, a distinction is made between nearby explosions and those remote from the structure. For the unification and convenience of modeling explosive effects on building structures, a parameter of the scaled distance z (m/kg$^{1/3}$) is introduced, which takes into account the distance to the explosive device, its mass and makes it possible to assess the resistance of structures to explosive effects, based on the equivalent pressure of the blast wave on the building structure. In most studies carried out in recent years [20–24], this parameter varied from 0.4 to 6 m/kg$^{1/3}$. This range of values is consistent with the cases of real explosions leading to the progressive collapse of buildings and structures. Thus, in the 1995 terrorist attack on the federal building of Alfred Murray, as noted by Tagel-Din, H., & Rahman, NA [25], an explosive device weighing about 4000 pounds (about 1814 kg) was detonated at a distance of 14 feet (about 4.27 m) from the entrance group of the building (z = 0.35 m/kg$^{1/3}$) led to the fragmentation of the column of the first floor nearest to the epicenter of the explosion in 0.3-0.4 seconds from the moment of detonation, as well as damage to the adjacent girders and columns leaving on the facade of the building (figure 1, a - b). This provoked, after 1.5 seconds, a complete collapse of the girder over the destroyed column and the formation of plastic hinges in the girders of the overlying floors above the removed load-bearing element. The complete collapse of the supporting system of the building occurred after 4.5 seconds.

a)



b)

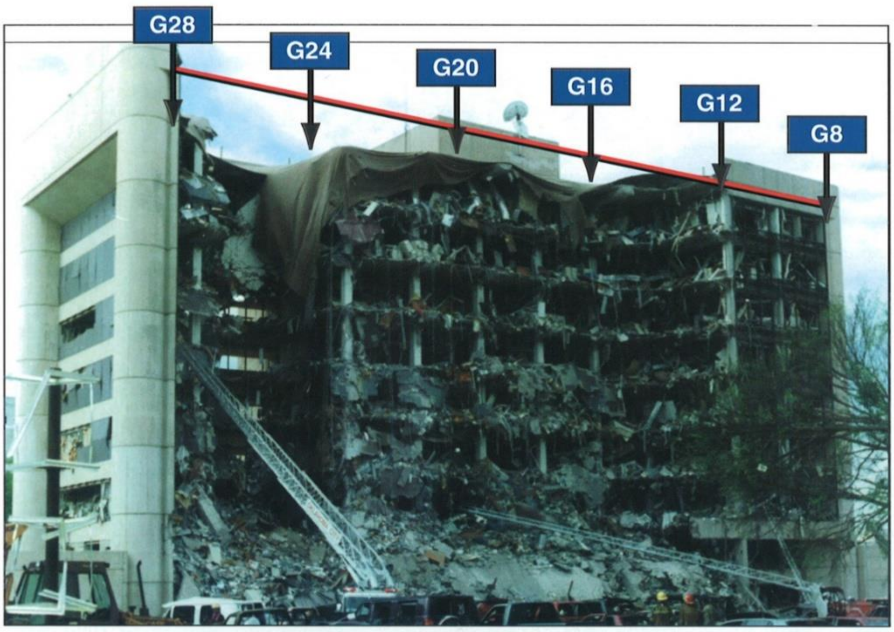


Figure 1 - A picture of the collapse of a building by Alfred Murray, Oklahoma City, USA, 1995 [27]: diagram of the destruction of the structural structures of the building caused by the blast wave - a view from the side of the northern facade (a) general view of the eastern and northern facades of the building after the collapse (b)

Yan J et. al [20] found that at close detonation of an explosive device (z = 0.4 - 0.54 m/kg$^{1/3}$), brittle shear fracture was observed for CFRP columns. The destruction of the models under consideration occurred depending on the percentage of reinforcement CFRP 10 - 25 ms after the contact of the blast wave with the structure. Similar results were obtained by Hu et. al. [21], who established that the zone strengthening of a column using CFRP does not prevent its brittle fracture at the considered intensity of the blast wave. In studies by C. Zhang, Abedini, and Mehrmashhadi [23], the destruction of an element exposed to the action of a blast wave from a close detonation of an explosive device was 0.08-0.1 seconds.

For an H-section steel column, Momeni et al. [24] found that the greatest deflection was achieved in 0.004 seconds from the moment the explosion pressure was applied to the structure.

Lim K. et al. [26], having numerically investigated the resistance of a monolithic joint between a reinforced concrete floor slab and a column at a scaled distance of 0.1 m/kg$^{1/3}$ to the epicenter of the explosion, they came to the conclusion that the explosion has a greater effect on the floor slab than on the column. Even with small rotations of the slab sections in the zone of abutment to the column, significant damage was observed, which indicated the fragile nature of the destruction.

According to Kiakojouri et al. [3] the situational approach adopted in the current standards, consisting in the exclusion of one of the load-bearing elements of the system from the design scheme, is poorly suited to the analysis of resistance to progressive collapse under explosive effects, since in real explosions (see, for example, [25]), as a rule, it turns out damaged more than one load-bearing element

2.2. Mechanical collisions

Primary local failures in the bearing systems of buildings and structures from mechanical collisions are associated, as a rule, with transverse impacts of vehicles crashing into the bearing structures located along the outer contour of the building or structure. The most susceptible to such initial damage are the supports of bridges and transport overpasses, less often the columns and pylons of the extreme rows or the outer walls of civil buildings located near sections of roads with heavy traffic. Referring to the 1970s research by Leyendecker and Burnett, Ellingwood B.R. et al. [18] indicate that the probability of such an impact on the structure during the year is 6x10-4. Collisions of cars with curb weight from 2203 kg [28] to 8000 kg [29], moving at speeds from 40 to 120 km / h, with parts of structures are considered as scenarios of impacts for this type of emergency situations in the scientific literature.

Influence of the column structure (flexibility; cross-sectional shape; the presence of fiber for reinforced concrete structures), as well as the impact parameters (the height at which the collision occurs; the angle at which the transverse impact occurs; the vehicle speed; the forces in the column before the collision) on the nature of deformation and destruction load-bearing element in transverse impact was investigated by Gholipour, Zhang, and Mousavi [30,31], NH Yi et al. [29], Abdelkarim and El Gawady [32], Wu, Jin, and Du [33], R. W. Li, Zhou, and Wu [34], [28], C. Demrtino et al. [35], Radchenko P.A., Batuev S.P., Plevkov V.S., Radchenko A.V. [36,37], Belov N.N., Dzyuba P.V., Kabantsev O.V., Kopanitsa D.G., Yugov A.A., Yugov N.T. [38], Afanasyeva S.A., Belov N.N., Kopanitsa D.G., Yugov N.T., Yugov A.A. [39] and others. Since testing of full-scale structures under the considered type of impact seems to be an extremely expensive and difficult to implement measure, most of the above studies were carried out by modeling an emergency situation using FEM, mainly using LS Dyna. At the same time, the numerical models were verified on the basis of comparison with the data of tests of scale models of columns for transverse impact. Such experimental studies were carried out mainly according to two methods: with a vertical free fall of a load on a column set in a horizontal position and pre-compressed using jacks or external prestressed steel rods [40] or when a pendulum load hits a vertically installed and loaded column structure [34].

The results of the studies considered show that in collisions of vehicles with columns of buildings and structures, the probability of their destruction according to the shear scenario increases significantly as the speed and mass of the vehicle increase. In experimental studies of column models under impacts with pendulum loads performed by R. W. Li, Zhou, and Wu [34], a change in the longitudinal force in the column under transverse impact was observed. The authors also draw attention to the not entirely correct reproduction of the dynamic effect of the gravitational load on a column when simulating a lateral impact using freely falling weights. Numerical simulation results obtained by Sohel K. et al. [28] show that the deflections of the column upon lateral impact from a vehicle moving at a speed of 40 km / h reach their maximum in the interval from 20 to 30 ms from the moment of the beginning of mechanical contact. The authors of the studies [20] note that with an increase in the value of the longitudinal force in the column in relation to its limiting value, it led to an increase in the bearing capacity of the columns under transverse mechanical impact, however, as noted [31], in this case, the fragile fracture mechanism became more probable. for reducing the range of plastic work of the material.

Yankelevsky et al. [41] considered as a design emergency a mechanical collision when a floor slab falls, caused by the exhaustion of the punching shear capacity, onto the underlying floor. The aim of the study was to establish the numerical values of the impact parameters (the height of the fall, the weight of the falling floor, the size of the overhangs of the floor slab), which determine the development of progressive collapse or the decay of the fracture process after the first mechanical collision. Based on the results of the performed numerical simulation in ANSYS, it was found that at a ceiling fall height of 12 m, a local failure of the column was observed directly under the floor exposed to mechanical shock, which was estimated by the authors of [41] as a local buckling loss. This led to the complete collapse of the entire load-bearing system of the building, and not only to the destruction of floors in the area of direct mechanical collision.

Performed by a group of researchers Radchenko P.A., Batuev S.P., Plevkov V.S., Radchenko A.V. [37] numerical modeling of the resistance to destruction of the structure of the protective dome of a nuclear power plant when a Boeing 747-400 plane crashes showed that structural measures alone cannot provide effective protection of the structure's load-bearing system under the type of impact under consideration.

2.3. Errors in design and construction

According to the estimates given in the work of Ellingwood B.R. et al. [18] the majority of cases (more than 80%) of collapse of the bearing systems of buildings and structures, as well as the cost of repair and restoration after damage, are associated with errors and violations made during the design, production of work or subsequent operation. Examples of such collapses include the collapse of the Sampun shopping center (1995, Seoul, Republic of Korea), caused by both ambiguous design decisions (reduction of the cross-sections of several columns, an increase in the thickness of the floor slab compared to the original design), and disruptions in operation (exceeding the load by overlapping due to a change in the functional purpose of the premises led to the formation of cracks). Errors in design, as a result of which the required load-bearing capacity of the structures was not provided, also led in 1981 to the complete collapse of the 5-storey building of Harbor Cay Condominium, USA [42].

Analysis of the causes of destruction of wooden elements of load-bearing systems of buildings and structures, carried out by Eva Frühwald Hansson [43], shows that most often the failure of structures is caused by mistakes made at the stage of elaboration of structural schemes of structures, as well as during the subsequent calculation justification of the adopted design solutions: 34 % of cases out of 295 considered emergency situations. At the same time, the causes of failures characteristic of steel and reinforced concrete structures associated with violation of the work technology (25% [44] and 40% [45], respectively, for steel and reinforced concrete structures), for wooden structures accounted for a significantly smaller share in the total number of failures - 14% [43]. Johannes AJ Huber, Mats Ekevad, Ulf Arne Girhammar & Sven Berg [46], having performed a comparative analysis of the mechanisms of resistance to destruction of steel, reinforced concrete and wooden structures, came to the conclusion that the peculiarities of wood do not allow to fully apply the same approaches to the calculation. on progressive collapse, as for other structural materials.

According to the research data of Dietsch P, Winter S [47], Blaß HJ, Frese M [45], the distribution of failures by types of load-bearing structures was as follows: beams (55% [47] and 72% [45], respectively), wooden and metal elements. timber trusses (19% [47] and 5% [45], respectively), frames (19% [47] and 10% [45], respectively), columns (2% [47] and 6% [45], respectively).

Belostotsky A.M. and Pavlov A.S. [48] based on the results of detailed numerical modeling of the entire load-bearing system and individual load-bearing elements and their interfaces for the sports and recreation complex "Transvaal-Park" (Moscow), which collapsed on February 14, 2004, showed that the accident was caused by mistakes made in the design : incorrect consideration of the conditions for coupling the column with the pavement structure and the local buckling of the column, which was revealed in the detailed modeling of the column's operation under load using the shell FE model (figure 2 a-b).

a)

b)

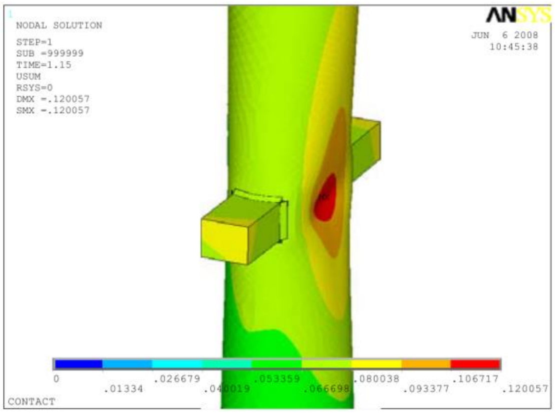


Figure 2 - Collapse of the sports and recreation complex "Transvaal-Park":
General view (a); local buckling of the column (FEA result), which became one of the causes of collapse [48] (b)

The reasons for such collapses as Skyline Plaza, USA, 1971 and Ice-hockey stadium in Humpolec, Czech Republic, 2004 were mistakes made during the work [42]: in the first case - premature removal of the formwork, in the second - connections from the plane were not established.

The indicated errors and irregularities in the design, production of work and operation are difficult to quantify and, unfortunately, in most cases cannot be taken into account by design standards. To reduce the risk of such errors, a high qualification of a design engineer is required to design the bearing systems of buildings and structures, performers at the construction site who perform construction work, and persons responsible for the operation of buildings and structures.

2.4. Degradation of material properties

Analysis of emergency situations with capital construction facilities [3,13,49] that have occurred in recent decades, such as the collapse of the Hotel New World (1986, Singapore), the Sampun shopping center (1995, Seoul, Republic of Korea), the collapse of the Basmanny market (2006, Moscow, Russia), eight-story Rana Plaza building (2013, Savar, Bangladesh), Maxima shopping center (2013, Zolitude, Latvia), Synagogue Church Of All Nations building (2014, Lagos state, Nigeria), Xinjia Express Hotel (2020 , Quanzhou, Fujian Province, China) and others, shows that the destruction of reinforced concrete structures of load-bearing systems of buildings and structures in many cases occurs after several years, and in some cases - decades from the date of completion of their construction and commissioning. The collapse of the buildings in use poses the greatest danger, since it leads to catastrophic consequences: a large number of human casualties and significant material damage. With regard to reinforced concrete frames of buildings and structures of normal and increased levels of responsibility [50] to reduce the risk of collapse after the sudden removal of one of the elements of the bearing system due to the impact of an unknown nature within the framework of the situational approach adopted in the regulatory documents [2, 51], at the stage of calculation justification adopted design solutions for protection against progressive fracture, it is necessary to take into account not only the physical nonlinearity of materials and the geometric nonlinearity of elements during their short-term loading, but also creep deformation, environmental or mechanical damage [52] accumulated during operation. The listed factors of the force and environmental resistance of reinforced concrete lead to a change in the rigidity of the elements of the bearing system and, as a consequence, to the redistribution of efforts in them, i.e., changes in the design scheme of the structure [53].

According to V.M. Bondarenko [54], the most important component in solving the problem of the structural safety of buildings and structures is to take into account their operational wear and tear. Evolutionary accumulation of damage (for example, corrosive wear) can ultimately also lead to the sudden brittle destruction of individual bonds or elements and the subsequent local or avalanche-like collapse of the structural system.

Thus, the collapse of the roof of the Basmanny market in Moscow on February 23, 2006 was the result of unsatisfactory operation, which led to waterlogging of the material of the reinforced concrete shell of the coating and corrosive wear of the cables supporting it. It was the break of one of the cables that served as the initial local destruction, which led to the collapse of the entire coating [55].

To take into account long-term processes of corrosion damage to structural elements in contact with an aggressive medium, in our opinion, it is convenient to use a phenomenological model of the environmental resistance of concrete, for example, proposed by V.M. Bondarenko [56].

The analysis of the force resistance of loaded and at the same time corrosively damaged reinforced concrete frame-bar structural systems with sudden structural changes in them from the accumulation of corrosion damage is given in the work of N.V. Klyueva, N.O. Prasolov and V.I. Kolchunov [57]. It is shown that the evolutionary accumulation of corrosion damage in the connections of the frame-rod system leads to a sudden destruction of the strut due to the loss of stability from a change in its free length. Subsequent numerical [58–60] and experimental [61, 62] studies of deformation show a significant effect of corrosion processes on the parameters of deformability of structural materials under special influences caused by the sudden removal of one of its elements from the bearing system of a building or structure.

As the experience of accidents shows, such as, for example, the collapse of the World Trade Center in New York [4], a decrease in the parameters of strength and deformability of materials of load-bearing structures of buildings and structures can also occur for a short time, calculated in minutes, from high-temperature effects caused by fires.

In the studies of A.G. Tamrazyan. and Avetisyan L.A. [63, 64] it was shown that fire effects affect the parameters of strength and deformability of structures, causing a decrease in their bearing capacity, as well as a change in the dynamic parameters of the supporting system as a whole, which can cause its progressive collapse.

Fedorov V.S. and Levitsky V.E. [65] found that the ultimate thermal-force resistance of a reinforced concrete beam depends on the stiffness of the fastenings from displacements and turns in the support nodes. Due to the implementation of adaptation mechanisms, higher levels of fire resistance of structures can be achieved. The same authors proposed a phenomenological model of the thermal-force resistance of reinforced concrete [66], which allows describing the behavior of structures under high-temperature heating modes. The possibility of loss of stability of eccentrically compressed elements under the considered type of impacts due to a decrease in the parameters of strength and deformability is noted [67].

2.5. Influence of the nature of the impact on the deformation mode and the nature of destruction

The analysis of the results of the study of the influence of the impact parameters on the nature of deformation and destruction of the bearing elements of structural systems of buildings and structures considered above in this section of this article allows us to draw the following conclusions:

- for buildings and structures not only of increased, but also of a normal level of responsibility (the classification is adopted according to [50]), the possibility of high-impulse impacts on individual structural elements or their groups cannot be excluded. An example of this is the collapse of a significant part of the Alfred Murray building (Oklahoma City, USA, 1995) after the terrorist attack.

- high-impulse impacts caused by detonation of powerful explosive devices located close to the load-bearing structures, as well as collisions with load-bearing structures of vehicles moving at high speeds, can lead to a sudden loss of load-bearing capacity of the elements of load-bearing systems of buildings and structures exposed to such effects in a fraction of a second.

- when modeling the resistance to progressive collapse, one should also take into account the possibility of reducing the bearing capacity of structures due to the action of blast waves, as well as factors of prolonged loading (creep in concrete, corrosion damage to concrete and steel), high-temperature effects. An example of this is the collapse of the WTC towers in New York on September 11, 2001, which was largely the result of fires caused by aircraft collisions with structures, rather than the collisions themselves.

- the sudden nature of the removal of one of the elements of the bearing system is equivalent to impact and requires taking into account the dynamic effects arising in the structural system of the building under such impacts.

Experimental data on the dynamic resistance of structural materials under dynamic loading made it possible to introduce the coefficients of dynamic hardening of materials into design and research practice. In the studies carried out by G.A. Geniev [68], Yu.M. Bazhenov [69], Nam et al. [70], Malvar L.J. [71] and others show stress-strain state diagrams for concrete and steel depending on the strain rates. These data show a significant change in the strength and deformability parameters of the materials under consideration under high-speed loading, which

However, a number of studies performed on the deformation and destruction of concrete under static-dynamic loading conditions [72, 73] have revealed quantitative and qualitative differences in the resistance of elastically brittle plastic materials, such as concrete, to fracture depending on the loading mode.

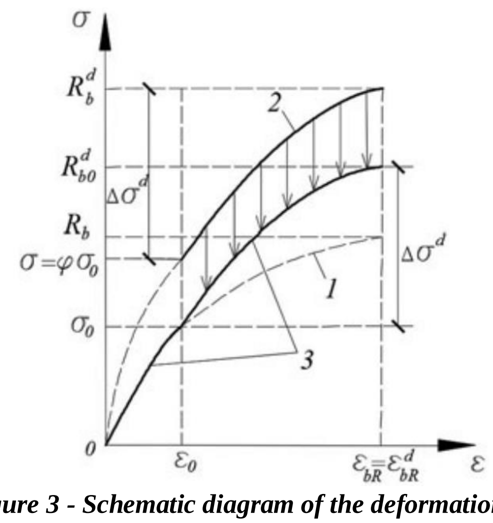


Figure 3 - Schematic diagram of the deformation of reinforced concrete under static-dynamic loading mode caused by a special emergency action [74]:
1 - single short-term (quasi-static) loading; 2 - single dynamic (impulse) loading; 3 - static-dynamic loading

In emergency situations associated with a sudden loss of the bearing capacity of one of the elements of the building's structural system, there is a dynamic reloading of the surviving structures, in which at the time of the emergency there are forces from the operating load. In this regard, Kolchunov V.I., Kolchunov Vl.I. and Fedorova N.V. [74] propose to use static-dynamic deformation diagrams (figure 3) instead of standard diagrams for single loading.

In studies [75, 76], it is noted that the formation of cracks in elastic-brittle-plastic materials is of a dynamic nature and should also be taken into account when analyzing the resistance of elements of bearing systems of buildings and structures to progressive collapse under special influences.

3. Progressive collapse simulation

3.1. Experimental studies of progressive collapse

3.1.1. Testing of buildings and structures to be demolished

In recent years, in order to study the mechanisms of resistance of the bearing systems of buildings to progressive collapse with the instantaneous removal of one of the columns, a large number of numerical and experimental studies have been carried out. Below we will dwell in more detail on some of the most characteristic models of experimental reinforced concrete structures that were used for full-scale tests, test methods, as well as the main results obtained during their conduct.

A separate group consists of studies carried out on the reinforced concrete frames of real buildings to be demolished, for example, studies of the progressive collapse resistance of a hotel structure in San Diego carried out by Sasani et al. [77]. The initial destruction (the corner column and the column of the extreme row at the end of the building) was created by detonating explosive devices installed in the holes previously drilled in the columns. Analysis of the displacement diagram of the node above the removed column shows that at the initial moment of time, measured in milliseconds, it moved slightly upward (tenths of a millimeter), which was caused by an explosion. Then, in a time of 0.079 seconds, the node moved downward by 5.7 mm (the first peak in the time-displacement diagram, $t = T / 4$). The maximum displacement of the node downward by 6.2 mm was achieved after 0.29 seconds ($t = 13T / 4$) and after 0.6 seconds from the beginning of the impact, having completed 4 full vibrations, the carrying system stabilized, while the displacement of the node under consideration was 6.1 mm.

Song and Sezen [78] investigated the progressive collapse resistance of a steel-framed civil building to be demolished by successively removing columns in different parts of the building (4 columns were removed in total). It is shown that for the steel 4-storey frame under consideration, the structural elements most susceptible to destruction are the columns above the remote bearing element, primarily on the upper floors of the building. This is due to the smaller dimensions of the cross-sections of the columns of the upper floors, as well as to the increase due to the structural rearrangement of the bending moments acting in them.

Undoubtedly, the studies of the resistance to progressive collapse of the bearing systems of buildings considered in this section, carried out during their demolition, are of the greatest value, however, for obvious reasons, they are extremely few, difficult to implement and, as a rule, cover design solutions that are already outdated and not used in modern construction practice. In this regard, they do not allow the collection of a sufficient amount of statistical data.

3.1.2. Scale model testing

Another approach to the experimental study of the mechanisms of resistance to progressive collapse is to test 2 or 3-storey flat or spatial 2-span, 3-span (less often with a larger number of spans) scale models of building frames. The validity of the choice of these parameters of scale models is consistent with the results of M. Botez, L. Bredean, A.M. Ioani [79] nonlinear dynamic analysis of a three-storey reinforced concrete building frame for instant removal of a column using three design options: for the entire building frame, for two spans, and for one span. The numerical calculations performed by them showed that to assess the forces and displacements in the building frame for the type of beyond design impact under consideration, it is sufficient to limit ourselves to considering a fragment of the frame bounded by two spans adjacent on each side to the zone of local destruction. This experimental approach is presented by Yi WJ, He QF, Xiao Y, Kunnath S [80], Wang, Zhang, Zhao and Chen [15], Anil Özgür and Altin Sinan [81], Shan Sidi, Li Shuang, Xu Shiyu, Xie Lili [82], Zheng Yongkang, Xiong Jingang, Wu Zhaoqiang, He Yinong [83], Li Shuang, Shan Sidi, Zhai Changhai, Xie Lili [84], Fedorova NV, Ngoc Vu Tuyen [85], Kolchunov V.I., Prasolov N.O., Kozharinova L.V. [86], Fedorova N.V., Korenkov P.A. [8] and [87]. The listed works can be conditionally divided into two groups depending on the method of modeling the removal of the column: quasi-static using hydraulic jacks and dynamic using gravitational loading devices [8,85,86]. Among the most characteristic works of the first group is the work of Wang, Zhang, Zhao and Chen [15], in which a study was made of the resistance to disproportionate failure of elements of a model of a fragment of a reinforced concrete frame of a building, made on a scale of 1: 3, when the corner column was removed (figure 4, a). The experimental space frame was under the influence of a constant load evenly distributed over the floor surface. A concentrated load was transferred to the column of the second floor, created by a hydraulic jack (figure 4, b) at a controlled piston movement speed of 2 mm / min. Beyond design basis impact was modeled by removing a movable steel post installed in place of the corner column of the first floor.

As a result of the tests carried out by Wang, Zhang, Zhao and Chen, it was revealed that the redistribution of force flows mainly covers structural elements directly adjacent to the zone of local destruction, and a positive effect of the arched effect on the resistance of the frame to progressive collapse was established.

In the works of Fedorova N. V., Ngoc Vu Tuyen [85], Fedorova N.V. and Korenkov P.A. [8] provides a detailed description of the methodology for conducting an experimental study of the deformation of scale models of flat reinforced concrete frames with an instantaneous removal of the load-bearing element. Figure 5 shows a diagram of a stand prepared for testing a two-span three-story frame for instant removal of the middle row column.

a) b)

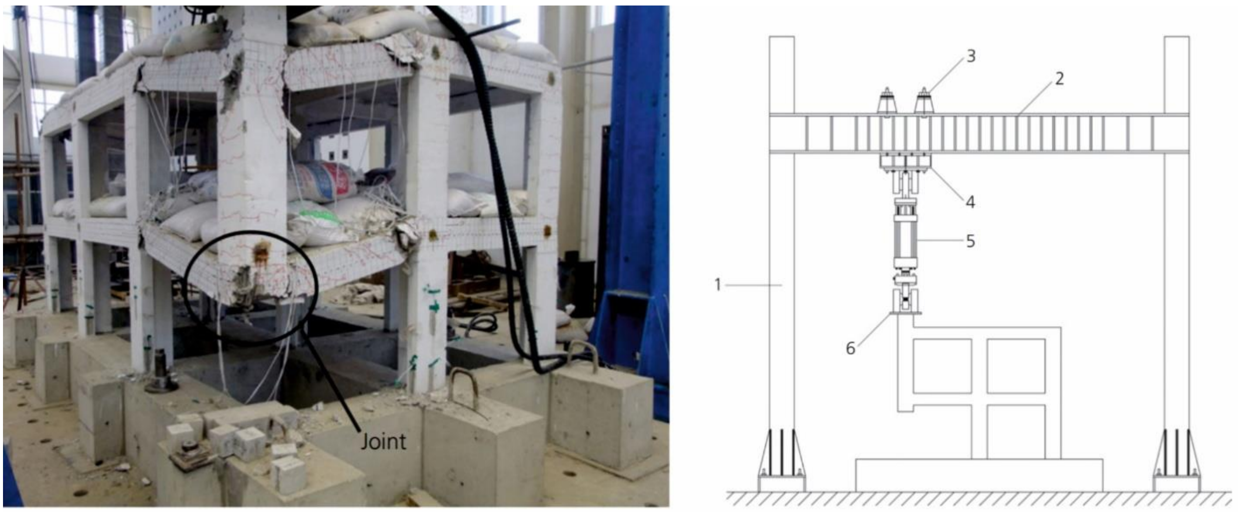


Figure 4 - General view of destruction (a) and test stand diagram (b) [15]:
1 - column, 2 - beam, 3, 4 - cross beams, 5 - hydraulic jack, 6 - distribution steel plate

Figure 5 - General view of the test bench when testing frames N.V. Fedorova and Korenkov P.A. [8]

The considered approach to experimental research makes it possible to model with sufficient accuracy the process of redistribution of power flows in the building frame, to reveal the features of the implementation of resistance mechanisms to progressive collapse, depending on the design features of the structural system, and not only its individual nodes in the zone of local destruction. In the considered experimental studies, in which hydraulic loading devices were used, it is possible to test models close in their geometrical dimensions to real structures, however, the possibility of taking into account the inertia forces arising in the instant scenario of the column removal was practically excluded. The use of a gravitational-lever loading system made it possible to simulate the dynamic effects in the tested models associated with the occurrence of inertial forces, but imposed restrictions on the dimensions of the experimental structures.

3.1.3. Testing of substructures and fragments of structural systems

The most common way to experimentally study the mechanisms of resistance to disproportionate failure and the nature of the work of structural elements during the redistribution of power flows is to conduct quasi-static tests on individual substructures, separated by the decomposition method from the building frame. Such studies include, for example, works by Yu Jun and Tan Kang Hai [88], Kang Shao-Bo, Tan Kang Hai and Yang En-Hua [89], Forquin Pascal and Chen Wen [90], Han Qinghua, Li Xinxia, Liu Mingjie and Spencer Billie F. [91], et al. [92–95]. Figure 6 shows a typical for this method of full-scale tests a scheme of a stand with a substructure in the form of a two-span girder used by Shao-Bo Kang, Kang Hai Tan, En-Hua Yang [89] to study the mechanisms of resistance to progressive collapse. In this approach, a hydraulic jack is used to simulate the removal of the middle row column, which transfers the force to the substructure at a controlled speed of movement of the moving part of the loading device. The resistance to rotation of the end sections of the girder adjacent to the columns is modeled using damping devices. Shao-Bo Kang, Kang Hai Tan, En-Hua Yang [89] established a sequential change of the arched resistance mechanism to the cable-stayed mechanism as the crossbar-column interface unit of the middle row moved under the action of the loading device.

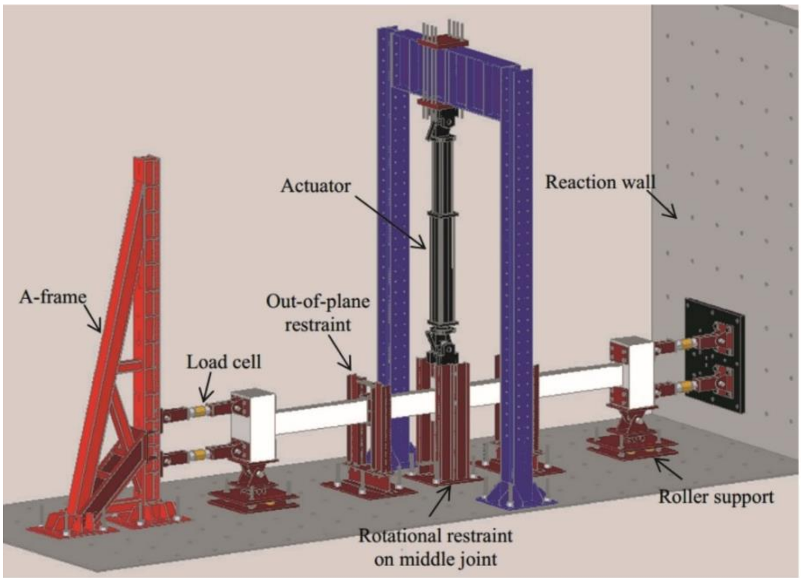


Figure 6 - Schematic of a prefabricated substructure test performed by Shao-Bo Kang, Kang Hai Tan, En-Hua Yang [89]

The approach described above makes it possible to simplify the design of the experimental model. The structural members most sensitive to abnormal impacts are usually well predictable and accessible for observation, they can be investigated in detail using a relatively small number of measuring instruments. However, with this approach, an additional complexity arises associated with modeling the nonlinear response of the entire structural system to the beyond design basis. To solve this problem, a number of researchers, such as, for example, performed by Shao-Bo Kang,

Kang Hai Tan, En-Hua Yang [89], have resorted to the use of damping devices. However, even in this case, questions remain about the correspondence between the operation of dampers and the physical and structural nonlinearity observed during the deformation of real structures. In turn, modeling the beyond design basis impact of hydraulic loading devices does not allow to recreate in the experimental model the dynamic effects [5] associated with the occurrence of inertial forces, as well as to study the features of the dynamic deformation of reinforcing bars and a concrete matrix of preloaded reinforced concrete elements.

3.1.4. Assessment of the experimental research methods relevance

After analyzing the most typical experimental research methods, it is pertinent to note that almost all the works considered above are related to the study of the mechanisms of resistance to the progressive collapse of bending and compressive-bending girders, as well as stretched and eccentrically stretched columns of reinforced concrete frames of buildings. However, separate numerical and analytical studies of the deformation of steel frames of buildings carried out by Pantidis P. and Gerasimidis S. [96,97], as well as the fragments of reinforced concrete frame and frame-braced frames identified by the decomposition method [58,98,99] indicate that secondary fractures in such structural systems under a number of conditions (high flexibility in an undeformed state or the presence of corrosion damage) can be associated with the loss of stability of compressed-bent elements.

Executed by V.I. Kolchunov, N.O. Prasolov. and Kozharinova L.The. [86] experimental studies on the model of a single-storey frame (figure 7) made it possible to establish the features of deformation and loss of stability of elements with a sudden change in the calculated length of one of the frame struts due to disconnection of the connection or the formation of a plastic hinge in the junction with the crossbar. However, this design of the experimental frame did not fully allow simulating the emergence of inertial forces and additional dynamic loading of the remaining structural elements, which was observed in later experiments on models of three-story frames [8, 85].

Figure 7 - General view of testing scale models of flat reinforced concrete frames of building frames [86]

Full-scale tests of models of reinforced concrete frames or substructures in order to study the process of loss of stability of their elements under a static-dynamic loading regime, typical for the case of a sudden removal of the load-bearing element of the system, apparently have not been carried out so far. The results of buckling tests presented in the scientific literature refer to individual specimens made of concrete or reinforced concrete [100–102], as a rule, under static loading conditions, studies of static-dynamic deformation of specimens are extremely few [73]. As for the tests of frame models, they were carried out mainly in a static setting and on metal structures

[103, 104]. However, as applied to structures made of reinforced concrete, it is necessary to take into account a number of additional features, including resistance to resistance under the action of tensile and compressive stresses, the fragile nature of the destruction of the concrete matrix, significant nonlinearity and the presence of residual deformations already at the initial stages of loading. All these factors are reflected in the nature of the dissipation of the deformation energy under dynamic influences.

Summarizing the results of the analysis of publications presented in the scientific literature with the data of experimental studies, the following conclusions can be drawn:

• The largest number of experimental studies was carried out for large-scale or full-scale models of substructures including a two-span continuous girder and its joints with columns. This test method allows one to concentrate on a detailed study of the deformation of individual structures, but excludes the possibility of taking into account the nonlinear nature of the deformation of nodes as elements of a whole structural system.

• Testing of large-scale flat and spatial models of frameworks allow taking into account the influence of structural elements adjacent to the zone of local destruction. However, they give an order of magnitude larger amount of data, which complicates the analysis.

• In experimental modeling of structural member removal, a quasi-static approach prevails, in which the load is transferred directly to the model above the removed structure using hydraulic jacks. This approach does not allow one to accurately simulate the emergence of inertial forces and the resulting dynamic effect.

• Studies using dynamic loading of frame models with gravitational loading devices are relatively few and currently cover a small number of variants of structural systems.

• Experimental studies of scenarios of resistance to disproportionate failure associated with the loss of stability of compressed-bending elements of reinforced concrete structural systems are practically absent.

3.2. Methods for numerical modeling of progressive collapse

3.2.1. Nonlinear static analysis

Since most of the structural materials used in construction allow plastic deformation, the calculation in the linear formulation does not allow taking into account the changes in the design scheme of the structure in the process of loading and deformation, noted in [53]. The non-linear static method for calculating the resistance of the bearing systems of buildings and structures to progressive collapse is based on the representation of the dynamic effect acting in a system with a discarded connection, its static equivalent. The validity of using the static calculation method is confirmed by the studies of Marchand Kirk, McKay Aldo, Stevens David J. [105]. At the same time, in the scientific literature, two main approaches to modeling the dynamic effect of loading can be distinguished. According to the first one presented in the UFC and the works of V.O. Almazov. [106], the dynamic effects are taken into account by multiplying the values of the loads applied to the floors and covering over the removed element by the dynamic factors (figure 8).

In the studies of G.A. Geniyev [107,108], Weng J. et al. [109], Yan J. et al. [20] and others to simulate the dynamic effect, a model of a system with one degree of freedom is used, in which the entire dynamic effect "condenses" in the form of a generalized effort in a node above a discarded connection (element). A comparative analysis performed for a scale model of a two-story reinforced concrete frame using the described approach showed good convergence with the direct dynamic calculation method [110].

According to the approach proposed by G.A. Geniyev [107, 108], the determination of the deformed state of the building frame under a special emergency impact is carried out by a quasi-static method. In this case, the stiffness and coordinates of the sections (nodal points) are assigned to the bar elements of the design model in accordance with the results of the deformation calculation according to the primary design scheme of the second level, and instead of the load acting at the stage of normal operation, only the generalized force is applied at the place of the discarded connection, which is determined from taking into account the forces acting in the removed element of the structural system at the stage of normal operation and taken with the opposite sign (figure 9), according to the condition of constancy of the total specific energy of deformation of the structural element:

$$\Phi(\varepsilon_{n-1}^{d}) - \Phi(\varepsilon_{n}^{s}) = \sigma_{n-1}^{s}(\varepsilon_{n-1}^{d} - \varepsilon_{n}^{s}),$$
$$\sigma_{n-1}^{d} = 2\sigma_{n-1}^{s} - \sigma_{n}^{s},$$
$$N_{n-1}^{d} = 2N_{n-1}^{s} - N_{n}^{s},$$

where σ_{n-1}^{d}, σ_{n-1}^{s}, σ_{n}^{s}, ε_{n-1}^{d}, ε_{n-1}^{s}, ε_{n}^{s} are respectively, stresses and strains in the n-1 system (with the removed member) under dynamic (d) and static (s) loading and in the n-system under static loading; $\Phi(\varepsilon_{n-1}^{d})$, $\Phi(\varepsilon_{n}^{s})$ are respectively, the potential energy of deformation under dynamic and static loading in systems n-1 and n.

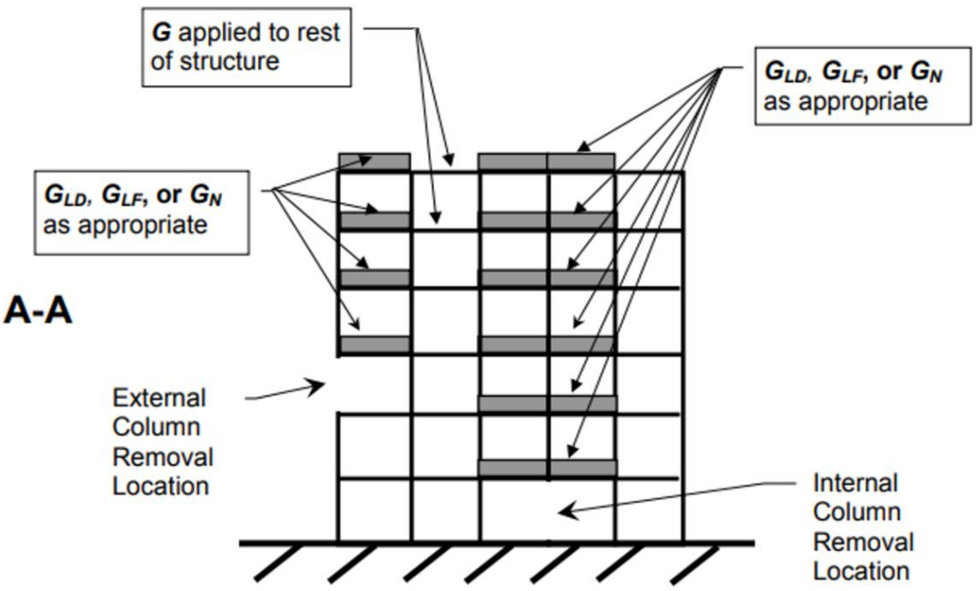


Figure 8 - Loads and Load Locations for External and Internal Column Removal for Linear and Nonlinear Static Models (Left Side Demonstrates External Column Removal; Right Side Shows Internal Column Removal) [2]

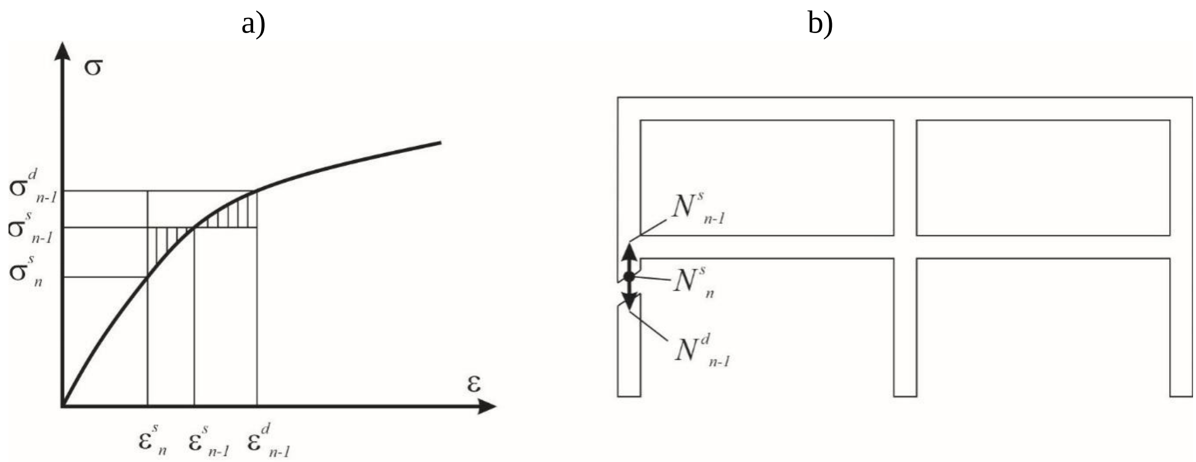


Figure 9 - To the definition of the generalized force at the place of the discarded connection (structural element): a) diagram of concrete work under uniaxial compression; b) generalized force in place of the removed column of the building frame

Despite the relative simplicity of the implementation of nonlinear static analysis on modern computers, this approach significantly complicates the procedure for finding optimal structural solutions to ensure the structural safety of a structure in the event of a sudden failure of one of its load-bearing elements. In this regard, at the initial stages of the search for preliminary design solutions, highly linearized methods have been developed in recent years (see, for example, [111]), which make it possible, based on a combination of iterative procedures and the introduction of a "defining" load, including a combination of loads according to SP 385.1325800. 2018, to perform not only verification of the decisions made, but also imply some design calculations related to the selection of the parameters of sections of structural elements.

3.2.2. Nonlinear dynamic analysis

Nonlinear dynamic analysis is the most complex method for modeling the resistance of load-bearing structures of buildings and structures to progressive collapse, however, it provides the most detailed and accurate information about the deformation and destruction of building frame elements under special influences. This method is based on direct integration of the equations of motion [112].

Nonlinear dynamic analysis uses nonlinear material deformation diagrams that take into account the effects of residual plastic deformations (hysteresis). This approach makes it possible to most correctly take into account the hardening of the material or the decrease in adhesion over the contact surface of composite and composite structures, which, as a rule, cannot be correctly taken into account when solving in the frequency domain.

However, when using the described approach in combination with the standard implementation of the finite element method (FEM), it does not allow obtaining correct results of calculating deformation at an out-of-limit stage for structures made of brittle materials and composite structures, which are characterized by a discrete change in the stiffness parameters in narrowly localized areas (for example, the process cracking in concrete). In this regard, in recent years, discrete-continuous methods have been actively developed and introduced, in particular the Applied Element Method (AEM) [113], in which the connection between the elements is modeled using elastic-compliant springs that simulate the work in compression - tension and shear. Comparison of the AEM calculation results with the standard FEM implementation and experimental data indicates the preference of using the discrete-continuous approach (AEM) when modeling physically and structurally nonlinear bearing systems of buildings and structures under special influences [3].

3.2.3. Modeling of 2D stressed joints of load-bearing structures

When analyzing the mechanisms of resistance of reinforced concrete frame-tie frames of buildings and structures to progressive collapse, taking into account the possibility of local destruction in them in any section of the bearing system, researchers and design engineers mainly use spatial rod, plate or plate-rod finite element (FE) models [5,6,15,58,114-117] or similar models of the Applied Element Method [118,119]. For a more detailed analysis of the features of deformation and destruction of nodal joints, substructures and fragments of frames of buildings and structures under special influences caused by structural rearrangements of their bearing systems due to the sudden removal of one of the elements, using the decomposition method, such elements are separated from the spatial core design model of the entire structure, and then perform a computational analysis of their models built from volumetric finite elements [85,95,120,121].

The results of such numerical modeling, in combination with the data of experimental studies, demonstrated the need to take into account the peculiarities of the operation of nodal connections of load-bearing structures, such as girder-column, slab-column, etc., to ensure overall resistance to the progressive collapse of the load-bearing systems of buildings and structures. In the listed types of nodal connections and in sections of rod structures (girders, columns), directly adjacent to such nodes, a complex biaxial or volumetric stress state is realized, which requires taking into account additional components of stresses and deformations. In this regard, for a more rigorous analysis of the stress-strain state of the supporting structures of buildings and structures during design emergencies associated with the occurrence of initial local destruction, it is advisable to resort to the combined use of the two approaches listed above - combining spatial rod models with models of nodal connections from volumetric finite elements or simplified semi-empirical models.

The combination of such approaches, taking into account the variation of scenarios of emergency design situations, leads to a high laboriousness of solving the problem under consideration. In this regard, high requirements are imposed on the qualifications of the designer-constructor, who, on the one hand, must be able to make the correct choice of the most unfavorable scenarios of emergency design situations from the point of view of the power work of the supporting system of the building, and on the other hand, exclude minor variants of initial local destruction, obviously not posing a threat to the structural safety of the structure. However, even in this case, due to the presence of a human factor, one of the scenarios of an emergency design situation can slip out of sight, which can subsequently be realized during the life cycle of the structure. Therefore, to reduce the complexity of computations when enumerating a large number of possible variants of initial local fractures, computational models can be used, which, by analogy with the method of applied elements, would consist of rod elements of columns and girders interconnected by elastically compliant bonds, the parameters of which would be refined by solving a plane or volumetric (depending on the design of the node) problems of the nonlinear theory of elasticity of an anisotropic body. Analysis of the calculated models of the girder-column interface nodes presented in the scientific literature shows that most of them are based on a simplified representation of a complexly stressed element by replacing stresses with generalized forces. Thus, highlighting two characteristic resistance mechanisms, truss and compressed inclined strip, Shyh-Jiann Hwang and Hung-Jen Lee [122] evaluate the possibility of their implementation separately. A similar approach to the analysis of the work of the girder and column interface units, which are somewhat different in their design, can be found in the works of other authors [88,123,124]. In works [125–127], the work of a flat joint element is modeled using elastic ties (springs). The introduction of such elastic-yielding bonds between elements into the computational model allowed De-Cheng Feng and Ning Chao-Lie [127] to achieve better quantitative and qualitative convergence with experimental data than when using traditional rod models of the finite element method with rigid nodal joints. However, this approach does not allow to fully assess the resistance of the nodal connection itself.

In the study of a 2D fragment of a multi-storey building frame, N.V. Fedorova, N.T. and Yakovenko I.A. [128] to assess the special limiting state of a girder-column nodal connection, a shell FE model was used, in which two characteristic elements were identified and their strength was analyzed using the deformation theory of plasticity of reinforced concrete by GA. Geniyev [68]. However, the use of strength conditions according to this theory in combination with the use of shell FE models of frame fragments, subject to variations in a large number of emergency design scenarios, which must be analyzed, following the requirements of the code of rules SP 385.1325800.2018 " Protection of buildings and structures against progressive collapse", according to which local destruction can occur anywhere in the building, leads to the solution of an extremely time-consuming task. At the same time, it seems that the approach used in [128] to assess the strength is quite effective and can be used to construct a universal computational model of a special element that simulates a junction of vertical and horizontal load-bearing structures. Such an element could be integrated into spatial bar and plate-bar FE computational models to improve their accuracy.

Summarizing the results of the above brief analysis of studies on modeling the operation of load-bearing systems of buildings and structures, taking into account the peculiarities of deformation and destruction of the junction points of vertical and horizontal load-bearing structures, it can be concluded that there are apparently no universal design models that could be used to assess the resistance to progressive collapse of such joints during their dynamic loading, which occurs as a result of the sudden destruction of one of the load-bearing elements of the structural system. In this regard, the purpose of this study is to fill this gap - to build a computational model that could be implemented in the form of a special finite element of the interface node and integrated into the standard procedure of finite element analysis to improve the accuracy of its results when assessing the special limiting state of such complexly stressed elements of supporting structures.

3.2.4. Consideration of the contact interaction of elements of composite structures

It should also be noted that when modeling the elements of bearing systems of buildings and structures, design designers usually use rod or plate analogies, which, as a rule, imply absolutely rigid adhesion of reinforcement to concrete, which does not fully reflect the nature of their actual joint work. in areas with a high stress gradient, for example, at the junctions of a column with a girder [129].

Experimental studies of the adhesion of reinforcement to concrete carried out by various authors [59, 129–131] have shown that adhesion is influenced by a number of factors: concrete resistance to axial tension, the type of reinforcement surface and its diameter, the presence or absence of prestressing, etc. In studies [131, 132] with dynamic loading of a reinforced concrete element, an increase in the adhesion resistance of reinforcement to concrete was observed by more than 1.3 times at a loading rate of 1 N / ($mm^2 \cdot ms$) compared to monotonic quasi-static loading. At the same time, in reinforced concrete elements subject to long-term action of force and environmental factors, adhesion can decrease over time due to a change in the stress-strain state of the elements, strength and deformation characteristics of the concrete matrix [133, 134].

The analysis of scientific publications on modeling the adhesion of reinforcement to concrete in bent and eccentrically compressed elements of reinforced concrete structures made it possible to identify two main directions for solving deformation problems and problems of stability. The first area deals with performing finite element analysis using models consisting of 3D concrete elements and 2D rebar elements. In this case, the interaction of concrete and reinforcement is set through special elements of elastic ties of zero length. To take into account the increased deformability in areas with cracks, shear force transfer coefficients for open and closed cracks are set. The values of these coefficients vary from 0 (in the absence of adhesion at all) to 1 (in the absence of displacements in the nodes). The described finite element models are mainly used to clarify the fracture mechanisms and parameters of the contact interaction of reinforcement with concrete: shear force transfer coefficients for open and closed cracks; coefficients that take into account corrosion damage to steel reinforcement, etc. The objects of modeling in this case, as a rule, are the junctions of girders and columns (see, for example, [124,129,130,135,136]), individual structural elements [133,137] or typical substructures [125]. The advantage of the considered approach is the ability to achieve high convergence of the results of numerical simulation with experimental data. However, the application of this approach to the computational analysis of the entire structure seems to be an extremely laborious task, examples of the solution of which, apparently, are absent in the scientific literature.

The second approach to taking into account the effect of shears on the deformation of structural elements is based on the theory of rods by Engesser [138], Harings [139, 140], and A.R. Rzhanitsyn [141]. In [138–140], the influence of shear stiffness and transverse forces on the nature of the deformation of sections and the loss of stability of compressed bar elements was investigated. In [141], on the basis of a bar analogy, a general solution to the problem of the deformed state of a composite bar with branches made of nonlinear elastic material, connected by structural ties in the form of lattices of braces or strips, is presented. The considered solutions, built on the basis of a bar analogy, are less laborious than 3D finite element analysis, however, the author of this study did not identify the solution to the problem of accounting for the adhesion of reinforcing bars and concrete under eccentric compression of dynamically loaded reinforced concrete elements of building frames in the scientific literature.

4. Mechanisms of resistance to progressive collapse and criteria for a special limit state

4.1. Analysis of resistance mechanisms of structural systems and their elements to progressive collapse

In the survey and analytical work [3], several mechanisms of progressive destruction of the bearing systems of buildings and structures after the appearance of the initial local destruction (figure 10, a) were identified: “zipper-type” (figure 10, b), pancake-type (figure 10, c), dominoes (figure 10, d) and their combination.

However, the implementation of any of the listed mechanisms of propagation of destruction in many cases is preceded by the destruction of structures above the remote element (link). Since in the regulatory documents [2,12] the propagation of the chain of failures of load-bearing elements outside the local destruction zone is considered unacceptable, a significant number of studies of the mechanisms of resistance to progressive collapse presented in the scientific literature are concentrated on the analysis of deformation and destruction of substructures limited by 1-2 spans and 1 -2 floors above the remote structure (brace).

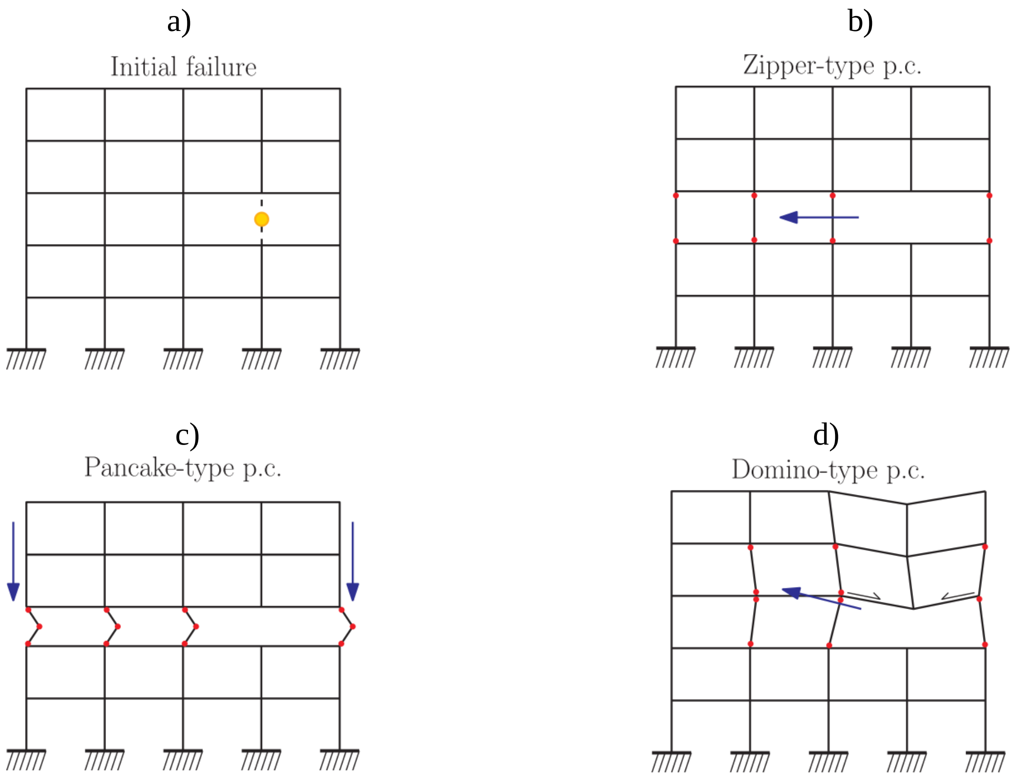


Figure 10 - The most common mechanisms of progressive collapse of the frames of buildings and structures [3]: initial failure (a); zipper-type (b), pancake-type (c), domino-type (d)

Adam et al. and Qiao, Yang, and Zhang [13,142] identify three main mechanisms of resistance to progressive collapse:

• Arch / shell (figure 11, a);
• Catenary / membrane (figure 11, b);
• Virendel's truss.

Almusallam et al. [143] note that the implementation of various resistance mechanisms depends on many factors. They investigated the influence of the magnitude of the efforts in the columns of a multi-storey building frame on the implementation of the arched mechanism of resistance to destruction. It is shown that with insufficient stiffness of the cross-sections of the columns, the arched and cable-stayed mechanisms of resistance to destruction may not be realized.

In the article [117] it was established that the resistance mechanism can be influenced by setting the pre-compression forces in the floor elements.

With regard to vertical load-bearing elements of building frames (columns, pylons), the failure mechanism can be associated with shear failure (see, for example, collapse of columns along the "G" axis on the second floor of the Alfred Murray building (Figure 1)), bending or buckling. The boundary between the last two mechanisms can be considered conditional in a sense if we go from the stability of the form of the Lagrange - Euler equilibrium to the stability of motion according to Lyapunov.

In emergency situations caused by the sudden removal of one of the load-bearing elements from the building frame, in the sections of eccentrically compressed structural elements (columns, pylons, braces and truss chords, etc.), a stress-strain state of more than disadvantageous in comparison with their VAT at the stage of normal operation from the action of the main and special combinations of loads according to SP 20.13330.2016 "Loads and actions". The deterioration of the conditions for the strength resistance of such structural elements is also caused by the degradation of the conditions for their fastening in the process of emergency loading or an increase in the calculated lengths when the fastening structural element is removed. In cases where the eccentrically compressed elements of the structural system reloaded as a result of an emergency have a "graceful" section, or have acquired environmental (corrosion) or mechanical (chips, death) damage during operation, the loss of form stability.

Experimental studies by V.I. Kolchunov and N.O. Prasolov [86], performed on scale models of flat reinforced concrete frames of building frames, demonstrated the possibility of implementing this scenario of destruction of structural elements with a sudden removal of the element of vertical ties.

a) b)

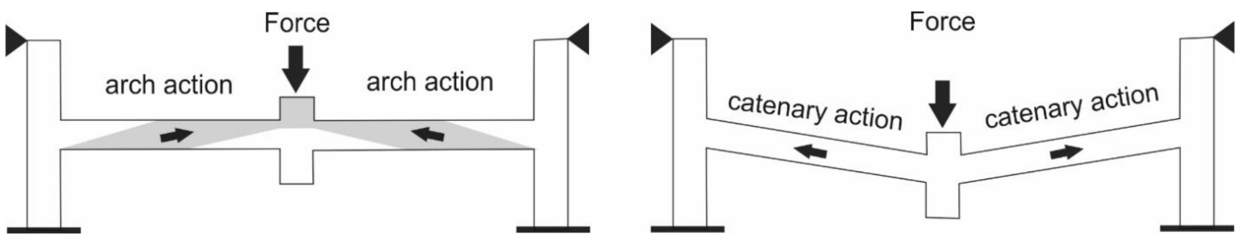


Figure 11 - Mechanisms of resistance to the disproportionate failure of floor structures and roofs: arch / shell (a); catenary / membrane (b)

4.2. Analysis of special limit state criteria

The transcendental state of structures after the initial destruction in the supporting system of the building was called the ultimate limit state [2]. UFC 4-023-03 specifies ultimate forces and deformations as criteria for evaluating such a transcendental state. At the same time, to assess alternative load transfer paths (Alternate Load Paths), the nominal values of the strength of materials are multiplied by the strength reduction factor.

To assess the bearing capacity of structures in extreme states caused by the sudden removal of one of the bearing elements of the structural system, the concept of a special limit state was introduced in SP 385.1325800.2018. As criteria for a special limiting state in SP 385.1325800.2018, the limiting deformations in the elements of the bearing system and the limiting deflections of the elements were taken. In contrast to the norms for the design of structures for the purposes of normal operation in SP 385.1325800.2018, the criteria for the bearing of a special limiting state were established according to the normative characteristics of the strength and deformability of materials, and for the case of a sudden initial failure, leading to dynamic additional loading of the preserved structures, it is allowed to take into account the dynamic strengthening of the material by multiplying its normative resistance by the corresponding coefficient given in the normative document.

Following SP 385.1325800.2018, the deflections of bending elements of the structural system for a special limiting state, provided that the minimum permissible length of the support zone and anchoring of tensile reinforcement is ensured, should not exceed 1/30 of the span length, with the exception of reinforced concrete structures reinforced with high-strength reinforcement with a nominal yield strength, for which deflections should not exceed 1/50 of the span.

In the studies presented in the scientific literature, as a rule, the ultimate deformations of materials are used as criteria for the exhaustion of the bearing capacity, taking into account their dynamic hardening on the basis of diagrams and analytical expressions depending on the strain rate [144–146].

The critical force N_{cr} can be considered as criteria for the special limiting state associated with the loss of shape stability for individual elements of building frames:

$$N < N_{cr},$$

or other parameters derived from it (critical stiffness, critical eccentricity).

To identify the most dangerous from the point of view of loss of stability of structural system elements, the energy criteria proposed by A.V. Alexandrov and V.I. Travush [147], determined by the work of the nodal bending moments and shear forces A (M, Q) in the bending process. The load-bearing element of the building frame, which is losing stability, corresponds to the largest negative work of the nodal bending moments and shear forces in absolute value:

$$A_i\ (M, Q) < 0.$$

Trekin N.N. and E.N. Kodysh [148] considered the deformation criteria limiting the relative limiting deflections of structures [*f/l*] as integral criteria for the special limiting state of bending reinforced concrete elements of the frames of buildings and structures. A special limiting state in accordance with [50] should be understood as such a state of structures after exceeding the limit of the bearing capacity in the first and deformability in the second limiting states, in which they do not fully meet the functional requirements, a further increase in loads and (or) impacts leads to their destruction ... It seems that it is also advisable to introduce similar integral criteria for assessing the special limiting state of eccentrically compressed rod elements of reinforced concrete bearing systems. However, the deformation, loss of stability and destruction of such elements have their own specifics, which must be taken into account when constructing deformation criteria for their special limiting state. In particular, it is necessary to take into account the ratio of the sizes and the structure of sections of the elements of the structural system, the conditions of conjugation at the nodes, as well as the ratio of the forces acting in the element.

5. Conclusion

Analysis of emergency situations that have occurred in recent decades and led to the progressive collapse of the bearing systems of buildings and structures, as well as experimental and theoretical studies of the disproportionate collapse problem allows us to formulate the following conclusions:

- for buildings and structures of not only an increased, but also a normal level of responsibility, the possibility of high-impulse impacts on individual structural elements or their groups cannot be excluded.

- high-impulse effects caused by detonation of powerful explosive devices or those close to the load-bearing structures, as well as collisions with load-bearing structures of vehicles moving at high speeds, can lead to a sudden (fractions of a second) loss of load-bearing capacity of the elements of the load-bearing systems of buildings and structures exposed to such effects.

- when modeling the resistance to progressive collapse, it is also advisable to take into account the possibility of reducing the bearing capacity of structures due to related factors, for example, the action of blast waves, as well as factors of long-term loading, such as creep in concrete, corrosion damage to concrete and steel, high-temperature effects.

- the sudden nature of the removal of one of the elements of the bearing system is equivalent to impact and requires taking into account the dynamic effects arising in the structural system of the building under such impacts.

- in case of high-impulse shocks, accompanied by the transfer of huge kinetic energy, such as when an aircraft collides with a structure, the protection of the bearing systems of structures using only constructive measures is impractical, in this case organizational measures related to the prevention of such emergencies will be more effective.

- one of the possible causes of secondary destruction in structural systems of buildings and structures after initial local destruction under a number of conditions, such as high flexibility or the presence of corrosion damage, may be the loss of stability of the deformed state.

- at present, the most studied are the mechanisms of resistance to the progressive collapse of floor structures and coatings of buildings and structures, while issues related to the bearing capacity of eccentrically compressed elements, taking into account the effect of the bearing system on their deformation, require more detailed study.

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