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ANALYSIS OF FOREIGN EXPERIENCE IN RESEARCH CASES OF PROGRESSIVE COLLAPSE OF BUILDINGS AND STRUCTURES

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Abstract. One of the leading areas of the engineering scientific community is the research of the performance of structures and systems in general during unlikely (extreme) events, in particular, the progressive collapse of buildings and structures. A large number of cases of collapse of buildings and structures of various purposes and levels of responsibility are known, and researchers in the field of progressive collapse are interested only in cases of the highest level of responsibility because the social, political, and economic impact of the loss of such buildings and structures is the most significant.

The purpose of this paper is to comprehensively analyze the phenomenon of the progressive collapse of buildings and structures based on the experience of significant foreign cases. The analysis includes the causes of progressive collapse initiation, the degree of disproportionality of progressive collapse, types of progressive collapse, and design features of progressive collapse cases.

The study uses an approach that not only includes the results of the analysis of direct cases of progressive collapse, but also provides statistical characteristics depending on the cause of initiation, type of collapse, and geometric location of the initial damage. Particular attention is paid to the compliance of the accepted methods for modeling progressive collapse with real cases of progressive collapse.

The study results showed that the existing estimates of progressive collapse cases take into account the so-called degree of disproportionality of the collapse. This is because it is only possible to guarantee resistance to progressive collapse if the collapse is only disproportionate. The fact that the initial failure of one or more columns occurred in about half of the progressive collapse cases indicates that modeling progressive collapse due to sudden column removal is rational.

Further research can focus on finding real collapse scenarios, in particular, the choice of a column that is suddenly removed from the scheme, studying the correctness of load redistribution when a column is suddenly removed, and studying the resistance to progressive collapse of buildings with structural schemes made of wood or precast concrete.

Keywords: progressive collapse, degree of disproportionality, destruction, column removal, modeling, design features, stability.

Introduction. Social and political challenges, increasing the safety and comfort of people's lives, the introduction of economic technologies, and the modern technological development of computing are the key factors that lead a wide range of scientists and engineers to investigate hitherto unknown phenomena and processes. In structural engineering, one such process is the study of the operation of structures and systems in general during unlikely (extreme) events. Such events cause the destruction of individual small but important structures, which can subsequently spread to the entire system or a significant part of it. This phenomenon is known as the progressive collapse of buildings and structures.

In general, a large number of cases of collapse of buildings and structures of various purposes and levels of responsibility have been recorded in world history. Researchers in the field of progressive collapse are directly interested in cases of only the highest level of responsibility because the social, political, and economic impact of the loss of such buildings and structures is the most significant. As of the middle of the third decade of the 21st century, more than 40 thoroughly investigated cases of progressive collapse of buildings and structures of the highest level of responsibility have been recorded. These are mainly multi-family housing, business centers, educational institutions, governments, etc.

Analysis of Recent Research and Publications. The first case of progressive collapse, which marked the beginning of the study of this phenomenon, occurred in 1968 in London, Great Britain. A 22-story precast concrete residential building called the Ronan Point partially collapsed after 3 months of operation, Fig. 1. A gas explosion on the 18th floor caused the destruction of the factory-made load-bearing wall panel, which in turn caused the progressive collapse of an entire corner of the building due to the impact load from the floors above [4, 5]. This tragedy led to changes, first of all, in the regulatory frameworks of the United Kingdom – the first recommendations for ensuring stability in case of progressive collapse (for large-panel buildings) were introduced, and later in the United States, Canada, and Europe. These changes were more focused on preventive measures to prevent the occurrence of progressive collapse.

Despite the impulsive start of scientific research in the 1970s after the Ronan Point progressive collapse case, and the emergence of several other global cases, the number of studies gradually decreased until the mid-1990s, when new significant cases of this phenomenon occurred and interest in the topic was renewed [9].

About a third of the Alfred P. Murrah Federal Building in Oklahoma City was destroyed in 1995 as a result of a terrorist attack, Fig. 2. The peculiarity of this case is that the explosion of a truck filled with explosives caused the destruction of at least three columns at once, and the loss of these columns led to the destruction of the key beam on which all the above structures were transferred.

Fig. 1. The collapse of the Ronan Point residential building in London, Great Britain, 1968

Fig. 2. Collapse of the Alfred P. Murrah Federal Building in Oklahoma City, USA, 1995

The collapse of the Sampoong shopping center in Seoul, South Korea, in 1995 was caused by gross errors in design decisions, lack of appropriate control during design and construction, and violations during construction and operation, Fig. 3. The condition of the building before the collapse was accompanied by constantly increasing excessive deflections in the roof and cracking in the columns, a situation that was aggravated by the dynamic impact of air conditioners located on the roof. The process of building collapse was initiated by the destruction of a column on the 5th floor, which caused the collapse of the roof structures to the lower floor, the load was not withstood by the supporting columns of the lower floors, and the building collapsed completely [6]. Before the September 11, 2001, terrorist attacks, this was the largest building collapse in modern world history in terms of the number of victims.

The collapse of the World Trade Center towers occurred on September 11, 2001, in New York, USA, during the largest terrorist attack in world history, codenamed "911", Fig. 4. An airliner crashed into each of the twin towers at high speed, and the collisions caused serious damage to the towers' structures and fires inside. The destruction of both the south and north towers did not occur instantly, but 56 and 102 minutes after the impacts, respectively. Directly in the impact zones, some of the structures were destroyed immediately, while the remaining structures gradually began to lose their bearing capacity and stability over time due to the combined effects of the fire and additional loads resulting from the redistribution of the load from the destroyed structures. Over time, this course of events resulted in the inability of the load-bearing structures in the collision zone to transfer loads from the floors above. As a result, the upper part of the tower collapsed on the lower floors, which led to the collapse of the lower floors, which spread to the ground [5].

Fig. 3. Collapse of the Sampoong shopping center in Seoul, South Korea, 1995

Fig. 4. Collapse of the WTC towers in New York, USA, 2001

In general, the last cited case of progressive collapse was the starting point for intensifying research into this phenomenon. The twin towers were designed to withstand both airplane impact and fire, but they were not designed for the combined impact that caused the towers to collapse. First of all, in the United States, which is a leader in this field, several scientific studies have been performed and broad recommendations have been issued to ensure resistance to progressive collapse, including options for modeling progressive collapse using numerical methods during design work [9, 12].

A comparative review of the main world cases of progressive collapse (13-14 cases) was made in [3, 7, 9]. Paper [12] defines the state of research on the progressive collapse of building structures in the 21st century.

The purpose of this paper is to comprehensively analyze the phenomenon of progressive collapse of buildings and structures based on the experience of foreign significant cases. The main objectives of this study are as follows:

– searching for the causes of progressive collapse initiation;

– determination the classification of collapse by the amount of initial damage;

– determination the classification by the type of collapse development;

– determination of the design features of progressive collapse cases;

– determination of compliance of existing modeling methods with real cases of progressive collapse.

Materials and Methods. This paper uses various methods to analyze the foreign experience of researching cases of progressive collapse of buildings and structures. First of all, these are the methods of literature review and comparative analysis.

The following materials were used for this work: scholarly articles, conference proceedings, documents of government organizations, etc.

Research results. *Causes of progressive collapse initiation.* In a general sense, the phenomenon of progressive collapse of buildings and structures is possible due to the occurrence of certain special influences (causes of initiation) that cause the destruction of individual elements of buildings and structures. The following ways of occurrence of this phenomenon are distinguished [3]:

– due to off-design (abnormal) impact on structures;
– due to the effects of structural deficiencies;
– the combined effect of the previous points.

Off-design (abnormal) impacts are the consequences of actions such as fires, terrorist attacks, hostilities, natural disasters, errors during construction, operation, etc. These impacts are unlikely, but they create unforeseen dynamic loads that are often not taken into account in established design practices.

The impact of structural deficiencies includes defects in materials, geometric parameters of structures, and characteristics of the operating conditions of the structure. For example, corrosion of reinforcement in reinforced concrete structures can reduce the bearing capacity, which in turn can lead to the destruction of individual elements even at design loads. Also, errors in the design of structures can lead to an incorrect assessment of the bearing capacity of an element, causing an accident under the design loads.

The study [7] on statistical processing of global cases of progressive collapse found that, as a rule, there were several causes of initiation at the same time, i.e., the so-called combined combination of causes. Among the 41 analyzed cases, the following causes were identified, which acted as a separate cause (mainly explosive and impact), and as part of a combination:

– errors during design – 15/41;
– errors during construction – 12/41;
– terrorist acts – 6/41;
– fires – 3/41;
– degradation of materials – 2/41;
– change of use of the facility – 2/41;
– accidental explosion – 1/41.

Thus, the prevention of progressive collapse is to some extent characterized by the strength of individual structural elements of buildings and structures. However, the vast majority of structural schemes are inseparable schemes that take into account the overall interaction of structural elements, ensuring the joint operation of the entire system [3].

The degree of disproportionality of the progressive collapse. The interpretation of the phenomenon of progressive collapse is covered in different ways in foreign scientific literature and foreign regulatory documents. For example, the American guidelines [1] state the following: “progressive collapse is defined as an extent of damage or collapse that is disproportionate to the magnitude of the initiating event. Since this definition focuses on the relative consequence or magnitude of the collapse rather than the manner in which it occurs, it is often referred to in the industry as "disproportionate" rather than "progressive" collapse". At the same time, some studies indicate the correctness of using the term "progressive collapse" instead of "disproportionate collapse" [5].

Comparing the cases of the Ronan Point and the Alfred P. Murrah Federal Building, it can be established that they both meet the term progressive collapse defined above, but if we consider them in terms of disproportionality, differences arise [5]. The magnitude of the collapse of the federal building was significant, but the cause of the collapse – a truck bomb – was also significant, and the number of structures destroyed by the explosion (not by subsequent collapse) was not single, unlike the collapse of the residential building.

Similarly, the case of the World Trade Center towers can be cited, where these cases are also classified as progressive collapse, but they should not be defined as disproportionate, since the magnitude of the initiating impact – the collision of an airliner – was significant. Although the initial recommendations for ensuring resistance to progressive collapse were implemented, namely, the redundancy of the bearing capacity of the frame columns was ensured (according to the conclusions of some researchers, the redundancy was so great, in particular, of the extreme frame structures), but the combined impact of the impact and fire was so large that the redundancy did not change the result in general [5]. However, it must be admitted that this allowed precious time to evacuate people below the collision zone before the final collapse of the towers. The conclusion that none of the measures adopted to prevent disproportionate progressive collapse would have been useful for the World Trade Center towers supports the idea that the collapse of these buildings was not disproportionate to begin with [5].

In view of the above, the scientific community is divided on the definition of disproportionality:

1) determination in terms of the ratio of the cause of the collapse initiation to the amount of final damage [1];

2) determination in terms of the ratio of the initial damage to the final damage [3].

However, the question arises as to the appropriateness of using the word "progressive", since any destruction/collapse is a process that occurs (is observed) in time, i.e. all possible destructions can be considered progressive. Therefore, it can be assumed that a non-progressive collapse cannot exist [8].

Thus, existing assessments of progressive collapse cases take into account the so-called degree of disproportionality of collapse (separation of the characteristics of the cause of initiation, the magnitude of the initial damage, and the magnitude of the final damage) [3]. This is because it is only possible to guarantee resistance to progressive collapse if the collapse is disproportionate.

One of the tasks in terms of ensuring the reliability of construction facilities should not be to prevent progressive collapse in general, but to prevent disproportionate progressive collapse. In the event of failure to prevent progressive collapse, the priority is to ensure that the collapse of the building is delayed.

Types of progressive collapse. After the noted cases of progressive collapse, U. Starosek proposed a classification of types of progressive collapse [10, 11]. Each type of progressive collapse characterizes the mechanics of collapse development in structures. The main types are as follows:

– pancake type;
– domino type;
– zipper type;
– section type;
– instability type;
– mixed type.

The pancake and domino types can be grouped into a separate super category of impact collapses, since they are caused by the sudden dissipation of the potential energy of the collapsed elements into kinetic energy. The zipper type and the sectional type can be classified as a separate super category of redistributive collapse since they occur as a result of the redistribution of forces from the destroyed structures to other structures [9, 12].

The pancake type of collapse is characterized, first of all, by the initial destruction of the load-bearing structure responsible for the transmission of the vertical load. Further collapse occurs due to the simultaneous destruction of other vertical load-bearing elements that are unable to withstand the increased redistributed load and the impact of higher structures on lower structures. Progressive collapse develops in the vertical direction [3]. An example of such a collapse is the WTC towers.

The domino type of collapse is characterized by the initial overturning of one of the load-bearing elements, which leads to a lateral impact of the overturned element on the side surface of the next element. Thus, horizontal loading through a chain reaction causes a progressive collapse in the direction of overturning. An example of such a collapse is the cascading destruction of power line towers [13]. The influence of the collapsing element can be indirect, the pushing force can be replaced by a pulling force through the connecting elements [7].

The zipper type of collapse is characterized by the initial destruction of one or more structural elements, which leads to dynamic impulse overloading of other structures due to the redistribution of forces. The development of this type of progressive collapse occurs in the horizontal direction. An example of such a collapse is a sudden break of bridge cables or retaining wall anchors [13]. The section type of collapse is similar to the zipper type. The main difference is replacing the terms cross-section and part of the cross-section with a structural element. It is assumed that the cross-section is amorphous and homogeneous, while other structures may consist of separate elements, each with different characteristics [14].

The type of collapse instability is characterized by the initial destruction of an element that ensures the stability and spatial rigidity of the system as a whole. An example of such a collapse is the destruction of the ligament elements of steel spatial frames, which prevents the frame from being resistant to lateral loads, such as wind.

A mixed type of progressive collapse is a combination of these simple types. The analyzed world cases of progressive collapse show that in real conditions, collapse rarely occurs within one type. As a rule, mixed types prevail. Among the 31 cases analyzed, the pancake type of collapse was recorded in 87% of cases, "lightning" in 45%, and "domino" in 10% [7].

Design features of progressive collapse events. The analyzed world cases of progressive collapse are characterized by the presence of initial failure of one or more structural elements, the failure of which extends to the destruction of the system as a whole or a significant part of it. The localization of the initial failure is reduced to the horizontal and vertical positions. In work [7] on the statistical processing of cases of progressive collapse, it was found that in the plane of the horizontal position, out of 31 analyzed cases, initial failure occurred:

– in the regional zones 6/31 – 19%;
– in the inner zones 14/31 – 45%;
– combined in the regional and inland zones 3/31 – 10%;
– not established 8/31 – 10%.

Already in the plane of the vertical position, out of 31 cases analyzed, the initial destruction occurred [7]:

– roof 8/31 – 26%;
– upper part of the building 8/31 – 26%;
– lower part of the building 4/31 –13%;
– ground floor 6/31 – 19%;
– basement 1/31 – 3%;
– not installed 4/31 – 13%.

Equally important is the analysis of the structures that led to the progressive collapse. Initial failure occurred in columns, beams, slabs, walls, etc. Among all the cases analyzed, in 45% of the cases, the initial failure of one or more columns led to progressive collapse. In 64% of them, the initial failure occurred simultaneously in two or more columns [7]. Such a distribution confirms the rationality of modeling progressive collapse due to the removal of sudden columns, as recommended by various regulatory documents.

According to research [3], the location of the initial failure significantly affects the behavior of the system during progressive collapse. As a rule, engineers model the removal of columns on the lower floors, because, firstly, the probability of anomalous impact is much higher, and secondly, these columns are in the zone of the greatest load. Also, modeling the removal of a corner column has worse consequences on a local scale compared to another location, and on a global scale, the failure of an internal column can have more significant consequences.

The current stage of the progressive collapse modeling is focused on modeling the removal of a single column, as this is in line with accepted guidelines. However, given the statistical data, such simulations do not reflect real-world collapse scenarios where multiple columns may collapse at once, and more structures may be damaged.

In a general sense, the analysis of progressive collapse raises the issue of studying the correctness of load redistribution in case of failure of different structural elements and different numbers of failures of structural elements. Such redistribution can be influenced by:

– structural scheme;
– planned placement of structures, regularity of the grid, span sizes;
– ensuring spatial rigidity;
– number of stories;
– material of structural elements.

For example, according to recommendations [1], structures with more floors have a better load redistribution effect. The presence of more elements above the removed structure contributes to better redistribution [3].

An analysis of significant cases of progressive collapse of buildings and structures has shown that the load-bearing structures were mainly made of monolithic reinforced concrete or rolled steel. Structural schemes made of prefabricated elements, including precast concrete and wood, have not been studied much in the field of resistance to progressive collapse. The main problem of ensuring the resistance to progressive collapse of structural schemes made of precast concrete elements is a rather low value of the connection between the elements (welding of embedded parts), compared to other schemes, in particular monolithic ones. This is a direct violation of one of the key recommendations for ensuring resistance to progressive collapse, namely the installation of indistinguishability.

Conclusions:

1. Researchers in the field of progressive collapse are directly interested in cases of only the highest level of responsibility because the social, political, and economic impact of the loss of such buildings and structures is the most significant. As of the middle of the third decade of the 21st century, more than 40 thoroughly investigated cases of progressive collapse of buildings and structures of the highest level of responsibility have been recorded.

2. The collapse of the WTC towers became the starting point for intensifying the study of the progressive collapse phenomenon. After the event, a few scientific studies were performed and broad recommendations were issued to ensure resistance to progressive collapse, including options for modeling progressive collapse using numerical methods during design work.

3. The phenomenon of progressive collapse of buildings and structures is possible due to the occurrence of certain special impacts (causes of initiation) that cause the destruction of individual elements of buildings and structures. There is a distinction between the occurrence of this phenomenon due to off-design (abnormal) impact on structures, due to the effects of structural defects and the combined effect of the previous points.

4. Existing assessments of progressive collapse cases take into account the so-called degree of disproportionality of collapse (separation of the characterization of the cause of initiation, the magnitude of the initial damage, and the magnitude of the final damage). This is because it is only possible to guarantee resistance to progressive collapse if the collapse is only disproportionate.

5. One of the tasks from the point of view of ensuring the reliability of construction objects should not be the prevention of progressive collapse in general, but the prevention of disproportionate progressive collapse. In the case of failure to prevent progressive collapse, the priority is to ensure the delay in time of collapse of building objects.

6. Each type of progressive collapse characterizes the mechanics of collapse development in structures. The mixed type of progressive collapse is a certain combination of simple types. The analyzed world cases of progressive collapse show that in real conditions the collapse is extremely rare within one type. Mixed types prevail, where the pancake type of collapse is the most common (recorded in 87% of cases). This means that the initial collapse of, for example, one column leads to some localized collapse on a larger scale. Structures above the removed column, due to the lack of supporting vertical structures and the inability to withstand emergency loads, hit the structures below.

7. Initial collapse of one or more columns occurred in 45% of cases of progressive collapse (64% of which occurred simultaneously in two or more columns), indicating that modeling of progressive collapse due to sudden removal of columns is rational.

8. The search for realistic collapse scenarios, in particular the selection of a column that is suddenly removed from the scheme, should be based on a comparison of the probabilistic analysis of the occurrence of such a scenario.

9. In a general sense, the analysis of progressive collapse raises the issue of studying the correctness of load redistribution in case of failure of different structural elements and different numbers of failures of structural elements.

10. The analysis of significant cases of progressive collapse of buildings and structures showed that the load-bearing structures were mainly made of monolithic reinforced concrete or rolled steel. Structural schemes made of prefabricated elements, including precast concrete and wood, have not been studied much in the area of resistance to progressive collapse.

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АНАЛІЗ ЗАКОРДОННОГО ДОСВІДУ ДОСЛІДЖЕННЯ ВИПАДКІВ ПРОГРЕСУЮЧОГО ОБВАЛЕННЯ БУДІВЕЛЬ І СПОРУД

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Анотація. Одним із передових напрямків інженерної наукової спільноти є дослідження роботи конструкцій та систем загалом під час малоймовірних (екстремальних) подій, зокрема прогресуючого обвалення будівель і споруд. Відомо про численну кількість випадків обвалення будівель і споруд різного роду призначення та рівня відповідальності, а вже дослідникам у сфері прогресуючого обвалення цікавлять випадки лише найвищого рівня відповідальності, це пояснюється тим, що соціальний, політичний та економічний вплив втрати таких будівель та споруд найсуттєвіший.

Метою роботи є всебічний аналіз явища прогресуючого обвалення будівель і споруд на основі досвіду закордонних визначних випадків. До аналізу винесено: причини ініціації прогресуючого обвалення, ступінь непропорційності прогресуючого обвалення, види прогресуючого обвалення, конструктивні особливості випадків прогресуючого обвалення.

У дослідженні використано підхід, що включає не лише результати аналізу безпосередніх випадків прогресуючого обвалення, а і наведено статистичну характеристику залежно від причини ініціації, виду обвалення, геометричного розміщення початкового пошкодження. Особливу увагу приділено відповідності прийнятих методик моделювання прогресуючого обвалення до реальних випадків прогресуючого обвалення.

Результати дослідження показали, що існуючі оцінки випадків прогресуючого обвалення враховують так званий ступінь непропорційності обвалення. Це пояснюється тим, що гарантування забезпечення стійкості до прогресуючого обвалення можливе лише за умови, якщо обвалення лише є непропорційним. Початкове руйнування однієї або декількох колон відбулось у близько половини випадків прогресуючого обвалення свідчить про раціональність моделювання прогресуючого обвалення через раптове видалення колон.

Подальші дослідження можуть бути зосереджені на пошуку реальних сценаріїв обвалення, зокрема вибір колони, що раптово видаляється із схеми, дослідженні коректності перерозподілу навантажень при раптовому видаленні колони, дослідженні забезпечення стійкості до прогресуючого обвалення будівель з конструктивними схемами, що виконані із деревини або збірного залізобетону.

Ключові слова: прогресуюче обвалення, ступінь непропорційності, руйнування, видалення колони, моделювання, конструктивні особливості, стійкість.

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