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RESEARCH AND STANDARDS ON PROGRESSIVE COLLAPSE OF STEEL BUILDING UNDER ABNORMAL LOADS

Abstract. The phenomenon of progressive collapse of building structures is an important focus in construction design. After the chain destruction of the Ronan Point in 1968, a range of studies were directed on the causes establishment of the appearance of progressive collapse and methods of protection against them. Trigger accident events contributed to damage have a different nature and are referred to as abnormal loading. The performance of the building collapse is also in depending on the construction materials and the design schemes. Many scientists from different countries dealt with the challenges of progressive collapse. Their research has found application in modern building codes and regulations. This article provides a brief review of current analysis methods for progressive collapse of steel structures under abnormal loads, as well as Russian and foreign standards related to this academic field.

Keywords: progressive collapse, abnormal loads, assessment methods

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ИССЛЕДОВАНИЯ И СТАНДАРТЫ ПО ПРОГРЕССИВНОМУ РАЗРУШЕНИЮ СТАЛЬНЫХ ЗДАНИЙ ПРИ АНОМАЛЬНЫХ НАГРУЗКАХ

Аннотация. Явление прогрессирующего обрушения строительных конструкций является важным направлением в строительном проектировании. После цепного обрушения жилого дома Ронан Пойнт в 1968 году целый ряд исследований был направлен на установление причин возникновения прогрессирующего разрушения и методов защиты от него. Триггерные аварийные события, способствующие повреждению, имеют иную природу и называются особой нагрузкой. Вид обрушения здания также зависит от строительных материалов и конструктивных схем. Многие ученые из разных стран занимались проблемами прогрессирующего обрушения. Их исследования нашли применение в современных строительных нормах и правилах. В данной статье представлен краткий обзор современных методов анализа прогрессирующего разрушения металлоконструкций при особых нагрузках, а также российских и зарубежных стандартов, относящихся к данной научной области.

Ключевые слова: прогрессирующее обрушение, особые нагрузки, методы оценки

Introduction

Term of progressive collapse means sequential (chain) destruction of load-bearing building structures, resulting in the collapse of the entire structure or its parts due to local damage [1]. Another definition, given in [2], appoints progressive collapse as the spread of an initial local damage in a structure to surrounding elements which eventually leads to the collapse of a disproportionately large part or the entire structure. In various literature synonyms of this term can be found, namely disproportionate or chain collapse or progressive failure.

This phenomena attracted attention of researchers and practitioners firstly after collapse of entire south-east corner at Ronan Point apartment block in 1968 due to a gas explosion. This event can be considered the beginning of exploration progressive collapse issues [3]. At the present moment this research area is only at the stage of genesis and formation into a separate scientific discipline. Many scientists' efforts were aimed at studying both causes of disproportionate collapse, and the mechanics of its origin and performance.

The following reasons may trigger progressive collapse occurrence [4–6]: a natural event (hurricanes, earthquakes), accidental event (gas explosions, fires), industrial accidents, human errors in design, construction and reconstruction, deliberate event (terrorist attacks), soil collapsing and sinkhole, etc.

It is assumed all the mentioned above trigger events contributing to limited local damage unite at a group of abnormal loads. In [6] it is also describes possible scenarios for the development of local deformations. Generally researchers are limited to only one of all scenarios namely column loss scenario under abnormal loading to assess the potential for progressive collapse, i. e. it is used to check if a building can successfully absorb loss of a critical column, or a brace or brace/column combination when pay no attention on the nature of loading [7]. There is also a less common scenario of sudden transport impact load considered in [8]. However the question of the occurrence probability of such scenario compared to others discussed in [9, 10] omitted in case of that researches.

There is a range of method of simulation the procedure of progressive failure analysis for definition the response of the frame, developed in recent years. They consider the process of developing progressive collapse from various angles, including dynamic aspects, load history, time history analysis, etc. But there are no common methods and evaluation criteria of progressive collapse resistance related for steel, reinforced concrete and composite construction [11].

1. Progressive collapse assessment regulation

Currently, more than 30 leading research, design and construction organizations are engaged in research in the field of progressive collapse. One of the goals of their work is to create novel design standards and update the existing ones with this phenomenon in mind.

1.1. Russian Federation regulations concerning progressive collapse

Due to the great interest on the part of scientific and design organizations, in recent years new regulatory documents in the field of progressive destruction have been developed and issued.

Contrary to popular belief, the first regulatory documents related to the progressive-failure issue appeared in the Soviet Union in 1986 [12]. At the beginning of the 21st century, guidelines for protection of buildings with a long stay of a large number of people and unique buildings (high-rise and long-span) from progressive collapse were formulated in Russian standards. However, these recommendations mostly relate to reinforced concrete buildings of various design schemes and purposes, i. e. there is a gap in the regulatory framework governing the progressive collapse analysis of steel structures.

Currently, in the framework of progressive collapse of the supporting structures of buildings and structures, the main regulatory documents are: [1, 13] define the objects for which progressive collapse analysis is mandatory; [14] regulate load combinations for event of abnormal loading; [15–16] determine the design rules and the procedure for calculating metal structures, as well as the recently introduced [4, 17] regulating the procedure of the progressive collapse analysis.

Additionally, the question of introducing an additional third group of limiting states caused by special impacts and accidental events that lead to the damage of structures with catastrophic consequences is discussed in the Russian-language scientific community [18–19].

Nevertheless, gaps in the regulatory remain with the introduction of recent documents, for example, the procedure for accounting for dynamic coefficients, the criterion of progressive destruction of the structural system of buildings with metal structures with no occurrence of stabilization of strength conditions for sections are not clearly defined.

1.2. The USA regulations concerning progressive collapse

Of all the variety of international codes and standards in the field of construction American guidelines, which acknowledged and depicted the outcome of the research efforts towards the quantification of disproportionate collapse deserve special attention [20–24]. Nowadays they are the most advanced and constantly updated standards. Many countries use these standards as prototypes of their own. These documents so far include several different design methods; the indirect methods such as the tie force method and the direct methods such as the specific local resistance method and the alternate load path method.

The highest value represents the alternate path method incorporated the event of a vertical element failure tuning the structure such that can bridge over the failed element through the redistribution of the load to the remaining structure. Therefore, the critical elements of such structures mainly include columns. The method employs three analysis procedures: linear static, nonlinear static and nonlinear dynamic.

Indirect measures imply prevention or reduction to an acceptable level of probability of appearance and/or intensity of special impact due to the use of preventive or organizational measures (prohibition of storage of explosive materials, installation of protective screens, shells, safety barriers, increase in areas inaccessible for terrorist threat, etc.). As well as carrying out constructive measures to ensure the integral integrity, continuity, multiply connectedness of the system, plastic deformability (tie method), etc.

1.3. Another regulations concerning progressive collapse

In the practice of international regulation of progressive collapse, it is also worth to note the Great Britain regulation and Eurocodes.

The UK was one of the first countries to incorporate the main provisions for assessing the progressive collapse of buildings into its standards. The main provisions of measures for protection against progressive collapse are given in BS 6399 [25]. Specific requirements for protection against progressive collapse for steel, reinforced concrete and masonry structures are given in material-specific BS 5950 [26], BS 8110 [27], BS 5628 [28], respectively.

Eurocode is a regional regulation of the European Union member countries. They are not intended for direct use and must be adapted to local conditions. For this purpose, in each country, national annexes to Eurocodes are developed, which specify the parameters to the country, and may also provide additional explanations of inaccuracies that arose in connection with the translation of the standard from English to the national language, application features and other information. In the Eurocode EN 1991-1-7 [29], provisions (strategies and rules) for designing buildings against identifiable and unidentifiable specific impacts are provided. However, it is stated that this document does not specifically address the special effects caused by external explosions, military and terrorist acts. Thus, the design of structures against the possible threat of a terrorist attack must be carried out in accordance with the provisions on the specified special effect.

A comparative analysis of certain norms is given in [30].

2. Progressive collapse assessment methods

As noted above, at the moment there is universally accepted approach to the assessment of progressive collapse, and the regulations may recommend different provisions and even contradict each other. The methods applied to structures made of different materials should reflect the main features of their work both at the design load stage and at the stage of operation loads. Additionally, the schematic diagram of the building depended on the used materials determines the model of progressive collapse and means by which its effects may be mitigated. In this regard, it is advisable to separate the methods applied to metal, reinforced concrete, wood and combined structures.

There is no single concept for solving the problem of the progressive collapse of the steel frame structure in terms of modeling the emergency load situation and its consequences so far. Therefore linear static, quasi-static, nonlinear static and nonlinear dynamic methods are outline in various literatures. Some of them are described below.

2.1. Approaches to progressive collapse assessment

Mainly methods progressive collapse assessment can be divided into linear and nonlinear calculations. A simple but rather conservative way of analyzing a structure under the scenario of a failed element is using a linear static method [31]. This method already has described in all the relevant American guidelines as an acceptable way of analyzing the problem. However, it involves the application of the load increase factors or dynamic amplification factors in order to compensate dynamic structure behavior which a static analysis cannot include. The nonlinear effects were deliberately not accounted in the study in order to highlight the results.

Quasi-static nonlinear pushover analysis methods originally use to estimation seismic load. And in article [32] its application for other extreme events, such as blast loads and tornado winds is considered and illustrated by an example.

In study [33] the vertical push-down analysis was conducted to investigate the resistance of steel moment frames for progressive collapse. The analysis was carried out by gradually increasing the vertical displacement in the location of the removed column and the vertical load in all spans corresponding to the increase of vertical displacement.

Nonlinear quasi-static computational procedure for progressive failure analysis use to trace the post-elastic stiffness and strength deterioration of building frameworks subjected to abnormal loading [34]. Also a nonlinear dynamic analysis methodology has been proposed for tracking the dynamic behavior of progressive collapse [35].

Kim and Park [36] applied a plastic design method for the design of steel moment-resisting structures against disproportionate collapse using a dynamic method of analysis.

However, few researchers take into account the spatial behavior of regular framework, the consideration of various combinations of internal efforts, and also require verification of the results of the proposed progressive-failure analysis procedure. Nevertheless, the nonlinearity of the phenomenon, which plays a major role in the response of the structure, is included in upcoming publications by other researchers.

2.2. Analysis levels of building structures for progressive collapse

When analyzing buildings for progressive collapse, it is represented as a hierarchical structure. The following structural elements of the building are distinguished: individual elements of the building (assembles and separate structures), substruction (groups of structural elements), flat spatial systems of several characteristic elements (floors or frames) and the building as a whole. Due to the different objectives of the study, scientists consider certain structures and their work under the influence of abnormal loads.

Individual elements of the building. Rigid steel beam-to-column frame structures are applied to counteract to progressive collapse and to implement the alternative path method by means of catenary effects or compressive arching action.

Analysis of the actual operation of the connections shows that they have compliance [37]. Thus, when evaluating the progressive collapse, it is necessary to consider not conditionally “rigid” and “hinge” joints, but to take into account their actual work.

The research works of George Vasdravellis et al., Bo Yang et al. [38–40] are devoted to the study of rigid connection under the application of a abnormal load. The authors dealt with various types of assembles and created computational models of them in highly organized software complexes ABAQUS and ANSYS, as well as verified such models using special tests. On the basis of verified models, the authors conducted numerical experiments and made recommendations on the use of joints of various configurations.

Substruction of building structure. When analyzing the strength of structures for progressive collapse, it is necessary to analyze not only the connections, but also the stress-strain state of the structures immediately adjacent to the damaged element.

The importance of this analysis lies in the fact that internal forces arise in the elements calculated for one stress-strain state, contributing to the transition of the structure to another. Thus, in [41] complex task of analyzing a flat frame section direct influence area regarded as the main investigation region when using the APM is considered. The paper discussed in detail aspects of modeling such structures in ABAQUS software, investigated the effect of the boundary constraints at the beam end on the anticollapse performance of an assembly and conclusions of flexural and catenary actions in a beam.

Planar frames of building structure. At a certain stage in the development of mathematical modeling, the analysis of progressive collapse was limited to flat frames because they are much simpler than spatial models. However, already on the basis of data from numerical experiments [34, 42, 43] it was possible to get an idea of the mode of a chain reaction in the term of progressive collapse and on the entirely operation of the building frame during the occurrence of the column loss scenario entirely.

Entire building. The works, aimed to spatial analysis of the building, are of particular interest. They implement the most complete force transfer model in the case of alternate load path method. In addition, in [42] a comparison of space and flat analysis of building structures was got. Such experiments in nature are quite costly. However Song et al. [44] managed to put an experiment of loss of columns of various positions on the plan in the building intended for demolition. Such a large-scale experiment allowed us to verify the numerical model for further research.

Complex analisys. It is also worth noting the Izzudin and Vlassis research [9, 45], devoted to a comprehensive assessment of the progressive collapse of buildings. In this paper, an approach that allowed test how to resist constructions is formulated. In the companion paper, the authors demonstrated their method on the example of a simple-shaped building model.

3. Development directions of progressive destruction analysis

The most dangerous structures from the of progressive collapse point of view are long-span and high-altitude (unique) one due to failure of structural elements such as supporting contour of guy or convex shells, bearing pylons or columns of a high-rise building, suspension systems of cable-stayed systems, etc. Also, buildings with irregular structure and a small number of basic bearing elements may be included to the group of such unique systems.

For industrial buildings of ferrous metallurgy of the review’s author interest, a cellular framing structural scheme is often used. The scheme consists of a series of flat frames located in the vertical planes of all transverse axes. Frames provide lateral rigidity and stability of the building. Longitudinal stiffness is achieved by introducing in some parts vertical ties, installed on the entire height of the building that forms a stable framework in combination with hard disks. Blast furnace buildings are objects of increased responsibility, since their failure can lead to great economic, environmental and material consequences, as well as to human losses. However, the complexity of the technological process that takes place in the blast furnaces building preclude the installation of a large number of redundant elements to provide excessive static indeterminacy, which in turn complicates the designer’s task.

Blast furnaces buildings have some features of operation, which can contribute to the development of accidents and as a result, progressive collapse. For instance, there is a strong temperature effect of a wide range of temperatures with their uneven distribution in space and in time, low-cycle heavy loads, leading to the appearance of fatigue cracks in metal structures, as well as in homogeneity phenomena in welded joints [11].

These buildings are of interest to the researcher for several reasons. First, it is necessary to correctly build a analytical model and evaluate the influence of closely located structures on each other in the event of a design accident. Secondly, it is necessary to analyze the possibility of the occurrence of a design accident and thereby limit the possible scenarios of progressive collapse. Thirdly, it is necessary to study the actual operation structural frame connections in the event of a abnormal load, since their shapes differs from those previously discussed in Sec. 2.2. Solving the above problems will improve the quality of design solutions and the level of safety during operation, reduce the risks of the possibility of progressive collapse of ferrous metallurgy facilities, as well as the cost of constructing the facilities.

Conclusion

Experimental studies directly affect the further development of regulatory documents in the field of constructive safety of buildings and structures. At the moment, the study of the causes of progressive collapse and the mechanism of operation of structures under the application of anormal loads has already achieved success, but there is still an urgent need to formalize the methods of progressive destruction.

In conclusion, it can be noted that further theoretical and experimental research in this area is necessary for a detailed study of the redistribution of efforts in a constructive system and the stress-strain state of structures to a particular effect, especially operated and reconstructed buildings and structures.

Industrial buildings with steel framework are of particular interest in this matter. The wide size range of steel structures, the possibility of severe service and the resulting flexibility of space causes their widespread use. However, along with this, the risk of an emergency in industrial buildings is higher, as well as the complexity of design solutions. Therefore, the issue of safety and the protection of industrial buildings from progressive collapse play an important role in design issues.

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