The calculating the progressive collapse problem in the light of the existing regulatory framework of the Russian Federation

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Abstract. It has become increasingly important to consider emergency situations having a low occurrence probability and short duration and being important from the point of view of the reaching the limiting conditions consequences that may arise in such situations, in recent time, when designing industrial and civil engineering facilities. An example of such emergency is one of the supporting building structures failure, which can lead to its progressive (avalanche-like) collapse. At the same time, one of the main problems in this situation until recently was that until 2018-2019 there was no single regulatory document in the Russian Federation regulating both the actual calculation for progressive collapse and the criteria according to which the structures can be considered stable or unstable to progressive collapse.

Introduction

The necessity of calculating the progressive collapse was mentioned in [1]. In particular, articles 5.2.6 of this document state that it is necessary to calculate the progressive collapse for buildings and structures of KS-3 class (corresponding to an increased level of responsibility), as well as buildings and structures of KS-2 class (corresponding to a normal level of responsibility) with mass finding people. The list of buildings and structures with a mass presence of people is determined by Appendix B [1] and includes residential, office, administrative and public buildings of 5 floors or more in height, buildings for 100 seats and more in which restaurants, cafes and other similar premises are located, buildings of preschool educational institutions, schools, educational institutions for 100 visitors and having 2 floors or more in height, as well as some other objects. Thus, according to [1], it is prescribed to perform a calculation for progressive collapse for the vast majority of public and residential buildings belonging to the normal and elevated responsibility level. Also, a clear definition of progressive collapse is formulated in this document - this is a sequential (chain) destruction of bearing building structures, leading to the entire structure collapse or its parts due to initial local damage.

In [2], the buildings and construction structures are required to have reliability and durability, taking into account possible dangerous effects, as well as resistance to progressive collapse, confirmed by appropriate calculations. At the same time, as mentioned earlier, not a single regulatory document contained criteria for assessing the buildings and structures sustainability to progressive collapse, as well as a clearly formulated calculation method.

Main part

Requirements for the necessity of calculating the progressive collapse were also contained in [3], as well as in a number of other normative documents. It should be noted that all these documents regulated the calculations for the progressive collapse of mostly monolithic reinforced concrete or large-panel multi-storey buildings related to new construction, and did not address the issues of multi- and single-storey industrial buildings with metal frames and the reconstruction of existing industrial enterprises and civil facilities, bringing them in line with current regulatory documents establishing the need to ensure their resistance to progressive collapse.
The calculation issues and resistance to progressive collapse for various types of structures are covered in a number of scientific articles [4,5,6,7,8], where the authors argue whether further work on the regulatory framework is needed: its refinement and expansion.

Thus, as it can be seen from the review of normative documents and articles devoted to the issue, there was no single document regulating the procedure for calculating the progressive collapse for all types of buildings and structures until 2018-2019, as well as clear and precise criteria according to which the buildings structures could be considered resistant or unsustainable to progressive collapse.

In 2018-2019, two regulatory documents were enacted in the Russian Federation, in which an attempt to combine previously disparate and sometimes contradictory documents regulating the calculations for progressive collapse was made. So, [9] divided all the special loads on normalized and emergency. Rated loads are the special loads, the intensity and distribution of which over the surface or structures volume are known and given in the current regulatory documents or design assignments: extreme climatic influences, loads from explosions outside or inside the structure, shock loads, loads from fire trucks). Emergency loads are those which action is taken into account by the structures for progressive collapse calculation.

Another normative document [10] was the first document in Russia in which the authors made an attempt to put together previously scattered information, gave a clear definition of progressive collapse (almost completely repeats the definition given in [1]), and also formulated the criteria for the buildings and structures sustainability to progressive collapse.

According to [10], the building possible collapse cause or its part is the initial local destruction - the bearing capacity loss of a structural element or group of supporting structural elements in a limited area due to accidental impact. Resilience against progressive collapse of the document determines the provision of bearing capacity as a structural design of the structure as a whole, and structural elements adjacent to the zone of local collapse. When calculating the load-bearing structures of one (any) floor of a building and structure, the zone of local destruction according to [10] is determined by a circle of at least 28 m² (diameter 6.0 m) for the buildings and structures at a height of up to 75 m, at least 80 m² (diameter 10 m) for the buildings and structures with a height of 75 to 200 m and not less than 100 m² (diameter 11.5 m) for the buildings and structures more than 200 m high. These requirements, judging by the context, refer to the buildings and structures made of precast and monolithic reinforced concrete. In single-storey industrial buildings, the destruction or the supporting structure removal in the area of two adjacent steps in single-span buildings and adjacent spans of multi-span buildings should be considered. It does not specify what kind of design is meant (farm, column, coating beam). For large-span buildings and structures, the destruction (removal) of one of the bearing elements should be considered as local destruction, in other cases, according to the design assignment, depending on the construction type, but not less than one of the bearing elements.

- The local destruction zone can be located anywhere in the structure and should not lead to the entire structure progressive collapse. At the same time, to assess the stability of buildings and structures against progressive collapse, the most dangerous local destruction should be considered.
- In [10], a number of assumptions for the calculation of progressive collapse are given, in particular:
  - the materials calculated strength characteristics are assumed to be equal to their standard values, and for reconstructed buildings and structures - taking into account the survey results;
  - load values in the calculation of resistance to progressive collapse should be taken in accordance with [9] and [11]. Namely, the load safety factors \( \gamma_i \) for constant, long-term and short-term loads, as well as the load combination factors, should be taken in accordance with the guidelines [11], as for special combinations;
  - the reliability coefficient for the buildings and structures responsibility when calculating for progressive collapse is assumed to be \( \gamma_s = 1.0 \), while for the buildings and structures of 75 to 200 m high or a span of 50 to 120 m or with console structures with departures from 10 to 20 m establishes the reliability coefficient for liability \( \gamma_s = 1.1 \), for the buildings more than 200 m high or with a span of
more than 120 m or with cantilevered departures over 20 m, the reliability coefficient for liability is assumed to be equal to $\gamma_n = 1.2$;

- in the design model, consideration should be given to the inclusion in the work of elements that during normal operation of the structure are not the carriers (for example, hinged exterior wall panels, parapets, etc.);
- the calculation for progressive collapse is performed for each of the considered local collapses separately, independently of other local collapses.

It is also indicated in [10] that for the calculation of structures for resistance against progressive collapse, it is necessary to use a quasistatic or dynamic method, according to which the sudden removal of an element to be switched off is simulated by the forces determined in this element when calculating by the primary design scheme (i.e. switching off the element from work), which are applied in the secondary design scheme with the opposite sign.

The disadvantages [10] include the following:

- The specified set of rules is intended mainly for use in the buildings and structures made of precast or monolithic reinforced concrete, mainly civilian, since the concept of “local collapse” is most applicable to them;
- The building (structure) resistance determination to progressive collapse, given in the joint venture, has little relevance to reality. In particular, in industrial buildings with a metal frame, the removal of one of the key elements (columns, bolts of the covering or floor) in most cases will lead to failure of the elements supported on them, that is, buildings (structures) will not be resistant to progressive collapse. It does not matter how many elements failed after the removal of one of the key elements, as well as their degree of importance for the framework;
- The rulebook did not reflect the calculations adequate application question for progressive collapse to already existing industrial buildings and structures built prior to the emergence of the very concept of progressive collapse and, accordingly, in inconsistent advance with modern standards. Bringing the fixed assets of industrial enterprises into line with the new joint venture is a long and laborious process, requiring significant material investments, and in some cases stopping production for reconstruction, which causes direct economic damage to the owners of these enterprises and is not taken into account by the joint venture developers.
- Thus, although [10] is a step forward in the calculations’ regulation for resistance to progressive collapse, it also seems unsuitable for practical work on the design of certain types of structures - in particular, metal frame buildings and structures, including reconstruction Soviet / Russian industrial enterprises.

As an example of the problems encountered in the new joint venture application, it is proposed to consider the enrichment production transshipment unit (construction class KS-3) design, performed according to the frame structural scheme (Figure 1).
The transshipment hub is a rectangular multi-storey building bounded by axes A-G / 1-4 with dimensions of sides in axes of 9.0 × 16.5 m. The maximum building height (along the parapet) is 29.8 m.

In order to ensure the building stability to the transshipment hub structure progressive collapse, they are made according to the frame-linkage scheme (in both directions) and consist of a series of transverse frames arranged along digital axes with variable pitch from 5.0 to 6.0 m, connected by crossbars and struts. The transverse frames are formed by the articulated columns of rolling I-beams, articulated with the foundations, as well as with the floors crossbars and rolling I-beams coatings that match with the frame columns according to a rigid scheme. The cover girders span is 9.0 m. The longitudinal frames are arranged along the letter axes A, B and D and consist of pivotally connected to the columns’ foundations, as well as girders of floors, paired with the columns according to a rigid scheme.

The transshipment hub overlap is located at elevations +15.150 and +20.850 and is made in the form of beam cells consisting of main (girders of overlap) and secondary beams, paired with each other in the same level along rigid - to ensure resistance to progressive collapse - or hinge schemes.

The building roof is arranged on the rolling I-beams runs, located on the coating crossbars with a step of 1.5 m and made continuous on the building entire length.

The building frame rigidity and geometrical immutability in the longitudinal and transverse directions are provided by the frame nodes of the conjugation of the crossbars of the ceilings and the covering with the columns of the frame, as well as by the steel vertical ties and struts. The coating rigidity is provided by horizontal connections on the coating crossbars at the building ends.

The building frame stability against progressive collapse is provided by the columns and girders frame junctions of floors and coverings, continuity of girders and floors, rigid coupling of separate secondary beams with girders of floors (has a supporting effect when removing frame elements), as well as the introduction of rigidly matched with the frame columns beams in the coating level, oriented along the letter axes A and G.

Emergency impacts are taken in the building starting local destruction form. As a part of the calculation, 193 scenarios of structure various elements failure (193 scenarios of local collapses) were considered. For the calculations, it is possible to use a number of programs, for example, Plaxis [13], SCAD. In this study, the SCAD software package was used.

According to the primary calculations results (without taking into account the progressive collapse), as well as 193 secondary design schemes in the SCAD software package, the transshipment unit building main supporting structures elements sections were selected (Figure 2). It should be noted
that in the overwhelming majority of cases, the main criterion for the sections’ selection was precisely the resistance calculation to progressive collapse. The sections selection results for all the computational schemes were compared with the sections selection result for the primary design scheme (without taking into account the progressive collapse factor). The metal intensity of the frame increased 1.3 times (from 105.2 to 136.7 tons).

Figure 2. The transshipment unit structures sections use coefficients in an emergency with the column section exception

As the above example shows, based on [10], it is possible to design a building that is resistant to progressive collapse (Figure 3). However, this raises the question of the economic feasibility of such design, especially relevant to already constructed objects according to old standards.

The developers [9] in clause 4.5 mention that the effect of emergency special loads, to which the progressive collapse also applies, is allowed to be disregarded if the design, constructive and organizational measures listed in paragraph 5.11 of the same BC are fulfilled. Further in clause 5.12 it is indicated that for constructions of class KS-3 it is allowed to develop constructive solutions taking into account the risk assessment, the regulatory (design) and emergency specific impacts and costs associated with carrying out measures (constructive and organizational) consequences analysis to limit the damage area. Article 5.2.6 [1] also mentions that it is allowed not to carry out the calculation for progressive collapse if special measures are provided. However, as the design organizations communication experience with the Glavgosexpertise of Russia shows, that neither arguments about the economic disadvantage of applying new standards with regard to real industrial buildings and structures (especially existing ones), nor the implementation of the measures listed in paragraph 5.11 are taken into account [9]. Another “loophole” for the design organizations, which until recently was special technical conditions (stipulated by [13] and [14]), developed for a specific capital construction project and containing provisions compensating for deviations from the mandatory application requirements is also no longer taken by state experts into account, even if they are approved by the Ministry of Construction.
Figure 3. Measures to ensure the frame stability to progressive collapse

Summary
Thus, the current legal and regulatory framework on the buildings and structures sustainability ensuring issue against the progressive collapse is incomplete, controversial and needs further refinement. The new standards application in the reconstruction of existing enterprises within the framework of technical re-equipment conducted by the owners is particularly acute, since strengthening existing structures in addition to significant direct financial costs also often requires stopping the production chain, which in turn causes additional economic damage to enterprises, reducing their competitiveness.

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