The improvement of protection methods from the progressive collapse of one-storey industrial buildings

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Abstract. The article deals with the main calculation methods of load-bearing systems for protection from the progressive collapse used both in Russia and in foreign countries. On the basis of the existing experience the recommended engineering decisions help to protect single-storey industrial buildings made of precast concrete structures from the progressive collapse. There are significant heights, rare step of columns and large spans of roof structures in this type of buildings. In the case of reinforced concrete buildings they also have significant loads from their own weight so it is a difficult to design the protection from the progressive collapse especially in the case of narrow conditions and in the reconstructed construction sites. The authors suppose that the use of the recommended engineering decisions help to perform effectively the protection from progressive collapse and to reduce time and financial costs.

Key words: protection from the progressive collapse, moving connections, sub-truss, engineering decision, cable connections, reinforcement.

1. Basic Calculation Methods of Protection From the Progressive Collapse

In the last few decades the protection of construction projects from the progressive collapse is becoming especially important due to the frequent cases of impacts on the building structures and facilities not provided for by regulations leading to their collapse. Such impacts include terrorist acts, explosions of town gas and mechanical collapse of supports due to the motor transport collision, etc.

In accordance with the active regulations (Federal Law of 30.12.2009 N 384-OЗ [3]) the progressive collapse protection of new and existing construction projects (that meet the requirements of SP 385.1325800 [7]) is important for the reconstructed construction projects. The engineering society faces the lack of the necessary volume of recommended constructive decisions in the regulations and manuals including the protection design of single-storey industrial buildings from the progressive collapse. Such impacts have not been fully taken into account for economic reasons. This is of special importance for the reconstructed buildings made of precast concrete elements in operation.
The protection of construction projects from the progressive collapse are studied worldwide. There are a great number of publications in the world; they are shown in the papers [9–17; 21–27]; some statements are presented in the regulations [6-8; 18-20].

At present in Russia and in some foreign countries there are two approaches to the protection design of construction projects from progressive collapse:

1. "Direct method" (the method using spatial calculation model) – provides for the direct (explicit) resistance of a structural system to progressive collapse when designing protection from progressive collapse. This method is close to the method presented in UFC 4-023-03. Unified Facilities Criteria (UFC). Design of Buildings to Resist Progressive Collapse [19] - the method of alternative trajectories (alternate path direct design approach) determining the alternative ways of the force flows in the case of removal of one of the main bearing structures (e.g. column, crossbar, bearing wall, etc). The calculation according to this method can be made in two ways:
   - the structural system must not lose the load-bearing capacity when removing one load-bearing structure in case of emergency of unidentified (accidental) volume and nature. The structural system is designed so that the hypothetical loss of one load-bearing component does not lead to the progressive collapse. It must provide the alternative ways of transferring loads by redistributing loads localizing the damage area. It is necessary to use the admissible minimum area or volume of a construction damage to calculate according to this method. The operation of the project constructive system is analyzed by direct removal of one load-bearing component from the design scheme and simultaneous verification of the possible progress of this collapse. The use of this approach is complicated by the correct removal of load-bearing components from the constructive system.
   - the constructive system must not lose load-bearing capacity in case of emergency load of predetermined nature and volume. In this case, the integrity and rigidity of the main constructive components carrying additional emergency loads is provided by their strengthening. This option involves the intensity standardization of the emergency load.

2. "Indirect" method includes indirect resistance of the structural system to the progressive collapse. It also includes two ways:
   - the use of organizational, technical or preventive measures to reduce or completely eliminate the occurrence and progress of progressive collapse in case of emergency load.
   - the improvement of static indeterminability (the imposition of additional connections) to create almost continuous load-bearing building structures. This approach (e.g. presented in MDS 20-2. 2008 [8]) is similar to the method of joint forces (specific local resistance direct design approach) presented in [19]. The connections analysis improving the static indeterminability includes the carrying differently oriented loads in space. They can appear at the displacement or hanging of building structures in case of emergency load.

2. The Protection Design of one-storey Industrial Buildings From the Progressive Collapse

The studied above sources and active regulations (such as Building Act 385 [7] and Building Act 296 [6]) let us design the protection from progressive collapse of the most buildings under construction, but they do not answer some questions such as protection of linear structures, including power lines and engineering structures including reservoirs from the progressive collapse. If we study a protection from progressive collapse according to the methods in Building Act 385 [7] the contents of the capacitive structures will be lost. Previously used regulations for tanks with dangerous contents define the collapse operations to restrain the spill of dangerous contents. Similar requirements cannot be used for linear constructions, overpasses, pipelines and other engineering constructions. The research work will help to solve this problem. Also there are some problems of the components of calculation, for example, specification of the criteria for the special limit state.

The protection of one-storey industrial buildings from the progressive collapse including precast concrete components must be thoroughly studied. The structural method stipulated by the Russian regulations preventing single-storey industrial buildings from the progressive collapse includes the improvement of static indeterminability of building structures, using the continuous sub-trusses, the
implementation of additional connections; it increases the metal content of the construction project, and in some cases it is necessary to work on details (the reconstruction of a construction project, the removal of extreme columns).

Also there are some ways to simplify the protection from the progressive collapse – to divide the building into blocks of a certain length to limit the areas of collapse, and to use the cable sub-truss systems and connections.

The protection of one-story buildings from the progressive collapse when removing the corner column is nowadays the least studied because it is extremely difficult to use the sub-truss systems that can keep the component from the collapse. The use of additional vertical connections is irrational due to temperature deformations. Some components of the building are in a special limit state when calculating the progressive collapse. The Building Act [7] defines the criteria and methods of calculation which can be clarified after integrated experimental studies of the building structure operation and materials in a special limit state.

It is necessary to define other possible approaches to the progressive collapse of industrial one-storey buildings, including its reconstruction:

- the local protection of escape routes from the progressive collapse is important for all construction projects;
- the use of moving connections-stops limiting the vertical movement of load-bearing structures in case of emergency connected with the removal of the lower part of the column, including corner column;
- the use of roof slabs with reinforced embedded parts carrying loads arising from large slab movements in the vertical direction. It also reduces or eliminates the collapse of the roof during the roof beams collapse, for example, truss.

Also the possibility of using cable sub-truss and connection systems is studied.

The authors studied and performed a number of numerical experiments simulating the existing and recommended constructive solutions.

3. Cable Sub-Truss and Connection Systems

To protect one-storey industrial buildings under reconstruction from the progressive collapse it is possible to use a system of cable sub-truss constructions consisting of metal cables stretched on stepped trunnion bands (figure 1). This solution protects the construction projects from the progressive collapse without significant load increase at the existing foundations. If necessary, the strengthening of reinforced concrete columns can be made by pasting with carbon tapes, carbon fiber lamellae or other traditional materials (figure 2). The use of reinforcement from the carbon materials avoids a significant load increase of its own weight at the existing structures and foundations.

The structural decision made with cable sub-truss connections has a number of difficulties such as the high accuracy requirements of the force cable tension, the necessity of regular monitoring and the protection of cables and tension mechanisms from rusting when operating these products outdoors. It is very difficult to ensure the required fire resistance of the recommended constructions; so, it is necessary to use additional measures to protect them from fire.
Figure 1. Step trunnion truss with metal cable (The constructive decision was developed by the company Mosenergoproject)

Figure 2. The operation of cable sub-truss system in case of failure of the lower part of the column

4. Reinforced Anchoring of Roof Slabs

The variant of the anchor strengthening of roof slabs after the corresponding design rationale includes the compliance of the slab joints (e.g. according to [28]). It can be recommended as a measure of protection from the progressive collapse. The roof slabs can be considered as components of the hanging system, allowing the significant vertical movement with the support at the remaining roof beams; but the collapse of the roof is eliminated.
Figure 3. Reinforced connection of roof slabs

Figure 4. Unit A. The connection of the roof slabs by means of a clamp and caulking with a concrete mixture

Figure 5. Unit B. Reinforced connection of the roof slabs with a metal connecting plate welded to the embedded parts

5. Sliding Connections

The protection from progressive collapse after the removal of the corner column must be studied thoroughly. The design of sub-truss structures holding the truss structures with the absence of the
lower part of the corner column is expensive and sometimes impossible; the installation of vertical connections located at the end part of the building prevents the thermal deformation.

The structural variants of struts installation with sliding support (sliding connections) in the area of the corner columns of the building significantly reduces the continuous sub-truss cross-section. It is necessary to limit the maximum vertical movements of the structures of the building span. Sliding connections can be installed at each column of the building that significantly reduces the cross-section of the sub-truss structures in the area of corner and ordinary columns. This method allows to mount the progressive collapse protection in the narrow conditions and in the object under reconstruction. Mobile connections do not lead to temperature deformations of a building frame. They insignificantly load the columns with their own weight without carrying operational loadings during their operation (figure 6-8). The strut is based on the foundation of the column. This engineering decision is distinguished with the use of a support slab and metal stops. The strut displacement after removal of the end column is made till stops on the PTFE gasket. The inclination angle of the strut determines the carried load. The junction of the sliding connection to the head or to the upper attachment point it made hinged to eliminate the load transfer from temperature deformations as well as from the operational deformations of neighbor structures.

This engineering decision can be used when the building is under reconstruction. The calculations of the numerical experiment of a one-storey industrial building with the use of mobile connections showed the prospects of this method. The engineering model helps to test the progressive collapse protection of a one-storey industrial building made of precast concrete components of a building under reconstruction.

![Figure 6. Fragment of the engineering model of the building with the installation of sub-truss connections. The continuous sub-truss in the extreme span of the building is not shown for convenience](image-url)
6. Conclusions

Engineering decisions and recommendations for the protection of buildings from the progressive collapse presented in the active regulations of Russia do not contain a sufficient volume of recommendations that can protect single-storey industrial buildings from the progressive collapse, even if they are made of widespread precast concrete structures and have the greatest load from their own weight. A number of engineering decisions are presented for discussion, such as connections with a sliding support, cable sub-truss systems, their fastening units and reinforced anchor units used in roof slabs. The authors consider that the further development of these engineering decisions can overcome the difficulties of protection of single-storey industrial buildings made of precast concrete constructions, for new construction and under reconstruction from the progressive collapse.

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