Simulation of an emergency situation of a digital architecture object

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Abstract. The article considers information modeling an emergency impact in the study of the stability of a digital architecture building to progressive collapse with the help of a local destruction simulator using the finite element method. A non-linear processor was used, the calculations were performed by the step-iterative method with automatic step selection. When calculating a digital architecture building for progressive collapse, a technique in a quasi-static formulation was used. Measures were developed to effectively counter the emergency. Since the placement of stiffness floors in the current regulatory documentation is advisory in nature, the need to install outrigger floors in relation to a digital architecture building was studied. The concept of a building of digital architecture of a complex shape in the plan was developed. To determine the most loaded rod element of the calculation model, the calculation of the frame of a unique building was performed at the stage of normal operation. At the 2nd stage, this element was switched off from work, and a computational model was obtained for simulating an emergency. As a result of a series of numerical experiments, taking into account various scenarios of emergency impact on the frame of a digital architecture building, a constructive scheme of a unique building with outrigger floors was developed. The unique building resulting from shaping will have a low weight skeleton, taking into account the use of innovative materials. The collaboration of digital technologies and innovative materials will allow the construction industry to move to a completely new level of development.
Keywords: modeling, digital architecture, emergency, progressive collapse, finite element method.

1 Introduction

Currently, it is impossible to completely exclude the possibility of emergency situations during the entire life cycle of a building or structure. It is necessary to ensure the safety of people in buildings and the safety of their property by reducing the likelihood of progressive collapse in case of local destruction of load-bearing structures.

In his works, V.O. Almazov considers special issues related to the design of buildings and structures protected from avalanche collapse [1]. The main direction of research is to increase the efficiency of design solutions while ensuring safety in case of progressive collapse [2].

The presented review of the main legislative requirements of technical regulation in the field of ensuring the mechanical safety of buildings and structures made by Travush V.I. is

considered. [3]. As a result of the review, it was found that nowadays the current legislative and regulatory documents do not contain a clear answer to the question of what kind of buildings and structures should be designed to be resistant to progressive collapse [4].

The first versions of the regulatory documentation adhered to the technique of partial force pulldown analysis. The technique assumed modeling in the design scheme instead of the removed load-bearing element with a value equal to the reaction in this element with the opposite sign, multiplied by the dynamic factor. Krasnikova A.E. describes several methods for calculating the coefficients of dynamism according to the norms, including foreign ones [5].

In the latest versions of the design standards, the methodology was corrected and brought to the calculation according to the principle of partial pushdown analysis, which assumes an increase in loads on horizontal structures adjacent to the supporting frame above the removed element using the dynamic factor. It should be noted that the two described approaches are not equivalent in their results (Fig. 1) and the dynamic coefficients used in them are different.

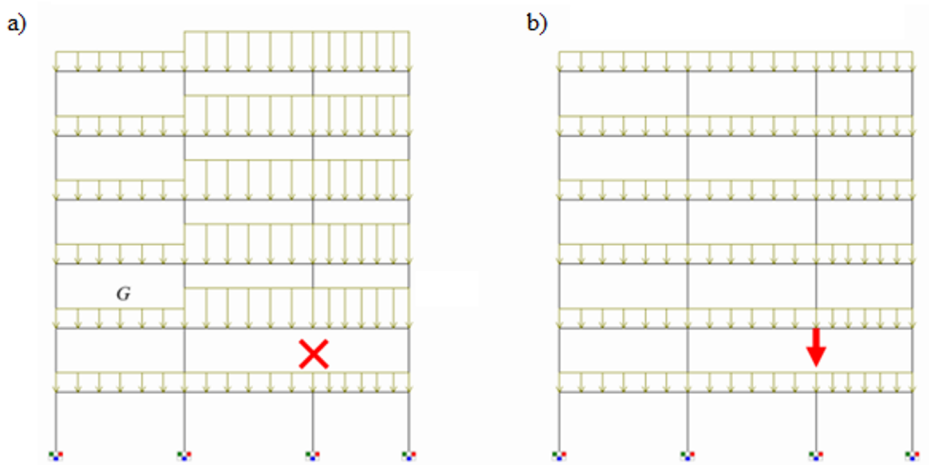

Fig. 1. Visual difference between calculation methods: a) pushdown; b) pulldown

Counteracting the avalanche collapse of a structure involves the use of a number of design solutions that most effectively prevent such a process. The main approaches to the creation of load-bearing structural systems of high-rise buildings of the optimal design scheme are set out in the works of Baranov A.O. The author describes in detail the unique engineering solutions that found their application in construction practice [6].

The possibility of effective operation of a hanging system that occurs during an emergency action, which is accompanied by large deflections of the floors, should be achieved by creating two outrigger floors with beam-wall structures of the radial directions relative to the stiffening core [7].

In view of the large size of the grid of columns and the number of storeys of the building, a constructive solution of a girderless floor was proposed, including capitals of columns (pylons) in the support zones [8-9]. This solution allows the most rational way to reduce the size of the compressed zone of concrete, and, consequently, the coefficient of dynamism of the girderless floor. This will slightly increase the consumption of concrete, but significantly reduce the consumption of reinforcement in the support areas.

The purpose of the study is to calculate the building of parametric architecture for emergency impact with variation and comparison of scenarios of dynamic impact on the structure.

2 Methods

A twisted surface with congruent ellipses in parallel planes is considered as a form that sets an object of parametric architecture. The concept of a unique building was obtained by combining 5 analytical surfaces defined by two parametric equations. The highest part of the building is the central tower, the shape of which degenerates into a cylinder (Fig. 2).

As a load-bearing structural system, a frame-stem scheme using monolithic reinforced concrete structures was chosen as the most optimal solution for the structure [10-11].

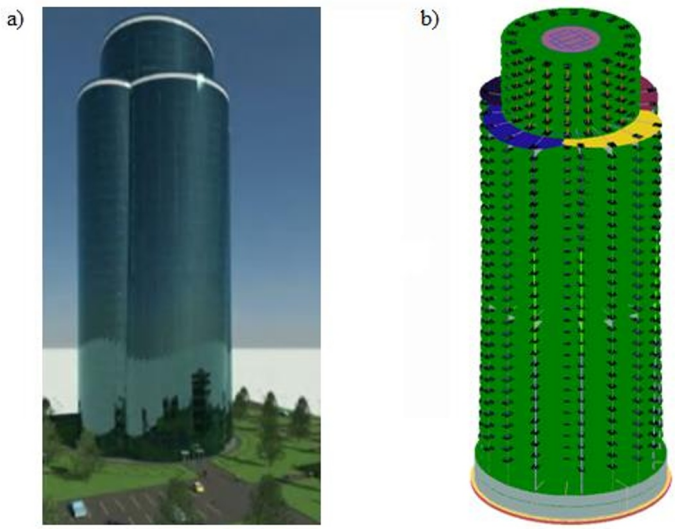

Fig. 2. Studied object: a) visualization; b) finite element model

In the building designed, stability against progressive collapse is ensured by the continuity of a part of the design reinforcement of the main load-bearing structural elements (columns, walls, floors) both horizontally and vertically [12-13]. "Vitality" of the building, i.e. its ability to dissipate energy due to the redistribution of forces is provided by the properties of the reinforcement and the design sections of the elements [14]. Efficient operation of the reinforcement is possible only with sufficient plasticity of the rods under tension in the limit state. For this, it is necessary that, after reaching the maximum force, the rod does not turn off from work, continuing to plastically deform up to an elongation of the order of several millimeters with a non-decreasing tensile force and does not lose adhesion to concrete. Therefore, it is advisable to use reinforcement of strength class A500. This reinforcement has deformations corresponding to the conditional yield strength, exceeding the limiting deformations of concrete during compression, which, with sufficient transverse reinforcement, makes it possible to maintain the stability of the compressed rods in concrete and exclude its premature failure under extreme emergency loads. At the same time, high reliability of the reinforcement anchoring in the places of its breakage or joining, especially in the supporting and middle span sections, that is, in the zones of maximum bending moments or shear forces, should be ensured. The most effective method is the continuous reinforcement of reinforced concrete statically indeterminate elements, in particular, slabs.

At the first stage of the study, the building is calculated for static loads, the geometric parameters of the sections of the load-bearing elements and their reinforcement are determined, which is necessary to fulfill the requirements of I and II limit states.

At the 2nd stage, the strength of the load-bearing elements of the building is calculated for various options for the destruction of structures, taking into account the dynamic nature

of the loading. Measures are determined to ensure the load-bearing capacity of structures in order to prevent their progressive destruction. The essence of the calculation lies in the fact that for each variant of possible destruction of structures, the strength of the elements of the damaged frame must be ensured, and, consequently, progressive destruction is excluded under the action of an equivalent static load. For structures designed for the action of emergency dynamic loads, only the limit state is established to ensure the safety of the structure from loss of load-bearing capacity. In this case, significant residual deformations and local destruction can be allowed with the overall integrity of the frame [15].

The LIRA-SAPR software package makes it possible to successfully solve dynamic problems in an elastic formulation, and to evaluate the dynamic effect in structural calculations. It is advisable to use the dynamic coefficient, which takes into account the degree of plastic deformation of structures [16]. To calculate the emergency impact, a refined finite element scheme is created on the basis of the existing one. According to the above provisions of the calculation, in the parameters of reinforced concrete structures for all elements, the requirement to conduct calculations for the limit states of group II is disabled.

According to the requirements of regulatory documentation, the calculated strength characteristics of materials are taken equal to their standard values, and the values of deformation limitation on the diagrams of the stages of concrete and reinforcement work are corrected.

It is important to take into account the stages of erection of a structure in order to more correctly take into account the accumulation of stresses and deformations of structures [17]. Therefore, in the quasi-static approach, a special “installation” system is used, which allows to take into account this condition by creating installation stages that simulate the sequential erection of a structure and further additional loading of the structure, which already has initial deformations from the own weight of the erected structures, with useful and operational loads.

At stages 1-7, the sequential erection of the structure was modeled. On fig. 3, the elements under construction at the current stage are marked in red: the underground part of the structure and further blocks of six floors.

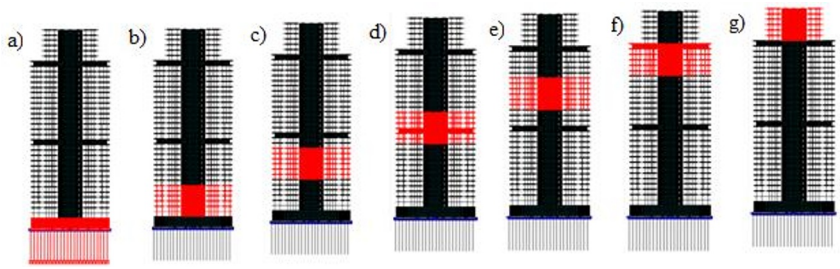

Fig. 3. Building erection stages: a) stage 1; b) stage 2; c) stage 3; d) stage 4; e) stage 5; e) stage 6; g) stage 7

Stages 8-14 are the application of loads acting on the structure. In stage 15, the failure of a supporting element or a group of such elements is modeled, the destruction of which is most likely or will bear the most adverse consequences.

According to the instructions of the regulatory documentation, the calculation of the protection of buildings and structures from progressive collapse should be performed for a special combination of loads, including permanent and long-term temporary loads, including reduced values of short-term loads, taking into account changes in the design scheme of the building and structure as a result of local destruction.

In the rules for choosing the element which failure will have the most fatal effect on the structure, they are reduced to general recommendations and the fact that each building has

its own unique set of possible failure scenarios. Therefore, the choice of the element or group of such elements to be removed largely remains with the designer.

In the study, at the first iteration, the failure of the most loaded element of the structure was simulated. The calculation was performed without dismantling assignment to one of the elements of the design scheme in stage 15, and the analysis of the stress-strain state of the structure and its individual parts was performed. Thus, the most loaded column of the 1st floor with a section of 600x1400 with a force of 1643 tons was chosen as the subsequently destroyed element (Fig. 4 a).

At the next iteration, the object of analysis is the column, which in the scheme is the point of support of the slab in the section of the largest span of 11.9 m. There are 8 such frame elements on each floor. Of these, the most loaded is selected by analogy with the first iteration. Thus, a column of the 1st floor with a section of 500x1150 was marked, the force in which was 1250 tons (Fig. 4 b).

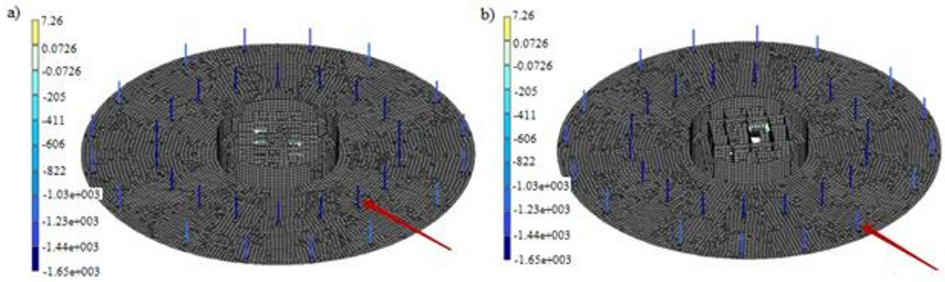

Fig. 4. Forces in the columns of the 1st floor at the installation stage 14: a) iteration 1; b) iteration 2

3 Results

The primary assessment is carried out according to the values of vertical deformations for the slab of the 2nd floor (Fig. 5).

An analysis of the calculation results showed that the relative deformation of the slab was 36.7 mm, which does not exceed the normalized values [18]. Therefore, in the event of the exit of the specified column from the working state, the nearest load-bearing elements of the structural system will be able to fully absorb the loads and will not allow the avalanche collapse of the load-bearing elements of the building.

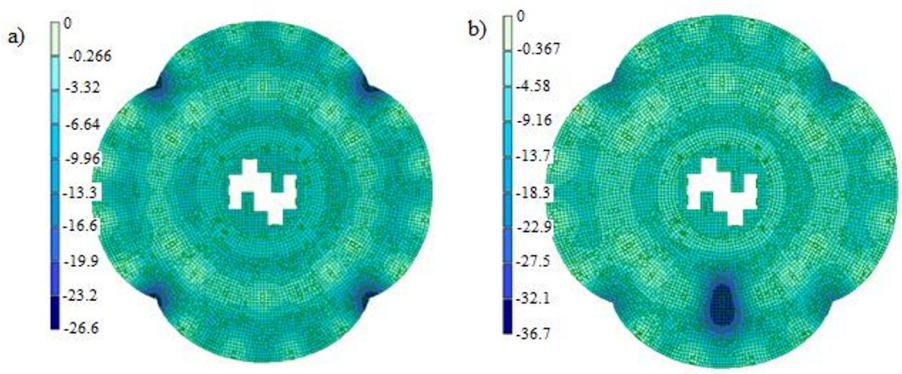

Fig. 5. Isofields of deflections of the slab of the 2nd floor: a) stage 14; b) stage 15

The most loaded column in stage 15 is indicated as dismantled, and the calculation is performed again, followed by an assessment of the consequences of removing the designated element from work.

The deflections of the slab at the pre-dismantling stage are completely similar to the values of iteration 1 and amount to 26.6 mm, and at the critical stage in the zone with the "destroyed" column they grow to a value of 71.3 mm (Fig. 6a). This value is several times higher than the maximum allowable deflection, and, obviously, the requirements of the II limit state are no longer met. But the magnitude of the stresses arising in it does not exceed those that can be perceived by the working reinforcement in the stage of plastic deformation, therefore, the requirement for a state of limited performance under conditions of progressive collapse is met.

It is appropriate to simultaneously evaluate the effectiveness of outrigger structures and the degree of their influence on the indicators of the stress-strain state of the system [19]. The value of vertical deformations after the removal of the load-bearing element was taken as a parameter for evaluation, since comparative information has already been accumulated about this parameter, and such an analysis will be the most illustrative. The values of this parameter in the circuit without an outrigger are shown in Fig. 6b.

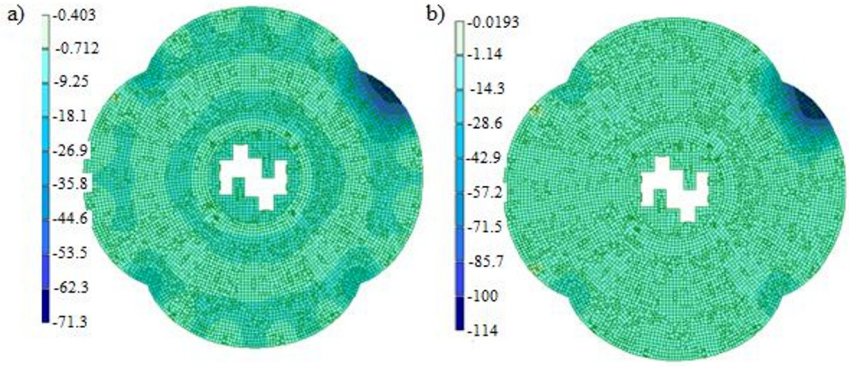

Fig. 6. Deflection isofields of the slab of the 2nd floor: a) stage 15; b) stage 15 in the scheme without outriggers

The slab deflections in this case reached 114 mm. Thus, the use of two outriggers in the scheme makes it possible to reduce the deflections of the most deformable floor by 37.8% in the event of the above scenario of emergency action.

Let us consider how the redistribution of forces in schemes with different design affects the reactions in columns [20]. In the scheme without an outrigger, after the "destruction" of a column of a larger radius, the maximum force reaches a value of 2180 tons and falls on one column (Fig. 7 a). In the scheme with two outrigger levels, the redistribution of forces occurs more evenly, and the maximum force occurs in two columns near the source with a value of 1970 t (Fig. 7 b).

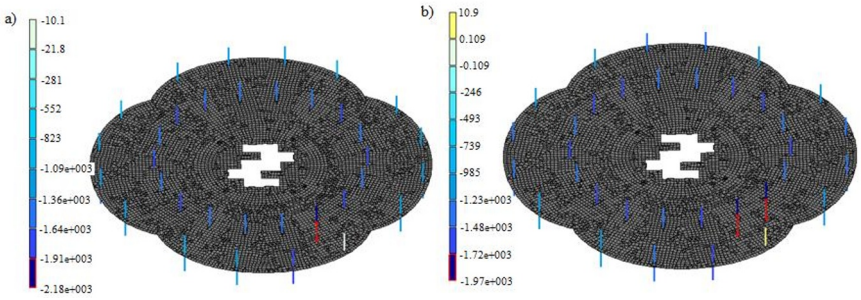

Fig. 7. Forces in columns after dismantling: a) in the scheme without outriggers; b) in a scheme with outriggers

4 Discussion

The load-bearing element above the “destroyed” column in Fig. 7a remained compressed and did not change the sign of the resulting internal forces. This indicates not the most correct operation of the circuit and raises questions. And in the circuit in Fig. 7b, such an element is stretched and there are no doubts about the correct operation of the circuit. Obviously, the structure in the area above the indicated element works like a suspension, which is completely logical in the conditions of the described progressive collapse scenario.

5 Conclusions

A technique for calculating a building for progressive collapse in a quasi-static setting in LIRA-SAPR with subsequent modeling and analysis of various scenarios for the destruction of the supporting structures of the 1st floor was studied. The effect of outrigger structures on counteracting progressive collapse was studied.

The results of the conducted studies showed that the structures of the building of the multifunctional complex fully meet the requirements of the I and II limit state and the parameters of the dynamic comfort of people's stay. The structure is safe from the point of view of the possibility of an emergency, accompanied by partial destruction of the load-bearing structures, and the evacuation of people. According to the tested scenarios, it was concluded that the building resists the avalanche collapse, and its structures are included in critical operating modes and form a "suspension" scheme. Practical recommendations for the design of parametric architecture objects were developed, including a method for a rational way of combining analytical surfaces in a concept.

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