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# Structural system collapse risk limitation strategy

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This article presents a general strategy for limiting the structural system risk collapse a using the real construction object example. In the course of the work, an analysis of possible accident scenarios at a construction site was carried out. A statistical data analysis is presented to create the most systematic method for the possible accident scenario in construction. The article presents the calculations results of the building frame spatial model for progressive structure destruction to determine the accident possibility. When changing the monolithic floor geometry and removing the columns, the failure probability of the supporting structures and the consequences to which this accident could lead were considered. Also, in this work, the economic consequences question is raised. The scheme calculation result is presented and the corresponding conclusions are drawn

**Keywords:** statistics, modeling, accident, building, probability of an accident, destruction, consequences, systematization

# Стратегія обмеження ризику обвалення конструктивної системи

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Наведено загальну стратегію обмеження ризику обвалення конструктивної системи на прикладі реального будівельного об'єкта. Проаналізовано різноманітні підходи до розрахунку можливості виникнення аварії або, іншими словами, ймовірності відмови тієї чи іншої конструкції. Надано результати розрахунку виникнення можливої відмови конструкції будівельного об'єкта на прикладі створеної моделі. У ході роботи був проведений аналіз сценаріїв можливого виникнення аварії на будівельному об'єкті. Виділяються й описуються характерні особливості найбільш систематизованого алгоритму сценарію можливого виникнення аварії в будівництві, для якого має велике значення збір даних про аварії, що виникли, їх систематизація та осмислення, тому що подібна практика збільшує шанси на безаварійне будівництво. Значну увагу приділено підходу до опису аварії, який може бути розглянутий із її вірогідності. Надано класифікацію аварій за ймовірністю їх виникнення. Розрахунок ризиків прогресуючого обвалення розглядався при певному переліку загроз. Наведено результати розрахунків просторової моделі каркаса будівлі на прогресуюче руйнування конструкції для визначення можливості виникнення аварії. При зміні геометрії монолітного перекриття та вилученні окремих колон розглядалася ймовірність відмови несучих конструкцій і наслідки, до яких така аварія може призвести. У результаті чисельного моделювання отримано якісну оцінку характеристик стійкості конструкції стосовно прогресуючого руйнування. Розглянуто найпростішу схему конструкції будівлі, за якою відома ймовірність відмови об'єкта. Для підрахунку можливих матеріальних збитків і (або) соціальних втрат від відмови об'єкта, пов'язаних із припиненням експлуатації чи втратою його цілісності, визначалися найбільш імовірні прогнози можливої аварії, що сталася з техногенних або природних причин.

**Ключові слова:** статистика, моделювання, аварія, будівля, імовірність аварії, руйнування, наслідки, систематизація

## Introduction

Nowadays, the failure probability calculation and predicting accidents at the construction site design stage is being introduced with government regulations in developing countries. This fact makes it clear the need to develop an appropriate methodology in this matter. Studying the historical experience of creating various algorithms types, it is necessary, in turn, to improve them. The reasons for this are the technical and informational development of the construction industry as a whole, the increase in the complexity of engineering tasks, the concept renewal of architectural forms and buildings purposes. [1].

In connection with the approaches spread to predicting the construction objects accidents in the design documentation, various approaches are being created to the development and situation modeling building fail individual structural elements. The main task at the moment is to create an algorithm for modeling and calculating such emergency situations and the creation of uniform building codes on this issue.

## Review of the research sources and publications

Speaking about the accidents analysis in construction, it is worth noting such scientists as Belyaev B.I. [2], Laschenko M.N. [3], Sakhnovsky M.M. [4], Shkinov F.N. [5], Perelmuter A.V. [6] and other authors, who in turn also paid considerable attention to the accident statistics development and tried to classify them. For example, a fairly detailed accidents statistic for 2009 was presented in the Eremin K.I. work [7]. The accident possibility calculation, or in other words, the particular structure failure probability, was carried out by such scientists as Raiser V.D. [8, 9], Pichugin S.F. [10 11], Semko A.V., Voskoboynik O.P. [12] and others [13].

Stewart M.G., Melchers R.E. dealt with an engineering system probabilistic risk assessment issues [14]. Milchers R.E in his works raised the reliability and forecasting analysis issue in the construction industry [15]. It is also advisable to pay attention to the works of such scientists as Ellingwood B.R., Smilowitz R., Dusenberry D., Duthinh D. [1] in whose works the buildings progressive destruction issue was raised.

A striking example of the legal basis creation for calculating progressive collapse is the first rules set edition, entitled “Protection of buildings and structures from progressive collapse. Design rules [16].

## Definition of unsolved aspects of the problem

To date, an important issue is the development of a methodology and algorithm for analyzing the predicting probability the accident possibility in construction.

## Problem statement

The work purpose is to determine a general strategy for limiting the danger (risk) of structural system collapse, to reveal the concept of a possible accident scenario at a construction site and to calculate the possible failure occurrence of a construction site using the created model example.

## Basic material and results

*General strategy for limiting the hazard (risk) of structural system collapse*

When designing in construction, an important factor after the structure reliability is its financial side of the issue, that is, the direct construction cost. Ensuring structural reliability must be provided by cost-effective design solutions. In order to the costs invested in the structure safety to be justified, a risk assessment should be carried out, the magnitude of depends on the failure probability and its consequences. Thus, risk analysis consists of two independent tasks: determining the failure probability and assessing its consequences.

Calculating the risks associated with the structural system collapse, in particular when exposed to special (abnormal) influences, the most difficult in all respects life and health valuation of people exposed to potential threats.

The progressive collapse risks calculation is considered with a certain threats list, including in the general case:

1) pathological, special effects (natural or errors in design and construction);

2) violation of operation;

3) object crashes.

The general strategy for limiting the danger (risk) of the structural system progressive collapse should contain the following stages:

1) risk assessment and probabilistic formulation of structural criteria (for example, the structural elements destruction probability is allowed);

2) impact damage characteristics;

3) strategy development to limit threats from special impacts;

4) implementation in professional practice.

As can be seen from the general strategy description for limiting the structural system progressive collapse danger, the first and one of the main strategy elements is the risk assessment and, accordingly, the probabilistic structural criteria formulation for further calculation.

*The concept of the possible accident scenario at the construction site*

To calculate the possible material losses and (or) social losses from the facility associated refusal with the operation termination or with the integrity loss, the most probable predictions of a possible accident are determined (for example, damage, failure, building destruction, structure, linear engineering and transportation facility, infrastructure or their parts) that occurred due to man-made or natural causes. Potential losses are assessed based on the predicted accident scenario, taking into account the measures provided for by the project to localize a possible accident (for example, dividing the construction object into separate parts).

It is recommended to consider the possibility of the following events, for example:

- failure and destruction of a separate supporting structure due to its overload in excess of combinations loads and effects;
- the occurrence of soil foundations large subsidence during their emergency soaking;

- the possible karst sinkhole impact, landslides, etc .;
- the impacts from vehicles collisions;
- the structures failure possibility in the fire event;
- damage to building structures by accidental explosions (for example, household gas);
- the technological regulations violation possibility or damage to equipment (pipeline ruptures, falling loads, others for design impacts) [10].

For s high-rise apartment buildings and structure, the hypothetical collapses listed in clause E.1.2 of DBN V.2.2-24:2009 should be considered as initiating events [17].

Potential social losses from abandonment should be weighed against risk factors such as:
- danger to people health and life;
- a sharp ecological situation deterioration in the territory adjacent to the object (for example, when the storage of toxic liquids or gases is destroyed, the sewerage treatment facilities fail, etc.);
- history and culture monuments loss or other spiritual society values;
- termination of the communication systems and networks functioning, power supply, transport or other elements of population or public safety life support;
- impossibility to organize assistance to accidents and natural disasters victims;
- the threat to the country's defense.

Possible economic losses should be assessed by the costs associated with both the need to restore the facility and with incidental losses (losses from stopping production, lost profits, etc.).

The possible consequences characteristics are the basis for the construction objects classification according to three consequences (responsibility)classes – CC1, CC2 and CC3.

When calculating structures, the following design situations types should be considered:
- established, for which the implementation duration of Tsit is the same order as the established service life of the construction site Tef (for example, the operation period between two major repairs or changes in the technological process);
- transitional, for which the implementation duration Tsit is small compared to the established service life Tef (for example, the object construction period, major repairs, reconstruction);
- emergency, which is characterized by a low probability of Psit occurrence and, as a rule, a short duration of Tsit << Tef implementation, but which are quite important from the point of view of the possible failures consequences (for example, situations that arise during explosions, fires, equipment failures, collisions vehicles, as well as immediately after the any structural element failure). [10].

*Construction accident statistics*

To create the most systematic method for the possible accident scenario in construction, it is of great importance to collect data on accidents that have occurred, their systematization and understanding, since this practice increases the chances of accident-free construction.

Without pretending to cover the problem as a whole, we can single out the most common buildings destruction cases, as: engineers' errors in calculations; builders' negligence in the facility construction, misuse or improper reconstruction, the incidence of which has increased significantly over the past few years.

A sudden collapse leads to a prolonged the building failure, the fires outbreak, the utilities and energy networks destruction, the blockages formation, injury and people death [18].

Using the example of India, we can give the corresponding figures for the statistics of construction accidents victims. India's National Crime Bureau (NCRB) data indicate that between 2001 and 2015, 38,363 people died in the destruction of various buildings. Most of the people died as a result of the residential buildings collapse. Uttar Pradesh recorded the largest number of deaths during this period (5690) [19].

Accidents should also be divided by the class of consequences, in accordance with the National Standard of Ukraine [20]. Taking into account the conducted research, the most common structures accidents can be considered objects with the class of consequences CC2, including residential buildings with the number of people who are constantly in the building, up to 400 people.

The methodology for collecting, processing and presenting statistical information is an almost independent section of probabilistic calculation methods (for example, the theory of building elements reliability and systems). In this case, the theory should specifically determine the quality and quantity of information required for practical use in calculations.

The building materials properties and elements can be represented by parametric distribution laws. This assumption can be substantiated by the fact that the materials and structures properties do not change significantly over time and, as a rule, have a corresponding tendency. The foregoing should be understood in such a way that possible changes in properties are, as a rule, not random in nature, only the numerical value of this property has a random character.

The next part of the statistical information processing is a more detailed division of the resulting general table by the objects type that have collapsed. For example, the accidents types can be divided into three components: buildings and structures destruction at the stage of construction and acceptance into operation, during reconstruction of facilities and accidents due to the large building age. The classification based on these characteristics is due to the high level of their frequency in the course of the issue study, from which it follows that the appearance of such an accident is the highest.

On the research basis carried out, graphs and diagrams are created that reflect the results obtained, on which final conclusions are already drawn.

An example of generalized data processing is the annual accidents statistics created by the Russian company "City Center for Expertise". A work feature of this company is its transparency and results publicity. The statistics provided over the past few years are freely available on the Internet, with the components of which anyone can get acquainted. At the same time, citizens do not have access to official statistics, which are kept by government. Based on this, there is a need to address the issue of transparency in the commission's work the for the accident investigation in buildings and structures.

The possibility of providing public information can be a significant step in resolving the accidents issues that occurred during the construction phase, since the incidents publicity and the work results carried out by a special commission will become a great impetus for the certain accidents type elimination.

In addition, the statistical data processing on accidents at construction sites makes us pay attention to the problem of old buildings that are being decommissioned but not dismantled in the future. Most often, the authorities do not pay attention to their accident rate and the highest collapse probability. Long-term dismantling, and in most cases, its complete absence, can result in human lives.

If until sometime the accident was considered as a probabilistic event that has no regularity, and the results of which cannot be predicted, then at the present stage scientists have made a tangible breakthrough in this knowledge area. With the concepts introduction such as economic and non-economic consequences, the development and implementation of possible losses calculations, depending on the particular structure failure, begins.

The approach to describing an accident can be considered with its probability. That is, an accident can be probable, impossible, or accidental (Fig. 1).

Let us give examples of situations in which an accident is probable. In this case, this is an accident that occurred near the city of Mumbai, April 6, 2016 [21]. The seven-story residential building collapse provoked a number of reasons, such as construction standards violation, negligence during construction, and the construction work illegality. The occurrence probability was the highest in this case.

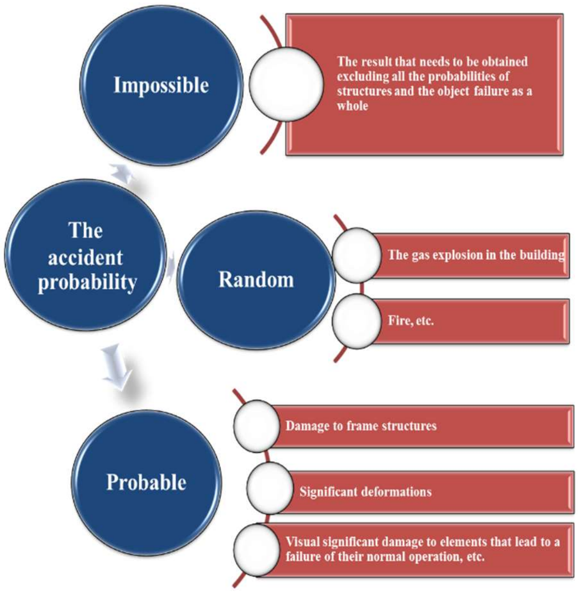


**Figure 1 – Classification of accidents with the probability of their occurrence**

Accidental accidents include a gas explosion in a residential building in Brussels, which took place on March 18, 2017, as a result of which one person died [22]. One building collapsed completely, only the facade remained from the other. Or the fire that happened on February 21, 2015 in the UAE, where the high building "Torch" lit up [23]. No harm done.

The result of the accidents analysis that occurred in construction should be the accident impossibility. A striking example of the past years' experience processing, the implementation of the necessary improvements and prevention of various accidents types is the modern complex "Federation", which consists of two skyscrapers with a height of 324 meters [8].

*Constructive solution and calculation of a construction object*

For a more detailed consideration of the modeling possible accident occurrence issue, we will calculate a real construction object, namely, an industrial building (fig. 2).

The frame design was carried out by the finite element method, taking into account the following provisions:

a) introduction of three-line deformation diagrams for concrete and two-line diagrams for reinforcement;

b) the frame structure is considered as a system of frames with rigid nodes, which are located in two mutually perpendicular directions;

c) the non-girder floor structure was calculated for the load, evenly distributed over the entire floor or part of it;

d) the structures were calculated for strength, deformability and crack opening under the static load action.

The structure design model has been created and is shown in Fig 3.

*Relying on progressive destruction*

In the building structures calculating for progressive destruction in the LIRA software package, the following calculation stages were implemented [24]:

1) performed linear calculation with the determination of the frame deformation (Fig. 4);

2) exclusion from work in the structural scheme of individual load-bearing elements (columns 10, 11, 15), the calculation of the scheme, as a result of which reinforcement is assigned for the model calculation in the non-linear phase;

3) the building calculation taking into account physical and geometric nonlinearity and dynamic coefficient.

It should be noted that at the third calculation stage, the criteria for the structures destruction are the geometric system variability at the nth step, an avalanche-like growth of deformations and the system displacement.

To determine the most dangerous structure section in the spatial building model, the number and location of supporting structures (columns) were experimentally changed (Fig. 5–7).

When the K-15 column was removed from the general scheme, the deformation frame calculation was carried out again. The calculation result is shown in Fig.5.

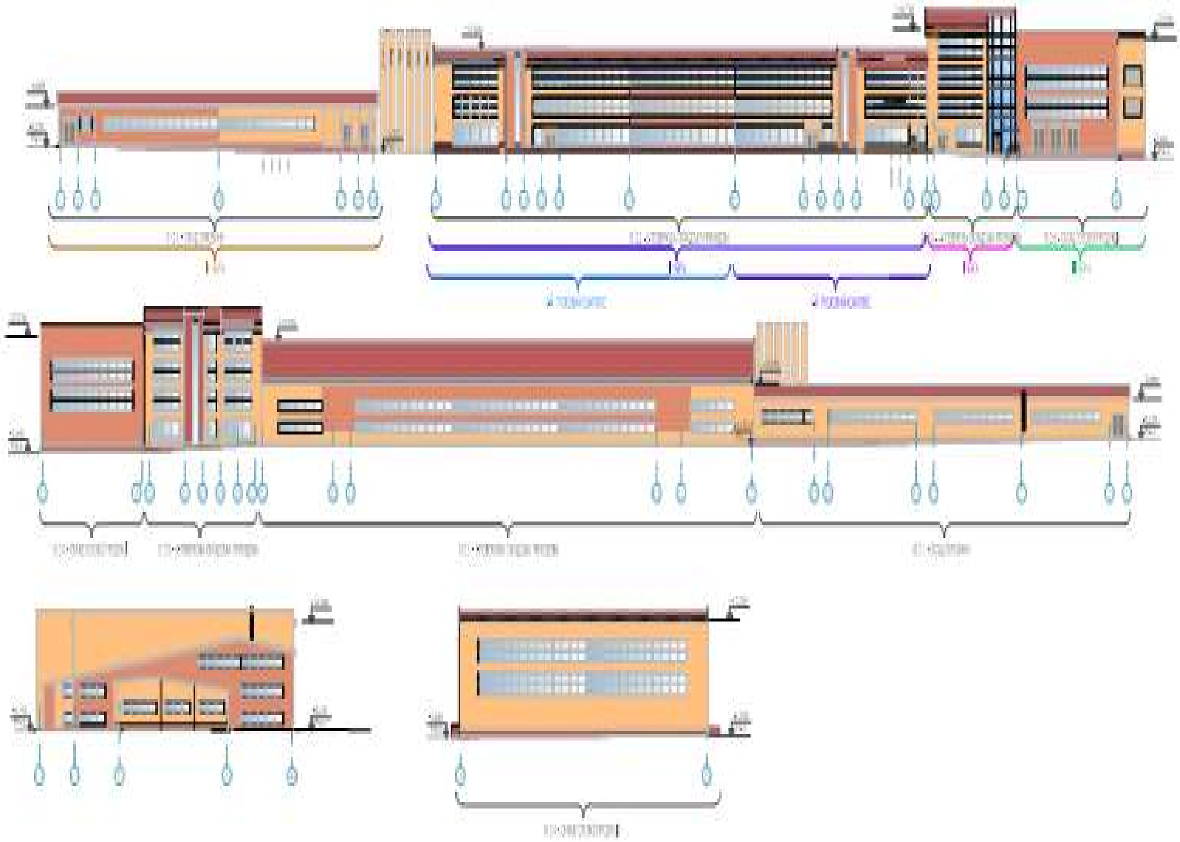

**Figure 2 – Factory buildings facades**

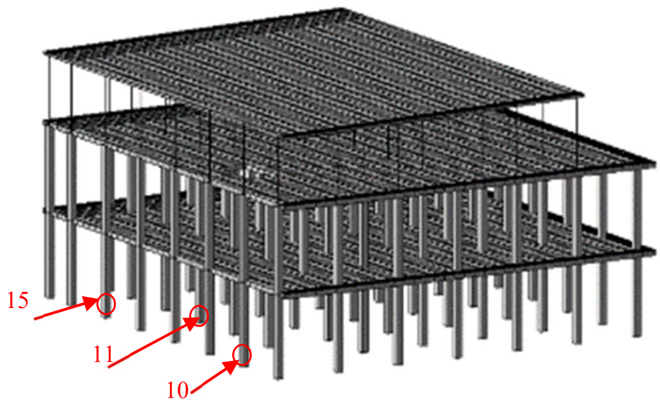


**Figure 3 – The design model of the designed structure, with the given structural elements**

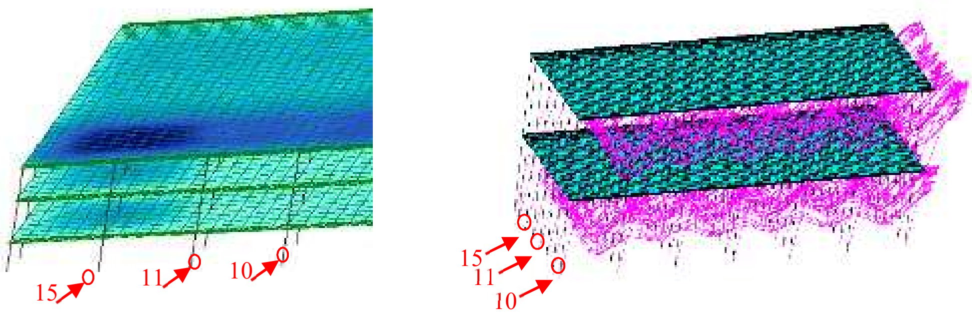


**Figure 4 – Results of building deformation analysis**

A similar frame calculation for deformation was performed when the column K-10 (Fig.6).

Also, the calculation of the frame was carried out when the middle column K-11 was excluded from the work, which made it possible to carry out further analysis of the progressive failure effect on the structure (Fig. 7).

Situations were also checked when changing the solid floor geometry, by removing the structure timewattle (Fig. 8).

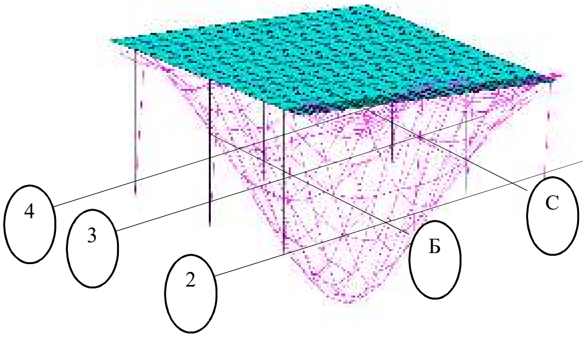


**Figure 5 – The frame calculation result on deformation with the decommissioning of the middle column K-15**

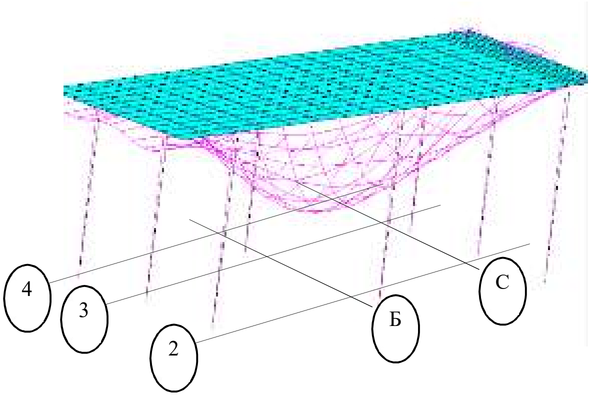


**Figure 6 – The result of calculating the frame on deformation with the decommissioning of the second row column K-10**

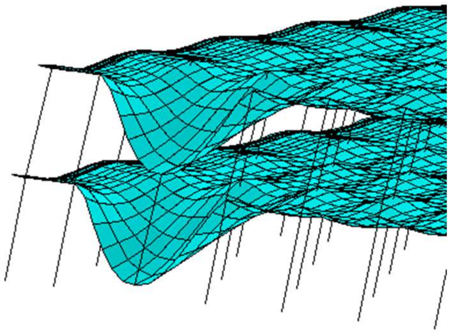

**Figure 7 – The result of the calculation of the frame on deformation with the decommissioning of the extreme column K-11**

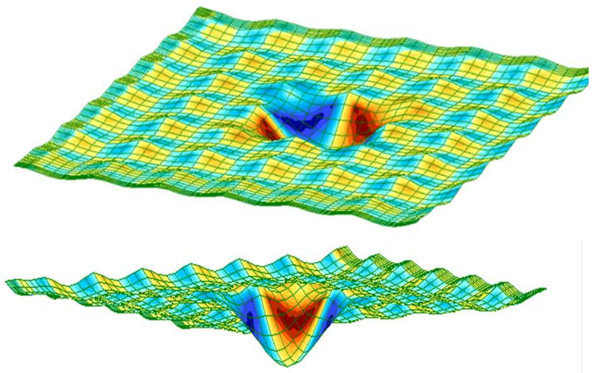

**Figure 8 – The results of the design calculation in the accident simulation - removal of the K-15 column (Isofield of stresses on moss)**

**Conclusions**

The prerequisites for the implementation of the methodology and algorithm for modeling the accident possibility at a high-risk construction site gave impetus to the development of such a direction in the scientific activity of the construction industry as predicting the progressive structures destruction.

It is important to take into account that the calculation progressive destruction risks directly considers a number of threats, among which it is advisable to single out the main ones, such as abnormal ones, violations in operation and failures of a construction facility.

At the same time, the main task for our time is to determine the main strategy for limiting the risk of a particular accident.

As a numerical modeling result, it is possible to obtain a qualitative characteristics assessment of the structure stability in relation to progressive destruction, as well as to compare several possible scenarios of destruction in order to identify the weak structure points.

The calculation result is the forces, stresses and displacements at each of the load application stages, cracks patterns in walls and slabs, places of plastic hinges occurrence, information about the elements that are destroyed in the first place. It is also possible to determine the load at which the first structural element collapses and from it to conclude the available reserves in bearing capacity terms.

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