Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: Sergii Pichugin *et al* 2026 *J. Phys.: Conf. Ser.* **3251** 012045

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Modeling Potential Construction Failures: An Algorithmic Method to Increase Project Reliability

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Abstract. The study presents a methodology for increasing the reliability of construction projects by developing and applying an algorithm for modeling possible accident occurrences. The research is based on a comprehensive statistical analysis of construction accidents from 2000 to 2022, identifying the most frequent causes and patterns of failures. The developed algorithm allows simulation of accident scenarios at different design and operational stages of a building, distinguishing three levels of modeling significance. The methodology was tested on a multi-storey industrial building using GSA standards. The analysis demonstrated that the proposed approach effectively identifies critical structural elements and potential failure scenarios, enabling preventive design measures. **The practical significance of this work lies in its ability to provide engineers and designers with a reliable tool for predicting and preventing failures in construction projects, thereby improving structural safety and reducing economic losses.** The results confirm the algorithm's applicability as a practical tool for enhancing safety and robustness of building structures.

1. Introduction

Review of the latest research sources and publications. The work complexity is reflected in the need to use different types of research approaches. An important strategy in the modeling algorithm creation was the combination of an accident database statistical study with studies: accidents cause models in general, as in the example of works [1], risk strategies [2,3] and progressive destruction possibility research [4,5].

Definition of unsolved aspects of the problem. The study of buildings and structures accidents in modern times makes it possible to single out the previously unresearched issue of developing scenarios of buildings and structures accidents based on real examples. The importance of such research appears in the development of a methodology for the destruction scenarios creation with the possibility of conducting a corresponding structure analysis. This work presents an example of the developed methodology implementation with the aim of its future use by engineers and builders.

Problem statement. The purpose of the work is to present an example of the algorithm implementation for modeling the possible building and construction accident occurrence, for use by engineers and designers at the construction stage.

2. Prerequisites for creating an algorithm

The algorithm for modeling the possible occurrence of a building and construction accident is an algorithm that is recommended for implementation by design engineers at the stage of developing a working project of a new building, or to check the reliability of an existing one.

This algorithm is a step-by-step list of possible failure scenarios recommended for implementation in the volumetric space of the corresponding model type of building and its responsibility class. Failure scenarios are modelled at different stages of building operation.

Prerequisites for creation the increasing construction objects reliability concept were served by quite a number of factors of civil construction development in the industrial and scientific sectors in general.

The basis of the destruction models analysis is the principle of studying the frame progressive destruction. Such a concept as progressive destruction is quite common in implementation in present. And after the United States developed an official regulatory document in 2000 on preventing the possibility of progressive destruction, this strategy began to be mandatory [6].

At the moment, the regulatory documents of the GSA [7] are the fundamental basis for performing such inspections for buildings of increased responsibility level of public and government facilities. Design considering the prevention of progressive destruction is carried out all over the world for skyscrapers, unique high-rise buildings that pose a high risk in the event of failures in the operation of the frame structures with significant economic and non-economic consequences [8].

The concept of progressive destruction is characterized by the occurrence of such destructions, when one element failure of the frame causes occurring a chain of failures according to the "house of cards" principle, resulting in an avalanche-like destruction. The danger of such destruction was reflected in the terrible events of September 11, 2001 [9]. It was after the infamous catastrophe of the destruction of skyscrapers that this concept arose, and active scientific development began, the result of which were implemented GSA norms.

Progressive destruction remains a relevant issue for further research in the scientific field today. This is justified by the difficulty in researching such destruction, for which the time factor is important, which must also be taken into account when modeling such failures. There is also a difficulty in interpreting the dependence of elements on each other in conditions of operation outside the limit states. But the peculiarity of the rapid development of building design and projecting concepts, unique solutions and extraordinary approaches to their implementation, the appearance of a significant number of modern structures, materials, frames in general - force the development of new approaches to ensuring the reliability of buildings and structures that could complement already existing concepts.

3. Database of accidents and structures

Existing approaches and developments in the issue of progressive destruction are widely applicable to multi-story public buildings with a high level of responsibility (skyscrapers) [10]. For such buildings, the main simulation scenario is to check the operation of the frame in the event of a terrorist act (explosion). This scenario is developed and implemented with further study of the building's frame, and if as a result, the building is able to resist progressive regulation in all parameters, the project is approved.

If to look at construction accidents in general? What can be said about the destruction dynamics over the last century? Which accidents continue to occur year after year with significant consequences?

That is why we decided to collect the material of building and construction accidents in the 21st century with their further statistical research. In [11], the main strategy for collecting material is presented, which is shown in the form of a block diagram in Figure 1.

If at first we used the examples of scientific predecessors to classify the database, then with the increase of the processed material there was an obvious opportunity to significantly expand the classifiers. Thus, the general database represents information with the following classifiers shown in Figure 2.3 in the form of a block diagram [12].

In the future, the study of accidents according to these classifiers will become the basis for creating an algorithm for modeling the possible occurrence of a building or construction accident.

Step 1. Collection of information	**Step 2. Accidents classification**	**Step 3. Marking accidents by type**	**Step 4. Statistical analysis**
• buildings and structures accidents collection • accidents database creation by time of occurrence, country, cause of the accident, number of victims	• buildings and tructuresaccidents classification according to the work period of construction • accident research by construction type, causes and consequences	• at the stage of operation • by building type • by cause of the accident • by type of destruction	• creating graphs and charts based on the database • statistical calculation ofaccident probability

Figure 1. Analytical data processing stages of buildings and structures accident statistics.

4. Statistical study of buildings and structures accidents for the years 2000-2022

The analysis showed that the highest percentage of accidents occurs at the stage of construction and acceptance in the operation (54%) for residential multistory buildings (55%), which is mostly caused by non-compliance with construction standards (50%) (violation of safety rules, designers mistakes, conducting illegal construction and using low-quality materials).

The analysis of buildings and structures made it possible to identify the most widespread destruction of buildings and structures. These include non-observance of norms during construction 39% (namely, mistakes of builders 46%, illegal construction 17%, use of unsuitable material or its saving 23% and non-observance of safety techniques for construction and assembly work 14%), errors about - construction workers 7%, incorrect operation 28%, incorrect

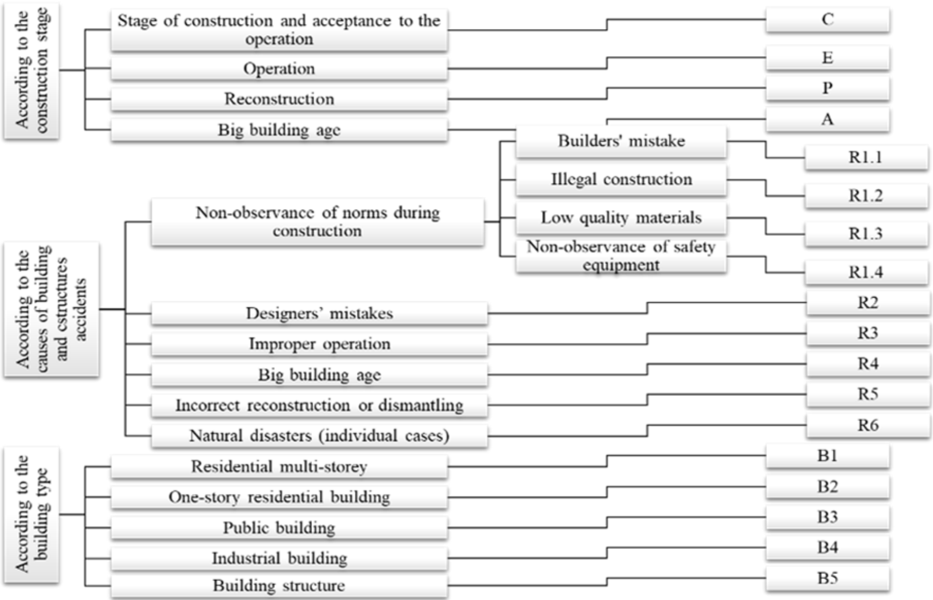

Figure 2. Classification table of the buildings and structures accidents general database.

reconstruction and/or dismantling 11% and accidents due to the old age of the object (non-observance of the period of operation, untimely examination and reconstruction) 13%.

Accidents at the stage of construction and acceptance in operation of a building or structure have a fairly comprehensive list of scenarios, which are connected by the main factor - industrial errors. That is, all possible accident scenarios are based on one or another professional error. Such an explanation is obvious, but no less important for research. Thus, work [13] provides an analysis of the interconnection between accidents at the construction stage and the country where the incident occurred, as well as general information about the tendency of similar destructions to occur over the years.

The given analysis includes not only building accidents of different responsibility levels, but also the building accidents possibility. Special attention in the analysis was paid to such buildings as stadiums and reservoirs. The scenarios of steel vertical tanks destruction are developed and presented in the algorithm on the basis of previous studies [13].

As a result of the analysis, it is interesting to note the following:

A review of documented structural failures indicates that the majority of progressive collapse events involve multi-storey residential buildings, which account for slightly more than half of all recorded cases (approximately 51%). Despite the fact that regulatory frameworks primarily emphasize safety measures for public facilities, these structures also represent a considerable proportion of incidents — around 24%. At the same time, residential buildings appear to remain comparatively underregulated and, according to the analyzed data, require enhanced safety measures and stricter design provisions.

It is also noteworthy that failures caused by the loss of load-bearing capacity in structural columns constitute only about 1% of all reported incidents, indicating that such causes play a relatively minor role in the overall statistics of progressive collapse.

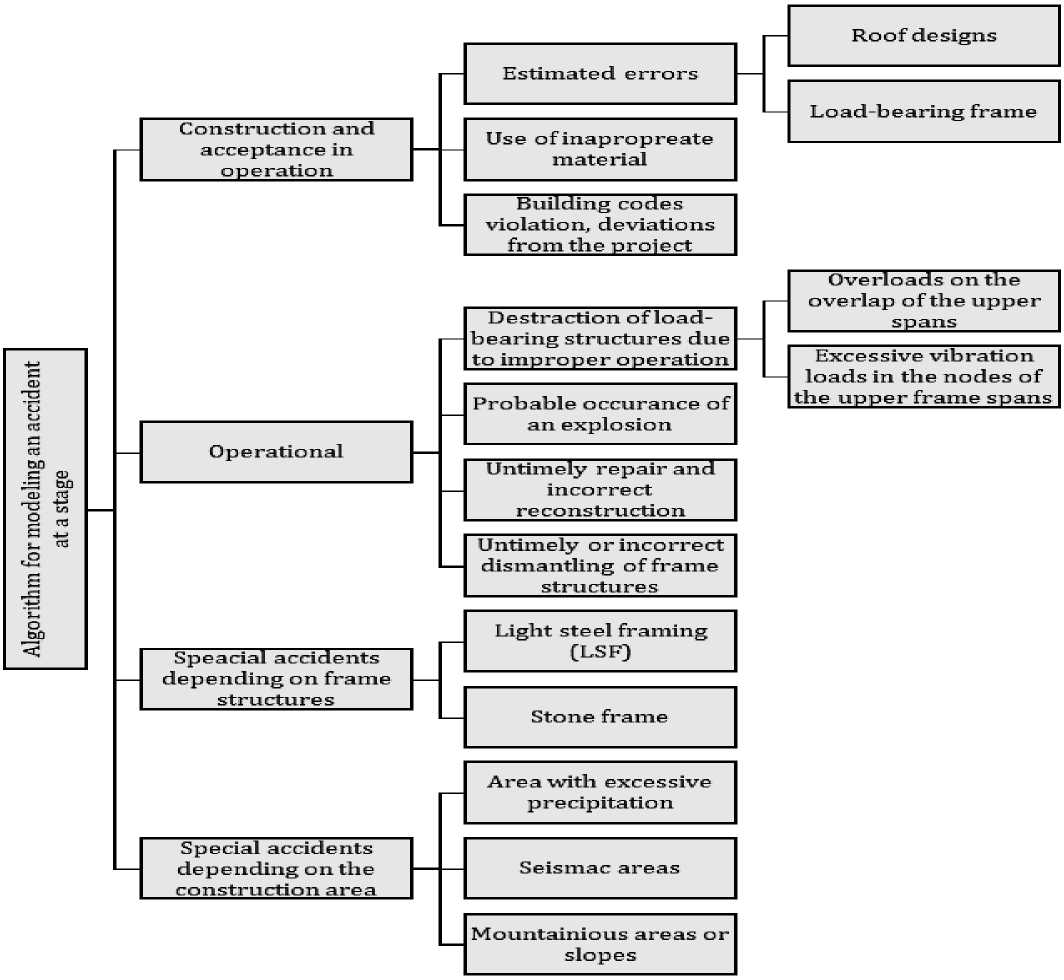

Figure 3. The algorithm structure.

- accidents that caused a complete sudden collapse of the building as a result of multi-component destruction (simultaneous destruction of several load-bearing structures of different types with an avalanche-like rapid destruction of the entire building frame, which can be defined as progressive destruction) make up 22% of the total number of accidents;

- accidents caused by the loss of the load-bearing capacity of the building overlapping make up 11% of the total analyzed accidents number.

It is clear from the obtained results that modeling and research of progressive destruction should be accompanied by modeling of local destruction, which in turn should also have a clear methodology.

Also, it is worth noting the need to conduct multi-component modeling, taking into account all possible negative factors. The developed algorithm is based on the factors that most often occurred during 2000-2022 and led to significant destruction, economic and non-economic consequences.

The result of statistical studies and simulations with the help of engineering software complexes is the created algorithm for modeling the possible occurrence of an accident at a construction site. This algorithm includes all possible scenarios of building or construction accidents, which, based on the study of accidents in construction around the world for the years 2000-2022, have a high percentage of occurrence probability and significant economic and non-economic consequences.

5. Implementation of the algorithm on the example of a real construction project

5.1 Characteristics of the designed building

To implement the developed algorithm, a multi-story industrial building was designed (Fig. 4). The design is considered as a system of frames with rigid nodes, which are located in two mutually perpendicular directions. In a monolithic structure, each frame is formed by columns and an overlap strip, which is equal in width to the distance between the middles of two spans adjacent to the corresponding row of columns. The problem of bending the plate system is solved by the finite element method. Stresses for the calculation of the upper reinforcement above the supports are determined taking into account the width of the supporting plates. The beamless design is designed for loads evenly distributed over the entire floor or part of it.

The loads acting on the overlap are approximately reduced to the equivalent uniformly distributed loads in terms of bending moments, transverse forces or deformations depending on the limit states for which the calculation is carried out. When calculating individual parts of the

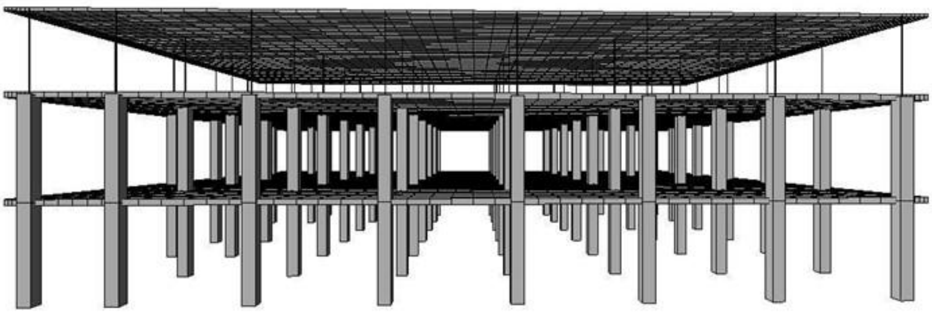

Figure 4. A three-dimensional model of the building under study.

structure (for example, for compression), the actual nature of the load is taken into account.

Reinforced concrete columns with a section of 600x600 mm. Concrete structures of class C25/30.

The significance level of the algorithm execution, depending on the building type, is aimed at distinguishing the stages of modeling the possible accident occurrence at the building site.

Significance level 1 - corresponds to all types of modeling on calculations of the possible accident occurrence, which are mandatory in the design.

Significance level 2 - corresponds to all types of modeling on calculations of the possible accident occurrence, which are necessary, but not mandatory during the implementation of the project.

Significance level 3 - corresponds to all types of modeling on calculations of the possible accident occurrence, which are recommended during the project implementation.

5.2 Execution of the simulation algorithm of a possible accident according to the level of significance 1

Journal of Physics: Conference Series **3251** (2026) 012045 doi:10.1088/1742-6596/3251/1/012045

For the presented industrial building, the stages of the algorithm are provided in the form of a block diagram in Fig. 5.

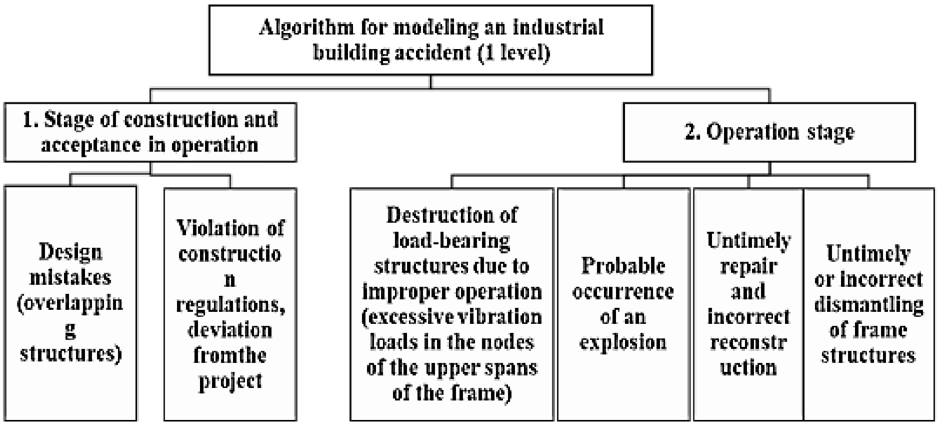

Figure 5. Algorithm for modeling the 1st level of significance of the possible industrial building accidents occurrence.

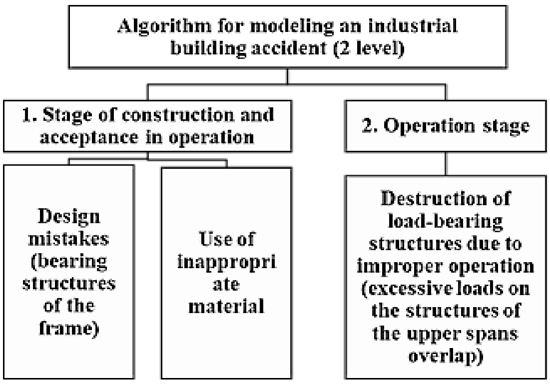

Figure 6. Algorithm for modeling the 2nd significance level of the possible industrial building accidents occurrence.

This block diagram is based on an algorithm and represents the first and main calculation for this framework. This approach considers the possibility of destruction at the stage of construction and acceptance in operation and at the operation stage. The building does not have special design solutions in the use of frame structures and the construction area, which in turn does not require an individual approach to modeling.

Thus, the main general modeling analysis of the of the possible accident occurrence will consist of consideration of 6 accident scenarios for this construction object.

The "Facilities Standards for the Public Buildings Service" developed by the US General Services Administration (GSA) [7] were used for the modeling analysis.

5.3 Execution of the algorithm according to the level of significance 2

In the event that significant structural damage is identified during the modeling process, indicating the potential for progressive collapse of the building, it is necessary to perform calculations corresponding to the second and third levels of modeling significance for possible failure scenarios. The block diagram illustrating the modeling stages for Level 2 of an industrial building is presented in Figure 6.

Thus, three more scenarios of the possible accident occurrence at a construction site of this type are proposed for consideration.

5.4 The general dynamics of the indicators Demand Capacity Ratio (DCR)

The value dynamics of Demand Capacity Ratio (DCR) depending on the accident modeling scenario is displayed on the graphs for the first significance level and for the second (Fig. 7) depending on the selected comparison parameters (Fig. 8).

It can be seen from the diagrams that the most dangerous accident scenarios, which indicate the possibility of significant destruction, for the main stage of modeling (the first level of significance) include the following scenarios:

- the probable occurrence of an explosion, when the load-bearing vertical structures (columns) are removed from work, there is a loss of load-bearing capacity for two adjacent columns (elements 45 and 2327) with a destruction area of 156 m^2;

- untimely or incorrect dismantling of frame structures leads to the appearance of significant movements in the system and the occurrence of maximum extreme forces in the columns (elements 2333 and 20);

- exclusion of the floor element, which leads to destruction with an area of 90 m^2, and loss of bearing capacity for two elements (2333 and 2335, columns).

The second significance level with the peak values of DCR depending on the type of simulated scenario for different maximum forces in the frame elements is presented in Fig. 7.

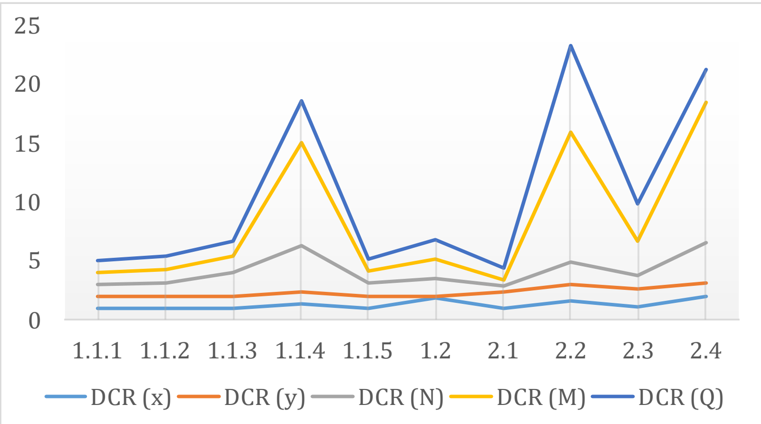

Figure 7. Comparative graph for the values of DCR parameters for the first significance level of the execution of the modeling algorithm implementation for the possible accident occurrence of the designed building.

Thus, it can be seen from the graph (Fig. 8) that when performing the analysis of the second level of significance, the probability of destruction occurrence is insignificant, the DCR indicators do not exceed the norm, and there is no danger of progressive destruction in the frame structure.

5.4 Recommendations for strengthening the most dangerous bearing element of the frame

Talking about the most dangerous element of the frame, it is necessary to clearly define what type of emergency situation we are talking about. If the primary task of strengthening the structure frame is to prevent the most likely emergency situation, then we will be talking about the less responsible elements, which belong to category B.

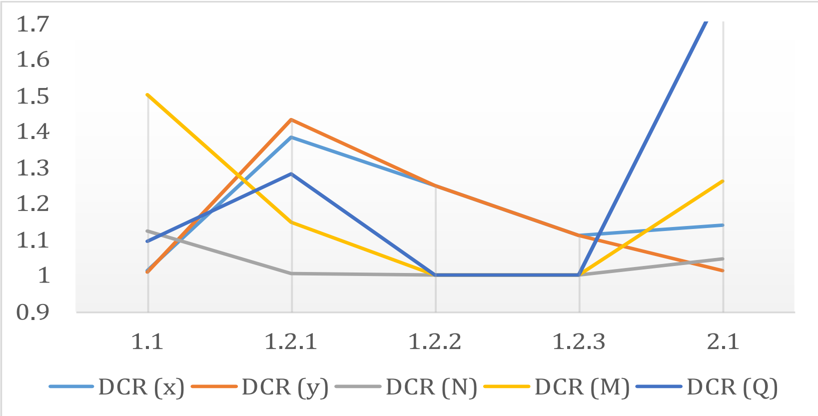

Figure 8. Comparative graphs of the dynamics of the DCR values ratio of comparative parameters for the second significance level of the modeling algorithm implementation for the possible accident occurrence of the designed building.

Thus, based on the processed material from construction accidents and the determination of the most repeated incidents, more attention should be paid to the roof of the building, and during construction, control norms should be strengthened during the construction.

Considering structures that belong to categories B and A, the problem of using low-quality materials in construction should be clearly identified. For the most part, taking into account the territorial and geographical features of the construction location, it is recommended that designers separately take into account the possibility of improper building operation with additional reserve factors.

In solving this problem, the most extensive building destruction was simulated as a result of the supporting column K1 destruction on the first floor. This accident belongs to the probable type (damage to load-bearing structures) or (depending on the accident scenario) - accidental, but at the same time it has a small percentage of occurrence. Speaking about this type of accident, it should be clearly understood in which case it can occur. Consider this issue in more detail.

Probable destruction of the K1 column of the industrial building:

- as a result of incorrect structure operation, creation of extremely difficult environmental conditions of the object;
- as a result of untimely column reconstruction;
- due to poor repair work;
- as a result of non-compliance of the actual operating conditions and specified loads on the structure with the project conditions.

Accidental destruction of column K1 of the industrial building:

- explosion of explosive substances, if the column hits the affected area;
- fire at the facility, which belongs to the highest category of danger.

Having considered a number of possible emergency situations and after conducting calculations of economic and non-economic losses during the simulation of this emergency situation, the following proposals can be made for strengthening the reliability of the structure under consideration:

- exclude the possibility of finding explosive materials (unforeseen by the technological process in this workshop);

- carry out regular inspections of the structure during the entire period of operation;
- timely reinforcement of the structure, if necessary;
- correct building operation (mostly this refers to the possibility of installing heavier machinery and equipment on other floors that are not foreseen by the project);
- if it is necessary to install heavy equipment on other floors of the workshop not foreseen by the building project, it is necessary to contact specialists in order to arrange reinforcement of the existing building frame.

In addition, focusing on the last point, it should be noted the need to introduce similar obligations of the owner into state regulations, and, if necessary, adopt a law on penalties for non-compliance with these regulations.

The first experience of the practical algorithm application showed its perspective and the possibility of using it as a tool for ensuring the reliability and safety of buildings and structures.

6. Conclusions

As part of the implemented algorithm designed to simulate potential accidents at an industrial construction site, nine distinct structural failure scenarios were analyzed, each reflecting different causal factors.

Six accident scenarios are modeled for the first level of significance for an industrial building, namely:

- two scenarios related to the construction and commissioning stages were assessed: identifying calculation inaccuracies in the roof structure design, and evaluating the structural frame behavior under potential violations of construction standards or deviations from the design;
- four operational-stage scenarios were included: potential collapse of load-bearing elements due to excessive floor vibrations, assessment of explosion likelihood within the building, degradation of the structure caused by neglected or improper maintenance, and risks associated with incorrect dismantling of frame components.

Three accident scenarios are simulated for the second level of significance for an industrial building, namely:

- possible accident occurrence at the stage of construction and acceptance in operation (2 scenarios): check for calculation errors (supporting structures of the frame) and use of inappropriate material.
- two scenarios were examined for the construction and commissioning phases: identifying design miscalculations in load-bearing frame elements and evaluating risks associated with the use of unsuitable construction materials.

The calculation of economic and non-economic consequences was carried out, which in turn made it possible to establish the level of building responsibility the and possible damages as a result of possible destruction.

As a result of the implementation of the algorithm for modeling the possible accident occurrence at a construction site, namely an industrial building, the following was established:

- when modeling accident scenarios for all significance levels, avalanche-like destruction of frame structures did not occur, which indicates that the building in question is not prone to progressive destruction;
- the destruction during the simulation was local, with a maximum destruction area of 156 m^2;

- the most dangerous scenarios for this building: probable explosion occurrence, untimely or incorrect dismantling and removal from operation of a key overlapping element;

- according to the above most dangerous accident scenarios, it is advisable to recommend strict compliance with the terms of inspections of the operational technical condition of the building in accordance with state regulations and, if necessary, to develop a project for dismantling or reconstruction of the building with the end of the operational period.

The practical use of the algorithm showed its perspective and the possibility of using it as a tool for ensuring the reliability and safety of buildings and structures.

The study of the buildings and structures destruction always be relevant in the scientific and industrial fields. On the basis of such studies, it becomes possible to follow the real frame work, taking into account time factors, the endurance of operational periods (especially for buildings designed in the last century according to no longer valid building standards). The study of all these issues provides significant potential for understanding the dynamics of the buildings and structures collapse, their features and factors.

To ensure the failure-free operation of the structure, the accidents analysis is an important basis in the possibility of modeling accident scenarios that have already taken place in the construction industry. This approach makes it possible to ensure the stability of the construction object against progressive destruction and aims to prevent the occurrence of the destruction probability and increase the building or structure reliability.

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