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LOD of a Computational Numerical Model for Evaluating the Mechanical Safety of Steel Structures

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Abstract: The article addressed the relevant problem of building information modeling. The suggestion was to introduce a BIM-based expert system into the design process. The proposed expert system encompasses the development of three levels of detail for a calculation model and digital interactive models of applicable regulatory documents. The proposed expert model has a modular structure, and it has a control module, a calculation scheme development module, a module for interaction with FEM solvers, and a module in charge of the database of interactive digital design standards. Standard operating conditions and non-standard emergency impacts are taken into account. The case of design standards for steel structures was used to describe the interaction between the expert system and the information model, and the characteristics and the structure of a digital model of a regulatory document. The data, calculated using the proposed LOD, were compared with the experimental findings. The structure of a real industrial building was designed, and its safety was evaluated. The proposed approach is a proven method applicable for designing safe bearing structures. In addition, their adequate deformation is most accurately taken account of at the stage of normal accident-free operation and in emergency situations.

Keywords: LOD; numerical simulation; steel frames; columns; finite element analysis; supplementary dynamic loading; BIM; mechanical safety

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1. Introduction

1.1. Review of Works Addressing the Research Problem

The application of building information modeling (BIM) technologies is a promising direction in construction. BIM technologies are extensively used in the construction industry worldwide; they are an important tool, and are designed to improve the efficiency and quality of construction undertakings [1–4].

BIM models contain information about the geometry of buildings, materials, heating, ventilation and air conditioning systems, electrical systems, sanitary systems, etc. They can also contain information about deadlines, budgets, and other project-related facts.

BIM has a number of advantages over traditional design methods (CAD methods) [5–7].

An important feature of BIM is that all engineering solutions are developed within a single general model which synchronizes and transfers data between developers of various design sections. Hence, a change in one parameter is visible to all participants of the design process. Thanks to BIM, 3D collisions, arising due to mutually intersecting structures or items of indoor equipment, can be quickly identified and eliminated at the stage of design. Therefore, the number of design errors is greatly reduced and their effect on deadlines and costs of production and installation of structures is prevented.

Hence, the use of BIM can improve the quality of design, reduce the time and cost of construction, reduce the number of errors and defects at the stage of construction, and ensure more efficient project management [8,9].

In addition to new construction projects, BIM is also effectively used to reconstruct existing facilities [10–12].

Given the complexity of the design process, it is important to regulate and standardize the use of BIM in practice [13,14]. The standards regulate the requirements for the development and use of information models of structures, having different sizes (3D—geometry, 4D—time and planning; 5D—costs and budgets; 6D—sustainability; 7D—facility management), levels of detail (LOD), and parameterization [15,16]. Additionally, rules and methods of using, storing, processing, transmitting, and protecting information both within the model and in the course of its interaction with other models are standardized.

LOD (Level of Development) is a classification system used in BIM to determine the level of detail for a model of a building or a structure at each stage of its design and construction. LOD makes it clear to project participants what information a model contains at each stage of design and construction and what changes the model should undergo at subsequent stages.

There are several concepts for classifying building information models by levels of detail, and they are conveyed in the regulations of various countries.

The most widespread system was developed by the American Institute of Architects (AIA) and the American Institute of Civil Engineers (ASCE). According to the AIA/ASCE system, levels of detail range from less (LOD 100) detailed to more (LOD 500) detailed ones.

As a rule, these levels of detail are linked to a particular stage in the lifecycle of a structure. Indeed, conceptual design is linked to LOD 100; schematic design is linked to LOD 200; construction and shop drawings apply to LOD 300, fabrication and assembly deal with LOD 400, and facility management require LOD 500. LOD 100 and 200 models are the simplest ones; they contain general information about the building geometry. LOD 300 models contain information about the structure and details of a building, including its dimensions, shape, location, orientation, and materials of its elements. LOD 400 models contain all the information needed to draft construction documents, including specifications, amounts of materials, and other data. LOD 500 models correspond to the actual condition of a structure after its construction; it includes data on its maintenance, repair, and replacement of elements, and it can be used to operate and maintain buildings.

LOD 300 and LOD 400 models are most frequently used for design purposes (about 60–80% of all designs are made using models of these levels). The frequency of the use of LOD 500 models is below 5%, which means a worse adaptation of BIM for the needs of facility management [17].

Some researchers argued that approaches to levels of detail are being improved thanks to the past practical application of BIM [18–22]. Other authors suggested two new levels of detail, LOD 600 and LOD 700 [19]. LOD 600 models should contain relevant data about a structure at the stage of its operation; the data must take into account each change that a structure undergoes, such as the history of its wear and the damage of its elements, replacement of items of its engineering equipment and networks, dismantling of individual elements and introduction of new ones, etc. LOD 700 models are to be used at the stage of the structure dismantling and potential reuse of its elements, which is particularly relevant for structures that have steel elements, which are relatively simple to reuse.

Another author [20] proposed a 2D conceptual model for the LOD decision plan, describing differences between various levels of detail at each design stage.

The degree of detail influences the time, spent on developing an information model, as well as its size. Hence, it is important to strike the right balance between a high level of model detail and its dimension; the concept of multi-LOD models was developed for this purpose [21]. In a multi-LOD model, levels of detail can vary for different elements of one structure, depending on the level of detail of information about a particular element required at each stage of the facility lifecycle, starting from its design and construction and ending with its operation and renovation.

The current approach allows for a high-quality standardization of the process of facility design, manufacturing, and erection; however, it fails to standardize any aspects

of the required bearing capacity and survivability of structures, let alone their energy efficiency. Hence, it is advisable to introduce additional levels of the model detail based on various parameters within the concept of multi-LOD models. In this case, the level of the model detail is also determined by the effect of specific structural and other factors on a building. For example, in [22], such approaches were proposed to ensure the required energy efficiency of a building at the stage of its design.

The review of the research articles demonstrated that the division of models into levels of detail mainly deals with the degree of elaboration of a digital model of a facility, including its bearing and enclosing structures, engineering equipment, engineering networks, etc.

It is noteworthy that an integrated digital model of a building should consolidate the information that several models contain. Models of building structures, engineering pipelines, architectural details are usually developed by different groups of designers using different software. For the integrated digital model to contain relevant information updated in furtherance of changes made in one of its sections, the interoperability of all models, containing information about structural and other solutions, is needed [23,24].

One of the most important tasks to be solved in the course of design is to perform a proper strength analysis of a structure, which allows selecting its most optimal structural scheme and cross-sections of bearing elements, and constructing their joints. The accuracy and reliability of the results depend on the degree of detail of the facility model.

The experience shows that the interoperability of graphical editors and software complexes is currently insufficient within a model, and there is no direct correlation between the extent of elaboration of an integrated digital model of a building and the quality of a calculation model obtained on its basis. For example, there are no tools enabling a designer to develop a calculation model that can automatically take into account the actual rigidity of joints of a bearing structure with regard to the design solutions developed in the general digital model of a building. Every time, it requires the involvement of a designer and supplementary testing calculations, which affect the time frame of the design process.

Indeed, the generally accepted definition of the level of model detail (LOD) does not correlate with the level of accuracy of the strength analysis of a structure model. Hence, the reliability of results and the sufficiency of calculations cannot be verified using LOD to ensure the pre-set standards of reliability and safety of a structure (for example, the need for a progressive collapse analysis).

In this connection, the calculation model of a structure can be reasonably broken down into different levels of detail same as those of an integrated digital model of a structure. The choice of the level of detail for a calculation model should depend on the effect of particular structural and other factors on the actual behavior and bearing capacity of the building structures and, as a consequence, on the result of calculations.

The level of detail of a calculation model should convey the information about the extent of elaboration of a calculation model, for example, whether it is a 2D or a 3D model.

The level of detail of a calculation model, as well as the general level of detail, depends on the stage of design. For example, at the conceptual design stage, a 2D calculation model can be used, but in the process of operation and reconstruction of a building, 3D calculation models are needed to minimize retrofitting, because such models ensure the most precise results of the bearing capacity testing due to the consideration of various structural and other factors (including the stiffness and ductility of joints).

Given that the development of software packages is taken into account, it is proposed to establish a relationship between the levels of detail of calculation models and integrated digital models to develop a system of exhaustive interoperability between the calculation model and the general model of a structure. In this case, a structural solution of a joint modeled in a graphical model will be imported into the calculation model together with its actual stiffness. Similarly, the interaction between the frame and the foundation can be taken into account together with other structural factors, such as the stiffness of enclosing structures, the actual ductility of bolted connections, etc.

Additionally, it is advisable to link the engineering component of a project (equipment, pipelines, etc.) to its calculation-focused component, so that the transfer of load from the equipment is imported from the general model to the calculation model taking into account its location. Hence, loads from pipelines should be transferred from software packages, responsible for pipeline calculations, into the general model. Thus, in the future, it will be possible to establish the interrelation between different LODs within the framework of different models, containing information about a facility, and the general level of detail of an integrated model, which will convey the degree of the model elaboration in terms of all its parameters and aspects of the design process.

1.2. Purpose and Objectives of the Research Addressed in this Article—Scientific Novelty

The purpose of the research, described in this article, was to improve the mechanical safety of steel structures at the stages of their design and operation using information modeling technologies. The following tasks were solved to achieve this purpose:

1. Using advanced BIM technologies (Section 2.1.1) to develop the concept for an expert system for calculations justifying structural solutions. Emergency situations were considered on top of standard operating conditions. In this connection, three levels of detail were introduced into a calculation model (Section 2.1.2).
2. Describing specific principles underlying the implementation of approaches aimed at designing a finite-element model for various levels of detail of beam and beam-plate models (Section 2.2); generating a workspace to ensure the interaction between the expert system and the digital models of regulatory documents.
3. Using LODs to validate calculation models by comparing them with the experimental data (Sections 3.1.1 and 3.1.2); providing a practical example of the calculation of a real building structure and evaluating its mechanical safety.

The scientific novelty of the research lies in a reasonable approach to the levels of detail for a calculation model of bearing structures proposed by the author. This approach can be used to design safe structural systems and to consider their actual behavior more thoroughly. Cases of design of steel structures were analyzed to verify the proposed approach.

2. Materials and Methods

2.1. Statement of the Research Problem

2.1.1. General Concept of an Expert System for Calculating Building Structures for Information Modeling Purposes

An expert system that will simplify the process of preparing a design model by a designer was considered. This model should adequately describe the actual behavior of a structure, which is a condition of the mechanical safety of a designed facility. The conceptual scheme of the expert system is shown in Figure 1. Its operation, as well as the content of some of its main blocks, are explained below.

Initially, information about a bearing system or an individual building structure component is transferred in the IFC format to the main control center block from architectural, structural, and, if necessary, other models. General information about the calculation model is entered and refined in this block. This can be carried out either by applying voice control procedures via links 1 or by employing a manual preprocessor. If a finite-element scheme has already been generated within the framework of transformations of a structure model, the preprocessing module can allow for some refinements. Here, information exchange links 2 (Figure 1) were employed to transfer general design constants, such as the proposed LOD, construction materials, facility location, types of floor slabs, etc.

Furthermore, the general information, taken together with the IFC description and initial data about the finite element model, was transferred to the calculation scheme generation module by means of structured data arrays (link 3). Arrays and request identifiers were formed (link 8) on the basis of this information, and the requested standards, needed for design purposes, were selected from the database of digitalized interactive norms and regulations. These standards have clarifying constants or functions applying to loads and

deformation of materials, which were transferred by means of links 9 to the module for generation of calculation schemes. Then, the calculation model was generated in accordance with the pre-set LOD and conditions of calculation. Generation results were visible in the LOD of the calculation module preview center block and, if necessary, they can be refined in the manual preprocessor block (links 6). Once this refinement was complete, the model was sent to the appropriate FE solver. The results of the analysis were available in the postprocessor as (1) SSS components and (2) the resulting calculation report (link 7). In case of an error or an unsatisfactory result, one can go back to the preprocessor and make any necessary changes (link 10).

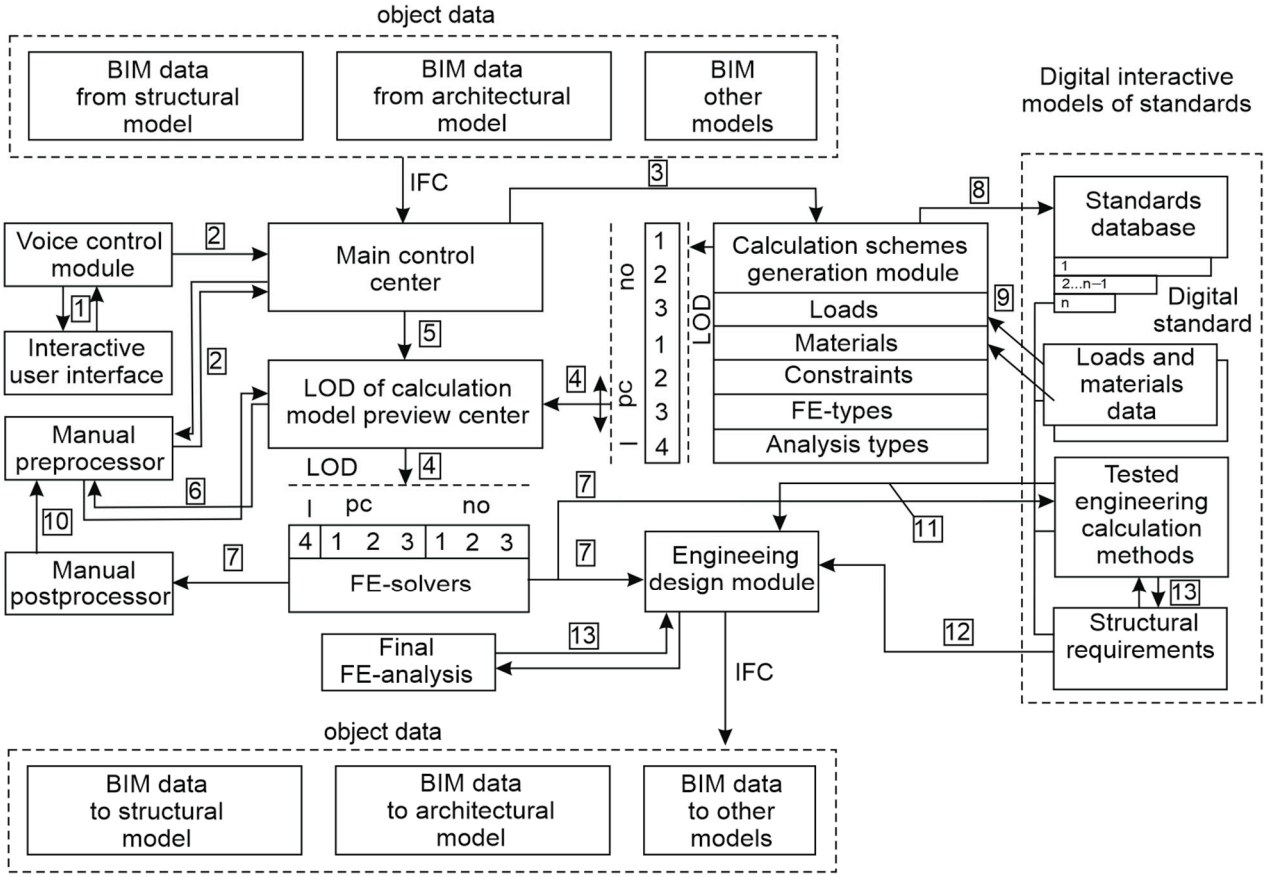


Figure 1. The structure of the expert system for the calculation of building structures: information transfer links 1–13.

When the calculation results were available, the data were transferred to the design module in the form of arrays of internal forces, stresses, and deformations. The information about structural elements was also transferred there. To ensure local strength and stability conditions, as well as structural constraints, verification results (link 11) and requirements for dimensions, location, grades, etc., applied to structural elements (link 12) were transferred from the digital standard. When the design solution was changed, the performance of the modified solution was verified (link 13). If this solution met the design requirements, it was considered to be final. When the final design solution was obtained, the information was converted to the IFC format and transferred to the target information models.

2.1.2. Levels of Detail of a Calculation Model

In accordance with the generally accepted notations of BIM levels of detail, "cm" is a calculation model, "no" is normal operation, "pc" is progressive collapse, "i" is investigation, 100 . . . 400 are numbers of level. The following levels were introduced:

- "LODcm-100no". At this level, static calculations were performed in the linear formulation using simplified schemes based on beam models. On top of finite-element models, automatable methods of manual analytical calculations, based on fundamental provisions of structural mechanics, can be used.
- "LODcm-200no". Here, static calculations took into account physical geometric, structural non-linearity. At this stage, they were brought to maximum static equivalents in the case of dynamic loading. This was possible due to the application of dynamical ratios and supplementary dynamic loading. At this stage, calculations can take account of sequential supplementary loading that describes the sequential erection of building floors. Calculation models may include plates, beams, and shells.
- "LODcm-300no". Here, the dynamic analysis, based on the modal analysis or direct integration of equations of motion, was made. All kinds of nonlinearities, damping properties of materials, inertial properties of the medium, primary and secondary imperfections, developed in the course of operation, were taken into account. A change of loads in time was taken into account; contact interactions, erosion, birth and death of elements were also considered. Complex material models were considered, including three-phase soil, packs of layers of mutually perpendicular plywood, shear layers, etc. The possibility of interaction between the soil base and the structure was taken into account. In general, beams, plates, shells, 3D elements, and all other special kinds of elements were applied here to simulate the actual behavior of a structure.
- "LODcm-100pc". A static or quasi-static calculation was considered here, taking into account the physically nonlinear behavior of the material of a damaged structure. Simplified beam models were used. A single local damage was considered within the framework of one most probable accident scenario. The local damage was considered instantaneous.
- "LODcm-200pc". The dynamic calculation of a damaged structure with physical, geometric and structural nonlinearity was considered. Several accident development scenarios were taken into account in case of a single damage. The calculation scheme encompassed the soil base modeled using simplified models (Winkler, Pasternak models, etc.) Beams, plates, shells, and their combinations were used.
- "LODcm-300pc". At this level, all calculations described at the "LODcm-300no" level were employed, but they were applied to a damaged system. Additionally, numerous local damages and their scenarios can be taken into account here. Features of transient dynamic processes, related to (1) the consecutively developing inability of elements to take loads, (2) the contact interaction with other structures or soil in an emergency situation were considered in detail.
- "LODcm -400i". This level encompassed research as part of the scientific support of projects. Most of calculations were made using 3D finite element schemes. Specific loads and impacts, such as cyclic sign variable loads, repetitive impacts, thermomechanical loads, and other extraordinary natural and man-induced impacts were modeled here.

2.2. Implementation of Numerical Modeling

The proposed approach of levels of detail of a calculation model is generally applicable and can be implemented using any finite element (FE) software systems that have the calculation capabilities required for a particular level of detail. Thus, for example, when performing high-precision calculations (LODcm-300no, LODcm-300pc), it is necessary to use nonlinear solvers that implement both geometric and physical nonlinearity, and for simplified calculations (LODcm-100no, LODcm-100pc), it is sufficient to use a linear solver.

The simulation procedure consists of the schematic representation of the geometry, loads, and constraints for a finite element model. If such procedures are implemented for real complex facilities without the involvement of humans, it can lead to incorrect calculations and improper design results and, so, some of the operations must be performed under the supervision and with the involvement of a dedicated expert. At the

levels of "LODcm-300no, LODcm-300pc, LODcm-400i" BIM geometry, consisting of 3D bodies, cannot be simplified; rather, it should be subjected to hexahedral breakdown or tetrahedronization. Automatically generated constraints and loading conditions must be verified by a human.

2.2.1. Beam Calculation Models

Model geometry transformation can be performed in the "Main control center" block both in the automatic mode (simplest constructions) and in the automated mode (with the involvement of humans). The geometry of structural elements is initially reduced to the simplified geometry used to generate a finite element mesh. Mesh generation can be performed for the following types of elements:

- Spatial beam ("Rod", "Beam");
- Spatial beam with a cross section whose dimensions vary along its length;
- Curved beam.

The following steps can be taken to convert BIM geometry to the geometry applicable for the purposes of developing a finite element model and a finite element mesh:

1. Defining an object (primitive) or a group of objects, which will be replaced by a straight line, on which finite elements will be generated;
2. Getting this line to pass through the points of the centers of gravity of the edge sections;
3. Determining or selecting the step of the straight line partitioning, geometric characteristics and orientation of the section of a beam finite element.

This approach is illustrated in Figure 2. If the element is a composite section (e.g., a two-member column, a reinforced concrete beam, etc.), the members and the mesh connecting them can be approximated by separate beam elements connected either by separate intermediate nodes or rigid beam elements (RBE).

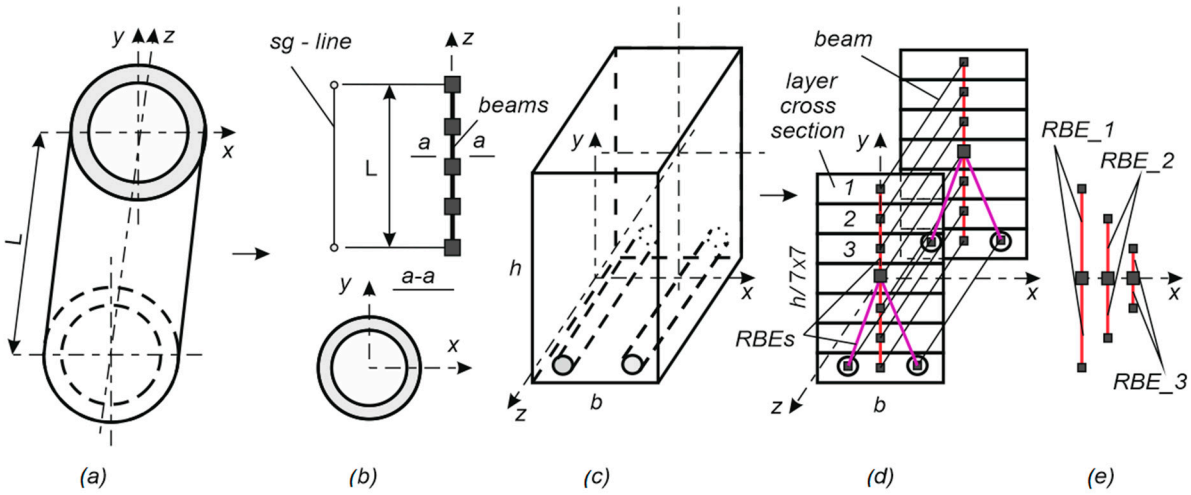


Figure 2. Stages of generation of a mesh of beam finite elements: BIM geometry for an isotropic beam (**a**); geometry simplification for calculation purposes (**b**), sg—simple geometry; BIM geometry for a composite beam structure with reinforcement (**c**); representation of a structure as layers made of RBE elements (**d**); layout of RBE elements for section layers (**e**).

2.2.2. Plate and Plate-Beam Models

When plates are used to model building structures, BIM geometry is replaced by a plane that coincides with the middle surface of the plate. If the structural solution involves the use of different plate thicknesses (e.g., when column capitals are modeled), RBEs are used. A similar approach can be applied to model laminated plates or composite plates with external or internal reinforcement. It should be taken into account that the bond (shear deformations) between the layers is not taken into account. If the shear is the determinant of

the structure's behaviour, it is necessary to use a 3D multilayered model with a shear layer or to pre-set the contact conditions at the boundary of the layers. For plate finite elements that are variable in thickness, thickness arrays must be transferred from the BIM geometry, taking into account the actual positions of nodes for the mesh of elements. Geometry simplification and meshing are shown in Figure 3 for some cases of modeling of structures.

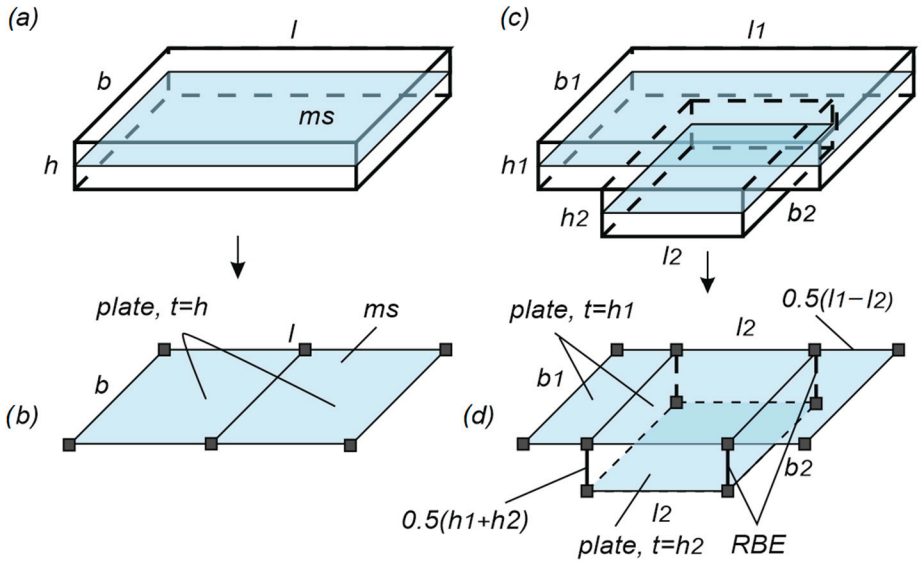


Figure 3. Stages of generation of a mesh for plate structures: BIM geometry (**a**), ms is the middle surface; simplification in the form of a middle surface with its breakdown into 2 elements (**b**); plate and capital geometry (**c**); finite-element scheme using RBE (**d**).

2.3. Digital Model of an Interactive Regulatory Document

The development of a digital interactive model of a regulatory document (DIMS) had the simplest possible structure (its option is shown in Figure 1), which may involve the following steps:

- Entry of general input data;
- Entry of specialized data for the regulations of a particular type;
- Entry of initial data about structural elements, forces, stresses and deformations inside them;
- Verification of conditions of general and local strength, stiffness, general and local stability;
- Analysis of data about the structural elements entered into the system; correction of non-compliances with the structural requirements;
- Output of the SSS evaluation results and a corrected version of the structural solution.

General input data may include characteristics of a building or a structure, basic requirements applied to its construction, basic design requirements, operating conditions of structures, materials of structures and connections. Specialized data (e.g., those applied to steel structure design standards) may include:

- Strength characteristics of steel determined taking into account the group of structures, design temperature, impact ductility and chemical composition requirements;
- Welding materials;
- Bolted connection materials;
- Requirements for structures made of profiled or rolled plates;
- Requirements for cables, ties, elements of pre-stressed structures.

It is obvious that the DIMS version must fully correspond to the paper or conventional electronic version of a regulatory document.

2.4. Safety Evaluation of Design Solutions at Different Levels of Detail

The value of the absolute risk of socio-economic losses R, caused by the failure of the structure, will be used to quantify the safety of the structure:

$$R = p(U + C), \tag{1}$$

where p is the probability of progressive collapse of a structure in an emergency situation; U is the cost of material damage due to an emergency situation; C is the cost of compensation to victims as a result of an emergency situation.

The following formulas of the reliability theory will be used to calculate the probability of failure, taking into account the provisions of [25] applied to steel structures:

$$\delta(\Delta\varepsilon) = \sqrt{S^2(\varepsilon_q) + S^2(\varepsilon_R)}, \tag{2}$$

$$\beta_\varepsilon = \frac{\Delta\bar{\varepsilon}_y}{\delta(\Delta\varepsilon)}, \tag{3}$$

$$p(\Delta\varepsilon) = 1 - (0,5 + \Phi(\beta_\varepsilon)), \tag{4}$$

where $\Delta\bar{\varepsilon}_y$ is the mathematical expectation of the value $\Delta\varepsilon = (\varepsilon_R - \varepsilon_q)$ taking into account the imperfections; $S^2(\varepsilon_q)$, $S^2(\varepsilon_R)$ are mean-square deviations of relative deformations, triggered by the emergency loading, as well as the relative limiting deformations; $\Phi(\cdot)$ is the Laplace function for some argument.

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \; t = \frac{x - m(x)}{\sigma(x)\sqrt{2}} \tag{5}$$

The Laplace function is defined by the equation, where the argument x—is the value β_ε, defined in Equation (3), $m(x)$, $\sigma(x)$—are the expected value and standard deviation of this random variable for the normal distribution, respectively.

Alternatively, the value of the relative risk can be used in the strength conditions for the design of bearing structures, as shown in [26]. This approach can be applied to any LOD of a numerical model.

2.5. Economic and Other Aspects of Benefits

The proposed approach is quite easy to implement in design practice. This will not require additional costs from the business. Depending on the design stage (conceptual design or reconstruction of an existing building), the complexity of technical and structural solutions (typical or unique structure), as well as the level of responsibility of the object, it is necessary to use the calculation models with different LOD, which will require the involvement of specialists of the appropriate level of knowledge and competencies. Thus, for example, at the stage of preliminary design or for typical buildings of normal level of responsibility, it is sufficient to use models of low LOD. The specialists of ordinary qualifications are needed for this case. At the same time, to perform a high detailed analysis of the load-bearing capacity of the frame, taking into account a large complex of factors affecting its behavior, it is necessary to involve highly qualified engineering personnel, and in some cases, researchers.

The decision on the necessity to use a calculation model of particular LOD and appropriate engineering team is made by the chief engineer of the project on the basis of the analysis of the object and design tasks. Thus, in cases when calculations of low level of detail are sufficient to ensure the required reliability and safety of the structure operation, it is possible to achieve both reduction in time spent on calculations and cost of works.

In turn, the use of high LOD models makes it possible to identify all reserves of structures bearing capacity, thereby reducing the weight of structures, simplifying their

installation and transportation, which will provide economic benefits. This is especially important for the reconstruction of existing buildings, for example, during the technical re-equipment of complex industrial buildings with continuous technological processes (for example, converter shops, blast furnaces, and other structures of metallurgical industry). When using calculation models of low and medium LOD, overloading of load-bearing structures can be observed according to the results of calculations. This will require reinforcement of overloaded structures, the implementation of which is difficult and sometimes impossible to perform, in the conditions of the continuous technological process undergoing in the building. Stopping the production process to reinforce the frame will entail a large loss of profit for the customers and is actually unacceptable. Using calculation models with a high LOD allows to analyze bearing capacity more accurately, to reduce the number of overloaded elements, and, if necessary, to develop compensating or other measures that will be aimed at unloading overloaded structures that cannot be reinforced.

3. Results

3.1. Experimental Verification of Calculation Models at Different Levels of Detail

3.1.1. The Experiment: Description and Results

Specimens of transverse frames with rigid beams 3 to columns 1 joints and safety ties 5 were subjected to testing procedures (Figure 4). In the course of the experiment, column 2 could swiftly become unable to take loads. Out-of-plane movements of a frame were limited by tubular beams 8, rigidly connected to beams 3 at one end and to columns 4 at the other end. Slots were made in these columns, allowing for the vertical displacement of beams 8. Three stages of loading were implemented: at the first stage, one load 7 was placed into each span; at the second stage, two loads were placed there, and at the third stage, all loads were placed into spans. A hydraulic jack and a support table were used to place loads into cages.

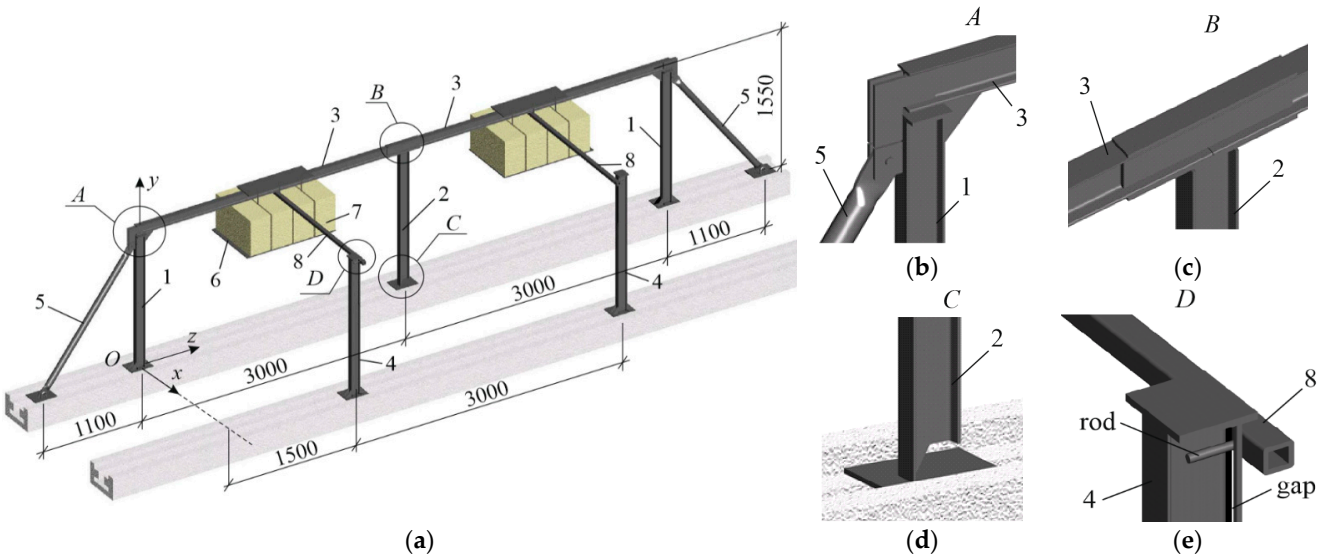


Figure 4. Model of the experimental facility: general view (**a**); connection nodes (**b**–**e**).

Following the placement of loads, the column was quickly removed, and the frame executed free oscillations. Measurements were not taken after the decay of oscillations. The structure was made of steel with the yield strength of 345 MPa according to the results of experimental tensile testing. Values of normal axial stresses were calculated and vibration diagrams of the structure were made using the data obtained as a result of the experiment. The testing scheme and characteristic findings of the testing procedure are provided in Figures 5 and 6 and in Tables 1 and 2.

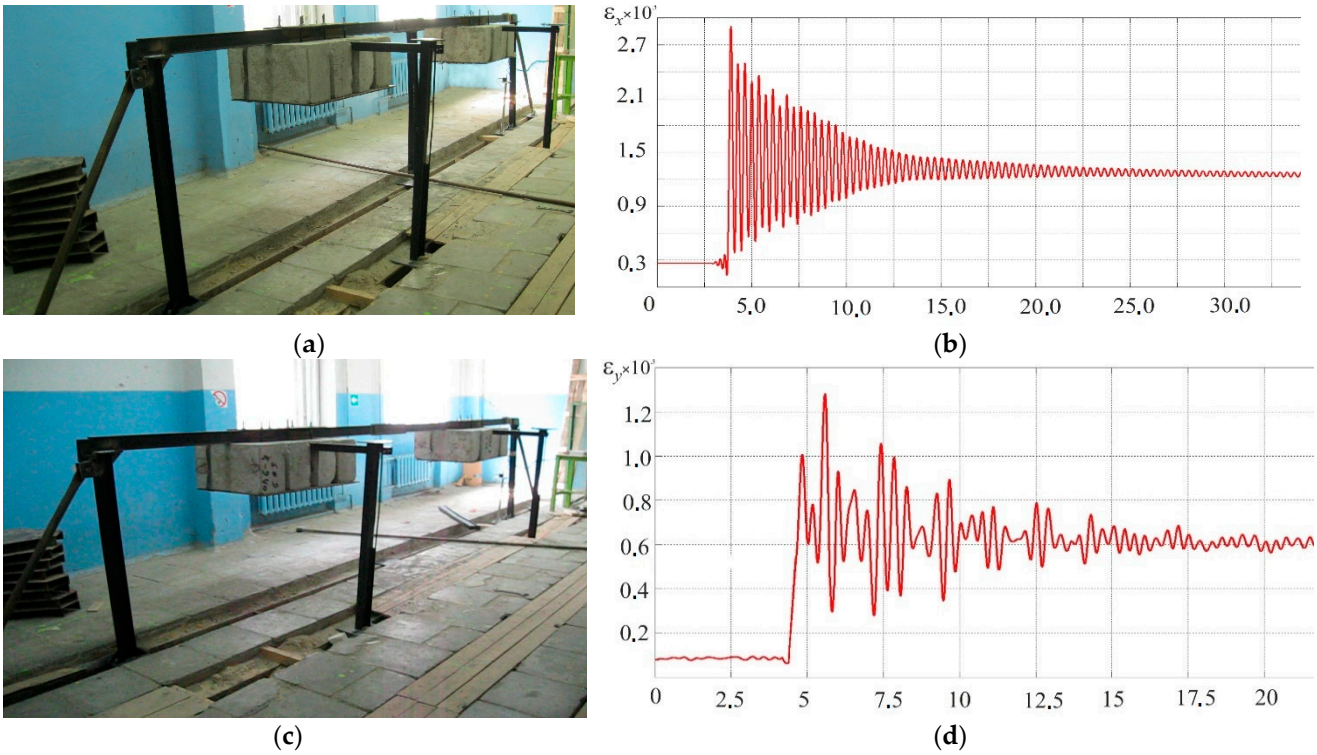


Figure 5. Testing unit and results of dynamic analysis: (**a**) the frame before the testing procedure at the third stage of loading; (**b**) the frame after the swift removal of the middle column; graphs of changes in longitudinal (**c**) and transverse (**d**) deformations in time.

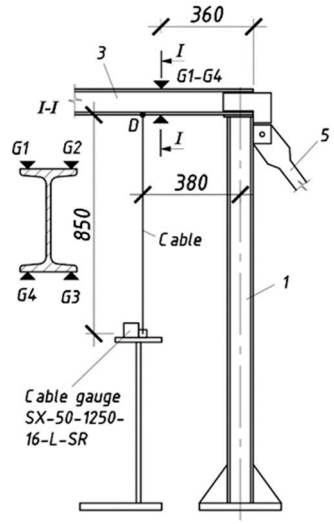


Figure 6. Positions of strain gauges, pos. 1, 3, 5 are in Figure 4a.

Table 1. SSS component measurement results.

Sensor in Figure 6	Post-Oscillation Value	
	Sensor Deformation	Stresses σ, MPa
G1	9.7×10^{-4}	200
G2	9.85×10^{-4}	203
G3	-7.71×10^{-4}	−159
G4	-7.62×10^{-4}	−157

Table 2. Measured vertical deflections of the frame.

Loading Stage	Maximum Value (Dynamics)	Static Value (Post-Oscillation Value)	
	y_D, mm (Refer to Table 1 for D)	y_D, mm	y_{Dst}, mm
1	2.05	1.2	13
2	4.5	2.3	25
3	7.3	3.8	45

At each stage of loading, column 2 was removed and the following experimental data were identified:

1. Maximum vertical displacements of the beam at point D (Figure 6);
2. Maximum vertical displacements y_{Dst} of the beam at the point of the beam support by the middle column;
3. Deformations in the characteristic directions for the edge column and the beam.

3.1.2. Comparison of Modeling Results with Experimental Data, Taking into Account the Levels of Detail

If the finite-element model of the experimental specimen is considered at different levels of detail, the matrix pattern of the classical displacement method or the model of the finite element method, using beams in the linear-elastic formulation, can be applied to solve the problem of SSS evaluation at the LODcm-100pc level. The dynamic effect will be evaluated in the quasi-static formulation using coefficient k:

$$k = \left(2M_{st}^{dam} - M_{st}\right) / M_{st}^{dam}, \quad (6)$$

where M_{st}^{dam} is the bending moment in the cross-section of the damaged structure (without column 2, Figure 5c) in the static calculation; M_{st} is the moment in this cross-section for the system without damage.

The second level of LODcm-200pc considers a 3D shell model, in the case that the behavior of its material is physically nonlinear based on the bilinear diagram with a tangent modulus of elasticity equal to zero. Here, the calculation was performed in the dynamic formulation, taking into account the time factor and using the step method of numerical integration of equations of motion of a system with a removed column.

The third level of LODcm-300pc takes into account the ductility of the column fixtures, which corresponds to the real design of the experimental specimen. It encompasses a bolted connection to the reinforced floor, consideration of initial geometric imperfections, the general stiffness of the structure from out of the frame plane. A shell model is used. The calculation was performed in the dynamic formulation, taking into account physical and geometric nonlinearities. As a result, values of deflections, provided in Table 3, and stresses, provided in Table 4, were obtained.

According to Table 3, moduli of average deviation values, based on evaluated displacements, were 17.77% for LODcm-100pc, 7.84% for LODcm-200pc, 5.63% for LODcm-300pc, which means that the results were satisfactory for all levels of detail. In this particular example, LODcm-300pc demonstrated the smallest error.

According to Table 4, moduli of average deviation values, based on evaluated stresses, were 0.24% for LODcm-100pc, 16.00% for LODcm-200pc, 15.93% for LODcm-300pc. In this example, LODcm-100pc demonstrated the smallest error.

An analysis of the results, provided in Tables 3 and 4, showed that there was a LOD-dependent discrepancy in the evaluation of the stress–strain state. This discrepancy did not exceed 18% in relation to the experimental data, which means that each of the approaches were sufficiently accurate. The data, calculated for different LODs, differed from each other within the range of 35%, which proves the effect of stiffness of joints and different methods of calculation of geometrical characteristics on the final result. Nevertheless, if

it is necessary to obtain detailed information about stresses, arising in joints, the effect of non-linear behavior of materials and large displacements, then a high level of detail of a calculation model is absolutely necessary.

Table 3. Calculated vertical deflections of the frame.

Loading Stage	Maximum Value (Dynamics)		Static Value (Post-Oscillation Value)				Level of Detail
	y_D, mm	Δ, %	y_D, mm	Δ, %	y_{Dst}, mm	Δ, %	LODcm
1	2.75	−25.45	1.90	−36.84	15.10	−13.90	100pc
	2.03	0.98	1.46	−17.80	13.08	−0.61	200pc
	2.09	−1.91	1.49	−19.46	13.22	−1.66	300pc
2	4.48	0.44	3.10	−25.80	24.60	1.62	100pc
	3.31	35.95	2.37	−2.95	21.30	17.37	200pc
	3.41	31.96	2.42	−4.95	21.53	16.11	300pc
3	7.86	−7.12	5.44	−30.14	43.15	4.28	100pc
	5.80	25.86	4.16	−8.65	37.37	20.41	200pc
	5.98	22.07	4.25	−10.58	37.77	19.14	300pc

Table 4. Comparison of calculation results for the experiment and models with different levels of detail.

Sensor	Post-Oscillation Value					
	LODcm-100pc		LODcm-200pc		LODcm-300pc	
	σ_x, MPa	Δ, %	σ_x, MPa	Δ, %	σ_x, MPa	Δ, %
G1	194.03	2.98	155.72	−22.14	155.30	−22.35
G2	194.03	4.43	155.72	−23.29	155.30	−23.50
G3	−164.60	−3.52	−172.65	−8.58	−172.13	−8.26
G4	−164.60	−4.84	−172.65	−9.97	−172.13	−9.64

Some frame calculation results are provided in Figure 7.

3.2. The Case of Calculation of an Industrial Building Frame

The transverse frame of a single-storey single-span slab warehouse of a converter shop of a metal smelter was considered. The span was 36 m. The step of transverse frames in the building was 12 m. The design of a transverse frame is provided in Figure 8.

The columns had two elements; the bottom part was a multi-element rod that had pillars in the form of welded I-beams and a diagonal lattice made of single L-shaped elements welded to the flanges. The top part of the column was made as a continuous welded I-beam. The cross-section of the top part of the column had an opening for the crane runway maintenance.

Roof trusses were made of twin hot-rolled L-shaped elements; they hinged the columns with the help of the support, having an I-beam section. The structures were made of steel with the yield strength of 345 MPa. The building accommodated travel crab cranes with the bearing capacity of 120 tons. The worst loading combinations were considered, taking into account possible crane positions in the frame span and on the crane runway.

Working loads, applied to the frame, were reduced to nodal forces and applied to the nodes of the finite-element model. Resistance of the transverse frame to progressive collapse was analyzed for the case of a sudden local damage of the column. The calculation was based on the values, provided in the applicable regulations, governing permanent and continuous loads (Table 5). The calculation model made in the form of a planar frame was considered to illustrate the approach to the levels of detail. Three levels of detail were considered for the structural solution of the column and its components:

- LODcm-100pc. The frame was modeled using "beam" elements only (see Figure 9a). Joints of structural elements, which do not take substantial bending moments, were idealized as hinges. Supporting connections were assumed to be absolutely rigid.

- LODcm-200pc. Structural elements of the column were modeled using "plate" finite elements, and mesh elements were modeled using "beam" elements, as at the previous level (Figure 9b). Other parameters of the model remained the same as at the previous level of detail.
- LODcm-300pc. The column was modeled using finite elements of the "plate" type only (Figure 9c). The calculation showed actual connection stiffness values of structural elements without any structural simplification.

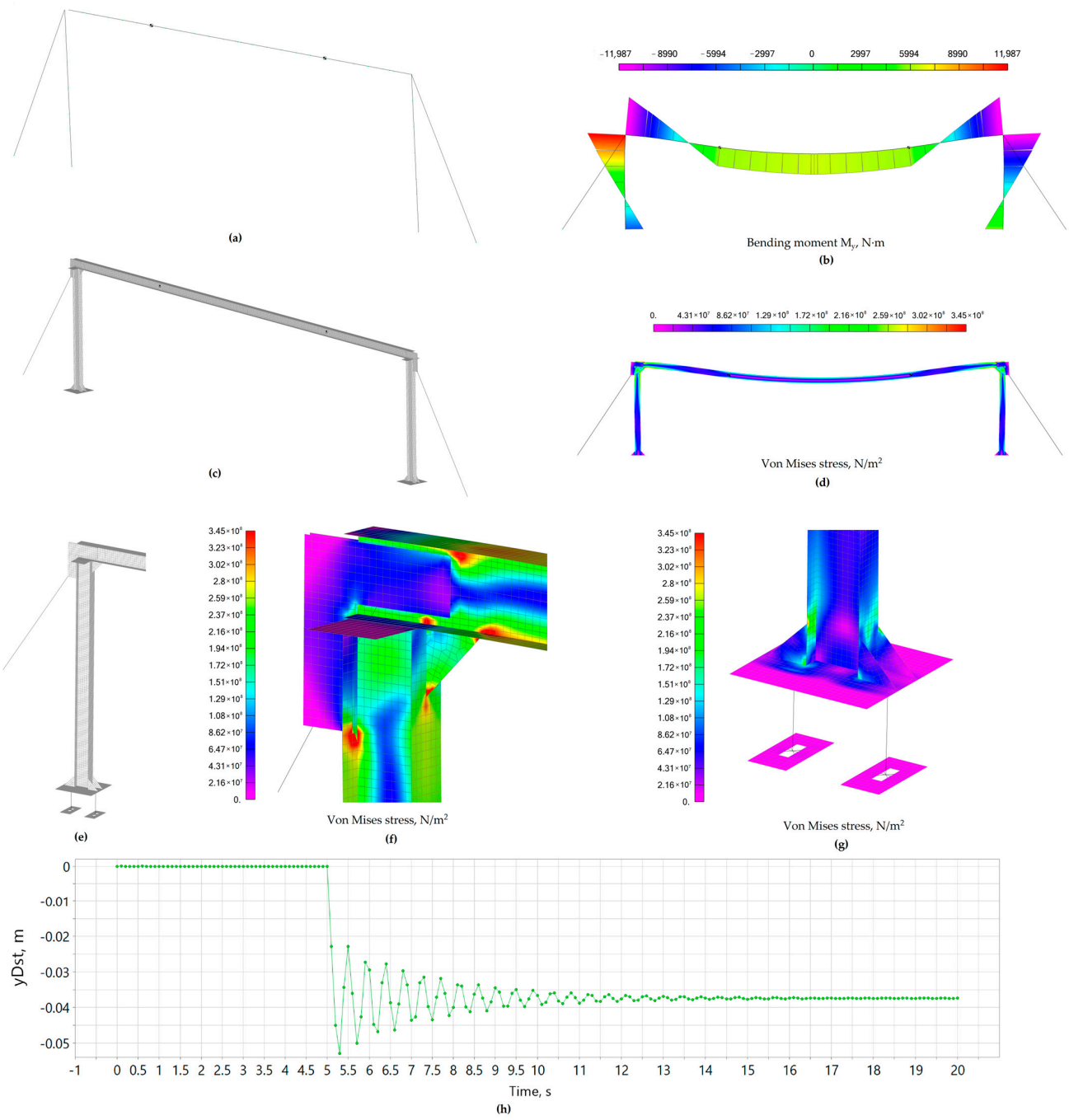


Figure 7. Results of modeling and SSS evaluation for the frame in case of different LODs: LODcm-100pc (**a**,**b**), LOCcm-200pc (**c**,**d**), LODcm-300 (**e**–**g**), diagram of displacement in time (**h**).

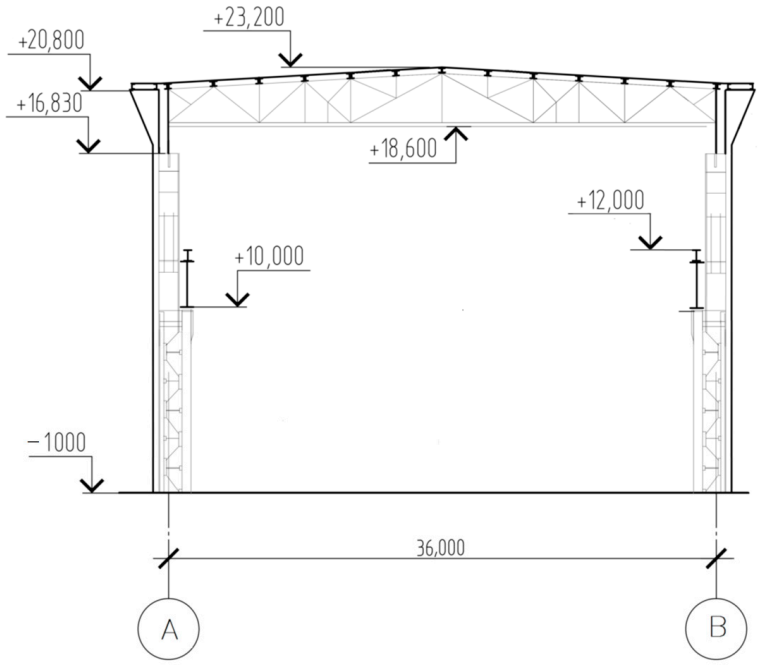


Figure 8. The design of a transverse frame of a slab warehouse.

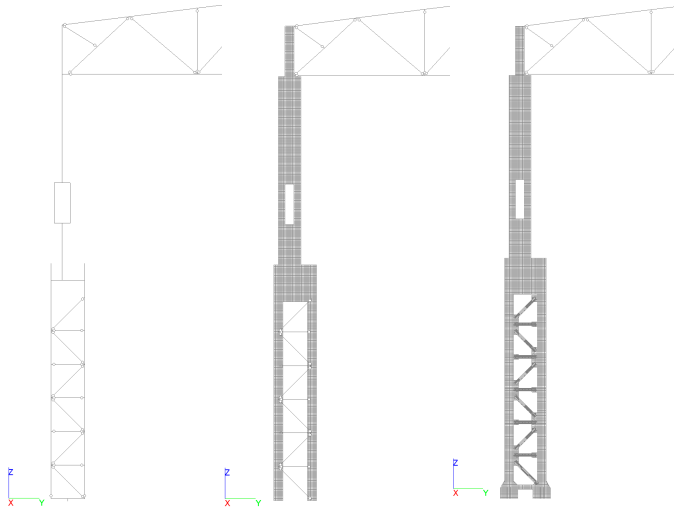
Table 5. Frame loading in the course of normal operation.

No.	Origin of Loading	Loading Safety Factor, $\gamma_{f,i}$	Reliability Safety Factor, γ_n	Type of Loading	Duration Factor, $k_{dur,i}$
1	Dead load–bearing structures	1.05	1.1	Constant load	1
2	Dead load–roof	1.05	1.1	Constant load	1
3	Dead load–walls	1.3	1.1	Constant load	1
4	Dead load–platforms	1.05	1.1	Constant load	1
5	Snow load	1.4	1.1	Short-term load	0.5
6	Wind load	1.4	1.1	Short-term load	0
7	Vertical crane load	1.2	1.1	Short-term load	0.7
8	Horizontal crane load	1.2	1.1	Short-term load	0
9	Payload	1.3	1.1	Short-term load	0.35

Each level of detail involved the following calculations:

- Analysis, made in the quasi-static formulation, whereby the column element removal was modeled using the static equivalent of a dynamic reaction, applied to the system in the direction opposite to the actual reaction of the column;
- Analysis in the dynamic formulation, whereby reactions or forces were applied to the removed external or internal links of the system, and they were removed from the calculation scheme after the phase of dynamic relaxation. In this case, the dynamic calculation was preceded by the calculation of natural oscillations of the damaged system. This calculation determined the oscillation frequencies range, in which the shape of oscillations, typical for the emergency removal of an element, was excited.

Table 6 shows the types of the column element stiffness for LODcm-300pc. Figure 10 shows patterns of deformation, corresponding to maximum deflections in the dynamic calculation made for different levels of detail. The results of calculations are provided in Tables 7 and 8.



(**a**) (**b**) (**c**)

Figure 9. Levels of detail for a calculation model of a column.

Table 6. Types of stiffness of column elements.

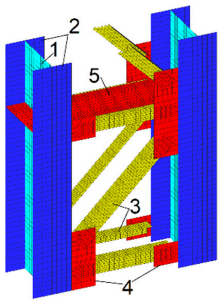
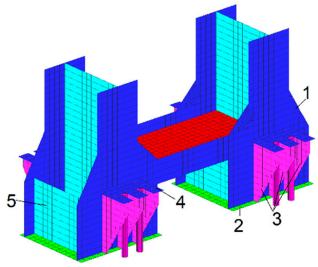
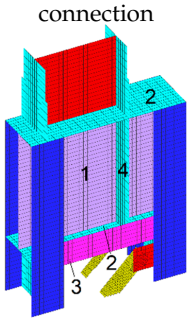
Structure	Element	Cross-Section	Pos	Dimensions	Stiffness
1	2	3	4	5	6
Under-crane part of the column	Branches and braces 	Branches welded I-section	1	web −570 × 20	t20
			2	flanges −400 × 30	t30
		Braces Single hot rolled angle	3	L125 × 10	t10
		Gusset	4	−12	t12
		Diaphragm (3 m each)	5	−12	t12
	Base of column 	Traverse	1	−800 × 500 × 30	t30
		Base plate	2	−800 × 700 × 50	t50
		Transverse ribs	3	−500 × 250 × 16	t16
		Anchor plate	4	−600 × 500 × 30	t30
		Reinforcing ribs	5	−600 × 450 × 20	t20
	Under-crane with overhead part connection 	Traverse beam	1	web −1480 × 25	t25
			2	flanges −570 × 20	t20
		Stiffeners of lower flange	3	2–300 × 16	t16
		Rib under column flange	4	−20	t20

Table 6. *Cont.*

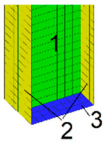
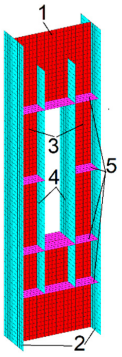
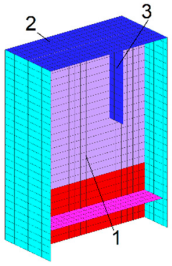
Structure	Element	Cross-Section	Pos	Dimensions	Stiffness
1	2	3	4	5	6
Above column rack	Rack 	Welded I-section	1	web −380 × 6	t6
			2	flanges −300 × 10	t10
		Base plate	3	−400 × 300 × 30	t30
Overhead part of the column	Column rod 	Column rod Welded I-section	1	web −980 × 12	t12
			2	flanges −500 × 20	t20
		Opening for passageway	3	web −280 × 12	t12
			4	flange −400 × 20	t20
		Stiffening rib	5	−16	t16
	Column head 	Web	1	−980 × 25	t25
		End plate	2	−1000 × 500 × 30	t30
		Support rib on the web	3	−600 × 300 × 30	t30

Table 7. Results of evaluation of the frame SSS for different levels of detail.

Calculation	Parameter	Level of Detail					
		LODcm-100pc		LODcm-200pc		LODcm-300pc	
		Max	Stable	Max	Stable	Max	Stable
Quasi-static approach LODcm-100pc k = 1.539 (6) LODcm-200pc k = 1.547 (6) LODcm-300pc k = 1.506 (6)	Vertical displacement of a collapsed column element, mm	15.71	11.09	14.27	9.84	12.31	8.65
	Horizontal displacement of the column at the point of the rail-to-column connection, mm	80.92	56.99	72.27	50.19	64.09	45.27
	Normal stresses in the pillar, MPa	−426.1	−313.3	−300.0	−219.5	−291.1	−217.7
	Normal stresses in the top element of the column above the traverse beam, MPa	−162.7	−124.8	−173.6	−132.4	−157.6	−122.8
Dynamic approach	Vertical displacement of a collapsed column element, mm	15.13	11.09	13.23	9.69	11.52	8.43
	Horizontal displacement of the column at the point of the rail-to-column connection, mm	85.34	56.98	72.96	49.54	65.55	44.26
	Normal stresses in the outer column element, MPa	−402.9	−313.3	−301.3	−237.1	−294.8	−233.1
	Normal stresses in the top element of the column above the traverse beam, MPa	−139.6	−124.8	−130.3	−113.1	−131.9	−120.7

Table 8. Comparison between calculation results obtained using quasi-static and dynamic methods at different levels of detail.

Parameter	LODcm-100pc		LODcm-200pc		LODcm-300pc	
	Max	Δ	Max	Δ	Max	Δ
Vertical displacement of a collapsed column element, mm	15.71	3.83%	14.27	7.86%	12.31	6.86%
Horizontal displacement of the column at the point of the rail-to-column connection, mm	80.92	−5.18%	72.27	−0.95%	64.09	−2.23%
Normal stresses in the outer column element, MPa	−425.1	5.75%	−300.0	−0.44%	−291.1	−1.27%
Normal stresses in the top element of the column above the traverse beam, MPa	−162.7	14.20%	−173.6	24.92%	−157.6	16.32%

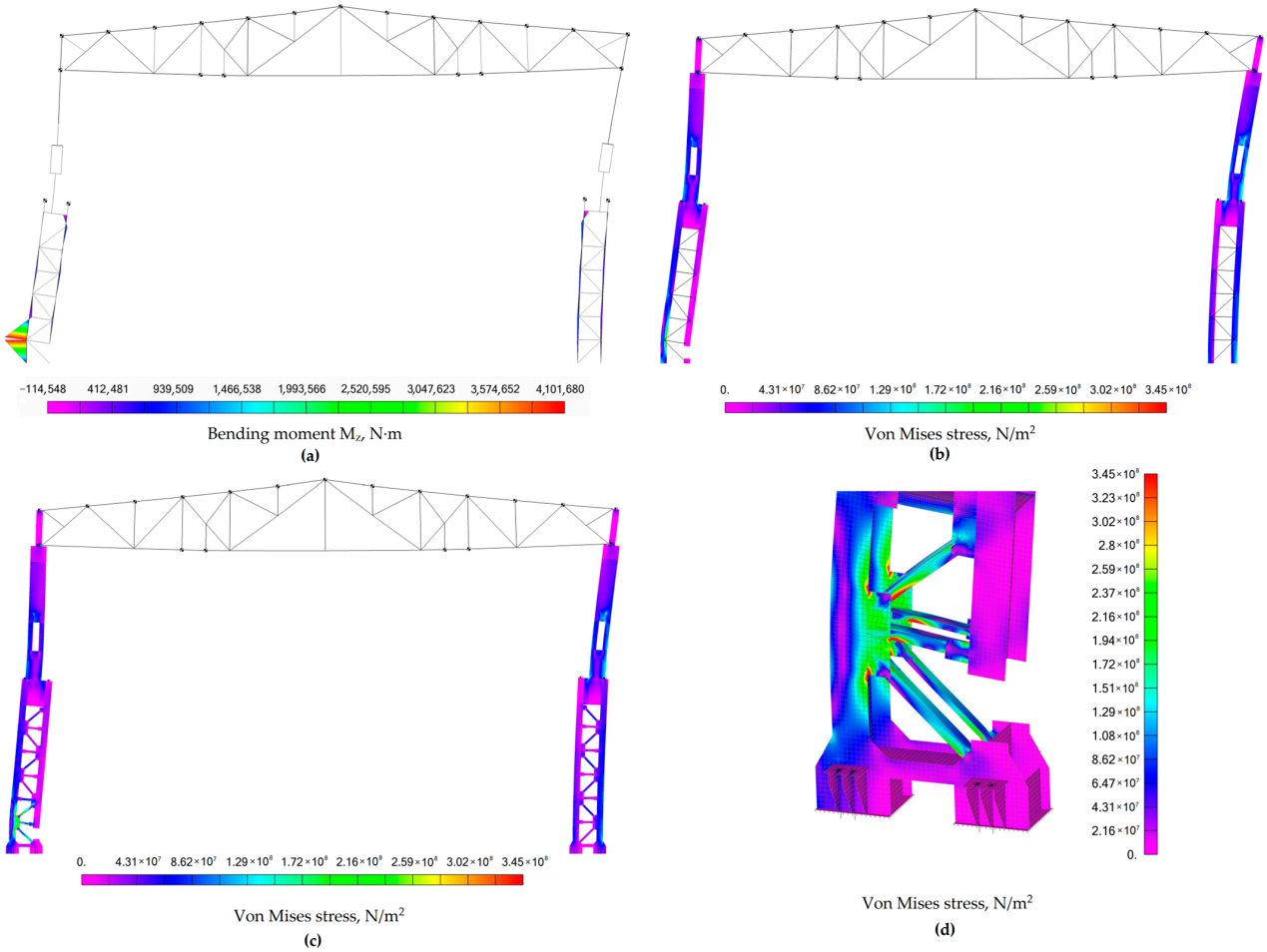


Figure 10. Schemes of the frame structure deformation: LODcm-100pc (**a**), LODcm-200pc (**b**), LODcm-300pc (**c**), LODcm-300pc support node (**d**).

The results of the calculation, made using the quasi-static method, differed from the results of dynamic analysis in the case of availability of the bearing capacity margin, and the discrepancy did not exceed 25%. Hence, the application of the quasi-static approach at LODcm-100pc is acceptable and can be recommended for the simplified evaluation made with a guaranteed safety margin.

4. Discussion and Further Investigation Prospects

Various automated calculations, made in the course of design, are a promising direction in the development of information technologies in structural design [27–32]. However, the

fact that the control, exercised by a specialist, cannot yet replace any software should not be neglected.

The development of automated calculation systems has great prospects in terms of adapting analysis algorithms to the type of the bearing structure under study and to conditions of its operation. In this connection, the breakdown of factors, applied in risk management, is another promising area of research addressed in [33]. If applied to calculation models, these are the risks related to the development of a calculation scheme, simplified deformations of materials, and the accurate description of loadings.

Damage to structures can occur for various reasons, among which are explosive impacts, action of fire or high temperatures, subsidence of supports, local or general loss of stability, etc. [34,35]. One of the most frequent causes (up to 65% of all cases) of initial damage of structures are design errors [36]. The use of calculation models of high LODs will reduce the number of design errors due to a more correct analysis of the frame behavior.

The time of structural failure significantly affects dynamic factors and depends on the stress state of the structure and causes of its damage. It is important to determine both the causes of structural failure and the type of destroyed structure. An analysis of the influence of all these factors on the process of progressive collapse is explored in one of the future studies.

5. Conclusions

1. The BIM-based concept of an expert system for the design of buildings and structures, which takes into account the levels of detail of a digital calculation model and evaluates the safety of bearing systems, was proposed. Three levels of detail of a digital calculation model were introduced for cases of its normal operation (without accidents), and three levels of detail were to be applied at the onset of progressive collapse and its further localizing.
2. The use of the suggested levels of detail of a calculation model system will provide more correct and rational implementation of the design process. It will reduce the time and cost of design, reduce the material consumption, and simplify the transportation and installation of structures. The required level of system reliability was provided by the limit state design. The load-bearing capacity security according to the limit state design was not less than 0.999.
3. Cases of experimental verification showed that any LOD can be applied to adequately describe the actual behavior of any structure with a sufficient degree of accuracy. If it is necessary to adjust the value of SSS of joints of elements, as in the cases of emergency effects, higher order LOD, or LODcm -400i, is recommended. The case of a transverse frame structure of a building demonstrates the effective application of LOD of a digital calculation model.

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