

# Efficient building practices: 3D models for process optimization

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**Abstract.** The study proposed a framework for integrating building information modeling (BIM) and value engineering (VE) processes to reduce material and reinforcement consumption, assessing the possibility of cost reduction without compromising quality and considering long life cycle tunnel ventilation building, class of structures KC-3 (increased level of responsibility). The paper shows a selected study carried out within the framework of the implementation of scientific and technical support division (STS), which included recommendations on the selection of rational reinforcement in the calculation of construction of tunnel ventilation buildings taking into account seismic effects and accidental collapse. Calculation of building structures is performed using several software and computer complexes, a comparative analysis of calculation in two programs is given: SCAD (Structure CAD) and MIDAS Software, conclusions about the convergence of the results are drawn, and the main results of calculations with the use of automatic reinforcement for monolithic reinforced concrete elements are given. Keywords: 3D model, building information modeling, BIM modeling, safety of buildings and structures, reliability level as for responsibility, specific combination of loads, seismic loads, seismicity of the construction site, tunnel ventilation building

## 1 Introduction

Optimization of construction includes a number of key steps to improve efficiency and reduce costs, one of the key ones is Value Engineering (VE) with the use of BIM. The application of BIM simplifies the management of a construction project at all stages: design, construction, operation and renovation and allows to significantly reduce the project development time, significantly reduces material and labor costs, ensures high quality, error avoidance and accuracy of results.

Improvement of processes of integration, universalization and intellectualization of software complexes due to built-in expert systems, graphical analysis, comparison with the bank of historical data of solutions of a virtual object using the technology of "digital twins" throughout the life cycle - these are the main vectors for the development of digital engineering calculations. This is the optimal solution (alternatives) for selecting the most

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preferable multi-criteria solutions using 3D models, methods and algorithms based on the use of mathematical apparatus of systems theory, artificial intelligence, decision-making theory, control theory, forecasting theory, etc. to ensure the safety of buildings and structures under resource and time constraints.

However, the final decision will still be chosen based on the natural intelligence and professional competencies of the engineers (led by the chief engineer of the project together with the scientific support team) for a long time to come.

Taking into account the increased class of tunnel structures, optimization of solutions takes place within the framework of scientific and technical support, which includes:

- (a) preparatory work;
- b) basic works of 3D computer modeling (performance of alternative verification calculations, analysis and evaluation of calculation results, comparison of the results of the main and alternative calculations, formation of conclusions about reliability and safety of the object);
- c) preparation of intermediate scientific and technical reports on objects and final report with conclusion and results of optimization of solutions.

Analysis of the completed design documentation for compliance with the current norms and rules, design task in terms of mechanical safety and suitability for normal operation is carried out in the following order (work algorithm):

1. comparison of the load assumed in the project;
2. identification of emergency scenarios;
3. verification of completeness and correctness of performed calculations: analysis of fulfillment of conditions of the 1st group of limit states (strength, stability, etc.);
4. verification of completeness and correctness of performed calculations: analysis of fulfillment of conditions of the 2nd group of limit states (deflections and displacements, crack opening width, etc.);
5. alternative calculations of the load-bearing system of the building and its building structures, taking into account seismic impact and emergency collapse on the basis of standards;
6. development of recommendations for adjusting design solutions when it is necessary to make changes to previously developed design documentation in order to increase the load-bearing capacity and seismic resistance of buildings and structures;
7. current control over the implementation of recommendations on making appropriate changes to optimize design solutions and final evaluation of the adopted design solutions for correctness and compliance with regulatory documentation.

The purpose of scientific support of works: ensuring the quality and reliability of design solutions obtained on the basis of using the results and recommendations of engineering survey, survey and research works, application of modern calculation and analytical methods in order to save material and labor resources, avoid errors and accuracy of results and optimization of construction technologies.

Future trends and technologies in training and professional development for digital construction are aimed at creating specialized training centers, transferring knowledge and training of engineers in the field of BIM technologies, increasing the scope and areas of implementation of additive technologies with universal interdisciplinary software applications within artificial intelligent (AI) and machine learning (ML) [1,2], development of methods for optimizing 3D modeling for bridges and tunnels [3,6] at all stages of the life cycle [7-11] and assessing the impact of the introduction of "digital twins" [12-15].

## 2 Example of selecting options for constructive solutions of a building

The structural scheme of the building is frame-wall. Horizontal rigidity is provided by a monolithic ribbed floor. The building dimensions along the axes are 16.0x25.5m. The total height is 8.0 m. The walls of the building are 250 mm thick for the whole height. The walls are hinged on the foundations. For this purpose, along the central axis of the walls there are reinforcement releases from the foundation, which allow to compensate seismic loads on the building and at the same time do not allow the walls to move from the foundations. The walls with the cover slab are rigidly connected to each other. The frame of the building with load-bearing walls, and therefore is accepted for engineering calculations of structures for strength, rigidity and stability as a deformable system.

The level of responsibility of the structure is increased, class KS-3,  $\gamma_n=1,1$ . The requirement to assign and apply the reliability coefficient of responsibility  $\gamma_n=1.1$  for the object of the calculation model seems to be quite reasonable, since in case of collapse of the retaining structures "social, environmental and economic consequences", as well as the delay in the construction of the main structure, are quite significant.

Calculation of the structure building according to the limit states of the first and second groups is performed taking into account the unfavorable combination of loads. Structural solutions are taken taking into account the corresponding forces. The calculations are performed using Midas program complexes together with SCAD.

At the preparatory stage the design solutions were evaluated taking into account the results of engineering surveys and identifying the possibility of optimizing the design solutions aimed at reducing material intensity without reducing the structural reliability and safety of the facility.

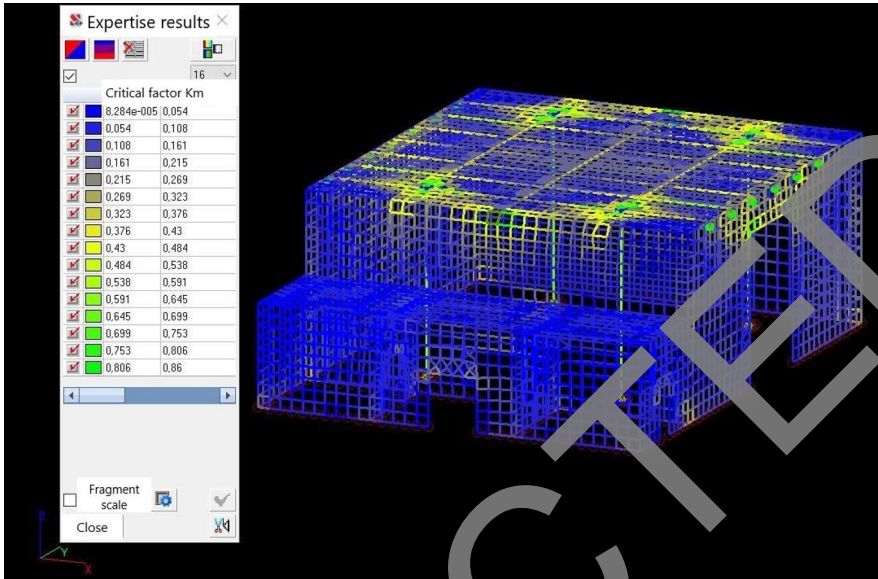
At the first stage, the operation of the structures was analyzed and the main scenarios of the most dangerous damage to the load-bearing system were developed for use in calculations for protection against progressive collapse; the design schemes were adjusted and local design schemes were created for calculations for progressive collapse and for seismic effects; after the calculations, the results of the calculations (stress-strain state, damage to the load-bearing system, etc.) were analyzed for each object and compared with the results of the calculations (stress-strain state, damage to the load-bearing system, etc.).

The adjustment of the calculation schemes in the second stage in the calculation of the building for dynamic effects (seismic, wind pulsation) was mainly caused by the need to form a mass matrix. The dynamic mass may either not be assembled in the right percentage of the total mass or may be incorrectly assembled, for example, due to dummy elements or dissimilarity of structures. It is recommended that the minimum number of natural vibration modes taken into account in the calculation be set so that the sum of the effective modal masses taken into account in the calculation is at least 90 % of the total mass of the system excited in the direction of seismic action for horizontal actions and at least 75 % for vertical actions. According to the norms, in terms of achieving the required level of accounting for effective modal masses, the linear degrees of freedom should be controlled.

Taking into account the fact that at the adopted preliminary design geometric parameters and percentages of reinforcement of the floor beam system and columns, the limit state criteria established in the standards for the considered emergency scenarios were not initially fulfilled, the parameters and percentages of reinforcement of the floor beams were increased, and then the building frame was recalculated for special impacts and the design documentation was adjusted in terms of reinforcement of the main sections in order to fulfill the checks and ensure the load-bearing capacity of the building.

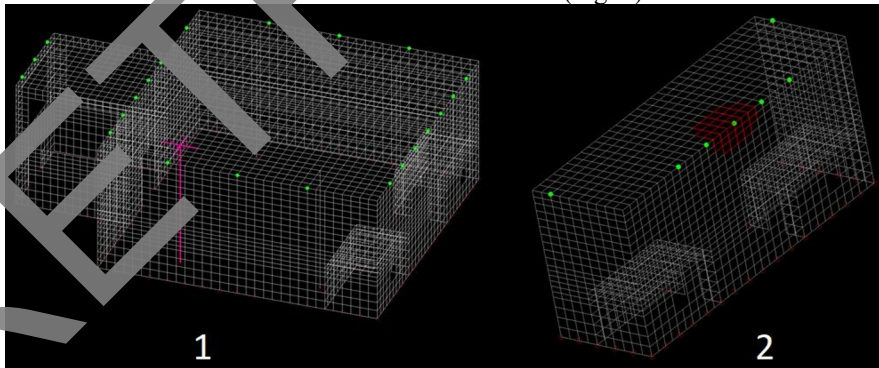
As a result of the calculation of the spatial model of the structure for the first and second group of limit states, the load-bearing capacity of the building structures is ensured, since

the utilization factors for the elements do not exceed the permissible value ( $K_{max} < 1$ , Fig. 1).



**Fig. 1** Screenshot of a separate screen area with the results of the examination of reinforced concrete elements

To account for sudden removal of structures (risk-based emergencies), as well as to account for the weight of collapsed structures, a dynamic coefficient = 2 was introduced. Instantaneous removal of collapsed elements is modeled by the forces (determined by the primary scheme) at the nodes with which the removed elements act on the rest of the scheme and applied with the opposite sign, which corresponds to the algorithm of quasi-static calculation at instantaneous removal of an element (Fig. 2).



**Fig. 2.** Screenshot of an individual area under the progressive failure scenario: secondary structural schemes: the removed element is highlighted in red - simulation of collision failure of an intermediate column (1) and wall elements (2)

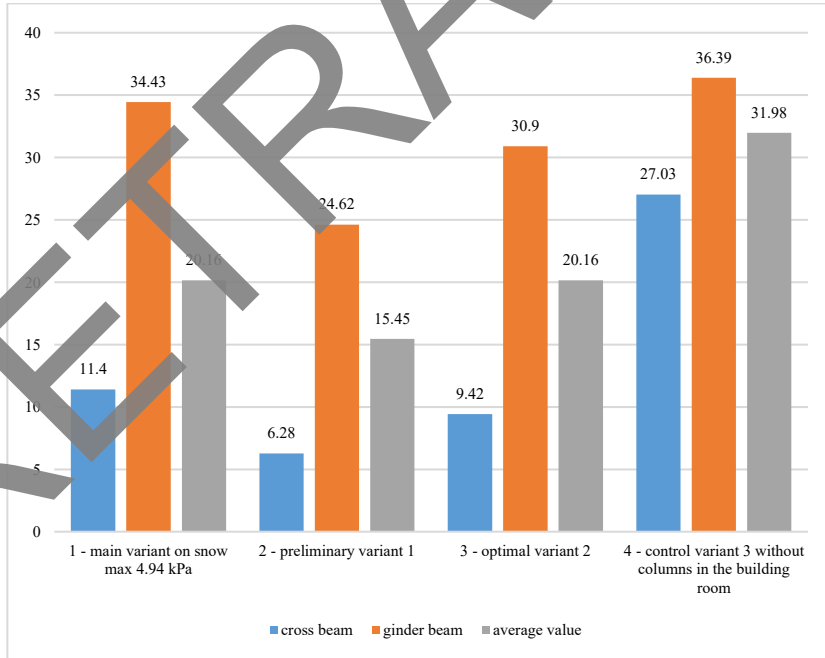
### 3 Calculation of a building for progressive (avalanche-like) collapse

The load carrying capacity was evaluated by comparing the acting forces in reinforced concrete structures with the load carrying capacity of sections with ultimate forces - the strength region presented in graphical interpolation or with the load carrying capacity of the section.

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When selecting the design variants, additional variants were considered and calculations were carried out and recorded. The change (growth) of reinforcement for the main loaded elements of the slab beam structure during recalculations is presented for the main design variants in Fig. 3:

- 1) The cross beam bottom reinforcement was initially taken 2d 20 (preliminary variant 1) became 3d 22 (optimal variant 2), also the 3d 25+2d 28 reinforcement was calculated (control variant 3 without columns in the building room);
- 2) Central purlin (main beam) history of changes on reinforcement of the bottom part was 4d 28 (preliminary variant 1) adopted 4d 28 +2d 20 (optimal variant 2) and 6d 28 (control variant 3 without columns in the building room).



**Fig. 3** - Dynamics of changes in conversions of a given type of reinforcement by variants (values of reinforcement cross-sectional area in cm<sup>2</sup>)

## 4 Calculation of a building in earthquake-prone areas

Selection of scenario earthquakes in calculations in accordance with the seismicity map (taking into account earthquakes with recurrence periods of ~1000 years).

When performing seismic design of buildings, two design situations must be considered:

1) Seismic loads correspond to the design earthquake (DER) level. The purpose of the calculation is to prevent partial or total loss of performance of the structure.

2) Seismic loads correspond to the level of the reference earthquake (RE). The purpose of the calculation is to prevent global collapse of the structure or its parts.

To protect the structural system of the building under consideration from seismic effects, recalculations were performed for the longitudinal and transverse pavement beam system.

The repeated calculation taking into account the seismic impact shows that taking into account the implemented structural measures to strengthen the main load-bearing elements for the considered structural system are fulfilled.

According to the table of norms "Loads and Impacts" horizontal displacements of buildings should not exceed the values: for one-storey buildings the limiting displacement is  $h/300$ , where  $h$  - the height of the building - 7.3 m (design value is  $7300/300 = 24.3$  mm).

According to the calculation results, the maximum horizontal displacement for the building is 12 mm, check:  $12 < 24.3$  mm, the condition is met.

## 5 Convergence checks for SCAD and Midas software KE-complexes

One of the important and obligatory works in the scientific and technical support at the design stage is an alternative calculation of the load-bearing system of the building. Such calculation allows to reveal errors in the formation of the design scheme and modeling of structures.

The paragraph of the norms states that adequate calculation models should be used in the design, and the calculations themselves should be carried out with ensured accuracy; therefore, it is recommended to carry out parallel calculations, which use independently developed certified software tools, comparative analysis of design schemes and obtained calculation results.

In order to bring the quality level of design checks to justify design decisions, calculations were performed for two certified, independently developed and tested in practice PEs with a comparative analysis of the obtained results.

The main conclusions of the performed calculations: analyzing the obtained calculation results, some differences in values are recorded. The largest vertical displacements do not differ significantly (about 5 %), and normal stresses maximum and minimum (from 5 to 10 %) are more significant.

The maximum relative error between calculations on the first forms at the first iteration of calculations gives the best convergence and makes up to 5 %, that testifies to good enough convergence of results for program KE-complexes SCAD and Midas.

Compliance of the calculation results is considered sufficient with deviation values not more than 20% according to the norms of the draft set of rules "Scientific and technical support of engineering surveys and design. Basic Provisions". According to the results of convergence calculations, the maximum deviations did not exceed  $10% < 20%$ , the **condition is met**.

## 6 Main results of calculations

As a result of the calculations performed for the first and second group of limit states, checks on the bearing capacity of structures for the over-bore ventilation building of the tunnel structure with regard to seismic impact and emergency collapse have been performed.

The following main computational results were performed and obtained in the course of the research:

1. Two independent building models with different design schemes were built: wall (without columns) and frame-wall (with columns). The use of the automatic reinforcement function significantly accelerates the process of reinforcement placement in monolithic reinforced concrete elements.

2. The expediency of using the basic structure of slabs without columns is shown. The results of comparative analysis of reinforcement of the floor slab of reinforced concrete ventilated buildings are given. Calculations of forces arising in the floor slab are made and optimal reinforcement parameters are selected (design rationality - 18%).

4. The validity of the performed calculations is confirmed by the use of objective and reasonable methods, consistency of the obtained data with convergence of alternative calculations in the software KE-complexes SCAD and Midas.

5. Adjustment of documentation to reduce material and reinforcement consumption with an assessment of the possibility to reduce costs without compromising quality and taking into account the long service life by integrating the BIM 3D calculation model greatly facilitates the process of optimization and visualization of the construction project.

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