THE SUBSTANTIATION OF THE SELECTION OF THE TYPE OF THE FINITE ELEMENT WITH THE ACCOUNT OF ITS IMPACT ON THE ACCURACY OF CALCULATION AT DESIGNING METAL BUILDING STRUCTURES

D. O. KUZMENKO
Master of Engineering Science
(Belorusian-Russian university, the Republic of Belarus)

V. M. FRIDKIN
Doctor of Engineering Science, professor
(Moscow State University of Railway Transport of Emperor Nicholaj II)

I. M. KUZMENKO
Candidate of Science, assistant professor
(Belorusian-Russian university, the Republic of Belarus)

Modern engineering structures used for designing buildings and structures have various types and design variants [1-8].

Load-carrying elements of the metal engineering structures are designed as “rod” elements that are manufactured from metal sheets which are connected in tridimensional rods by “nodal” load-carrying elements (of thick planks – “gusset plates”). Each gusset plate connects adjacent butt-jointed in nodals rod elements in tridimensional rods and finally in the tridimensional structure.

If quite simple building structures (e.g. industrial building door frames that consist of door bolts, columns, trusses etc.) under model engineering and estimation do not require high processing capacity, then estimation of wide-span bridges or floor structures of entertainment facilities demands a vast amount of calculations.

Structures, representing a rod system, can be calculated with the help of volume, shell or beam finite elements.

You can deal with the “complicated” structures (that do not have a uniform section, but with structural elements with a complicated form, made from different materials) only with the help of volume finite elements, with some minor exceptions applying for shell elements.

Nowadays there are lots of software programs that allow within a certain period of time to calculate any engineering structure to the external influence.

The software programs of CAE/CAD systems can solve any problem within a short period of time, therewith they allow to make changes to the structure if this is necessary after the calculations.

The results of experimental verification of the accuracy of numerical models are presented in [9].

In the work [10] the influence of the finite element size on the accuracy of statistical estimation was considered. The requirements that are specified in developing the computer models to the mesh definition of the finite elements are described in the work [11].

However, there are no direct comparisons of the various types of the finite elements and their influence on the accuracy, calculating speed and resource-intensiveness of the problem being solved in these publications.

THE MAIN TYPES OF THE FINITE ELEMENTS AND THEIR FEATURES

Finite element types used in various software complexes, for example, in CAE / CAD Ansys WB, are described in [12, 13]. From all the variety of types of finite elements (FE) for solving the static problem of calculating the rod systems, in our opinion, it is quite sufficient to use FE types of BEAM, SHELL, SOLID.

The size of the finite element of the BEAM, SHELL, SOLID type is standardized by the segment length between the nodes of the element. By that it is meant that the whole element has a uniform section, geometrical characteristics and the material characteristics.

All volume BEAM types have two nodes that can have three or six degrees of freedom on the main coordinate axes.

All volume SHELL types have from four to eight nodes that can have three or six degrees of freedom on the main coordinate axes.

The element SOLID type can change its shape (cube, tetrahedron, hexahedron), depending on the problem to be solved. All volume SOLID types have from eight to twenty nodes that can have three or six degrees of freedom on the main coordinate axes.

Comparative analysis of the accuracy and resource capacity of the solution of the problem of calculating the load-bearing rod elements of metal building structures can be done using finite elements BEAM 188, SHELL 181 and SOLID 186.

We give a detailed description of each of these FE.

BEAM 188 (Figure 1, a) – three-dimensional linear beam element with finite deformations. Element suitable for direct modeling of beam structures with a moderate ratio of length to thickness. It is built on the basis of Timoshenko's beam. It takes into account the effects of tangential (shear) deformations.

It has six or seven degrees of freedom in each node. This includes movements in the direction of the X, Y and Z axes and rotations around the X, Y and Z axes. Under certain conditions, a seventh degree of freedom (cross-sectional deformation) is added. This element is suitable for linear as well as nonlinear problems with large rotations and (or) large deformations.

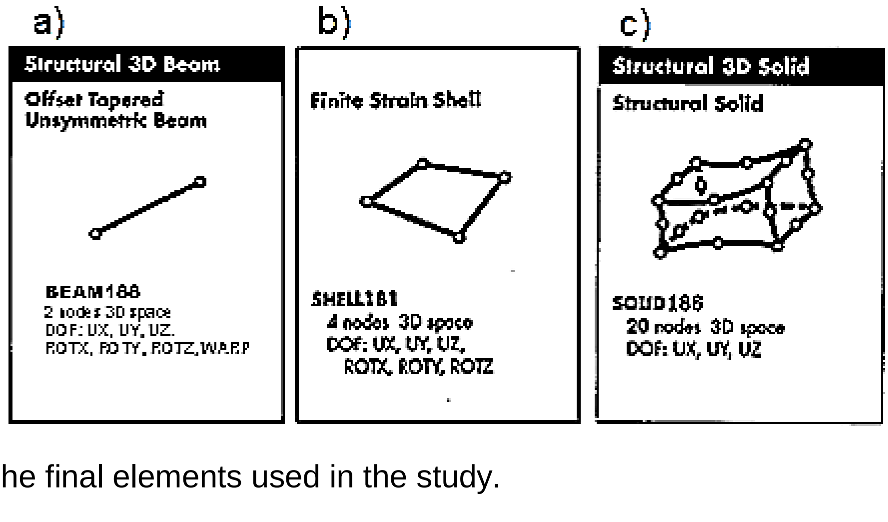

Figure 1. The final elements used in the study.

The element has, by default, the ability to account for the change in stiffness when loaded. The presence of an allowance for the change in rigidity during loading makes it possible to use this element to study stability problems in compression, bending, and torsion (by applying eigenvalues and by studying the loss of stability by the method of searching along the length of the arc).

SHELL 181 (Figure 1, b) – multilayer shell with finite deformations. The element is well suited for calculating shell models with small or moderate thickness. The element has four nodes and six degrees of freedom in each node: moves in the direction of the X, Y, and Z axes of the nodal coordinate system and rotations around the X, Y, and Z axes of the nodal coordinate system. Elements of triangular shape can be used only as transition elements in grids.

It can be used in linear problems and in nonlinear problems with large rotations and (or) deformations. In nonlinear problems, the change in shell thickness is taken into account. As applied to the element, full and truncated variants of numerical integration are supported. The element can be used to calculate multilayer or three-layer shells.

SOLID 186 (Figure 1, c) – three-dimensional (3D) element of a volume stress-strain state with twenty nodes. The element has a quadratic representation of the displacements and is able to use an irregular grid shape (for example, based on models imported from various CAD complexes).

The element is defined by twenty nodes, having three degrees of freedom in each node moving to direction of the X, Y, and Z axes of the nodal coordinate system. It can have an arbitrary orientation in space, has the properties of plasticity, hyperelasticity, creep, changes in rigidity when applying loads, large displacements and large deformations.

Mixed formulation for the calculation of almost incompressible elastoplastic materials and completely incompressible hyperelastic materials. To control the output of data, there are special options. In addition, these CEs allow analyzing the concentration of stresses.

When performing the calculations of the majority of the supporting rod elements, in our opinion, it is necessary to use the FE of type BEAM.

When calculating the load-bearing rod elements with a thin wall, it is necessary to use the FE type BEAM or SHELL.

The most accurate values for the calculation of structures with load-bearing rod elements of any complexity can be obtained using a SOLID-type EC.

PROBLEM OF STATEMENT AND OBJECTS OF THE STUDY

In this paper, the possibility of using more "simple" types of finite elements (FE) is justified, without loss of accuracy of calculation. In this case, the calculation procedure will require less computing resources. This will make it possible to use fairly accurate and least resource-intensive solutions in future studies of large-span structures.

The test objects were considered the simplest rod bearing element and on the other hand, conventionally used in metallic building structures I-shaped cross section (Figure 2, a).

Dimensions: h = 200 mm; b_f = 100 mm; t_f = 8 mm; t_s = 6 mm; ℓ = 3000 mm. Material of the rod is low-alloy steel.

Numerical experiments were performed on bulk, beam and shell models. A static analysis (Static Structural) and a calculation for loss of stability by its own value (Eigenvalue Buckling) were performed.

The results of the numerical MFE experiment were compared with the values obtained by engineering calculation in Construction Regulation Standards Building Code (CRSBC) and Technical Code of Common Practice EN (TCP EN) [14, 15].

The boundary conditions were taken as follows: for a beam working on transverse bending, in accordance with Figure 2, b; to calculate the rod for longitudinal bending (calculation for stability) – in accordance with Figure 2, c. This approach made it possible to disclose the advantages of using certain types of FE depending on the loading of the rod.

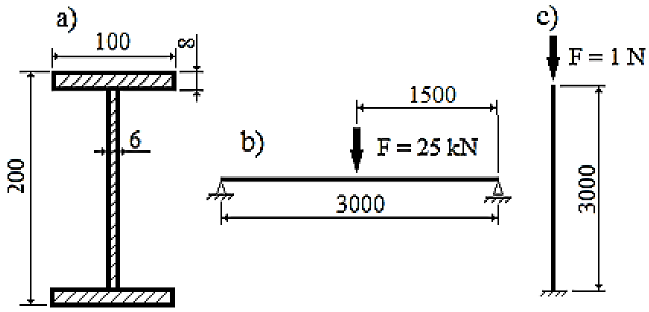

Figure 2. Objects of research: cross-section of investigated models (a); setting boundary conditions (b, c).

The dimensions of the final elements are chosen as follows: for BEAM – 1 mm; for SHELL – 6 [mm]; for SOLID – 2 [mm]. In the study of the loss of stability, the dimensions of the final element were assumed to be equal: for shell FE (SHELL) – 4 [mm] and for volumetric FE (SOLID) 6 [mm].

When using the SOLID type of FE, the normal stresses and deflections were determined in the lower (stretched) layer in the section where the force is applied.

As parameters determining the load-carrying capacity of the rod in transverse bending, normal stresses and deflections are chosen.

In the longitudinal bending of the rod (central compression), the critical forces and the values of the stability factors were determined.

THE ENGINEERING CALCULATIONS OF THE ROD ON THE BEND AND STABILITY LOSS

The engineering calculations based on the Construction Regulation Standards Building Code II-23-81*[14]

Calculation of the strength of the rod for a straight transverse bend. When evaluating strength, the following condition must be met:

$$\frac{M}{W_{n,min}} \leq R_y \cdot \gamma_c,$$

where M – calculated value of the bending moment corresponding to the material reaching the rod in the dangerous section of the yield point;

$W_{n,\,min}$ – moment of section resistance (see Figure 2, a). When this cross-section is used in the elastic stage, we take $W_{n,\,min} = W_{pl} = 1.78689 \cdot 10^{-4}$ [м^3];

R_y – yield strength for steel (we accept 250 [MPa]);

γ_c – coefficient of conditions of the design. It is assumed to be 1.1 (see Table 6 [14]).

The values of the calculated and acting moments in the middle of the span (see figure 2, b) and the maximum normal stresses are shown in Table 1.

Calculation of the deflection value for transverse bending. To ensure the bearing capacity for deflections, the following conditions must be met:

$$f \le f_y,$$

where f – calculated maximum deflection of the beam;

f_y – standard deflection of the beam.

The ultimate deflection according to CRSBC 2.01.07-85 * [15] for the loading scheme (see Figure 2, b) should not exceed L / 150. The Young's modulus for steel is assumed to be 206000 [MPa].

The results of calculating the bearing capacity for deflections are also presented in Table 1.

Calculation according to Technical Code of Common Practice EN 1993-1-1-2009, p. 6.2.5 [16]:

The first limit state. The design value of the bending moment M_{Ed} in each cross-section must satisfy the condition:

$$\frac{M_{Ed}}{M_{c,Rd}} \le 1{,}0,$$

where $M_{c,\,Rd}$ – effective value of the bending moment. It is determined taking into account the design load-bearing capacity for bending in the plastic stage of operation $M_{pl,\,Rd}$, and also the partial reliability factor γ_{M0}. In accordance with 6.1 (1) B and table NP.4 [15], γ_{M0} = 1.025 / 1.1 = 0.932.

By calculation, the specified values of the moments and normal stresses of the correspond to the values obtained by the method of CRSBC II-23-81 * (see Table 1).

The second limit state. Determination of the maximum deflection is carried out according to a constructive criterion. The ultimate deflection in this case should not exceed L / 300. Load deflection (adopted earlier in the CRSBC) f = δ = 0.00382 [m]. Limit deflection according to the norm δ_{limit} = 3/300 = 0.01 [m]. Thus, the deflection from the action of force does not exceed the normative one.

The bearing capacity of the beam with respect to the second limiting state is ensured.

Calculation of the rod for loss of stability.

The calculation was carried out using traditional methods of material mechanics.

Critical Strength (F_{cr}) is a load exceeding which causes the loss of stability of the original form (position) of the body. From the moment of the onset of the critical state to the moment of destruction of the deformation, the systems grow extremely rapidly.

In this way, when calculated for stability, the critical load is similar to the breaking load when calculated for strength. The stability condition is written in the following form:

$$F_{max} \leq F_{cr.}$$

The flexibility of the I-beam cross-section (see figure 2, a, c) λ = 270.3, and the ultimate flexibility of steel λ_u = 100.8.

For $\lambda > \lambda_u$, the critical force was determined by Euler's formula: F_{cr} = 75.35 [kN].

Table 1. Results of the calculation of the rod for transverse bending according to the methods of CRSBC II-23-81 * (clause 1) and TCP EN 1993-1-1-2009 (clause 2)

№	The design moment **M**, [N·м]	Actual moment **M_d**, [N·м]	Maximum normal stresses **σ**, [MPa]	Normative deflection **f_y**, [м]	Limiting deflection **f**, [м]
1	49139.48	18750	104.93	0.00382	0.02
2	54822.96	18750	104.93	0.00382	0.01

CALCULATION OF THE BENDING BODY IN THE ANSYS WB PROGRAM COMPLEX

Figure 3 shows the finite element mesh partitioning and boundary conditions by the example of the solution of the problem, using 3D (finite element type SOLID).

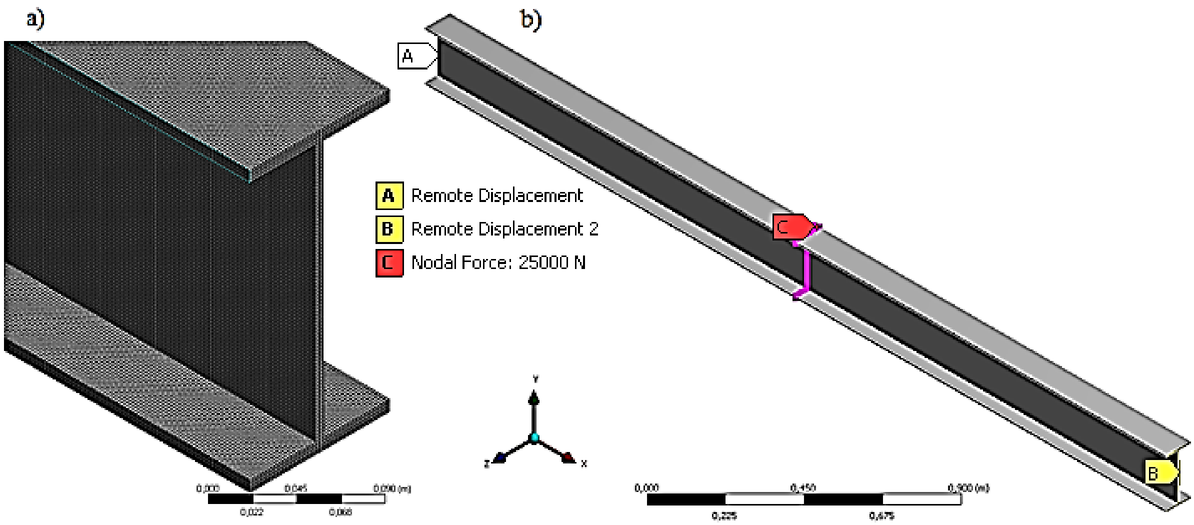

Figure 3. To the calculation of the rod for bending: the fragment of the partitioning of the I-beam into finite elements (a); boundary conditions (b).

For models in which other types of finite elements were used, the boundary conditions were set similarly.

The initial load (see Figure 3, b, marker C) was set with the condition that the resulting stresses do not exceed the tensile-compressive yield strength of steel, which is assumed to be 250 MPa for the basic calculation in ANSYS WB. The ultimate tensile strength is 460 MPa.

Support of the rod (see Figure 3, b, markers A and B) was made at the point of the geometric center of gravity of the crosssection for all models, while for the model with a finite element of the SHELL type three sections of the section (corresponding to two shelves and the I-beam wall) were fixed; for FE type SOLID, the fastening was made behind the end of the beam on the surface, and for the FE type of BEAM – at the extreme points of the element.

The results of the calculations are presented in Table 2 and in Figure 4.

Table 2. Results of the numerical study of the work of the rod on bending with the use of FE of different types

	Finite element type			**Engineering calculation**
	BEAM 188	**SHELL 181**	**SOLID 186**	
Deflection, [mm]	4.1506	4.2209	4.1605	3.82
Normal stresses, [MPa]	104.93	102.40	104.48	104.93
Δ in deflection, %	7.98	10.49	8.91	
Δ on the basis of stresses, %	0	2.41	0.43	

Note: the Δ symbol in Tables 2 and 3 indicates the percentage discrepancies between the results of FEM calculations and engineering calculations for CRSBC and TCP EN.

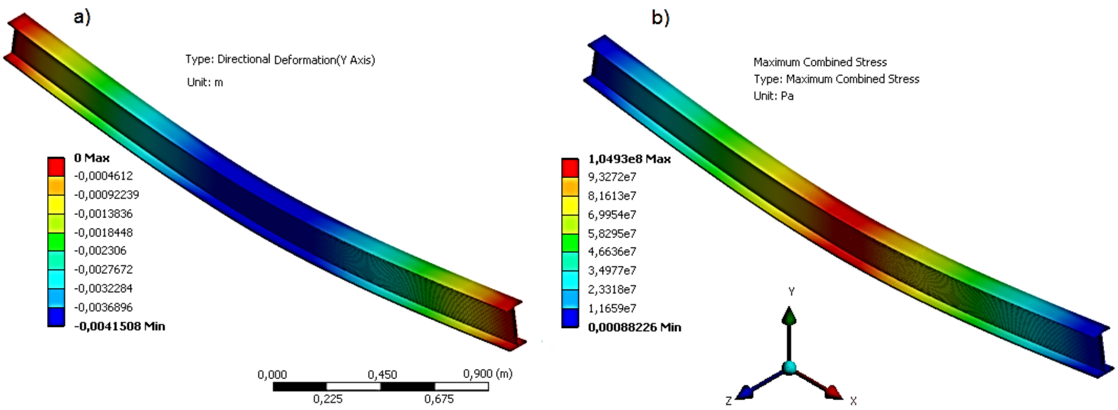

Figure 4. Results of the calculation of the rod for bending (FE of the BEAM type): deflection a); normal stresses b).

WORK OF THE ROD FOR LOSS OF SUSTAINABILITY IN THE SOFTWARE COMPLETE ANSYS WB

We consider the finite element mesh partitioning and boundary conditions on the example of the solution of the problem, using the volumetric (SOLID) type of finite elements (Figure 5).

The support (hard sealing) of the rod (see Figure 5, b, marker A) was made at the point of the geometric center of gravity of the cross section for all models. In this case, for the model with the FE-type SHELL, three faces of the section were fixed (corresponding to two shelves and the I-beam wall), for the SOLID type of cage, the fastening was carried out along the surface of the support section, and for FE of BEAM type – at the end point of the element. The results of the calculations are given in Table 3.

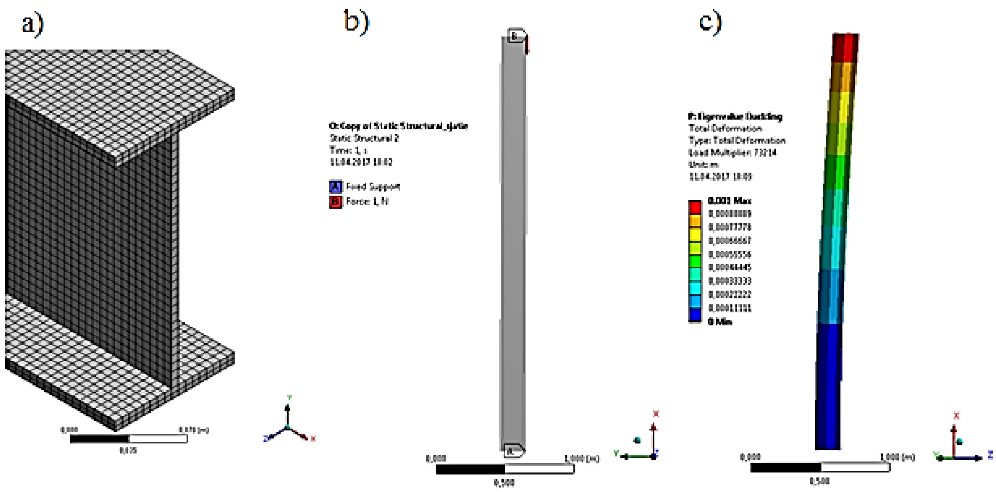

Figure 5. The results of the calculation of the rod for longitudinal bending, (type of SOLID): a fragment of the partitioning of the I-beam into finite elements (a); boundary conditions (b); form of loss of stability (c).

Table 3. Results of a numerical study of the operation of the beam on the loss of stability with the use of FE of different types

	Finite element type			Engineering calculation
	BEAM 188	SHELL 181	SOLID 186	
Critical force, [N]	73312	73200	73214	75350.7
Δ by the critical force, %	2.71	2.85	2.84	

RESOURCEPTIBILITY OF CALCULATION AS DEPENDENT ON THE TYPE OF FE

The resource intensity of the calculation is determined by the time required to complete the calculation, the amount of information the computer operates (the amount of computational RAM, the disk space for calculating and storing equations, the size of the file with the results of the research), and also by the productivity (the computational frequency of the solver of the equations).

The calculations were performed on a computer with the following characteristics:

• Intel (R) Core (TM) processor i7-4790K CPU @ 4.00GHz;
• RAM DDR3 8GB
• WINDOWS x64 platform
• Operating system Windows 7 Service Pack
• Ansys version 17.1
• Calculation modes: a) Static Structural; B) Eigenvalue Buckling

Table 4 shows the results of a comparative analysis of the computational parameters required to calculate the beam for bending.

Table 4. The resource intensity of the calculation, depending on the type of the final element

Analysis parameter	**Finite element type**		
	BEAM 188	**SHELL 181**	**SOLID 186**
Number of cells FE	3000	18424	328000
Number of nodes FE	6001	18852	1718506
The required amount of RAM, [MB]	2112	2112	6421
Required disk space for calculation, [MB]	57	329	6420.99
The size of the results file, [MB]	7,9375	21.75	490.63
The computing frequency of the equation solver, [MFlops]	1670	18480	13034.4
Total processor time, [s]	2	2.8	451

As can be seen from the table, the use of finite elements of the BEAM type has more advantages, with respect to other types (in this case we will make a reservation, with one size considerably exceeding others), both in comparison with engineering calculation and in comparison with saving the PC resource.

CONCLUSION

1. The use of modern software systems based on CAE / CAD systems, and sufficiently powerful personal computers, allows to optimize the calculation of building structures.

2. Comparison of calculation results in the Ansys WB software package and engineering calculation (Table 2) that the closest values of the normal stresses and deflections of the I-beam were obtained using finite elements such as BEAM and SOLID. The finite SHELL element has a greater percentage of discrepancy, and is not recommended for use.

3. When studying the operation of the rod for stability, it is possible to use the FE of all the types considered, although there is some advantage in the FE type of BE (Table 3).

4. The use of FE type BEAM significantly facilitates the work of a personal computer, without loss of accuracy of the calculation itself, especially when calculating large-span structures with a large number of elements of constant cross-section, without requiring large computational resources (Table 4).

5. When calculating the FEM based on CAE / CAD systems of rod elements, one of the dimensions of which considerably exceeds the cross-sectional dimensions, the optimal type of FE is BEAM.

LITERATURE

[1] **Kuzmenko, I.M.** Application of welded load-bearing elements in new composite building structures/I.M. Kuzmenko, S.K. Pavlyuk, V.M. Fridkin // M.: Welding. – 2003. – No. 9. – P. 47-50.

[2] Aspects of designing a composite bearing element using CAD/I.M. Kuzmenko [et al.] // Mogilev: Vestn. Belorusian.-Ros. University. – 2006. – No. 4. – P. 198-202.

[3] **Fridkin, V.M.** Formation of building structures: monograph/V.M. Fridkin. – M.: MGSU, 2011. – 171 p.

[4] **Bogdanov, S. V.** Features of the design of fast-erecting welded walls of vertical cylindrical tanks of composite bearing elements/S.V. Bogdanov // Mogilev: Vestn. Belorusian.-Ros. University. – 2011. – No. 3. – P. 6-16.

[5] Experience of application in the Republic of Belarus of new constructive solutions of span structures of road bridges / I.M. Kuzmenko [and others] // Naukovedenie [Electronic resource]. – M., 2014. – No. 5 (24). – Access mode: http: // naukovedenie.ru/PDF/21KO514/pdf.

[6] **Kuzmenko, I. M.** Belarusian-russian innovation: creation of engineering structures of the XXI century / I. M. Kuzmenko, V. M. Fridkin, S. N. Markov // Proceedings of the METNET – Seminar 2015. – Hungary: University of Applied Sciences, 2015. – P. 40-51.

[7] **Фридкин, В. М.** Engineering facilities of underground power engineering: monograph: V. M. Fridkin, S.A. Chesnokov, A.E. Kokosadze. – M.: ASV, 2015. – 119 p.

[8] **Kuzmenko, I.M., Fridkin, V.M.** Prospects for the development of building structures of engineering structures: monograph. – Mogilev: Belorusian.-Ros. Univ., 2017. – 171 p.

[9] Experimental verification of the accuracy of numerical models in the study of deformation fields in fast-erecting objects from composite bearing elements / S.V. Bogdanov [et al.] // New materials, equipment and technologies in industry: materials of the Intern. Scientific-techn. Conf. Young scientists. – Mogilev: Belorusian.-Ros. Univ., 2013. – P. 119.

[10] **Lagerev, I.A.** Influence of the size of the finite element on the accuracy of the static calculation of the load-bearing metal structure of the overhead crane / Journal of Science and Modernity. № 32-2 / 2014, BSU them. Ak. I.G. Petrovsky, Bryansk. –P. 36-40.

[11] **Shimanovsky, A.O.** Application of the finite element method in solving problems of applied mechanics: the teaching method. Manual for students of technical specialties / A.O. Shimanovsky, A.V. Putyato; Ministry of Education of the Republic of. Belarus, Byelorussia. State. Un-t trans. – Gomel: BelGUT, 2008. – 61 p.

[12] **Basov, K.A.** ANSYS in examples and problems / K. A. Basov. – M.: Computer-Press, 2002. – 224 p.
[13] **Basov, K.A.** ANSYS: user's guide. – M.: DMK Press, 2005. – 640 p.
[14] CRSBC II-23-81 *. Steel structures / Gosstroy USSR. – M.: TsITP Gosstroy USSR, 1990. – 96 p.
[15] CRSBC 2.01-07-85 *. Loads and effects / Gosstroy USSR. M.: TsITP State Building of the USSR, 1986. – 36 p.
[16] Eurocode 3. Design of Steel Constructions. Part 1-1. General rules and rules for buildings: TCP EN 1993-1-1-2009. – M: MAIS, 2010. – 85 p.