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Analytical and numerical estimates of the stress state of units of a mining shovel boom

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Abstract. The boom units of a mining shovel are structurally complex metal structures of large dimensions. Traditional methods of design calculations for such structures are based on beam-type structural models, while the actual configuration is taken into account by introducing complex built-up sections which include sections of pipes, sheets, and ribs. The correspondence of such beam-type structural models has not been systematically studied yet, which leads to crack initiation and destruction of structures on the one hand and to an unreasonably high use of metal on the other. As a result of numerical analysis of the boom units in three-dimensional statement, the actual errors of beam-type structural models in characteristic sections of structures in the most complex design cases of mining shovel loading have been determined and analysed.

1. Introduction
The selection of design schemes and models of structurally complex load-bearing structures of technical objects is typically a complicated task and largely determines the correspondence of the obtained results to the actual behaviour of the structure [1, 2]. The choice of a certain design model of a beam, frame, plate, or shell for a real object is not always obvious.

The calculations of structures that use beam-type (bar-type) structural models are widely used in designing technical objects regardless of their application field. The advantages of beam-type approximations are: well-developed theoretical approaches (structural mechanics of bar systems, strength of materials), low dimensionality of design models, as well as the estimations of ability to withstand the main effects of mechanical behaviour (deformations) for objects of various configurations. The listed advantages however suggest the need for additional studies of correspondence of beam-type approximations to the deformation mechanics of a particular object, justifications for the applicability of known design schemes and models, and analysis of uncertainty of the obtained results. The reason for this is that not always the deformation mechanics of real objects corresponds to the hypotheses and assumptions (plane section hypothesis, small size of sections compared to the beam span etc.) which the development of beam-type structural models is based on. In this case, the calculation data may be either underrated or overrated by a previously unknown value, which does not allow reasonably minimizing the use of metal and avoiding crack initiation and destruction during operation.

Here are some examples of evaluating the correspondence of the results obtained by using beam approximations. The results of the study of the stressed state of bones that uses three-dimensional finite-element models and beam-type structural models [3] show that the uncertainty of the latter in calculating principal stresses is 142 % for compressing, 12 % for bending, and 14 % for torsion. The

results of beam solutions for problems of stability of a rectangular linearly elastic isotropic plate weakened by a central crack [4] are found to be incorrect: the dependence of the critical load on the crack length obtained by using analytical methods of the three-dimensional theory of stability of elastic bodies and rough beam approximation was studied. Along with that, the difference in the results of the finite element analysis of natural frequencies and forms of free vibrations of the wind generator blade with a section variable in length performed in three-dimensional statement by using a beam-type model turned out to be not more than 2.5 % [5]. It is obvious that the magnitude of error of beam approximations must be determined for each object taking into account its configuration and loading conditions. It determines the relevance of comparative study of analytical and numerical analysis of the stressed state of technical objects structures, the design calculations of which are typically conducted by using beam-type structural models.

2. Problem formulation

The subject of this study is the metal structure of the mining shovel boom comprised of hinged lower I and top II units (Fig. 1). Both units are made of 09G2S steel and consist of pipes 1 (figure 1 shows parts of similar type in the same colour), castings 2, ribs 3 and shaped metal sheets 4 welded together. The total length of the boom is about 18 m, sections of pipes amount to 600×16, 600×14, 426×9 and 426×25 mm, sections of ribs amount to 10, 20 and 25 mm, section of the shaped metal sheet amounts to 10 mm.
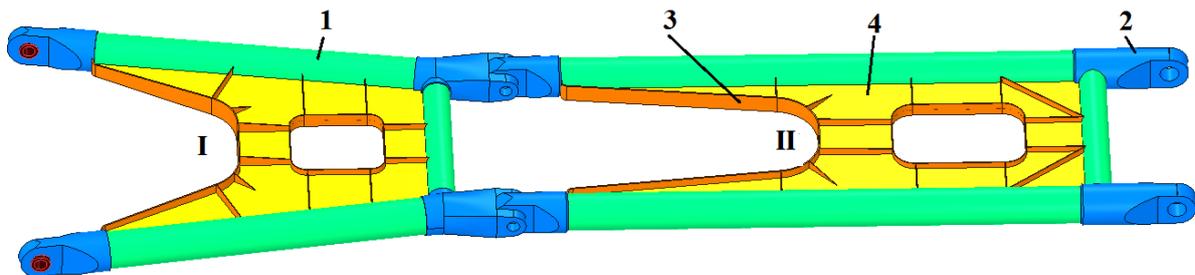
Figure 1. EKG-12,5 mining shovel boom: I is lower unit; II is top unit; 1 are pipes; 2 are castings; 3 are ribs; 4 are metal sheets.

In the engineering practice of domestic excavator manufacturing, design calculations of booms were traditionally accomplished by using beam approximations. Despite the wide use of computer assisted design and engineering systems (CAD and CAE systems), equipment fleet of mining companies still contain a considerable number of machines manufactured several decades ago and designed by using traditional methods and beam-type structural models. When analysing operational faults and reliability, the question about the contribution of uncertainty of these methods and design models to the formation of conditions for cracking and destruction arises.

The object of this study is the stressed state of the boom units in typical design load cases.

The objective of this study is to obtain and compare the results of analysis of the stressed state in characteristic sections of boom units by using beam approximations based on methods of structural and theoretical mechanics and three-dimensional finite-element simulation.

3. Design load cases, schemes, models and methods

Design load cases reflect the most heavy-duty operating modes and are determined for different combinations of hoisting and thrust forces, self-weight in static and dynamic (by taking into account inertial effects) statements. For the top unit of the EKG-12,5 mining shovel boom, normal (cases A, B) and emergency (case C) design cases are characterized as follows:

Case A: hoisting force is 130 tf, self-weight, dynamic factor for hoist ropes is 1.5.

Case B: inertial forces occurring when turning with a loaded bucket during braking with an acceleration of 0.08 m/s^2, self-weight.

Case C: hoisting force is 130 tf, self-weight, dynamic factor for hoist ropes is 2.0, the load between the boom beams is distributed unevenly at the ratio of 0.25:0.75.

For the bottom boom section, the corresponding load cases are characterized as follows:

Case A: hoisting force is 130 tf, thrust force is 60 tf, self-weight, dynamic factors for hoist and thrust ropes is 1.5.

Case B: inertial forces occurring when turning with a loaded bucket during braking with an acceleration of 0.08 m/s^2.

Case C: hoisting force is 130 tf, thrust force is 60 tf, self-weight, dynamic factors for hoist and thrust ropes is 2.0, the load between the boom beams is distributed unevenly at the ratio of 0.25:0.75.

The representation of an actual three-dimensional object in beam-type structural models is not obvious or one-valued: in most cases, alternative beam approximations are possible. In this study, beam-type structural models (frames) used for design calculations of the mining shovel boom at the Izhorskiy Heavy Equipment Plant are analysed (figure 2).

(a)   (b)   (c)   (d)
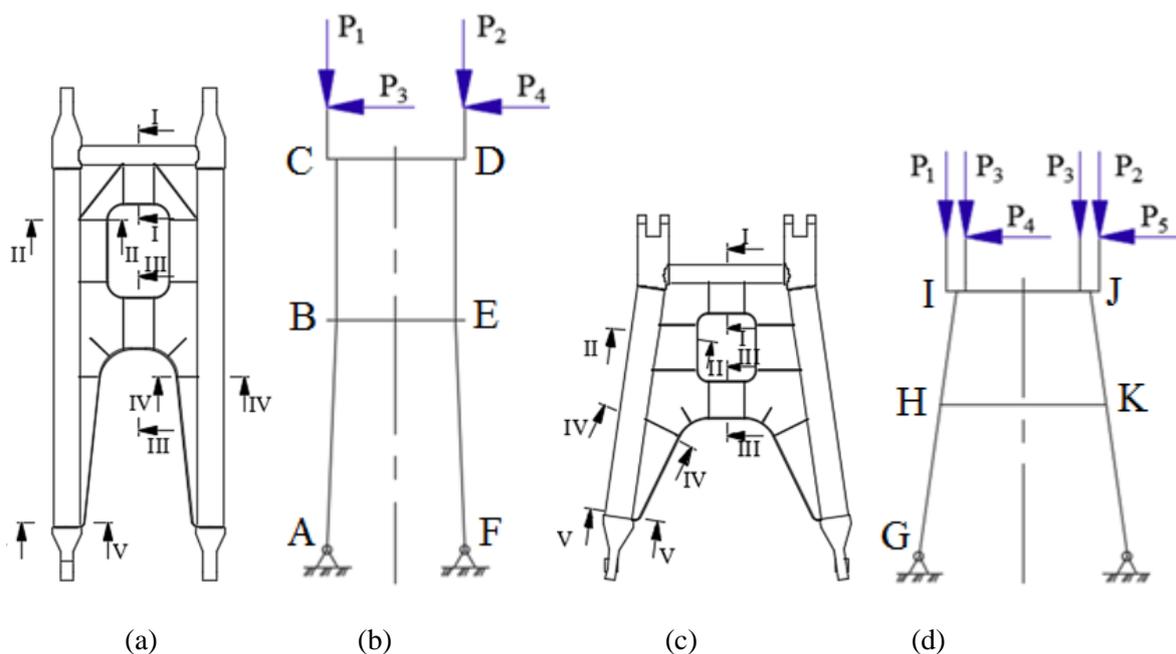
Figure 2. Characteristic sections (a, c) and beam-type structural models (b, d) of the top (a, b) and lower (c, d) boom units.

Analytical and numerical analysis of the stressed state is further reviewed in five characteristic sections of the beam-type structural model (figure 2, a, c, and table 1).

Stresses for the structural models (figure 2, b, d) under examination are determined by using equilibrium equations that reflect force polygons constructed for the considered design load cases (table 2). Then, the canonical equations of the work method were composed and solved, which allowed to determine the forces and moments in beams AB, BC, CD, BE, EF (figure 2, b), GH, HI, IJ, HK (figure 2, d) containing the design sections of the boom (table 1). For these sections, the stresses in the extreme fibres the most distant from the neutral axis of the section were calculated using the known equations of the material strengths (table 3). The reason for this is that in accordance with the theory of material strength, the maximum bending and torsion stresses occur in the extreme fibres of the section.

As an alternative approach to determination of the stressed state of sections, a numerical (finite element) solution of a three-dimensional linear elasticity problem with the use of solid finite elements was employed. In order to take into account the three-axis nature of deformation and ensure the required accuracy of the analysis, discretization of the model was as fine as possible so that there were several layers of finite elements over the thickness of thin-walled parts, and the mesh independence

condition was fulfilled. The number of nodes of the finite-element models of the top and bottom units amounted to about 1.7 and 1.3 million, respectively. The analysis is executed for the calculated load cases according to table 2, the results expressed in the von Mises equivalent stresses are obtained for the design sections according to table 1.

Table 1. Design sections of the boom

Section	Top unit	Lower unit
I-I		
II-II		
III-III		
IV-IV		
V-V		

In order to ensure comparability of the results of numerical and analytical analyses, stresses in the extreme fibres of the studied sections were recorded as well. However, in comparison with the beam-type structural models, solutions in three-dimensional statement sometimes allow to establish the presence of maximum stresses not in the extreme fibres of the sections. The reason for this is a significantly different nature of deformation of beams and three-dimensional parts. Thus, for example, according to the numerical analysis results, stresses in the I-I cross-section of the bottom boom section

in the calculated load case C at the cross-section points which correspond to the extreme fibres in the beam-type structural model are 52 and 54 MPa (figure 3). Meanwhile, the maximum stress of 60 MPa is observed at a point which does not correspond to the extreme fibre.

Table 2. Forces of the design load cases

Load case	Forces (top unit / lower unit), N				
	P_1	P_2	P_3	P_4	P_5
A	2099340 / 2133673	2099340 / 2133673	– / 552303	– / 68670	– / -68670
B	676890 / 1105587	676890 / 434583	77793 / 261927	24525 / 91429	– / 30705
C	4051530 / 4806900	1422450 / 2226870	– / 735750	– / 113207	– / -113207
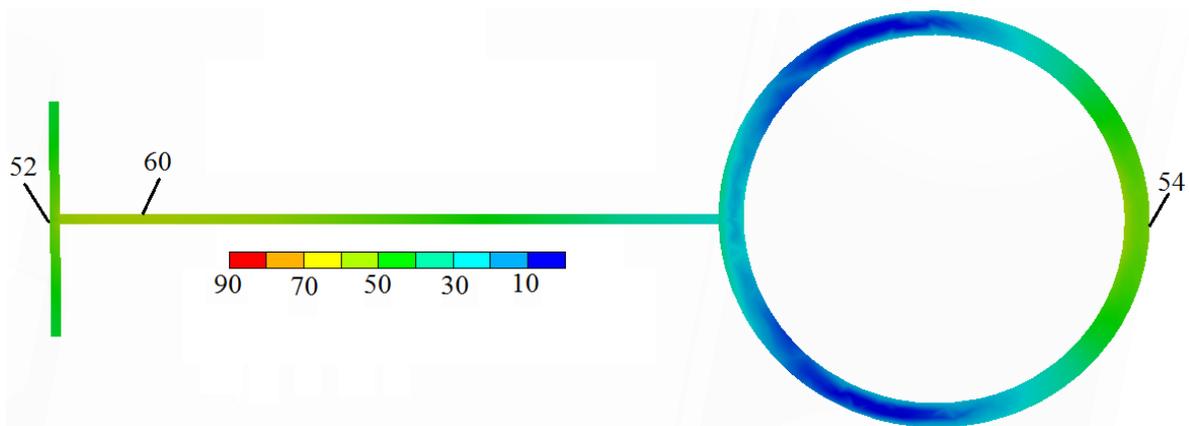
Figure 3. Equivalent stresses in section I-I of the lower boom unit in design load case C.

Table 3 summarizes the results of numerical analysis of stresses in the design sections. The results for sections which are assumed to be the most stressed ones in a particular design load case are shown. The maximal stresses found not in the extreme fibres were recorded as well.

4. Comparative study of analytical and numerical estimates of stresses in characteristic sections of boom units

Let us analyse a summary table of stresses in the characteristic cross-sections of the boom units in the design load cases under examination (table 3). As one can see, the results of analytical and numerical stress analysis correlate rather well with each other in general. This fact indirectly confirms the absence of errors in both analytical and numerical analyses.

Table 3. Maximum stresses in cross-sections of the boom units, MPa

Section	Estimate	Top unit			Lower unit		
		Case A	Case B	Case C	Case A	Case B	Case C
I-I	Analytical			36.2			61.7
	Numerical			33.7			54.0; 60.0 [a]
II-II	Analytical	76.5	24.4	143.6	86.5	46.5	198.0
	Numerical	63.4; 71.4 [a]	22.3; 28.1 [a]	139.1	110.0	61.2	244.7
III-III	Analytical			28.8			82.8
	Numerical			11.3; 16.8 [a]			58.0; 89.6 [a]
IV-IV	Analytical	58.6	27.4	127.0	60.4	36.4	150.6
	Numerical	101.5	16.2	112.5	77.5	45.9	176.3
V-V	Analytical	83.0	40.0	154.0	93.5		177.0
	Numerical	69.1; 136.9 [a]	43.5	134.0; 255.0 [a]	62.3; 153.0 [a]		135.9; 240.0 [a]

[a] Maximum stress is not in the extreme fibers

The comparative study results showed the following.

There are no values that systematically exceed other values: in some cases, the analytical values are bigger, in other cases, the numerical values exceed the analytical ones.

In 42 % of estimates (9 out of 21 ones), the maximum stress is not in the extreme fibres, which is inconsistent with the idea of beam approximation. This is evidence of a more complex nature of deformation than the one described by the beam-type structural models.

For the V cross-section of both the top and bottom units, the numerical values exceed the stress level specified by the design regulations. Thus, the yield strength of rolled 09G2S steel of up to 20 mm in thickness is 325-345 MPa. Then, for the safety factor of 1.5, the permissible stresses under static loading are 325/1.5 = 216 MPa. According to the analytical estimation results, the yield strength condition is fulfilled in all sections. However, numerical estimation results indicate a violation of the yield strength condition in the emergency load case C. It does not mean that the structural elements will collapse under single loading, but it indicates the risk of a rapid accumulation of fatigue damages in this section.

5. Discussion of the results

Let us consider possible reasons for the differences between the results of analytical and numerical analysis of stresses.

Let us characterize the ratio of beam lengths in the structural models of units (figure 2, b, d) and the maximum dimensions of cross-sections. The lengths of the beams are $l_{AB} = l_{FE} = 5500$ mm, $l_{BC} = 3470$ mm, $l_{CD} = l_{BE} = 3200$ mm, $l_{GH} = 3900$ mm, $l_{HI} = 2640$ mm, $l_{HK} = 4440$ mm, $l_{IJ} = 3200$ mm. The maximum section dimensions (table 1) of the top unit are $l^{It} = 1326$ mm, $l^{IIt} = 1200$ mm, $l^{IIIt} = 1190$ mm, $l^{IVt} = 1045$ mm, $l^{Vt} = 710$ mm. Accordingly, the dimensions of the lower unit are $l^{Ib} = 1086$ mm, $l^{IIb} = 1400$ mm, $l^{IIIb} = 830$ mm, $l^{IVb} = 1320$ mm, $l^{Vb} = 762$ mm. Subsequently, the ratio of the length of the beam to the dimension of its cross-section is $l_{CD} / l^{It} = 3200 / 1326 = 2.4$; $l_{BC} / l^{IIt} = 3470 / 1200 = 2.9$; $l_{BC} / l^{IIIt} = 3200 / 1190 = 2.7$; $l_{FE} / l^{IVt} = 5500 / 1045 = 5.3$; $l_{AB} / l^{Vt} = 5500 / 710 = 7.7$; $l_{IJ} / l^{Ib} = 3200 / 1086 = 2.9$; $l_{HI} / l^{IIb} = 2640 / 1400 = 1.9$; $l_{HK} / l^{IIIb} = 1440 / 830 = 5.3$; $l_{GH} / l^{IVb} = 3900 / 1320 = 3.0$; $l_{GH} / l^{Vb} = 3900 / 762 = 5.1$. As one can see, one of the main conditions that the beam design theory is based on is not fulfilled, which is a significant excess of the length of the beam over the dimension of its cross-section.

The boom units are comprised of a large number of structural stress raisers. They include local welding areas of pipes, ribs, and a shaped metal sheet. The beam-type structural models do not allow to take into account the impact of stress concentration, while the numerical three-dimensional analysis of the stressed state shows all the characteristics of the redistribution of power flows and stress concentration in the areas of sudden changes in the section geometry.

In some cases, the study of the numerical analysis results shows a significant change in the stresses over the thickness of the sections. This confirms the presence and relevance of the impact of the volumetric stress state, which cannot be taken into account by the beam-type structural models.

6. Conclusion

Despite the listed reasons for differences in analytical and numerical results, the examined analytical beam-type structural models for the units of the mining shovel boom allow to determine their stressed state with accuracy acceptable for ensuring the static load strength of structures. It is problematic however to ensure fatigue and dynamic load strength based on analytical analysis results. Hence, at the stage of design calculations of mining shovel structures, it is necessary to validate, develop and test numerical design schemes and models reflecting all the peculiarities of the systematic interaction of structural elements. As for an equipment fleet in use, the determination of its stressed state using numerical analysis can be used to improve the accuracy of forecasting its technical condition and operational life in order to improve equipment operational reliability.

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