The effect of restraints type on the generated stresses in gantry crane beam

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Abstract. This paper includes an analysis of the mechanical phenomena in the gantry crane beam, because the cranes are currently one of the most common devices for the transporting loads. Designing modern mechanical structures is a complex task that requires the use of appropriate tools. Such a modern tool is the numerical simulation, which uses different numerical methods. One of the best known methods is the finite element method, also used here. Simulations are limited to analysis of the strength of the gantry crane beam that was the loaded of the force load movement along its length. The numerical analysis was made to the gantry crane beam which cross-section was an I-beam and ends were fixed in different ways. As the result of numerical calculations, the stresses and displacements of the structure of gantry were obtained. The influence of the restraints type and changing the loading force position on generate the Huber-Misses stress in the gantry crane beam was estimated. The aim was to ensure that the maximum equivalent stress generated in the gantry crane beam was less than the strength of material, because then the construction is safe.

Keywords: numerical modelling, stresses analysis, computational mechanics, FEM

1 Introduction

The cranes are currently one of the most known devices for lifting and transporting horizontally heavy load from one position to another. They are applied in heavy industry, shipyards, car factories and auto workshops. The new design or improve existing mechanical constructions of cranes is a complex task that requires use of appropriate tools [1]. Such a modern tool, that make possible to analyze strength parameters of designed structures, appears to be numerical simulation which usually uses the Finite Element Method (FEM) [2-7].

Finite element analysis software offers inexpensive solutions to the problem of crane girder failure and is the primary tool for helping us identify the cause of the problem, and recommends solutions. Therefore the numerical simulation should be adopted as standard tool in failure [1]. When analyzing works on the study of these problems, it is noted that different types of finite elements are used in MES because it appears that this has an effect on the received results of numerical simulations [2, 3]. In paper [2] the finite element meshes with 4-node tetrahedral and 4-node quadrilateral shell elements were generated

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from the solid and shell models of FEM, respectively. After a comparison results of the finite element analyses with the conventional calculations and the measurement performances on the existing crane, it was found that the analysis using quadratic shell elements give the most realistic results. Other researchers using the solid and shell elements in FEM did not notice significant differences in the results of numerical simulations [3]. It is supposed that the reason of this situation was too great element dimension along the beam length in case using the solid element [2].

Analysis of the load motion is an important issue in the design of large gantry cranes [8]. Usually, the load movement is neglected in numerical simulations and analysis is performed for one position of load force in the center of the beam length [2-4, 6]. Numerical simulations that allow for the analysis of mechanical phenomena in subsequent positions of the load force along the whole length of the beam can be found in [5] and are presented in this paper.

The aim of this paper is to obtain information relating to the boundary conditions what should be assumed, in what number and how to position them, so that they do not cause an increase of stress in the gantry crane beam. The problem of stress concentration and localization of maximum displacement will also be discussed. Therefore, numerical simulations for different cases of beam fixing were performed to obtain the distribution of stresses and displacements in the gantry crane beam. The value of the calculated stresses is compared to the allowable stresses of the beam material. If they are less than the allowable stresses, then it is considered that the structure is safe.

2 The mathematical model of mechanical phenomena

The analysis of mechanical phenomena in elastic range is based on classic equilibrium equations, supplemented by constitutive relations and boundary conditions. The mathematical description is based on solving the following set of equations [5, 9, 10]:

– the equilibrium equations:

$$\sigma_{ij.j} = 0, \qquad \sigma_{ij} = \sigma_{ji}\,, \tag{1}$$

– the constitutive equations – general Hook's law:

$$\sigma_{ij} = D_{ijks}\varepsilon_{ks}\,, \tag{2}$$

– the Cauchy's equations:

$$\varepsilon_{ks} = \frac{1}{2}(u_{k,s} + u_{s,k})\,, \tag{3}$$

where σ_{ij} is stress tensor, ε_{ks} is strains tensor, u_i is displacement vector, D_{ijks} is matrix of elasticity (a tensor of material properties).

Equation (1) is completed by boundary conditions (displacements), which are assumed to ensure the static determination of considered system [5, 7, 9, 10]:

$$\sigma_{ij}n_j = p_i\big|_{\Gamma}, \quad u_i = u_i\big|_{\Gamma}\,, \tag{4}$$

where p_i is components of force per unit area acting on a plane (Γ) with normal n_j.

The numerical model uses FEM and is derived from the criterion of weighted residuals method [4-7]. Equation (1) is multiplied by the weighting function and integrated over the considered region. As the result of using Gauss-Green's theorem and Galerkin's method, which were described in the work [7], the following matrix equation is obtained [5, 9, 10]:

$$\mathbf{K} \cdot \mathbf{u} = \mathbf{R}, \tag{5}$$

where **K** is the element stiffness matrix, **u** is the vector of nodal displacement, **R** is the vector of nodal forces resulting from the boundary load.

By solving the matrix equation (5), nodal displacement is obtained in the area under investigation. Then, using the equations (3) and (2), the searched stress fields are obtained.

3 Description of the problem

To analyze the influence of beam restraint type and position of beam load force on the stress distribution in gantry crane, the static system of beam shown in Figure 1 was considered. The gantry crane beam with a length 4.8 m is restrained on two supporting column with a width of 0.6 m or as described in the variants defined below. One end of the beam (right) can not move in three directions and the second end (left) is free to shift along the z-axis or can not move in three directions, in according to variant restrain. Cross section of the beam is I-beam with dimensions 300x125x10 mm (Fig. 1).

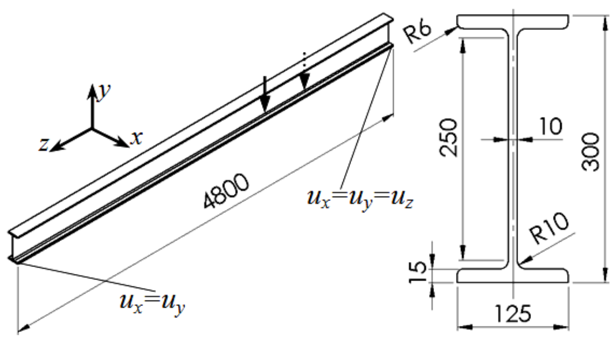

Fig. 1. Scheme of the test problem, I-beam cross section of the gantry crane beam

The structure is loaded by pressure perpendicular to the lower flange of the beam and directed downwards, i.e. opposite to the y-axis. The pressure value is due to the total weight of the loaded crane trolley that can move along the lower flange of the gantry crane beam. The crane trolley movement is carried out by shifting the pressure that acts on the contact surface of the trolley wheels with the beam to the next positions along the crane beam, ignoring the effects of inertia. The assumed pressure value of 13 513 513.514 Pa multiplied by the contact surface of the trolley wheels with the beam corresponds to the force load equal to 50 kN. The loads were taken into account in the elastic range and therefore the elastic constants were assumed, corresponding to the steel S235: Young's modulus (E) equal to 2.1x10^5 MPa, the Poisson's ratio (v) of 0.28 and the yield strength (R_e) of 235 MPa [2-6]. Value of the allowable stress the steel beam material (σ_{all}) amounts to 120 MPa. The value of these stresses results from the division of the yield strength by the safety factor that is assumed to be of 1.98. The safety factor should be set up in the range from 1.5 to 3 for the crane girder project in accordance with the recommendations [2, 3].

Analysis of the stresses of the gantry crane structure was performed using professional software (Star module), supplemented by an additional procedure movement of force. The gantry crane beam was discretized by a mesh 39 003 nodes, which define 19 224 finite elements. In this study, a parabolic tetrahedral solid element is used. Research carried out in order to increase the strength of the structure of the gantry crane allow for the evaluation of the stress state, indicating the critical areas and values.

4 Results and discussion

In order to simulate considered phenomena, the advanced numerical methods are used. Numerical analysis of the stresses, strains and displacements of the one-beam gantry crane structure was made using finite element method. The influence of restraints type on the generated stresses in gantry crane beam has been analyzed. To obtain stress distribution and displacement in the gantry crane beam, the numerical simulations were performed for various beam restraining cases (Figs 2-13). The difference between these cases of fixing the ends of the beam is due to the number of zero displacements and their placement on the crane beam.

The following variants of restraint were taken into consideration:

- I restraint variant: one end of the beam (left) is free to shift along the *z*-axis (displacement equal to u_x=u_y=0) and the other end can not move in three directions (u_x=u_y=u_z=0) (Figs 2-7).
- II restraint variant: left and right end of beam can not move in three directions (u_x=u_y=u_z=0) (Figs 8, 9).
- The displacement of the finite element nodes located on the contact surface of the crane beam with the support column are set to zero in the directions given in variant I or II.
- III restraint variant: displacements are set to zero at point (u_x) and on the line (u_y, u_z) laying in 0.6 m from the right end and at point (u_x) and on the line (u_y) laying in 0.6 m from the left end of beam (Figs 10).
- IV restraint variant: displacements are set to zero at point (u_x) and on the line (u_y, u_z) laying in 0.6 m from the right end and at point (u_x) and on the line (u_y, u_z) laying in 0.6 m from the left end of beam (Figs 11).
- V restraint variant: displacements are set to zero at point (u_x) and on the line (u_y, u_z) laying on the right end and at point (u_x) and on the line (u_y) laying on the left end of beam (Figs 12).
- VI restraint variant: displacements are set to zero at point (u_x) and on the line (u_y, u_z) laying on the right end and at point (u_x) and on the line (u_y, u_z) laying on the left end of beam (Figs 13).

The effect of changing the loading force position on generate the equivalent stress (σ_{eq}) in the crane beam was evaluated. The Huber-Misses-Hencky stress distribution in the gantry crane beam (I-beam) for various positions of load force identified *z*-coordinate are shown in Figures 2-5. The strength condition was checked using the value of generated stresses in successive loading force positions. It sought to that the maximum value of Huber-Mises-Hencky stress induced in the gantry crane beam was less than the strength of beam material ($\sigma_{eq} < \sigma_{all}$), because then the design is safe. The strength condition has not been met in all cases of beam attachment (III and V variant). Generally, the area of increased stresses is related to the current position of the load force and shifts with it, achieving a maximum value in the middle of the beam length, but not in all cases of attachment. The displacement of the gantry crane structure is shown in Figure 6, 7 and 9. They reached a maximum value for the central position of load force (Figs 6, 9). In order to verify the value of the displacement obtained, the ratio of vertical displacement in the half of the beam to beam length should be checked. The research performed allows the evaluation of the stress state, pointing out the critical areas and values. They were made in order to increase the strength of structure of the gantry crane.

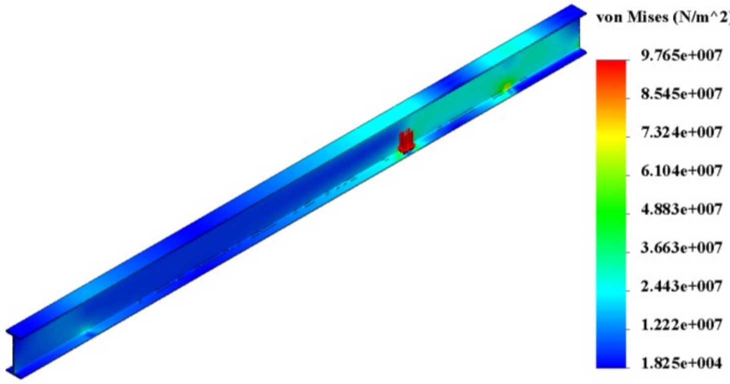

Fig. 2. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 1.5 m, I variant

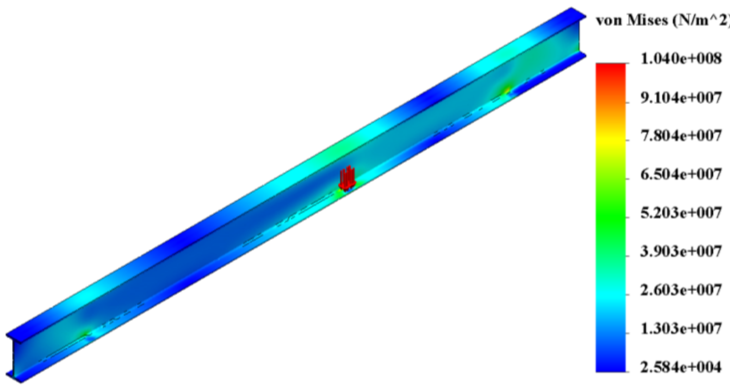

Fig. 3. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2 m, I variant

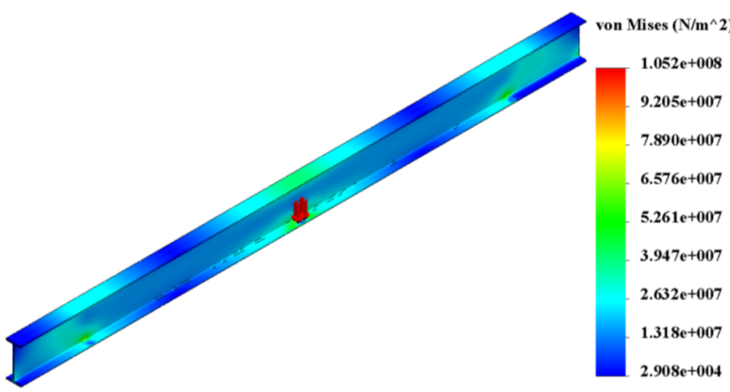

Fig. 4. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2.4 m, I variant

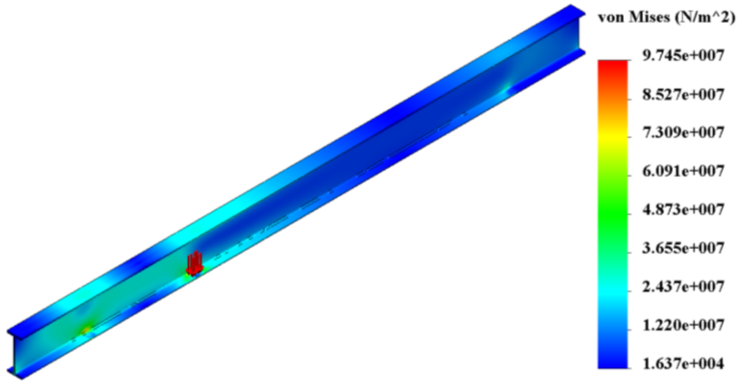

Fig. 5. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 3.3 m, I variant

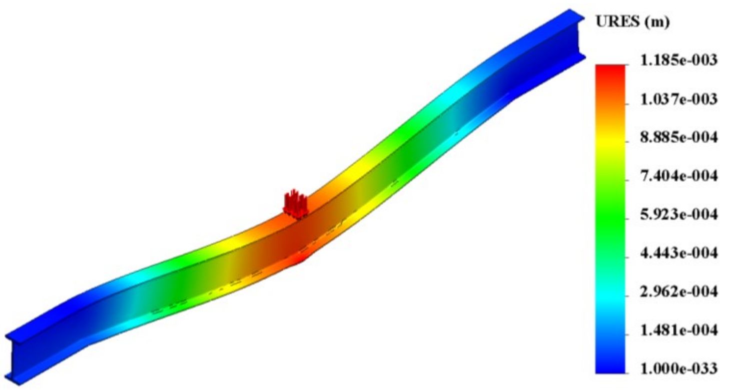

Fig. 6. Displacement field in the gantry crane beam for location of the force load z = 2.4 m, I variant

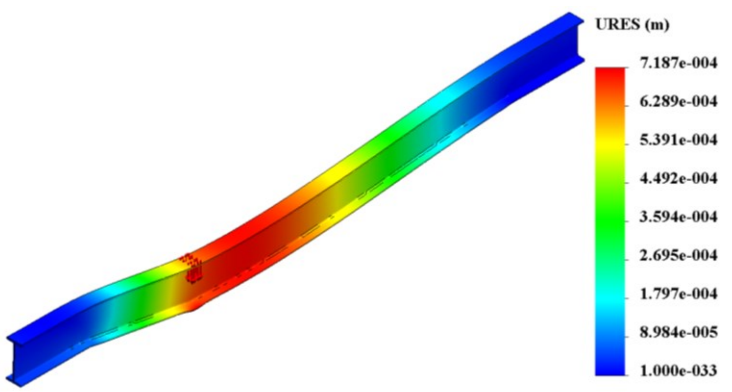

Fig. 7. Displacement field in the gantry crane beam for location of the force load z = 3.3 m, I variant

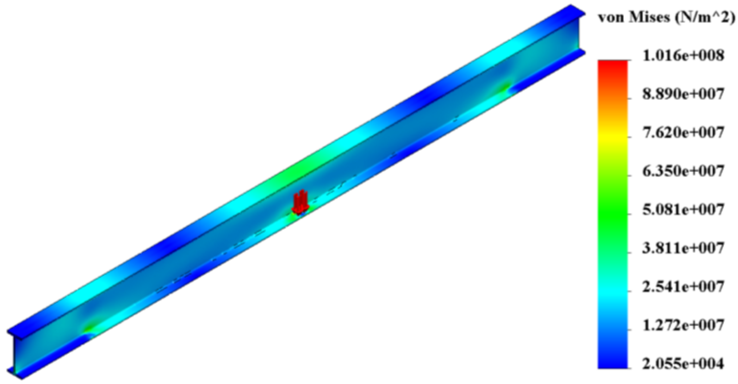

Fig. 8. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2.4 m, II variant

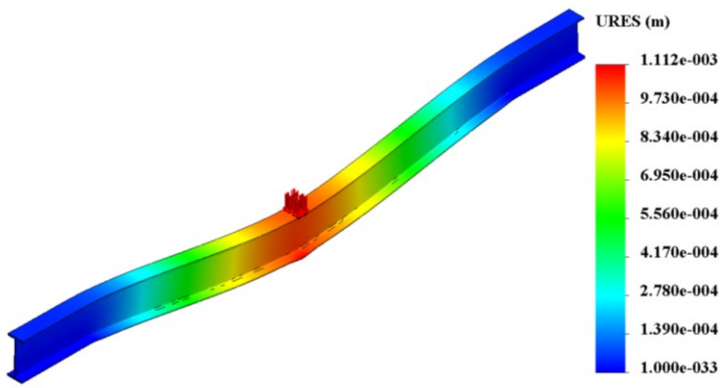

Fig. 9. Displacement field in the gantry crane beam for location of the force load z = 2.4 m, II variant

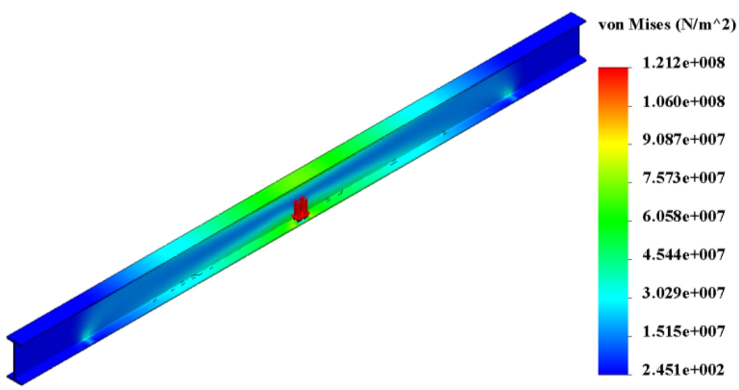

Fig. 10. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2.4 m, III variant

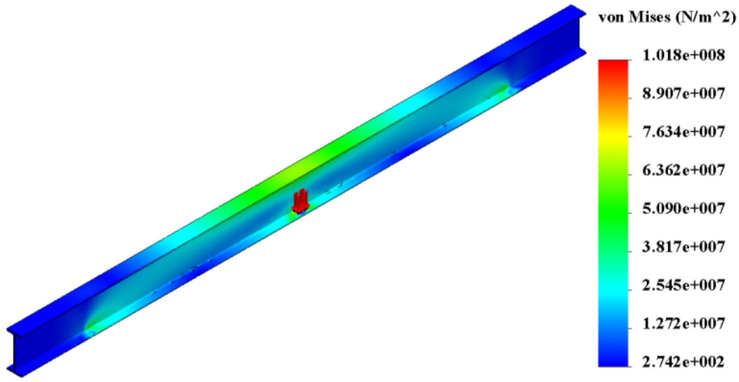

Fig. 11. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2.4 m, IV variant

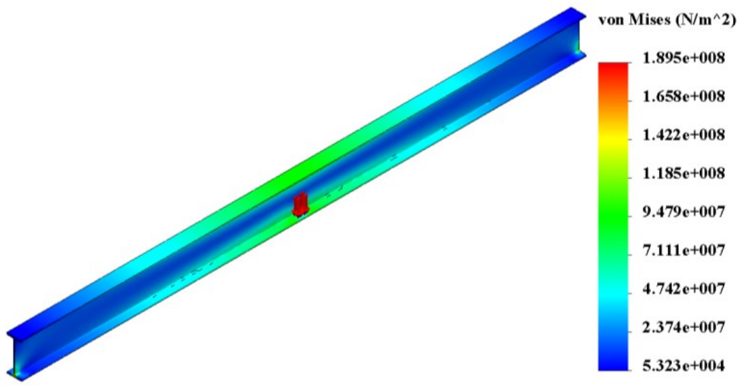

Fig. 12. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2.4 m, V variant

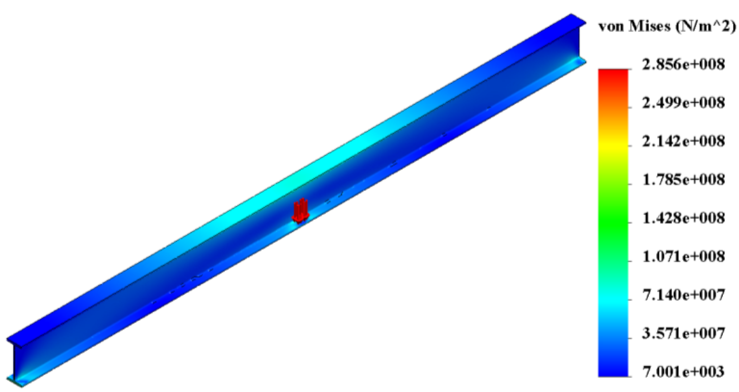

Fig. 13. Huber-Misses-Hencky stress distribution in the gantry crane beam for location of the force load z = 2.4 m, VI variant

Conclusions

This paper focuses mainly on the numerical simulations of mechanical phenomena occurring in the I-beam of gantry crane.. The influence of beam restraint type and changing the loading force position on generate the equivalent stress in the gantry crane beam was evaluated. The region of stresses increased is associated, to the current position of the load force and moves with it (Figs 2-5). These stresses reach the maximum value in the half of beam length under the load force for the restrain variant I, II, III (Figs 4, 8, 10), whereas in variants IV, V and VI (Figs 11, 12, 13) the maximal stresses occur at the points where the beam is attached. The large value of stress at this location does not significantly affect on the safety of the gantry crane structure. Equivalent stress located in the beam center exceed the allowable-values in the variants III and V while in other cases they are less than the allowable stress of the material beam. Analyzing the obtained displacement values (exemplary results in Figs 6, 7, 9), the ratio of the maximum displacement to the beam length was checked. In general, this ratio is within acceptable limits for all restrain variants [6]. The manner of restraining the beam III and especially V are not recommended because it may cause incorrect assessment of the real state of stresses in the examined crane structure. Fixing the beam by immobilizing of its contact surface with supporting column gives the most realistic results of the assessment of the crane beam strength.

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