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Comparison of Analytical and Numerical Approach in Bridge Crane Solution

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A crane bridge is a dominant component of all bridge crane. It is imperative to pay attention on its strength features and go through a strength analysis. The introductory part of this paper points out characteristics of a bridge crane, mainly a crane bridge and materials used to produce the crane bridge, namely S235 structural steel. The paper set out the strength analysis of the main girder of a single girder bridge crane model in the means of comparing analytical and numerical solutions. The calculations take into account the load of the main beam in its centre according to the standard STN 27 0103. The bridge crane model is designed for a 500 kg load carrying capacity. The numerical solutions are represented by finite element method (FEM) analysis in Ansys software. The intention is to determine the deformation of the main girder depending on the weight of a load and a hoist, to determine the maximum deflection and resulted bending stress. Furthermore, one of the purposes is to create the precise 3D CAD model of the main girder. The 3D CAD software Catia V5 was used to design the bridge crane model. The strength analysis of the main girder of IPE 100 profile was performed by the FEM analysis using the Ansys software and by analytical calculations. The results obtained by the computing software Ansys were only slightly smaller in comparison with the analytical calculations. Results obtained by Ansys can be considered as more accurate. It can be concluded, such the designed and strength-checked main girder can be in the future put into a production.

Keywords: Bridge crane, Girder, Strength analysis, Analytical calculation, FEM analysis

1 Introduction

Machinery and equipment for transport and handling technology are an essential part of all branches of industrial production. In addition, their characteristic feature is that they do not affect the growth of the final product quality. Thus, although they enter into almost all operations in the entire production chain of the industry, they do not, in principle, participate in enhancing the quality characteristics and utility value of the final products. However, their entry into the whole process results in a boost in production and other costs. Lifting devices are of particular importance in the field of transport and handling technology, with cranes forming one group of a wide range of these devices [1]. A crane is considered to be a mechanical lifting device ensuring the hoisting and lowering of materials by means of a winder, steel ropes and a pulley system. Cranes are exploited chiefly in the manufacturing industry, construction industry and transport industry. Thus, their functions are to load and to unload goods, to move materials. Cranes also play a significant role in facilitating the assembly of heavy equipment. It operates on a larger floor area than any other lifting arrangement of a lasting type, while the range of its work is limited by its own travelling restrictions. Principle functions of an overhead crane are grabbing, handling and transferring heavy loads from one place to another [2]. In practice, overhead travelling cranes are a very favourite selection for transporting loads at close range thanks to their immense functionality and not limiting the primary production space [3,4]. The demonstrable benefits of a bridge crane include enormous load capacity, great dependability and a comparatively simple production process. With regard to development, the requirements placed on bridge cranes are increasing more and more. On the one hand in terms of increasing their load capacity to large tonnages, high parameters and on the other hand in terms of requiring low vibrations and a tendency to reduce the weight of cranes. These growing requirements are arduous for bridge cranes to meet [5,6].

Bridge cranes can be comprehended as those types of cranes in which the supporting steel structure consists of a crane bridge moving approximately at the level of the elevated crane track. The crane (hoist) trolley rides over the crane bridge, conceivably inside it or even under it. The crane trolley can have distinct designs depending on its purpose. Bridge crane is made up of many constructional components. Whole double girder bridge crane with its all components is depicted on Fig. 1. The Fig. 1 shows the crane bridge, which consists of two main girders, with the crane trolley moving in the horizontal direction on upper flange of girders. The crane truck is used to support the hoist. The load is usually suspended by means of lashings on a hook. The hook is attached to a rope or a chain. The rope or chain, the hook, the pulley system and the induction motor together form the hoist. The crane also includes other important elements such as end trucks, control and safety elements, crane wheels and more [7]. Bridge cranes are very popular, especially in point of view their high efficiency and operability. Specifically, they can involve handling on a large area bounded by the travel length and the span of the crane. This is exceedingly advantageous when changing material flow quickly, which does not desire such high organization. Another advantage is, above all, their high load bearing capacity and substantial lift, notably when assembling machines and equipment [8].

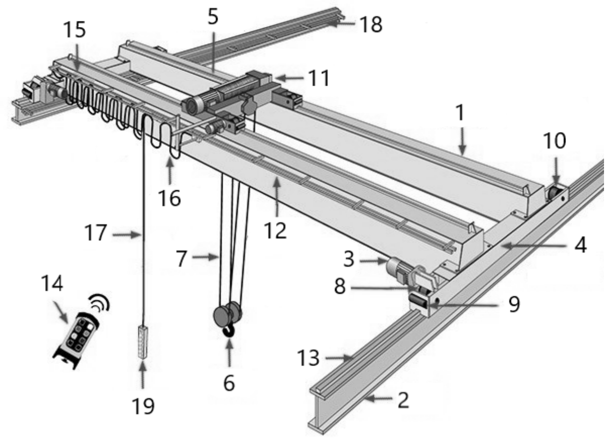


Fig. 16 *Double girder bridge crane: 1 – bridge girder, 2 – runway beam, 3 – bridge drive, 4 – end truck, 5 – hoist, 6 – hook block, 7 – wire rope, 8 – bridge drive wheel, 9 – end truck bumper, 10 – bridge idler wheel. 11 – trolley frame, 12 – pendant / conductor track, 13 – runway rail, 14 – radio control, 15 – panel, 16 – trolley festoon, 17 – pendant cable, 18 – downshop conductors, 19 – pendant*

The general procedure for design of girders of electric overhead travelling (EOT) cranes is accomplished using codes and standards. In this paper a 3D CAD model of a main girder in Catia V5 software and finite element analysis (FEA) in Ansys software are performed to find a maximum deflection and a maximum bending stress. Also, the strength analysis done by analytical calculations is performed according to the standard STN 27 0103. Apart from this, a comparison between results from analytic calculations and results of FEA is investigated. The main girder under investigation is designed and strength-checked for the single-girder bridge crane with a load capacity of 500 kg. Its possible production for the mentioned crane is assumed. "The design of the steel structures of the cranes is essential to carry out according to the standard STN 27 0103. This standard contains various types of loads, local stresses, tables of values of various coefficients, but also types of crane operation [9]. "

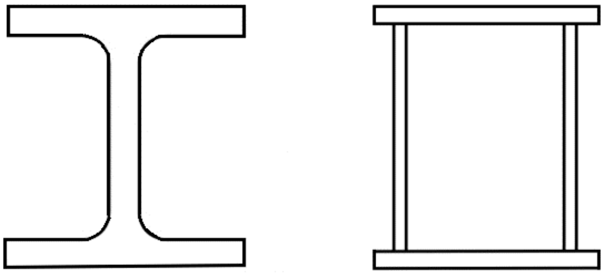
2 Materials used for the manufacture of bridge cranes

The materials used to manufacture the cranes can be divided into two groups. The first group comprises the materials used for manufacturing components of the crane mechanisms. The second group consists of materials for metal structures. Various types of carbon steel are the most used materials. Along with them, alloy and low-alloy steels, light alloys and polymers are becoming more and more widespread in crane construction. The materials exploited in the manufacture of cranes must be correctly selected for the stresses to which they will be subjected. Load-bearing parts, with the exception of girders and tow ropes, shall be so designed that the calculated static stress in the material, which is based on the rated load, does not exceed 20 % of the assumed mean ultimate strength of the material. Non-ferrous metals and their alloys are also used in the construction of cranes. These are chiefly materials such as copper, tin, brass, aluminium, and lead [10-12].

2.1 Materials for a crane bridge

The crane bridge is the predominant structural component of every overhead crane. It is made up of one or more major load bearing beams or girders which together with the cross members form a rigid frame. The one of the principal function of the main girder of the crane bridge is to transfer the load to the cross beams. The crane bridge bears a hoist trolley that moves along the entire length of the girders at the time its operation. Sufficient rigidity is required from the crane bridge to prevent the crane from crossing. From the point of view of stress, the crane bridge is stressed for bending both in the vertical and in the horizontal plane. It is also exposed to torsional stress. In the case of single girder bridge cranes, the main girder is commonly formed by a rolled profile I. Besides that, in the case of larger lifting capacities and spans, a girder of box triangular or quadrangular cross-section finds its application. In other words, steel box girders or rolled-steel joists (see Fig. 2) obtain significant utilization in the manufacturing process of crane bridges. Depending on the design, crane bridges can be constituted by the following types of main girders:

- rolled girder
- box girder
- plate girder
- lattice girder
- frame girder [7,8]



a) b)

Fig. 17 *Profiles of main girders: a) I-rolled joist, b) box girder*

The material S235JR steel or S355 steel is quite often used to produce the main girder of a crane bridge [6]. Steel EN 10025 S235JR (1.0038) is characterized according to the European standard as non-alloy structural steel of the hot-rolled quality class. It is characterized by good plasticity, toughness, and weldability, has a certain strength and good cold bending properties. The following tables (see Tab. 1, Tab. 2, Tab. 3) show the specification of S235JR steel, including chemical composition, yield strength and tensile strength [16].

Tab. 20 *Chemical composition of S235 steel [16]*

			Chemical composition (%)						
Standard	**Material**	**Steel class (number of steel)**	**C**	**Si**	**Mn**	**P**	**S**	**Cu**	**N**
EN 10025-2	**S235 steel**	**S235JR (1.0038)**	0.17	–	1.40	0.035	0.035	0.55	0.012
		S235J0 (1.0114)	0.17	–	1.40	0.030	0.030	0.55	0.012
		S235J2 (1.0117)	0.17	–	1.40	0.025	0.025	0.55	–

Tab. 21 *Yield strength values of S235 steel for different diameters [16]*

		Yield strength (N/mm^2); d - diameter (mm)					
Type of steel	**Steel class (number of steel)**	d≤16	16<d≤40	40<d≤100	100<d≤150	150<d≤200	200<d≤250
S235	**S235JR (1.0038)**	235	225	215	195	185	175

Tab. 22 *Tensile strength of S235 steel for different diameters [16]*

		Tensile strength (N/mm^2); d - diameter (mm)			
Type of steel	**Steel class (number of steel)**	d<3	3≤d≤100	100<d≤150	150<d≤250
S235	**S235JR (1.0038)**	360-510	360-510	350-500	340-490

3 Strength analysis of a main girder of a crane bridge

The main girder of the crane bridge is exposed to several stresses during its operation. From the point of view of stress, it is substantial to assess how the loading forces can affect the strength of the main girder. These loading forces depend on the weight of load and the hoist. Due to these facts, we are interested in the values of bending stress and total deflection of the main girder. The main girder under strength analysis investigation is designed for a single girder bridge crane with a load capacity of 500 kg, which is depicted in Fig. 3. This 3D model of bridge crane is designed using CATIA V5 software.

The IPE 100 profile of main girder was designed and calculated based on STN 27 0103 standard for mentioned bridge crane. Detailed calculations are presented in [14]. This main girder has length 1600 mm. The material of main girder is constructional steel S235JR+AR / 1.0038. The IPE 100 profile with its dimensions is depicted in Fig. 4. Cross-sectional properties of this IPE profile of main girder are provided in the Tab. 4.

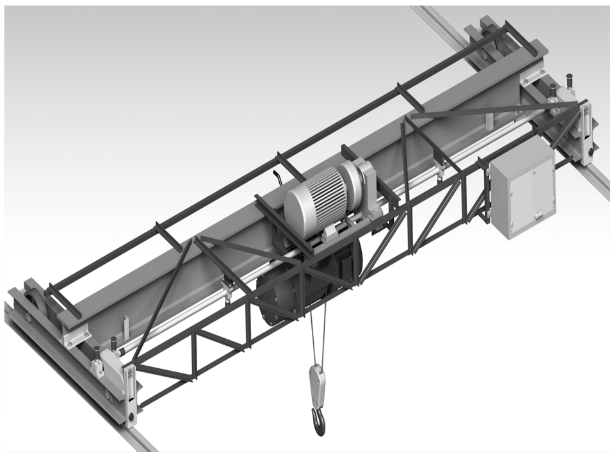


***Fig. 18** 3D CAD model of single girder bridge crane with 500 kg load capacity*

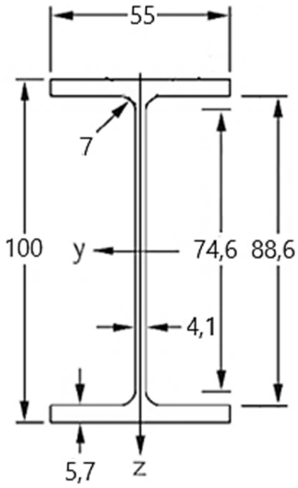


***Fig. 19** Selected profile IPE 100 of the main girder*

***Tab. 23** Cross-sectional properties of the IPE 100 profile*

Sectional property	Denotation	Value
Moment of inertia of the cross-section to the y-axis	I_y	171 cm^4
Section modulus in bending to the y-axis	W_{oy}	34.20 cm^3
Plasticity modulus of the profile to the y-axis	$W_{pl.y}$	39.41 cm^3
Area of cross section	A	1030 mm^2

3.1 Determination of the main girder deflection according to standard STN 27 0103

Based on this standard, the calculation of the deflection of the main girder w_{max} is diminished to the instance of the load representing by the total load of the main girder F_t. The action of this force is in the middle of the girder. The above facts are shown through the schema in Fig. 5.

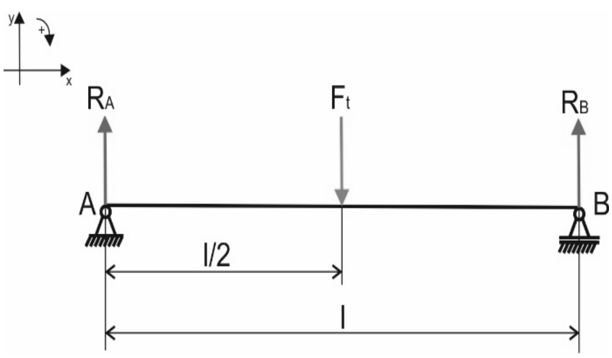


***Fig. 20** Loading of the main girder by the acting force in the middle*

For the calculation of total deflection and bending stress it is indispensable to determine the value of the total loading force which depends on the weight of the load Q = 500 kg and weight of the hoist m_h = 32.4 kg. Total loading force is defined by equation (1).

$$F_t = \left(Q \cdot \gamma_{lo} \cdot \delta_h + m_h \cdot \gamma_g \cdot \delta_t\right) \cdot g\ [N], \qquad (1)$$

Where:
F_c…Total loading force depends on load and hoist [N],
Q…Weight of load [kg],
γ_{lo}…Load coefficient [-],
δ_h…Dynamic lifting coefficient [-],
m_h…Weight of hoist [kg],
γ_g…Self-weight load factor [-],
δ_t…Dynamic travelling coefficient [-],
g…Gravitational acceleration [m·s^{-2}].

Tab. 5 presents values of coefficients and factors, which are selected from the tables listed in STN 27 0103 standard [15].

***Tab. 24** Coefficients and factors taking into account safety*

Coefficient/factor	Denotation	Value [-]
Load coefficient	γ_{lo}	1.3
Dynamic lifting coefficient	δ_h	1.217
Dynamic travelling coefficient	δ_t	1.1
Self-weight load factor	γ_g	1.1

After substituting the values into the equation (1).

$$F_t = \left(500 \cdot 1.3 \cdot 1.217 + 324 \cdot 1.1 \cdot 1.1\right) \cdot 9.81 = 8144.8 N, \qquad (2)$$

Based on Fig. 5 and using equations (3) and (4), the balance of forces directing in the y-axis and the moment balance to the point A can be determined.

$$\sum F_{iy} = 0;\ 0 = R_A + R_B - F_t\ [N], \qquad (3)$$

$$\sum M_{iA} = 0;\ 0 = -R_B \cdot l + F_t \cdot \left(\frac{l}{2}\right)\ [N \cdot m], \qquad (4)$$

Where:
$\sum F_{iy}$…The sum of all forces acting in the y direction [N],
$\sum M_{iA}$…The sum of all moments with respect to point A [N·m],
R_A…Reaction at point A [N],
R_B…Reaction at point B [N],
F_t…Total loading force depends on load and hoist [N],
l…Length of the main girder [m].

Subsequently, the reactions R_A and R_B are expressed from equations (3), (4) as:

$$R_A = R_B = \frac{F_t}{2}\ [N], \tag{5}$$

After substituting values into equation (6).

$$R_A = R_B = \frac{8144.8}{2} = 4072.4\ N\ , \tag{6}$$

To calculate the maximum deflection of this main girder, it is necessary to divide it, in this case into 2 sections, based on the action of external and internal loads and with respect to the geometry (Fig. 6).

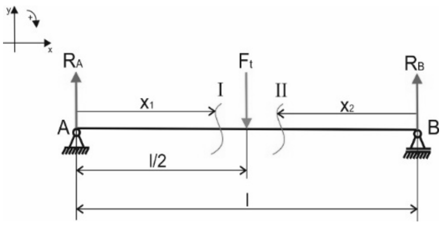


Fig. 21 *Schema for calculation of the maximum deflection with the action of the force in the centre of the girder*

For the section I, the following is employed:

$$x_1 \in \left(0, \frac{l}{2}\right)\ [m]; \qquad M_{b1} = R_A \cdot x_1 = \frac{F_t}{2} \cdot x_1\ [N \cdot m], \tag{7}$$

thus, the value of the bending moment in boundary positions is calculated as follows:

$$x_1 = 0; \qquad M_{b1} = 0\ N \cdot m,$$

$$x_1 = \frac{l}{2}; \quad M_{b1} = \frac{F_t \cdot l}{4} = \frac{8144.8 \cdot 1.6}{4} = 3257.92\ N \cdot m, \tag{8}$$

For section II:

$$x_2 \in \left(0, \frac{l}{2}\right)\ [m]; \qquad M_{b2} = R_B \cdot x_2 = \frac{F_t}{2} \cdot x_2\ [N \cdot m], \tag{9}$$

the bending moment in both boundary positions using equation (9):

$$x_2 = 0; \qquad M_{b2} = 0\ N \cdot m,$$

$$x_2 = \frac{l}{2}; \quad M_{b2} = \frac{F_t \cdot l}{4} = \frac{8144.8 \cdot 1.6}{4} = 3257.92\ N \cdot m \tag{10}$$

From the above calculations, it can be asserted that the maximum deflection of the main girder in this case will be in the centre of the girder. The formula (11) listed in the standard STN 27 0103 is exploited to determine the value of the maximum deflection.

$$w\left(\frac{l}{2}\right) = w_{max} = \frac{F_t \cdot l^3}{48 \cdot E \cdot I_y}\ [mm], \tag{11}$$

Where:
w…Deflection of the girder in a certain place [mm],
w_{max}…Maximum deflection of the main girder [mm],
F_t…Total loading force depends on weight of load and hoist [N],
l…Length of the main girder [mm],
E…Young's modulus of elasticity [MPa],
I_y…Moment of inertia of the cross-section to the y-axis [mm^4].

After substituting the values into the formula (11):

$$w_{max} = \frac{8144.8 \cdot 1600^3}{48 \cdot 2.1 \cdot 10^5 \cdot 171 \cdot 10^4} = 1.9355\, mm \tag{12}$$

3.2 Calculation of bending stress according to standard STN 27 0103

From the point of view of strength analysis, it is substantial to assess the resulting bending stress in the critical cross-section of the main girder. Commonly, the bending stress for arbitrary cross-section is determined in the manner of the following formula (13).

$$\sigma_b = \frac{M_b}{W_b}\ [MPa], \tag{13}$$

Where:
σ_b…Bending stress [MPa],
M_b…Bending moment [N·mm],
W_b…Section modulus in bending [mm^3].

The resulting bending stress at the considered place according to the standard STN 27 0103 [15], when the main girder is loaded in its centre by the total force from the weight of the load and the hoist, is defined by the equation (14).

$$\sigma_b = \frac{F_t \cdot l}{4 \cdot W_{oy}}\ [MPa], \tag{14}$$

Where:
σ_b…Bending stress [MPa],
F_t…Total force from the weight of the load and the hoist [N],
l…Length of the main girder [mm],
W_{oy}…Section modulus in bending to the y-axis [mm^3].

After substituting values into equation (14), the bending stress at considered place.

$$\sigma_b = \frac{8144.8 \cdot 1600}{4 \cdot 34.2 \cdot 10^3} = 95.261\ MPa\ , \tag{15}$$

4 3-D Modelling and finite element analysis (FEA) of main girder of the bridge crane model

Finite element method (FEM), occasionally concerned as finite element analysis (FEA), is considered as numerical method that can be exploited for acquiring approximate solutions to the intricate engineering problems. It comprises two predominant parameters, i.e. elements and nodes. This technique substantially is made up of estimating the piecewise continuous function for the solution and acquiring the parameters of function. This tends to a manner that diminishes the flaw in the solution. The finite element method can be employed to scrutinized any geometry, and based on the known applied loads it is capable to determine stresses, deflections and displacements [13]. The fundamental FEA workflow is represented by Fig. 6.

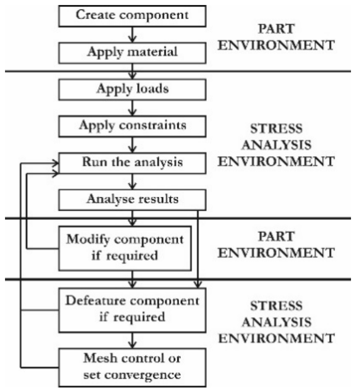


Fig. 22 *FEA workflow [2]*

4.1 3D modelling of the main girder with respect to standard STN 27 0103

Ansys engineering simulation software working on the basis of the finite element method is employed to determine the maximum deflection and bending stress when loading of the main girder is in its centre according to the standard STN 27 0103 [15]. Software Catia V5 has been used for designing the 3D model of the main girder (Fig. 8). First, the main girder is modelled in the form of solid. The solid model of this main girder is designed based on the dimensions of the selected IPE 100 profile shown in Fig. 4.

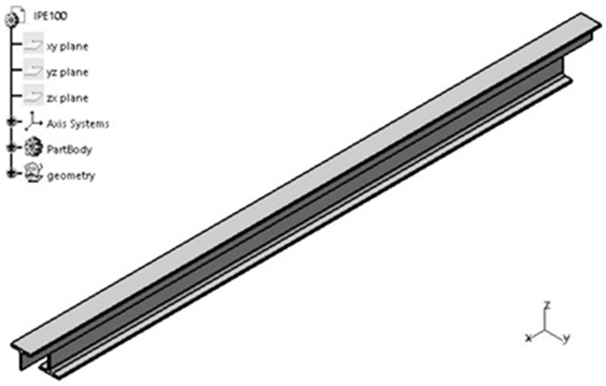


Fig. 23 *3D model of the main girder*

Second, this solid model of main girder has been imported into the Ansys software. The model of main girder has been modified to a shell geometry for a more accurate computation and all the indispensable thicknesses has been assigned to it. Constructional steel S235 material with the yield strength 235 MPa is applied to the main girder. After assigning the material, the boundary conditions have been set in the form of remote displacements. One end of the girder is fixed and the other can move in the direction of the x-axis in this case. There is also a presumption of loosening in both bonds - rotation around the y-axis. In the case of a load, the total loading force 8144.8 N is applied to the surface depending on the wheelbase of the hoist trolley and the width of the girder. This surface is created on the lower flange of the main girder in the centre of girder. The above-mentioned facts are depicted in Fig. 9

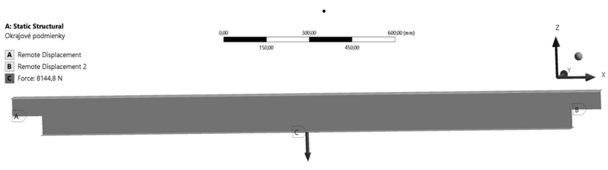


Fig. 24 *Boundary conditions applied to the main girder*

Subsequently, the girder has been meshed (Fig. 10). Element size is 10 mm. The elements are of the quadratic type due to a better description of the sudden shape change. The number of created nodes is 10548 and number of elements is 3386.

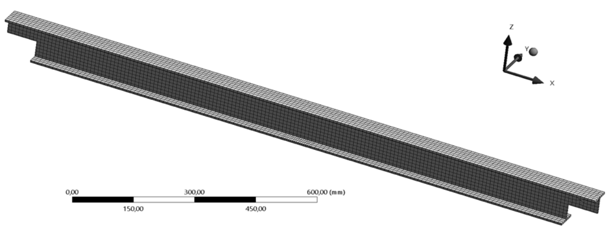


Fig. 25 *Meshed model of the main girder*

4.2 Results obtained from the finite element analysis of the main girder by using Ansys software

As has been mentioned, the quadratic type of element was exploited for the finite element analysis. The maximum bending moment arises in the middle of the main girder. Young's Modulus (E) is 210 GPa and the Poisson Ratio is 0.3 for the finite element analysis. The maximum bending stress (Von Mises) of the main girder at considered place is 88, 823 MPa. This value is marked by blue frame in Fig. 11. It is clearly depicted from the Fig. 11 that the maximum stresses are formed at the supports.

Tab. 25 *Comparison between permissible values, FEA results and results from analytical calculations*

Characteristic	Denotation	Permissible values	Results obtained by analytical calculations	Results obtained by FEA

Maximum bending stress	σ_b	146.88 MPa	95.261 MPa	88.823 MPa
Minimum safety factor	k	1.6	2.467	2.646
Maximum deflection in Y-direction	w_{ymax}	3.2 mm	1.9355 mm	1.7803 mm

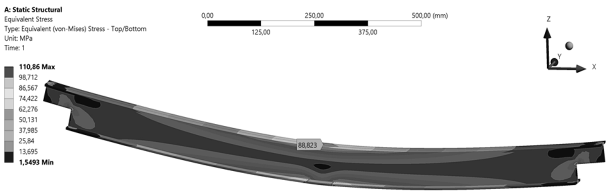


Fig. 26 *Representation of Von Mises stress arising on the main girder*

The result of determining the maximum deflection using the Ansys computational and simulation software is the maximum deflection of the main girder with the value of 1.7803 mm. The total deformation of the main girder and the value of the maximum deflection are depicted in Fig. 12. The maximum deflection at the considered place is marked by red frame in Fig. 12.

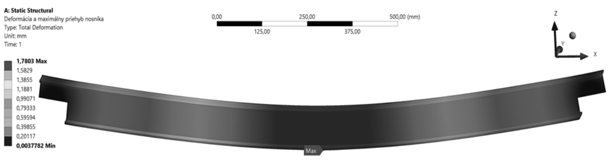


Fig. 27 *Total deformation of the main girder*

Comparing the maximum deflection acquired by analytical calculation according to the standard STN 27 0103 [15] and the maximum deflection obtained by FEM analysis in Ansys, it can be stated that the value of the maximum deflection obtained by Ansys software is 8.12% less. The value of the maximum deflection and bending stress obtained by FEM analysis in Ansys can be considered as more accurate. Results obtained by analytical calculations and using finite element method is presented in the Tab.

5. Conclusion

One of the main goals of this work is to approach the issue of bridge cranes, chiefly from the perspective of a crane bridge. The theoretical part of this paper deals with the characteristics of bridge cranes and their feasible applications. In addition, the predominant attention was paid to the crane bridge not only in terms of stress and the types of commonly used girder profiles, but also in terms of an exploiting of materials for their production. The I girders and box girders are preferred girder types. The most frequently employed material is structural steel S235 or S355. Characteristics of S235 steel were also put forward in this paper. The next part of this paper is focused on the strength analysis of the main girder designed for a single girder bridge crane with a load capacity of 500 kg. Two calculation methods were used, namely analytical calculation and calculation by means of FEM analysis in Ansys software. Both methods considered the load of the main girder in its centre according to the standard STN 27 0103. From the point of view of strength analysis, the value of maximum deflection, bending stress and the deformation diagram of the girder have a great significance. Through analytical calculation, the value of maximum deflection 1.9355 mm and the value of bending stress 95.261 MPa were precisely acquired. The maximum deflection value obtained by FEM analysis was 1.7803 mm and the bending stress (Von Mises) value was 88.823 MPa. It is emerged from the Fig. 12 that the maximum deflection is in the centre of the girder as was expected. To sum up, from the above comparison represented by Tab. 7 between the permissible values, results from analytical calculations according to the STN 27 0103 standard and the results of FEM analysis of the main girder model, it is clearly observed that the maximum bending stress and maximum deflection which is obtained from FEA and analytical calculations were within the permissible values. In addition, values of maximum bending stress and maximum deflection obtained from FEA are lower than values from analytical calculations performed according to STN 27013 standard. The safety factor, obtained by both methods is on higher side against the permissible value. Thus, can be stated that the designed main girder model is satisfying from the point of view of strength and rigidity. Moreover, considering the above results the investigated main girder can be the element of the designed bridge crane 3D CAD model depicted in this paper. These facts in other words conceive a precondition for potential production of this main girder as the predominant component of the single girder bridge crane.

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