WEB ISSN 1314-507X; PRINT ISSN 1313-0226

MATERIAL DEFORMATION ANALYSIS IN BRIDGE CRANE DURING TRAVEL MOTION WITH FULL LOADING

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Abstract: *This paper deals with dynamic analysis of bridge crane with single girder in order to determine material deformations in their main parts – cables and girder's, while moving and carrying load. It is known that these are mostly loaded parts in crane, while they accept forces, moments and oscillations from lifting mechanism and load. Analysis will be accomplished using computer modeling and simulations. Work process of crane in the study is forward travel motion. It is assumed that this motion process makes major impact in the deformations of lifting cables and girders due to stress, oscillations, and negative effect of load swinging. The analysis will be concentrated in finding the nature of oscillations that acts on crane and finding the extent and form of materials stress and deformations that can cause fatigue, failures and accidents. Question is whether acting loads exceed elasticity limits, or there are plasticity deformations which lead to permanent damages. Results will be shown in the form of diagrams, contour stress and strain in cables and girders. They will be compared with experimental measurements. Conclusions of these analyses can be useful for design considerations and safety.*

Keywords: BRIDGE CRANE, SINGLE GIRDER, MATERIALS, DEFORMATIONS, TRAVEL MOTION, OSCILLATIONS, MODELING, SIMULATIONS

1. Introduction

Bridge crane is modeled based on manufacturer *Prim Co Company, Type* JP100 (Fig.1) [1]. Crane is mounted in rails in the walls of one factory. Max carrying load & Pulley system is $G = 5100$ kg $= 50$ kN. It has one main girder, and two side girders (left & right). Height position of girders is H = 6.5 m. Length of main girder is $L_m = 12.2$ m (Fig.2). Length of side girders is $L_s = 2$ m. (Fig.2). Velocity of crane $v_{cr} = 0.5$ m/s. Velocity of telpher $v_{cr} = 0.33$ m/s. Diameter of crane wheels D_v = 200 mm. Crane is moving on 4 wheels, 2 per each side, mounted on side girders (Fig.1, 3). Before simulations, weight Q (workload) is in the position of relative rest at the height H = 1.5 m from basement.

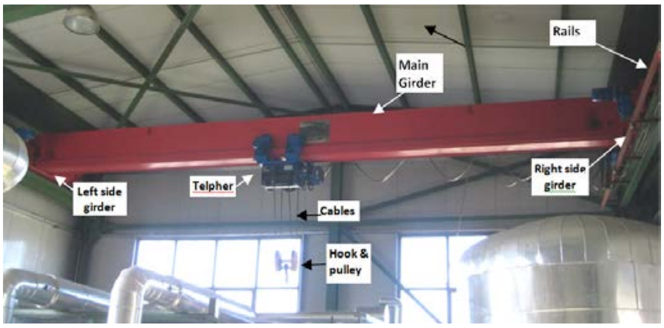

Fig.1. *Bridge crane with parts in the work environment [1]*

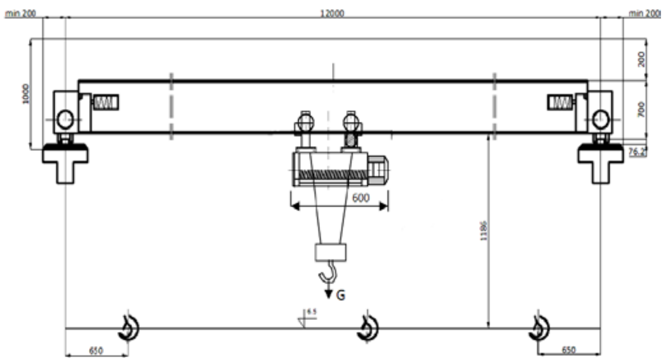

Fig.2. *Bridge crane main dimensions [1]*

2. Properties of Girders

- *Main girder* has profile (Cross section) of Hollow Box Beam, with thin wall section, with dimensions shown in Fig. 3. Material of Main girder is made of Steel S355 [11]. In most structural steel specifications the yield strength, ultimate tensile strength, elongation and in some specifications also the Charpy V values are specified [10]. Mass of main girder is 2000 kg.

- *Side girders* have profile of partially Hollow Box, shown in Fig.3. Its bottom is open to mount wheels of crane. Material is also Steel S355 [11]. Mass of each side girder is 300 kg.

When load acts in girders, it will deflect and deform them. Main type of strain and deflection that acts on girders is bending towards vertical axes and shear. It is suggested that also torsion appears during forward traveling of crane, which we will search in this work.

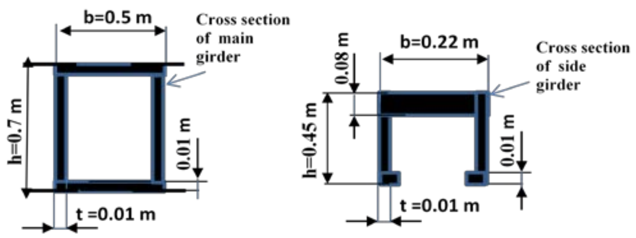

Fig.3. *Cross sections of main girder and side girders*

3. Modelling of Bridge crane

In Fig.4 is presented model of bridge crane done in software [4] including working environment, which is also modeled. Working environment includes metal frames, bars, rails and basement.

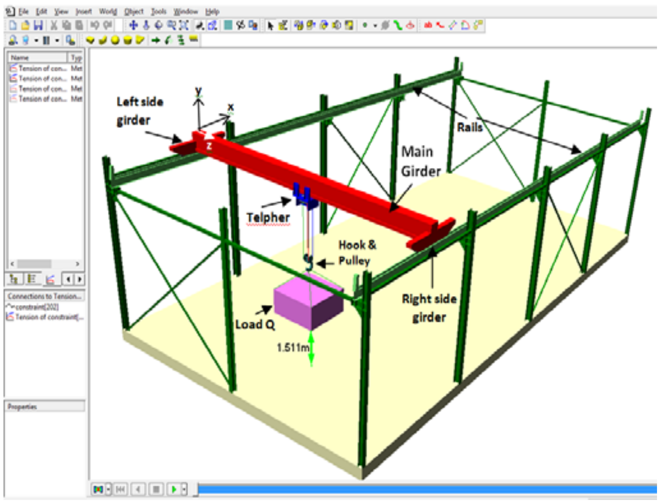

Fig.4. *Model of bridge crane in the working environment where simulations will apply, created with software SimWise 4d [4]*

YEAR XI, ISSUE 8, P.P. 389-392 (2017)

Lifting mechanism is designed in the form of double pendulum. Working load has prismatic form with dimensions 2 m x 2m x 1 m, with mass Q = 5000 kg (including Pulley and Hook mass) (Fig.2) [7]. Load height from basement is 1 m. It is positioned in the center of main girder. We consider that best results will be achieved with max carrying load Q = 5100 kg, as given by manufacturer [1].

Crane's model of main girder and side girders, with side extensions for telpher is shown in Fig.5. [8], [3]

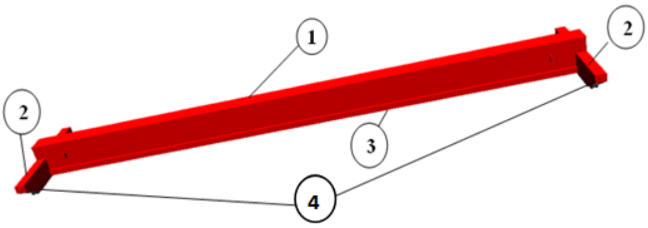

Fig.5. *Model of main girder and side girders: 1-Main girder; 2-Side girders; 3-Side extensions for the laying telpher; 4-Crane wheels;*

Simulations will be planned for crane traveling - translational motion for time $t = 8$ *s*, which converts to travel length l = 4 m. Simulations are planned to reflect real travel of crane in order to achieve reliable results and comparable with measurements. For the proper scenario of travelling process, simulation will start without travelling until time t = 0.5 s. This in order to have the stability of load hanging on cables. After t=0.5 s, will start the travel of crane with griven speed. Travelling will end on time $t = 8$ *s*, which converts in length $l = 4$ *m*.. (Fig.7) [4], [8].

4. Experimental measurements

Lifting cables are heavily loaded part, while they carry load and hoist mechanism. There are 4 branches of cables connected with Hook and pulley system, which connects to drum with 2 lifting branches. Measurements in crane are done in place where crane is mounted, in one local company (Fig.1). They will be used for validation of results [5]. Main measured parameter was tensile force in lifting/lowering cables – $\boldsymbol{F_t}$. In this crane there are 4 branches of lifting cables connecting between drum and pulley system.

Type of cables are wire ropes type 6X37, with diameter $d_c = 19$ *mm* [1]. Other properties are: Modulus of elasticity: $E = 7.58\cdot10^{10}$ *Pa,* Minimum breaking strength $F_b = 212$ *kN*, Safe Load $F_s = 42.3$ *kN* [1], [14].

Tensile force was measured with dynamometer type *Dini Argeo* attached to the Hook [9], during motion of crane (Fig.6). There were 5 measurements achieved, and results are shown in Table.1:

Time of travel (s)	Tensile Force in all lifting cables - Ft (N)	Force in each branch of lifting cables (Ft/4) (N) (aprox.)
1	51800	12950
3	49800	12450
6	52700	13175
8	50600	12650
12	50750	12687

Table 1. *Results of F_t with dynamometer in hanging cables*

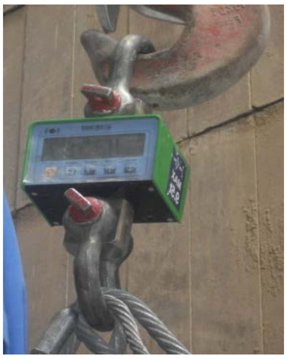

Fig.6. *Measurements with Dynamometer during motion of crane*

5. Results in lifting cables

In Fig. 7 is given graph of Force F_t in one cable branch after simulations of crane travel. Result are shown for time of crane travel t = 8 s.

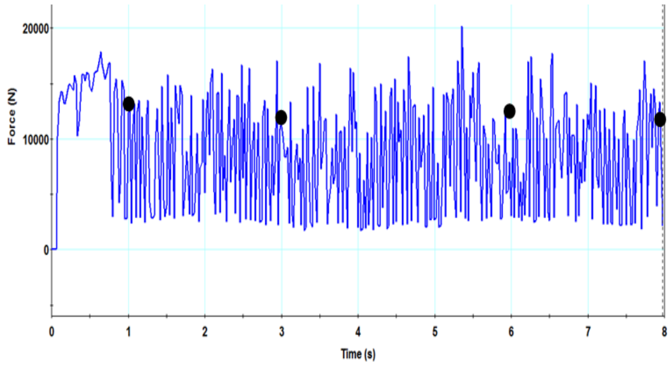

Fig. 7. *Tensile force F_t in one branch of lifting cable. Black dots are experimental values from Table 1.*

Based on graph in Fig.7, we can conclude that force in lifting cables during crane travel is comparable with experimental values, which are shown with black dots. This validates results with simulations and makes them reliable and trustworthy.

Graph of Force in cables is dynamic in nature, with high frequencies that reach up to $\upsilon = 17$ *Hz*, maximum value of force is achieved in time $t = 6.5$ *s*, with value $F_{dmax} = 20000$ *N* $= 20$ *kN*.

Based on literature, strength properties of lifting cables are: Minimum breaking strength $F_b = 212$ *kN*, Safe Load $F_s = 42.3$ *kN* [1], [14]. It can be concluded that $F_{max} < F_s$, cables of crane can stand the dynamic tensile force without major deformations.

But, value of dynamic coefficient Ψ, which is the ratio between maximal dynamic force and static force is high [6], [8] :

$$\Psi = = \frac{F_{dmax}}{F_s} = \frac{20}{50/4} = \frac{20}{12.5} = 1.6$$

This results that cables undergo 60% more dynamic forces compared to static forces. This is a matter of concern while cables strength will decrease by time and express fatigue after defined time frame, which requires frequent control of their condition.

4. Results in main girder

Girders are considered most important part of Crane (Fig.1, Fig.2). On main girder is mounted telpher that hangs in side extensions (Fig.2,4), which has also mounted on it hoisting mechanism and load Q. Dynamics and oscillations from the load Q and hoisting mechanism are passed on girder.

Main parameters that define material loading deformations are stresses and strains based on acting forces and moments. Results of these parameters are most important for analysis and conlcusions.

Formula of normal stress for Hollox Box profile is [2], [10]

$$\sigma_x = \frac{M}{J_x} \cdot y \qquad (2.1)$$

M - Bending Moment; J_x – Moment of inertia; *y* – position in the cross section.

Max value of stress is: $\sigma_x = \frac{M}{W_x}$ (2.2)

Where $W_x = \frac{J_x}{y_{max}} = \frac{4}{3} \cdot b^2 \cdot t$ - resisting moment of inertia (2.3)

Formula of Shear stress for Hollox Box profile is:

$$\tau_{xy} = \frac{T_{max}}{J_x} \cdot \frac{S'}{t} \qquad (2.4)$$

where: $I_x = 2 \cdot t \cdot h^3 /12 + 2 \cdot (b-2t) \cdot t \cdot (h/2-t/2)^2$

$S' = 2 \cdot h/2 \cdot t \cdot h/4 + (b-2t) \cdot t \cdot (h/2-t/2)$ (2.5)

T_{max} – max value of shear force; S' – Static moment of profile area *h* –hight of profile area; *b* – width of profile area; *t* – thikness of profile walls [2], [10].

In the Theoy of constructions using Finite Elements Method, and in calculation of stresses by software [3], there is implementation of Von Misses Stress, which is widely used by designers to check whether their design will withstand a given load condition. It is a value used to determine if a given material will yield or fracture. It is mostly used for ductile materials, such as metals. The von Mises yield criterion states that if the von Mises stress of a material under load is equal or greater than the yield limit of the same material under simple tension. General von Mises equation, using principal stresses is [12], [13]:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_{11}-\sigma_{12})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2 + 6(\sigma_{12}{}^2 + \sigma_{23}{}^2 + \sigma_{31}{}^2)]} \quad (2.6)$$

Where stress componets are part of Cauchy stress tensor:

$$\sigma = \sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{x} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{y} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{z} \end{bmatrix} \quad (2.7)$$

Some of these textbooks for machine design show that the von Mises stress with respect to non-principal axes can also be expressed as [13]:

$$\sigma' = \frac{1}{\sqrt{2}}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)\right]^{1/2} \quad (2.8)$$

When only σ_x, and τ_{xy} are present (as in combined torsion and bending/axial stress or pure torsion), the Von Mises stress is:

$$\sigma_v = \sqrt{\sigma_x{}^2 + 3\tau_{xy}^2} \quad (2.9)$$

Note that in pure shear or pure torsion $\sigma_x = 0$. If $\sigma_x = 0$, then:

$$\sigma_v = \sqrt{3\tau_{xy}^2} = \sqrt{3} \cdot \tau_{xy} \quad (2.10)$$

According to distortion energy theory, yielding occurs when σ_v reached the yield strength *Sy*. Therefore in pure shear, yielding occurs when τ_{xy} reaches 58% of *Sy* [12]. In further analysis, Von Mises stress and its components will be calculated and shown as main result for girders.

Results will be achieved using Numerical methods (Kutta-Merson) and Finite Elements Method (FEM), supported by software in order to achieve best results.

Other properties of main girder are: Elastic Modulus: $E=2 \cdot 10^{11}$ *Pa*, Yield Stress $\sigma_{yi} = 3.31 \cdot 10^8$ *Pa* ; Ultimate Tensile Stress $\sigma_{ut} = 4.48 \cdot 10^8$ *Pa* ; Poisson's Ratio $\upsilon = 0.29$. [1]

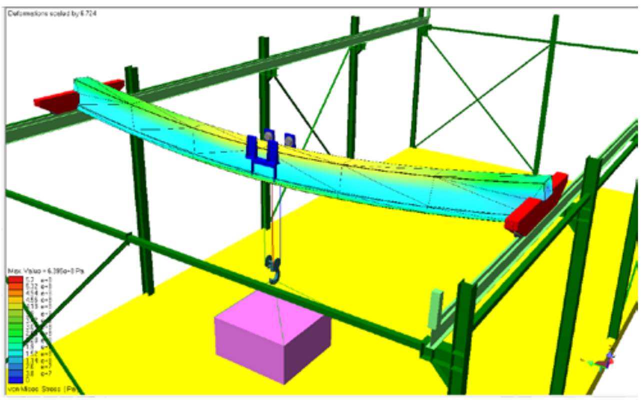

Fig.8. Deformation of main girder (Scaled by 6.274), and contour spread of Von Misses Stress

Based on model created, results are achieved for main dynamic parameters for measurement of deformations: *Stress and strain* [4], [8],[2]. Stress will be type Von Misses Stress. Results are shown in Fig.9 to Fig.12. In Fig. 8 is shown discretization of girder in volume FEM Elements, values of contour Stresses, and deformation of girder (Scaled by 6.274).

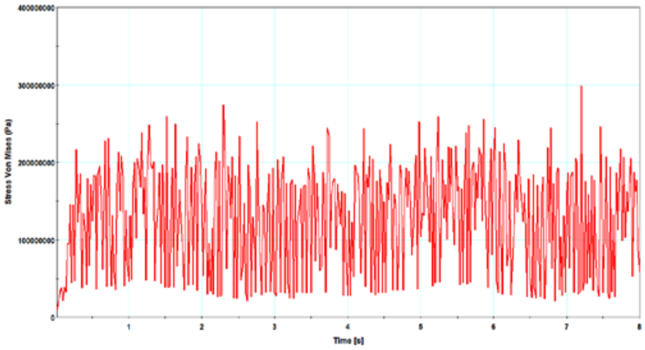

***Fig.9.** Stress Von Misses in main girder*

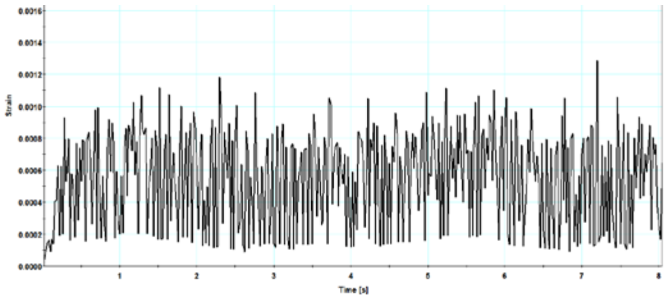

***Fig.10.** Strain Von Misses in main girder*

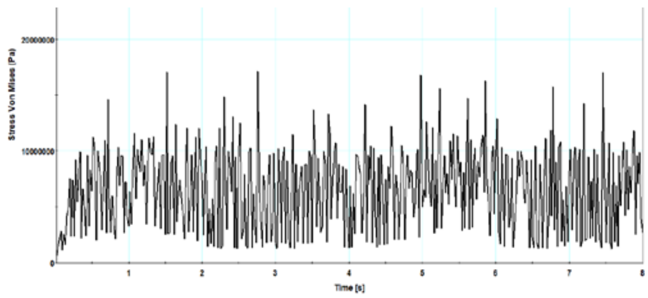

***Fig.11.** Torsion stress in main girder – τ_{xy}. Main girder undergoes torsion*

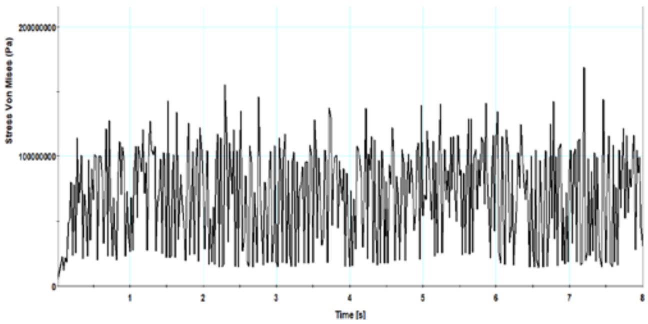

***Fig.12.** Shear stress in main girder – τ_{yz}*

Based on results from Fig.9 to Fig.12, we can conclude that main girder undergoes heavy dynamic stresses and strain, with frequent oscillations, high amplitudes and high frequencies that reach up to $\upsilon = 18$ *Hz*. Max value of Von Misses stress occurs in time $t \approx 6.6$ *s*, and has value $\sigma_{max} = 3 \cdot 10^8$ *Pa* (Fig.9). This value of stress is less then Yield stress $\sigma_{max} < \sigma_{yi} = 3.31 \cdot 10^8$ *Pa* of material. This concludes that girder's structure can handle the loading, but is near to boundary Yield stress and near to possible deformations.

In Fig.10 is given graph of Strain for girder - ε. Graph is similar in form and dynamics of change with the one of stress. Max value of strain is $\varepsilon = 0.0013$ occurring in time t ≈ 7.5 s.

In Fig.11 is given graph of Torsion for girder. It can be concluded that girder is loaded with torsion, but the intensity is small, $\tau_{xymax} \approx 1.3 \cdot 10^8$.

In Fig.13 is given graph of Shear stress for girder. Maximal Intensity is small, $\tau_{yzmax} \approx 1.5 \cdot 10^9$.

5. *Results in side girder for travel motion*

In Fig.13 to Fig.16 are shown graphical results for Right Side Girder. Results of graphs of Side Girder (Fig.14,15) are similar in form and dynamic occurrence with ones of Front girder.

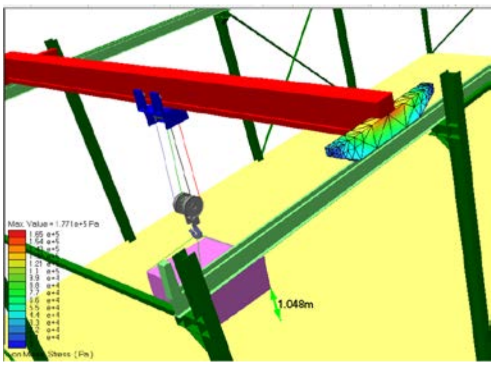

Fig.13. *Contour spread of Von Misses stress in right side girder*

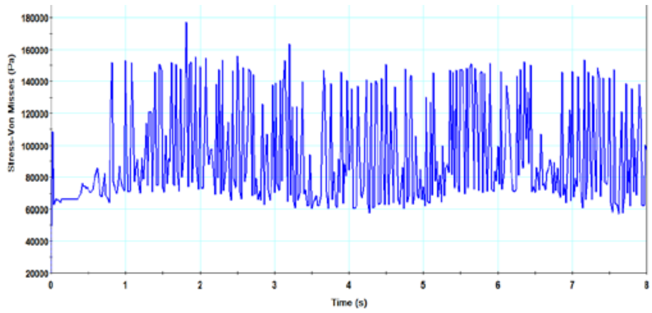

Fig.14. *Stress Von Misses in side girder*

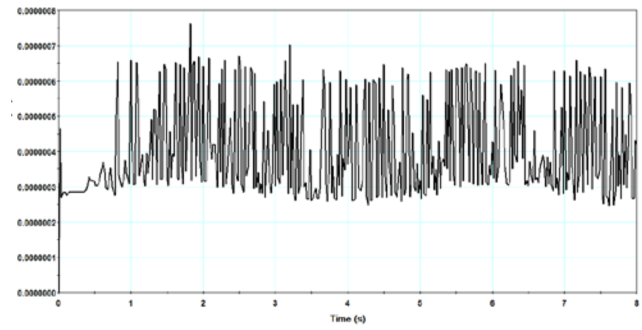

Fig.15. *Strain Von Misses in right side girder*

Based on results from Fig.14 and Fig.15, we can conclude that main girder undergoes heavy dynamic stresses and strain, with frequent oscillations and high frequencies.

Values of Von Misses Stress are smaller than for main girder (Fig.14). Max value occurs in time t≈ 3 s, and has value $\sigma_{max} = 1.7 \cdot 10^5$ *Pa* (fig.9). This value of stress is less then yield stress of material $\sigma_{max} < \sigma_{yi} = 3.31 \cdot 10^8$ *pa* of material, which means that girder's structure can handle the loading.

in fig.10 is given graph of strain for girder -ε. Graph is similar in form and dynamics of change with the one of stress, but values are smaller. max value is $\varepsilon = 0.0000007$ occurring in time t≈ 1.8 s.

Another important conclusion from results is that oscillations occurring on load *Q* and cables are passed in other parts of crane with similar form of curve, periods, and frequencies.

6. Conclusions

The main problem in bridge cranes during travel are oscillations as dynamic occurrences. It is important to identify and minimize them. Their influence will impact material deformations significantly. Oscillations in cranes often are difficult to measure with instruments. They are mainly induced by load and pulley swinging that induces forces in cables, and furthers other forces, moments and stress in other parts. To find their form of occurrence we created model of bridge crane and implemented simulations. Results are also compared with experimental analysis. Important part of analysis is finding proper simulations plan that reflects real crane's travel motion, so that results are reliable. Results are gained for main dynamic parameters that represent material loading and deformations. Based on results, it can be concluded that main parts of crane analyzed undergo oscillations that are heavy and mostly with irregular occurrence. They occur in different planes. They have negative effect in parts and deform them. According to results we can conclude that crane parts analyzed can handle dynamic loads and don't show problems of overload or plasticity deformations. But this is acceptable only if proper type of material is selected. Also long term oscillations of this form will decrease strength of parts and increase chances for fatigue and damage. It is important to minimize oscillations in order to achieve minimal dynamic loads [5], [8]. Speed of travel must remain in optimal value, as lower as possible to minimize negative effects of load swinging, deformations of parts and other safety considerations.

This work is also important for safety at work with bridge cranes. It can be used also for further material strength analysis, and in the future can be used for other work processes like load lifting and cart travel.

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