Numerical Modelling of I-Beam Jib Crane with Local Stresses in Wheel Supporting Flanges - Influence of Hoisting Speed

Numerički model I-bočne prednje dizalice s lokalnim silama na podupirajuće šarke na kotačićima – Utjecaj brzine podizanja

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Summary

This article presents an approach of numerical modelling of I-beam crane jib, with using the finite element method particularly the most loaded elements at different speeds. One of the possible methods for use in the design process of hoisting dynamics modelling and its effects on the load-carrying structure for the marine jib crane is shown. For proper modelling, the impact of the load and hoisting speed on the load-carrying structure jib, dynamics simulations of hoisting the load using Matlab-Simulink software were carried out and in the field of finite element method. To carry out such a simulation, hybrid calculations had to be applied, where the response from the phenomenological model based on solving a system of differential equations of motion in Matlab-Simulink was used to stimulate the crane I-beam jib during the FEM simulation, which permits to determine dynamic properties of the load-carrying structure for two example different hoisting speeds. The basic strength parameters for a typical light marine jib crane, obtained in the case of static calculations and using the proposed approach between the two computing environments were compared.

KEY WORDS

I-Beam
Local Stress
Implicit
Dynamic
Hoisting Process
Hoisting Speed.

Sažetak

Ovaj članak predstavlja određeni pristup numeričkom modelu I-bočne prednje dizalice koristeći se metodom ograničenoga elementa, a posebno najčešće ukrcavanih elemenata prema različitim brzinama. Prikazana je jedna od mogućih metoda uporabe pri predviđanju procesa modeliranja, dinamike podizanja i njezinih utjecaja na strukturu prijevoza tereta za pomorsku dizalicu. Za pravilno modeliranje izvršen je utjecaj opterećenja i brzine podizanja na nosivu strukturu dizalice, te simulacija dinamike podizanja tereta korištenjem Matlab-Simulnik softvera, a sve unutar okvira ograničene metode. Kako bi se izvršila takva simulacija, morale su se primijeniti hibridne kalkulacije. Upotrebljen je odgovor na fenomenološki utemeljenom modelu baziran na rješavanju sustava diferencijalnih jednadžbi gibanja prema Matlab-Simulnik modelu, kako bi se simuliralo I-bočnu prednju dizalicu za vrijeme FEM simulacije koja dopušta određivanje dinamičke osobitosti strukture opterećenja za dva primjera različitih brzina podizanja. Uspoređeni su osnovni parametri čvrstoće za tipičnu pomorsku dizalicu, dobiveni statističkim izračunima i korištenjem predloženog računalno osmišljenog pristupa.

KLJUČNE RIJEČI

I-Beam
lokalne sile
implicitni
dinamički
proces podizanja
brzina podizanja

1. INTRODUCTION/*Uvod*

Cranes with girders or jibs in the construction of I-beam are widely used in industry, during handling, assembly and light manufacturing. They provide good value and costs compared to operating parameters. The advantages of such structures are primarily light weight, the simplicity of design and ease of installation, low price, the possibility of suspending any hoist. Despite the lower mass, compared with box or truss jibs or girders, they are slenderer and therefore not suitable for large crane span or radius [12, 14]. In addition to the drawbacks of these devices it should also be included roadway wear and problems with its regeneration and the presence of additional stress on the lower flange of the hoist wheels [1, 8, 10, 11, 13, 19].

Most of these disadvantages do not occur in the case of I-beam jib cranes used in marinas and yacht harbours, whose mission is to hoist and lower the water boats and yachts. The manifold applications of slewing jib cranes in marinas, boatbuilding, or shipyards are almost unlimited. Post mounted jib cranes are a very space-saving solution for ships to be

a) b) c)

Figure 1 A typical form of jib crane constructions with the arm in the form of I-beam:

Slika 1. Tipičan oblik konstrukcije bočne dizalice u obliku I

a) Post-mounted jib crane with 1 hoisting point (single jib with hoisting frame) b) Post-mounted jib crane with 4 independently controllable hoisting points [21] c) Post-mounted jib crane with 4 independently controllable hoisting points and counterweight [22]

a) Naknadno montirana dizalica s 1 točkom podizanja (jedan krak s okvirom za podizanje b) Naknadno montirana dizalica sa 4 točke koje mogu kontrolirati podizanje (21) c) Naknadno montirana dizalica sa 4 neovisno kontrolirane točke i kontra opterećenjem (22)

lifted out of the water. Such jib cranes normally do not require large radiuses and load capacities and their class [16] are low. Therefore, it is popular to produce their jibs in the construction of I-beam. In this case, instead of winches, hoists are used - easy to use lifting devices (usually movable), whose mounting structure is very simple. There are three main types of jib crane load-carrying structure construction used in small ports and yacht marinas: with a counterweight or without, with one hoisting point (single jib), using in many cases a hoisting frame or with 4 independently controllable hoisting points without the need of hoisting frame, and with brackets or without it.

An advantage of construction with 4 independently controllable hoisting points is that each arm can separately lift a quarter of the total lifting weight and the front cross beam can be moved forward and backward. Another major advantage of this type of jib crane is that yachts with standing mast are possible to hoist. Counterweight or supports are used to increase the stability of the crane and to maximize load-capacity, height of lift or travel. There are also combinations of the aforementioned types. Crane radius of such structures is usually small and do not exceed several meters. Already radius of several meters is enough for launching and hoisting the majority of yachts and small boats. Load capacities that are offered by manufacturers reach up to 100 t, but in most cases, 20 t is sufficient even for relatively large vessels. There can be used chain or rope electric or hydraulic hoists. A typical example of different types of post-mounted jib cranes with I-beam jibs is presented in Fig. 1.

For all cranes, their primary task is hoisting and transportation of goods over short distances. For both of these movements (in most cases running simultaneously) a substantial dynamic impact on their structure is made, causing the formation of vibration [8, 9]. It is a negative phenomenon during all operations of the crane and has a negative impact on all of its strength and movement parameters [10, 11]. In the design phase of each crane, the load-carrying structure must, therefore, be modeled the hoisting of the unrestrained grounded load. Simplified arrangements for such modeling (providing ready-made templates and guidelines) give national and international standards. Modeling of hoisting phenomenon, either in ISO and EN [12-14], is based on the use of dynamic factor, which function is to "increase" the value of a static force acting on the structure and achieve an effect of quasi-dynamics. Theoretical illustration of this situation in accordance with standard EN13001-2 is shown in Fig. 2.

The value of such coefficient is calculated with a more or less accurate empirical formulas. It is, however, permissible, to use the numerical methods. An important element of the analytical approach that is present in European and world

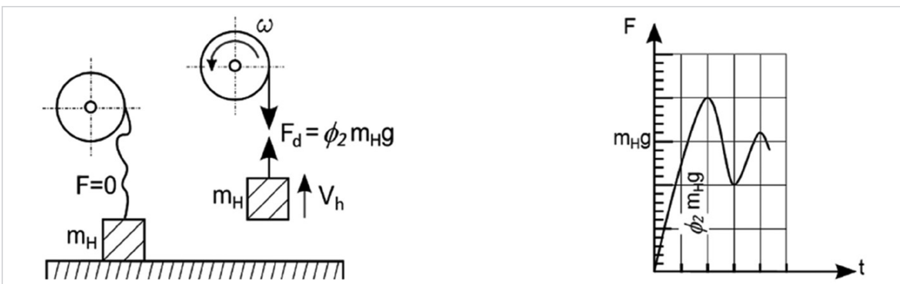


Figure 2 Influence of dynamics on generated hoisting force value: a) the behavior of the load, b) the dynamic force [12] where: $m_h g$ – force, ϕ_2 – dynamic coefficient, V_h – hoisting speed, m_H – load mass

Slika 2. Utjecaj dinamičnosti na proizvedenu vrijednost sile podizanja a) ponašanje tereta b) dinamička sila (12) gdje je: $m_h g$ sila, ϕ_2 - dinamički koeficijent, V_h – brzina podizanja, m_H - masa tereta

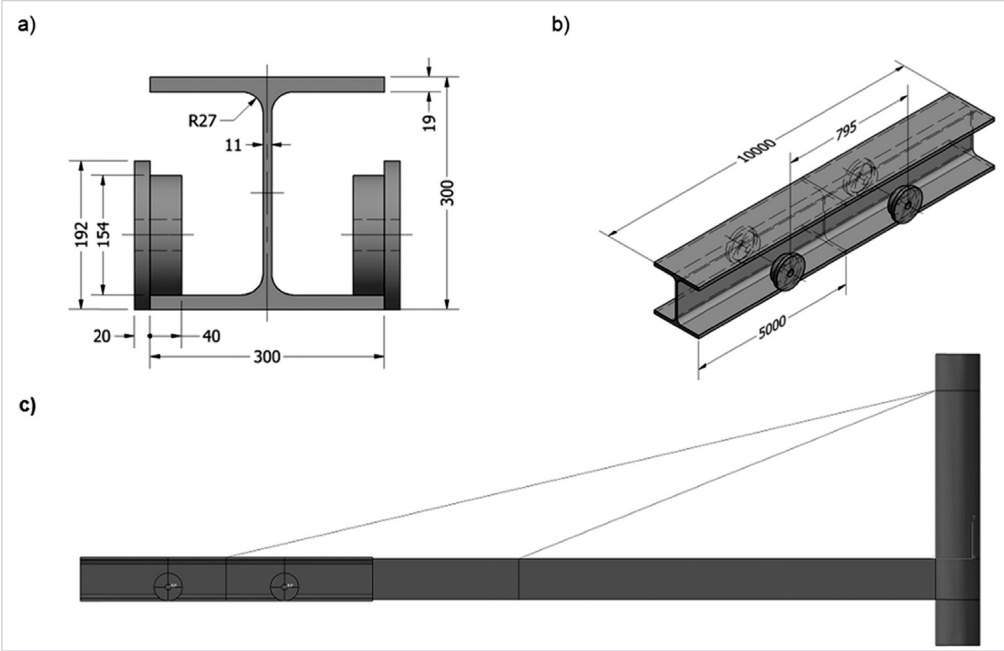


Figure 3 Model dimensions: a) general geometric data of I-beam jib, b) general geometric data of traversing hoist, c) post-mounted jib

Slika 3. Dimenzije modela: a) općeniti geometrijski podaci I-nosača, b) općeniti geometrijski podaci o poprečnom dizanju, c) naknadno postavljeni krak

standardization [15-17] is also a suitable model of hoisting mechanism. The hoisting class (determined on the basis of the dynamic characteristics of the drive mechanism) determines the appropriate design parameters to calculate the dynamic factor for hoisting an unrestrained grounded load.

Transportation using cranes demands high safety [20], therefore in case of different speeds, there is a need of dynamic models creation, that includes effects of failures or human errors like sudden brake or lifting cargo with not pre-strained rope. This allows the study of the structure behavior and particularly the most loaded elements at different speeds. Therefore, the analyzed value of the deflection and stress important from this point of view, is defined in the lower flange of I-beam jib, as the most loaded structure element.

2. NUMERICAL MODEL OF I-BEAM GIRDER / *Numerički model I-bočne dizalice*

The model for numerical calculations of the jib crane was made for HEB 300 I-beam with a length of 6 m and mounted hoist with a hoisting capacity of 5 t and wheel span of 0.795 m. The used construction had a bearing on the pillar and two brackets mounted on it. The model was loaded in the end position of the hoist on the jib. Geometrical relationships are shown in Fig. 3.

Table 1 shows the general characteristics of the tested jib crane, prepared on the basis of the technical documentation.

With analyzing the structure using FEM, it can be determined the basic data like stress, form, and frequency of natural vibration or deflection due to its own weight, load and boundary conditions. In the case of FEM, difficulties arise when it is necessary to enforce modelling caused by a moving truck or hoisting loads from the ground. Therefore, in the case of analysis of complex movements in FEM modelling becomes insufficient [5, 7, 12]. The shown methodology proposes using hybrid approach involving the coupling of two models - FEM and the phenomenological one.

In the case of using the hybrid method, as mentioned in the introduction, there was a need to create two models, FEA and phenomenological model of a jib crane. For the research, a FEM model was used that was shown in the work [6].

N, mm, MPa system of units was applied, therefore results of stresses are in MPa and displacements in mm are shown. The load – carrying structure was made from S355 steel where the limit design stress for sheets thickness < 63 mm is 305 MPa [17]. There were used mainly standardized general purpose four-node shell element S4R, eight-node brick element with reduced integration C3D8R and two-node beam element B31 from Abaqus Software Documentation [18]. Model presented in Figure 4 and 5 consists of 112750 elements and 138298 nodes.

Table 1 Characteristics of experimental crane

Tablica 1. Karakteristike eksperimentalne dizalice

Description		Symbol	Dimension	Value
	hoisting capacity	Q	[kg]	5000
	crane radius	L	[m]	6
	hoisting height	$H_{p\,max}$	[m]	5
operating speed	hoisting	v_h	[m/s]	1st 0.11, 2nd 0.22
	hoist travel	v_{jw}	[m/s]	0.34
	supply voltage	U	[V]	380

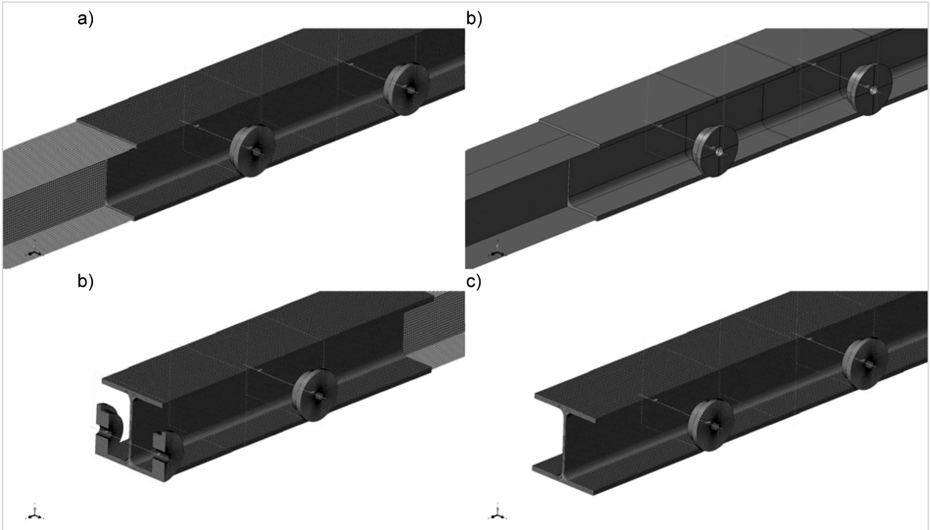


Figure 4 FEM model: a) c) d) mesh, b) geometry
Slika 4 FEM model: a) c) d) mreža, b) geometrija

The boundary conditions were established through reference points, which tied with the construction bonds type MPC Beam (figure 5). The design of the jib is divided into two parts - one surface-type and a solid type (in order to reduce the computation time and take the possibility to calculation stress state between wheels and beam). These parts are connected to one another by bonding a shell to solid coupling, which connects the lateral surface of the solid model with the edge surface of the shell model. Loads were applied by force to the wheel axle hoist through means of a kinematic coupling. Load of the I-beam jib lower flange was implemented by means of a surface to surface contact for the wheel - upper flange plane and near the side plane with a coefficient of friction in the value of 0,15. Extraction art was modelled by using beam type element and was connected to beam and also the mast which is made by using shell elements.

Figure 5 FEM model and reference points
Slika 5. FEM model i referentne točke

Calculations were made using the cluster IBM BladeCenter HS21. The solver was Abaqus Implicit according to MNiSW/IBM_BC_HS21/PŚląska/026/2014 grant.

3. PHENOMENOLOGICAL MODEL OF JIB CRANES STRUCTURE / *Fenomenološki model strukture prednje dizalice*

A dynamic model of the jib crane with the hoisting mechanism is shown in Figure 6. This model includes in its structure elements such as a jib, rope drum, wire rope, and ground.

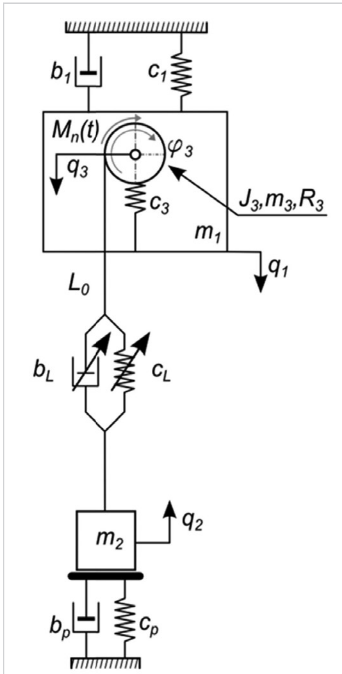


Figure 6 Simplified phenomenological model of examined jib crane, which includes Kelvin-Voigt model of wire rope
Slika 6. Pojednostavljeni fenomenološki model ispitivane kranske dizalice koja uključuje Kevin-Voigt žičani model

On the basis of the concept of generalized coordinates, and phenomenological model shown in Figure 6, the equations of motion can be written as second type Lagrange equations [2, 3, 5, 7, 12]:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_j}\right)-\frac{\partial E_k}{\partial q_j}+\frac{\partial E_p}{\partial q_j}+\frac{\partial E_R}{\partial \dot{q}_j}=F_j,\ \ j=1,2,....,n \qquad (1)$$

where:

t – time, q_j – generalized displacement, $\dot{q}_j$ – generalized velocity, n – number of degrees of freedom, F_j – generalized force, E_k – kinetic energy, E_p – potential energy, E_R – energy dissipation function.

This approach allows to obtain the differential equations of motion in the form of kinetic energy of the system:

$$E_k = 0.5m_1\dot{q}_1^2 + 0.5m_2\dot{q}_2^2 + 0.5m_3\dot{q}_3^2 + 0.5J_3\dot{\varphi}_3^2 \qquad (2)$$

where:

m_1 – reduced mass of jib, m_2 – mass of load, m_3 – mass of the rope drum, J_3 – mass moment of inertia of the rope drum, $\dot{q}_1$, $\dot{q}_2$, $\dot{q}_3$, $\dot{\varphi}_3$ – generalized velocity.

the potential energy of the system:

$$E_p = 0.5c_3\left(q_1 - q_3\right)^2 + 0.5c_p q_2^2 + 0.5c_1 q_1^2 + 0.5c_L\left(-q_2 - q_3 + R_3\varphi_3 i_w^{-1}\right)^2 \qquad (3)$$

where:

c_3 – stiffness coefficient of the cable drum axle, c_p – stiffness coefficient of the ground, c_1 – stiffness coefficient of jib, c_L – stiffness coefficient of wire rope, R_3 – radius of the cable drum, i_w – gear ratio of pulley blocks, q_1, q_2, q_3, φ_3 – generalized displacements.

and energy dissipation function:

$$E_R = 0.5b_1\dot{q}_1^2 + 0.5b_p\dot{q}_2^2 + 0.5b_L\left(-\dot{q}_2 - \dot{q}_3 + R_3\dot{\varphi}_3 i_w^{-1}\right)^2 \qquad (4)$$

where:

b_1 – jib damping ratio, b_p – ground damping ratio, b_L – wire rope damping ratio, m_{liny} – mass of rope.

Rope stiffness coefficient defined by the formula (5), and its value depends on the length of the rope:

$$c_L = \frac{n_{lin} \cdot A_l E_l}{\left(L_0 - R_3\varphi_3\right)} \text{ where: } E_l = (0,4 \div 0,65)E_s \qquad (5)$$

where:

n_{lin} – number of bands of wire rope, L_0 – initial length of the rope, E_l – modulus of elasticity, A_l – metallic cross-sectional area of wire rope, E_s –Young modulus for steel.

Variable damping coefficient of wire rope strand, is founded according to the publications [3, 9]:

$$b_L = 2\zeta\sqrt{c_L\left(m_2 + n_{lin}\rho_l A_l\left(L_0 - R_3\varphi_3\right)\right)} \qquad (6)$$

where:

ζ – dimensionless coefficient, ρ_l – density of steel.

The reaction of a ground N, made dependent on displacement. At rest, the elastic force and the damping force of the ground affect the cargo. At the time of hoisting load, the force will be switched off from the system. The value of this reaction is described below:

$$N = \begin{cases} 0 & q_2 \geq 0 \\ -c_p q_2 & q_2 < 0 \end{cases} \qquad (7)$$

where:

N – elastic response of ground.

In Matlab-Simulink environment the dynamic model was formulated. Table 2 shows the physical parameters describing the considered vibrating model, which are estimated on the basis of the technical documentation of overhead travelling crane. Then the numerical experiments for the data presented and the assumed initial conditions with the classical model of elastic-damping model (Kelvin-Voigt) for the wire rope were performed. As the extortion signal – the constant driving torque, corresponding to the fast start of the engine is used, without the control system (the worst control case). In accordance with the applicable standard [16] the hoist drive class HD1, for the hoisting mechanisms without creep speed was examined.

Simulations were carried out using algorithm ode4, with the constant step of integration 1E-04 s. Simulations were performed for a load value of 5000 kg, where the cargo is on the end of i-beam. After a series of numerical experiments, many model parameters were obtained, such as jib and cargo acceleration.

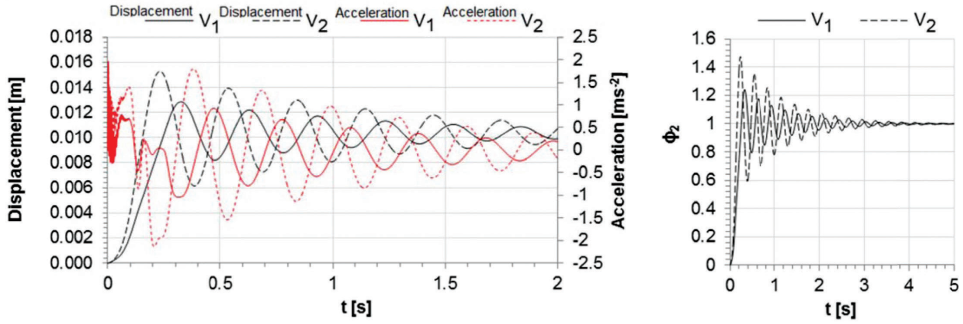
4. RESULTS AND DISCUSSION / *Rezultati i rasprava*

Figure 7 shows the displacement and acceleration waveforms of the test beam with a load of 5 t obtained by simulation in Matlab/Simulink for the HD1 class of hoisting mechanism in accordance with the [7].

The maximum beam deflection reaches a value of 12.62 mm for V_1 hoisting speed and the acceleration of approximately 1.97 m/s^2.(fig 8). The maximum beam deflection for V_2 hoisting speed reaches a value of 15,01 mm, and the acceleration of approximately 1.94 m/s^2. Obtained displacement values were inputs parameters and one of the boundary conditions in FEM simulation. For better understanding, this phenomenon and its influence on construction a specialty measurements of vibration must be prepared for validation of model [4]. The results of a simulation using the finite element method are shown in Figures 8-10, simultaneously comparing them with the results of static calculations.

Table 2 Physical parameters describing the dynamic system
Tablica 2. Fizički parametri koji opisuju dinamički sustav

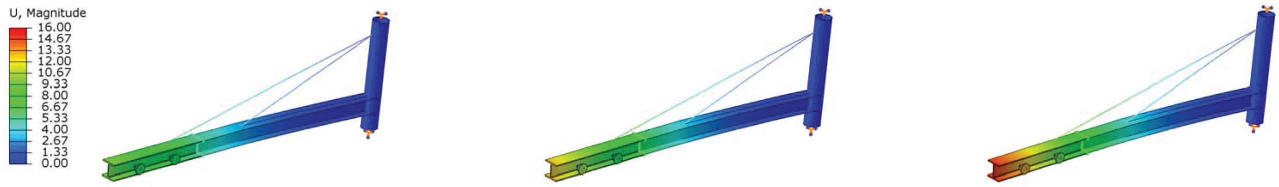
No.	Symbol	Value	Unit	No.	Symbol	Value	Unit
1	m_1	721	[kg]	14	L_0	5	[m]
2	m_2	5000	[kg]	15	A_l	5,53e-5	[m^2]
3	m_3	176	[kg]	16	ρ_l	7850	[kg/m^3]
4	m_{liny}	17,36	[kg]	17	E_s	2,1e011	[Pa]
5	J_3	3,0454	[kgm^2]	18	E_l	1,155e011	[Pa]
6	c_1	4,74e6	[N/m]	19	g	9,81	[m/s^2]
7	c_p	2,0e8	[N/m]	20	V_p	0,11 or 0,22	[m/s]
8	c_3	1,8e8	[N/m]	21	ω_b	1,63	[rad/s]
9	b_p	1,0e6	[Ns/m]	22	n_{lin}	4	[-]
10	b_1	23,7e3	[Ns/m]	23	ζ	0,07	[-]
11	R_3	0,14	[m]	24	i_p	60	[-]
12	R_{3w}	0,1225	[m]	25	i_w	1 or 2	[-]
13	d_l	0,0125	[m]				



a) b)

Figure 7 Displacement and acceleration waveforms measured at the end of the jib for the case when the ropes are loose at start-up for two deferent hoisting speed a), b), c) relationship between dynamic coefficient and time

Slika 7. Deplasman i ubrzanje oblika vala izmjerenog na kraju kraka za slučaj kada su konopi labavi na početku za dvije različite brzine podizanja a), b), c) odnos između dinamičkog koeficijenta i vremena



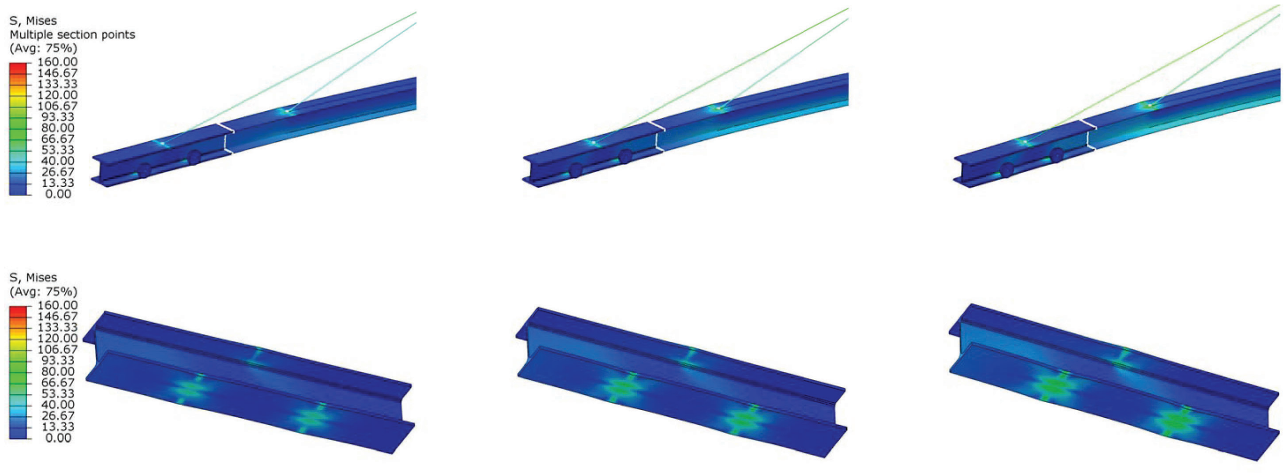
a) b) c)

Figure 8 Displacement in I-beam: a) static simulation – 10.18 mm, b) dynamic simulation for V_1 speed 12.62 mm, c) dynamic simulation for V_2 speed 15.01 mm

Slika 8. Deplasman kod I-poprečne grede a) statistička simulacija – 10,18 mm b) dinamička simulacija za V brzinu 12,62 mm, c) dinamička simulacija za V2 brzinu 15,01 mm

Figure 9 shows the stress results in jib modeled with solid and shell elements. In the case of dynamic load, stresses reach values close to 152 MPa with V_2 speed, which is a significant difference compared to the simulation applying for a static load. Stress values obtained in accordance with the Huber-Mises-Hencky theory is the most common parameter in design practice. Taking that case into account, in the case of hoisting mechanism HD1 class-type, the difference between static and dynamic types of simulation is very high and reaches over 19.5% for slower speed and 47.5% for higher speed in case of stress. The values of dynamic factor obtained by the standard [12, 16] for this type of mechanism differ by 2.5% and 9% from obtained values. Of course, this is the most unfavorable case from the point of view of the designer because of the most "rigid" characteristic of the mechanism.

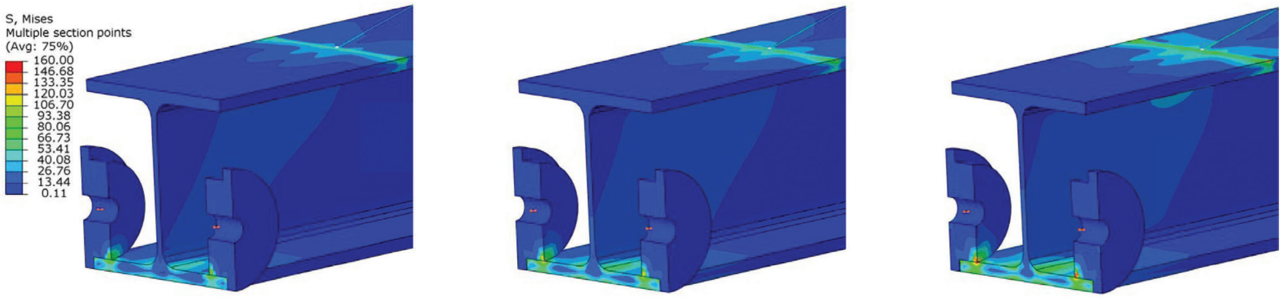
Figure 10 shows the stress distribution through the cross section of the lower flange and wheel for the case of the static and dynamic load caused by a sudden load increase. The waveforms of stresses in the cross-section of the bottom I-beam jib flange are the basis for determining stress in so-called characteristic points set in the standard [15] for local deflection of the lower flange (roadway of the hoist).



a) b) c)

Figure 9 Stress in I-beam according to Huber-Mises-Hencky theory (without wheels): a) static simulation, b) dynamic simulation for V_1 speed, c) dynamic simulation for V_2 speed

Slika 9. Napor kod I-grede prema Huber-Mises-Hencky teoriji (bez kotačića) a) statička simulacija b)dinamička simulacija za V1 brzinu c) dinamička simulacija za V2 brzinu



a) b) c)

Figure 10 Stress in I-beam according to Huber-Mises-Hencky theory (with wheels): a) static simulation 103MPa, b) dynamic simulation for V_1 speed 123 MPa, c) dynamic simulation for V_2 speed 152 MPa

Slika 10. Napor kod I-grede prema Huber-Mises-Hencky teoriji (s kotačićima), a) statička simulacija 103MPa, b) dinamička simulacija za V2 brzinu 152 MPa

5. CONCLUSIONS/*Zaključci*

- It is possible to use a hybrid method for modeling the dynamics of hoisting the load in cranes research and design, increasing the benefits of the finite element method for obtaining a more realistic simulation results.

- In the case of simulation that takes into account, the dynamic effects of hoisting the load with different speed, difference values for the stress is over 19,5% and 47,5% for the assigned HD1 class, almost the same in the case of deflection.

- proposed methodology for the calculation shows a good coincidence of the results with theoretical recommendations in existing standards. It may serve as a basis for load-carrying structure verification at the design stage.

- Further analysis should be based on a comparison of the impact of other classes of mechanism on design strength parameters and verification of the results with the recommendations in the existing normative acts.

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