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Topological Optimization and Finite Element Method Analysis of Wheels on the Carts Winch Bridge Crane

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Abstract **– In this paper, an analytical calculation of load on bridge crane carts winch wheel loads was performed based on which FEM analysis and topological wheel optimization were performed. After the calculation, a standard wheel diameter was adopted. During FEM analysis in the CAD system, SolidWorks noted that certain surface areas had extremely low stress values, which was the main reason for the topological optimization of the wheel. The topological optimization of the geometric 3D model of the wheel is made in the CAESS ProTOp software, resulting in optimized 3D geometric wheel model. These models offer a number of advantages, such as saving materials to produce, reducing their own weight, balance stress conditions and easy customization model optimized technologies of additive manufacturing. This model of analysis and optimization was performed on the laboratory model of the bridge crane and it is applicable to all types of cranes.**

Keywords **– bridge crane, wheel, finite element method, topological optimization.**

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1. Introduction

Bridge cranes are used for handling in large workshops or storages. Usually working under the roof, and if necessary in the open. They move by two parallel rails placed along the length of the hall or storage on pillars or consoles. Their main advantage is that they cover the whole area of the hall or warehouse, enabling them to move in all directions. The movement of cranes (of the bridge) on the rails and the driving winch (carts) across the bridge to transport from one place to another within the working range of the crane. For all these movements it is necessary to set the wheels that allow the movement of both the carts winch and the bridge of the bridge crane.

Figure 1 Model of bridge crane with carts winch

Figure 1. shows a model of a bridge crane with a carts winch that moves on the bridge of a bridge crane. On the carts winch of the bridge crane, the wheels are made to fit the ropes mounted on the bridge of the bridge crane. The wheel dimensions were obtained by analytical calculation and as such were mounted on the carts winch [1]. In this paper a 3D geometric wheel model will be formed in which FEM analysis will be performed. Today, due to global competitiveness it is required for the designed product to be both functional and be the best among its competitors. Criteria that play a major role in this are: dimensions, time of production, compatibility, reliability, durability, weight and price. Therefore, great importance in the development of products has the optimization. The main goal of optimization is to find the best solution for the default conditions. Optimizing is not just a process and a way to set up an engineering task, but also a tool that helps to make

decisions in the widest sense. The methods of intuitive optimization are based on intuition, professional experience, numerous attempts, etc. [2], [3], [4].

Today, alongside appropriate algorithms, software tools, and the application of high-power computers, it is possible to optimize based on computer simulation of physical models. The advantages of virtual models are that making and analyzing towards physical models is cheaper and saving time is great. Optimization procedures are applied in a variety of linear and nonlinear problems, such as the problems of optimizing mechanical structures [5], [6], [7].

Optimization is an integral part of the design. In general, it can be said that the construction process can be seen as an optimization problem in which various measures need to be optimized to meet the construction requirements. The goal of topological optimization is to find places to add or subtract materials to optimize the construction. There are a large number of works dealing with topological optimization aiming to find the optimal shape of structure in relation to some criterion, and is of great importance in the field of structural design [8], [9], [10].

Software CAESS ProTOp supports 3D geometric models created in Solid Works. For this reason, the initial 3D geometric model will be formed in SolidWorks so that topological optimization can be made in the mentioned software. Based on the topology optimized 3D geometric wheel model in the CATIA software, a dimensional point optimization will be performed, and then re-FEM analysis.

2. Analytical calculation and wheel dimensioning of the bridge crane model

The forces on the wheels will be determined by using Andre's method of determining the force [11], [12]. This method assumes that the resulting vertical force R is transferred to the imaginative AB support that relies on the carrier on which the T_1 and T_2 wheels and the T_3 and T_4 wheel carrier are located, Figure 2. It is assumed that the carriers are articulated, thus decreasing the pressure on the wheels to a static assignment.

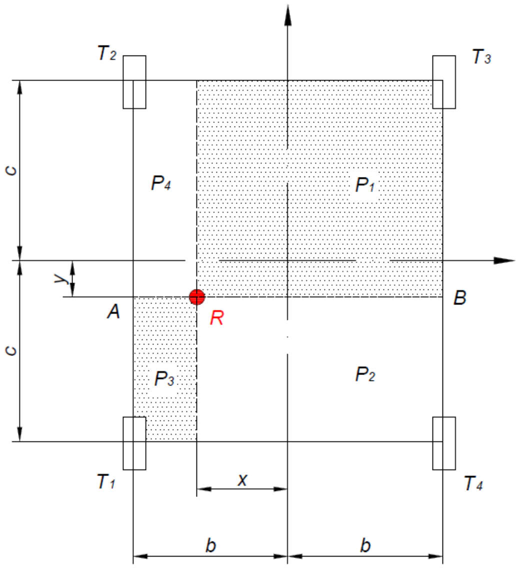


Figure 2. The force on the wheels according to Andre's method

The resulting force R represents the sum of the load capacity of the crane, which in this case is 250 kg (2452.5 N) and the weight of the carts winch is 150 N.

From the balance condition for the girders supported by T_1 and T_2, T_3 and T_4, we get:

$$T_1 = \frac{R}{4 \cdot b \cdot c}(b + x) \cdot (c + y)$$

$$T_2 = \frac{R}{4 \cdot b \cdot c}(b + x) \cdot (c - y)$$

$$T_3 = \frac{R}{4 \cdot b \cdot c}(b - x) \cdot (c - y) \quad (1)$$

$$T_4 = \frac{R}{4 \cdot b \cdot c}(b - x) \cdot (c + y)$$

Tags: *a, b, c, x, y* represent geometrical characteristics that depend on the structure of the carts winch (Figure 2.). By adding the known values to the expression (1), we reach the value of the force on the wheels shown in Table 1.

Table 1. Value of the force on the wheels

Wheel	Force (N)
T_1	1143,6 N
T_2	873,3 N
T_3	253,5 N
T_4	332 N

From Table 1. it is clear that the force at the point T_1 is greatest and we will use that force in the further calculation and dimensioning of the bridge crane wheel model.

2.1 Calculation wheel diameter

Crane wheels can be of various shapes and constructions. They are made of steel or coated steel molds which are heated to the toes in a heated condition and such wheels have a longer life span. Both in the one and the other surface, the layer is thermally processed. For the wheel used here for low loads, there is no need for thermal treatment. For the proper rolling of the rails, the wheels usually have obliques on one or both sides [13], [14], [15].

The wheel diameter is calculated from the relation:

$$D_T \geq \frac{F}{p_{dr} \cdot k_2 \cdot k_3 \cdot (b_0 - 2 \cdot r)} \quad \text{[mm]} \tag{2}$$

where:

$p_{dr} = p_{dur} \cdot k_{1r}$ – permissible surface pressure of the wheel for the flat shape of the head of the rail,
p_{dur} = 7,5 [MPa] – permissible pressure,
b_0 = 8 [mm] – the width of the rail head,
r = 0,5 [mm] – radius of rail rounding,
k_{1r}, k_2, k_3 – coefficients according to Tables 3.2,3.3,3.4.[11].

Force F corresponds to the force of the most loaded wheel T_1 = 1143.6 N.
By incorporating known values, we get:

$$D_T \geq 29{,}6 \quad \text{[mm]}$$

Due to pre-constructed wheelchairs (square tubes 40x40x3), for constructive reasons we adopt a wheel diameter:

$$D_T = 40 \quad \text{[mm]}$$

The wheel axle will be viewed as a beam with two supports and one concentric force. The first step is to determine the reactions in the supports, based on which the maximum bending moment is determined. Then, from the maximum permissible stress condition, the circular cross-section of the wheel diameter is determined. Figure 3. shows the axle as a beam with dimensions and load [1].

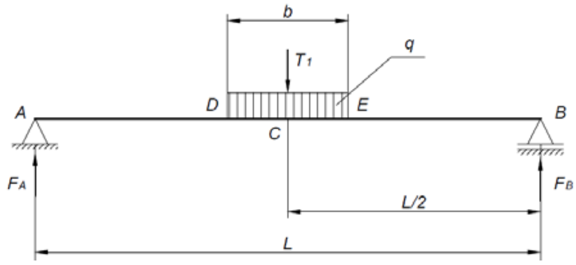


Figure 3. Wheel axle is represented as a beam with two supports and one load

Tags from the image are:

L = 44 mm = 0,044 m – axle length on the most loaded T_1 wheel,
T_1 = 1143,6 N – force on wheel,
q = 76240 N/m – force T_1 a continuous load,
b = 15 mm – width of the wheel.

By solving this static problem, we will get a maximum torque value of M_{smax} = 9.88 Nm.
The maximum axle bending stress is calculated from [16]:

$$\sigma_s = \frac{M_{smax}}{W_x} \leq \sigma_{doz} \tag{3}$$

Where:
σ_s [MPa] – bending stress,
M_{smax} [Nm] – maximal bending moment,
W_x [cm^3] – resistant moment of inertia,
σ_{doz}= 183 MPa - allowable stress for the selected material (GS 295 N, EN 10027-1)

From the expression (3) we get:

$$W_x = \frac{d^3 \cdot \pi}{16} = 54 \text{ mm}^3 \tag{4}$$

From the expression (4):

$$d \geq \sqrt[3]{\frac{W_x \cdot 16}{\pi}} \tag{5}$$

$$d \geq 6{,}5 \text{ mm}$$

According to literature [11], [12], [13] we have a standard wheel diameter d = 8 mm.

Figure 4. Wheel with axle

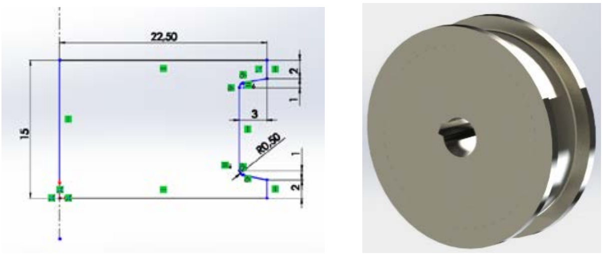
According to these dimensions, the wheel assembly is made and shown in Figure 4.

3. Formation of 3D geometric model and FEM wheel analysis

The geometric model has its own physical form (in the space it is a mechanical part), an abstract form in the form of drawings, an information form (hierarchy of elements) and an internal form in a database. Since the formed geometric model is one logical unit, it can be further used for the production of constructive documentation, different graphic representations, technological preparation of

production (CAP / CAPP / CAM) and ultimately for engineering analysis and optimization.
Creating a geometric model in SolidWorks software consists of two steps:

- In the first step, we create a 2D drawing (Sketch) of our element according to exactly defined dimensions (Figure 5a).
- The second step is to provide the third dimension with the drawing provided by the software provided by us (Figure 5b).



a) *b)*

Figure 5. a) Sketch, b) 3D geometrical model

The following is a FEM analysis of the carts winch wheel analysis using the 3D finite element in SolidWorks software in the Simulation module. The analysis consists of several steps:

1- selection of materials,
2- constraints definition,
3- load definition,
4- the formation of finite element mesh,
5- calculation execution and review results.

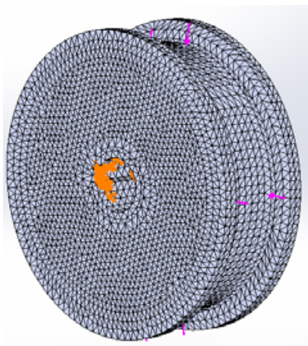


Figure 6. The wheel model in the preparation phase for FEM analysis

All the steps were taken on the wheel model and are shown in Figure 6.

Figures 7.a and 7.b show the stress and deformation values that occur on the wheel model.

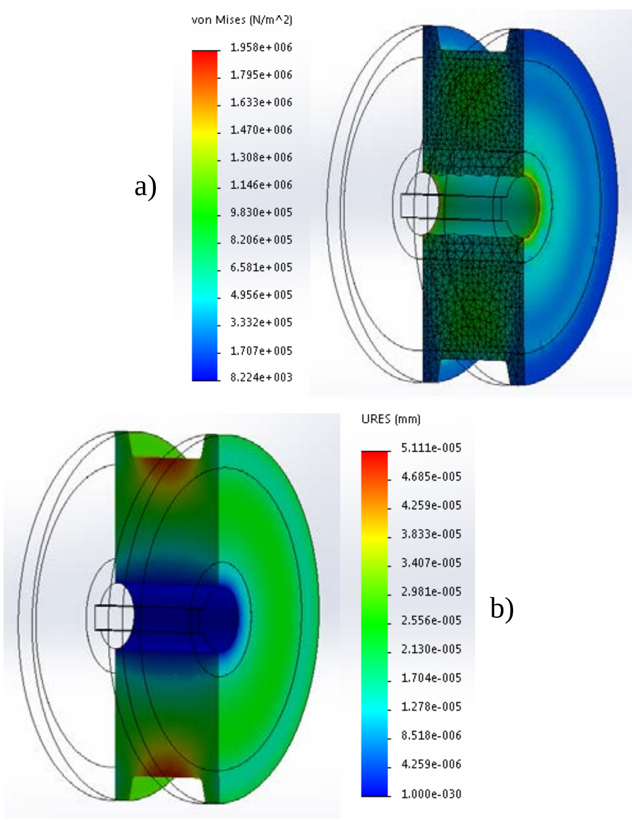


Figure 7. a) Stress, b) Deformation

Data obtained using SolidWorks software is presented in Table 2.

Table 2. Data obtained using SolidWorks software

Von Mises stress (MPa)	Deformation (mm)	Mass (kg)
1,985	$5,1\cdot10^{-5}$	0,147

4. Topological optimization

Optimization is a process whereby designing or planning determines the best possible choice of parameters (variables) based on predefined criteria (objective function). Optimization is not just a process and way of setting up an engineering task, but also a tool that helps to make decisions in the widest sense. Engineers have always been trying to optimize processes in an intuitive way, but such a way is very subjective and subject to mistakes. The methods of intuitive optimization are based on intuition, professional experience, numerous attempts, etc. Topological optimization and optimization of the form given by the implicit function is complex and required numerical procedure due to the large number of variables, boundary conditions, and the possible high degree of nonlinearity of the functions being solved. By topological optimization, we optimize the distribution of materials by geometry of the body, we change the structure of geometry with respect to different possible criteria (such as minimum mass, minimum stress, minimum deformation ...).

The step-by-step optimization process is shown in the flow diagram in Figure 8.

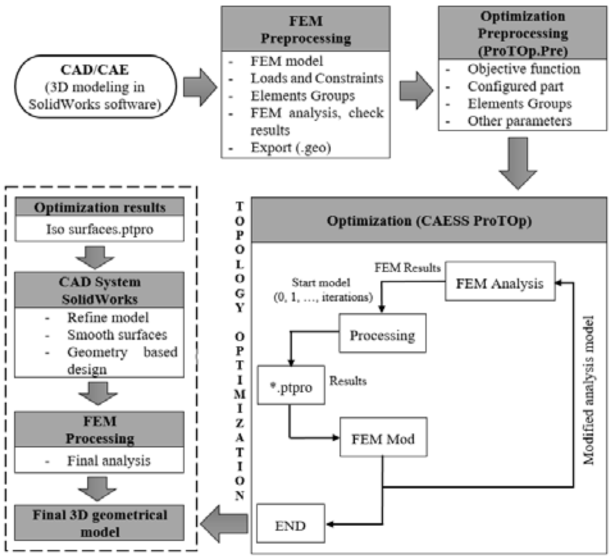


Figure 8. Optimization diagram

4.1 *Topological optimization of wheel in CAESS ProTOp software*

ProTOp is software that has the capability to topologically optimize 3D geometric models. The software is developed by the Slovenian CAESS (Center for Advanced Engineering Software and Simulations). Before the optimization approaches in the said software it is required to import the previously formed FEM model in ProTOp. By selecting the tool for exporting the analyzed 3D geometric models within SolidWorks software, we choose the file extension .geo, then we open such a 3D geometric model within the ProTOp software. The next step is to set the optimization constraints. The software offers quite a lot of options for defining the type of optimization, the geometry of the optimization part (sample), and here we choose to work with Solid and Lattice with topological optimization. When creating optimization settings, the goal function is to reduce the mass. In order to successfully optimize, it is necessary to define a fixed geometry. A fixed geometry implies a surface on an element that should remain the same at the end of the optimization. In our example, during the analytical calculation we obtained an external diameter of the wheel and a shaft diameter, and these two dimensions fall under fixed geometry. ProTOp software offers the possibility of selecting fixed and free geometry as shown in Figure 9.

Figure 9. shows a 3D geometric model with all the settings needed to start the optimization.

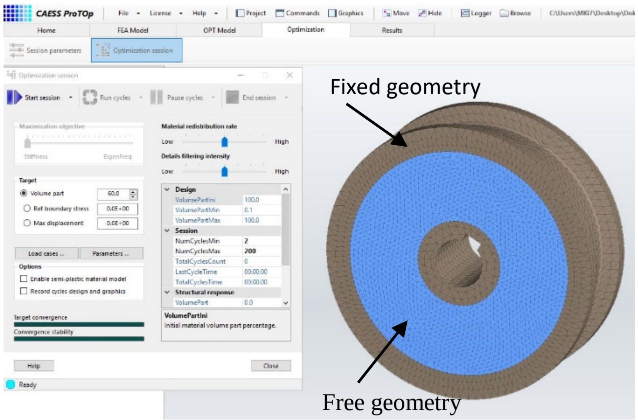


Figure 9. 3D geometric model with optimization settings

The result of the Lattice topological optimization is shown in Figure 10. The shape of the wheel structure in Figure *10.a* could be made by conventional and additive technologies. The shape of the wheel structure in Figure *10.b* would be produced by some of the additive manufacturing technologies, e.g. by 3D printing. The advantage of such a model is very low mass and large material utilization.

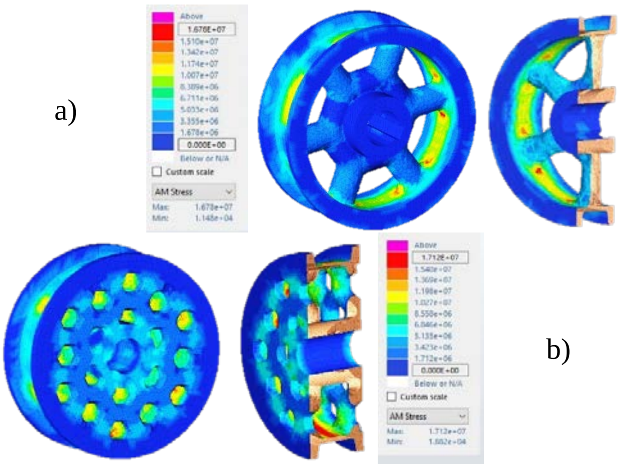


Figure 10. Examples of the model of the wheels obtained by using the Lattice topological optimization

Considering the technological limitations below, a wheel that can be produced by conventional methods (CNC machines, etc.) will be shown. In this section, we used Solid topological optimization.

After starting and finishing the Solid Topological Optimization, a 3D geometric model (Figure 11.) is obtained, which we will export from the ProTOp software using the special tools to the IGES file. When opening an optimized 3D geometric model in SolidWorks, we will get *Surface* based on which we will form a model for FEM analysis.

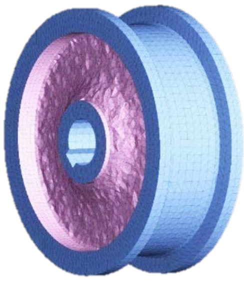
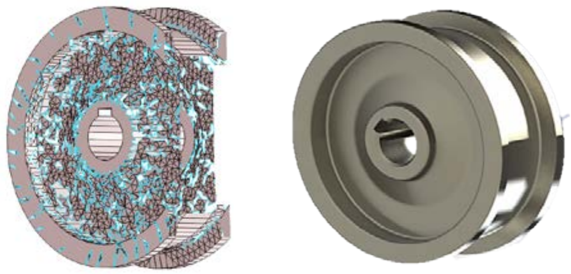


Figure 11. Optimized 3D geometric wheel model

When opening an optimized 3D geometric model in SolidWorks, we will get very rough surfaces that need to be edited to make the model usable for FEM analysis. Figures 12.a and 12.b show 3D geometric models after completion of topological optimization and model after alignment of surfaces within the SolidWorks system.



a) b)

Figure 12. a) Model after topological optimization, b) 3D geometric model for FEM analysis

Figures 13.a and 13.b show the results of the FEM analysis of the optimized 3D geometric model.

a)

b)

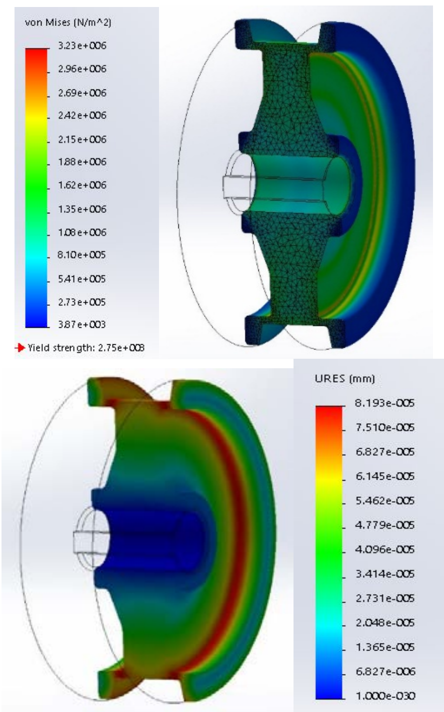
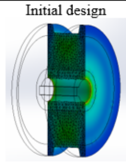
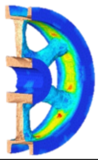
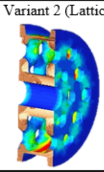
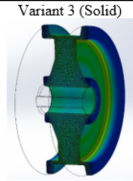


Figure 13. Displays the stress status of the optimized 3D geometry model

5. Results

This chapter will show the comparison of FEM analysis and mass results, initial and optimized 3D geometric models. The comparison of the results is shown in Table 3.

Table 3. Results.

Wheel model	Von Misses Stress (MPa)	Displacement (mm)	Mass (kg)
Initial design 	1,985 MPa	$5{,}1 \cdot 10^{-5}$ mm	0,147 kg
Variant 1 (Lattice) 	16,78 MPa	$42{,}6 \cdot 10^{-5}$ mm	0,085 kg
Variant 2 (Lattice) 	17,12 MPa	$29{,}4 \cdot 10^{-5}$ mm	0,09 kg
Variant 3 (Solid) 	3,23 MPa	$8{,}2 \cdot 10^{-5}$ mm	0,095 kg

According to Table 3. it is clear that by optimization we reduced the weight of the wheel by not limiting the permitted stress and deformation range.

6. Conclusion

Optimization is a process whereby designing or planning determines the best possible choice of variables based on predefined criteria. In modern production, great attention is paid to optimizing the product due to resource and time saving. In engineering sense, optimization is the search for the extreme of the function while satisfying the necessary constraints. The main goal of optimization is to minimize costs, which is reduced to a minimum of mass, energy…

From this paper it can be concluded that topological optimization accelerates the construction process by providing us with a suitable constructional solution in a short time. Of course, optimization can be applied to any problems that arise in product design. This paper examines the example of a wheel that is built on a model crane. A detailed analytical calculation of the forces acting on the wheels of the carts winch was made and the most critical case or the most loaded wheel was observed.

Then is generated a 3D geometric model in Solid Works software and performed a FEM analysis. The model was imported into CAESS ProTOp software in which we received three optimized models for three different settings. The first model (*Variant 1*) can be produced by conventional (3D print) and additive manufacturing methods. The second model (*Variant 2*) can be made by conventional production methods (3D print). On the third (Variant 3) model, care was taken of the technology, i.e. that it has the ability to manufacture on a CNC machine. All optimized models have lost a lot of weight from 35% to 45% of the mass, provided that the permissible stress limits are not compromised.

Compared to Variant 1 with the initial model, the mass was reduced by **42.2%.** For Variant 2, the weight was reduced by **38.3%.** The weight of Variant 3 was reduced by **35.4%.** From Table 3. we can conclude that the stress did not exceed the allowed values and the mass was significantly reduced. Variant 1 is the most optimal in terms of the mass that was the goal of optimization. This type of optimization can be applied to several types of cranes that have the possibility of horizontally moving loads, primarily the bridge cranes.

Acknowledgements

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