CAD STRUCTURAL OPTIMIZATION OF LARGE CANTILEVER GIRDERS ON CRANES

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ABSTRACT

The paper deals with the structural optimization of the cantilever girder. Standard CAD optimization tool is used for the model of the main girder on a large jib crane. The objective function is the minimum weight of the girder subjected to the given payload, while constraint functions are postulated according to the usual structural rules and regulations. The illustrative example shows an easy way of optimization which can be used in everyday CAD designing practice. It gives practical recommendations in the selection of variable parameters. The obtained results indicate that the algorithm is time-saving when compared to the analytical approach, especially when variability of the section needs to be included in the design.

Keywords: Structural optimization, CAD, FEA, CATIAV5, jib crane, cantilever

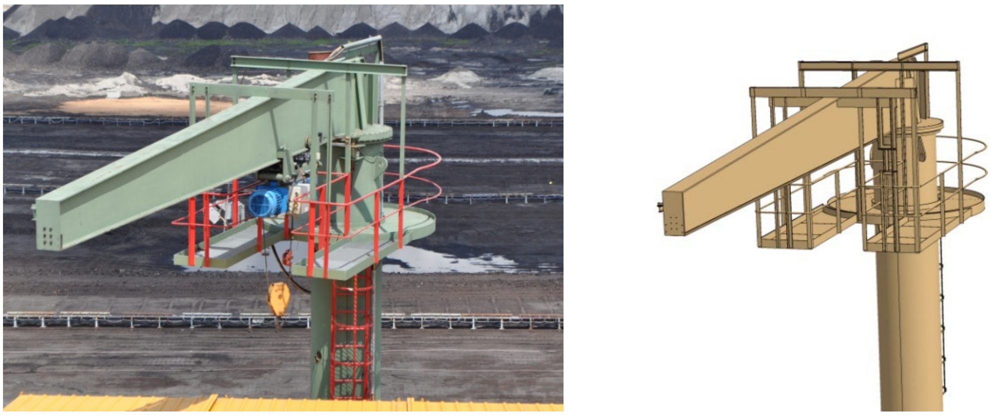
INTRODUCTION

Optimization is an everlasting tendency in mechanical engineering. Having started as an empirical approach, optimization in the modern age has brought the techniques which are fully related to applied mathematics. As in all other fields of engineering, the methods of optimization can be classified into analytical and numerical methods.

Analytical methods played an important role in structural optimization in the 20th century. However, their limitations in finding a close-formed solution for the given problem opened up the space for a strong development of numerical methods. Nowadays, in structural analysis, the numerical method implies the usage of Finite Element Analysis (FEA) with the accompanying Computer Aided Design (CAD). They are used as an engineering tool for design in almost all fields of mechanical engineering because they offer a simple way of representing complex structures. The modern CAD software also stands for a product development tool for mechanical structures, i.e. for optimization. The related studies were numerous in the last twenty years and can be easily found.

Within the structural optimization problems, there is a following classification (Spillers, 2009): (1) size optimization, which deals with the calibration of cross-sectional properties and structural elements dimensions, (2) shape optimization, which deals with the optimization of the boundary shape of the structure, and (3) topology optimization, which consists of the distribution of material within the structural space.

CAD is used for the design of “heavy” machinery jib cranes as well (Fig. 1). However, designers of such structures tend to follow the usual recommendations which reduce the possibility for structural optimization.



(a) (b)

Figure 1: Foot-mounted jib crane: a) Real model, b) CAD model

The aim of this paper is to show one way of structural optimization of cantilever girders on big jib cranes subjected to the main vertical load (payload). The authors are fully aware that the calculation model belongs to the class of “simple” models, but the safety of these cranes highlights the importance of this topic. The postulation brings this problem into the field of variability of the cross-sections over span. It has to be pointed out that design examples are based on the realistic/possible object of the jib cranes. Of course, the goal is the reduction of girder mass with the preservation of the constraints which are defined by main structural proofs.

CATIA implemented Simulated Annealing optimizer is used as one of the basic algorithms within the Product Engineering Optimizer workbench. Due to the class of the title problem, this can be adopted as a sufficient enough postulation of the optimization tool.

Further, this paper is aimed at encouraging the designers of big jib cranes to include the variability of dimensions of structural elements, which is rarely done in practice (Fig.1).

RESEARCH BACKGROUND

Many analytical approaches can be found when it comes to the problems of structural optimization. Mostly, they deal with the method of Lagrange multiplication for the optimization of structural cross-sections asin research (Šelmić et al., 2006) or (Anđelić et al., 2007). The constraints in those cases correspond to main safety requirements, such as the allowed stresses and displacements. This kind of approach belongs to the class of size optimization. In spite of the fact it is carried out manually, this technique can be a good basis for the improvement of structural products.

Another kind of approach, used in this paper, is the consideration of variability of the cross-section over length of structural elements. Theoretically, this idea is covered within the topic of strength of materials. However, it can be used only for simple models of beams (usually made of I-sections) under very few constraints. This kind of postulation belongs to the class of shape optimization. The addition of constraints, such as the effect of torsion on open beams, increases the complexity of the postulated problem, as shown in research (Gašić et al., 2018).

In practice, the tendency for variation of the cross-section over length has been present since the beginning of the industrialization of structures. In early stages, it was strongly connected with the limits of production technology for steel beams as in the book (Kurt, 1969), which forced engineers to tailor beams with the existing ones.

However, the above-mentioned possibilities are often neglected in structural design due to a missing link in the calculation of manufacturing costs vs. operational costs between the manufacturer and the user.

Hence, one may find the following characteristics of structural optimization as an overview of the mentioned techniques:

- minimal mass of structure is almost always the priority,
- optimization is often done manually and is a time-consuming process,
- class of optimization is mostly separated.

Here, some of the disadvantages with analytical methods will be avoided with the CAD based optimization. The object of optimization is a cantilever girder of the big jib crane. The weight of the girder does not influence the performance of the crane and any reduction of the weight has a positive effect on the energy consumption-cost within the operation of the rotation of the girder (Fig 1.a). The task is to adjust the structural parameters of the existing girder and to save the material, with the preservation of the given requirements and product performance.

The idea is not to go towards the truss structure, which would lead to topology optimization (Marjanović et al., 2009), but to maintain the beam-like element due to the manufacturing cost.

Firstly, the variation of height comes as a natural and known way for the shape optimization of the given problem. However, it is rarely done in practice. Schematically, the postulation is depicted in Fig. 2a, where the girder has a left (clamped) end-L, right (free) end-R, length l and (payload) capacity Q. The usual cross-section of these cantilevers is made of wide I-sections or box sections (Fig. 2b). The first class is generally used in jib cranes because the production process requires only the purchase of the rolled section girder. Thus, variation of height would increase the manufacturing costs in that case. For the jib cranes with a bigger length/reach and high capacity, the box section has to be involved. It is made by welding of the sheet metal plates. Even in this case, manufacturers tend to make a uniform section over length. The only excuse for this kind of production postulation can be found in the fact that these cranes are not subjected to mass production and that the calculation method comes from the standard analytical approach.

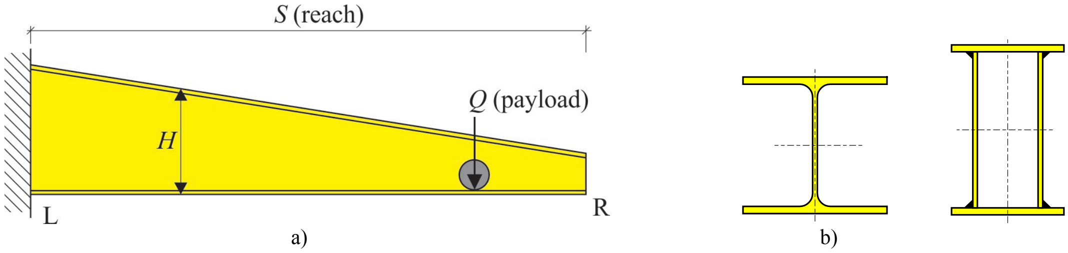


Figure2: a) Schematic model of jib (cantilever), b) Typically used sections

The objective function is the minimal mass (volume) of structure, which obviously corresponds to the minimal weight. The constraint functions are defined as:

$$g_1 = f_R - f_d \quad \text{(Eq.1)}$$

$$g_2 = \sigma_L - \sigma_d \quad \text{(Eq.2)}$$

$$g_2 = \tau_R - \tau_d \quad \text{(Eq.3)}$$

where f_R is the displacement of the free end, σ_L is Von Misses stress at the clamped section, τ_R is shear stress near the free end and the corresponding values (noted with index d) are the allowed values coming from structural rules and regulations. This can be considered as basic and sufficient enough conditions for the dimensioning of the main girder on cranes.

The first constraint function, in analytical formulation, has challenges in the determination of the cantilever flexibility when complex variational section is introduced. In addition, one has to calculate the influence of both the payload and load due to self-weight of the girder. Therefore, one may use approximative/substitutional models, which are presented in book (Tuma et al., 1971). However, they are time-consuming and require a large number of iterations/rehearsals. This is the main difficulty when variability of the section is included. The effect of the carrying capacity due to bending is simple and obvious even with the analytical approach and the authors will not emphasise this furthermore. Constraint functions can be added by implementing the effects of local bending stresses, lateral buckling, etc. However, this can be considered as a disadvantage of the CAD optimization because of the limits with FEA when different structural phenomena have to be considered. According to the authors, in that case, the CAD optimization should be used to get a good enough model under basic constraints and to perform additional checks afterwards.

THE CANTILEVER MODEL

The title problem deals with big jib cranes, which stand for long reach and high capacity. In practice, this can be represented by the jib cranes with the payload capacity of 5 t (Q) and reach of 6 m (S). According to the authors, this can be established as a starting point, where the inclusion of the variation of height and cross-section properties can give benefits versus increased costs due to the manufacturing process of such a cantilever. Thus, in order to follow the effects of mass minimization with CAD optimization, one illustrative model of the cantilever beam is given (Fig.3a). The material is common structural steel S235, with the following nominal characteristics: yield strength f_y = 235 MPa, modulus of elasticity E = 210000 MPa and Poisson's ratio v = 0.3. It is considered a box cross-section, with symmetry over vertical axis and with the geometry postulated in Fig. 3b. With respect to practical aspects of the trolleys which are mounted on the bottom flange on the jib section, some parameters have to be constants like B_1, B and t_1.

It should be pointed out that basic knowledge of the beam-like structures is important in this phase, in order to avoid misleading or impractical design results. The optimization workbench requires the starting parametric model, which is here designed in CAD and noted as V-1.

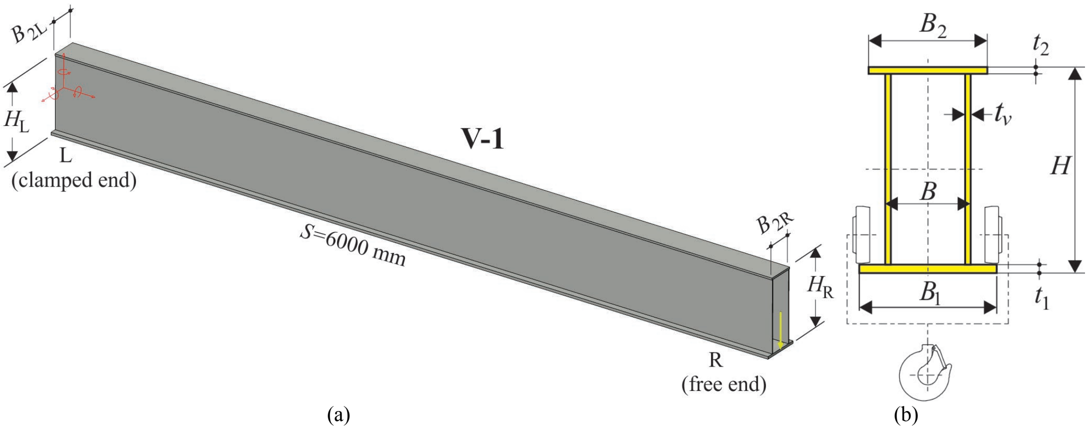


Figure 3: a) Starting model of jib (cantilever), b) Parameters of the jib sections

The main parameters are given in Table 1. It starts with the uniform girder model where height is chosen as the S/10 as a general starting point for the beam-like structure.

CAD OPTIMIZATION

CATIA implemented Simulated Annealing optimizer is used, as one of the basic algorithms within the Product Engineering Optimizer workbench. The advanced algorithms can be used as an addition, as shown in research (Konig et al., 2004) or (Park et al., 2010). The variational parameters are taken to be H, t_2, t_v, and B_2. The lower limits are chosen upon the practical consideration of the sheet metal design, along with the geometrical postulations of the cross-section due to adopted constant parameters (Table 1).

The objective function is the minimal mass of the girder, while constraint functions are as follows: (1) allowable deflection of f_d=30 mm, which is taken upon the recommendation of S/200, (2)normal stress of σ_d =157 MPa and (3) shear stress of τ_d =90 MPa.

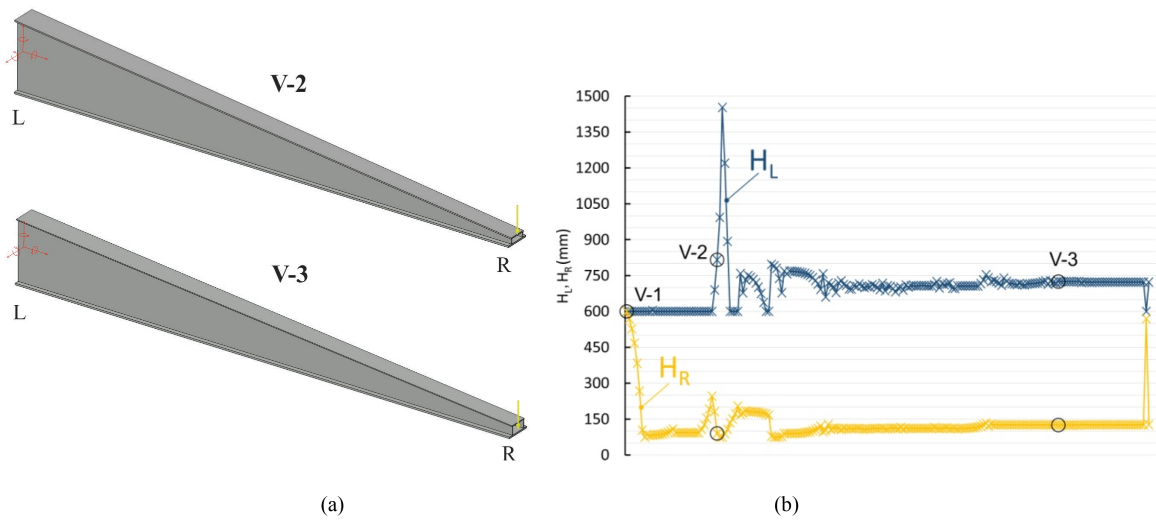


Figure 4. a) Variational models of jib (cantilever), b) Height variation in CAD algorithm

The Optimizer starts to change the given parameters and follows the value of the mass. It intermittently makes variations/attempts of all the parameters along with the measurement of sensitivity. Thus, one may find peaks in the beginning as shown for values of the heights in Fig. 4b. Any variant which exceeds the constraint function returns the process to recalculating. An algorithm ends if the model satisfies all the conditions for 20 iterations.

The model noted as V-2 is provided here for descriptive purpose only, while the end-optimized model is here presented as V-3 (Fig. 4.a).

NUMERICAL RESULTS AND DISCUSSION

Next, the CAD optimization of the model of the jib girder with given basic parameters and under basic structural regulations is performed. The starting and optimized parameters of the model, along with the obtained jib mass, are shown below in the tabular form.

Table1: The parameters of the optimization model

	Constants			*Variable parameters*						
	B_1 *(mm)*	t_1 *(mm)*	B *(mm)*	H_L *(mm)*	H_R *(mm)*	t_2 *(mm)*	t_v *(mm)*	B_{2L} *(mm)*	B_{2R} *(mm)*	*mass (kg)*
V-1	*300*	*20*	*200*	*600.0*	*600.0*	*15.0*	*10.0*	*220.0*	*220*	*970.26*
V-2	*300*	*20*	*200*	*816.1*	*90.5*	*14.3*	*6.0*	*300.0*	*212*	*691.81*
V-3	*300*	*20*	*200*	*722.3*	*126.3*	*10.0*	*6.0*	*265.0*	*212*	*617.77*

The reduction of mass is obvious throughout the whole process. The values cannot be compared directly because the starting model (V1) is checked to satisfy the postulated constraint functions, but presents only an initial model. The scope of the model was not an improvement of the specific design but aimed at making easy arrangements of the optimization of structural parameters under basic crane requirements. It is obvious that the workbench makes for easy dimensioning of the model within the given limits.

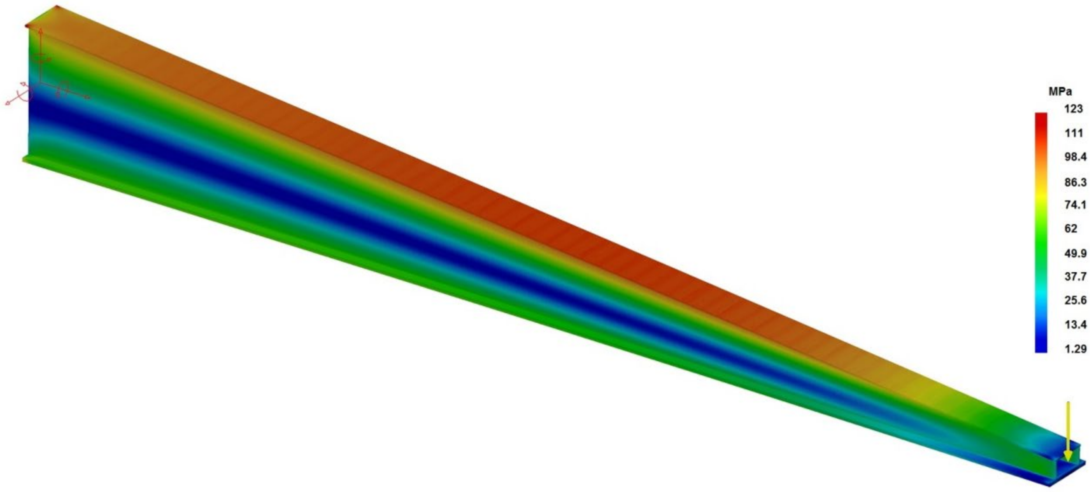


Figure 5. Stress state in the cantilever girder-V3

The stress state of the obtained model is shown (Fig. 5) in order to perform visual validation of the given constraints (Eq.2) and (Eq.3). The shape optimization, which corresponds here to the variation of height over length of the girder, has a positive effect on the utilization of the material. This is well-known from experience, but it can be noticed easily in the previous picture, where the allocation of high stresses is situated all over the upper flange of the girder. However, the governing constraint for this kind of structure is usually (Eq.1), which depends on the postulated deflection limit that is in direct relation with the crane load class.

CONCLUSION

The simple way of structural optimization of the cantilever girder on a jib crane is shown in the paper. Using CATIA Product Engineering Optimizer workbench, one illustrative model is subjected to optimization in order to obtain the minimum mass of the girder under given constraints. It combines the size and shape optimization, which is very difficult to achieve with the analytical approach. The procedure is also easy-to-use for the designers that use FEA and CAD in everyday practice and requires basic knowledge in mechanical engineering. Apart from that, it gives benefits in time-saving when variability of the cross section over span has to be considered because it demands a large number of manual hand iterations. Thus, time-consuming process is transferred to a computer.

The optimization of a beam section should always be the goal for designers in order to reduce weights and, consequently, operational costs which save energy. Even for the aesthetic purpose, under preservation of the mechanical/structural regulations and rules, the consideration of variability of geometrical parameters in engineering CAD designs produces ingenious designers and separates them from ordinary practice.

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