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HEAVY MACHINERY HM 2014

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KRALJEVO – SERBIA

THE EIGHTH INTERNATIONAL TRIENNIAL CONFERENCE

HEAVY MACHINERY
HM 2014

PROCEEDINGS

Zlatibor, June 25 – June 28 2014.

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PREFACE

The Faculty of Mechanical Engineering Kraljevo has been traditionally organizing the international scientific conference devoted to heavy machinery every three years. The VIII International Scientific Conference HM 2014 is considering modern methods and new technologies in the fields of transport design in machinery, control energy, production technologies, urban engineering and civili engineering through thematic sessions for the purpose of sustainable competitiveness of economic systems. Modern technologies are exposed to fast changes at the global world level so that their timely application both in large industrial systems and in medium and small enterprises is of considerable importance for the entire development and technological progress of economy as a whole.

The VIII International Scientific Conference Heavy Machinery HM 2014 is a place for exchange of experiences and results accomplished in domestic and foreign science and practice, with the goal to indicate directions of further development of our industry on its way toward integration in european and world economic trends. Exchange of experiences between our and foreign scientific workers should contribute to extension of international scientific-technical collaboration, initiation of new international scientific-research projects and broader international collaboration among universities.

The papers which will be presented at this Conference have been classified into seven thematic fields:

A. EARTH-MOVING AND TRANSPORTATION MACHINERY
B. PRODUCTION TECHNOLOGIES
C. CIVIL ENGINEERING AND MATERIALS
D. AUTOMATIC CONTROL, ROBOTICS AND FLUID TECHNIQUE
E. MACHINE DESIGN AND MECHANICS
F. RAILWAY ENGINEERING
G. URBAN ENGINEERING, THERMAL TECHNIQUE AND ENVIRONMENT PROTECTION

Within this Conference, the First International Students Symposium will be held. The aim is to open a scientific discussion on this actual problem in industry among young students.

The sponsorship by the Ministry of Science of the Republic of Serbia is the proper way to promote science and technology in the area of mechanical engineering in Serbia.

On behalf of the organizer, I would like to express our thanks to all organizations and institutions that have supported this Conference. I would also like to extend our thanks to all authors and participants from abroad and from our country for their contribution to the Conference. And last but not the least, dear guests and participants in the Conference, I wish you a good time in Kraljevo – Vrnjačka Banja and see you again at the Eight Conference, in three years.

Kraljevo – Zlatibor, June 2014

Conference Chairman,

М. Гашић

Prof. Dr Milomir Gašić, mech eng.

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SESSION A: EARTH-MOVING AND TRANSPORTATION MACHINERY

SESSION B: PRODUCTION TECHNOLOGIES

SESSION C: CIVIL ENGINEERING AND MATERIALS

SESSION D: AUTOMATIC CONTROL, ROBOTICS AND FLUID TECHNIQUE

SESSION E: MECHANICAL DESIGN AND MECHANICS

SESSION F: RAILWAY ENGINEERING

SESSION G: URBAN ENGINEERING, THERMAL TECHNIQUE AND ENVIRONMENT PROTECTION

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Freight Wagon Mass Reduction using Parametric Optimization

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Advancements in the railroad industry are driven by the need to have faster, lighter trains, while adhering to rigorous safety standards. Implementation of FEM analysis in wagon design enables engineers to examine every aspect of wagon construction in virtual space and to affirm that all safety requirements are satisfied before the first prototype is made. Using FEM, engineers can identify areas of stress concentration in wagon construction, and if those calculated stresses exceed maximum permissible stress, they need to modify the design of the wagon until safety factor is reached. Also, finite element results can be used to identify over dimensioned part of construction which unnecessarily increase the weight and cost of wagon. Every change in design requires entire wagon to be re-analyzed for every prescribed load condition, which can become a very tedious endeavour. Implementation of the parametric optimization in wagon design is an advanced approach which automates the process of changing numerous plate thicknesses simultaneously while keeping maximum stresses within safety limits. If the initial design satisfies all safety requirements this procedure helps engineers to further improve wagon design, while if the initial design is flawed, parametric optimization can be used to search for a solution that meets all safety conditions. This technique is used to enhance design of freight wagon which will be used for transportation of granular materials. Optimization results identified several plates which thickness can be reduced, while overall wagon design is proven to be very well dimensioned.

Keywords: Parametric Optimization, Design Improvement, Weight Reduction, FEM, Freight Wagon

1. INTRODUCTION

Since the invention of the locomotive in the late 18th century by James Watt, railroads have been driving force of modernization and industrialization enabling fast and cheap transportation of materials and goods [1]. Speed of freight trains is hampered by the great weight of wagons and cargo as well as a high centre of gravity, which increases chance of wagon leaving the track in railway curves with short radius [2]. Weight reduction is one of the main concerns in designing new wagons which also lowers wagon centre of gravity, material used, and unit production price [3].

Development of computer hardware and software lead to increasing use of computers for modelling and designing of wagons [4]. Finite Element Method (FEM) is used to simulate the wagon response to different loading condition, thus reducing design time and improving overall wagon characteristics [5]. FEM was successfully used to analyze welded joints of wagon constructions [6], creation and development of fractures in wagon construction [6],[7], heat conductivity of elements of wagon structure [8]. FEM is used for crash simulations [9], [10] and for determination of stress fields [11]. FEM analysis is the fastest way to determine if the proposed wagon design satisfies safety norms prescribed in numerous documents such are [12]-[15].

During wagon development process, based on FEM results, designers can see if there are areas in the wagon construction that have higher than prescribed stresses and to make design changes to reduce these high stress concentrations. FEM can also show if some parts of wagon construction have much lower stress than prescribed, and in that case, designers can choose to use plates with less thickness, to reduce weight and cost of wagon. For each change they make, designers must run a series of FEM analysis to check if the new design satisfies all loading conditions prescribed in standards [12]-[15]. If designers can vary the thickness of several parts of wagon structure, design process prolongs and becomes very tedious. This process of thickness variation and FEM verification can be automated using optimization [16].

Optimization techniques can be used to enhance production process [17]-[19] or to enhance design of the final product, which will be shown in this paper.

In railway industry optimization techniques are still insufficiently implemented, but in recent years several papers have been published introducing this advanced approach to railroad engineers. Example of good practice of optimization implementation is management of freight wagon distribution [20]. Selection process of material which will be used in wagon construction can also be optimized as shown in [21]. Finite elements results are used in optimization of composite material used for construction of light rail vehicle [22].

In this paper, we present an implementation of finite element analysis and structural optimization of freight wagon for transportation of granular material. Compared to the above mentioned related work, this paper demonstrates advantages of structural optimization methodology application in the railroad industry for the wagon weight reduction based on selection of an optimum combination of plate thicknesses.

In the next sections theoretical background is given, followed by a simple cantilever example, which is used to explain and highlight the advantages of the optimization procedure. This procedure is then applied on full model of freight wagon designed for transportation of granular materials, with all load conditions and all safety factors prescribed in regulating standards [12]-[15]. Results and discussion show that initial wagon design was very good, with only few plates that were initially over-dimensioned by engineers so this methodology can be successfully used to further improve wagon design.

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2. MATERIALS AND METHODS

2.1. Review of Optimization Theory

Structural optimization can be defined as the process of design improvement by finding best results under given conditions. There are two kinds of structural optimization: parametric and shape optimization (Fig. 1).

Shape optimization performs changes of part geometry until best combination of dimensions is reached [23],[24], while parametric optimization performs changes only to the properties of structures while geometry stays the same [25].

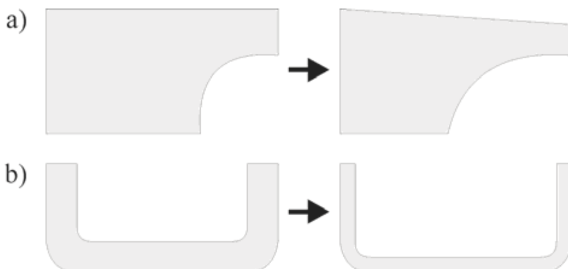

Figure 1: Types of optimization: a) shape optimization, and b) parametric optimization

Parameters are properties that describe the design of observed system (in case of the wagon, parameters are plate thicknesses). Parameters can be unchangeable (if certain plates of wagon construction must be made in specified thickness) or changeable (plate thickness can vary during the optimization procedure). Changeable parameters (also called design variables) $x_i \;\; i = 1,2,...n$, form vector of design variables which describes current configuration of modelled wagon [26].

$$\mathbf{X} = \begin{Bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{Bmatrix} \tag{1}$$

The goal of the optimization in engineering is often weight reduction and it is defined with objective function $f(\mathbf{X})$ which is a function of design variables vector i.e. function of combination of all shell thicknesses [27]. Design sensitivity coefficients (partial derivatives) describe the rate of change of objective function in relation to changes of design variable in particular shell thickness [28]. Restrictions that limit design variable values are called constraints [29]. Constraints can be a function of the design variables vector, or side constraints. Functional constraints can be inequality constraints $g_j(\mathbf{X}) \le g_{\max}$ or equality constraints $h_k(\mathbf{X}) = h_{def}$ [29].

Optimization can be viewed as:

minimize $f(\mathbf{X})$ (objective function)
subjected to:

$g_j(\mathbf{X}) \le g_{\max} \qquad j = 1,...,n_g$ (inequality constraints)

$h_k(\mathbf{X}) = h_{def} \qquad k = 1,...,n_h$ (equality constraints)

$x_i^l \le x_i \le x_i^u \quad i = 1,...,n$ (side constraints)

where $\mathbf{X} = \{x_1, x_2, ..., x_n\}$ is a vector of the design variables, $g_{\max}$ is the maximum allowed value of structural response, n_g number of inequality constraints, h_{def} response value that must be achieved, n_h number of equality constraints, x_i^l lower side constraint for considered design variable, x_i^u upper side constraint for considered design variable.

Design variables $x_i \;\; i = 1,2,...n$ form n-dimensioned space called design space [27]. Two dimension design space is shown in Figure 2, while multi dimension design space like the one we have in wagon optimization cannot be visualized, all the rules that govern two dimension design space apply to multi dimensioned space as well [29]. Constraints divide design space into the feasible region (wagon satisfies all requirements as all stresses are below prescribed maximum stress) $g_j(\mathbf{X}) < g_{\max}$ and infeasible region (stresses in some wagon plates exceed maximum prescribed stress) $g_j(\mathbf{X}) > g_{\max}$ [29]. Objective function of weight reduction defines surfaces in design space which are represented by contours of constant value objective function (same weight for different combination of plate thicknesses) $f(\mathbf{X}) = c = const$ [27]. Figure 2b shows that for every vector of design variables we can define usable-feasible region which contains lesser objective functions (less total wagon weight) than of the observed vector [29]. During the optimization process, optimizer searches usable-feasible region (Fig. 3) for the design variable vector which has the minimum objective function (minimum wagon weight that satisfy all safety requirements).

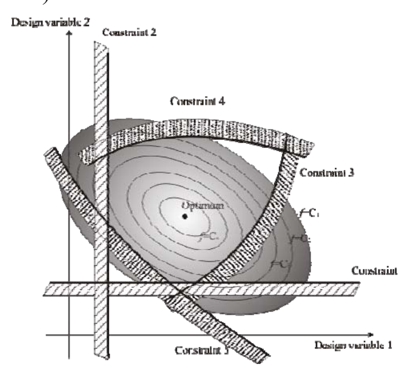

Figure 2: Optimization in two-dimensional design space: Design space with constraints

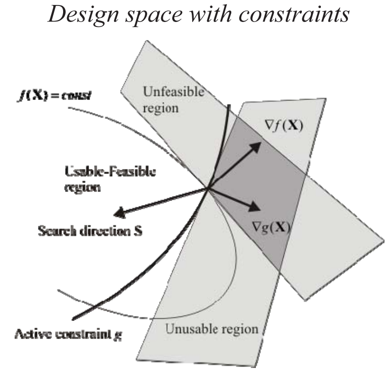

Figure 3: Active constraint with a usable-feasible region

Optimization is performed by following steps

1. Optimization starts with initial test design variable vector $\mathbf{X}_i$
2. Usable-feasible search direction $\mathbf{S}_i$ is determined
3. For search direction $\mathbf{S}_i$ corresponding scalar parameter λ_i^* is found
4. New design variable vector $\mathbf{X}_{i+1}$ is calculated using $\mathbf{X}_{i+1} = \mathbf{X}_i + \lambda_i^* \mathbf{S}_i$
5. New design variable vector $\mathbf{X}_{i+1}$ is checked for convergence to the optimum, and if optimum is achieved search for optimum is stopped, if optimum is not achieved increment is increased and procedure returns to step 2.

Based on position of initial test design variable vector $\mathbf{X}_i$ in regard to constraints, optimization can be with violated constraints, with active constraints or unconstrained [31],[32].

If some constraints are violated (stress in shell exceeds maximum prescribed stress), design variable vector is in infeasible region, and optimizer's first goal is to reach feasible region, even if it means increasing objective function $f(\mathbf{X})$. For violated constraint $g_j(\mathbf{X})$ search direction is opposite to $\nabla g_j(\mathbf{X})$. If the feasible region is not achieved in the first iteration, for the next iteration scalar move parameter λ_i^* is increased and also in every subsequent iteration as well. If feasible region is not reached in 20 iterations, the optimization process is stopped, as finding design variable vector $\mathbf{X}_i$ which would satisfy violated constraints is judged unlikely. In this case, an engineer needs to try with different initial design variable vector $\mathbf{X}_i$ or to change design of construction.

If a design variable vector is near a constraint (a region defined by +/- 3% of constraint value) constraint is considered active. In this case the search direction must reduce objective function while keeping design variable vector $\mathbf{X}_i$ within feasible region (Fig. 2). Mathematically usable search direction $\mathbf{S}$ must satisfy

$$\nabla f(\mathbf{X}) \cdot \mathbf{S} \le 0 \tag{2}$$

while feasible search direction $\mathbf{S}$ must satisfy

$$\nabla g(\mathbf{X}) \cdot \mathbf{S} \le 0 \tag{3}$$

Unconstrained optimization occurs when there are no active or violated constraints. In that case the goal is to reach optimum in as few as possible iterations. The Steepest Descent Method (Cauchy Method) is the simplest optimum search algorithm which defines the search direction as opposite of objective function gradient in that iteration [34].

$$\mathbf{S}_i = -\nabla f(\mathbf{X}_i) \tag{4}$$

When the value of objective function starts to increase, another search direction is defined (Fig. 4). This new direction is perpendicular to previous one. After each iteration, the objective function is closer to optimum. This "zigzag" path (shown in Figure 4) is inefficient and more advanced methods have been developed, such as Broyden-Fletcher-Goldfarb-Shanno method (BFGS), used in [31]. Optimization using BFGS algorithm is performed by following steps

1. Optimization starts with initial design variable vector $\mathbf{X}_1$ and with $n \times n$ positively defined symmetric matrix $[B_1]$ which approximate inverse Hessian of goal function f (usually for $[B_1]$ identity matrix $[I]$ is taken). Iteration counter is set to $i = 1$.
2. Gradient of the objective function f is calculated for design variable vector $\mathbf{X}_i$ and search direction is determined $\mathbf{S}_i = -[B_i]\nabla f_i$
3. Optimal scalar move parameter λ_i^* is calculated and used to obtain new design variable vector $\mathbf{X}_{i+1} = \mathbf{X}_i + \lambda_i^* \mathbf{S}_i$
4. Convergence criteria are assessed and if convergence is achieved the optimization process is finished.
5. If convergence is not achieved optimization continues and matrix $[B_i]$ is updated using $[B_{i+1}] = [B_1] + \frac{\mathbf{d}_i \mathbf{d}_i^T}{\mathbf{d}_i^T \mathbf{g}_i}\left(1 + \frac{\mathbf{g}_i^T [B_1] \mathbf{g}_i}{\mathbf{d}_i^T \mathbf{g}_i}\right) - \frac{[B_1]\mathbf{g}_i \mathbf{d}_i^T}{\mathbf{d}_i^T \mathbf{g}_i} - \frac{\mathbf{d}_i \mathbf{g}_i^T [B_1]}{\mathbf{d}_i^T \mathbf{g}_i}$

   where

   $\mathbf{d}_i = \mathbf{X}_{i+1} - \mathbf{X}_i = \lambda_i^* \mathbf{S}_i$

   $\mathbf{g}_i = \nabla f(\mathbf{X}_{i+1}) - \nabla f(\mathbf{X}_i)$
6. Value of iteration counter is increased $i = i + 1$ and optimization process returns to step 2

Advantages of the BFGS method in comparison to the Steepest Descent Method are illustrated in Figure 4.

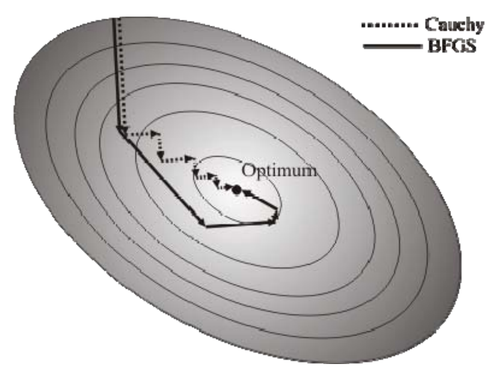

Figure 4: Cauchy and BFGS search direction algorithms

Optimum can lie on active constraint, it can be on constraint intersection or it can be unconstrained. To check if optimum is reached, unified criterion must be defined [33]. Kuhn-Tucker condition states that the vector sum of the objective and all active constraints must be equal to zero. For two active constraints with an optimum at their intersection Kuhn-Tucker condition is shown in Figure 5.

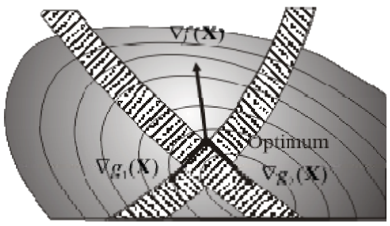

Figure 5: Kuhn-Thucker condition for constrained optimum

If there are no active constraints, objective is unconstrained and gradient of the objective function is equal to zero [31].

2.2. Parametric Optimization of Sheet Metal Constructions

In this section parametric optimization of sheet metal constructions is demonstrated on simple T-shaped cantilever. The initial cantilever design consists of two metal plates, 1 mm thick, made from the same material (Fig. 6)

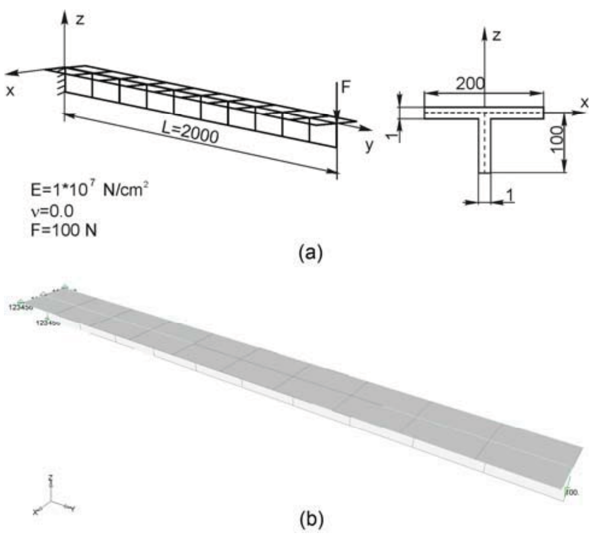

Figure 6: T-shaped cantilever: a) model, b) cross-section, c) finite element model, and d) material characteristics

To demonstrate optimization technique, we want to make cantilever of thinner plates. The goal is to determine the best combination of upper and lower plate thickness, which satisfies maximum stress criteria, while minimizing the total weight of the cantilever. Sheet metal constructions must withstand many different load conditions, and to optimize their design all load cases must be taken into consideration. We optimized cantilever subjected to two load cases, one is the vertical load at the free end of the cantilever modeled as a nodal force of 100 N, while the second load case is the horizontal load, also acting on the end of the cantilever, modeled as a nodal force of 150 N. These loads do not act at the same time; instead, only one load can be active at the time. Plate thickness of upper and lower part of cantilever profile must be chosen to withstand both loads, but not both at the same time.

Material characteristics and dimensions are shown in Figure 6. For each plate property is created defining the plate thickness. Model ready for analysis and optimization is shown in Figure 6b. The optimizer will increase thickness values in several iterations, until optimum combination is found. These thicknesses can change 5% per iteration. Optimization limits (constraints) are defined for both properties: Von Misses Stress must be between 0 and 30 MPa.

Optimum is found after 11 iterations (Table 1)

Table 1: optimization results for T-shaped cantilever

Iteration	Lower plate thickness	Upper plate thickness
0 initial	0.3 mm	0.3 mm
1	0.35 mm	0.35 mm
2	0.4 mm	0.4 mm
3	0.45 mm	0.45 mm
4	0.5 mm	0.48 mm
5	0.55 mm	0.51 mm
6	0.6 mm	0.54 mm
7	0.65 mm	0.58 mm
8	0.7 mm	0.61 mm
9	0.75 mm	0.65 mm
10	0.8 mm	0.7 mm
11 final	0.8 mm	0.7 mm

Overall weight reduction of the T shaped cantilever is 26%. Weight reduction of constructions varies depending on the quality of initial design which is based on engineer skill and experience.

2.3. Parametric Optimization of Freight Wagon

Analyzed wagon is 4-axle bogie wagon designed for the transport of sand (grain size 0–2mm), and gravel (grain size 8-32mm), with high resistance to atmospheric influence. Wagon loading is carried out through an opening at the top of the box, and unloading is done outside the rail, using two funnels (on each side of the car), as well as fixed and extra funnels mounted on the bottom of the box. Design, construction and equipment of the wagon is in accordance to the regulations prescribed in the standards [12]-[15]. Construction of wagon is shown in Figure 7.

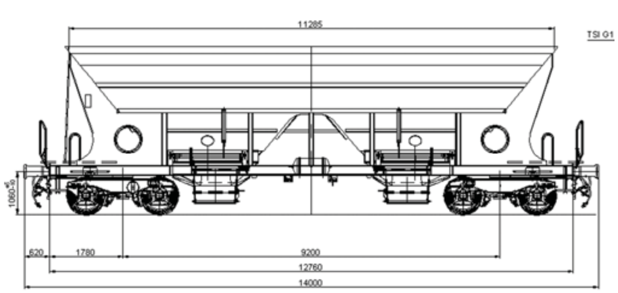

Figure 7: Drawing of 4–axle freight wagon

The wagon is modeled using the FEMAP software with NX Nastran solver. According to the construction type, shell elements of the appropriate thickness and 3D elements (for modeling of the support plate, compensating ring, traction stop) are used for creating the FEM mesh. The structure is modeled in details with 155045 elements and 156326 nodes and within the calculation there is a system of about nine hundred thousand equations being solved. General element side length is about 40 mm. This element size enables obtaining accurate analysis results within a reasonable amount of time. Figure 8 shows the FEM model of the whole wagon without bogies. Static linear analysis was performed with material with physical and mechanical characteristics given in Table 2

Table 2: physical and mechanical characteristics of material

Physical Characteristics			
Steel mark	E [N/mm^2]	ρ [kg/mm^3]	N
S355J2+N	2.1 10^5	7.85 10^{-6}	0.3
Mechanical Characteristics			
Steel mark	R_e [N/mm^2]	R_m [N/mm^2]	KV [J]
S355J2+N	355	470 – 630	27

The model consists of two subassemblies, underframe and wagon box, which are analyzed using FEM. Taking in consideration symmetry of the wagon, a quarter of the model is used in FEM simulation and optimization. FEM simulation is performed on all elements (3D and shell), while parametric optimization can be done only on shell elements. Some parts of a structure are already made of thinnest possible plates, some cannot be optimized due to the nature of the manufacturing process and some parts are too small and reduction of their mass would be insignificant in regards to mass of entire wagon.

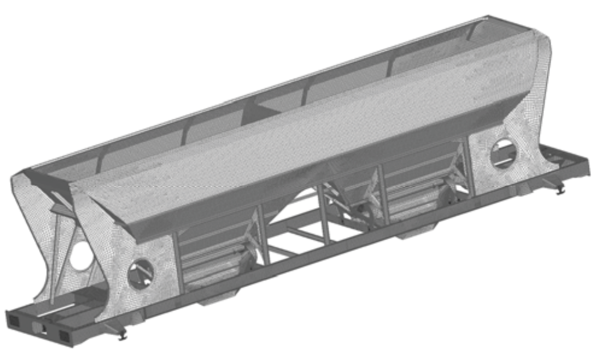

Figure 8: Finite element model of freight wagon

Plates that are taken into optimization process are shown in Figure 9 using dark gray color, while the light gray represents parts that cannot be optimized

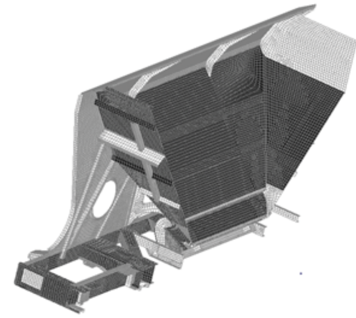

Figure 9: quarter of the model used for FEM analysis and parametric optimization

Wagon loaded with sand and grovel is shown on Fig. 10.

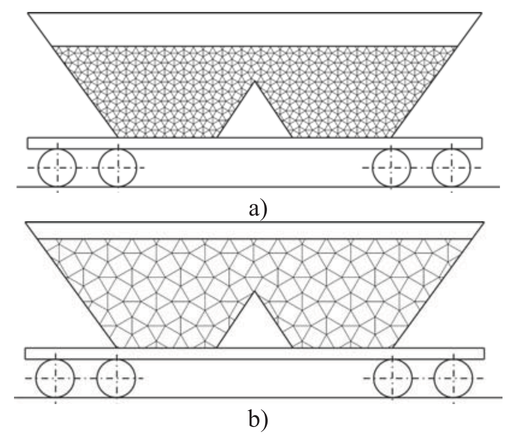

Figure 10 Wagon loaded with a) sand b) gravel

3. RESULTS AND DISCUSSION

A Since FEM analysis showed that maximum calculated stresses are concentrated in certain areas, while the rest of the wagon is stressed well below permissible stress, we wanted to see if we could use thinner plates for wagon construction while keeping design within safety limits. Parametric optimization can vary plate thickness of numerous wagon elements within the constraints defined by maximum stress. Initial wagon design satisfies all constraints, and therefore it belongs to feasible region so we used it as starting point for our optimization procedure. For FEM analysis all plates with same thickness are given the same property. For optimization purposes, every plate that we want to optimize must have its own property. Plate thicknesses are design variables, and their combination is vector of design variables. Maximum stress in every plate must be under permissible stress defining inequality constraints while side constraints limit plate thickness between 4 and 10 mm. Optimization was performed for every load case. It showed us a great variation of minimum required plate thickness depending on load case. Overall, as expected, load combinations were most demanding in terms of minimum required plate thickness. Optimization showed that wagon underframe was initially very well dimensioned, only thickness of one plate can be reduced (Figure 11). On the other hand, wagon box is over dimensioned and could be made of thinner plates (Figure 12).

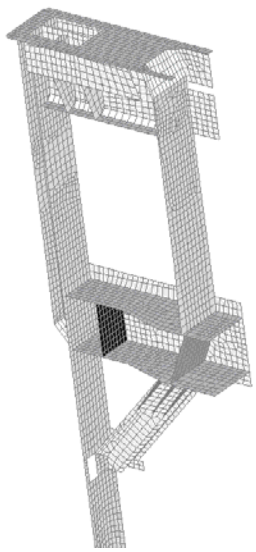

Figure 11: Dark gray represents optimized plates: view focused on the underframe,

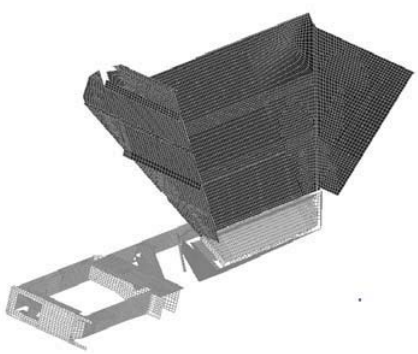

Figure 12: Dark gray represents optimized plates: view focused on wagon box

Optimization results, presented in Figures 11 and 12 show that initial wagon design had very well dimensioned elements and that there is little room for improvement. Out of 21 plates which we optimized, for 7 plates (1 in underframe and 6 in wagon box) weight reduction is achieved. The total weight reduction is 488.68 kg, which is 2.32% of empty wagon mass.

Numerical analysis of real life structures faces issues of results accuracy and reliability due to approximations and assumptions that engineers make during problem modeling. Since we obtained system response to various loading conditions prescribed in standards using FEM, and used those responses as input to parametric optimization, results that we get are also subjected to scrutiny, same as FEM. Parametric optimization itself is also influenced by choices engineers make when determining initial design and optimization parameters. Our assumption is that existing design (all plate thicknesses satisfy all safety criteria) of wagon which we optimized is the best starting point for optimization. We could also use minimum allowed plate thickness for all plates as starting point; or maximum plate thickness for that matter. Choosing existing design as a starting point ensures that initial design is in feasible region, and hopefully close to optimum. Another starting point might yield better results, or worse, or we might end up with the same plate thickness combination that we get using existing design as the starting point. Initial starting point for optimization process is one of the most important decisions that must be done by engineers, and optimization software cannot help them make the perfect choice, it's all up to the skill and experience of engineers.

Achieved weight reduction of 2.32% may bring into question if parametric optimization is really worth invested time and money. Compared to weight reduction of a cantilever beam, which we used to demonstrate techniques, one might expect the same results with wagon optimization, on the other hand, one should have in mind that initial cantilever design was over-dimensioned in order to demonstrate optimization process, while the initial design of the wagon was almost perfect. Nearly half a ton in saved material per unit, in large production series, can lead to great savings in material and money, justifying application of the optimization procedure in the final stages of designing a new wagon

4. CONCLUSION

Title This paper presents the implementation of parametric optimization in wagon design, which uses FEM results to determine the best combination of plate thickness in wagon design. FEM analysis has been used for years to simulate behavior of wagon under different loading conditions. These computer simulations reduced design time while ensuring safe behavior under operational load defined in regulations. Parametric optimization based on FEM analysis is the next logical step in computer aided design which has profound influence on ecological and economical aspects of wagon construction. It enables engineers to find the best combination of plate thicknesses, while adhering to safety regulations which are implemented through constrains into the optimization process. Implementation of parametric optimization during wagon designing results in reduced usage of material, production cost and energy consumption of locomotive during wagon operation lifetime. Improved characteristics of optimized wagons ensure their competitiveness and commercial success. In this paper state of the art theory is shown which is implemented in optimization software. Usability of the procedure is demonstrated on a simple cantilever problem, while the real life application is shown on the freight wagon. Achieved a weight reduction justified the implementation of parametric optimization in wagon design. Railroad engineers can greatly benefit from this technique by gathering experience on which parts they tend to over-dimension, which are crucial and which are non-essential parts of the construction. Parametric optimization can help young engineers develop skills more quickly and improve their experience all within the safety of virtual design space length.

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