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Topology Optimization of Electric Train Cable Carrier

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Abstract: In the area of mobility (transport), great efforts are being made to optimize means of transport. While reducing their mass the main goal is to maintain or even improve the performance of the means of transport. Additive manufacturing allows the production of very complex geometric shapes of products that cannot be made by traditional production processes; therefore it has become one of the significant tools in the design of modern vehicles or their parts. Additive manufacturing, combined with appropriate computer tools for numerical design analysis, also allows optimization of product design by topology optimization. In this paper, concept of topology optimization is applied to the roof carrier of a high voltage cable of electric train. Design optimization process was conducted based on two different optimization criteria: minimized part mass and maximized part stiffness.

Keywords: additive manufacturing; cable carrier; energy consumption; static load; topology optimization; weight reduction

1 INTRODUCTION

The motivation to reduce the energy consumption in transport is not only environmental in nature but has a direct correlation with the financial costs of organizations. Given that each organization aims to minimize costs and maximize profits, it is logical that the transport sector will turn to the goal of reducing the energy consumption. One of the main directions for implementing improvements in terms of reducing energy consumption has long been recognized by engineers working on the development of new aircraft, cars, trains or some other means of transport and that is the reduction in vehicle mass [1].

There have been computer tools on the market for many years that allow engineers to determine the loads and fixed points of some crucial components that they want to reduce mass and perform a numerical calculation on their own designs. The principles that allow these calculations are mainly based on numerical methods, and as the main numerical method in today's mechanical engineering in the context of reducing the mass of the structure is certainly the finite element method (FEM) [2].

Using FEM, it is possible to determine the peak stresses of the structure, as well as the displacements in some critical parts. Since conventional production processes are still largely limited by the shapes they can achieve, their use does not always make it possible to achieve a technology optimal shape of the structure. [3]

The optimal shape of the structure would be one that is often impossible to produce using conventional production processes, and structural optimization is a special branch of engineering aimed at making a structure that best stands imposed loads using minimum amount of the material. Therefore, it can be concluded that structural optimization is the main tool of engineers in the process of reducing the total mass of the structure, while the production of optimized parts is increasingly achieved using modern additive manufacturing (AM). [3, 4]

One of the most widespread methods of structural optimization in today's mechanical engineering is topology optimization. Topology optimization is still used as a kind of tool to get an idea during the conceptual phase of the product development, but with the introduction of additive manufacturing, it is increasingly used as a tool that gives the final form of the product. [3]

This paper presents an example of topology optimization design of the electric train cable carrier, based on two optimization criteria: minimizing cable carrier mass and maximizing cable carrier stiffness (minimizing compliance).

2 TOPOLOGY OPTIMIZATION

Optimizing structures is a way of obtaining structures that meet certain requirements, at imposed restrictions. The range of design optimization is usually divided into dimensional (size) optimization, shape optimization, and topology optimization (TO). [4, 5]

Topology optimization is basically the determination of the optimal distribution of materials in the design space that minimizes (or maximizes) the target function, while meeting the set limits [4]. The target function, for example, can be to minimize compliance, i.e. to maximize stiffness, for static problems, or to maximize the base frequency or frequency range for dynamic problems [6]. In the continuous approach, the design variables are the number of the gaps, their connection, shape and location (Fig. 1a), while in case of discrete approach, the variables are the thickness or cross-sectional surfaces of the design elements (Fig. 1b) [7].

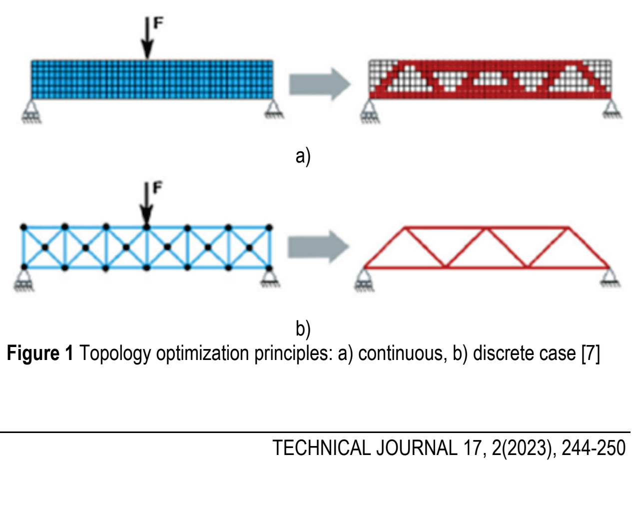

Figure 1 Topology optimization principles: a) continuous, b) discrete case [7]

Topology optimization, as a pre-processor for shape and size optimization, in its most general setting, should consist of finding out within the design domain Ω the best material distribution that minimizes an objective function f (Fig. 2).

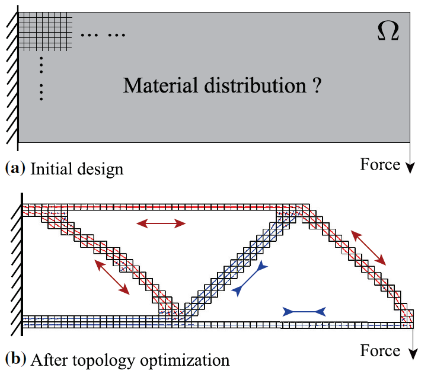

Figure 2 a) Initial design aimed for topology optimization, b) topology optimized design with stress presentation [8]

The traditional approach to topology optimization is to discretize the domain into a network of finite elements, which represents an isotropic solid microstructure. The distribution of material density within the project domain, variable $\rho(x)$, is discrete, and for each element is assigned a binary value [9]:

- ρ = 1, where material is required,
- ρ = 0, where the material is removed,

or describes whether the material exists at point $x \in \Omega$, as seen in Fig. 3.

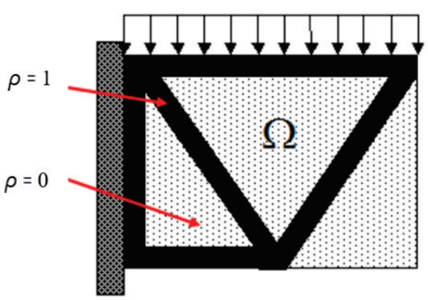

Figure 3 Distribution of material density - variable ρ(x) [9]

The most popular mathematical method for topology optimization is the Solid Isotropic Material with Penalization method (SIMP). The SIMP method predicts an optimal material distribution within a given design space, for given load cases, boundary conditions, manufacturing constraints, and performance requirements. The SIMP method is also used in Altair Inspire software, used in this paper. Topology optimization in general can be divided into 8 steps [10]:

1) Define design space
2) Define non-design space
3) Define boundary conditions
4) Define constraints and objectives
5) Define optimization settings
6) Solve
7) Interpret the results
8) Validate.

3 TOPOLOGY OPTIMIZATION OF TRAIN CABLE CARRIER

The primary function of the high-voltage cable of an electric train is to fasten the cable from undesirable shear when acting G forces and to direct the cable at a certain angle to the end devices. Its position in the CAD environment within the partial design of the train roof can be seen in Fig. 4.

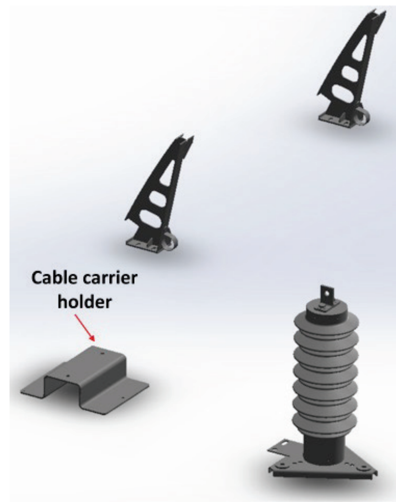

Figure 4 Cable carrier holder position in CAD environment [11]

3.1 Simulation Model Preparation

Before the execution of the cable carrier topology optimization, it is necessary to create the initial appearance of the structure. In order to exploit the full potential of the software and the topology optimization, the design will be quite primitively, solely for the purpose of performing the primary function of attaching and routing the cable as well as the possibility of attaching to the intended holder. The initial design of the cable carrier is shown in Fig. 5.

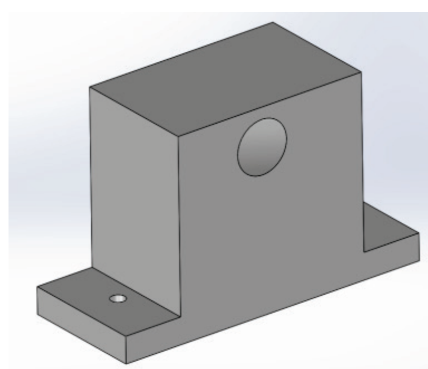

Figure 5 CAD model of initial cable carrier design [11]

The central bore, through which the cable passes, is made using a 3D sketch within assembly display, and using the material removal option per path shown in Fig. 6.

Topology optimization of the cable carrier design is performed in two ways. One way was optimization of the structure in such a way, that its mass is minimized, and to keep its mechanical resistance to the loads the unchanged.

Another way was to increase the stiffness of the structure with a certain limitation of the utilization of the volume space of the design domain according to multiple simulations. In this chapter, optimal design shapes for the two types of topology optimization will be presented.

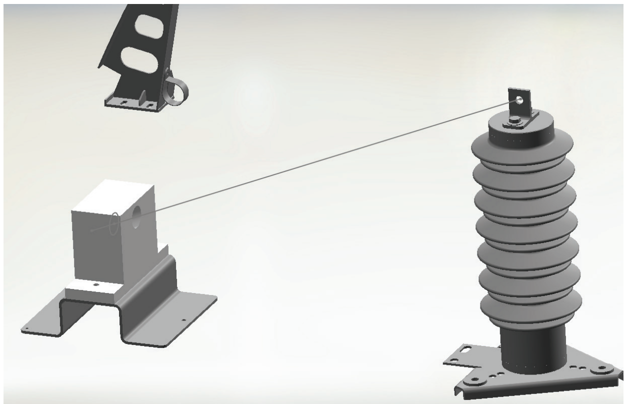

Figure 6 CAD model of assembly with cable path sketch [11]

When implementing topology optimization, it is necessary to determine the design and non-design space, and this is determined as part of the Altair Inspire program by isolating parts of the structure that do not enter the domain. First of all, it is necessary to make a "separation" bore from the volume limit of topology optimization, i.e. to make cylindrical shapes in holes that have a certain thickness and after topology optimization their shape will not change (Fig. 7).

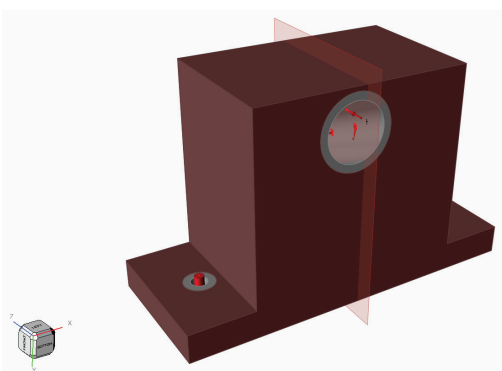

Figure 7 Prepared carrier CAD model for simulation (symmetric option) [11]

Before staring the design analysis, cable carrier material should be selected. As the final design should be 3D printed, as a referent material PLA (Polylactic acid) is selected.

3.2 Initial Design Static Analysis

Since the initial design is quite massive, the results shown in the Figs. 8 and 9 were expected. The displacements and peak stresses of the structure are almost negligible, while the minimum safety factor at the places of the supports is 3.5, which means that the initial design will not fails during the load (Figs. 8 and 9).

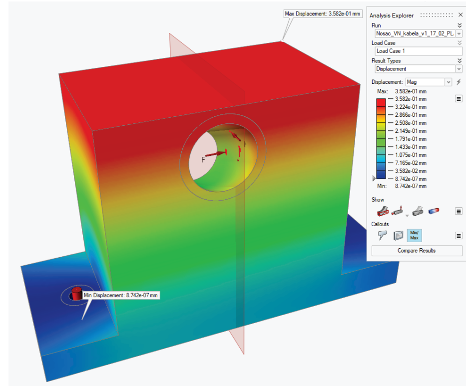

Figure 8 Initial design - displacement peak values [11]

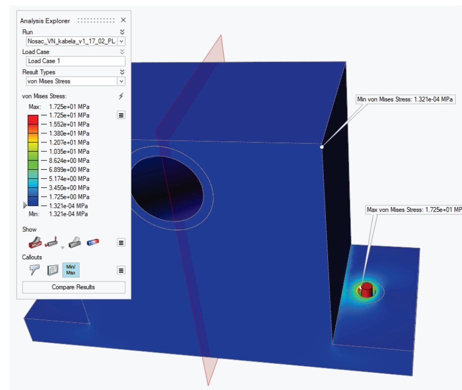

Figure 9 Initial design – stress peak values [11]

Here it can be observed that sharp transitions on the structure will be stress concentrators. Thus, it can be assumed that after topology optimization, it is the edge connecting the lower surface and the central part of the structure that will have the highest levels of stress.

Fig. 10 presents obtained distribution of safety factor over the initial cable carrier design.

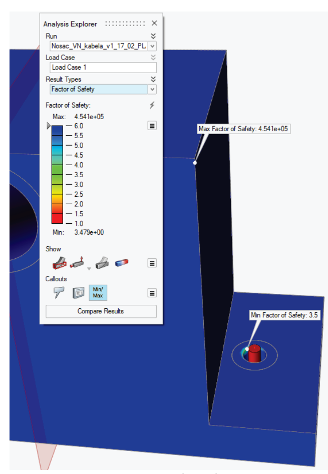

Figure 10 Initial design - safety factor distribution [11]

At this stage it is necessary to read the mass of the initial structure as a reference data for the end of the topology optimization. For given material (PLA), initial mass is 2.58 kg.

3.3 Initial Design Topology Optimization – Minimized Mass

The topology optimization of the existing initial design to minimize mass is performed with selection of safety factor 2 (Fig. 11). Selecting of this factor is the subjective estimate for making the first prototype. By conducting multiple simulations, with safety factors 1.2 and 1.5 it was concluded that, when minimizing mass, the program defines sharp transitions in structure with a lack of material. Selecting safety factor 2 gives a slightly more massive transition to the edge and will present itself as the optimal solution within this work.

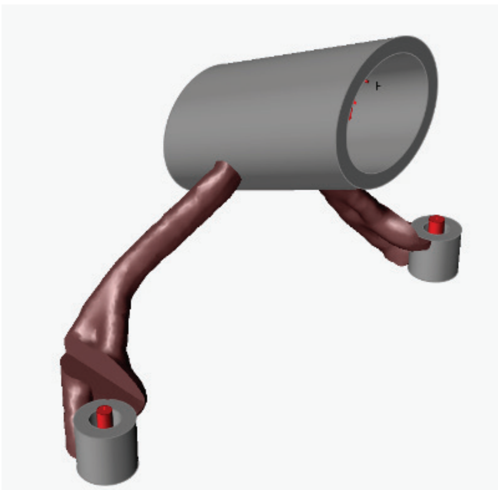

Figure 11 Topology optimized design – minimized mass [11]

Obtained design must primarily be statically analysed as it was done for the initial design and evaluated the results of the analysis.

3.4 Topology Optimized Design Static Analysis – Minimized Mass

As a part of the analysis of the optimization results, the same parameters will be observed as with the initial design. When analysing peak safety factor results, it was found that there was present design error, where the right support safety factor was 0.9, which is a clear sign that the design would not withstand the load. A way to correct this is to return to the result of topology optimization and increase the wall thickness of the weak structure, while the shape of the structure itself has not changed significantly. The results of analysis for such a thicker structure, are given in following figures.

If the maximum displacement of the topology optimized structure is compared with the initial design (Fig. 8), here the values are almost 10 times the initial value, which is not negligible, but also not critical in this specific application.

By analysing the peak stress values according to Von Mises' strength theory, it is evident that it is a magnification of the maximum stress of almost 2 times (Fig. 13). Since in the area of maximum stress the safety factor is still greater than 1, this will also not be considered as a critical value. Also, it is important to emphasize that a support that appears to be under more stress is one in the direction of which the inertial force acts when braking the train. Analysis of the peak values of safety factors shows that uniformity was not achieved throughout the entire optimized model (Fig. 14).

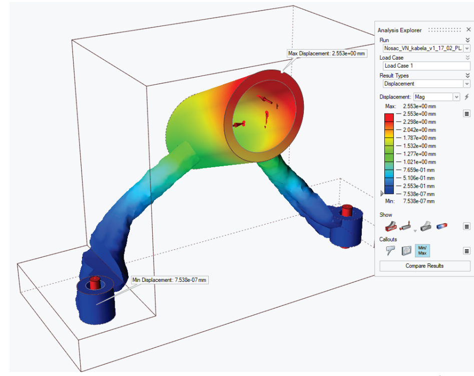

Figure 12 Topology optimized design – displacement distribution (min. mass) [11]

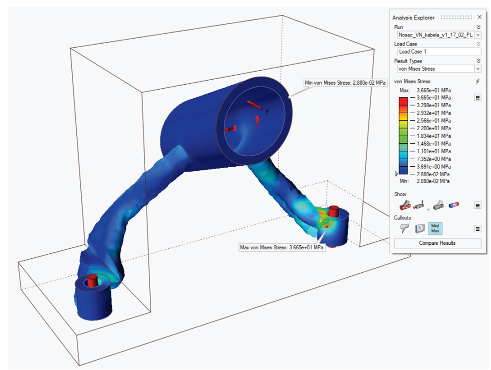

Figure 13 Topology optimized design – stress distribution (min. mass) [11]

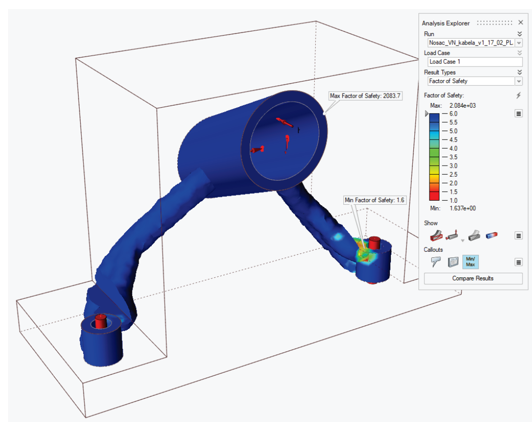

Figure 14 Topology optimized design – safety factor distribution (min. mass) [11]

Uniformity would occur if each point of a topology optimized design had a safety factor value lager than 2, as this was the basic condition given when defining optimization criteria. The value of the minimum safety factor is 1.6, and for the purpose of this paper it can be considered acceptable, so such design will be post-processed.

3.5 Topology Optimized Design Post-Processing – Minimized Mass

The post-processing of the topology optimized design is done for the aesthetic reason and to reduce the impact of sharp edges, for example by implementing rounding. As a part of Altair Inspire software, this is done in such a way that either automatically or manually "withdraws" material within the domain specified by topology optimization (Fig. 15).

Figure 15 Post-processed topology optimized design (minimized mass) [11]

The most important aspect of this topology optimization was to minimize the mass of the cable carrier – total mass of the optimized design was 0.10 kg. Thus, the optimized carrier has only ~3.9 % of the initial structure mass, which means that the topology optimization of this carrier saved over 96 % of the cable carrier mass. Consequently, this result can be used as an indicative input parameter for the next topology optimization step, which is optimization with the aim of increasing structure stiffness.

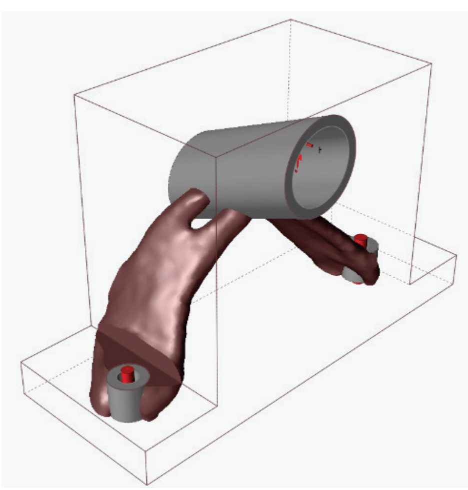

Figure 16 Topology optimized design – maximized stiffness [11]

3.6 Topology Optimized Design – Maximized Stiffness

Topology optimization with the aim of maximizing stiffness is the reverse of that with the aim of minimizing mass. Thus, it is logical to expect some conflicting results of the two analyses of the optimized design. The optimization process is performed in the same way as before, but instead of selecting the *Minimize mass* target function, *Maximize stiffness* is selected from the Altair Inspire menu. The result of this topology optimization step is shown in Fig. 16.

3.7 Topology Optimized Design Static Analysis – Maximized Stiffness

As it was the case for the previous type of topology optimization, static analysis will also be performed for the design obtained with optimization criterion – maximized stiffness. Fig. 17 presents results of displacement distribution and peak values.

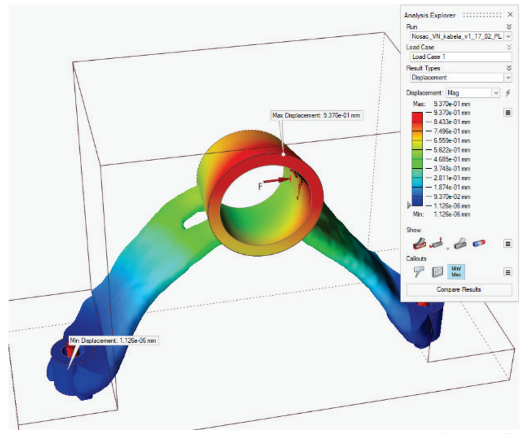

Figure 17 Topology optimized design – displacement distribution (max. stiffness) [11]

Analysing the results and comparing with previous one, it can be concluded that the value of the maximum displacement is almost 2.5 times less than the maximum displacement of the previously topology optimized structure. Consequently, it is concluded that the value of the maximum displacement is by no means critical for the optimized design.

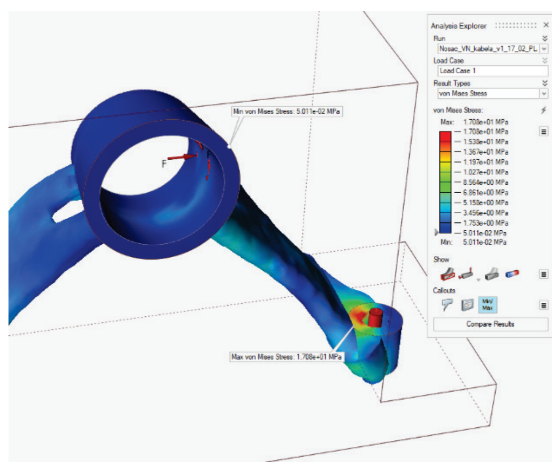

Figure 18 Topology optimized design – stress distribution (max. stiffness) [11]

According to the results of the analysis of the stress distribution and peak values of the topology optimized design (Fig. 18), it can be concluded that the maximum stress is also in the right support area, but here the stress value is almost the same as in the initial structure. Thus, it can be further concluded that such an optimized design will have similar peak values of stress as the initial design but will occupy a much smaller volume and consequently have a significantly smaller total mass.

From the Fig. 19, it can be concluded that the minimum value of the safety factor of optimized design is the same as of the initial structure.

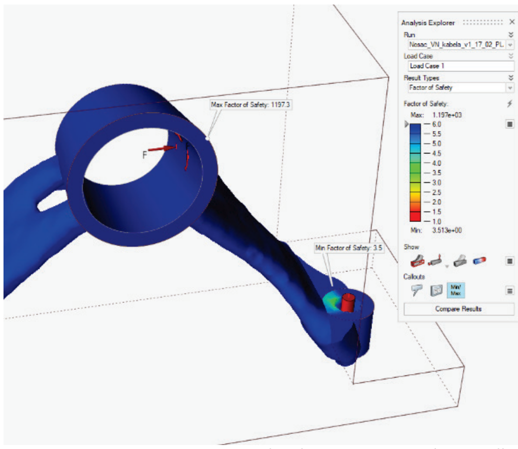

Figure 19 Topology optimized design – safety factor distribution (max. stiffness) [11]

Fig. 20 shows post-processed optimized design for maximized stiffness. The final mass of such optimized design is only 0.22 kg.

Figure 20 Post-processed topology optimized design (max. stiffness) [11]

Thus, the optimized carrier has only ~8.8 % of the mass of the initial structure, which means that the topology optimization of this carrier saved over 91 % of the mass of the predicted volume domain. Tab. 1 shows a summary and comparison of main parameters peak values of all three observed designs.

Table 1 Summary of topology optimization results [11]

Design	Max. stress (MPa)	Min. safety factor	Mass (kg)
Initial	17.35	3.5	2.58
TO – min. mass	36.65	1.6	0.10
TO – max. stiffness	17.08	3.5	0.22

4 CONCLUSION

This paper presents the process of topology optimization of the cable carrier of an electric train using the Altair Inspire software. The paper is structured as a case study, where two types of topology optimization on the same design are displayed and the results of their analysis are compared.

Structure topology optimization significantly reduces its mass, in both cases. Both topology optimized structures have a mass of less than 10 % of the initial structure, which means that a mass reduction of 90 % and more has been achieved. The first topology optimized design is slightly weaker than the second, mainly due to the topology optimization criterion. By minimizing mass, the software searches for the optimum in such a way as to sacrifice the stiffness of the structure, using the safety factor criterion assigned to it. The second topology optimized design is heavier than the first approximately 2 times but achieves significantly better stiffness properties and a safety factor the same as that of the initial structure. It can be concluded that using topology optimization on a given cable carrier drastically reduces its mass while retaining acceptable mechanical properties.

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