ADDITIVE MANUFACTURING CASE STUDY IN THE RAILWAY INDUSTRY

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ABSTRACT

Steel is the most widely used material on rolling stock in the railway industry. One of the big drivers in the railway industry to increase efficiency, is mass optimisation of rolling stock in order to increase the payload. Additve manufacturing can play an enabling role in the mass optimisation process as complex designs can be manufactured achieving both functionality and weight reduction. This study details the potential use of additive manufacturing, not necessarily as a replacement, but integration into existing manufacturing processes to prototype weight optimised designs with the support of simulation and topology optimisation software.

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1. INTRODUCTION

One of the biggest drivers in recent years in the railway industry to increase efficiency, is to increase the payload and reduce maintenance costs. This is quantified by a carried payload to carrying mass ratio [1-2]. Payload increase can be achieved through weight optimised designs of railway ccomponents. The drivers for weight reduction include energy costs and infrastructure running costs. Weight reduction can also be achieved by the use of lighter materials such as aluminium, titanium, and composites as adopted by the automotive and aerospace industries. However, these may be perceived as risky and costly without a well documented rolling stock use [1].

Additive Manufacturing (AM) has become an attractive method of manufacturing due to its inherent ability to create topology optimised complex structures. The impressive design freedom offered by AM allows for increased beneficial use of topology optimisation and generative design. [2]. According to the definition, topology optimization is a "mathematical approach that, within a given design space, and a set of loads and boundary conditions, provides a solution that respects certain constraints (i.e. displacements, accelerations, stresses) and either minimizes or maximizes the objective variable (i.e. mass, compliance, volume, displacement)" [2]. In the case of generative designs this "enables engineers to create thousands of design options by simply defining their design problem - inputting basic parameters such as height, weight it must support, strength, and material options" [3]. Topolgy optimisation and generative design has become an excellent tool for the design of weight optimised structures resulting in complex organic shapes and is available on many of the well-known CAD packages as an extension.

Optimizing is not just a process and a way to standalone engineering task, but a tool that helps to make decisions. Algorithms, software tools, and the application of high-power computers, have made it possible to optimise based on computer simulation of physical models. Virtual models make the process of designing and analyzing physical models cheaper while saving time. Optimization procedures are applied in a variety of linear and nonlinear problems, such as the problems of optimizing mechanical structures [4]. Topological optimization allows changes to be made not only in the geometry of the structure, but more specifically in its topology, modifying the number and connectivity of components, and creating in the medium some boundaries, branches and holes. The process offers optimal distribution of material and void regions inside a predefined design domain for a given set of loads and boundary conditions [5].

In this research, design and optimization principles are applied to the rail industry using the coupler system as a case study. The coupler is used to join rail cars and locomotives to each other so they all are securely linked together [6]. A coupler plays a key role in connecting the two railway cars with forces acting on it. A knuckle is the last member of the coupler that allows contact between two cars for connection. If the knuckle fails, there will be parting which may lead to derailment [6-7]. The coupling system is an essential part for the functionality of the train. Couplers must allow movement between cars vertically for suspension movements of each car, and horizontally for tracking differences and negotiating curves [8]. When designing a coupler, two factors must be considered: 1) the couplers must have sufficient strength and safety controls and factors. 2) the connection or disconnection of couplers must be simple [9-11]. An example of a coupler and knuckle assembly is shown in figure 1.

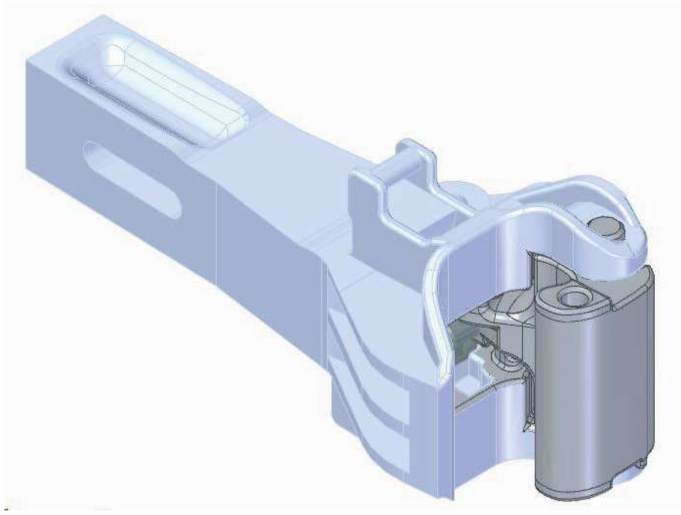

Figure 1: Knuckle (grey) and coupler assembly

This study focuses on a weight optimisation reduction case study of the knuckle using the Altair (Inspire) software package for static structural analysis and topolgy optimisation. A further comparison is made between steel and titanium materials for the study.The study illustrates the advantages of the union of topology optimization with Additive Manufacturing within the railway industry.

2. METHOD

The design requirements of the knuckle to meet the permanent set test and ultimate strength as prescribed in AAR Specification M-211 [10-11] tabulated below and guided by reference [6]. The CAD model design of the knuckle was subjected to the same loading conditions and a non-linear static strength FEA was performed.

	Permanent Set Test		Min Ultimate Load (kN)
	Load (kN)	Maximum set (mm)	
Knuckle	350	0.76	2.890

The design process flow used to obtain a topology-optimised part is shown in figure 2. A generic design of a knuckle was imported into Inspire. The model was simplified to reduce its complexity and the calculation time. The non-design spaces were defined (orange areas), such as mounting interfaces and contact surfaces. Boundary conditions and load cases were set according to reference [6]. The remaining volume (dark red) was set as the design space and is where the optimisation will take effect. Another analysis was done to confirm that the topology optimisation would be sufficient for the load cases. A “best fit” model was then created which best represented the optimised volume and the geometry was converted to a usable CAD format like STEP. A final analysis on this part was done, to prove that the topology optimised part would work in a real-world application.

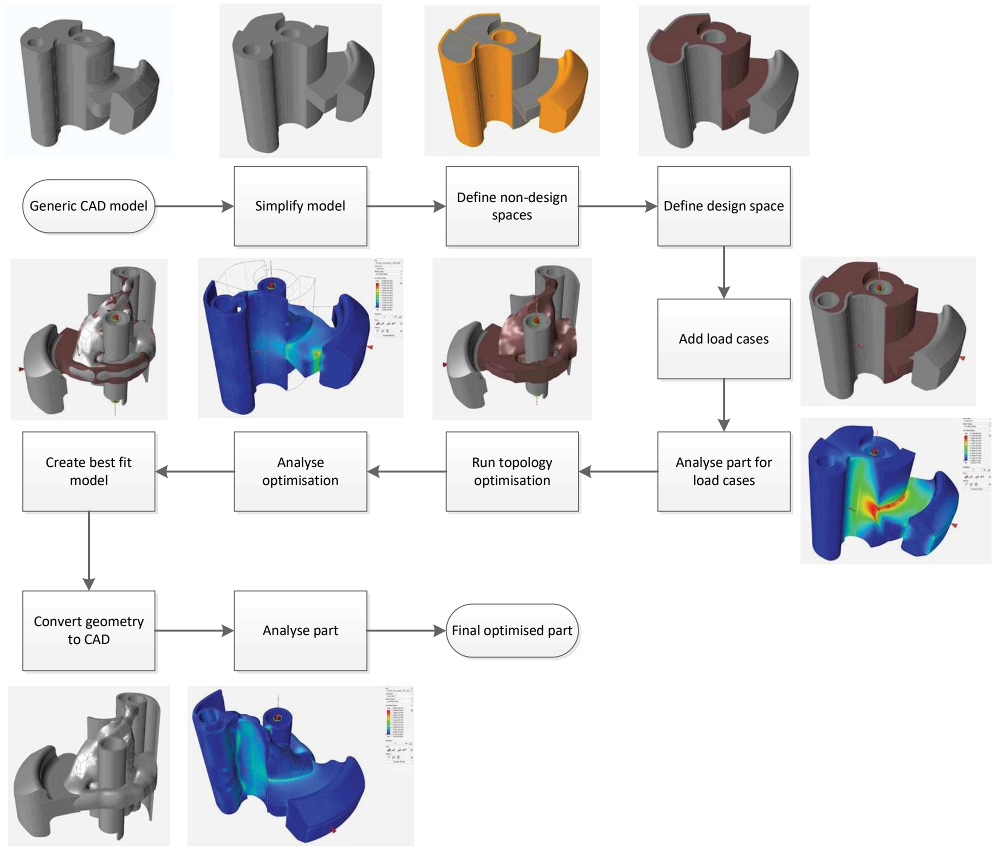

Figure 2: Process flow for the topology optimisation of the knuckle

3. RESULTS

The original design has low stress regions that allow for significant potential weight reduction of the part. The part's volume is 5728 cm^3, with a design weight of about 44.967 kg in the current grade E steel. Based on the simulation and the visual inspection, key regions have been identified that could be redesigned. Figure 3 shows the numerical analysis of the current design where the maximum stress is at the mating interface (1), buffing shoulder (2), and pulling lug region (3) (higher stressed regions).

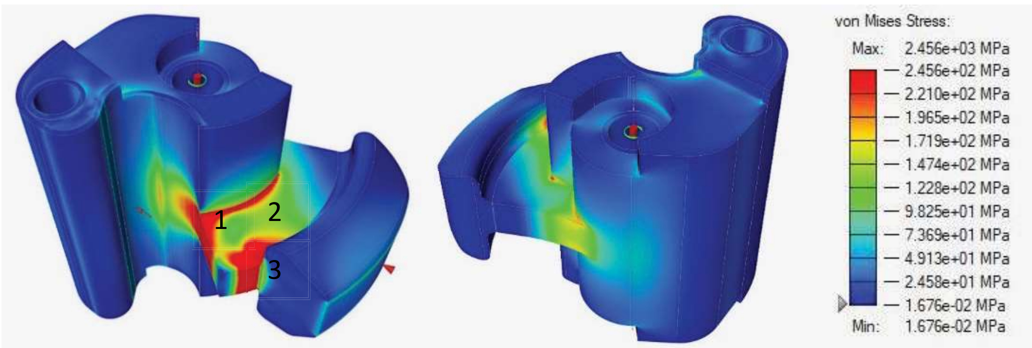

Figure 3: Generic design von Mises stress analysis

After the topology optimisation was completed on the Inspire software, the simulation was then redone to analyse the von Mises stress and a “best fit” model was completed as shown in figure 4. The volume of the new part is about 3169 cm^3, which comes down to a weight of 24.876 kg for the grade E steel (7.85 g/cm^3). This represents a weight reduction of 44.7 wt%. The results from FEA analysis are suggestions that the new design, through an interpretation of the design engineer, follows the shape proposed by the optimization software. In building the new parameterized CAD model, the design engineer usually includes manufacturing considerations and constraints, which hamper the full exploitation of the optimization and can potentially lead to compromised solutions. In the case of AM, the great design freedom allows to remove the extra weight and to achieve the best benefits from the optimization process.

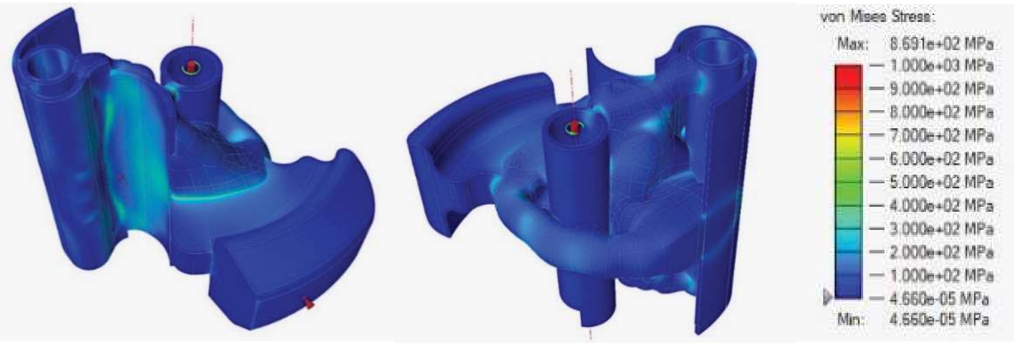

Figure 4: Topology optimised output from Inspire

The simulation results for the resulting von Mises stress distribution for the new design is shown in figure 4. It is seen that the regions of maximum stress are located mainly at the pulling lug region, the buffing shoulder and mating interface from inspection, the von Mises stress has a maximum value of approximately 870 MPa. This value is more than the material yield stress (689MPa) [6], and hence there are some areas that will fail under the specified load. However, after further investigation, it was determined that these high stresses are due to stress concentrations such as sharp corners and edges. This can be easily solved in CAD software by the re-designing of those features.

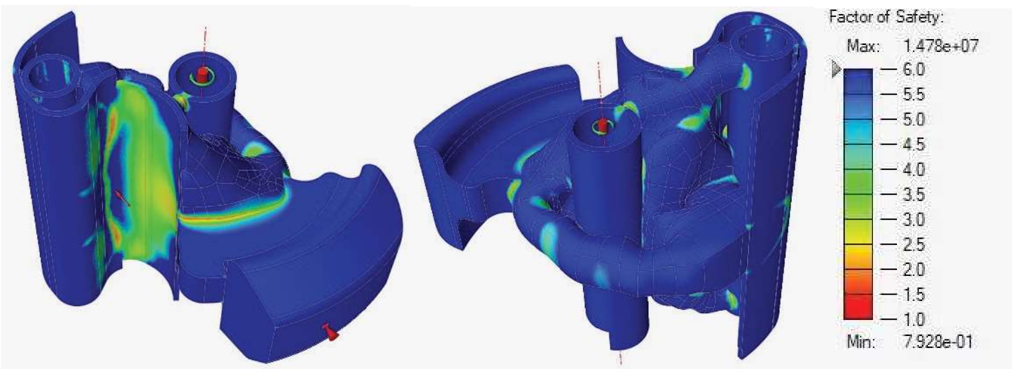

Figure 5: FoS for optimised part in Grade E steel

Factor of Safety, which is also known as safety factor, is calculated by using the ratio of the material yield stress to the actual stress in a part. The smaller the Factor of Safety, the higher chances that the design will fail, resulting in an uneconomical and non-functional design. As for higher Factor of Safety, the components would be more expensive resulting in a higher cost of the design. The FoS of a part is equal the lowest FoS of the entire part. The part showed a high Factor of Safety (FoS) in most areas, close to 6 in most areas. Other areas were observed to have a FoS close to 1 due to stress concentrations caused by sharp edges or corners, as mentioned previously. This can be rectified by modifying the areas with a low FoS. The mating interface also has a FoS of 2 to 3.5, which can also be improved by some redesign in that area. The benefits of the optimised design is shown in Table 2.

Table 2: Weight, and stress comparison

	Original Design	Optimised design
Design Weight (kg)	44.967	24.876
Part volume (cm^3)	5728	3169
Von mises stress (MPa	±246	±870

Figure 6 shows a final version of the new design taking into account the topology optimised results and considering the manufacturability of the part. Figure 7 shows the AM knuckle prototype manufactured by powder bed selective laser sintering (SLS), produced from nylon being trialled for fitment prior to manufacturing.

Figure 6: New design of the knuckle

Figure 7: Knuckle prototype fitment trial

4. CONCLUSION

After the topology optimisation, the simulation gave the "best fit" model with weight reduction of 44.7 wt%. The volume of the new part is about 3169 cm^3, which comes down to a weight of 24.876 kg for the grade E steel (7.85 g/cm^3). The mass optimised part showed high FoS, close to 6 in most areas however there were some areas with lower FoS due to the presence of sharp corners and edges. The design can easily be changed in the relevant CAD package to offer a functional and economic knuckle design. It should be noted that this case study was to prove that it is possible to design a much lighter part without affecting the core functionality and that some design refining is still required to ensure that a usable part can be produced considering manufacturing constraints. The FoS for this component, after the changes are made to remove stress concentrations and some redesign (figures 6 and 7), improves significantly without significant mass increase.

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