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Combined Structural and Multibody Optimization of Railway Vehicle Components: Application to a Railway Bogie

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Abstract

The growth of the railway sector pushes rolling stock manufacturers to find new structural solutions for reducing the overall design time of the main vehicle components. Within a market where details can make the difference in economic terms, the concept of design optimization is becoming established. Structural optimization processes represent an effective strategy for reducing manufacturing costs, resulting in geometries easier to design and produce. In this framework, the present paper proposes a new methodology to innovate railway bogie frame. It combines CAD, Finite Element Method and multibody environments. The optimization approach introduces also manufacturing constraints oriented to sand-casting process. An automatic loop allows fast iterations to assess the running dynamic of the whole vehicle. Object of the research work was the innovation of a tramway bogie frame. The project resulted in an innovative design of the component, feasible with sand-casting manufacturing technique. It showed optimal mechanical performance, with a reduction about 26% of the maximum stress calculated and an equivalent dynamics behaviour.

Keywords: railway vehicle, railway vehicle dynamics, structural optimization, topology optimization, multi-body dynamics, bogie.

1 Introduction

Nowadays, rolling stock manufacturers work to reduce the environmental impact of railway vehicles, that are one of the most important solutions for mass transport over the world [1], also for emerging countries. Innovation of the structural design and traction source represent the two main points of interest. Focusing on the first one, vehicles lightweight design allows to reduce the energy required during their operation conditions. With the objective to reach this ambitious result, structural optimization process can represent an effective support for the development of innovative components in railway field. However, the current standards for the design of carbody [2] and bogie frame [3], do not defined a role for this type of approach. Available literature illustrates that not many studies about optimization processes, especially applied on railway vehicles bogie frame, have been carried out. Referring to railway sector, a structural optimization approach with dynamic constraints for carbody lightweight design, was proposed and exploited in [4, 5]. A size optimization and a material selection method have been combined to test an electrical multiple unit (EMU) carbody [6]. Topology optimization and composite materials have been combined to redesign a railway anchor bracket [7]. An optimized hybrid body has been obtained with a mass saving of 29%. Topology optimization technique has been used in the lightweight design of a railway carbody, including crashworthiness performance within the methodology [8]. A multidisciplinary design optimization method of a lightweight carbody for fatigue life prediction was presented in [9], where a rigid-flexible multibody system dynamics model of vehicle and finite element model have been developed to simulate the coupled interactions. Some researchers have tried to combine structural optimization with manufacturing constraints. Wang and Kang [10] proposed a level set-based topology optimization method for the realization of concept design of casting components. Their method used velocity field design variables and combined the level set method with the gradient-based mathematical programming algorithm on the basis of the sensitivity scheme of the objective function and constraints. A similar level set method was also introduced by Allaire et al. [11], by Xia et al. [12,13] and by Liu et al. [14]. Gersborg and Andreasen [15] applied a Heaviside parametrization design to obtain manufacturable cast geometries in a gradient driven topology optimization. Running comfort condition must be carefully evaluated, ensuring the decouplment of the carbody from bogie instability motion, as well as from the suspension frequencies. Bogie is the most critical component of a railway vehicle and over the years it has undergone only minor changes. In order to fill this gap, authors have proposed a first topological optimization approach based on the reference European standard for bogie structural requirements, including manufacturing constraints oriented to casting production process, that combines different modelling environments: CAD, FEM and Multibody. The benchmark aims to define an effective procedure to redesign a railway bogie frame, ensuring the mechanical performance of the system, including static, dynamic and fatigue evaluations. In addition, a multibody analysis was conducted to compare the optimized solution and the original one in terms of running dynamic. A fundamental condition for a complete assessment of the bogie innovation. The procedure was tested on a bogie frame designed for a light rail vehicle, illustrated in Figure 1.

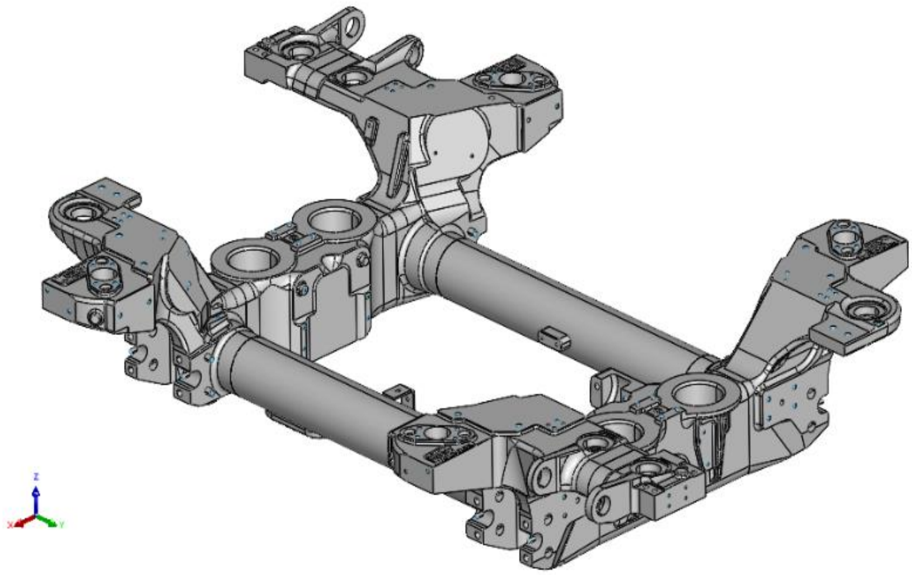


Figure 1: Bogie frame (CAD model).

2 Methods

The methodology adopted by the authors for the innovation of the present bogie frame is briefly described and summed up in Figure 2. It aims to combine CAD environment, FE calculation, structural optimization process involving technological constraints oriented to casting process and multibody analysis to assess the running dynamic of the railway vehicle. One important objective of the activity was to create a suitable bogie frame design to produce it with a sand-casting process. It represents a real innovation in railway field, where this type of mechanical system, due to its complex features, it is always made up with structural steel and assembled through a welding process. Furthermore, this research work employed an additional innovative approach, wherein an automatic tool was able to update the multibody model according to the new geometry of the bogie frame, and then carried out the running dynamic simulations of the whole vehicle. The ability to redesign a component while immediately assessing its impact on the overall vehicle dynamics would significantly reduce overall timeframes.

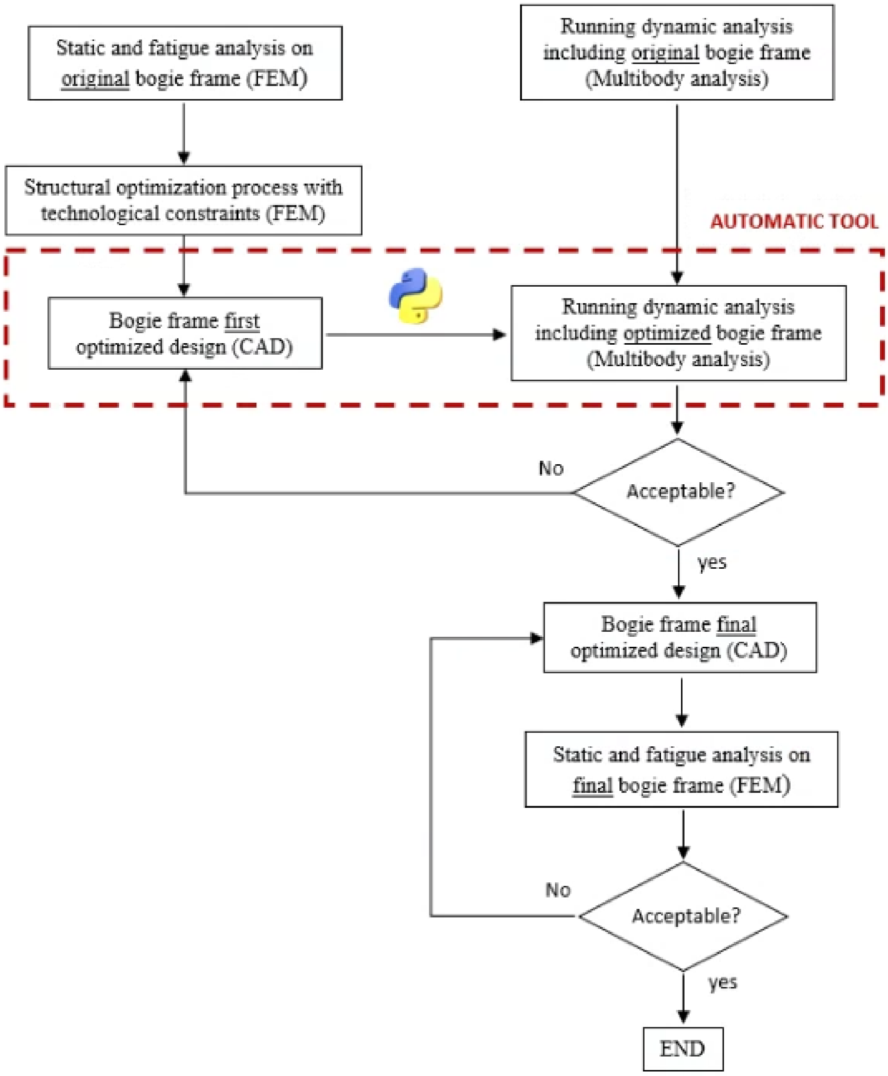


Figure 2: Flow chart of the methodology.

The initial crucial step in innovating a component is to understand its mechanical performance in its original form. Consequently, from a structural perspective, starting with a finite element model, the bogie frame was tested in accordance with static and fatigue loads specified in the reference standard EN 13749 [3]. In addition, a modal analysis in free-free condition was performed. Simultaneously, a multibody model of the vehicle was created, and the running dynamics were evaluated based on key parameters outlined in the following sections. The second step involved the implementation of structural optimization based on technological constraints. Simulation settings are presented in Table 1.

Table 1: Structural optimization settings.

Optimization settings		
General settings	Optimization objective	Weighted compliance minimization
	Optimization constraint	Mass fraction < 0.4
	Pattern grouping	Symmetry respect to a plane (y normal)
Technological settings	Minimum feature size	25 mm
	Draw single	Removing material along Z direction

The optimization process had the objective of minimizing the weighted compliance, calculated on all the load cases. The compliance is the sum of strain energy of the mechanical model. The higher the value, more the model is deformed under the same load. This essentially defines an inverse measure of stiffness, allowing the formulation of a more efficient minimum problem. The optimization process was executed using commercial software employing the gradient method as the solving algorithm. The user defined all input parameters for the optimization analysis, while the solution process was autonomously managed by the software. The solution was based on Gradient based Optimization Method [16]. As illustrated in Figure 3, before starting the procedure, the model of the bogie was adapted to be processed. With the aim of providing greater freedom to the optimizer for defining a new bogie design, the material volume of the frame was increased and geometrically simplified, using simple geometries and volumes. The dimensions were kept within an acceptable range defined by the mechanical component dimensions. The partitioning of design and non-design space was fundamental, allowing the definition of the portion of material on which the solver could act. In Figure 3, the design space is shown in light blue, while the non-design space is represented in red. The non-design space mainly included areas of interface with other systems, load application zones, and connection zones to supports. Giving special attention to the latter, this choice allowed for the main interfaces to remain unchanged, enabling the separate management of modifications to the main frame and those to the supports.

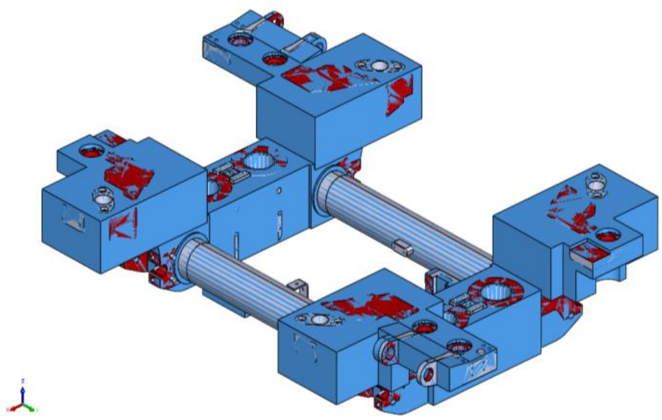


Figure 3: Railway bogie model set for structural optimization process.

Focusing on the main technological constraint condition called “Draw single”, it forced the removing of material along a predefined direction. It aims to simulate the extraction of the model from a mould, creating a geometry opened in the upper side or lower side, depending on the direction set. The third step included the closed loop between CAD and Multibody environments. Once the optimization process was completed, the obtained design for the cart was directly imported into the CAD environment. Subsequently, the mass and inertia characteristics of the component were extracted. Through a Python code, these pieces of information were then automatically introduced into the multibody environment. The simulations required for verifying the vehicle's dynamic walking behavior and the respective representative graphs were also automatically generated, reducing the user workload and allowing more iterations. After completing the verification of the dynamic behavior of the system, we proceed to a detailed modeling of the cart frame, necessary to conduct a precise assessment through a finite element model. The test conditions will be consistent with those of the original model.

3 Results

First of all, an evaluation of the structural performance of the original bogie frame was performed, highlighting the most stressed zones that should be carefully monitored. The structure was confirmed and was thus ready for further optimization. Simultaneously, a preliminary multibody analysis of the complete vehicle, including the original bogie frame, was conducted using Simpack [17]. The following parameters were evaluated: critical speed, Y lateral displacements, derailment coefficient (calculated as the ratio between Y and Q), normal and tangential forces at wheel-rail contact. A comparison between the original and optimized configuration is showed in the next paragraphs. The second step consisted in the structural optimization approach. Objective of the simulation was the minimization of the weighted compliance, while it was imposed a constraint condition on the mass fraction of the system. In addition, a condition on the maximum mean stress was included. Several runs of numerical simulation were carried out, including all the load conditions and combining them with different settings to study the impact on the final design. While for the longitudinal parts (along X axis) a common geometry was obtained, for the transversal beam different types of shapes were observed. Then, according to the simulation settings, its shape could change. Figure 4 illustrates the density distribution resulted from a topology optimization run.

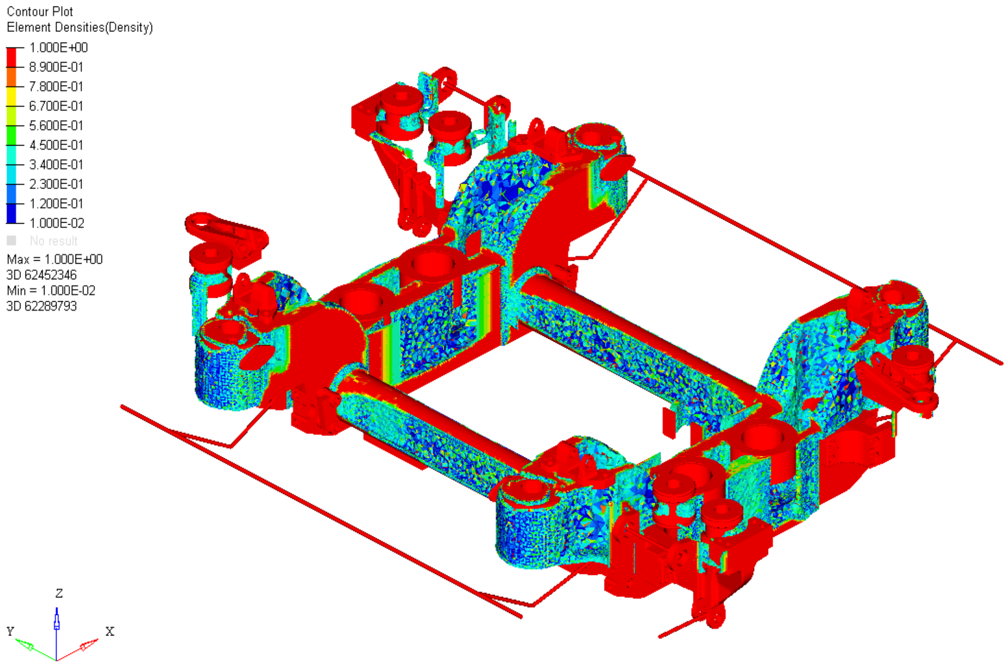
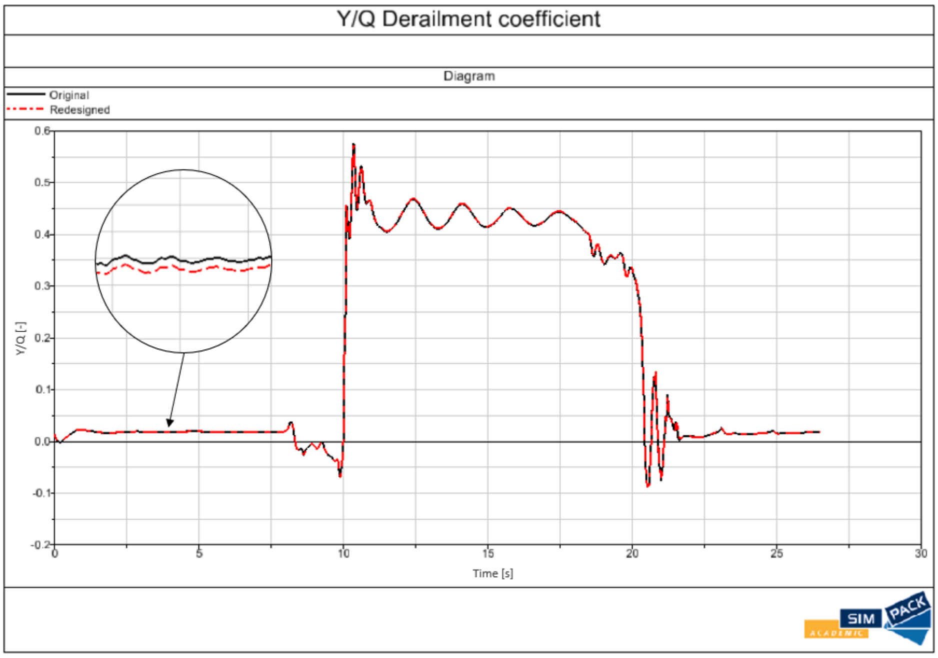
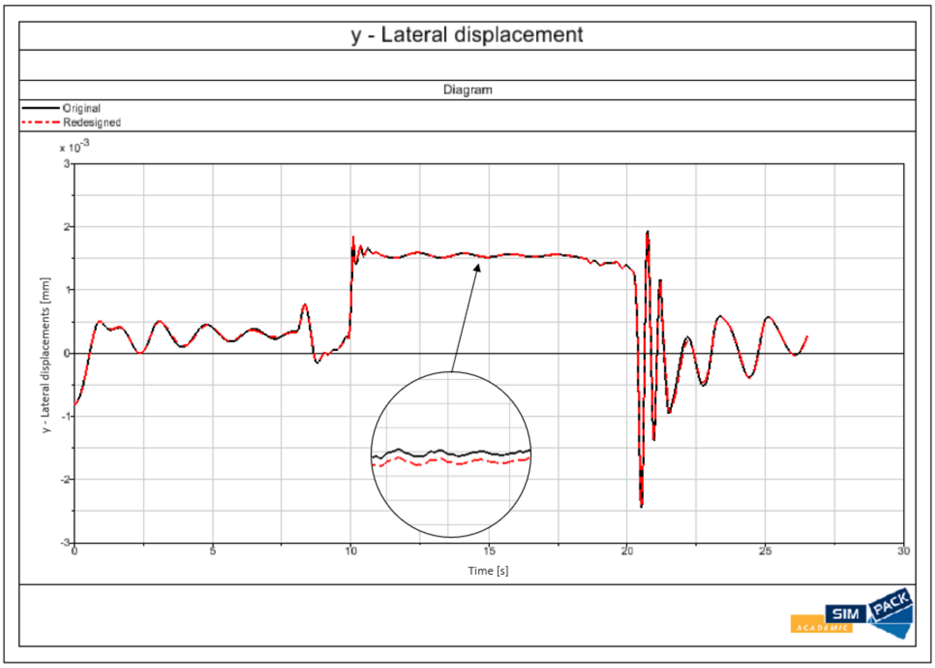


Figure 4: Topology optimization result in terms of element density.

Once completed the optimization process, resulting solid was introduced in a CAD software. At this point, mass and inertial characteristics of the optimized bogie frame were imported in the multibody software exploiting the automatic tool created with Python code. In the present research project, multibody model included only rigid bodies. According to the objectives of the work, two types of tracks were analysed: a straight track with a simple discontinuity and a curve of 100 metres. The running behaviour of the whole vehicle resulted coherent with that of the starting model that included the original bogie frame, showing minimum variations. Critical velocity was the same and equal to 90 km/h. Figure 5(a) shows the derailment coefficient for the curved track, confirming a value lower the permissible value of 1.2. Figure 5(b) shows the lateral displacement y of the wheelset for the curved track. Both pictures contain a circle zoom to highlights the minimum difference observed due to the difference in mass between the two models.



(a)



(b)

Figure 5: Running dynamic results: (a) derailment coefficient, (b) lateral displacements.

From the dynamic point of view the result was expected. Mass of the innovated frame was change in small percentage, as shown in Figures 5. In addition, as confirmed by a modal analysis carried out in free-free conditions, the natural dynamic behaviour of the system was very similar. As shown in Figure 6, a perfect matching in the first frequency of vibration was observed, with a value about 60 Hz.

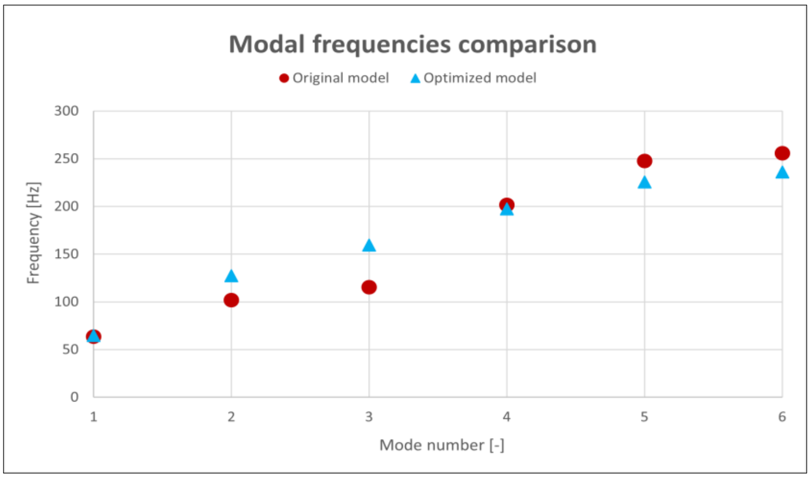


Figure 6: Modal frequency comparison.

These results would allow to replace the original bogie frame with the innovated one. Following this verification, a detailed model of it was created. The result is shown in Figure 7. The new design had an open shape, which made it potentially feasible for sand casting, as it had a single direction of extraction from the mold. Moreover, the central crossbeam was reinforced with inclined sets, useful for increasing the flexural and torsional stiffness of the frame, as well as facilitating the flow of molten material inside the mold. The constraint on minimum thicknesses imposed during the optimization process allowed for speeding up the geometry reconstruction process, as there were already numerous references available.

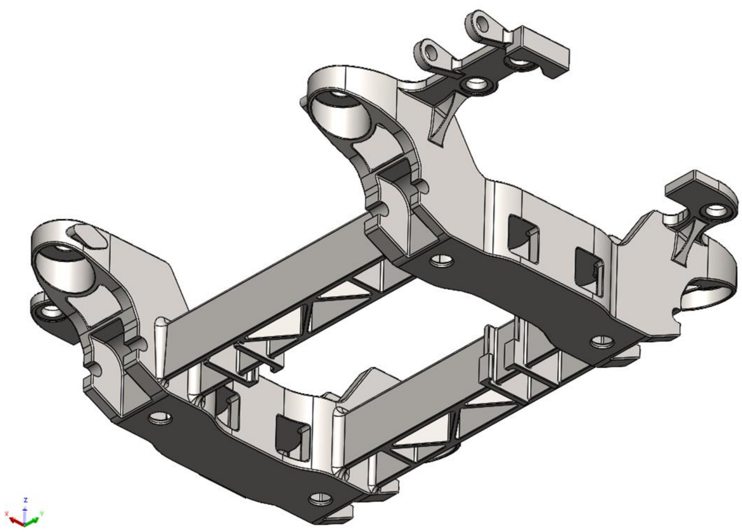


Figure 7: Final design of the bogie frame.

Finally, a complete structural strength assessment of the frame was carried out. In detail, the reference material was EN-GJS-450-10, whose mechanical characteristics can be found in [18]. According to the reference standard, the reference parameter to describe structural performance was the utilization factor, calculated as the ratio between the permissible value and the calculated value of stress. Globally the bogie frame showed good performance, with wide and admissible distributions of stress both for fatigue and static analysis, with a maximum value lower than 26% respect to the original one. As expected, some local concentrations of stress were observed near the main supports, strongly loaded in certain load conditions. These matched well those ones observed in the original frame. For this reason, at this stage of the work, they have not been further investigated.

4 Conclusions and Contributions

The research activity presented in this article focused on defining an effective method for redesigning the bogie frame of a railway vehicle. The proposed procedure aimed to combine structural optimization with technological constraints, along with a rapid assessment of the complete vehicle performance in terms of running dynamics. The procedure proved effective, resulting in the definition of a new design, producible through a sand-casting process, with better mechanical strength than the initial one and practically unchanged dynamic performance. The developed automatic tool allowed speeding up the verification process. As future developments, the possibility of introducing mechanical fatigue directly into structural optimization processes and transitioning to flexible multibody dynamics using flexible bodies would make the methodology even more effective.

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