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Development of a structural optimization procedure for tramway vehicles and carbody architecture innovation through composite structures

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Abstract

Nowadays, due to environmental pollution caused by CO_2-emissions, a global transition to electricity is taking place within railway industry. Lightweight design of railway vehicles could allow to reduce the power required during their operation conditions. Optimization processes, especially dynamic optimization approaches, are not widely used for designing of railway vehicles. In addition, in recent years, with the aim to increase weight reduction, sandwich structures were commonly introduced in the carbody structure. However, almost always they did not have any structural functionality. The present paper proposes the modelling and dynamic size optimization of a new roof assembly of a tramway vehicle including a sandwich structure. A new optimization procedure has been defined to support the traditional design approach. Subsequently, the roof assembly of the tram vehicle has been redesigned to allow the correct installation of the sandwich panel, fastened through a bonding joint. Encouraging results have been achieved in terms of mass saving and mechanical behaviour of the carbody shell. The developed methodology turns out to be a useful tool for supporting designers for obtaining a lightweight design. The innovative configuration of the roof assembly has shown promising performance in terms of mass saving, increasing of frequencies of vibration and costs.

Keywords: Tramway vehicle design, Carbody lightweight design, Tramway carbody engineering, Structural dynamic optimization, Size optimization, Dynamic optimization of railway components, Sandwich structures, Bonded joint.

1 Introduction

The transition to a globalised electrical power supply pushes rolling stock manufacturers to find structural solutions for reducing the power required by the vehicles. With the aim of meeting this requirement, mass reduction of the carbody structure could represent a solution. Within a market where details can make the difference in economic terms, the concept of design optimization is becoming established. The present industrial procedure to evaluate carbody structural strength in static field and according to EN 12663-1:2015 standard [1], does not include any optimization process. More in general, optimization processes, and especially dynamic optimization approaches, are not widely used for designing of railway vehicles. Some case studies are reported in [2,6]. In this framework, the present paper proposes a new dynamic optimization approach to support the design of railway vehicle bodies subjected to static loads. In addition, modelling and optimization of a new tramway vehicle roof that includes a sandwich structure, is presented. The benchmark aims to reduce the mass structure ensuring stiffness performance and costs adopting a new dynamic optimization approach. This innovative procedure was validated on the original vehicle and then applied on the innovative roof. In recent years, sandwich structures were commonly introduced in railway vehicles in order to increase space saving and weight reduction. The presence of a sandwich panel within the carbody shell, as structural component, was an important challenge. The proposed solution included an aluminium honeycomb sandwich panel fastened to the structure with a bonded joint. New model has been optimized through the proposed methodology and verified according to EN 12663-1:2015 standard. With the objective to understand if the new roof design could be economically competitive, first costs analysis was made. The reference tram vehicle is composed by five carbodies and three bogies, is monodirectional and it runs in an urban area. Figure 1 illustrates it. According to the reference standard it is part of P-V category, dedicated to tramway vehicles. The carbody has a welded structure and it is made with aluminium of alloys 6000 series with T6 heat treatment.

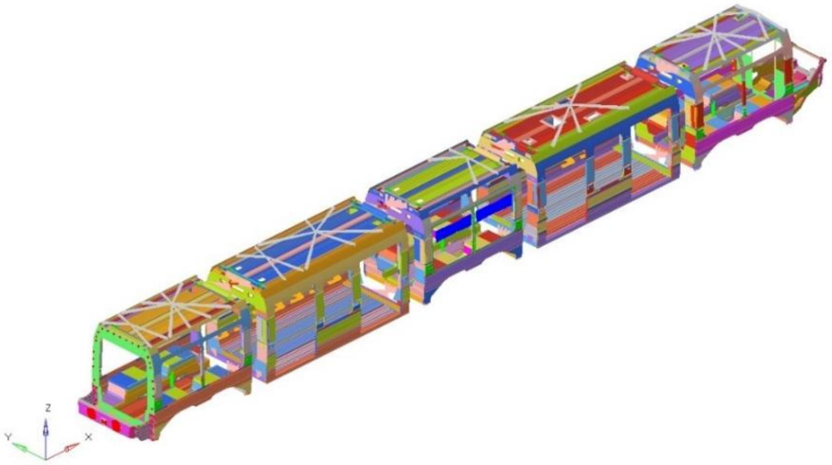

Figure 1: Tram vehicle (FE model).

2 Methods

Nowadays the realization of a good FE model of the vehicle is a fundamental step to streamline the design process and ensure the correct verification of its performance. Five loading cases have been selected from EN 12663-1:2015 standard. This selection aims to study the load conditions which more impact on the interested parts of the carbody structure, reducing global calculation time. Constraint conditions are always represented by an isostatic configuration: the carbody is supported vertically at the secondary suspension, laterally at the side pads and longitudinally at the posterior buffers of the cabin. Design philosophy of a railway carbody aims to achieve a very stiff structure. The dynamic size optimization process is applied on the single carbody and it is combined with modal analysis technique in free-free conditions. The proposed strategy allowed not only the reduction of the system mass but also to respect dynamic constraints in terms of natural frequencies. Natural frequencies of vibration and mode shapes of the carbody are functions of the structural properties of the system, as the simplest cantilever beam. For this reason, the stiffness of the carbody structure is the first parameter that designers need to consider: if a structure is sufficiently stiff, it will also be sufficiently resistant in terms of stresses. The dynamic optimization process acts simultaneously on two parameters, ensuring stiffness and minimizing mass, in agreement with the general principles of achieving a lightweight design [7]. It works on the thicknesses of the extrude profiles selected (design variables), changing their values within a predetermined range.

Sandwich structures can greatly increase stiffness of a component reducing its mass. With the objective to obtain same results with a tramway carbody, a sandwich panel, with structural functionalities, has been included in the roof assembly. It was mounted through a bonding joint that was verified by a dedicated procedure. Honeycomb core geometry was accurately modelled as shown in Figure 2 and Figure 3. This choice allows to evaluate possible local effects which cannot be observed with other simplified modelling strategies. Selected sandwich panel is totally made with aluminium alloy. This choice allows to saving mass, respecting fire resistance requirements. Once the new model of the carbody has been completed, it has been tested with the new procedure defined during the first part of the activity.

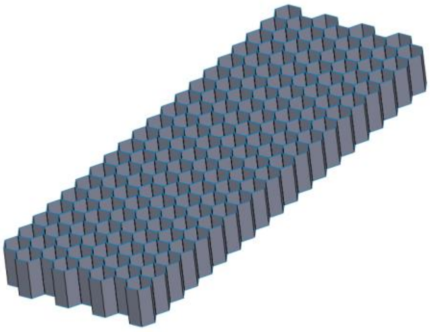

Figure 2: CAD model of a portion of honeycomb core.

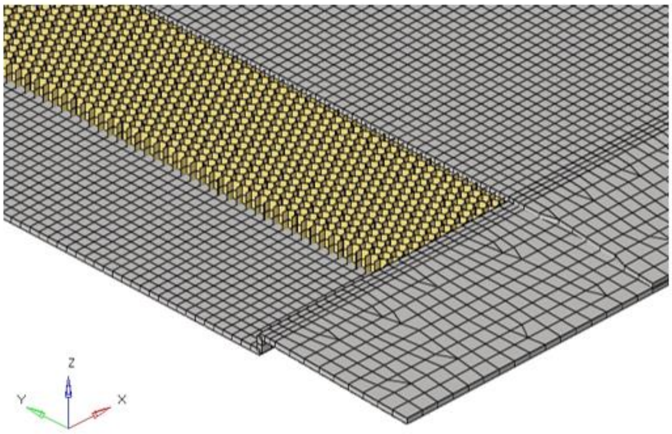

Figure 3: FE model of the sandwich panel.

3 Results

The flow chart of the new design procedure defined during the first part of this activity is illustrated in Figure 4. First, the original vehicle model must be verified according to the EN 12663-1:2015 standard. This is a necessary condition. Starting from the vehicle complete model, each carbody is isolated. The objective is to study its natural behaviour through a modal analysis in free-free conditions. After that, the dynamic size optimization process is applied on the single carbody. Objective function is the minimum mass of the system, while a condition on the minimum value of the first natural frequency of the structure is imposed as constraint function. Then, the original model need to be updated with new values of thickness and verified according to the reference standard. If the answer were “NO”, it would mean that the material has already reached its maximum performance considering the current geometric configuration.

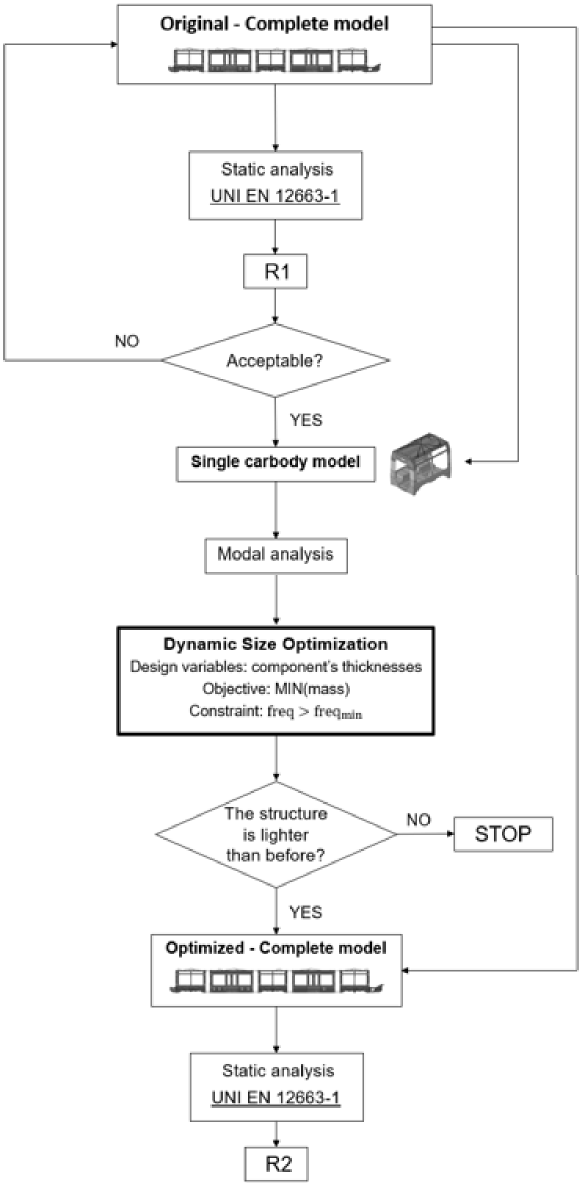

Figure 4: Flow chart of the proposed design methodology.

With the goal to evaluate the effectiveness of the procedure, it has been applied on the most critical roof assembly, due to its longitudinal dimensions and presence of several holes. The minimum first frequency of the structure required was 10 Hz, equal to the value of the original one. Results highlight a mass saving of 21% on the selected components. The first frequency of the structure is guaranteed. Results of the first part of the activity are reported in Table 1 and optimized components are shown in Figure 5.

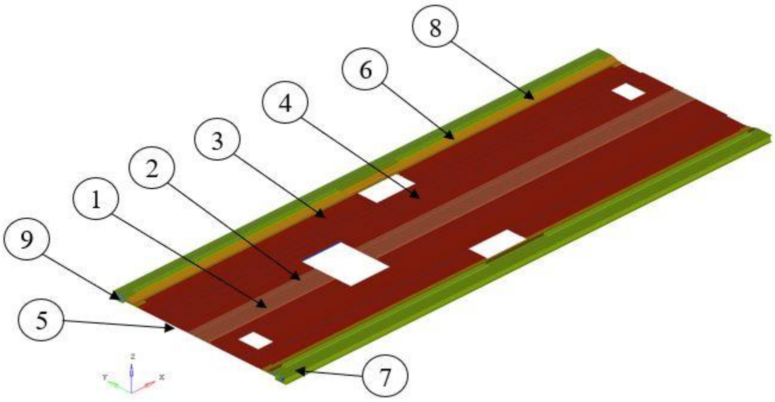

Figure 5: Optimized components with references.

Num.	Component	Thickness reduction (%)
[-]	[-]	[-]
1	Central extruded profile	20.00
2	Central extruded profile (set)	56.66
3	Medium extruded profile	10.00
4	Medium extruded profile (set)	16.66
5	Medium extruded profile (rail)	55.00
6	Medium-lateral extruded profile	25.00
7	Lateral extruded profile	33.33
8	Medium-lateral extruded profile (set)	0
9	Lateral extruded profile (set)	46.66

Table 1: Optimized component references and thickness reduction.

Then the optimized complete model of the vehicle was tested according to EN 12663-1:2015 standard and positively verified.

Once validated, the same approach has been applied on the innovative roof design which included the sandwich panel. A section view of the final FE model is shown in Figure 6.

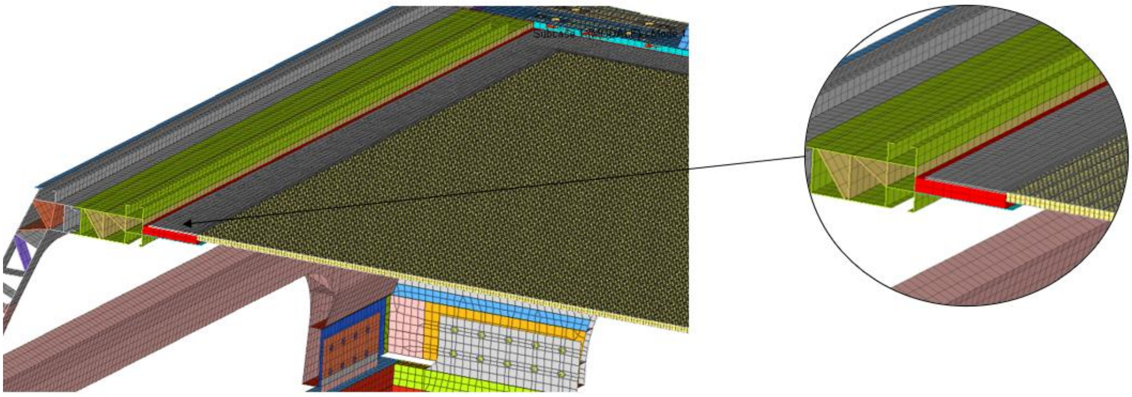

Figure 6: New carbody roof (cross-section view).

Results were successful, highlighting a mass saving of 63% on the selected components. Table 2 summarizes them.

Num.	Component	Thickness reduction (%)
[-]	[-]	[-]
1	Lateral extruded profile	66.67
2	Lateral extruded profile	66.67
3	Lateral extruded profile (set)	64.30
4	UPPER SKIN (sandwich panel)	50.00
5	LOWER SKIN (sandwich panel)	50.00

Table 2: Optimized components references and thickness reduction.

Then, the model was positively verified according to the reference standard. Comparison between the original carbody structure and the innovated-optimized one shows:

- mass reduction of 7.6%;
- first natural frequency increasing of 30%;
- comparable costs.

4 Conclusions and future developments

In this work authors have briefly presented an innovative approach to support carbody lightweight design exploiting a dynamic size optimization process. It has been applied on an innovative tramway vehicle roof, redesigned with the aim to include sandwich structures. Dynamic size optimization process allows to obtain a lighter and stiffer carbody, working on the modal behaviour of the structure. This approach could be seen as an important integration of the traditional process used for carbody structural design and verification, also considering its numerical efficiency in terms of calculation time. The thicknesses of the components obtained from the simulations must be considered minimum values. They are reference parameters for the designers, which are free to increase according to his evaluations. The innovative structure has performed well, highlighting good performance for both sandwich panel and bonded joint. The choice of using a bonded joint has ensured the possibility of deleting several critical welds on the roof of the vehicle. The cost of the new solution was resulted comparable to those of the original structure, making it even more competitive. Regarding future developments, in order to improve the accuracy of the model, bonded joint will need to be optimized in terms of size and geometry. In addition, the optimization process could be adapted to fatigue loads and crash tests.

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