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MULTI-MATERIAL DESIGN OPTIMIZATION OF A BUS BODY STRUCTURE

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Abstract

In the recent years the safety and eco-friendliness have gained much of attention of the automotive stakeholders. These two characteristics are especially important in the case of mass transportation vehicles, such as buses or coaches, which are in continues use for long periods of time, covering significant distances. In such situations, the economical aspects play major role for the transportation companies which try to minimize operational costs of their fleet, by choosing vehicles with reduced fuel consumption. In order to obtain improvements in all the mentioned areas and hence to strengthen their position on the market, bus manufacturers have recently turned their attention to multi-material design strategies. Structures built in that manner consist not only of regular steel parts, but contain also a mix of components made from various lightweight materials like aluminum alloys or composites, which allow for significant reduction in vehicle curb weight. However, due to the differences in mechanical characteristics which are especially evident in the case of laminates, the material substitution is not a straightforward task. In order to find the material distribution pattern that meets all the requirements, a great number of prototypic numerical models must be prepared and tested. To ease the search for the final solution, optimization techniques can be applied into the design process, allowing for automatic design modifications and assessment of the obtained results.

The paper presents an attempt of enhancing the operational characteristics of a bus body structure with simultaneous reduction in the structural weight. In order to find the optimal component configuration, a multi-material optimization was employed and supplemented by sensitivity and robustness analyses. Such a technique helps to discriminate the over-optimized solutions that are often pointed out as the most desirable by the optimization algorithms which neglect the uncertainties of the analysed system.

Keywords: *weight reduction, bus structure, structural optimization, multi-material design*

1. Introduction

The stakeholders on the nowadays automotive market have started to tackle with a design process that takes advantage of various non-ferrous materials available on the market, exploiting their specific properties. The main outcome of a multi-material design is a significant mass reduction and enhancements in structural mechanical properties, e.g. increased stiffness of crashworthiness.

The motivation for weight minimization comes from the fact that the mass of new vehicles has been growing steadily for the last four decades, exhibiting 1.1% of an annual increase [1]. Despite the fact that load bearing components are the subject of structural optimization approaches, the mass increase takes place due to the intensive use of auxiliary systems like air-conditioning, electronics or additional gas tanks [2]. Moreover, from the economical point of view, lower curb weight result in decrease of operational costs. This is particularly important in the case of the mass transport (e.g. buses or coaches), for which the annual mileage is very high.

Modern structural materials, very often adopted from the aeronautical industry, are characterized by very good specific strength and stiffness ratios. These quantities describe the chosen parameters of materials related to their density, comparatively indicating how much of the selected material type must be used, in order to withstand the applied loads (Tab. 1).

Aluminum has been used widely in the aerospace industry for decades, but has been also incorporated into the automotive design, replacing components traditionally made from steel. Its lower stiffness and strength is compensated by considerable lower density. Castings and extrusions are the most commonly encountered forms of aluminum parts preparation [3-5]. The material drawbacks are mainly connected with relatively high primary production costs and technical difficulties with steel to aluminum transition.

Magnesium is 75% and 30% lighter than steel and aluminum respectively. Its density is comparable with the density of polymers. It has many advantages like very good machinability, excellent damping capacity or the best strength-to-weight ratio among structural metals, but suffers from the general corrosion resistance problems and difficulties with joining with other metals. The material itself has been used in structural components for a relatively short time, thus recyclability has not been well developed yet – only about 20-30% of the produced material is reused [5-7].

Tab. 1. Mechanical parameters of the chosen structural materials

Material type	Density [g/ccm]	Young Modulus [GPa]	Tensile Strength [MPa]	Specific Modulus [GPa/g/ccm]	Specific strength [MPa/g/ccm]
Wrought Magnesium AZ80 – T5	1.8	45	380	25	211.1
Wrought Aluminum 6061-T6	2.7	69	310	25.6	114.8
Unidirectional Carbon Fiber Reinforced Plastic (standard modulus)	1.6	135	1500	84.4	937.5
E – Glass Fiber Reinforced Plastic	1.9	40	1000	21.1	526.3

Composites consist of two or more separate phases, among which reinforcement and load transmitting constituents can be found. A vast number of materials are commonly used in composite design, but the most appropriate for structural applications are the fiber reinforced plastics (FRP). Depending on the material composition, both: strength and stiffness can be higher when compared to mild steel. The most commonly used FRPs are composed of glass, aramid or carbon fibers in conjunction with epoxy or polymeric resins [8-10].

Modern structural materials have been also incorporated into mass transport vehicles, including bus superstructures. Harte *et al.* in [11] presented a study on utilization composites in lightweight rail cart, carrying out an optimization on walls' thicknesses and geometrical features. Colombo and Vergiani [12] presented a research on load carrying composite beams of a bus body, which was pultruded from glass fiber and polyester resin. They assessed the fatigue resistance, strength and weight of the examined parts, pointing out their superiority over the steel counterparts. Ko *et al.* investigated the application of composite sandwich panels in the bus structure, showing their usefulness in improving crashworthiness and rollover characteristics [13].

These mechanical performances along with the weight minimization were the subject of many optimization attempts. The test procedures needed to evaluate a rollover resistance of bus superstructures were established in 1987 by the Economic Commission for Europe in the ECE R66 regulation [14, 15]. The evaluation of the ECE R66 recommendations was done by Liang and Le in [16], in which they investigated the structural deformations and occupants' safety level, comparing them with equivalent quantities obtained on the basis of similar American FMVSS 220 regulation. The same authors in [17] presented a study on enhancing the bus rollover resistance. They identified the components that exhibited high internal energy level and applied on them structural modifications that were obtained by means of a simple one-variable regression-based optimization process. Similar studies were presented by Su et al. in [18] in which the authors conducted a weight optimization of a bus body, considering the sidewall intrusion and static stiffness constraints. Gauchia *et al.* [19] published results from a multi-objective optimization attempt in which weight and torsional stiffness parameters were improved simultaneously. The subject of the optimization process in both cases were only the thicknesses of sidewall beams, thus the final structures consisted entirely of steel.

2. Optimization strategy

The target of the optimization process was to redesign the bus superstructure to improve its mechanical characteristics. The bus body was first examined carefully in order to define the components that could be modified in the following steps. The criterion was the easiness of substitution and the efficiency of the possible modifications: only the elements which had a clear impact on the structural deformations were taken into consideration. The selected group included vertical beams that were parts of the pillars and the chosen sidewall beams – as shown in Fig. 1.

In order to save the computational time and to decrease the optimization complexity by lowering the number of the design variables, the process was divided into two steps carried out separately, as described in the following paragraphs.

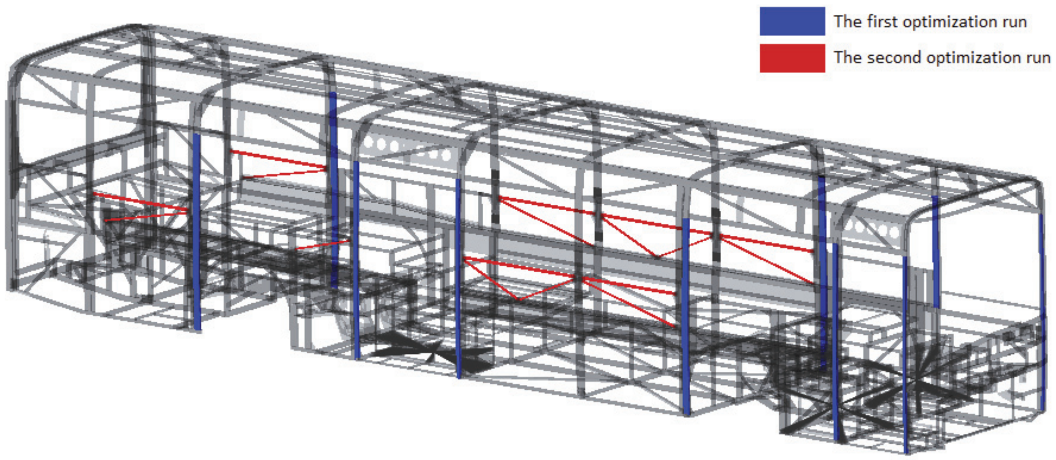

Fig. 1. The baseline bus superstructure. The marked components were the subjects of the optimization: blue and red – the first and the second run respectively

2.1. Design constraints

The boundary conditions described the geometry of the baseline structure and its mechanical performance. The former limitations were related to the assembly process of a full vehicle, preventing from changes in the components' external dimensions. The latter assured that the overall weight, torsional stiffness and side impact deflection of the optimized solution did not decrease compared to the baseline design.

2.2. Design variables

The scope of the presented process was to exploit the properties of different materials used in the nowadays automotive structural design. In the problem stated, five different material types were considered as input variables: standard and high modulus carbon fiber reinforced plastics (SM-CFRP and HM-CFRP respectively), glass fiber reinforced plastic (GFRP), aluminum and steel. Material substitution was supplemented by the wall thickness optimization. Beams used in the sidewall construction were assumed to be produced by means of pultrusion process, thus reinforcing fibers were oriented along the components, what excluded any orientation angle changes.

2.3. Optimization objectives

Regardless of the optimization phase, the targets were defined as the (Fig. 2):

- torsional stiffness,
- rollover resistance.

The torsional stiffness is considered as the deformation of a structure resulting from the presence of vertical loads applied in the front suspension mounting points, with the rear attachments fixed. The torsional stiffness coefficient is expressed by Eq. 1:

$$k_t = \frac{F \cdot d}{\varphi}, \tag{1}$$

where:
F – force,
d – distance between the load application points,
φ – twist angle.

The rollover conditions are described in detail in ECE R66 standard and will not be provided in this paper.

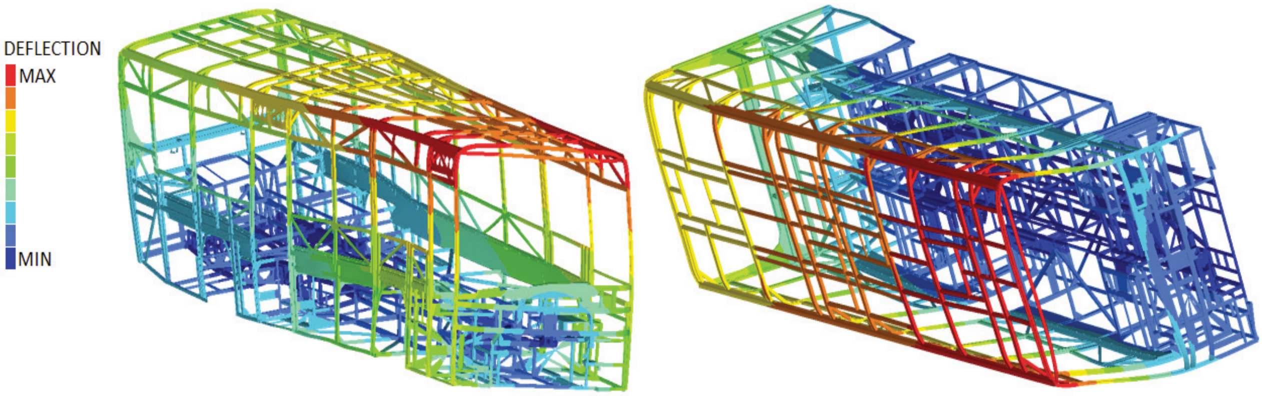

Fig. 2. Body torsional (left) and rollover (right) deflections

2.4. Robust design

The optimization process described above was carried out for input arguments without taking into consideration their variations, which can result from the production errors. In reality, the geometry of profiles suffers from some degree of inaccuracy, normally expressed as the dimension tolerances. The over-optimized solution is defined as the one that exhibits good, but unstable behavior that is easily negatively influenced by the input.

To prevent similar situations, robustness of the final design must be verified, as depicted in Fig. 3. In the example given, design A is more attractive because of the higher target function output, but even small changes in the input parameter can considerable deteriorate this value. Despite lower performance, the second solution is more stable against the input variations, thus it is more preferable.

The variations in the input parameters were obtained by monte carlo sampling method, with normal distribution of the values. To assess the stability of the output quantities, the relative standard deviation (%RSD) was monitored – Eq. 2:

$$\%RSD = 100 \cdot \sigma / \bar{x}, \tag{2}$$

where:
σ - standard deviation of the obtained objective values,
$\bar{x}$ - their mean value.

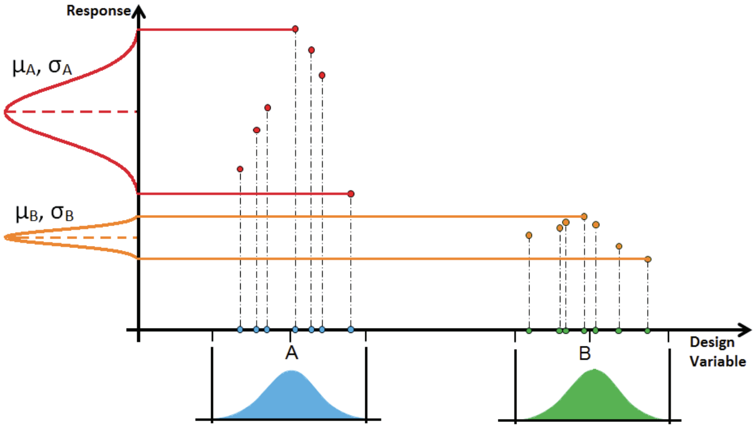

Fig. 3. An idea of robust optimal design. Solution B is more preferable, because of the higher robustness against the input function variations

However, despite the advantages, the robustness examination can be very time consuming because of the need of additional analyses. To prevent unacceptable computational expenses, only selected solutions that exhibited the most desirable improvements were tested.

2.5. Genetic algorithm

In order to find the optimal solution, the non – dominated sorting genetic algorithm II (NSGA-II) was exploited. The main features of the algorithm are:

- domination estimation and fitness assignation in every generation,
- crowding distance evaluation,
- selection of parents on the basis of the above.

The subject of GAs is extensive, thus will not be covered in this article. A detailed description of the exploited algorithm can be found in [20, 21].

3. Optimization and the final solution

As mentioned above, the optimization of the bus superstructure was divided into two stages: modification of the vertical beams being part of the pillars (blue colour in Fig. 1) and changes of the selected beams of the sidewall construction (red colour in Fig. 1).

After the selected number of simulation had finished, a number of designs that exhibited improvements compared to the baseline strength and weight parameters were found. In the case of a multi-objective optimization, the choice regarding the final design is always a matter of trade-off between the outputs categorized as quasi-optimal in the Pareto sense. The choice is made between solutions, for which an improvement in one quantity means a deterioration in others.

Table 2 presents the results obtained from the first optimization phase, in which the pillars were the subject of modifications. The presented designs were selected because of having the most profitable material distribution. In the following step, the robustness against the geometrical variations of all the presented solutions was tested, which in conjunction with economical premises was the decision-making criterion.

The material composition that provided the highest level of improvements, was clearly a mix of SM-CFRP and HM-CFRP. If other materials were used, not only the improvements were less attractive, but also the stability of the obtained solutions suffered. Aluminum was neglected by the optimization algorithm, what was caused by the demanding boundary conditions, concerning the geometry.

Because of the satisfactory level of improvements and material composition (Fig. 4), resulting in good material price and efficiency compromise, solution no. 7 was chosen as the input for the following optimization phase.

Tab. 2. Results obtained from the first optimization run: pillars modification

Robust design id	Material composition	Mean mass relative to the baseline [%]	%RSD mass [%]	Mean torsional stiffness relative to the baseline [%]	%RSD torsional stiffness [%]	Mean rollover deflection relative to baseline [%]	%RSD rollover deflection [%]
P1	SM-CFRP, HM-CFRP, GFRP	97.36	0.021	106.55	0.16	96.41	0.29
P2	SM-CFRP, HM-CFRP, GFRP	97.36	0.015	106.59	0.15	96.33	0.19
P3	SM-CFRP, HM-CFRP, GFRP, steel	97.45	0.016	106.56	0.15	95.95	0.18
P4	SM-CFRP, HM-CFRP	97.34	0.015	106.80	0.16	95.95	0.25
P5	SM-CFRP, HM-CFRP	97.35	0.013	106.82	0.15	95.13	0.09
P6	HM-CFRP	97.99	0.011	111.47	0.05	87.33	0.09
P7	SM-CFRP, HM-CFRP	97.35	0.014	107.06	0.13	95.41	0.28
P8	HM-CFRP	97.98	0.011	111.68	0.07	87.42	0.10
P9	HM-CFRP	98.01	0.012	111.44	0.31	87.20	0.10

During the second optimization run, the genetic algorithm had more difficulties with finding non-dominated designs providing an acceptable level of mechanical performance enhancements, thus the new Pareto front was less numerous. Nonetheless, three propositions were selected for further stability assessments, the results of which are combined in Tab. 3.

The analysis of the presented results leads to the conclusion, that the applied material modifications are not recommended. Although some degree of improvements in the torsional stiffness and overall weight were obtained, the rollover resistance was deteriorated. Moreover, the small observed outcomes were found exclusively by application of HM-CFRP, what would significantly increase the production cost.

Basing on the above, the P7 solution was chosen as the final one. As depicted in Tab. 2, compared to the baseline all-steel bus body, the optimized structure exhibits better rollover resistance (4.59%) and torsional stiffness (7.06%). The optimization provided also 2.65% savings in weight.

Tab. 3. Results from the second optimization run: sidewall beams modifications

Robust design id	Material composition	Mean mass relative to the baseline [%]	%RSD mass [%]	Mean torsional stiffness relative to the baseline [%]	%RSD torsional stiffness [%]	Mean rollover deflection relative to baseline [%]	%RSD rollover deflection [%]
B1	HM-CFRP	96.93	0.006	107.60	0.03	95.97	0.01
B2	HM-CFRP	96.91	0.006	107.55	0.02	95.98	0.02
B3	HM-CFRP	96.93	0.005	107.64	0.02	95.97	0.01

4. Conclusions

The two step optimization process was carried out in order to improve the mechanical characteristics of the bus superstructure. The design variables were defined as the material type and thickness of the selected sidewall beams, while the objectives were the mechanical performances under torsion and rollover conditions and the structure curb weight.

The first optimization phase (pillars modification) provided significant improvements in all the considered targets, by SM-CFRP and HM-CFRP application. Furthermore, the robustness against the production errors of the tested Pareto-optimal solutions was confirmed.

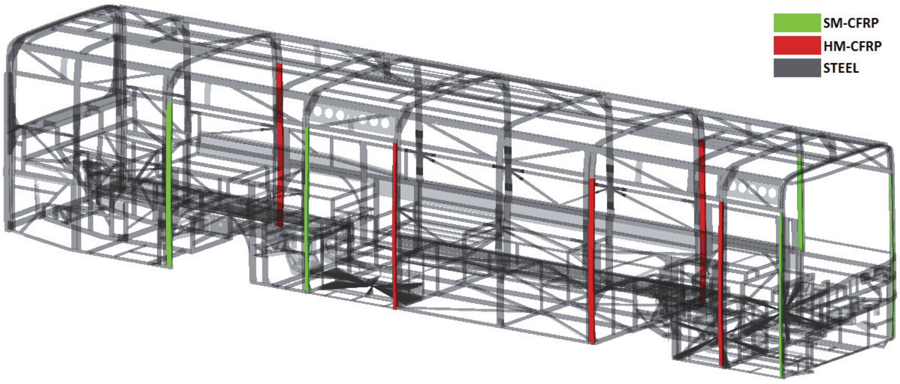

Fig. 4. final design modifications

The following optimization of sidewalls reinforcement beams was more demanding. The optimizer did not found simultaneous improvements in all of the targets, causing slight deterioration in rollover resistance. Moreover, any profitable modifications were possible only by application of the expensive HM-CFRP, thus this modification was not recommended. The final solution has been chosen from among the designs found in the first optimization run.

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