

# Simulation-based design process for railway metallic structures

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## Abstract

The German Aerospace Center (DLR) develops pioneering rail vehicle concepts that enable improvements in terms of energy and resource efficiency, as well as wear and comfort. For passenger car bodies, the focus is on lightweight construction and new materials. However, the use of lightweight structures due to their stiffness and vibration behaviour involves a conflict of objectives with regard to passenger comfort.

To meet these challenges, suitable design methods and verification concepts are needed that fully exploit the lightweight potential of the materials used. So far, static equivalent loads are generally used in the design of rail vehicles in accordance with the fatigue strength verification defined in the standards, as for instance EN 12663-1. However, this procedure assumes metallic materials, and it is not suitable for adequately considering the dynamic loads that actually occur during operation. This can lead to unnecessary oversizing of the vehicles, which runs counter to the goal of lightweight construction. So, we developed a methodology in which design and strength verification are carried out using dynamic loads from flexible multi-body simulation and fatigue strength calculation. This can pave the way for the application of lightweight construction concepts for railway vehicle car bodies.

Our method consists first to perform a model reduction in order to extract the flexible body of our car body. Then, multi-body simulations are carried out to determine realistic dynamic loads and stresses that occur during operation. The results of this stress analysis are directly used for a fatigue simulation. In addition, aerodynamic loads from CFD simulations are considered for the fatigue analysis. For the last step of our method, the welds are defined directly in the fatigue analysis software and a structural durability analysis is done. This last simulation allows us to detect the first damaged location on the structure and finally adapt it for the required life time.

## 1. Introduction

The goal of DLR's rail research is to make passenger rail transport more effective and attractive while considering the use of lightweight structures. In order to achieve our contradictory objectives, there is a need to develop new methods to improve the design of railway structures and components. Nowadays, most of the structures are oversized due to static design loads defined by established standards. The origin of these loads has been lost over the years, that is why it is difficult to judge whether they are reasonable for innovative car body designs. In order to optimize the sizing of structures and components, we need to consider the actual operating loads applied when the train is running. In the following paper, our method to size a structure or a component according to the operating loads is presented step by step.

## 2. Method

The DLR Next Generation Train (NGT) multiple unit high-speed train (HST) is regarded within the DLR Rolling Stock (RoSto [1]) project. The focus of this work is on the intermediate car of the NGT HST which consists of two powered bogies with independently rotating wheels and mechatronic track guidance, as well as a double-decker car body.

The goal of our method is to design a structure or a component as best as possible considering more realistic operating loads applied during service life, using a simulation process. To that end, a workflow is created, split into three main parts. This workflow is presented in Figure 1.

First, a finite element (FE) model is created that includes geometry, materials and initial conditions. This model is prepared for integration as a flexible body in the multi-body system (MBS) model by defining interface nodes for connecting MBS components (i.e. joints, force elements). In addition, a model reduction according to Craig-Bampton [2] is applied. Assuming small deformations and a limited frequency range, this mathematical method allows to reduce the numerical complexity of the FE model drastically. As a consequence, the computational effort of the simulation is reduced accordingly.

In the next step, the reduced car body model is imported into the MBS model of the intermediate car. This vehicle model is used to simulate various scenarios relevant for the damage calculation of the car body. The flexible modelling not only has the advantage of more realistic loads, but also makes it possible to calculate car body stresses directly in the MBS simulation. This data is finally imported into the fatigue software FEMFAT MAX [3] to estimate damage accumulation and durability of the structure. In order to be as realistic as possible, aerodynamic loads are also included into the fatigue analysis software.

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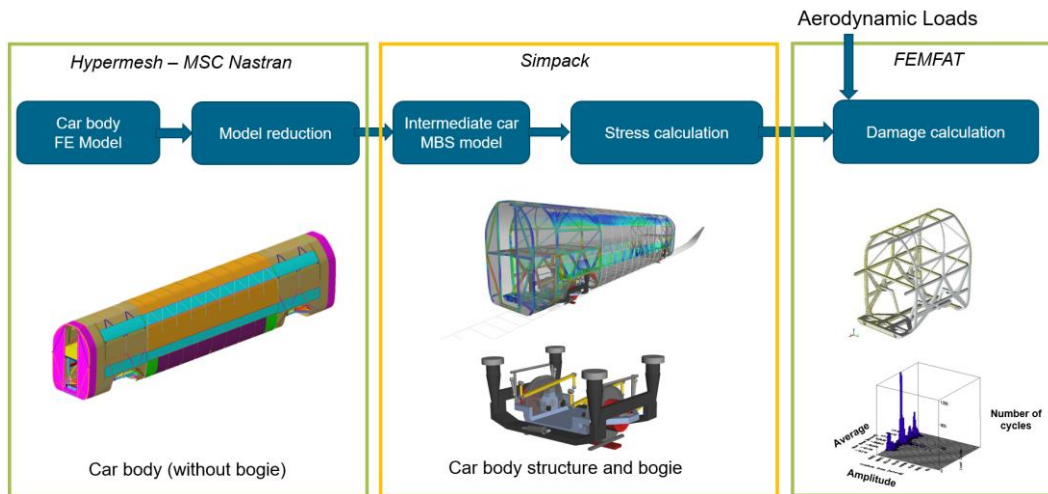


Figure 1: Workflow of our Method

### 3. FEM Model and Model reduction

As mentioned earlier, the stresses and strains are calculated directly in the Simpack MBS software using the Loads Stress & Strain module [4]. To perform this simulation, an fbi file is required that contains the flexible body data of the structure. The fbi file can be created directly by Optistruct [5]. However, this requires a long simulation time and the generated fbi file is very large, which makes data exchange between the two software tools cumbersome. So, we used MSC Nastran as FE solver and Simpack's fbi file generator for the flexible body data transfer.

The FE model reduction results in a modal representation of the flexible body. It is crucial for result quality and simulation performance to identify the required eigenmodes and skip the unneeded ones. Based on a frequency range of up to 50 Hz, which is relevant for the damage calculation, the number of eigenmodes considered has been selected so that frequencies of up to 75 Hz are mapped correctly, i.e. do not change significantly when further increasing the number of modes. Regarding two occupancy states, tare (19.7 t) and 80 % loaded (34.6 t), this resulted in an optimal number of dynamic modes of 330, respectively 400.

A model reduction corresponds to the creation of a superelement. This approach has several advantages:

- Comprehensive analysis options (large models, many degrees of freedom, time steps or frequencies)
- Reduction of simulation time and effort, the huge number of nodes contained in the mesh can be reduced to a few interface nodes with modal matrices (stiffness [K], mass [M] and damping [B])

The submodel of the intermediate car body is based on an FE model with approximately 1.5 million shell elements. Equipment components such as transformers, toilets, seats and also passengers are modelled as point masses.

#### **4. MBS Simulation with flexible car body structure**

From the very beginning, the evolutionary development of the NGT HST from the first concept studies to the real existing prototypes was accompanied by MBS simulation. Over many years, the models were developed from sketchy drafts to detailed representations of virtual and real prototypes. Today, a modular model database is available that can represent all relevant configurations from the running gear on roller rig to the high-speed train on measured rail tracks. Geometry and inertia data come from CAD models, and force element parameters were determined by test stand trials or data sheets.

For the structural durability calculation of the car body structure, load cases and simulation scenarios that are typical for the operation of the vehicle under consideration are primarily relevant. The MBS simulation makes it possible to create and vary scenarios with little effort. The three scenarios examined in RoSto so far are therefore to be understood as an exemplary selection that can be easily expanded or modified in line with the requirements of the fatigue evaluation.

In the first scenario, the intermediate car travels at a speed of 40 km/h through an S-curve, which in a simplified form reflects the track course of a double point of type EW190-1/9. This scenario simulates the journey through a station approach. The second scenario also involves passing through an S-curve, but at the maximum travel speed of 400 km/h with correspondingly larger curve radius (6000 m), transition curves (410 m) and superelevation (145 mm).

In addition to the two synthetic S-curve scenarios without rail irregularities, the journey on a realistic high-speed track is simulated. For this purpose, measurement data of a 51.5 km long section of the Ingolstadt-Nuremberg line, running at a speed of 320 km/h, can be used. Due to the longer simulation time of 579 s and the persistent excitation caused by rail irregularities, the calculation effort for this scenario is considerably higher. However, it also appears to be particularly significant for the fatigue strength analysis in terms of scope and relevance.

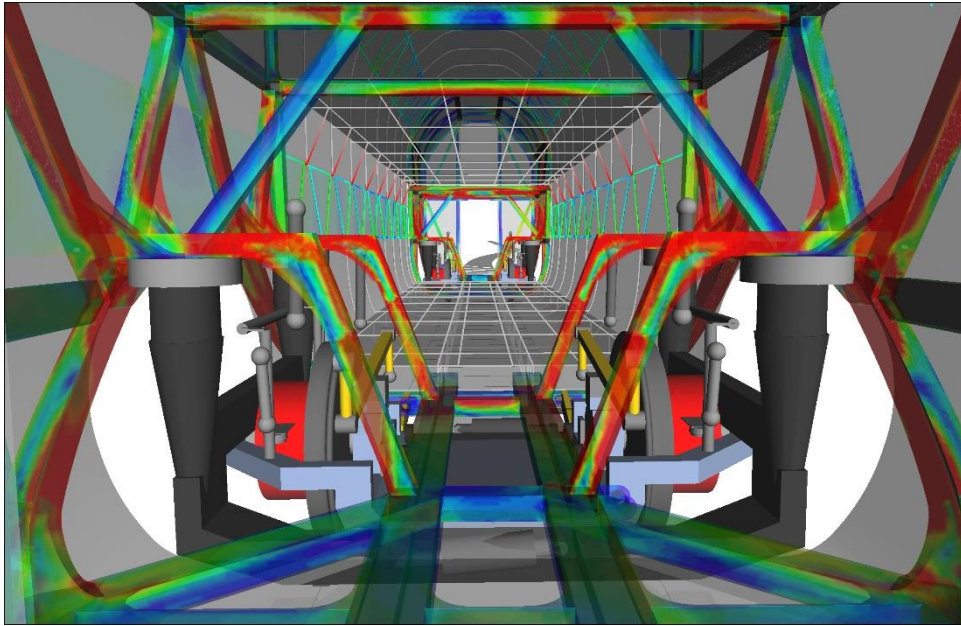


Figure 2: Simpack MBS Model with representation of the stresses in color

## 5. Aerodynamic loads

To perform the fatigue life simulation with FEMFAT, an FE model with static unit loads of 1 Pa ( $=1e-06$  MPa) has to be created first. This FE model is identical to the one used for the MBS export, but a pressure of 1 Pa is applied to the entire surface of the structure. After the simulation is performed with Optistruct, the h3d file containing the results is imported into FEMFAT. The file with the aerodynamic loads is also imported into FEMFAT. In this way, the unit loads defined in the initial FE model are replaced by the aerodynamic loads.

The aerodynamic loads were previously calculated following guidelines for determining aerodynamic loads on rail vehicles. This guide fills a regulatory gap in standards EN 12663-1 and EN 14067 for wagon body strength checks [6].

To take aerodynamic loads into account, the following simulation scenarios were examined:

- Travel through the Katzenbergtunnel at 400 km/h. The tunnel is 9385 m long and on the way between Karlsruhe-Basel.
- Train encounter in the middle of the tunnel at 400 km/h. The tunnel is the Escherbergtunnel, on the way Hannover-Würzburg. It is 3687 m long.
- Train encounter just before exit of the tunnel at 400 km/h. The tunnel is also the Escherbergtunnel.

- Train encounter on an open track at 320 km/h with a track center distance of 4.5 m.

All fatigue simulations are performed for these four simulation scenarios for the 80 % loaded car. It was found that the number of passengers has no influence on the fatigue results of the structure. Indeed, the loads are directly applied on the structure. The size of the train or the profile of the structure have an influence on these loads but not the weight of the train.

## 6. Fatigue strength model

In order to meet the challenges of environmental protection and lightweight construction, it is important to carry out fatigue strength calculations. In this way, the service life time of the structure can be increased and the parameters that have the greatest influence on the durability of the car body can be identified. All fatigue simulations are carried out with the FEMFAT software.

FEMFAT consists of several modules. In this work, the following modules are used:

- FEMFAT MAX: The MAX module makes it possible to predict the fatigue life for multi-axial loading. The superposition of several loads can cause fracture-critical total damage even at points that are not visible under single loads. [3]
- FEMFAT WELD: The WELD module allows the fatigue life of welded structures to be determined. Welds can be defined directly in FEMFAT Visualizer for 2D or 3D elements. The module can be combined with the Basic and MAX modules. [7]
- FEMFAT Visualizer: The Visualizer is a 3D post-processor that can be used to display FEMFAT results and FE stresses independently of the interface. The Visualizer also has a function for defining welds for body models. [8]

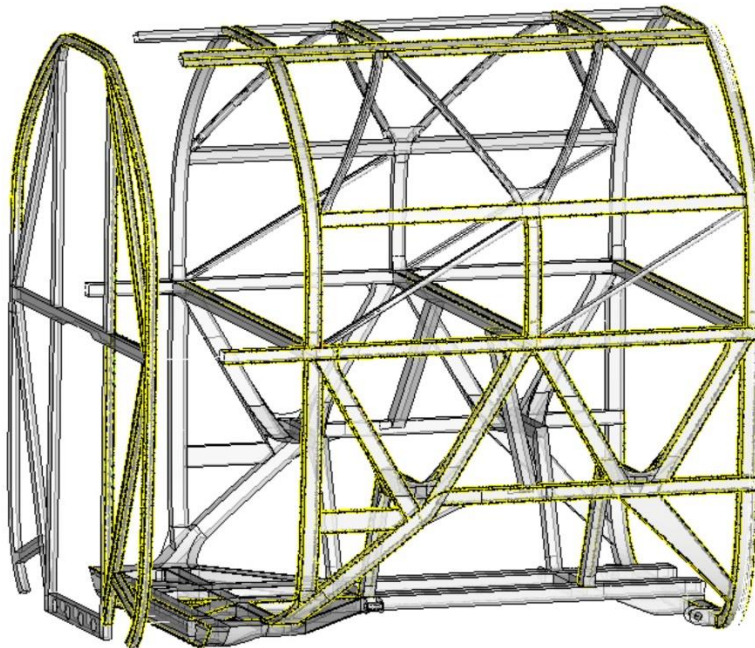
The FEMFAT MAX module enables the import of a max file, which contains multi-axial loads and is generated from the results of the MBS simulation using the Simpack Loads Durability module [4].

In rail vehicle construction, metals are mainly used and established methods are available for their fatigue strength verification. Within the framework of RoSto, a car body made of the wrought aluminum alloy AlCu4SiMg is therefore first defined. This aluminum is recommended in DVS 1608 [9] as a base material for welded joints of rail passenger car body vehicles.

After defining the car body material, the welds are defined. To shorten the simulation time, welds are only created at the front right part of the chassis module. Figure 3 shows the approximately 600 welds defined. It is assumed

that the loads on the car body are the same on the right and left sides, and that higher loads occur at the front end of the car body caused by the rail-wheel contact forces during curving.

The weld damage analysis is carried out according to the DVS1608 standard [9], which is directly integrated into the fatigue software.



*Figure 3: Fatigue analysis model with defined welds in yellow*

Fatigue analysis simulations is performed following the presented simulations scenarios. It is also possible to combine these scenarios. This means that we can sum up the dynamic and aerodynamic loads to inspect the total damage on the structure.

### **7. Conclusion**

To make rail transport more attractive and sustainable, it is important to improve passenger comfort, but also to reduce resource consumption and CO<sub>2</sub> emissions. To meet these requirements, a lightweight design must be used for the car body.

In this paper, it has been shown that the developed method works with several software packages in two different departments, despite all the necessary steps. The data transfer could be carried out without major difficulties. However, the combination of four different software tools in one workflow was not always straightforward. At the beginning of the project, a longer test phase had to be carried out to determine which software tools and versions can be used in

combination. E.g. the interface between our preferred tools Optistruct and Simpact did not support stress analysis.

The developed method allows for the sizing and fatigue assessment of the NGT HST car body. However, this method is applicable to any structure. First, an FE model must be created and then a model reduction must be performed. The flexible body is then transferred to a multi-body model that can be used to determine the actual operating loads and the associated stresses and deformations. The results are then used for fatigue simulations to estimate the structure's lifespan and identify the most vulnerable areas. The material used here is aluminum, but in principle any metal can be used. It is also possible to define composite materials, which is being investigated in another part of the RoSto project.

The final method works well, but it still needs to be validated and calibrated. This is our next goal, which is to be achieved by the end of 2025. In addition, the relationship between structural design and passenger comfort is to be analysed. The simulation-based design process presented here will therefore be used again and analysed with a modified car body structure.

## 8. References

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