Using Abaqus/Standard and Abaqus/Explicit for the Development of New Bi-Level Trains at Stadler Rail

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Abstract: In the development of the new bi-level train KISS Abaqus/Standard and Abaqus/Explicit have been intensively applied to optimize the structure with respect to stiffness and strength as well as to crashworthiness. Models up to 3 million shell elements have been used to prove the strength of the load carrying structure with respect to the standard EN12663-1. By using Abaqus/Standard the calculation times were minimized allowing for a significant number of iterations to optimize the structure with respect to lightweight engineering and with respect to a reduction of manufacturing time. Additionally, the Abaqus/Standard result files were used to investigate the fatigue strength of the structure, especially of the welds, with FEMFAT, a post-processor code from Magna Powertrain. The fatigue strength was proven for typical load collectives representing the operational life for 40 years of operation. In simultaneous analyses with Abaqus/Explicit the crash energy management structures have been optimized. All requirements of EN15227, the European crashworthiness standard, were successfully fulfilled. Comparisons with dynamic test results have shown that the numerical results are very close to the test data. Abaqus/Standard and Abaqus/Explicit have helped to minimize the overall development time of the structure of the new Stadler bi-level train KISS.

Keywords: Crashworthiness, Damage, Design Optimization, Dynamics, Elasticity, Experimental Verification, Failure, Fatigue, Fatigue Life, Impact, Minimum-Weight Structures, Optimization, Plasticity, Postprocessing, Railcar, Seam Welding, Shell Structures, Substructures, Visualization, Welding.

1. Introduction

Stadler Rail has developed the new bi-level train KISS which is now operated up to speeds of 200 kmph in Austria and Switzerland (see figure 1). The car body structure is made from hollow large scale aluminum extrusions. These aluminum profiles are welded with each other using MIG welding and friction stir welding techniques. Since the overall weight of the train is a critical parameter for the authorization process of the railway vehicle, light weight principles have been taken into account when designing the car body structure. The structure has to fulfill the requirements of the European standard EN 12663-1, category P-II: A compressive load of 1500 kN applied in the line of draft of the coupler has to be sustained without any plastic deformation. Thus, sophisticated large finite element models have to be established. Fatigue loads like damper forces acting between the car body and the bogie and accelerations in all major directions have to be considered for the design of the welds. The Abaqus/Standard result files were used to investigate the fatigue strength of the structure, especially of the welds, with FEMFAT, a post-processor code from Magna Powertrain. The fatigue strength was proven for typical load collectives representing the operational life for 40 years of operation. This fatigue life assessment method has been applied for the design of the welds in the car body structure and in the bogie frame.

Additionally, the car body structure has to match the crashworthiness requirements of the EN 15227, category C-I. Collision scenarios like the collision with a truck on a grade crossing at a speed of 110 kmph have to be investigated by dynamic analyses.

In this paper the finite element modeling for quasi-static analyses with ABAQUS/Standard as well as for dynamic analyses with ABAQUS/Explicit are discussed. Additionally, a procedure is presented for the validation of the finite element results by comparison with test results.

Figure 1: Stadler bi-level train KISS for the Austrian operator Westbahn

2. Finite Element Modeling

In order to perform a large spectrum of Analyses a FE-model of the bi-level train KISS has been created, that can be used in Abaqus/Standard as well as in Abaqus/Explicit (see figure 2). Thus, global linear static analyses as well as detail investigations with consideration of material-, geometric- or contact-nonlinearities may be performed without inducing major efforts. A special effort has been dedicated to the modelling of the welded seams for the evaluation according to the standards EN 15085 and the guideline DVS 1608. The characteristics of the bi-level train KISS FE-model are the followings:

- Number of elements: approx. 3 millions
- Number of DOF: approx. 12 millions
- Characteristic element length: 25 mm

Implemented non-linearity: elastic-plastic material properties, weld seam failure criteria, contact definitions, large deformations (NLGEOM), connector elements (CONN3D2)

The design of the bi-level train bases on aluminium extrusions, which have been modelled using linear shell elements with reduced integration (S4R). In areas with concentrated loads a small number of milled parts have been applied. The modelling of these parts has been performed with solid elements. Many fasteners are employed for the assembly of the structural components. The bolts and rivets properties have been implemented into one-dimensional beam elements. The element density as well as the mesh quality has been especially considered for an optimized capture of the stress gradients. In the structural homogeneous areas an isometric mesh has been generated to guarantee rapid model changes during the vehicle development. The number of triangular (for shells) and tetrahedral (solids) elements has been kept to a minimum.

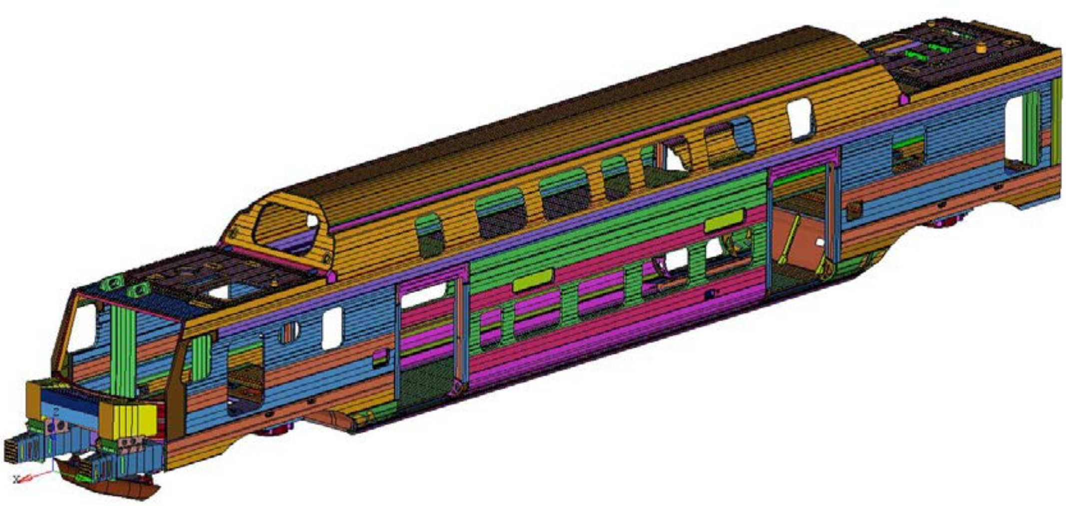

Figure 2: Overall FE-model of the bi-level train KISS car body

2.1 Static Analyses

The largest effort for the development and certification of the bi-level train KISS has been performed in the calculation and evaluation of the load cases according to the European standard EN 12663-1. For this purpose the Abaqus/Standard solver has been used within linear analyses. The car-body structures have been investigated within a total number of 45 global load cases, including passenger loads, coupler loads (see figure 3), loads on the upper frame, accelerations of the equipment and aerodynamic loads. The strength as well as the global stiffness of the car-body has been evaluated. The Eigen frequencies have also been investigated (see figure 4).

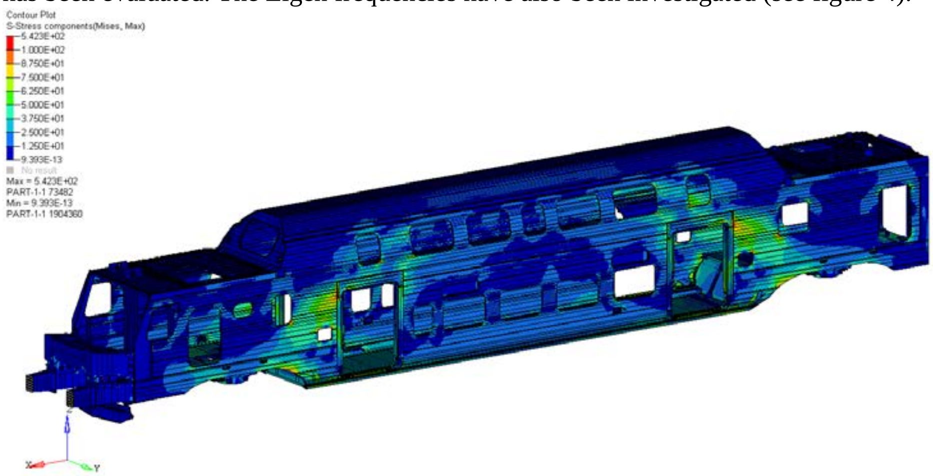

Figure 3: Von Mises stress results for the load case: coupler compression 1'500 kN

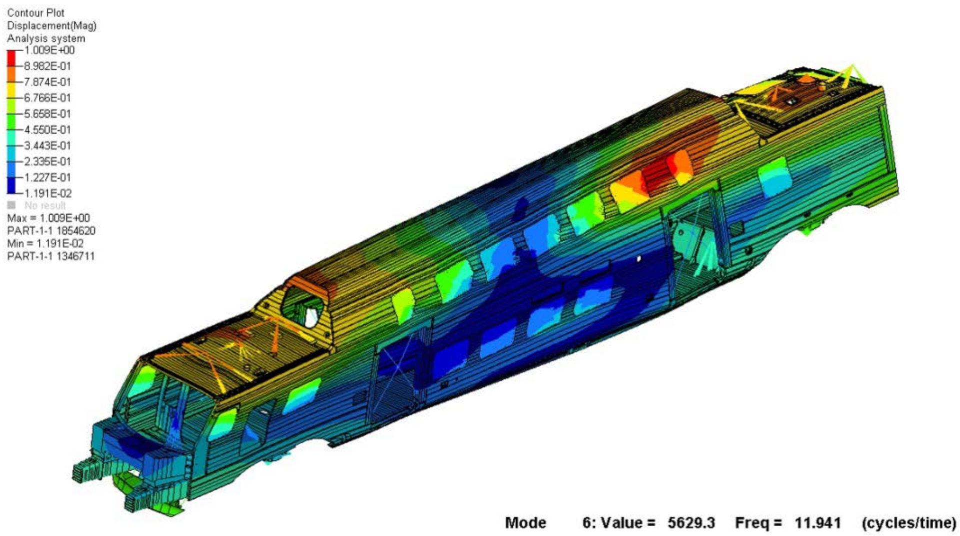

Figure 4: Eigen frequencies analysis: Torsional mode at 12 Hz

2.2 Fatigue Analysis

The fatigue strength of the railway vehicle structure has to sustain typical load collectives representing the operational life for 40 years of operation. Since the welds show a reduced fatigue strength in comparison with the base materials (especially for aluminum structures), the welds represent the weakest link for fatigue life. Standards like the IIW recommendations and the German guideline DVS 1608 for aluminum structures provide reliable fatigue strength parameters for design.

In the finite element model the weld lines are not modeled directly. The welds are represented by element or node sets (see figure 5 for a typical example). Stadler Rail applies the notch stress concept for the evaluation of the welds using FEMFAT, a post-processor code from Magna Powertrain.

The local stresses determined in the integration points are extrapolated to the location of the effective notch of the according weld type. The transition factors to determine the effective notch stress have been determined in separate analyses of the weld detail. These notch factors represent shape factors for the ratio between the local notch stress and the structural stress under the assumption of linear elastic material behavior. The load type and load direction have to be taken into account. In these detail models for the determination of the notch factors the weld toe and the weld root notch are rounded off with a notch radius of $r = 1$ mm following the theory of Radaj. Based on the stress tensor results in the integration point closest to the weld the stresses retrieved from the Abaqus/Standard result files are extrapolated to the most critical notch of the weld for all load cases to be considered for fatigue life. Thus, a total stress spectrum is based on the operation profile of the vehicle in order to determine the overall load collective. Cycle counting is carried out by the rain-flow counting method. Then a single-parameter, damage equivalent stress spectrum is established by amplitude transformation to $R = -1$ (relation between upper and lower stress)

with the corresponding mean stress sensitivity. Then, a cumulative damage calculation is performed with a modification of Miner's rule: Stadler Rail applies the method Miner elementary with cut-off-limit at 50% of the fatigue value at 5 million load cycles of the S-N curve (acc. to Zenner/Liu).
The calculation of the notch stresses, of the load collective, the rain-flow counting and the evaluation are all performed inside the FEMFAT code. The degrees of utilization are delivered for all welds and for all assessment directions (normal stress perpendicular to the weld line, normal stress longitudinal to the weld line, and shear stress).

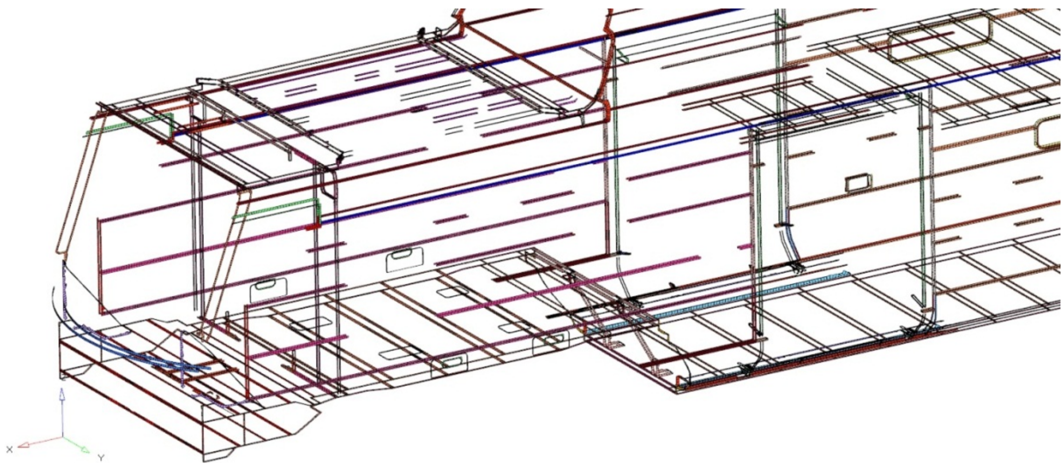

Figure 5: FE-model prepared for fatigue analysis – overview of weld seams

2.3 Crash Analysis

The European standard EN 15227 defines the requirements, which have to be fulfilled in order to guarantee the passive safety of the passengers and of the crew. In this standard four collision scenarios are defined, which have to be investigated in dynamic simulations (see Figures 6 and 7). For this purpose the solver Abaqus/Explicit has been used. The simulation of the 0.2 until 1.0 s long collision scenarios requires a large amount of hardware resources and calculation time. The calculation of the scenario 2, which foresees a collision between the train-unit and a conventional 80 t wagon needs the employment of 10 CPUs during approx. 30 hours. In the crash-analyses of the bi-level train all the non-linear features of the FE-model have been utilized. Since the investigation has to be applied on the complete train set, a simplified modelling of the following wagons was necessary. Therefore, the Abaqus/Explicit MBS-features have been exploited. Parts of the train set (wagons and bogies) have been modelled using connector- and mass-elements.

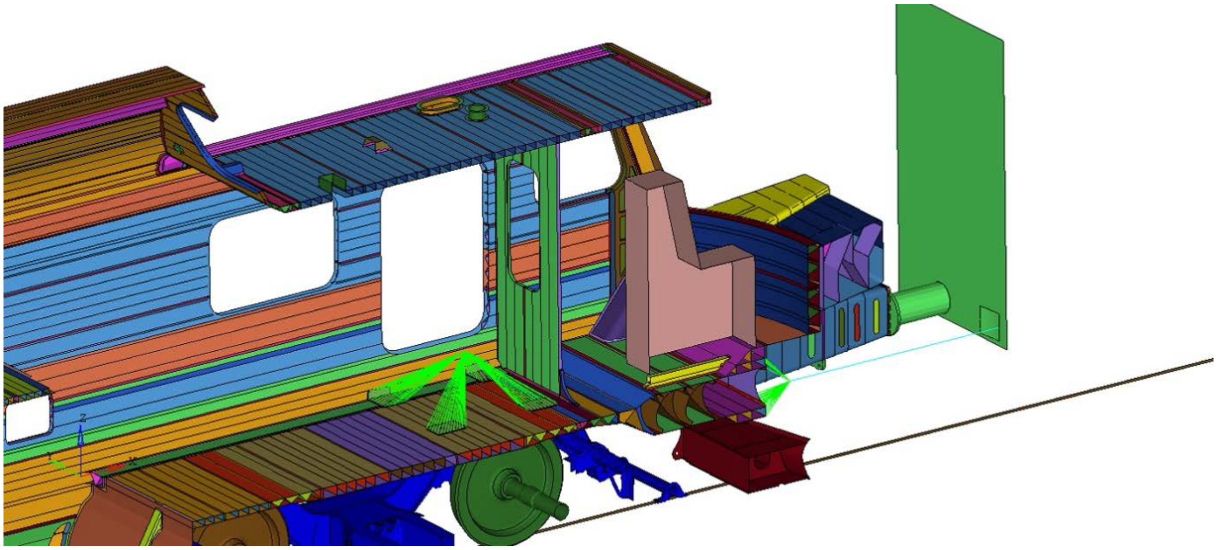

Figure 6: FE-model of the bi-level train KISS car body for collision simulations

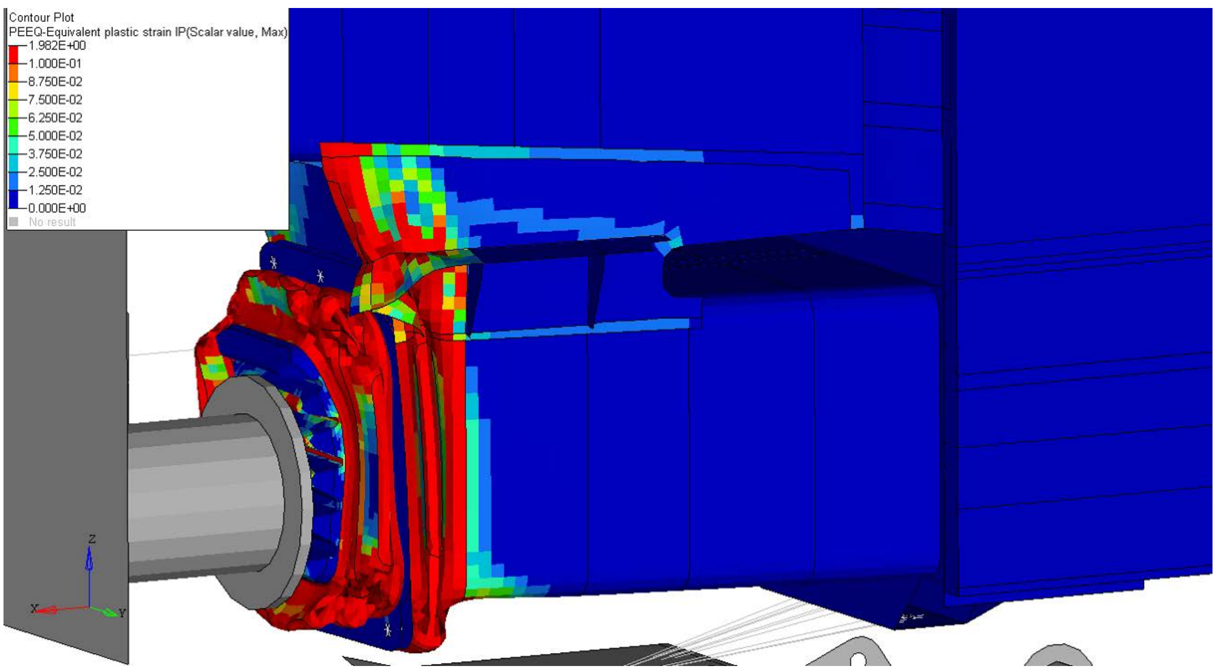

Figure 7: KISS car body model for collision simulations – Results for plastic strain in collision scenario 2

2.4 Interior and Equipment Structures

In addition to the car-body analyses several investigations concerning interior components and equipment structures have been performed. The requirements have been set according to several standards, in particular EN 12663-1, UIC 566 and DIN 5566-1. According to the global influence of the different load cases the whole or only a part of the car-body FE-model has been considered in the analyses.

An example for an investigation with global influence is the analysis of the whole stair area including the corresponding hand-rails (see Figures 8 and 9). This linear analysis has been performed with Abaqus/Standard within the car-body FE-model. Passenger mass as well as specific forces at the hand-rails have been applied on the structures.

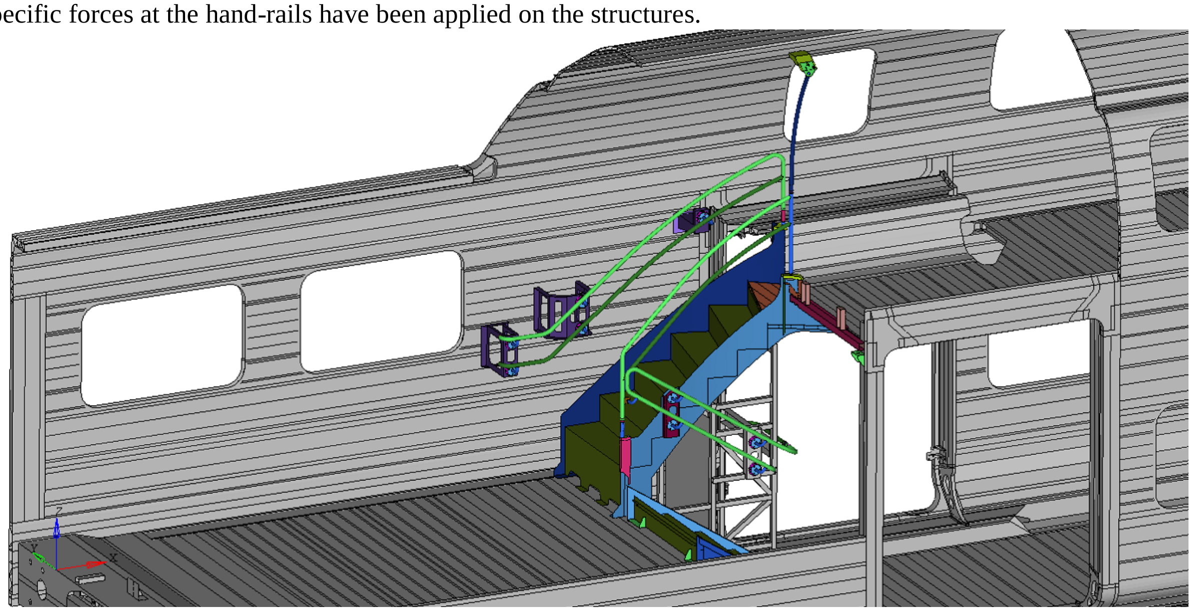

Figure 8: FE-model of the bi-level train KISS car body including interior components

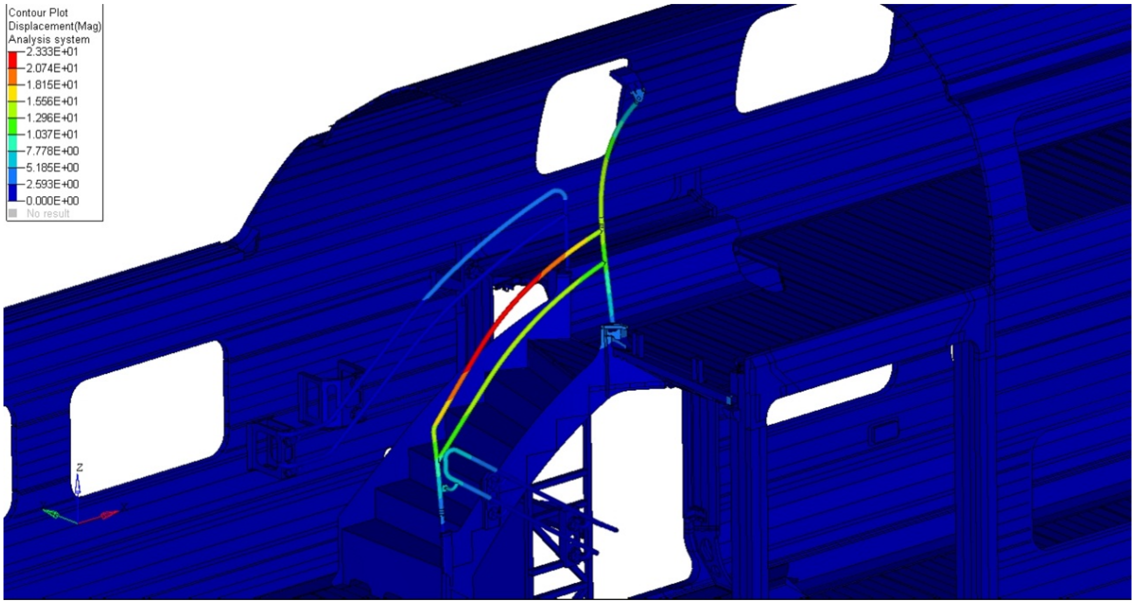

Figure 9: Bi-level train KISS interior analysis – Deformation results

A range of detailed analyses with consideration of non-linear phenomena have been performed. For the investigation of the cantilever-seat fixation (see Figures 10 and 11) according to the UIC 566 requirements, contact and pretension of bolted joints have been implemented in a partial FE-model. The different welded, milled or forged pieces of the assembly have been modelled using Solids, Shells, Beams and Trusses. The results of the analysis provided the basis to set bolts quality and assembly parameters.

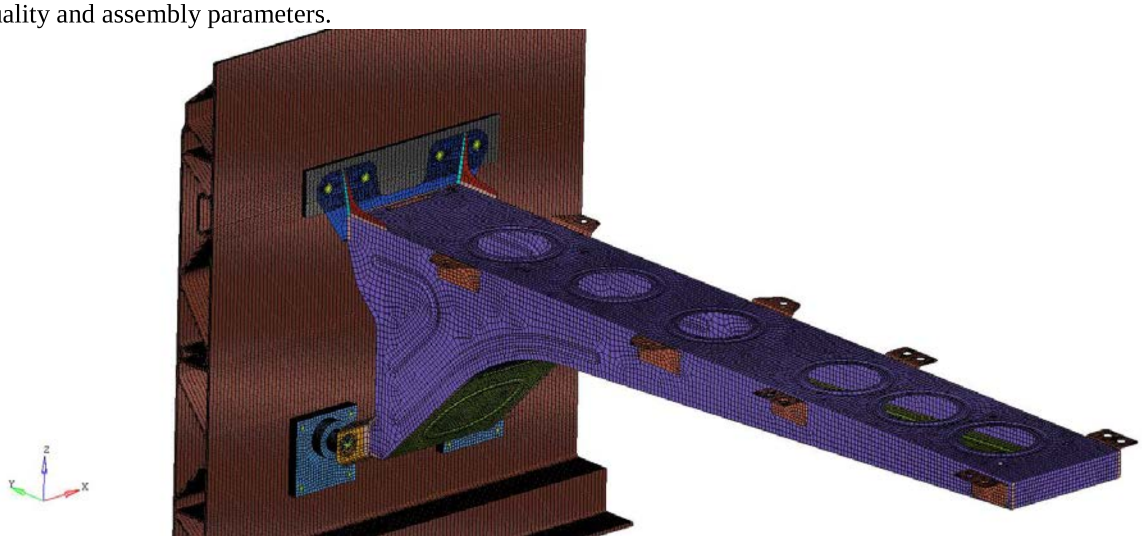

Figure 10: FE-model for the cantilever seat structure

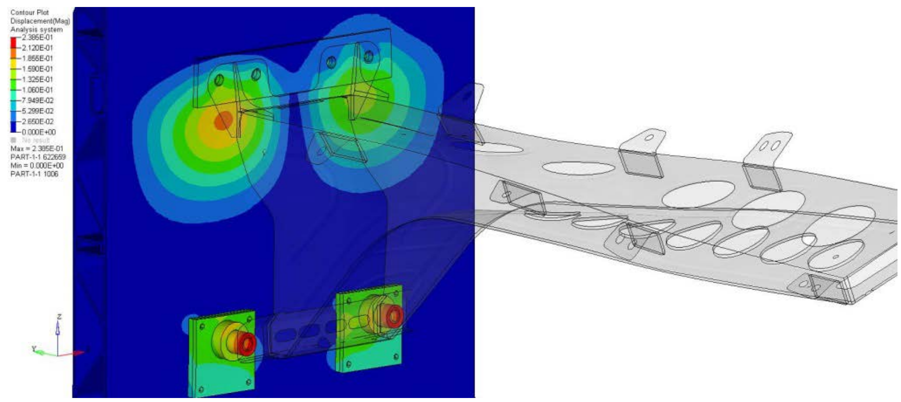

Figure 11: Displacements for the cantilever seat structure

Additional simulations have been performed using available Abaqus/Standard features. For example, vibrations of dynamic active equipment have been investigated. The transmission of vibration between the compressor unit and the car-body has been studied within a steady state dynamic analysis. The rotating mass of the compressor engine has been simulated by applying a dynamic force within a specific frequency spectrum. Finally, the damping performances of the compressor unit fixations on the roof of the car-body have been derived.

3. Validation

According to the standards EN 12663-1 and EN 15227 the FE-results of the static and dynamic analyses have to be validated within quasi-static and dynamic tests. The FE-Model has been adapted to the testing conditions; a prediction of the test results has been performed. Finally, the obtained values have been compared.
The static tests have been performed on the complete car-body structure (see Figure 12). The vertical and longitudinal loads have been applied for a range of relevant load cases using hydraulic actuators. The stress levels have been measured at more than 140 positions with strain gauges (see Figure 13).
The main deformations have also been measured. Finally, these values have been statistically processed in order to perform a comparison with the FE-calculations (see Figures 14 and 15).The deviation between the measured deflection curve of the longitudinal sole bar in the floor and the calculated deflection is nearly zero (see Figure 14). In Figure 15 the deviation of the calculated stress from the measured stress is shown for different deviation levels: 41 strain gauges stay below a deviation of 5 MPa, 43 strain gauges stay below a deviation of 10 MPa, 8 strain gauges stay below a deviation of 20 MPa, only three strain gauges show a deviation larger than 30 MPa. The reason for the deviation of 30 MPa in three strain gauges is due to local differences in details of the weld between the finite element model and the real test structure. For that reason, that deviation is accepted.

Figure 12: Setup for static testing

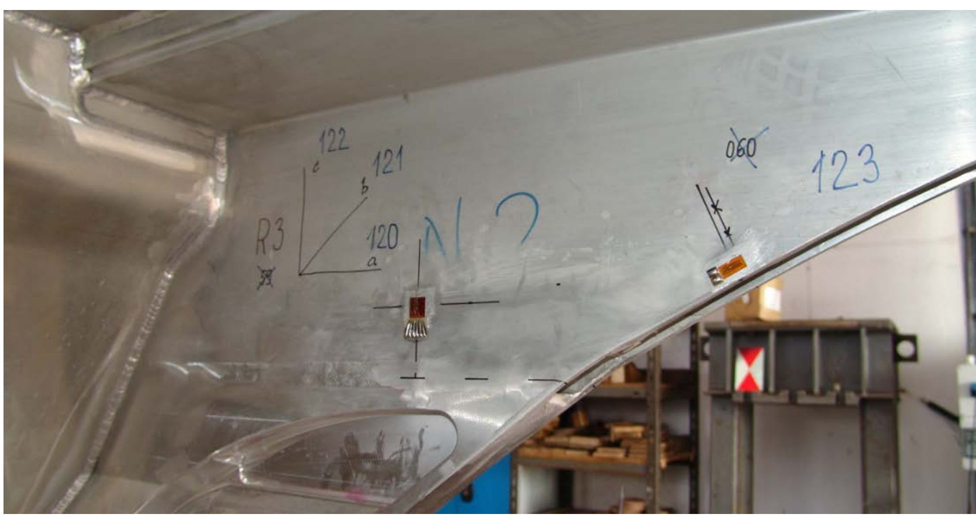

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Figure 13: Setup for static testing – strain gauge positioning in the under floor structure

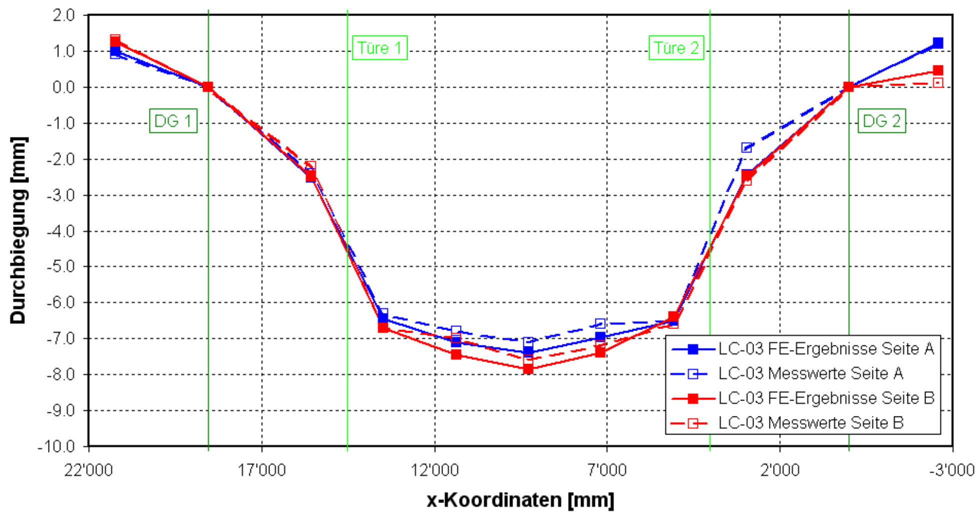

Figure 14: Validation of static test – comparison of deformation of the sole-bar

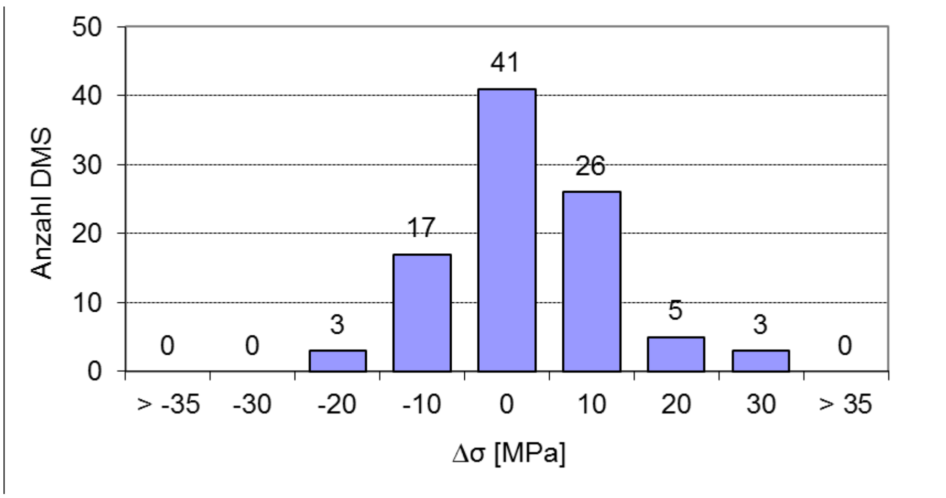

Figure 15: Validation of static test – Deviation of stress values between analysis and test

The principal components of the CEM-Structures of the bi-level train KISS have been dynamically tested in order to validate the performed simulations. The energy absorption capabilities as well as the force-crush characteristics have been measured within several component tests. The specially created detail models of the car-body components have been completed with the separately tested material properties of the metal sheets and solved within the test conditions. Finally, the measured curves have been compared with the results of these FE-simulations (see Figures 16 and 17). The analysis results are very close to the results of the dynamic tests. Thus, the finite element models as well as the finite element code have been successfully validated.

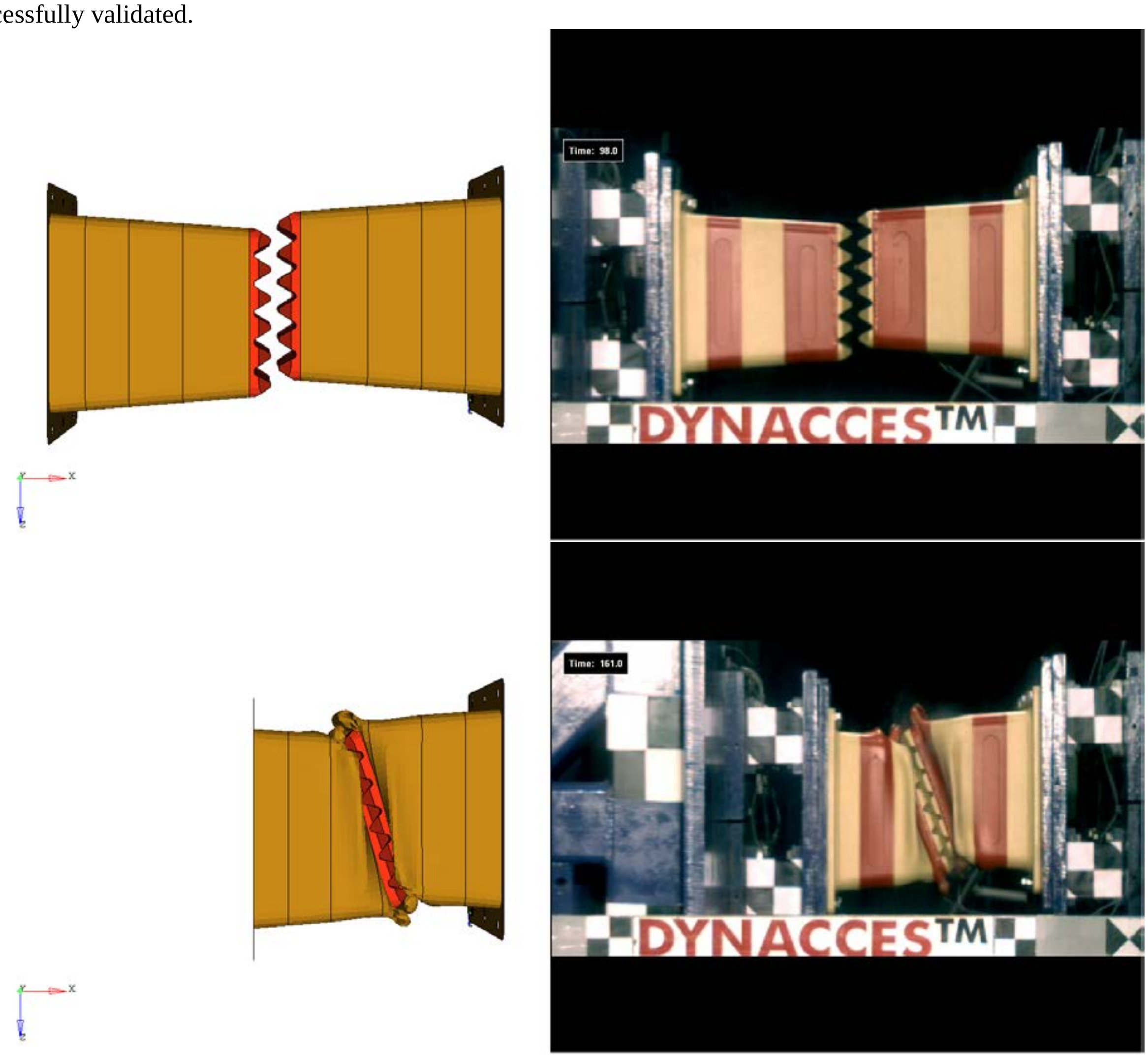

Figure 16: Validation of dynamic test of the crash module – comparison of the deformation process

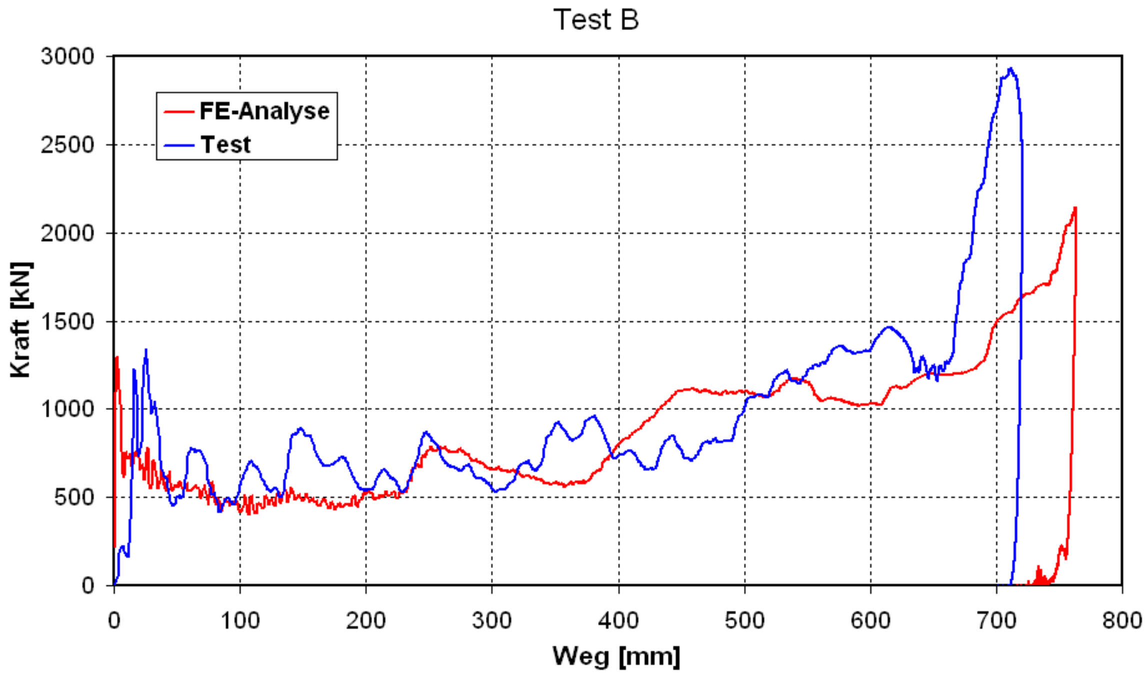

Figure 17: Validation of dynamic test of the crash module – comparison of the force-crush characteristics between test and analysis

4. Conclusions

In the development of the new bi-level train KISS Abaqus/Standard and Abaqus/Explicit have been intensively applied to optimize the structure with respect to stiffness and strength as well as to crashworthiness. Models up to 3 million shell elements have been used to prove the strength of the load carrying structure with respect to the standard EN12663-1. In simultaneous analyses with Abaqus/Explicit the crash energy management structures have been optimized. All requirements of EN15227, the European crashworthiness standard, were successfully fulfilled. Comparisons with dynamic test results have shown that the numerical results are very close to the test data. Abaqus/Standard and Abaqus/Explicit have helped to minimize the overall development time of the structure of the new Stadler bi-level train KISS. The stringent time schedule of the project has been met for all structural design releases.

5. References

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