On the Application of ABAQUS in The Validation Process of Crashworthiness of Railway Vehicles

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Abstract: New standards like prEN15227 and the TSI Highspeed prescribe the validation process for the crashworthiness of railway vehicles. Stadler Rail has introduced ABAQUS as explicit solver to simulate the design collision scenarios required: train against identical train at a closing speed of 36 km/h, train against 80-ton-freight wagon at a closing speed of 36 km/h, and train against a large deformable obstacle (representing a truck) at a closing speed of 110 km/h. The large deformable obstacle is defined in the standard by prescribing a load-deflection curve for the collision of a rigid sphere of a three-meter diameter against the obstacle. Suitable material laws in ABAQUS have enabled to achieve the required stiffness behavior for the deformable obstacle. Benchmarks with other explicit codes have shown that the ABAQUS simulation delivers a smooth and reliable behavior for simulating the large deformable obstacle.
Numerical analyses show that new crashworthy train designs guarantee sufficient and controlled energy absorption and maintain the survival space required. Dynamic testing has validated the results of the ABAQUS analyses.

Keywords: Crashworthiness, Design Optimization, Dynamics, Elasticity, Experimental Verification, Failure, Hyperfoam, Impact, Mechanisms, Multi-Body Dynamics, Output Database, Plasticity, Postprocessing, Railcar, Shell Structures, Welding.

1. Introduction

When crashworthiness has to be achieved for a railway vehicle, the dominant design goals are to reduce the risk of overriding, to absorb the energy in a controlled manner and to maintain the survival space and the structural integrity of the occupied areas.
The following collision scenarios are to be considered (see prEN15227, 2006, and TSI Highspeed, 2006):

1) A front end impact between two identical train units: closing speed 36 km/h

2) A front end impact with a different type of railway vehicle (80-ton freight wagon, closing speed 36 km/h)

3) Train unit front end impact with a large road vehicle on a level crossing: artificial large obstacle of 15 ton mass with prescribed stiffness behavior, closing speed 110 km/h

4) Train unit impact into low obstacle (e.g. car on a level crossing, animal, rubbish, etc.).

The following measures shall be employed to provide protection of occupants in the event of a collision:

- Reduce the risk of overriding;
- Absorb collision energy in a controlled manner;
- Maintain survival space and structural integrity of the occupied areas;
- Limit the deceleration;
- Reduce the risk of derailment and limit the consequences of hitting a track obstruction.

1.1 Survival space - Requirements

The structure forming the survival spaces shall remain intact and resist the maximum forces exerted upon it during the full collapse sequence of the energy absorbing elements. Local plastic deformation and local buckling are acceptable if it is demonstrated that they are sufficiently limited, so as not to reduce the survival spaces beyond the limits specified below.
When subject to the defined scenarios, the reduction in length of passenger survival spaces shall be limited to not more than 50 mm over any 5 m length or the plastic strain shall be limited to 10% in these areas.

1.2 Deceleration limit

The mean longitudinal deceleration in the survival spaces should be limited as far as is practicable to 5 g, and shall not be more than 7,5 g.
The method of determining the mean deceleration for each considered vehicle in the train unit shall correspond to the time from when the net contact force on the vehicle exceeds zero to the time when it next falls again to zero.

1.3 Overriding criteria

In the latest European regulations for the crashworthiness of railway vehicles new criteria for overriding constraints have been introduced – see prEN15227, 2006, and TSI Highspeed, 2006: In the design collision scenario 1, defining a front end impact between two identical train units at a closing speed of 36 km/h, a vertical offset of 40 mm has to be considered in addition to the

standard scenario of fully aligned vehicles. In the standard an initial vertical offset of 40 mm is regarded to be sufficient for the demonstration of the offset influence under typical railway conditions.
The new acceptance criterion for the overriding limitation for scenario 1 is that the validation process (simulation) demonstrates that, with an initial vertical offset of 40 mm at the point of impact (with the standing train unit at a lower level than the moving train unit) the criteria for deceleration and survival space are achieved. Nevertheless, the acceptance criteria for overriding are different in the standard prEN15227, 2006, and in the TSI Highspeed revised, 2006.

2. Crashworthiness Design of Railway Vehicles According to prEN15227

Previous designs developed for anti-climb units have used aluminum profiles that show a high capacity to absorb energy (see Gmür & Starlinger, 2002): Specific energy absorption capacities of up to 25 kJ/kg have been achieved for optimized cross sections by elastic-plastic folding mechanisms of aluminum extrusions in the alloy AA6008. Although the yield stress of these extrusions has been reduced by a special heat treatment to enable outstanding ductile behavior, the strength requirements were readily fulfilled. At the development time of those anti-climb units based on aluminum extrusions only a quasi-static out-of-plane force was prescribed.
The new offset criteria induce an eccentric force on the anti-climb unit that results in moment acting on the fixation of the anti-climb unit. Numerical analyses have shown that the folding mechanisms do not work anymore for eccentric loading – The structure fails in a shear mode with hardly any energy absorption. For that reason new design concepts have to be developed that allow for a stable folding mechanism even under the influence of eccentric loading.

2.1 Design Concept

In order to fulfill the overriding criteria imposed in prEN15227 a new design concept for an anti-climb unit has been developed for a Diesel-Multiple-Unit (DMU) railway vehicle, the Stadler GTW ARRIVA train. This DMU is equipped with two anti-climb units that incorporate an interlocking feature (see figure 1). This feature ensures that the contact faces cannot slide over each other vertically. Thus, the anti-climb units are fully engaged over the whole collision process.

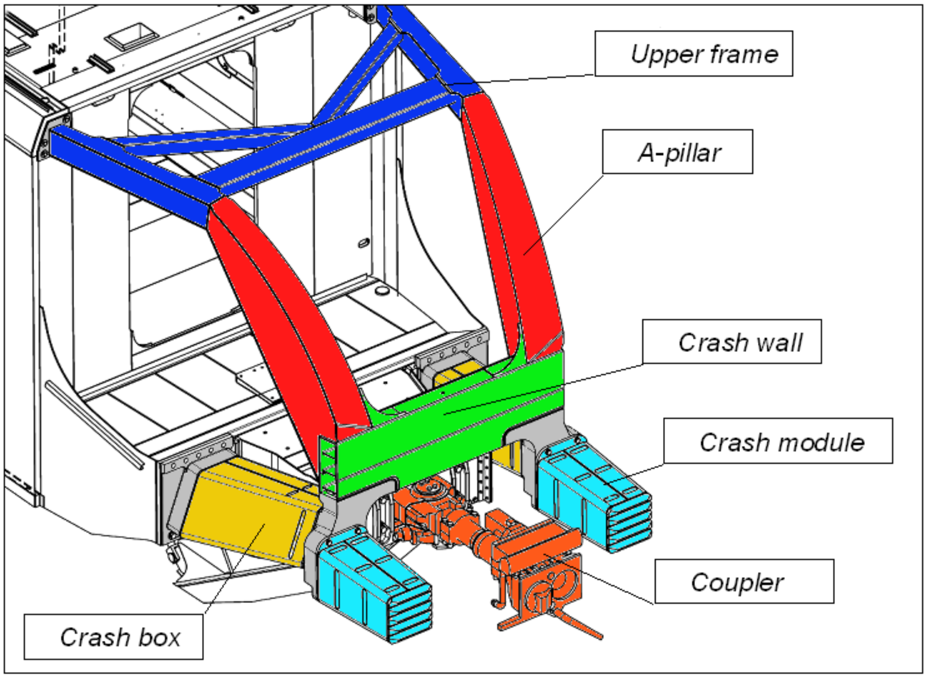

Figure 1. Front Structure – DMU Stadler GTW ARRIVA.

Both lateral anti-climb units (crash modules) are designed to absorb energy at a comparatively low force level and to deform before the yield level of the subsequent structural components is reached. Therefore, the crash modules are not foreseen to act as traditional buffers. They have not been designed to withstand the static loads according to the standard EN12663, 2000, without yielding.

The crash module design is based on sheets of aluminum alloy EN AW-5754. The major properties of this material are the low yield strength and the good plastic forming characteristics, which enable large deformations without fracture. The material parameters have been controlled to tighter limits than usual in railway structures.

The crash module is a tapered tube with a square cross section (see figure 2). The tube is divided into chambers by partition sheets. The division of the crash module into several chambers provides a better stability against eccentric forces acting on the structure.

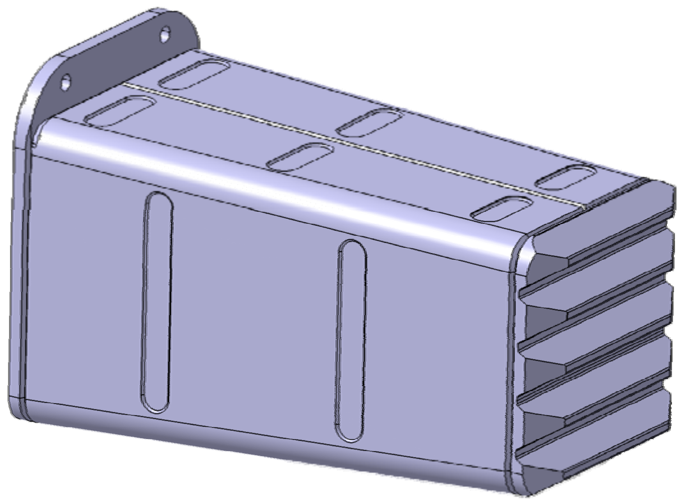

Figure 2. Anti-Climb Unit Design.

In order to induce a favorable deformation pattern and to reduce the initial force peak several trigger slots have been foreseen.
An anti-climb feature in the front plate completes the crash module structure. This anti-climb interlocking feature is composed by five horizontally aligned teeth, which have a depth of 40 mm. They are separated 70 mm from each other. Finally, the module is welded on an end plate that is bolted to the subsequent structure, the crash wall. Thus, in case of light collisions the crash modules can be substituted easily.

3. Validation of crashworthiness

The use of numerical simulation alone is sufficient for accurate prediction of structural behavior in areas of limited deformation. However, for areas of large deformation only, the validation program shall include the validation of the numerical models by appropriate tests (combined method).
The main steps for this combined method for a new design of structure are given below.

- Step 1: Test of energy absorbing devices and crumple zones (with full-size test specimen)

- Step 2: Calibration of the numerical model of the structure: by comparing the test results and the corresponding numerical simulation.

- Step 3: Numerical simulation of the design collision scenarios: based on a 3-D model of each type of vehicle structure that will be subjected to permanent deformation.

3.1 Numerical model validation

Models used in the simulations to demonstrate compliance with the scenarios shall be based on the same modeling techniques as those used for comparison with the tests. The modeling is considered to be of acceptable if, when compared to the tests, the following criteria are achieved:

- the same sequence of events occurs during the collision (i.e. where several phases of energy absorption occur they correspond);

- the same observed deformation patterns occur;

- the level of energy dissipated by the model is within 10% of the test value;

- the overall displacement (stroke) of the simulation is within 10% of the test value.

3.2 Large deformable obstacle

For the collisions between a train unit and a large heavy obstacle at a level crossing, the equivalent deformable obstacle shall take the form of a complete numerical model.
The obstacle to be used is unrestrained and is shown in figure 3. It is defined in terms of the following characteristics: mass = 15 000 kg; center of mass at 1 750 mm above rail level; Parts A and B may be modeled with or without cover sheets; continuous axial uniformity of density and stiffness; zero friction to the ground.

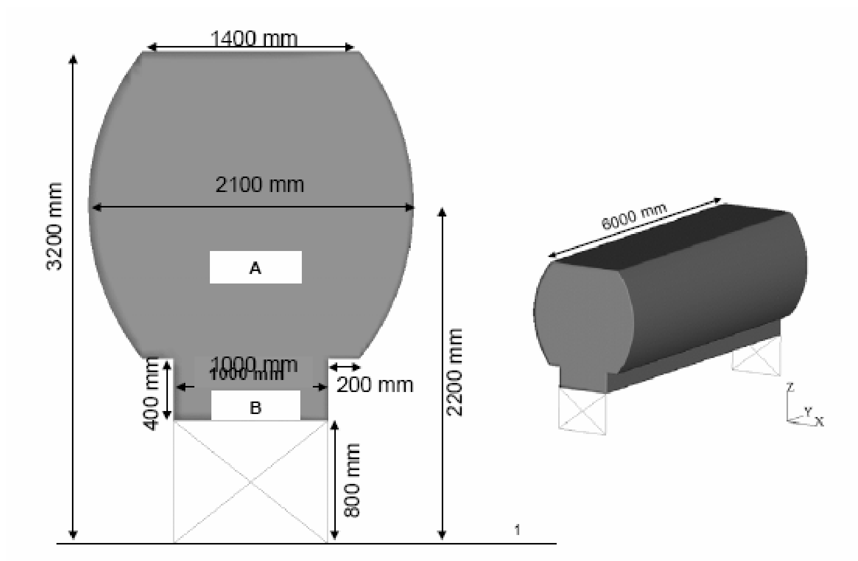

Figure 3. Definition of large deformable obstacle.

The stiffness of this obstacle shall match at least to the characteristics of the longitudinal force - displacement curve given in figure 4 when impacted at its centre by the solid, uniform sphere of 3 meter diameter (impactor mass – 50 000 kg, impact speed – 30 m/s).

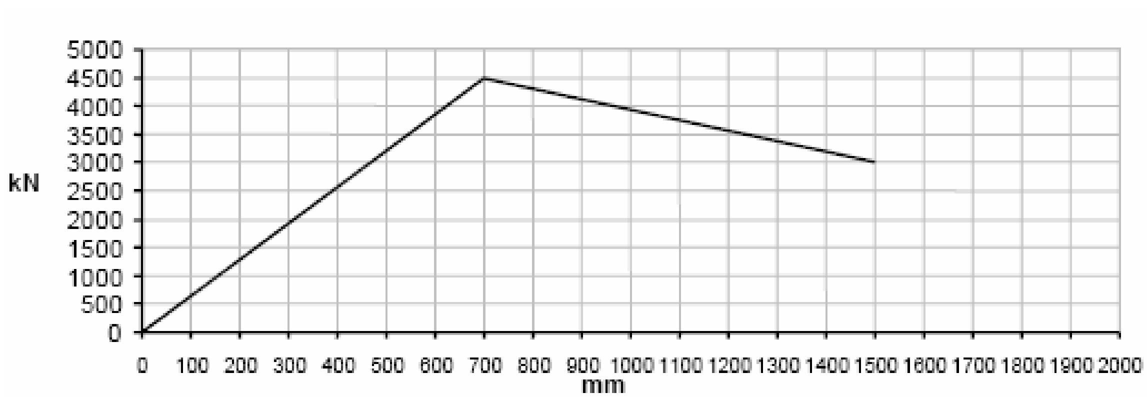

Figure 4. Deformable obstacle stiffness.

4. Numerical Analysis of Design Collision Scenarios

Numerical simulations have been performed using ABAQUS Explicit as solver. All components that do contribute to the energy absorption process are modeled. Nonlinearities are triggered by large deformations of shell structures, elastic-plastic material behavior, contact with friction and potential failure of the welds. Especially the global contact option in ABAQUS Explicit has helped to save pre-processing time tremendously.
Up to 450 000 shell elements have been used to model the dynamic behavior of the train. The collision time was between 0.2 and 0.4 seconds. Up to 350 000 time increments were necessary to find stable solutions. The trough-put-time reached up to 26 hours on a SGI ALTIX 350 with 4 Itanium processors with activated parallel processing.
In the course of the explicit analyses the global deformations and forces as well as the deceleration rates and the integrity of the survival space of the passengers have been determined.

The following basic parameters have been determined for the three relevant design collision scenarios:

Collision Scenario	Collision Mass	Obstacle	Kinetic Energy	Total Energy to be absorbed	Energy to be absorbed by a single train unit
	[kg]	[kg]	[kJ]	[kJ]	[kJ]
Scenario 1	100’000	100’000	4’460	2’230	1’115
Scenario 2	100’000	80’000	4’460	1’982	1’982
Scenario 3	100’000	15’000	27’874	3’636	-

4.1 Design Collision Scenario 1: Train against identical Train

In design collision scenario 1 a train collides with an identical at a closing speed of 36 km/h. In order to evaluate the overriding criterion a detailed finite element model has been investigated for design collision scenario 1. The running bogies at the vehicle front side as well as the characteristics of the suspensions have to be taken into account in order to capture the lift-off of the bogie axles. Contact conditions have been defined between wheels and rails as well as between bogie and car body. The other passenger coaches and the motor unit composing the vehicle as well as their suspensions have been introduced into the model using 1D elements and mass elements (see figure 5). Furthermore, gravity has been introduced for all the masses into the model.

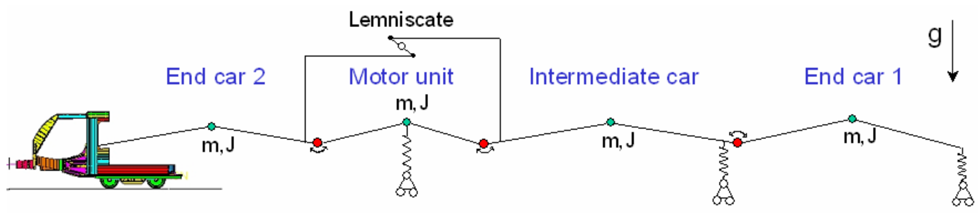

Figure 5: Global FE model for overriding analysis.

The wheel sets as well as the bogie frame have been separately defined as rigid body, while the primary and the secondary suspensions have been modeled with non-linear spring and damper elements. The maximum elongation of the secondary suspension has been limited by the lift off cables, which have also been introduced into the model using non-linear spring elements.
In order to capture the behavior of the whole train rake, all units have been modeled. These units have been represented by mass elements, by rotary mass elements and by rigid body definitions. The non-suspended and the primary suspended masses of the bogies have been represented by mass elements, while the characteristics of the primary and of the secondary suspensions have simulated with springs and dampers accordingly.
The results show a stable crushing process (see figure 6). After the anti-climber units have been engaged, the crash modules deform plastically. The crash modules absorb the energy, until they reach their maximum absorption capacity. Subsequently, the subsequent crash boxes absorb the remaining energy.

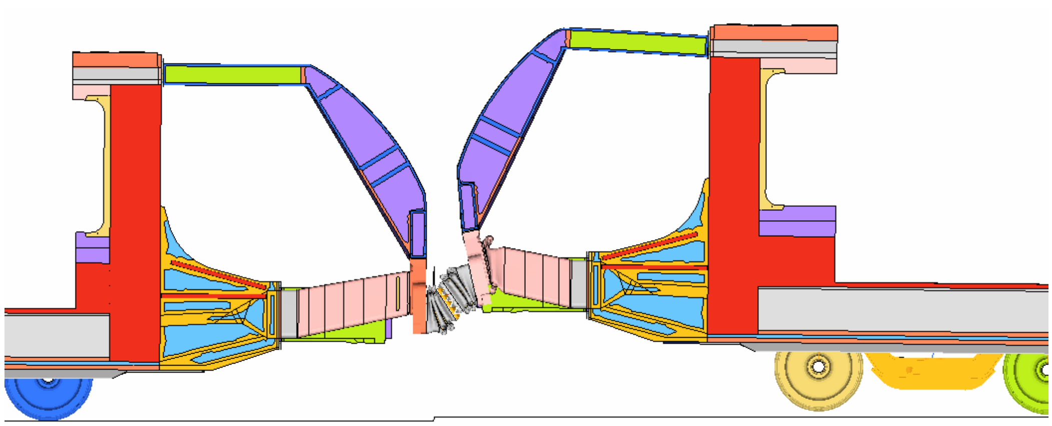

Figure 6: Final deformation state – scenario 1 (offset 40 mm).

The anti-climb units engage and provide a proper vertical lock. The energy absorbing devices do not show any instability. The survival space of the driver is guaranteed. The force-deflection curve is shown for scenario 1 (with 0 mm offset) in figure 7.

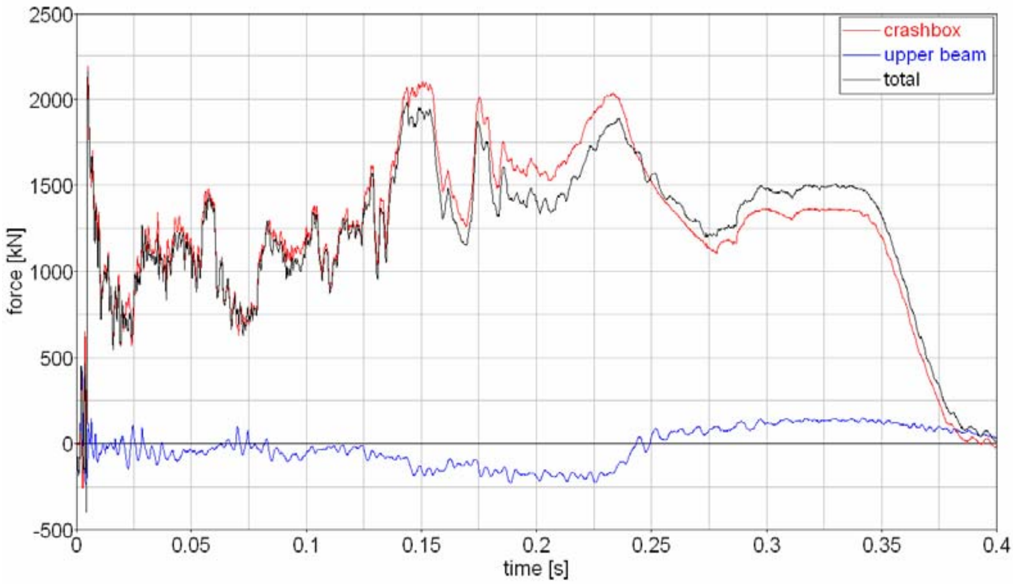

Figure 7: Force-deflection-behavior - scenario 1

The peak force reaches 2100 kN – This maximum load is beyond the limit defined in the standard EN12663 that prescribes the structural requirements of railway vehicles (i.e., 1500kN). Additional nonlinear elastic-plastic analyses have shown that a sufficient margin of safety towards global buckling of the survival zones is still achieved. Any plastic zones in the survival zones are rather small and locally limited. The requirements with respect to crashworthiness behavior as well as with respect to the structural integrity of the survival zones have been fulfilled.

4.2 Design Collision Scenario 3: Collision against a large deformable obstacle

In this design collision scenario the train impacts a large deformable obstacle at a speed of 110 km/h. In figure 8 the final deformation of the train front is shown.

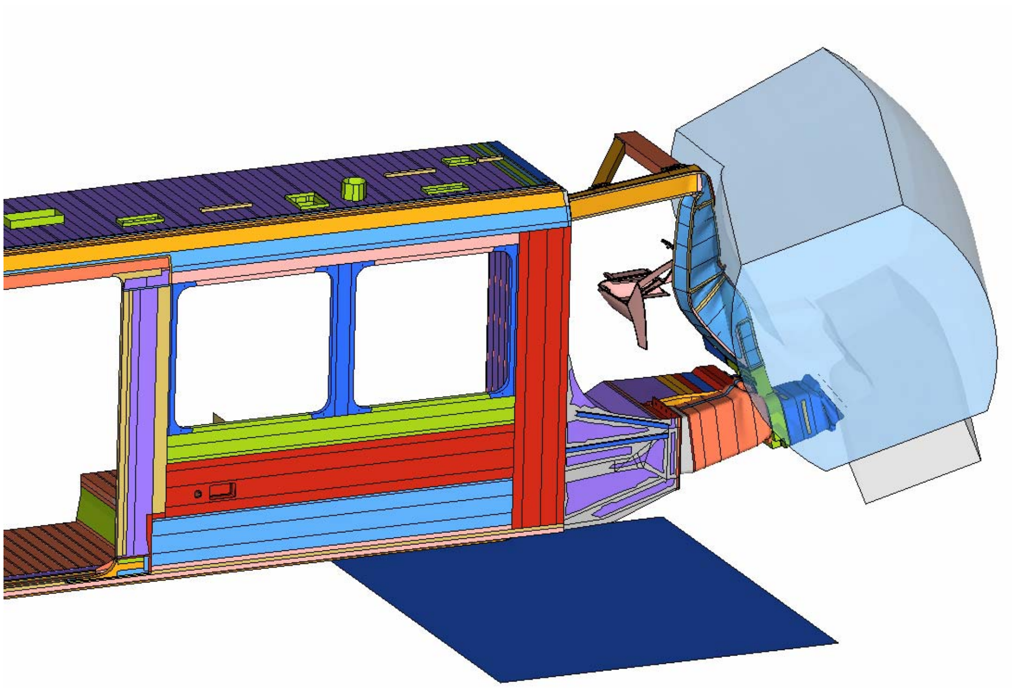

Figure 8: Final deformation – design collision scenario 3

Since the center of gravity of the large obstacle is positioned above the regular height of the coupler, the corner posts of the front are mainly activated. They undergo large deformations. The welds on the top joint of the pillar partially fail in a controlled manner. The crash modules are only partially engaged. The survival space of the driver is maintained. The corresponding load-deflection curve is shown in figure 9.

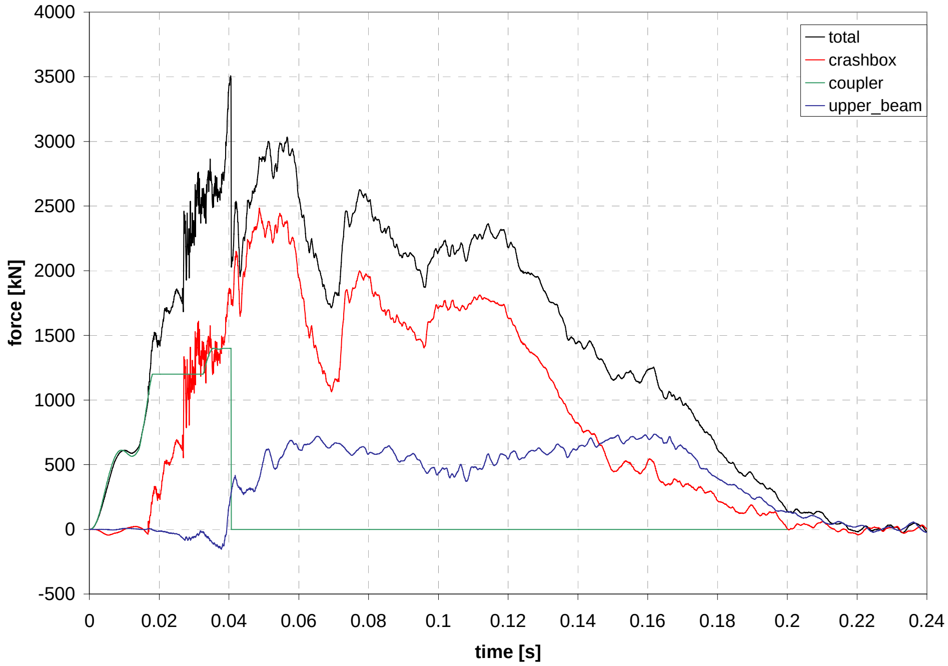

Figure 9: Force-deflection-behavior - scenario 3

The peak force even reaches 3500 kN – This maximum load is beyond the limit defined in the standard EN12663 that prescribes the structural requirements of railway vehicles (i.e., 1500kN). Additional nonlinear elastic-plastic analyses have shown that a sufficient margin of safety towards global buckling of the survival zones is still achieved. Any plastic zones in the survival zones are rather small and locally limited. The requirements with respect to crashworthiness behavior as well as with respect to the structural integrity of the survival zones have been fulfilled.

5. Dynamic Testing

In order to validate the results of these simulations, several dynamic tests have been performed on the energy absorbing anti-climb units.
The conditions from scenario 1, defined in the prEN15227 standard (front end impact between two identical train units), have been reproduced between two test wagons. Each test wagon has been equipped with a crash module on the front side. The collision test between the wagons has been performed with both modules in the nominal position and with a minimum vertical offset of 40 mm. In this last case, the crash modules have to absorb the energy required, while a stable crushing process has to be guaranteed, nevertheless.

The dynamic tests at DYNACCESS™ in Reichshoffen, France, have been performed with vertical offsets of 0mm and 53mm (see figure 10). The mass of the wagons and the impact speed have been chosen in order to be close to the conditions of design collision scenario 1. The impact speed of the test wagons was determined to be 28.3 km/h.

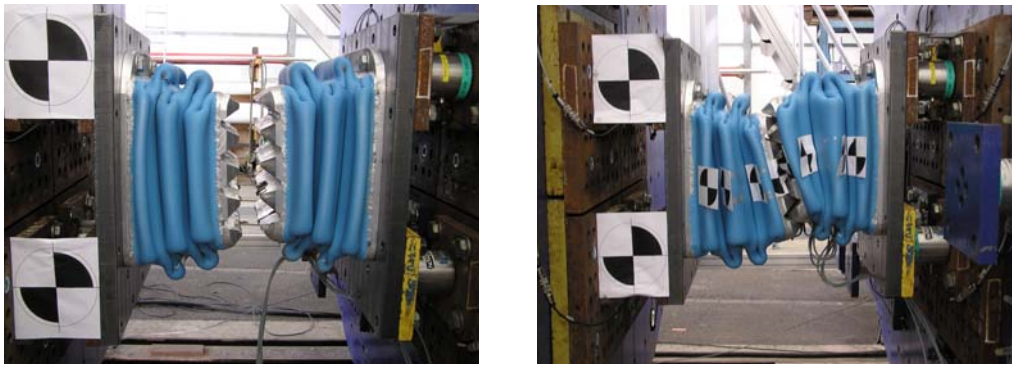

Figure 10: Anti-Climb Units for 0mm and for 53mm Offset after Testing

Originally, the vertical offset of 40mm should have been investigated, but due to non-linear effects in the spring system of the test wagons after the first test, an initial offset of 53 mm was achieved.

The crash modules have shown a good behavior during both dynamic tests. As foreseen, the anti-climbers engaged and did not allow any further transversal displacements. Subsequently, the chambers collapsed in a progressive sequence until the maximum deformation was reached. The progressive collapsing of the chambers allowed for a stable crushing process in the impact direction.
In the dynamic tests any significant failure of the welds has not been observed. In both tests the anti-climb units deformed in a controlled manner. The conditions of the standard prEN15227 with respect to overriding have been proven to be fulfilled. The tapered shape of the tube induced an increasing force level during progressive deformation. The triggers induced a favorable deformation pattern and reduced the initial force peaks.

In all tests satisfying energy absorption has been achieved. The behavior of the energy absorbing structures and of the anti-climber units matches the numerical simulation of the entire crash frame.

6. Comparison - Results of the Validation Model

The test conditions have been simulated in a detailed FE model. Subsequently, the results of these simulations have been compared with the test results.

The results of the validation model show a good correlation with the experimental results. The crushing process of the simulation is very similar to the observed process (see figure 11 for the 0mm offset configuration).

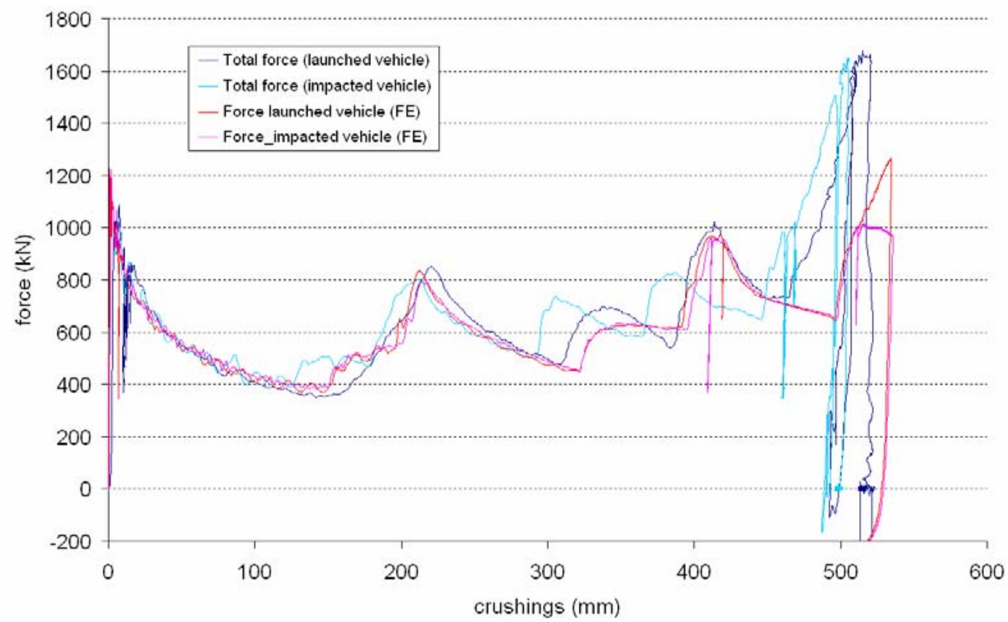

Figure 11: Force-Deflection Behavior of Anti-Climb Unit (0mm Offset)

Good agreement is especially achieved in the initial crushing phase. The initial force peaks and the forces match very well. After some simulation time, several differences have been observed in the collapse sequence of the chambers. This is due to imperfections in the tested modules caused by manufacturing (welding, bending, machining, etc.). Those divergences do not significantly influence the mean forces and the energy absorbed.

At the end of the crushing process, some larger divergences in the forces and in the crushing process end time have been observed. The divergences have partly been caused by the excess deformation energy. In the validation model the test wagons have been defined as infinite stiff, so any exceeding energy had to be absorbed by the crash modules only. Another difference between the validation model and the test conditions has been identified in the vehicle brakes. In the validation model the wagons have been considered non-braked, accordingly with the scenario 1 test conditions of prEN15227. However, the impacted vehicle has been braked during the dynamic tests.

7. Conclusions:

Value	Validation	Model Dynamic	Tests	Difference in [%]
End time	[ms]	290	273	+6
Initial force peak	[kN]	1060	1063	±0
Average force	[kN]	621	686	-9
Maximum crushing	[mm]	496	490	+1
Energy Absorbed	[kJ]	303	332	-9

Table 1. Result Comparison between FEA and Test for an Initial Offset of 53 mm.

Considering the results of the quasi-static- and dynamic tests and the comparison with the numerical simulations, the following conclusions are made:

- The material properties employed for the anti-climb units satisfy the specification;
- The numerical model as well as the modeling technique have been successfully validated by the comparison of the dynamic tests results with the validation model;
- The requirements of the standard prEN15227 have been fulfilled.
- ABAQUS Explicit has been proven as reliable tool to simulate dynamic crash processes of railway structures.

8. References

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