Modelling Study to Validate Finite Element Simulation of Railway Vehicle Behaviour in Collisions

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Modelling Study to Validate Finite Element Simulation of Railway Vehicle Behaviour in Collisions

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ABSTRACT

Half-width/full-length and half-width/half-length vehicle models, based on geometrical symmetries, have been adopted widely in the finite element modelling of rolling stock structural behaviour. These techniques have been successful in the analysis of rail vehicles undergoing static loading, such as the proof load test, and in basic impact studies. Until now, such rail vehicle impact tests and associated simulations have been largely confined to impact scenarios where a rail vehicle collides with a rigid wall or a rigid body. This is also a standard model specified in the crashworthiness section of the Technical Standards for Interoperability.

The authors identified a need to study the limitations of these impact scenarios and modelling techniques when applied to dynamic impacts. The authors of the paper present the results of studies focusing on the above areas. The work was carried out by means of finite element analysis and comparison. The train set studied is a conventionally designed high-speed electric multiple unit. Finite element models of full vehicle structures were used in all impact scenarios. It was found that impact modelling could mask some structural weaknesses when using a rigid wall as the impacted object. A symmetrical impact was shown to lead to an unsymmetrical result and, therefore, both half and quarter structure models may hide some aspects of crash behaviour. These findings have significance for both impact simulation and the physical testing of rail vehicles.

INTRODUCTION

Over a long period of development, rational and optimised structures and standard sections for conventional rail vehicles have evolved. However, these have been designed to satisfy the requirements of the static load case based traditional standards but have not considered structural deformation patterns.

Traditionally, rail vehicles have been designed to be as strong as possible, as long as weight criteria and other design conditions were satisfied. 'Proof load' standards require that the stressing of a rail vehicle's structure must be kept within the yield limit. Unfortunately, rail vehicles designed along these principles do not perform well in dynamic impact scenarios. In collisions, the substantial kinetic energy of an impacting rail vehicle can cause the vehicle structure to suffer large plastic deformation as the energy is dissipated in structural collapse. Hence, the study of crashworthiness must begin to address high strain rate deformation behaviour. Many widely used and well-accepted methodologies, principles and standards, as well as the structures created to satisfy proof-loading rules must thus be checked and validated.

The history of research into the crashworthiness of rail vehicles is relatively short. Most of the relevant studies have been carried out during the last two decades. New philosophies and standards for structural design and new requirements have been developed [1-3], to ensure that the designed vehicle deforms and collapses in a controlled manner, so that the impact energy can be dissipated safety outside the occupied part of the vehicles [4-6]. A new procedure and methodology of structural design for crashworthiness has also been proposed [7].

Both simulation work and practical tests have been carried out on the structural crush responses of rail vehicles. Many of the studies of the impact behaviour of rail vehicles though have been based on collisions with a rigid wall or body. This is also the standardised model adopted for the crashworthiness part of the Technical Standards for Interoperability or TSIs. Generally, finite element impact modelling of vehicles is based on (i) half-width / full-length (half) and (ii) half-width / half-length (quarter) structures, depending on the symmetry of the vehicle. Such models have been successfully used in the analysis of rail vehicle structures subjected to static loading, such as the proof load, but have not been validated for dynamic loading.

The authors thus identified a need to study the limitations of the above scenarios and models and to explore the weaknesses of the standard component shapes used in the design of rail vehicles when assessing the consequences of dynamic impacts. The authors' work presented in this paper covers two aspects of modelling: (i) An analysis of the limitations of using a rigid wall as the standard impact obstacle and of the symmetry approach in impact simulations and (ii) a study of the generic weaknesses of a conventionally designed rail vehicle.

The work was carried out through analysis of a conventionally designed rail vehicle with a driving cab. The research included both a mechanical analysis and finite element simulations. Based on an analysis of the structural characteristics of a generic rail vehicle and its components, the structural weaknesses of the vehicle were examined. The vehicle model was then tested in a simulated impact with a rigid wall and in a head-on impact between two identical vehicles. The differences in the way in which the vehicles responded in these two scenarios were compared and analysed, leading to suggestions for structural changes. Finally, the limitations of using a rigid wall as a standard impact object and of exploiting the symmetries of structures in modelling were analysed and are discussed. The explicit approach available in the finite element package LS-DYNA [8] was adopted for analysis. Full-vehicle finite element models of the rail vehicles were used in the simulation.

STRUCTURAL WEAKNESSES OF CASE STUDY RAIL VEHICLE

Introduction to the Cab Car

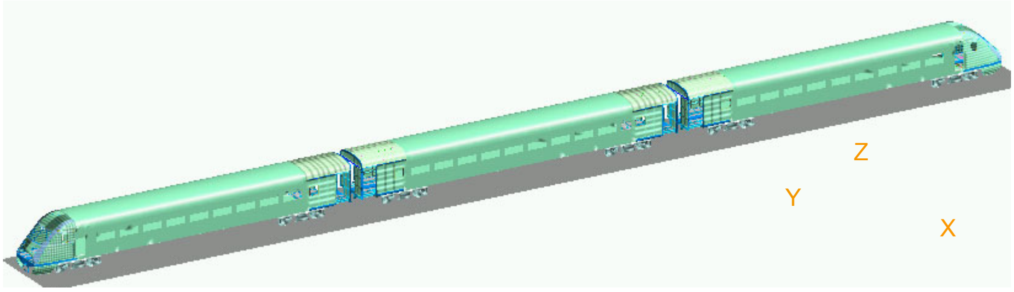


Figure 1 Finite Element Model of the Three Car EMU Set

The rail vehicle studied by the authors is the leading vehicle, i.e., the cab car, of an electric multiple unit (EMU). The maximum design and commercial operating speeds of this vehicle are 250 km/h and 200 km/h, respectively. The EMU successfully passed the 250km/h test in late 2001 and was put into regular operation in 2002. The cab car weighs 40 tonnes. Figure 1 shows the finiteelement model of complete three-car EMU composition, comprising two cab cars and one trailer.

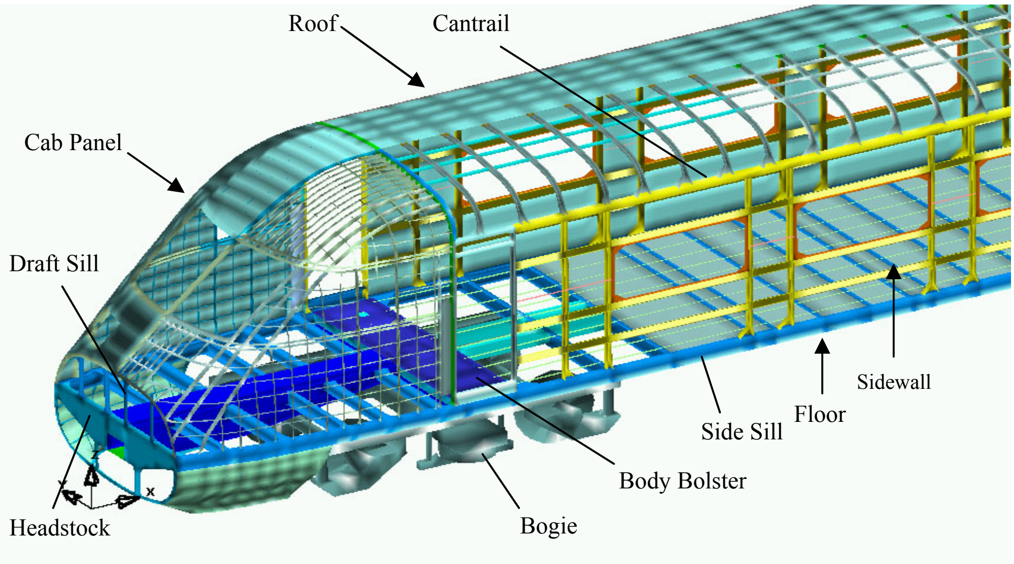


Figure 2 Structural View of Cab Car

Figure 2 shows the finite element model of the front of the cab car with shaded elements. Like most passenger rail vehicles, the vehicle studied has a tubular shape, consisting of thin-walled structures. From a manufacturing point of view, the structure is composed of the following substructures: floor panel, two sidewalls, roof, one end wall and one cab structure. Some parts of the body shell, floor and the nose cone have been made transparent in these illustrations for easier viewing of the structural elements. The authors concentrate on the analysis of the cab car in this paper. However, some trailer vehicle behaviour is also presented for comparison. The finite element model of the trailer can be found in another paper by the authors.

Analysis of Structural Weaknesses

The crashworthy design of rail vehicles requires that structures collapse in a progressive pattern. Tubular structures absorb substantial amounts of energy by ‘crumpling’ in a longitudinal direction, that is, the establishment of many hinges. However, simple bending is not an effective energy absorption method for vehicle structures and components. Structures fail before they can absorb enough energy and, subsequently, they may result in an irregular impact pattern. In this section, the deformation behaviour of the cab end structure and of the major longitudinal components are analysed, that is, the draft sill and side sills

Figure 3 shows the cab end structure. The front cab panel, the floor, apron and bogie are made transparent for ease of viewing. Examining the cab end structure, we can see that it is designed as a half-cone shape. In an axial impact, the normal directional component of the impact force on the cab panel F_n is acting downwards. The cab panel constrains the end of the floor panel from above and so it also has a tendency to bend downwards. Thus, both the cab panel and floor panel are weak in resisting downward bending.

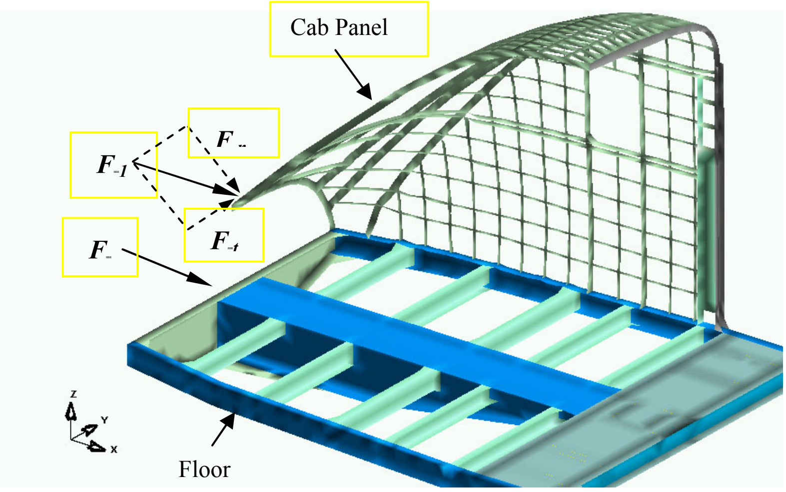


Figure 3 Impact Force on Cab End Structure

Figures 4 and 5 show the draft sills at the cab end and trailer end of the cab car. They consist of two vertical trough girders, covered with top and bottom plates. The back ends of the draft sills near the bolster must be shallow to avoid interference with the bogies below. The front part of the draft sill must be relatively deep to receive the coupler and draft gear. The draft sills are therefore formed as box shapes in cross section and as a fish-belly shape in the longitudinal direction. The height at the front of the draft sills depends on the type of the draft gear used. It then tapers towards the bolster. This rail vehicle is equipped with automatic couplers and the draft sills are therefore different from those of UIC standard European rail vehicles.

In this EMU, the couplers installed in the front draft sill and in the rear draft sill are different both in structure and position. As a result, the two draft sills have different structures and, thus, their deformation behaviours are different. The draft sills of the trailers though have the same structure as the draft sill at the back of the cab car.

The draft sill at the cab end is involved as a leading interface in any train collision. The resultant of a contact force generally acts on the geometric centre of the contact surface. Because the draft sill contains the low height coupler at the front and must allow space for the bogie and wheelset at its rear end, it has a fish-belly shape, as mentioned. This shape means that the forces acting on the two ends of the draft sill are at different heights. As a result, a pitch moment $M_{produced}$ develops (see Figure 6) and the draft sill has a tendency to bend downwards. The rear area is of reduced depth and should be stiffened to increase its ability to resist this bending moment.

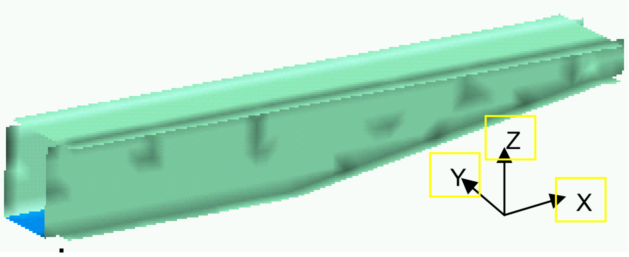


Figure 4 Draft Sill at Cab end of Cab Car

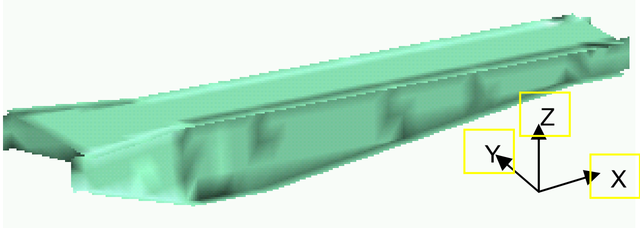


Figure 5 Draft Sill at Trailer End of Cab Car

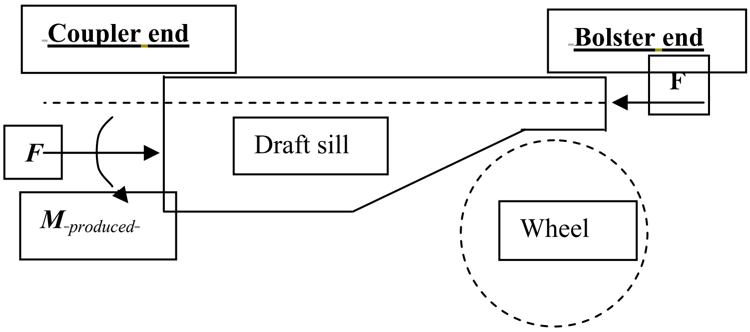


Figure 6 Impact Force on Draft Sill at Cab End

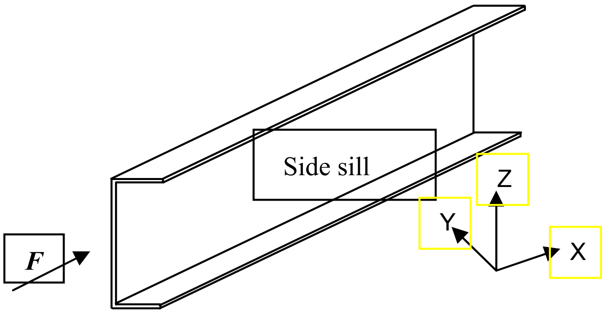


Figure 7 Side Sill Structure

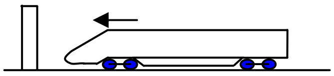
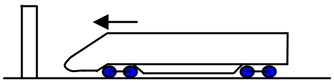
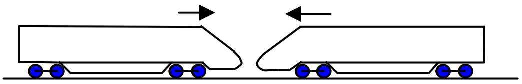
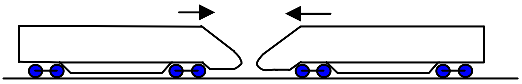
There are many long, thin components in the cab car. These are likely to bend or jack-knife in their weak direction, generally in the yaw direction, i.e., in the horizontal plane. As an example, Figure 7 shows the side sill of the cab car. It is a long, thin structure of channel cross-section. The channel forming the side sill reduces its stability and thus the lateral direction is its weak direction.

Bending or jack-knifing is thus an intrinsic structural weakness of the cab car and its components. The cab end structure and draft sill are prone to bend downwards. The side sill and other long, thin components are likely to bend in their weak direction, generally in the yaw direction of the cab car.

SIMULATIONS OF VEHICLE IMPACTS

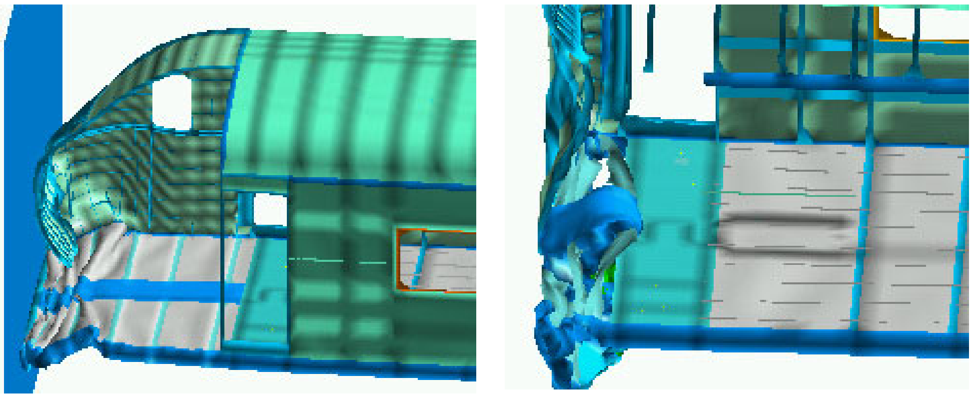
Two impact scenarios were tested. These are single vehicle impacts with a rigid wall and a head-on impact between two cab cars. For each scenario, the unmodified structure was tested first. Then, once the weaknesses had been identified, this structure was modified and tested again in the same scenario. By comparing the differences in the vehicle responses in these two scenarios, the limitations of the rigid wall model were analysed. Table 1 shows the scenarios covered by the authors.

Table 1 Impact Scenarios Covered by Authors

	Scenario	Diagram of Impact Case	Design
1	Original cab car impact with rigid wall at 80 km/h		Initial conventional structure
2	Modified cab car, version 2, impact with rigid wall at 80 km/h		Modified car based on Case 1 results
3	Head-on collision between two cab cars of version 2 at 75 km/h		Modified car based on Case 1 results
4	Head-on collision between two cab cars of version 3 at 75 km/h		Modified car based on Case 3 results

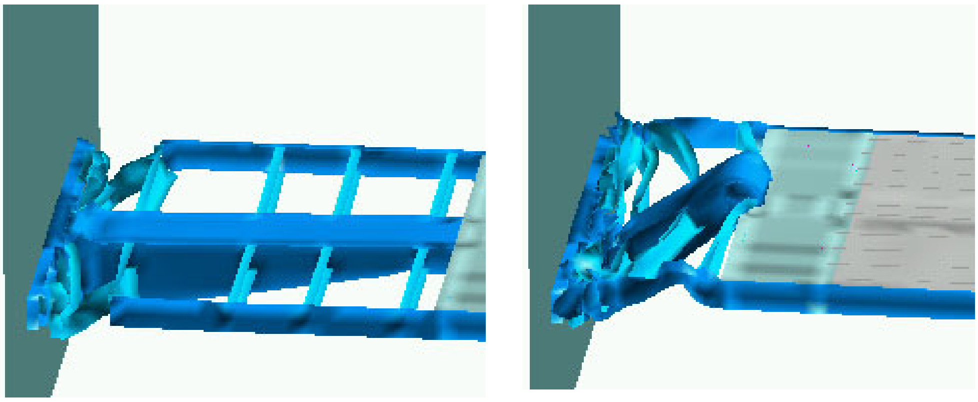
Single Vehicle Impact With a Rigid Wall

Figure 8 shows two pictures of the impact of the cab car with a rigid wall. It can be seen in picture (a) that the side sills bent in the horizontal direction at an early stage of the impact. As shown in picture (b), the draft sill bent in the vertical direction from its rear end during later impact stages, both components deforming inefficiently.



(a) Time = 50 ms (b) Time = 160 ms

Figure 8 Impact of Original Cab Car with Rigid Wall at 80 km/h



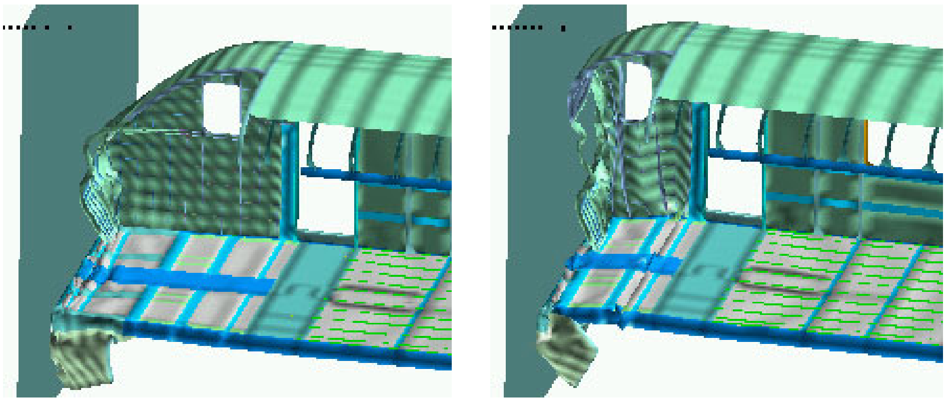
(a) Time = 40 ms (b) Time = 160 ms

Figure 9 Impact of Original Trailer with a Rigid Wall at 70 km/h

The impact of the trailer with a rigid wall is also presented, in Figure 9, to show the structural weaknesses of this type of rail vehicle. Only the trailer floor panel is shown although the whole vehicle was modelled. Similar to the cab car, the sole-bars bent in the horizontal direction at an early impact stage. During later impact stages, the draft sill bent in the vertical direction and the side sills bent in the horizontal direction.

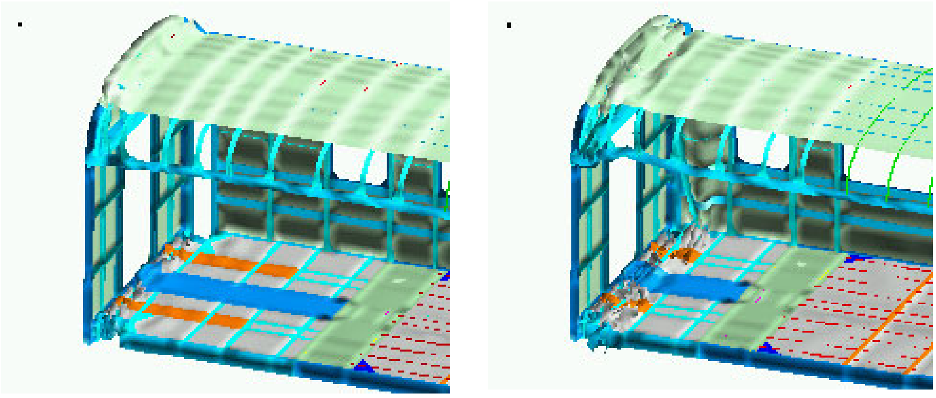
Again, as in the previous section, downward bending is shown to be the weakness of the draft sill. With a channel type cross section, the side sills and sole-bars both bent towards the open direction of the channel. To counteract the weaknesses, the draft sills were enhanced at their rear end. The cross-sections of the side sill and sole-bar were changed from channel to rectangular but the weight was kept the same as in the original. Two energy absorbers were also added at both sides of the draft sill to increase the ability of the structure to absorb energy and to increase stability. The vehicles modified based on the analysis of the responses to the impact with a rigid wall are labelled version 2.

The modified vehicles, version 2, were tested again in an impact with a rigid wall. Figures 10 and 11 show the impact effect on the modified cab car and trailer. Both vehicles collapsed progressively along their axial directions. The bending weakness of the draft sill, side sill and sole-bar were overcome.



Time = 50 ms Time = 120 ms

Figure 10 Impact of Modified Cab Car, Version 2, with Rigid Wall at 80 km/h



Time = 50 ms Time = 160 ms

Figure 11 Impact Modified Trailer, Version 2, with Rigid Wall at 70 km/h

The modifications are effective, particularly for the side sill of the cab car and the sole-bar of the trailer where the original design appeared to jack-knife soon after the start of the collisions. Figures 12 and 13 show the energy absorbed by both the modified and original side sill and sole-bar. Over the same crush distances, the energy absorbed by the side sill of the cab car and the sole-bar of the trailer increased by 81% and 92%, respectively, compared with the original structures.

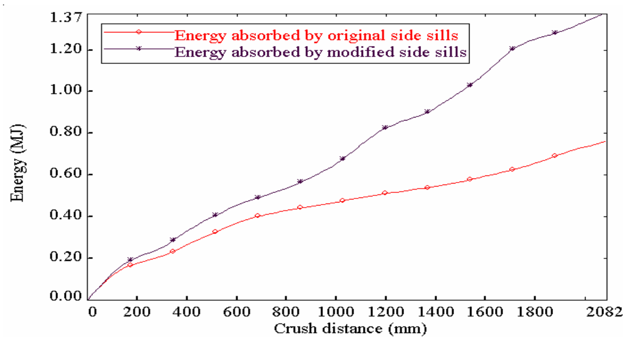


Figure 12 Energy Absorbed by Oirginal and Modified Side Sills

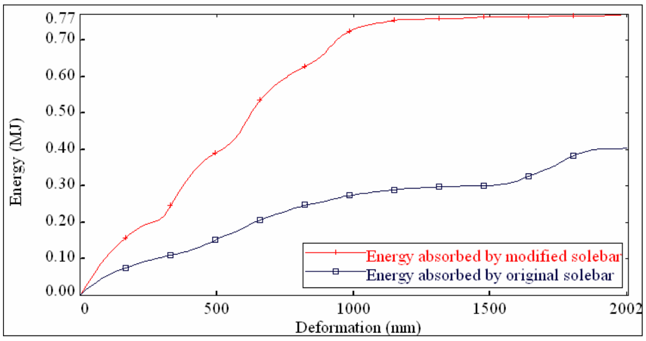
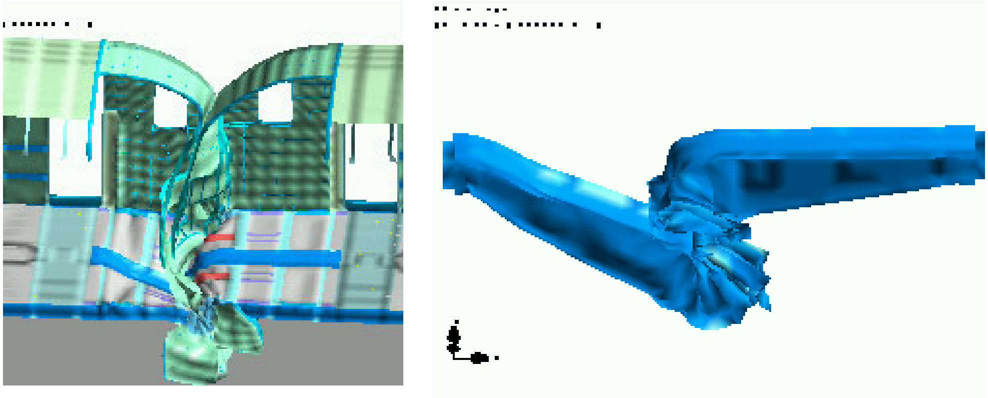


Figure 13 Energy Absorbed by Original and Modified Sole-Bars

Head-on Impact between Two Vehicles

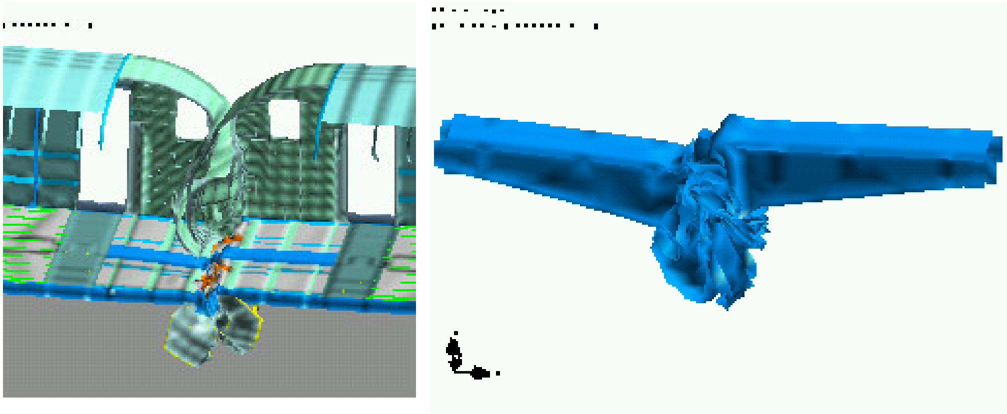
The modified cab car, version 2, was subsequently tested in the head-on impact scenario. Figure 14 shows the effects of the impact on the cab and draft sill. The revised draft sill bent again, even though it had performed well in the impact with a rigid wall. This showed that the draft sill behaves differently when subject to a head-on impact with another cab-car compared to a collision with a rigid wall. It can also be seen from Figure 14 that the bending deformations of the draft sills and end structures lead to the floor panels being displaced vertically with respect to each other. This implies that the vehicle will be in a weakened state once the end structures have collapsed and that overriding may be induced.



(a) Impacting Cab Areas

(b) Impacting Draft Sills

Figure 14 Effect of Head-On Impact Between Modified Cab Cars, version 2, at t = 160 ms



(a) Impacting Cab Areas (b) Impacting Draft Sills

Figure 15 Effect of Head-On Impact Between Modified Cab Cars, Version 3, at t = 160 ms

The head-on impact between two leading vehicles represents the most common impact scenario in real-life situations. The major difference between a head-on impact and an impact with a rigid wall is that the objects involved in a head-on impact are both deformable. This highlights that the impact of a rail vehicle with a rigid wall is so different from the impact with a real-life deformable vehicle that the former may not be a suitable test scenario. The reasons for this type of behaviour will be analysed in the next section. Suffice it to say that collisions with road vehicles placed on the tracks also involve deformable behaviour.

Version 3 of the cab car, modified again on the basis of the results of the further simulations, showed a progressive collapse pattern in a head-on impact, as demonstrated by Figure 15.

LIMITATIONS OF USING A RIGID WALL MODEL AND OF EXPLOITING THE SYMMETRY OF STRUCTURES IN COLLISION MODELLING

Analysis of Limitations of Rigid Wall Model

Figure 16 shows the forces on the contact interface between a vehicle cab-end and a rigid wall. The rigid wall is an idealised impacted object. It will remain in its original position and shape no matter how and by how much the impacting vehicle deforms. A rigid wall will provide a friction force to resist any sliding movement of an impacting object across the wall surface. Counteracting the tendency of the draft sill to bend downwards, the rigid wall effectively provides a moment $\boldsymbol{M}_{\boldsymbol{providing}}$ through the contact interface and a friction force ***R*** to resist this movement. A deformable object, by contrast, cannot provide this type of reaction. From this it can be deduced that a rigid wall effectively has correction function and, therefore, the draft sill and end floor panel are easier to maintain in a balanced position when impacting a rigid wall than in a collision with a deformable object. Hence, using a rigid wall as the impacted object may mask some structural weaknesses.

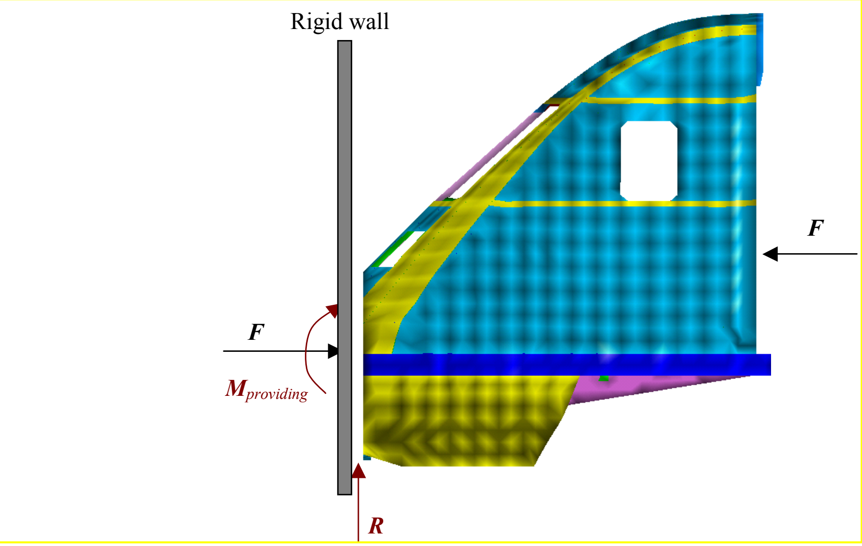


Figure 16 Forces Imposed on Draft Sill when Impacting a Rigid Wall

Discussion of Limitations of Symmetrical Structures in Collision Modelling

From the impact effects shown above, i.e., Figures 8(a), 9(a) and 14(a), it can be seen that the cab car appeared to suffer non-symmetrical deformation, even though both the scenarios involved entirely symmetrical impacts and the vehicles were geometrically completely symmetrical.

Theoretically, a symmetrical impact is expected to result in a symmetrical response. Based on this concept, half and quarter structures have been widely used in linear static analysis of rail vehicles. Model complexity and calculation times are reduced substantially thanks to the symmetry based approach. This concept has also been applied quite generally in the simulation of rail vehicle impacts, largely to reduce the amount of computation required.

The major differences between a linear static and a non-linear dynamic response arise in terms of (i) the stress level and (ii) the loading rate. The stress in a linear static structure, such as rail vehicles under proof-load conditions, is within the yield limits of the materials, by definition. Therefore, a linear static structure can maintain its stability. It is a stress-based problem and a symmetrical model will produce symmetrical responses. In a structure affected in a non-linear dynamic manner, the stress is beyond the yield limits of the materials. A non-linear impact situation creates a deformation-based problem and the performance is unstable. There is a significant effect of the stress waves on the structures.

When a component reaches the yield limit, large plastic deformations will occur in this component. If components located in symmetrical positions do not reach the yield limit at exactly the same time, some finite elements within these components will reach the yield limit first and will therefore collapse earlier. This will cause a redistribution of stresses in the next iteration step and will turn the initially symmetrical structure into a slightly unsymmetrical one. In an impact, it cannot be guaranteed that the components located at symmetrical positions reach the yield limits at the same time. If manufacturing tolerances in the real world are considered, even more unsymmetrical deformations may be expected.

Therefore, a symmetrical impact model may produce unsymmetrical responses. Thus, using half and a quarter structure based models exploiting geometrical symmetries are not suitable in all situations for modelling collisions of rail vehicles.

The above results thus show that there are differences between impacts with a rigid wall and with a deformable object and that the symmetrical impact between two identical vehicles cannot be satisfactorily modelled by an impact of one vehicle with a rigid wall.

CONCLUSIONS

Bending deformation is a key weakness in conventionally designed rail vehicles. There are many thin, long components in a rail vehicle, whose main failure pattern is bending or jack-knifing. The main longitudinal components of rail vehicles, such as the side sill, sole-bar and cantrail, should be designed to prevent failure through bending and should instead fail through a progressive axial deformation. Replacing an open cross-section, such as the asymmetrical channel section of the side beam in the case study example, with a symmetrical one results in evident improvements. Downward bending of the draft sill has been identified as a weakness in the behaviour of conventional rail vehicles impacting a rigid wall. Although this can be overcome by improving the structure, the problem appears again in supposedly symmetrical impacts between vehicles. Analysis shows that downward pitch bending is a characteristic problem of automatic coupler structures and must be given special attention.

By comparing simulations and analysis, it was found that the use of a rigid wall as an impacted obstacle in simulation modelling might mask severe structural weaknesses. This is because a rigid wall can resist sliding movements across the wall's surface and may be able to provide resisting moments. The rigid wall impact therefore tends to correct irregular deformation behaviour. This does not happen in collisions with realistic impact objects and should thus be considered in future modelling.

A frequently adopted strategy in modelling the proof load response of rail vehicles is to use a half section model if there is one plane of symmetry or a quarter section model if there are two planes of symmetry. The assumption is that a symmetrical problem, both in force and structure, will produce a symmetrical response. This assumption has been shown to be correct for static problems, where the stress imposed on the structure is less than the yield limit. However, the same modelling method has also been applied to the analysis of vehicle impact problems. Based on the authors' simulations and analysis, it is not safe to make this assumption for all scenarios and, notably, not for impact events. In an impact scenario, components are subject to stress waves and plastic deformation, placing the structure in an unstable state. Any non-symmetrical deformation may cause stresses to be redistributed in the structure and thus turns the problem into an asymmetrical one.

ACKNOWLEDGEMENTS

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