Crashworthiness of Conventionally Designed Railway Coaching Stock and Structural Modifications for Enhanced Performance

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ABSTRACT

In this paper, the authors present a crashworthiness assessment of a conventionally designed railway passenger vehicle and suggest modifications for its improvement. The analytical approach consisted of two stages. Firstly, the crashworthiness of the coach was assessed by simulating a collision between the coach and a rigid wall. Then, after analysing the structural weaknesses, the design of the coach was modified and simulated again in the same scenario. It was found that bending or jack-knifing is a main form of failure in conventionally designed rail vehicle structures and components. The coach design, as modified by the authors, overcomes the original weaknesses and shows the desired progressive collapse behaviour in simulation. The conclusions have general relevance and suggest the need for a rethink of some aspects of rail vehicle design.

INTRODUCTION

Considerable research has been undertaken in the area of structural crashworthiness of vehicles. It is now widely accepted that the conventional structural design philosophy of 'the stronger the better' is in conflict with the requirements of optimum occupant protection. A new philosophy of structural design has become increasingly accepted. Here the vehicle deforms and collapses in a controlled manner, so that the impact energy can be dissipated safely outside the part of the vehicle occupied by passengers or crew [1-3]. Amongst others, Chirwa [4] has proposed a new procedure and methodology of structural design for crashworthiness. Standards for crashworthiness of rail vehicles have been formed [5, 6] or are being drawn up [7].

The history of research into the crashworthiness of rail vehicles is not long. Most of the relevant projects were launched and completed during the last two decades. While there are some studies dealing with the crashworthy design of completely new rail vehicles [8-10] and with establishing the crashworthiness of existing conventionally designed rail vehicles [11, 12], no literature has been found by the authors focusing on analysing the structural characteristics and eliminating or mitigating the weaknesses of vehicles to existing designs with respect to crashworthiness.

Computational simulation is an important tool in studying the crashworthiness of rail vehicles. It is economic and flexible to use in all stages of design and improvement and allows the modelling of many options. With the development of relevant theory and techniques, computational simulation becomes more accurate and is playing an increasingly important role in crashworthiness studies.

In this paper, the authors present the results of the crashworthiness assessment of a conventionally designed rail vehicle and its enhancement. They focus on analysing and exploring the intrinsic weaknesses of a conventional design and provide suggestions for improvement. This paper is based on a case study of an existing design of electric multiple unit (EMU), consisting of a coach and a cab car (driving vehicle). The work carried out on improving the design of the cab car has been presented in an earlier paper [13]. The findings and conclusions have general relevance for the crashworthy design of rail vehicles.

RESPONSE OF CONVENTIONAL VEHICLE TO RIGID WALL IMPACT

Introduction to the Coach

The EMU studied for this analysis is a modern, conventionally designed train set. Crashworthiness requirements had not been considered in its design. The maximum design and commercial operating speeds are 250km/h and 200km/h, respectively. The EMU successfully passed the 250km/h test in late 2001 and was put into regular operation in 2002. The layout of the coach used in this study is shown in Figure 1.

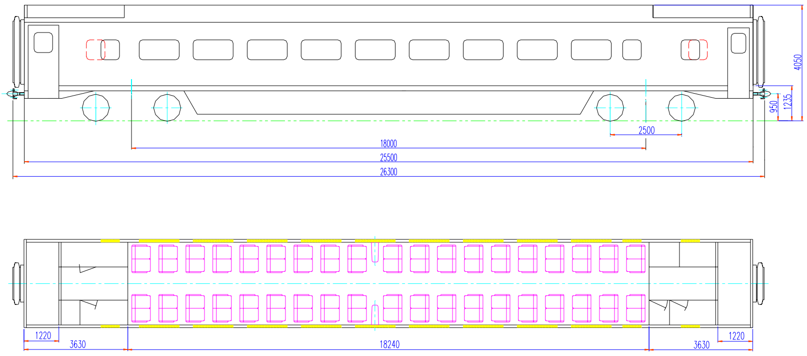


Figure 1 Layout of the Coach

Figure 1 shows that the coach features relatively large spaces in the vestibule (end) areas, where various facilities are located, such as entrance doors, gangway, toilets, luggage stacks, electric distribution boards and water supplies. This layout provides opportunities for the inclusion of energy dissipation zones outside the occupant zone.

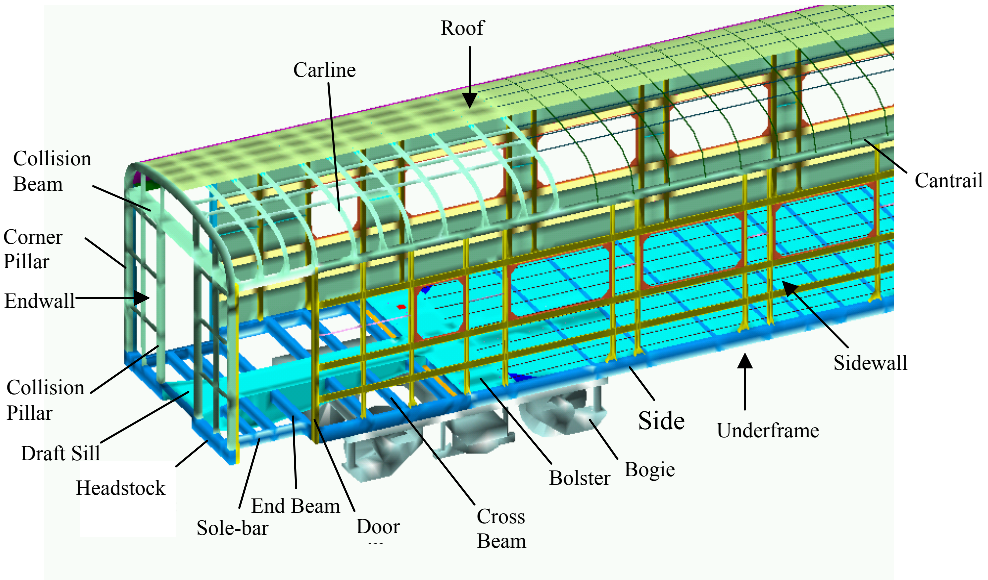
The car body of the case study coach is made of a steel alloy material. Like most passenger rail vehicles, the vehicle studied has a tubular shape, made up of thin-walled structures. From the manufacturing point of view, the structure is composed of the following substructures: a floor section, two sidewalls, two end walls and a roof section. Figure 2 shows the finite element models of the coach with shaded elements. Some parts of the body shell and floor are made transparent in these illustrations for easier viewing of the structural elements.

FE Model Establishment

In this study, a finite element (FE) model of the full vehicle structure was used to allow modelling of the effects of stress wave transmission through vehicles and of unsymmetrical deformations. The simulation software used by the authors is the explicit method implemented in the LS-DYNA code [14].

There are two types of elements used in vehicle modelling, namely, shell and rigid bodies. Nearly all the structure is modelled by shell elements. Bogies mainly play a supporting function in vehicle impact and are modelled as shell elements but with rigid body materials. Due to the large deformations that occur in the vestibule areas, the end structure was meshed in detail while the central structure used a relatively rough meshing. The complete model of the coach contains some 45,000 elements and is shown in Figure 3.

Figure 2 Structural view of Coach End Area



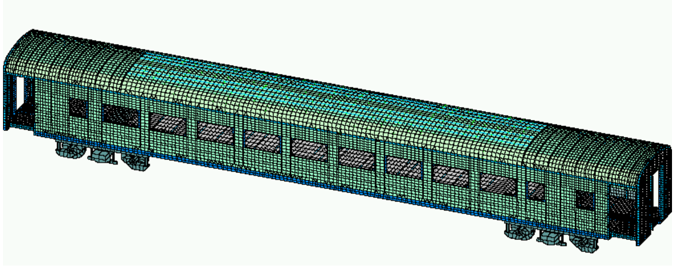


Figure 3 Finite Element Model of Coach

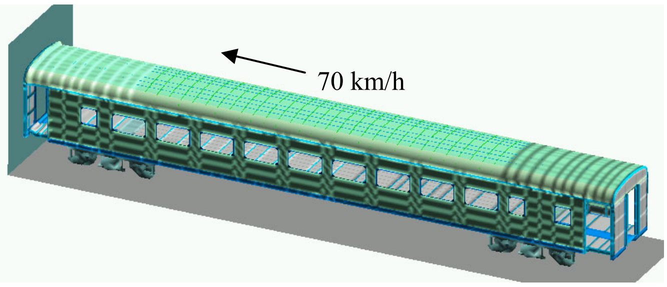


Figure 4 Coach Impact With Rigid Wall

It is assumed that the coach and the bogies have been in braking before the impact and that the bogies do not rotate in collision. A simple flat wheel tread surface is assumed, the rail being modelled as a rigid surface large enough to support the vehicle during the collision. Thus, the contact between wheel and rail was simplified as a static flat wheel in contact with a rigid finite surface. Since the impact forces and deformation mainly occur in the longitudinal direction of the vehicles, these simplifications rarely affect the results.

To examine the structural collapse behaviours of the coach, the impact speeds were chosen to be high enough to cause the whole vehicle end structure to collapse. The simulation case is based on the coach impacting with a rigid wall at a closing speed of 70 km/h, as shown in Figure 4.

Crash Structural Effect on the Vehicle

Based on a review of the trailer end structure (see Figure 5), i.e., the structure before the front bolster, this was divided into two regions for analysis, with the position of the rear door pillar and the end beam of the floor panel taken as the dividing line. The length of region 1, between the rear door pillar and the vehicle front, is 1170 mm. Region 1 may be viewed as a 'soft' structure area, containing the end wall, doors and gangway. Region 2 is a relatively stiff area and forms part of the main structure behind region 1 and the front of the bolster.

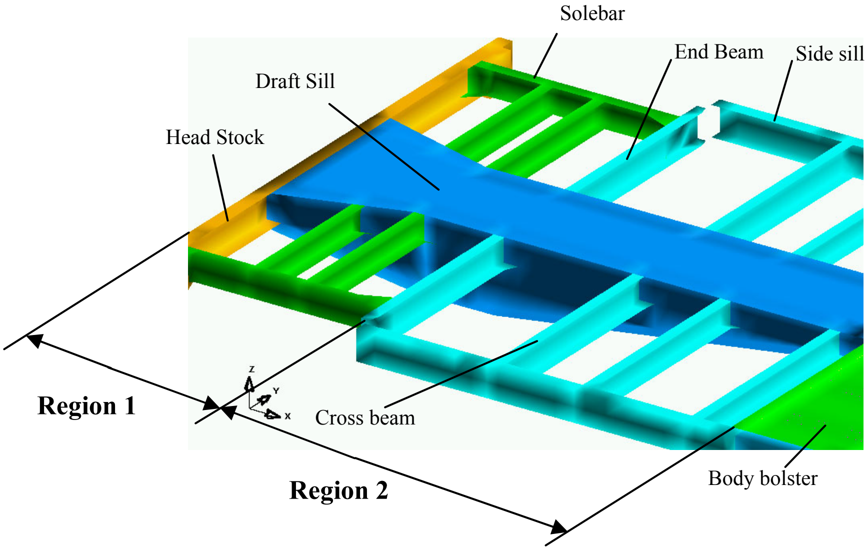
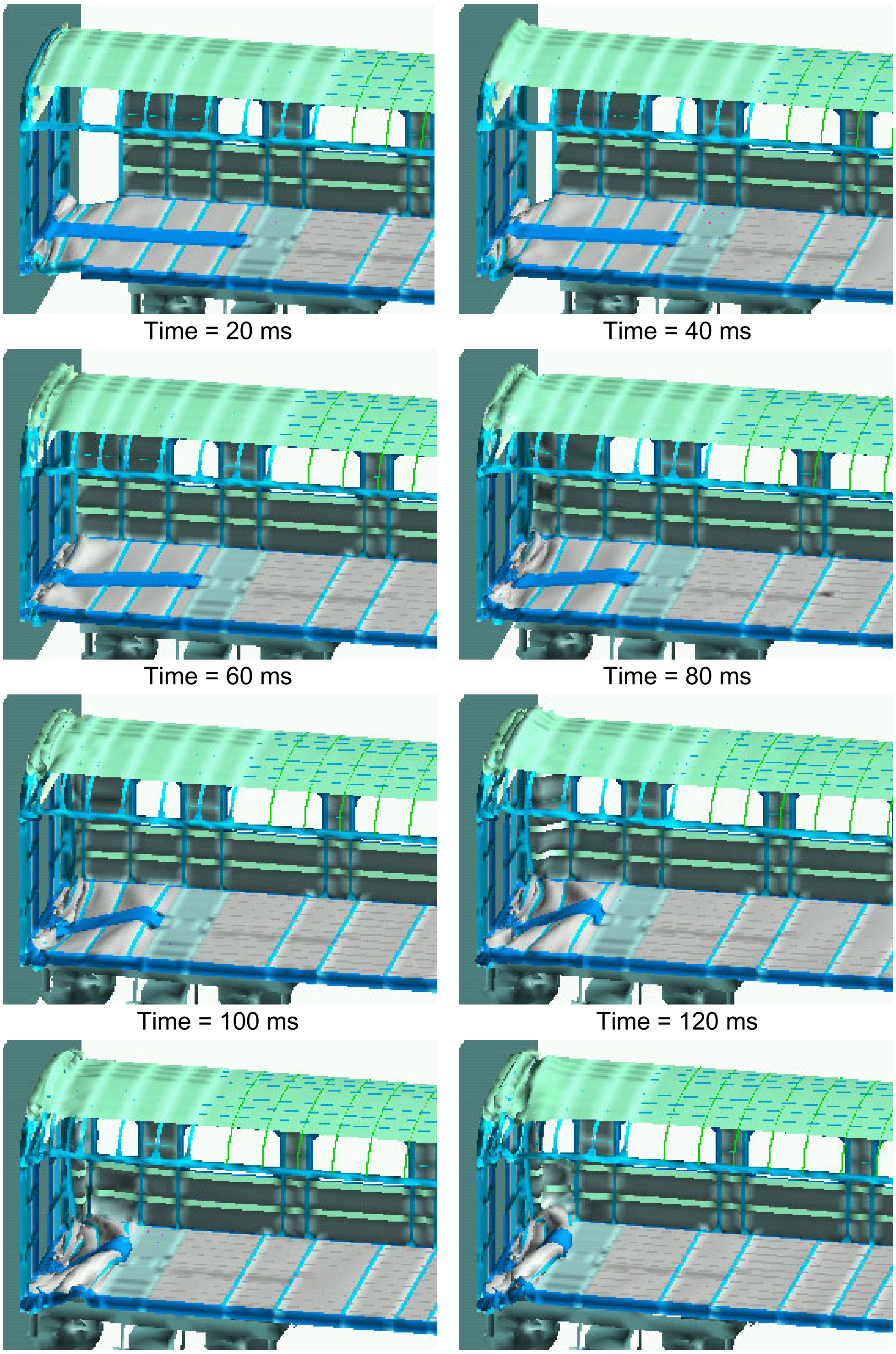


Figure 5 Region 1 and Region 2 in the End Floor Section

The crush progress of the vehicle structure is shown in Figure 6. The ground formed part of the simulation but has been removed for clarity. The front half of the sidewall was also made invisible, so as to give a clear view of the floor panel. Figure 6 shows that the deformation does not follow the desired progressive pattern. The sole-bar bent as soon as the impact started. The draft sill bent at a late stage of the impact, starting around 100 ms. The surface of the end of the floor bent upwards during the sole-bar bending and downwards with the draft sill bending.

Figure 7 shows the crush characteristic, i.e. the relationship between the force and displacement of the coach. The progress of the collision force can be divided into three stages. In the first stage, structural collapse occurs in region 1. The average reaction force is about 3.5 MN. In the second stage, the structure is crushed as far as 1850 mm in region 2. The average reaction force in has increased to about 4.5 MN. In the third stage, the average resisting force decreases to some 2.5 MN, This may be because some components of the end structure begin to lose effectiveness.



Time = 20 ms
Time = 40 ms
Time = 60 ms
Time = 80 ms
Time = 100 ms
Time = 120 ms
Time = 160 ms
Time = 200 ms

Figure 6 Crush Deformation Progress at the Vehicle End

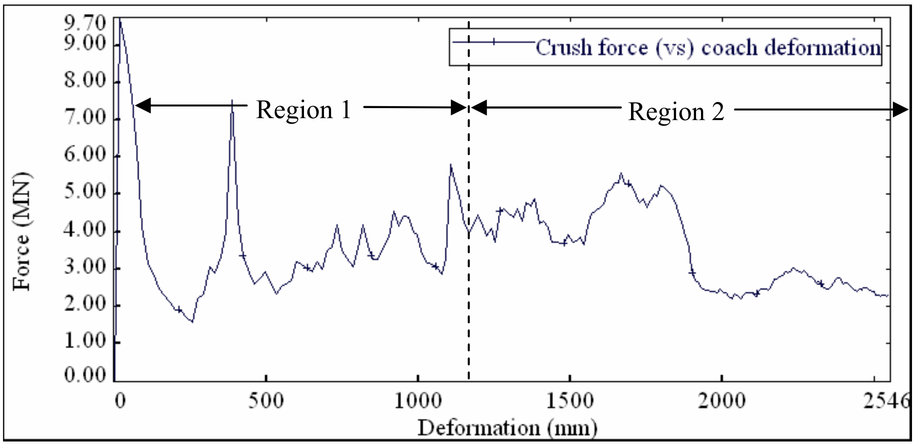


Figure 7 Force versus Deformation during Crushing

Figure 8 shows the time history of the energy absorbed by the vehicle structure. In the period soon after the initial impact (from t=18 ms to t=120 ms), the dissipated energy vs. crash time shows a near linear behaviour, which implies that the collision energy is absorbed in a stable fashion. After t=120 ms, the efficiency of energy absorption is reduced and the graph becomes flat. Over the total t=200 ms period modelled, 7.68 MJ of collision energy is absorbed. The energy absorbed by region 1 of the end structure, i.e., the structure before the gangway area, is 3.71 MJ.

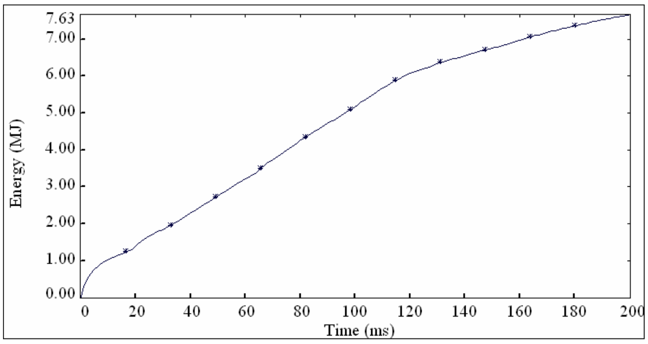


Figure 8 Collision Energy Absorbed by Vehicle Structure

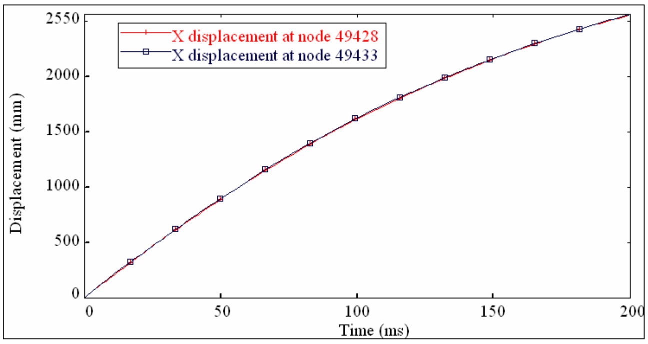


Figure 9 Displacements of two Reference Nodes

Figure 9 shows the displacement of two reference nodes, 49428 and 49433, which are located on the front and rear body bolster respectively. Thus, the displacement of the reference node 49428 represents the crush distance of the front-end structure and the difference between nodes 49433 and 49428 expresses the structural deformation of the central area between the two bolsters. It can be seen that the collapse distance as a function of the impact time, shows a stable and continual increase. The total distance of the end structure collapse is 2540 mm. From Figure 9, the displacements of the two reference nodes' are nearly the same throughout the whole crush process. This implies that the central area between the two bolsters suffers little deformation during the crash; only 4.6 mm by the end of the structural collapse and less than 12 mm throughout the whole impact.

Thus, the 3236 mm of end structure, i.e., the section before the front bolster, has been reduced in length by 2540 mm, with 1170 mm of deformation during the first crush stage and 1370mm during the second stage. The 18,000 mm long central area, suffered only some 12mm of deformation throughout the crash. Obviously, the end structure suffers vast plastic deformation and the central area, where the passenger compartment is located, has been under elastic deformation.

From the above, we can deduce that the coach structure can absorb a certain amount of collision energy on impact. But the structure has not shown the desired progressive deformation. The sole-bar, the draft sill as well as end floor panel bent. Table 1 shows the collision energy absorbed by the different parts of the coach and the vehicle structure as a whole.

Table 1 Collision Energy Absorbed by Different Vehicle Components (MJ)

Crush Stage	Overall	Floor	Side Walls	Roof	End Wall	Draft Sill	Shell & Floor
Region 1	3.71	1.78	0.624	0.699	0.168	1.16	0.71
Regions 1 & 2	7.68	3.99	1.84	1.67	0.178	2.27	2.12

It is clear from Table 1 that the energy absorbed by the floor area is more than the sum dissipated by all other parts. It is therefore the most important part of the vehicle in terms of dissipation of collision energy. It can be seen that the draft sill is the most important component in the floor for collision energy dissipation. In the crush of region 1, the draft sill has absorbed 65% of the energy dissipated by the floor. Over the whole crash process, the energy absorbed by the draft sill represents 57% of the energy dissipated through the floor. As a result of the cross-section reduction of the draft sill and the bending deformation in the second deformation stage, the draft sill performs less effectively in the later crush phases. The energy absorbed by the walls and floor together is slightly greater than that absorbed by the roof and two sidewalls, being 19% of the total energy absorbed by the whole vehicle structure in region 1 crush and 27% throughout the whole crash process.

STRUCTURAL WEAKNESS ANALYSIS AND CRASHWORTHINESS ENHANCEMENT

Structural Weaknesses

It has been shown above that the deformation process of the vehicle does not follow a desirable progressive pattern. In region 1, the sole-bars bend, causing the floor and crossties between the sole-bars and the draft sill to become less stable. In region 2, the draft sill bends from its connection with the bolster, which results in the floor and cross beams between the side sills and draft sill bending as well.

Instability may produce two results. One direct consequence is a reduction in the energy dissipation capability. The other effect is that an unstable structure may lose efficiency in some impact cases, such as in oblique impact and eccentric impact, even though it can absorb a limited amount of energy in idealised impact scenarios. Therefore, unstable parts of the structure must be improved. The occupant area though has suffered very little deformation and does not need to be modified.

There are many long, thin components in the coach structure. These were designed based on proof loadings, where the vehicle components are required to remain within the elastic limit of materials. The behaviours of the components beyond the yield limits of materials are not considered in conventional designs. The long, thin components, particularly those acting in the longitudinal direction, were examined and modified based on their deformation performance.

There are two standard approaches to structural modification. One is based on the modifying individual components to improve their plastic deformation behaviour. The other approach involves the addition of energy absorbers. Accordingly, there would be two plans for structural improvement. One includes structural modifications of design and the addition of energy absorbers. The other is concerned only with the structural modification of the components of the original coach. Both approaches were explored but only the former is presented in this paper.

Structural Modification

The thickness of the roof panel and that of the sidewall panels are strictly restricted to provide a spacious interior. Compared to the floor, the roof and sidewalls resist less impact force and absorb less collision energy. The rails and stiffeners in the roof and sidewalls are relatively small and so there is limited room for modification. Besides, no obvious weaknesses were found in the roof and sidewalls in the crash simulation. Therefore, the structural improvement work could be concentrated on the floor area, as shown in Figure 10.

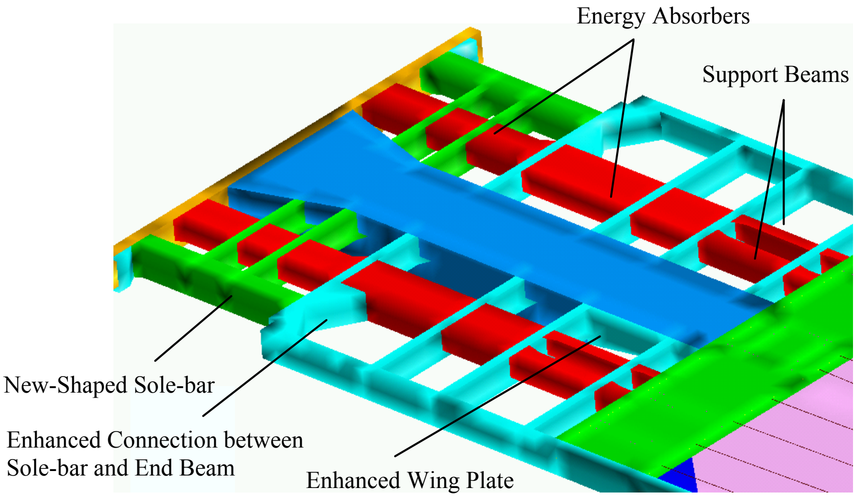


Figure 10 Modifications of the End Underframe

- To counteract the structural weaknesses, the draft sill was enhanced at its rear end and at the position where its height changes;
- To increase stability, the cross-section of the sole-bars was changed but the weight kept the same as the original;
- To dissipate the impact force transmitted from the sole-bar effectively, the cross connection between the sole-bar and end beam was enhanced;

-
- To increase the ability of the structure to absorb energy and to increase stability, two energy absorbers were added on either side of the draft sill. The absorbers were made of thin walled sections and do not increase structure weight greatly.

CRASH RESPONSES OF THE MODIFIED COACH

Crushing of the modified coach was simulated and the results of the modified and original structure were compared. The crash model used is the same as that of the original coach. That is, the coach impacts with a rigid wall at a closing speed of 70km/h. Figure 11 shows the crush progress of the end structure of the improved coach. A shaded model is used.

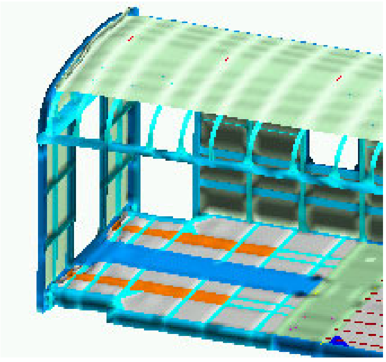
From Figure 11, it can be seen that the end structure undergoes a progressive deformation, which is the desired pattern for energy absorption. The problems that had appeared in the original vehicle, i.e., bending of the sole-bar, draft sill and the whole of the end of the floor, have been overcome. The reinforcing measures at the cross connection between the end beam and the sole-bar have prevented large scale bending of the end beam and thus losing efficiency.

Figure 12 shows the displacement of nodes 49428 and 49433 along the vehicle’s longitudinal direction and the difference between the two nodes. As in the original vehicle, nodes 49428 and 49433 were located on the front and rear bolster respectively. Thus, the displacement of node 49428 expresses the structural collapse distance of the end structure and the displacement difference of the two nodes is the represents the deformation between the two bolsters.

From Figure 12, it can be shown that over t=200 ms there has been 1980 mm of end structure collapse in the collision. Of this, 1170 mm represents the zone 1 collapse that occurs in the first 70ms. The deformation between the two bolsters, i.e. the passenger compartment, has remained small. Over the 18,000 mm of the central structure, the largest deformation is 21 mm at time 115 ms. From this fact, as well as the investigation of the stress distribution, the central structure has been under elastic stress during the crash progress.

Figure 13 shows the energy absorbed by the modified coach as a function of its structural deformation. The energy absorbed by the original coach is also shown in the figure for comparison. When crushed to 1980 mm, the energy absorbed by the modified coach is 8.49 MJ, 33% more than that of the original.

Figure 14 shows the crush characteristic, i.e., force-displacement, of the coach. The figure shows that there are some oscillations in the zone 1 crush. However, the average impact force has been sustained at a near-constant level over the whole crush period, which is a desired pattern for efficient energy absorption. Unlike the original structure (see Figure 7), there is no obvious weak stage in the improved structure.



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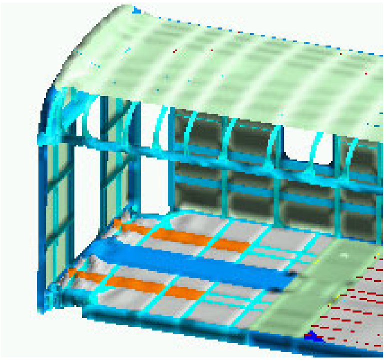

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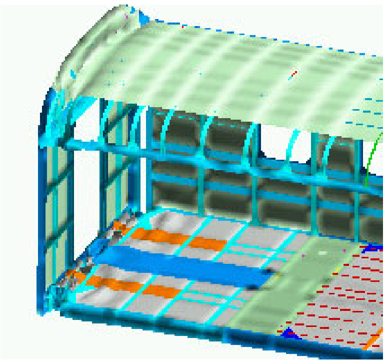
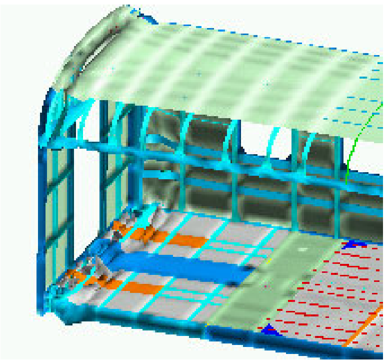


Time = 60 ms



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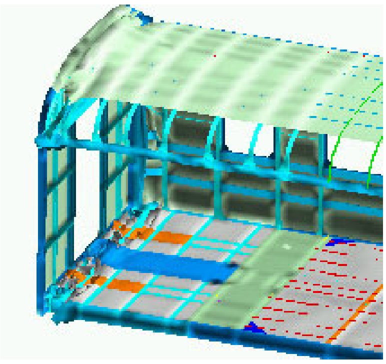

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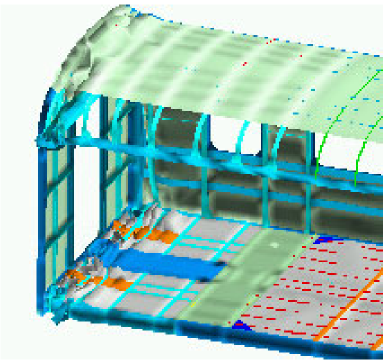
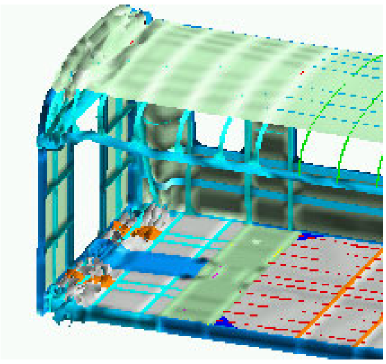
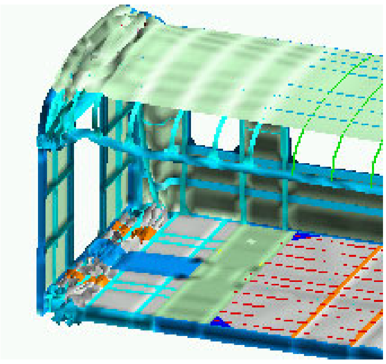


Time = 120 ms



Time = 160 ms



Time = 200 ms

Figure 11 Crush Progress of Modified Vehicle End

The average resisting force shows a slightly increasing trend in the zone 1 crush and has maintained a relatively high level in zone 2 crush. The impact resisting force during the collapse of zone 1, before 70 ms, has shown a certain increase compared with the original structure.

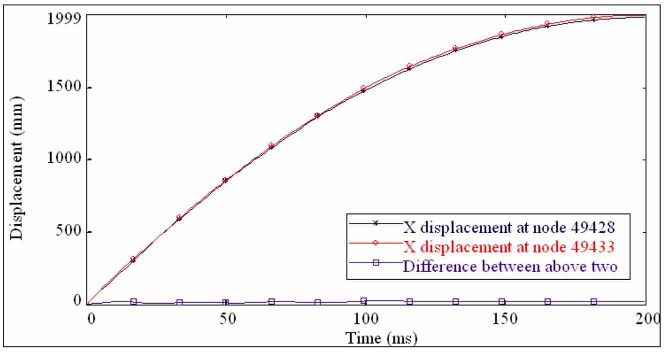


Figure 12 Collapse Distance of the Modified Vehicle

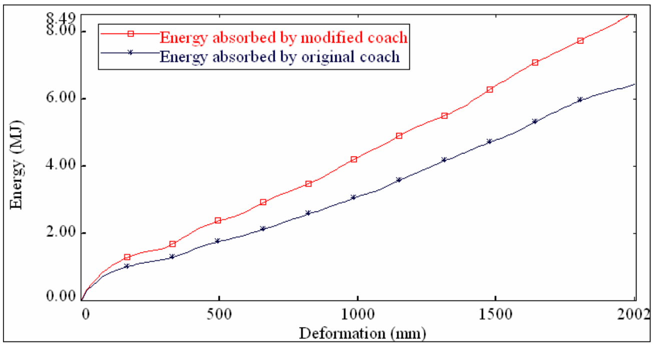


Figure 13 Collision Energy Absorbed by the Modified and Original Vehicle

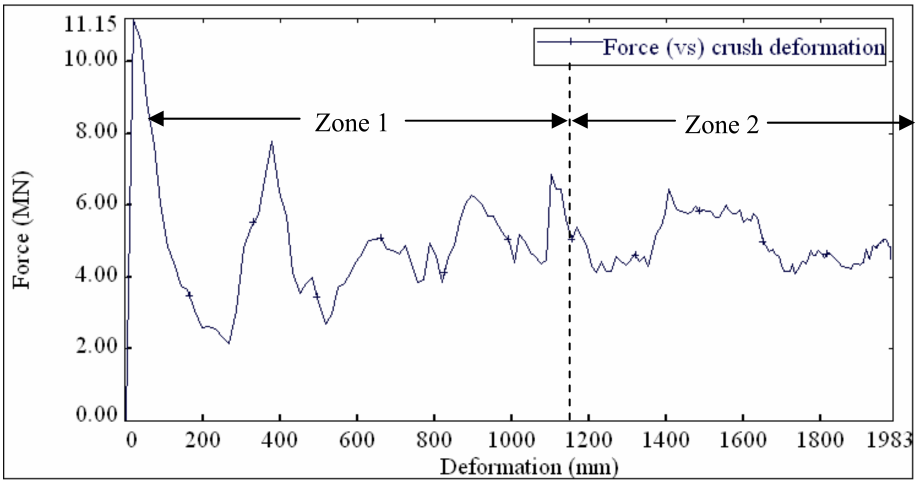


Figure 14 Force – Displacement Characteristic of the Modified Vehicle

The bending weaknesses of the sole-bar, draft sill and end floor have been overcome in the modified structure and their abilities to absorb energy have been increased. Figures 15 and 16 show the energy absorbed by the end floor and sole-bar respectively, for both the modified and original structures. The modified and original lines separate gradually with the increase of crush distance. The energies absorbed by the modified end floor and sole-bar over the crush distance of 1980 mm of the modified vehicle, are 5.53 MJ and 0.768 MJ. These have increased by 65.6% and 92.5% respectively compared with the original structures.

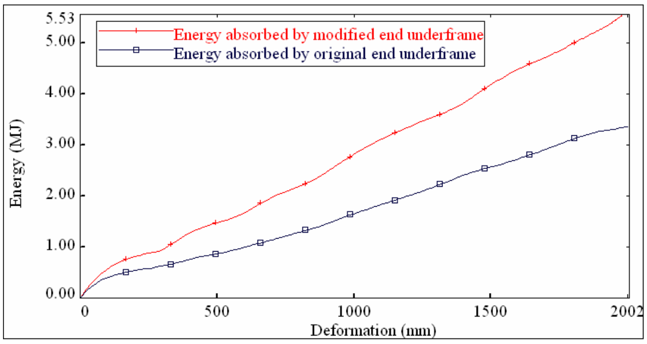


Figure 15 Energy Absorption by the Modified and Original End Floor Sections

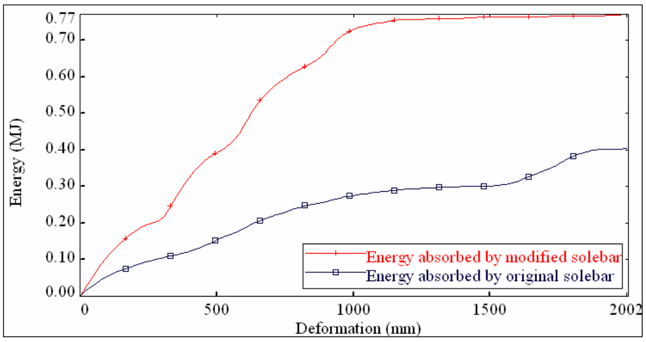


Figure 16 Energy Absorption by the Modified and Original Sole-Bars

Table 3 shows the collision energy absorbed by the end floor section, draft sill, sole-bar and the whole coach structure. The data for the original vehicle over the same crush distance as the modified coach are also listed in Table 3 for comparison. There are clear increases of the ability of energy absorption of the vehicle and components. From this table, it can also be seen that the modifications of the sole-bar and draft sill increased not only their own ability to absorb energy but also that of connected parts.

Table 3 Collision Energy Absorbed Overall and by Component

Structure	Collapse Area (mm)	Global (MJ)	End Floor (MJ)	Draft sill (MJ)	Sole-bar (MJ)	Absorbers (MJ)
Modified	To 1980mm	8.49	5.53	2.24	0.768	1.18
Original	To 1980mm	6.37	3.34	1.94	0.399	----
Percentage increased by		33.3%	65.6%	15.5%	92.5%	----

It can be seen from the above, that the modification approach has been effective in addressing the weaknesses. The problems of the bending deformation in the original coach, affecting the draft sill and sole-bar, have been overcome. The modified vehicle shows the desired progressive deformation. The ability of the modified structure to absorb energy has increased significantly. The amount of energy absorbed by the modified vehicle overall, the end area of the floor and the sole-bar increased by 33%, 66% and 93% respectively, compared with the original structures, when crushing by the same distance of the crush zones in the modified vehicle.

Concluding Remarks

Conventionally, rail vehicles are designed to withstand the proof load and to cope with ride dynamics requirements while the stressing of a rail vehicle's structure must remain within yield limits. Thus, a conventional rail vehicle is not designed to cope with the situation where stresses exceed the yield limits. As a result, when experiencing plastic deformation due to an impact, the behaviour of many components of the conventional rail vehicle is inadequate.

The original rail vehicle discussed by the authors has the ability to absorb energy during impact. However, the deformation process is unstable. The suggested structural modifications will enhance the energy dissipation capability and can stabilise the crush process. The measures include an enhancement of the rear end of the draft sill, a change to the cross-section of the sole-bars and the addition of energy absorbers.

The modified vehicle shows a better progressive deformation pattern than the original one. The major weaknesses that appeared in the original vehicle have been overcome. Once the designed crush zones have collapsed, 8.65 MJ of collision energy has been absorbed. This is some 33% more than the original cab car over the same distance of structural collapse.

In the modified structure, the central passenger compartment remained intact while the crush zones collapsed. During the crush zone collapse, the deformation of the occupant area of the vehicle was less than 21mm over the whole of its 18,000 mm length. The modified coach can thus keep the passenger compartment in elastic stress during the crush zone collapse.

Bending deformation of structural components 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 cant rail, should be designed to prevent failure through bending and should instead fail through a progressive axial deformation. For this purpose, replacing an asymmetrical and open cross-section, such as the channel section of the sole-bar, with a symmetrical one results in evident improvements.

The provision of energy absorbers is a significant feature in any crashworthy rail vehicle. Two thin walled energy absorbers were added to the model of the end structures of the coach, located either side of the draft sill and designed to absorb energy and to increase structural stability. The shape of the cross section and the slenderness ratio have a significant effect on the performance of an energy absorber. A large symmetrical cross section with small slenderness ratio will provide a more stable response. In this study, the energy absorbers were designed as rectangular cross sections and divided by the cross beams to shorten the length of the energy absorbers. These energy absorbers performed well in simulated vehicle impacts.

ACKNOWLEDGMENTS

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