Rail vehicle impact analysis: The unstable propensity of structural responses and the critical scenarios of structural failure

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Abstract
In this paper, the authors investigate the characterisation of the structural collapse of steel-bodied rail vehicles and propose modifications to a cab structure for improved structural crashworthiness. This is a mechanical- and simulation-based investigation, comprising three parts: after a mechanical description of the impact forces and energy conservation in collisions between trains, the characteristics of rail vehicle structures are examined to identify structural weaknesses in the context of impact stability. This is followed by a computer simulation of a cab structure to validate the conclusions from the theoretical analysis and to demonstrate the effectiveness of the design modifications. Focusing on the correlation between structural characterisation and impact stability, the authors highlight the following three findings: first, rail vehicles have a propensity to be unstable in the vertical direction due to the asymmetrical geometry and unbalanced impact loads; second, high shear stresses tend to be generated at the top corners of the rear pillars of the door region, leading to a localised fracture tendency; and third, impact stability can be enhanced through structural modifications by adopting symmetric cross sections or enhancing the stiffness in the weak direction for asymmetric structures, i.e. achieving geometric symmetry or stiffness balance on impact. The findings result in a better understanding of the mechanisms in structural crushing and advance the research into passive safety of rail vehicles.

Keywords
Impact stability of rail vehicles, crushing characterisation of rail vehicles, design modification of rail vehicles, passive safety of rail vehicles, computer simulation of structural collisions

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Introduction
The geometry and structure of rail vehicles allow them to cope with the characteristics of their operation. Longitudinally coupled by hinged couplers, vertically suspended on bogies and mechanically driven through the tiny patches of the wheel/rail contact, rail vehicles move in a flexible arrangement in a coordinated manner. In unexpected incidents, e.g. collisions, rail vehicles often experience unstable or irregular behaviours beyond their design scope. The irregular responses fall into two types, namely, motions beyond the bounds of the limitations of the degrees of freedom, as defined by the suspension and coupling systems between the structural parts, and those created by plastic deformation within structural parts. The collision responses of rail vehicles can thus be classified into two categories: first, the dynamic response measured by the motion of the vehicle as a whole, experienced as a change in kinetic energy; and second, the deformation response to structural collapse of the vehicle, observed as a change in potential energy. Energy conversion between kinetic and potential energies and dissipation through external work thus play fundamental roles in rail vehicle impacts.

In terms of kinetic energy due to structural movements, the impact responses of rail vehicles are closely correlated with the amount of kinetic energy released by the structural movements during the impact. Correspondingly, train impacts are generally classified into two categories: high-energy impacts and low-energy impacts, where the energy level is defined by the amount of energy dissipated through structural deformation. Trains running at low speeds can only be involved in low-energy impacts, whereas trains...
running at high speeds may experience either high- or low-energy impacts. The high level of kinetic energy stored within a fast-moving impacted train may be either dissipated through structural deformation, i.e. leading to a high-energy impact, or remain high after the impact, i.e. resulting in a low-energy impact. The latter behaviour occurs when a train collides with a car at a road level crossing. Crashworthiness studies thus require multiple approaches, including the two responses as follows: first, the structural collapse of rail vehicles, dominant in high-energy impacts; and second, the movement stability of trains, dominant in low-energy impacts.

In terms of the potential energy generated by structural deformation, the response of rail vehicles is closely related to the vehicle's structure, i.e. the nature of components and the ways in which they are assembled. Modern rail vehicles are good examples of state-of-the-art structures in being light in weight and in terms of their production techniques and spatial efficiency. The main bodies of rail vehicles are thin-walled tubes, built with a steel skin and reinforced by integrated stiffeners of pressed steels. At the ends of the tube, there are either end walls or cab structures. The vehicle bodies are flexibly connected with each other in the longitudinal direction through coupling systems and are individually supported on bogies. Auxiliary equipment is suspended beneath the underframe to enable increased stability through lowering of the centre of gravity. In collisions, the cab structure experiences the initial impact at the leading interface. This is followed by intermediate impacts between vehicles, spreading from the coupling systems to the vehicle ends. For non-articulated rail vehicles, bogies are usually not directly involved in the structural collapse. However, they play a key role in the impact stability of the vehicles.

The contribution of individual components, e.g. strengthening tubes, to the crashworthiness of the structures of rail vehicles is determined by their crushing behaviours under laboratory conditions and in realistic scenarios when the tubes are installed in vehicles. Energy absorbers in rail vehicles are devices or components that have a specific role: the energy absorber is the only component that is specifically designed for the purpose of energy absorption without being required to perform other duties. A variety of types of energy absorbers are therefore potentially applicable to rail vehicles. The energy absorber in rail vehicles is required to cope with the in-vivo environment of rail vehicles, including coordinating with other components and behaving in a stable manner during the collapse of the vehicle structure. Hence, apart from the general characteristics required for an energy absorber, energy absorbers for rail vehicles must demonstrate their functionality in different complex scenarios. A great deal of work has been done on the in-vitro behaviours of tube-shaped energy absorbers, including different shaped cross sections, e.g. square, circle and tapered tubes, and different materials, e.g. steels, aluminium and composites. In addition to conventional simple tube devices, work on energy absorbers based on foam-filled tubes is also attracting increased interest. In terms of the in-vivo behaviours of tubes, the work focuses on how to retain the in-vitro behaviours of tubes in realistic structures. In this respect, oblique impacts of tubes and dynamic sensitivity of tubes have particular relevance.

The requirements for structural collapse stability and energy dissipation efficiency often lead to conflicts, as the former requires a soft response by the structure and the latter demands a reasonable level of stiffness. Structural stiffness also affects the dynamic response of an entire vehicle, e.g. in the way accelerations are managed. A compromise between these two is often required for crashworthy designs. To increase collapse stability, couplers are designed with a shear-off or push-back structure, which enables the coupler to be removed from the collapse zone in the event of a collision. To increase energy absorption, energy absorbers can be installed in the end regions of vehicles for increased structural stability and force/displacement behaviour. To increase the stability of the rear part when a regular collapse of the front occurs, the forces are designed in a pattern that gradually increases through different collapse stages. The above measures have led to the formation of a well-accepted crashworthy design principle, in which rail vehicles are designed to deform in a controlled pattern progressively from couplers, to energy absorbers and the end structure, so that the kinetic energy of impact vehicles can be effectively dissipated outside passenger holding areas.

The structural behaviour of rail vehicles in collisions is closely related to occupant responses, as the primary impact of rail vehicle structures is followed by the secondary impact of occupants with vehicle interiors. The impacts between structures and occupants show a series of sequences from outside to inside, as follows.

1. The structural impact, including the initial impact and any consequential impacts after a derailment, results in structural collapses and accelerations.
2. Occupant impacts follow and are affected by the interior layout and vehicle accelerations.
3. The biomechanics impact on the occupants’ organs is then promoted by body decelerations generated by impacts with interior components.

In the structural impact, the dynamic response of the structure is the cause for the accelerations and the structural deformation is the means for energy absorption. For the second and third terms of occupant impact behaviours, the dynamic response is illustrated by the whole-body behaviour and studied by dummy dynamics. The deformation responses of
organisms, e.g. crushing of the brain, leakage of blood vessels and fracture of bones, often lead to more serious consequences than contact damage of external surfaces of occupants. In view of the differences on physics and materials, the above three terms are often studied separately by different research programmes. This paper focuses on structural responses of rail vehicles and, specifically, the stability in collisions.

Considerable work has been done in the last three decades in pursuing efficient energy dissipation in the design of rail vehicles. The late-1980s are generally considered as the datum line for the development of crashworthy rail vehicles. The following two decades, crashworthiness of rail vehicles had a ‘golden age’. Through intensive research projects carried out by the European Research Office Question 16511, British Rail⁸ and French Railways⁹, a good understanding of the impact responses of rail vehicles was obtained and the crashworthy design principles were established. Followed by further enhanced research through extended European projects (i.e. SAFETRAIN, SAFETRAM, TRAINSAFE, SAFEINTERIORS, ALJOIN, etc.) and the extensive US programmes¹⁰, crashworthy design and manufacturing have become an essential requirement within the rail industry.¹²¹³

The destructive nature of structural impacts and the scattering behaviour of dynamic responses determine that the three major analysis techniques: theoretical description, computer simulation, and experimental validation, must be applied in a different manner from conventional service-based applications. Due to the resulting destruction, full-scale dynamic tests are more suitable as a means of validation for representative scenarios. Because of the high cost of such tests, impact experiments often concentrate on components and, due to the variations in dynamic tests, generally start from quasi-static tests. The behavioural variations between standalone and installed components and between quasi-static and dynamic situations continue to pose challenges in appropriately evaluating experimental results to predict the behaviours of components when installed in rail vehicle systems. Theory-based studies and computer simulations are thus expected to play an increased role in train impact research, in particular for design prediction of new products and for the advanced stages of refining designs where experience and practical results are lacking.

Computer simulation faces different challenges from those for impact tests. Although the representativeness of testing is restricted by scenario availability, computer simulation is still required to validate the virtual prediction result against reality. In this respect, computer simulation and testing are closely linked. As a virtual approach, the accuracy of computer simulations is affected by both the expression of physical phenomena and the implementation of scenario details. Simulation accuracy can be increased if these two factors are treated separately. As a general rule, the first step must be to achieve an agreement between the simulation and test results to obtain a validated physics model. This can then be followed by focusing on the influence of different scenario specifications. A distinct advantage of theoretical analysis and numerical simulation is their convenience for prediction and comparison. As soon as a numerical setting is validated and theoretical analysis is rectified with existing practical cases, they can be easily extended to investigate a variety of new scenarios, to trace fundamental issues and to interpret quasi-static experiments. The resulting theories and numerical methods developed can in-turn provide guidance for further design and enhancement of products.

The work on impact safety of trains has been dominated, to date, by studies of the crashworthiness of rail vehicles, in the designs that exhibit a controlled regular crushing behaviour. This approach focuses on stable responses, from a positive perspective, that is, on how well rail vehicles perform in collisions and how they prevent impact fatalities. In view of the wide variations of dynamic responses and impact scenarios though, it is also necessary to study the impact/crash stability of trains by focussing on the irregular crushing behaviours of rail vehicles that arise when impact conditions and responses go beyond the design scope. The analysis of impact stability covers unstable responses, from a negative viewpoint, i.e. how poorly might rail vehicles behave in collisions and how could impact damage be reduced. Crash-worthiness and crash-stability analyses thus examine the impact behaviours of trains from two different angles. A combination of the two approaches can create a comprehensive picture of train collisions and lead to a better understanding of this phenomenon.

The authors of this paper study the impact stability of rail vehicles by analysing structural collapse behaviours, i.e. inside the vehicle. This paper can be considered as a companion to our recent publication¹⁴ where the focus was on rail vehicle interactions with outside environments on the basis of the entire system, including the pitfalls of the rigid-wall model and symmetric behaviour assumptions. The next section gives a mechanical description of the impact forces and energy conservation in train collisions. The structural characteristics and impact weaknesses of rail vehicles are then examined and discussed in the section ‘Mechanical analysis of the impact stability of rail vehicle’, which is followed, for validation purposes, by computer simulations of cab vehicle impacts in the section ‘Computational analysis and structural modification’.

**Mechanical and mathematical descriptions**

**Force generation in train collisions**

The force is the cause and the energy is the consequence of structural responses in train collisions.
The fundamental purpose of adjusting the structural deformation response is to establish an effective conversion route between impact forces and structural energy, where the prevention of unstable structural responses is an important objective in supporting crashworthiness.

The following three types of forces are the main contributors in train collisions.

1. **Contact forces.** Applied on boundary interfaces. As an interaction-based phenomenon, the magnitude of impact forces on the impact interface is extremely high, which leads the passive support forces on the wheel/rail interfaces often to be in a chaotic state.

2. **Field forces.** Applied in solid volumes by gravitational effect. In many cases, the gravitational force makes a balancing contribution on the vehicles in the vertical direction, which results in irregular responses of rail vehicles to be dominant in the transverse direction.

3. **Inertial/dynamic forces.** Applied on bodies associated with accelerations. Under high impact forces, the vehicle structure shows strong dynamic responses, manifesting themselves as the inertial response of the vehicle as a whole and as interactive responses between vehicle parts.

The above forces determine the following characteristics of train collisions.

1. **A transient dominant process.** Rail vehicle collisions last only a short time but result in destructive consequences, illustrating features of a dramatic process and fast dispersion. With a high aspect ratio of length to transverse sizes, wave propagation dominates over structure vibration.

2. **Progress from external to internal.** Internal responses of inertial behaviour and deformation are passive consequences of an external impact force acting on the interfaces. Structural impact thus represents an enforced process from the outside to the inside. As such, the immediate response often comes from the dynamic response of the entire structure. A vehicle’s internal responses then happen in expansion stages.

3. **Different responses between vertical and lateral directions.** The impact forces are likely to scatter along the vertical direction, however, the irregular responses often appear in the transverse direction. The initial impact force is mainly on the underframe that is weak under vertical bending. However, large gravitational loads can easily offset small forces. By contrast, there is no constraint and equilibrium forces in the transverse direction. Irregular transverse responses often lead to uncontrolled dynamic developments.

4. **Varying damage modes between vertical and lateral directions.** Corresponding to term 3, the damage in the vertical direction often shows force/deformation features and the damage in the transverse direction possesses dynamic movement features, either in translational or rotational modes.

The correlation of forces and vehicle responses can be expressed as follows

\[ M\ddot{u} + Ku = F(t) \]  

where \( M \) and \( K \) are the mass and stiffness matrices of the vehicle structure, \( u \) is the displacement vector at nodes (structural deformation as relative note displacements) and \( F(t) \) is the external force vector. \( F(t) \) refers to the impact force in the horizontal plane but needs to take into account gravitational loads and rail support forces if the vertical direction is considered. The first term on the left-hand side of equation (1) defines the acceleration \( \ddot{u} \) response of the vehicle \( (M) \) and the second term describes the stiffness response \( (K) \) over the notes \( (u) \) of the structure.

Equation (1) shows that a collision results in two consequences, the inertial motion of the entire vehicle and the structural deformation of the vehicle. As the mass matrix \( M \) is relatively constant, the responses of the vehicle are mainly determined by the stiffness matrix \( K \), i.e. the assembly manner of the vehicle structure. Hence, from the point of view of the force, structural crashworthiness denotes a process for building the vehicle to achieve an appropriate stiffness distribution.

The inertial response by the first term on the left-hand side of equation (1) concerns the kinetic energy of the vehicle and the deformation response in the second term is related to the potential energy of the vehicle. The correlation between kinetic and potential energies is described by the energy conservation law.

**Energy conversion in train collisions**

The generation of potential energy through structural deformation is promoted by the kinetic energy of the trains. During train collisions, the enormous amount of kinetic energy of the impact train(s) is converted to potential energy or dissipated through external work. The conversion of energy follows energy conservation laws, a derivation of the Lagrangian principle of the least action\(^{15}\), expressed as

\[ \Delta(E + U) = W^{\text{ex}} \]  

\[ (E_{\text{post}} + U_{\text{post}}) - (E_{\text{pre}} + U_{\text{pre}}) = W^{\text{ex}} \]  

where \( E \) and \( U \) are the kinetic and potential energies, subscripts \( \text{pre} \) and \( \text{post} \) refer to the moments before and after an impact, \( W^{\text{ex}} \) is the work done on the system by external forces, which is positive if the total amount of energy increases. The terms of
impact forces on the interfaces falls into the internal domain. In this case, the work by external forces, e.g., frictional work, can be ignored. Equation (2b) can thus be simplified to

$$E_{\text{pre}} = E_{\text{post}} + U_{\text{post}}$$  \hspace{1cm} (5)$$

Equation (5) shows the energy conversation when the impacting and impacted vehicles are included in a single system. According to equation (5), the aim to reduce the kinetic energy after the impact can be realised by increasing the potential energy through structural deformation. Note that, in this case $U_{\text{pre}} = 0$. From equation (3), the potential energy after the impact can be expressed as

$$U_{\text{post}} = W^{\text{in}} + W^{\text{ex}}$$  \hspace{1cm} (6)$$

where the subscripts $B$ and $S$ refer to the sets of beams and shells of the rail vehicle structure in a cross-section. Equation (6) shows that the structural internal work for the potential energy can be divided into two groups, that generated by beams and that by shells. Expressed by individual members, equation (6) becomes

$$U_{\text{post}} = \sum_i W_{\text{Bi}}^{\text{in}} + \sum_j W_{\text{Si}}^{\text{in}}$$

$$= \sum_i \int_{X_i}^{X_i} F_{\text{Bi}} \, dx + \sum_j \int_{X_j}^{X_j} F_{\text{Si}} \, dx$$  \hspace{1cm} (7)$$

where indexes $i$ and $j$ refer to individual components in beam and shell sets, respectively, $X_i$ and $X_j$ are the lengths to which the relevant components are crushed. Equation (7) shows that the ability to absorb energy is concerned with the number of beams and shells that are involved in the structural collapses and the extent to which individual components are crushed. Therefore, structural impact stability, i.e., the crushing lengths of $X_i$ and $X_j$, are crucial for structural crashworthiness of rail vehicles.

### Mechanical analysis of the impact stability of rail vehicles

#### Weakness characterisation of rail vehicles in structural collisions

Figure 1 shows the structure of the front part of the cab vehicle studied in this paper. Corresponding to the key issues on structural impact stability discussed on thin-walled tubes in the previous section, the cab vehicle structure shows the following characteristics.

1. **Geometry.** The cab vehicle possesses a symmetric geometry in the lateral direction and a non-symmetric geometry in the vertical direction. As a result, the cab vehicle experiences structural
instability in the vertical direction. With half a conical cab structure in the vertical direction, the weakness for vertical instability is towards downwards bending.

2. **Stiff distribution.** Very stiff, e.g. the bolster, and very soft, e.g. door regions, sections/parts are embodied in panels. Uncoordinated responses are likely to be induced when relevant sections are involved in crushing actions.

3. **Composition.** The framework of the cab vehicle is composed of reinforced beams with conventional open sections, i.e. channels, angles and I-beams. This indicates that, apart from the corresponding requirement between different panels in simple tubes, rail vehicles should also take into account the coordination localised between shells and associated beams.

4. **Structural patterns.** The underframe is much stronger and thicker than the side panels and roof. For crashworthiness designs, the underframe should be treated as a beam-dominated part covered with a thin plate, whereas the side panels and roof should be considered as panel-dominated thin-wall parts reinforced by beams. This difference in structural pattern indicates that the crushing manner of the underframe tends to be different from the side panels and roof.

The above characteristics highlight the differences between rail vehicles and simple tubes. These characteristics are the common features in modern rail vehicles, particularly for steel vehicles. This determines that the rail vehicle collapse is a more complex process than for a tube with flat plates. The purpose of the complex pattern of rail vehicle structures is to achieve global stiffness, which brings increased challenges for localised collapses. Promotion of local collapses or bending is thus the key matter for the structural impact stability of rail vehicles.

The construction of the structure of a rail vehicle has benefitted from using state-of-the-art pressed thin-walled structures, although this creates two challenges for further development.

1. The optimised structures leave limited space for implementing extra safety measures without altering the existing structural pattern. Consequently, unless there is a fundamental change, further modifications for crashworthiness would necessitate a compromise or some sacrifice from other aspects of the structural performance.

2. Continuous use of conventional standard sections of beams leads to crashworthy rail vehicles looking like a hybrid product, in which the global profile and assembly pattern are constructed based on crashworthy requirements (in particular, the vehicle’s end structures), whereas most of the localised components are still in conventional forms. The only exception is the newly supplemented energy absorber. This has hindered a systematic crashworthiness design of rail vehicles from the bottom-up. As a result, defects at the component level tend, frequently, to appear in collisions.

**Bending weakness: Downward bending tendency of rail vehicles at impact ends**

This weakness corresponds to the characteristics of the nonsymmetric geometry in the vertical direction and beam assembly pattern of the underframe. Figure 2 depicts the forces and relevant structural details at the impact end of the cab vehicle. The instability effects due to vehicle geometry, structural compositions and impact forces are summarised as follows.

- **Instability due to unbalanced structures.**

1. **End structure of the cab vehicle.** The underframe, the strongest part in the vehicle, is connected with cab panels (side panels at the vehicle’s centre) on the top, but is empty underneath. For any upward bending moment of the underframe, the top
structure can provide strong support to resist upward deformation. For a downward bending moment, however, the support from the top structure is limited, as the bending is closely localised to the bending region at the underframe.

2. Tapered draft sill. The tapered part of the draft sill leads to a downward pitch bending due to the following unbalanced effects: first, the downward moment due to unbalanced forces; second, the downward deformation due to the nonsymmetric tapered shape; and third, the reduced bending resistance of the draft sill due to a decrease of the cross-section in the tapered region.

3. Bar-shaped coupler. Possessing a large ratio of length to cross-section, the coupler tends to show unstable responses when experiencing an impact force in the axial direction. The unstable moment generated due to the offsets at the two ends is proportional to the length of the coupler. As a result, the longer the coupler, e.g. couplers between trailers, the worse the influence on instability.

Instability due to unbalanced forces.

1. Vehicle inertial forces. In a collision, a huge impact force and deceleration are produced. The impact force concentrates at the underframe level, whereas the resultant inertial force of the vehicle acts at the gravitational centre of the vehicle, above the underframe. The two forces produce a pitch moment, inducing downward pitch bending of the vehicle end.

2. Draft sill forces. For automatic coupling vehicles, the initial impact force applies at the coupler level, i.e. located at the front centre of the draft sill, whereas the support location of the draft sill is in the underframe level, which is higher than the coupler location. This pair of forces produces a downward pitch bending moment.

We can thus conclude that downward pitch bending is a weakness of rail vehicle ends as a result of the unbalanced structures and forces in the vehicles and draft sill. Taking the draft sill for examination, the unbalanced structure due to the fish-belly shape takes up a large amount of the draft sill in the vertical direction, leading to a greater influence of the structure than the forces for the draft case. For the cab end, by contrast, the unbalanced inertial force contributes more to the downward bending than the structure due to the heavy mass of the vehicle (tens of tons) and the clear height difference between the gravitational centre of the vehicle and the underframe. Crashworthiness measures for draft sills should therefore concentrate on structural enhancement of the height transition region, and measures for the vehicle end should concentrate on reducing the influence of the vehicle’s unbalanced inertial force.

In collisions, the downwards motion of a vehicle end is constrained by the ground through the bogie. As a result, downward bending at the vehicle end may cause a bounce of the vehicle, which increases the derailment risk and may also lead to an overriding risk. In this situation, as long as the bounce force, induced by the downward bending tendency of the vehicle end, becomes comparable with the gravitational force of the vehicle, the vehicle becomes unstable in the vertical direction. Similarly, if the draft sill is effectively bonded at the vehicle end, the downward bending tendency may cause the draft sill to bend upward at the internal end, as reported by Simons and Kirkpatrick in an impact test performed at the Volpe Centre in the USA. A number of impact tests and realistic incidents have shown the unbalanced tendency of rail vehicles in the vertical direction. As a safety measure, anti-climbing devices have become a standard instrument installed on the headstocks of the vehicle ends.

Weakness of shearing fracture: Irregular crushing responses due to uncoordinated structural stiffness

This weakness is related to the uneven distribution of stiffness in rail vehicles and the stress wave effect of impact structures. The reason, due to the
The stress wave propagation in a uniform long bar (without a need to consider deflected waves) can be expressed as

\[ \frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \]  

(8)

where

\[ c = \sqrt{\frac{k}{\rho}} \]

(9)

In equations (8) and (9), \( u \) is the particle displacement along bar axis \( x \), \( c \) is the wave propagation velocity, \( \rho \) is the material density, \( \sigma \) and \( \epsilon \) are the stress and strain of the bar, \( k = \partial \sigma / \partial \epsilon \) is the tangent slope of the stress–strain curve, representing material stiffness. In the elastic range \( k = E / \rho \), i.e. the Young’s modulus and for the plastic range \( k = P \), i.e. the tangent modulus. Equation (9) shows that the velocity of the stress wave is related to the material stiffness and density. When the stress wave encounters a section with two different materials parallel to the direction of travel, the velocities of the wave propagation in the two materials vary. Based on equation (9), the ratio of the squared velocities can be expressed as

\[ \frac{c_{\text{hard}}^2}{c_{\text{soft}}^2} = \frac{k_{\text{hard}}}{k_{\text{soft}}} \times \frac{\rho_{\text{soft}}}{\rho_{\text{hard}}} \neq 1 \]  

(10)

where the subscripts \( \text{hard} \) and \( \text{soft} \) refer to hard and soft materials. Equation (10) shows that the interface between the two materials experiences a shearing stress due to the different propagation speeds of the stress waves in the two materials. In rail vehicles, this shearing is of particular concern in two specific cases. One is the base metal material adjacent to an open space, i.e. doors or windows. The other is the ambient metal material adjacent to a very hard component or section, e.g. bolster beam or isolated devices.

**Fracture or unzipping trend at the rear upper corner of the front door.** In the case of door regions, the soft material refers to the opening space and the hard material to the adjacent edge beams. As \( k_{\text{soft}} = k_{\text{air}} \to 0 \), from equation (10), the ratio of the stress waves between the edge beams and the open region tends to be extremely high. Reflected in reality, the stress wave on the edges becomes relatively high as no wave is transmitted through the open door region. Although the induced shearing stress on the open interface is not a problem, it does cause uncoordinated shearing stress on the boundary, i.e. the corners between edge beams and the rear pillar.

Figure 3 shows the stress wave passing through a door region. Examining the rear pillar and its connections, the top and bottom beams of the pillar experience high stresses, whereas the rear pillar itself suffers little impact stress being directly transmitted from the open region of the door. As a result, at the top and bottom corners of the rear pillar, the gradient of the shear stress is very high. With different connection strengths at joints, the top corner is the critical region in this respect.

When the crushing of the structure reaches the door region, the situation becomes critical. In addition to the stress concentration at the top corner, there is also the possibility of bending of the top beam, which without a constraint from the opening space of the door can become a cantilever. When the top beam is built with a strong cross-section, such as vehicles with aluminium extrusion, the top corner of the door has a tendency to experience unzipping failures, as occurred in an aluminium coach in the accident at Ladbroke Grove in 1999. This conclusion, deduced from the viewpoint of structural composition, is in agreement with the ALJOIN work on materials for aluminium joints in rail vehicles performed by Kotsikos et al. This agreement shows that crashworthiness design is concerned with both structural and material behaviours and can be improved from either route.

**Warping trend when a rigid section is involved in the crushing.** In the case of a very stiff section merged into the vehicle structure, the soft material refers to the vehicle material and the hard material denotes the very stiff section. Assuming the two materials have the same mass density, from equation (10), the ratio of the stress waves between the very stiff section and the structural material becomes

\[ \frac{c_{\text{rigid}}}{c_{\text{metal}}} = \frac{\sqrt{k_{\text{rigid}}}}{\sqrt{k_{\text{metal}}} = \sqrt{\frac{k_{\text{rigid}}}{E_{\text{metal}}}} \]  

(11)

For a rigid-like part, \( k_{\text{rigid}} \to \infty \) leads to a difference in wave speeds between the two materials where \( c_{\text{metal}} = \) constant, \( c_{\text{rigid}} \to \infty \). This exerts an immediate transmission of impact stress through the very hard section to the region directly behind it and an uncoordinated deformation is generated, which is analysed below.

Figure 4 shows a tube that contains two rigid components/regions in its side panels. When the tube,
subjected to an impact force at one end, is crushed into a rigid component, the rigid component will directly transfer the impact force to regions behind it and shear the adjacent regions. The region behind the rigid component is likely to experience plastic stress and form plastic hinges. The regions adjacent to the rigid component experience a shear stress. With plastic deformations occurring around the rigid-like component, the motion of the rigid component becomes flexible, as will now be discussed.

1. If the rigid component remains stable during the motion, e.g. no rotation, the impact force on the rigid component will be transferred to the material directly behind it, inducing crushing behind and shearing beside. This situation, which tends to happen for objects with a small cross-section, leads to a penetration of the rigid component.

2. If the rigid component becomes unstable due to the created degrees of freedom of the plastic hinge, a rotation toward the outside direction of the tube will be created, inducing a warping deformation. This tends to happen for objects with a large cross-section, leads to a penetration of the rigid component.

3. To reduce the influence range for unbalanced responses and as the impact force and structural crushing are in the longitudinal direction, it is suggested that structures are designed based on cross sections. Taking the example of the fracture trend at the top corner of a rear pillar, a strong beam alignment with the cross-section, i.e. in the transverse direction connecting the pillar and the roof, will result in a higher stability than a strong cantrail across the whole region of the vehicle.

Computational analysis and structural modification

Finite element analysis of the original cab vehicle

Model setup. The computational investigation was targeted at the correlations between vehicle structure and collapse stability. Two scenarios, a single vehicle impact with a rigid wall and a head-on impact of two identical vehicles, were modelled for individual vehicle impacts. The reason for modelling these two scenarios was to examine the differences in the responses of rigid and deformable impacts. The studied cab vehicle was compiled as a realistic quasi-high-speed train of electric multiple units, running at 200 km/h. The vehicle body was built from pressed metal alloys of thin-walled skins and beams. High-impact velocities were used in the simulations to expose the crush pattern of the vehicles beyond defined scopes. The simulation result of a cab vehicle, i.e. lead vehicle with a cab, is briefly reported in terms of the aspects relevant to impact stability. The intermediate vehicle shows similar consequences in terms of structural collapse pattern.
The explicit finite element (FE) code LS-DYNA<sup>20</sup> was used in the modelling studies. Based on a single integration approach, explicit FE modelling centralises the information of each element at the centroid point of the element. Correspondingly, structural responses are represented by the differences among elements, rather than inside elements described by constant functions. This formulation leads to a large range of crushing deformations being taken into account, although it does result in a sacrifice of local detail, e.g. stress level. As explicit FE does not require equilibrium conditions to be met in the iterations, it is suited to the study of structural impacts where equilibrium states are difficult to find due to topological changes during the crushing of the structure.

Shell elements with the Belytscho–Tsay formulation were used for modelling the thin-walled structure of the cab vehicle in all the considered cases. In view of their indirect involvement in the crushing of the structure, the two bogies were approximately modelled by taking into account their support function. The time step length was chosen so that the distance travelled by stress waves in any time step, i.e. between two iterations of calculations, was smaller than the smallest element size, and thus all element responses could be taken into account thereby keeping a convergent iteration process. For the numerical process, central differences were used for extrapolation operations for the explicit advance in the FE in searching new points.

Figures 5 and 6 show the FE models of the cab vehicle for the FE mesh and head-on impact scenario, respectively. Some regions of shells have been made invisible to make viewing of the figure easier. The impact speeds were determined based on structural collapse distances, so that substantial structural deformations could be generated. Based on a series of trial cases, the impact speed for the scenario of impact with a rigid wall was set to 80 km/h and for the scenario of a head-on impact it was set to 75 km/h for each vehicle.

Two FE models were created for the simulation tests.

1. For the single vehicle impact scenario, the FE vehicle model was covered with deformable material elements, so that all characteristics and weaknesses of the collapse of the structure could be displayed and the rotational response and stress wave effects could be taken into account.

2. For the scenario of a head-on impact of two cab vehicles, corresponding to the simulation result of a single vehicle impact, a hybrid FE model was created with a front half vehicle modelled with deformable elements and a rear half with rigid elements.

The full deformable element model used in the single vehicle impact scenario can illustrate the deformation details of the entire structure of the vehicle. This provides a good basis for further investigations focusing on the sensitive regions where collapses tend to occur. A hybrid model, using the same dimensions and same mass distributions, can then adopt deformable elements in the front regions and rigid elements in the rear regions for a simplified representation. As the rear part modelled by rigid elements only requires six degrees of freedom to express, the simulation by the hybrid model becomes cost-effective.

Speeds of 80 and 75 km/h were selected for the impact velocities of the cab vehicle for the scenarios of rigid wall and head-on impacts, respectively. The representation of the impact scenarios to the impact cases at low-velocities depends on whether the cab vehicle can show crashworthy progressive deformations. This is because in crashworthiness cases, structures show a unique convergent response over the whole crushing range, resulting in similar behaviours in impacts at high and low velocities. Using high impact velocity cases allows results to be obtained over large ranges and also to offer a conservative design for low-velocity cases.

Train impacts involve a process of energy conversion, where the kinetic energy of the impacting train is transformed into potential energy by vehicle deformation and kinetic energy by vehicle movement. For impact cases with a high impact velocity, crashworthiness behaviour requires a rigorous response over the entire collapse distance and it lasts longer than impacts at low velocities, leading to a conservative design. The requirement for identical behaviours at different impact velocities is judged by the following
two aspects: first, whether the structural responses follow the same pattern at different impact velocities; and second, if there is enough time for structures to gradually negate the impact forces via structural deformation. Whereas the first aspect concerns the constitutive response of materials, the second aspect refers to a matter of dynamic transient characteristics. When one of these requirements cannot be met, as is the case in unstable cases, the kinetic energy increases, leading to scattered responses in dynamic movements or vibrations.

From the above discussions, the key for an identical response between different impact velocities is to ensure crashworthiness behaviour. As the cab vehicle of the modified design shows crashworthy responses, in this article the result from high-velocity impact is taken to be representative and its consequences are extrapolated to low-velocity impacts.

**Simulation of the original cab vehicle.** Figure 7 shows four snapshots of the simulation results for the rigid-wall impact of the original cab vehicle. Some of the front panel is not shown so as to create a clearer view. Globally the structure of the cab vehicle can retain stability during the collapse; however, locally bending appears in individual components. Two unstable responses can be observed: first, the structural weakness of downward bending, discussed in the section ‘Bending weakness: downward bending tendency of rail vehicles at impact ends’, is encountered at the late crushing stage; and second, the side sills and side panels lack localised progressive collapses.

The fracture weakness at the top corner of the door pillar, discussed in the section ‘Weakness of shearing fracture: irregular crushing responses due to uncoordinated structural stiffness’, did not appear in these simulations. One reason for this observation is that the crushing of the structure does not reach the door region. The other reason is that the current steel cab vehicle is built as a thin-walled structure, behaving more flexibly in crushing than aluminium vehicles with a structure made of thick walls. However, the fracture phenomenon at the top corner of the door region has been observed in real accidents such as the rail accident at Ladbroke Grove in 1999 that involved aluminium vehicles.

Unlike simple thin-walled tubes, the progressive deformations between the underframe and side panels do not fully correspond. The underframe shows multiple crushing lobes, whereas the side panels show a single bending lobe that corresponds to the entire irregular collapse of the side sills. The reason for the different deformation details between the underframe and the side panels is that the beam-dominated underframe can deform between individual cross beams, whereas the panel-dominated side panels are likely to show a large deformation on the basis of the entire panel.

The simulation results illustrate the benefit of structural stability obtained by using the constraints between the underframe and the side panels and side sills. The unstable deformation of the side sills and panels does not cause an unstable response of the entire structure due to the constraint from the underframe, in particular the strong draft sill, in the lateral...
direction. The downward bending of the underframe is retarded to a late stage under the constraint from the side panels in the vertical direction. However, the above two localised unstable responses represent unstable resources, requiring appropriate measures to restrain.

Located on the common edges of the underframe and the side panels, the stability of the side sills is determined by its structural pattern and interactions between the side panel and underframe. The impact behaviour of the side sills can thus offer valuable information. In the simulation, the side sills appear as a lateral rather than vertical deformation. The reasons for this choice are as follows.

1. From the standalone strength of side sills. Building with a channel section opening horizontally, the two side sills are weaker when bending in a lateral direction than in a vertical direction.
2. From the connection strength from cab panel. Positioned vertically and gradually transformed on the top side, the cab panel offers a much stronger resistance when bending vertically than laterally, which leads to the side sills tending to deform laterally.
3. From the connection strength from underframe. The side sills are connected with the strong draft sill through a thin-floor and some cross beams at intervals. An easy deformation is localised bending from the intervals between cross beams, which is the bending pattern of the side sills (see Figure 7).

**Modifications to the cab vehicle**

*Structural modifications and simulations of the modified cab vehicle.* In principle, structural modification concerns a process of design optimisation. Depending on the purpose and information available, the process may be an explicit method or a conceptual adjustment. For the explicit approach, the design optimisation concerns a theoretical process based on a mathematical algorithm where variables, objectives and constraint conditions are required to be functionally expressed. For the conceptual adjustment, the design optimisation is often based on a hybrid process where variables, objectives and constraints are required for the conditions available for adjustments. The modification approach is often a trial progress based on mechanical prediction and experience judgement. For such a complex system of rail vehicle collisions, assumptions and simplifications are inevitable for employing mathematical optimisation. As the purpose and effectiveness can be confidently predicted, conceptual optimisation, e.g. modification, is a practical approach.

Structural modification in this paper follows a conceptual approach. The modifications concentrate on overcoming irregular structural deformations, e.g. bending, that appear in the original design and supplementing energy absorbers for increased energy absorption ability. The stiffness and structure of the front part of the cab vehicle were redesigned based on the requirements of crush zones and driver safety cell. Figure 8 shows the original and modified cab vehicles. The enhancement measures were as follows.

1. Correction of downward bending of the underframe. The bending stiffness in the height transmission region of the draft sill is enhanced by implementing vertical wing plates on the open side of the two back-to-back channel beams in the rear end.
2. Correction of the bending weakness of the side sills in the lateral direction. The single channel beam is changed to a pair of face-to-face channel beams. Each channel beam of the pair possesses the same cross-section as the original but with half of the thickness, resulting in unchanged mass of the side sill.
3. Increase of energy absorption. Two thin-walled rectangular tubes are installed at the two sides of

![Figure 8](image-url)
the draft sill and act as energy absorbers. In addition to increasing the ability to absorb energy, the absorbers also increase the stiffness and structural integrity of the underframe, especially in the lateral direction.

4. **Design of crush zones and driver safety cell:** The region before the driver location, which is indicated by the window, is designed as crush zone 1. The region of the driver location is designed to be a safety cell by installing a rigid-frame ring across the underframe and side panels. The region behind the driver and before the strong bolster is designed to be crush zone 2. Undergoing a stress wave and designed with appropriate stiffness, crush zone 2 only starts to collapse after the completion of the crushing in zone 1.

The slight increase of the mass due to the modifications leads to a large increase in the structural integrity of the cab vehicle. The increase of the mass for structural enhancements includes enhancing wing plates added in local regions of the draft sill and the beams used to create the safety cell. The amount of increase in the mass due to these structural enhancements is small. The increase in mass for the function of energy absorption refers to the addition of the two energy absorbers. The influences of increasing mass on impact behaviour are discussed as follows.

1. **Structural partition effect by the rigid ring.** The driver safety cell effectively partitions the length of the cab into three regions, i.e. the two crush zones and the rigid ring. The decrease in section distances in the longitudinal direction leads to an increased bending resistance of the structure.

2. **Structural evenness in crush zone 1.** The two energy absorbers and the modified cross-section of the side sill increase the evenness of beam distributions in the lateral direction, changing the bending resistance from the individual behaviours of the beams to an assembly of three types of beams.

3. **Structural tolerance to individual failures.** In addition to its energy absorption ability, the extra energy absorbers increase the extent of structural stability during collapses, as the failure of an individual component now has a smaller effect on the stability of the entire system due to the increase in the number of lateral elements.

4. **Increased inertial force due to the increased mass.** Comparing with the benefits in the above three terms, the impact damage due to the increase of the mass is a trivial matter.

Figure 9 shows the simulations of the modified vehicle impacting with a rigid wall. The cab structure shows improved progressive deformation. The weakness of downward bending has been overcome. The bending of the side sills and the side panels is prevented. The crush zone 2 collapses after crush zone 1. The driver safety cell remains intact during the crushing of zones 1 and 2. Table 1 shows the energy dissipated in the structural collapses of the original and modified cab vehicles. In all the cases, the passenger compartment remains intact. When crushing to the same distance (2.115 m), the energy dissipated by the improved vehicle increases by 52%.

**Simulation of the modified cab vehicle in the head-on impact scenario.** After the simulation of the impact of the cab vehicle with a rigid wall, the head-on impact between two modified cab vehicles was performed. The purpose was to examine the difference between a rigid-wall impact and a head-on impact. Here the head-on impact is referred to as the impact scenario with a deformable and moveable object.

Figure 10 shows the simulated consequences of a head-on impact between two identical cab vehicles that behave well in the rigid-wall impact. The downwards pitch bending motion again appears.

![Figure 9.](image-url)
This indicates that downward bending is a major structural weakness of the cab vehicle.

The simulation also illustrates the following two phenomena: first, a rigid-wall impact can lead to a larger impact stability than an impact with a deformable object, as shown by the different responses between Figures 10 and 11; and second, a symmetric impact can result in asymmetric responses, as shown in Figure 7 where one side sill bends inwards and the other bends outwards. These two phenomena were discussed in detail in Xue et al.\textsuperscript{14} where the external behaviour, i.e. interactions between vehicles, rather than internal behaviour of vehicle structures was investigated.

Figure 10(a) shows that the downward bending motion is caused by the bending of the draft sill, whereas the side sills retain their vertical locations during the impact. After a further enhancement of the draft sill at the end part, the reinforced cab vehicle showed progressive deformation in the head-on impact, shown in Figure 11. This modification shows the importance of structural enhancement on the stiffness in the weak direction of asymmetric structures.
Conclusions

The impact behaviour of a structure is strongly correlated with its physical nature and its functional response, i.e. its geometry, composition and stability of deformation. Targeting these three aspects, this paper highlights the following conclusions and findings.

Effect of structural geometry

The effect of structural geometry on impact stability can be summarised as: first, a symmetric structure can increase the impact deformation stability of the structure although it cannot ensure a symmetric deformation of the structure; and second the solidification of boundary conditions on a structure plays a crucial role on the impact dynamic stability of the structure. The former aspect targets the structural response inside rail vehicles and the latter is concerned with the dynamic response of the entire rail vehicle. Note that the benefit of a symmetric geometry on stability is due to an even stiffness between different sides and thus stiffness enhancement by material or structural measures can create the compensation of the instability due to a nonsymmetric geometry.

Geometrically, rail vehicles are built to be symmetric in the lateral direction and asymmetric in the vertical direction. For the boundary conditions, rail vehicles are flexibly constrained in the lateral direction by wheel/rail contacts, supported solidly in the vertical direction by the gravitational effect and coupledlinearly in the longitudinal direction. These characteristics of rail vehicles determine that, in the vertical direction, rail vehicles have a propensity to irregular deformations, but those are easily controlled. In the lateral direction, rail vehicles have a tendency to respond in a regular manner, but easily reach uncontrolled instability as soon as irregular responses are generated. In the longitudinal direction, due to a lack of boundary constraints, the behaviour of rail vehicles is highly dependent on the collapse states of couplers and structures.

The instabilities of rail vehicles in the lateral and vertical directions are related to derailment and overriding risks, respectively. Based on boundary solidifications, for controlling the vertical instability, simple measures, e.g. anti-climbing devices, can be effective. For dealing with the lateral instability, however, comprehensive measures are required and stability behaviour after derailment needs to be considered. With regards to the vertical instability, downward pitch bending at the vehicle front is an intrinsic weakness of rail vehicles. This may promote a ‘bounce’ at the impact end of the vehicle.

Effect of structural compositions

The structural composition of a rail vehicle has an effect on the deformation stability due to interaction and coordination between components on the cross sections being crushed. The behaviour of a very stiff component (e.g. bolster) and a very soft section (door opening region) are analysed in this paper as the extreme cases of uncoordinated stiffness. A very stiff component directly transfers a load to the region behind it without deformation itself, whereas its adjacent regions collapse from the front. Depending on the size of the stiff component, warping or penetration may be induced. The open regions in doors cannot transfer any load to the rear. As a result, the rear pillar does not experience impact loads, whereas its two ends experience high forces in the longitudinal direction. Fracture or unzipping may occur at the top corner of the rear pillar.

Another coordination case is for the different behaviours of components between standalone and installed components. To simplify the process and focus on key characters, a great deal of impact testing targets standalone components, energy absorbers in particular. In many cases, however, the behaviour of a standalone component is different from its performance when installed in a vehicle. This is because, structurally, the interconnections between components in vehicles are more flexible and unstable during vehicle impacts than in the standalone condition and, dynamically, impact forces usually do not align with the directions of components. A similar case is the difference between a structural frame and a frame covered with skin shell. In order to concentrate on the key performance, crushworthy structures are often designed and tested based on the performance of standalone frames. Although the frame can give information about the general situation with respect to the converged crushworthy behaviour, it can only provide limited information about the diverged sensitive responses of unstable consequences.

Since many of the traditional pressed sections for beams used in rail vehicles are not designed for crashworthy purposes, irregular deformations on small elements are difficult to prevent. The deformation stability of rail vehicles should thus focus on the coordination of major components in a global sense.

Importance of deformation stability

Structural crashworthiness concerns structural behaviour during crushing deformation. As crushing is a consequence of plastic deformation, the stresses on all the components in crushing fall into similar ranges for metals. Therefore, strain or deformation, rather than stress, is the determining factor for structural behaviour in collisions. As collision collapse requires the involvement of all the parts on cross sections, the conventional practice of ‘the stronger the better’ setup for retaining an unchanged topology is inappropriate for structural impacts. Consequently, appropriation and cooperation are the key characteristics. The requirement for individual components
should be based on their contributions to the crushing process, so that each component can join the destructive process in an adequate manner with little disturbance to the crushing behaviour of the surroundings.

From a structural point of view, deformation behaviour depends on the distributions of structural stiffness on cross sections and along the crushing direction. From a material point of view, structural collapses are the consequence of strain plastic behaviour at local regions. Design and optimisation for the crashworthiness of vehicle structures should thus place an emphasis on creating structural stiffness for global behaviour and promoting material collapse at local regions, so that the global stability of the structure can be retained and progressive collapse at local regions can be generated. The deformation stability of a structure undergoing a transient dynamic process due to an impact should be examined in terms of its progressive performance to reduce the relevant risks from unstable scenarios.

The discussions and conclusions in this paper target rail vehicles but are also relevant to the impact behaviours of other thin-walled structures in other applications. The authors hope that this work can bring an insight into the mechanical fundamentals of structural impact behaviours and promote appropriate considerations in the design and research of rail vehicles and other means of surface transportation.

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