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Development issues for impact safety of rail vehicles: Robustness of crashworthy designs, effect of structural crashworthiness on passenger safety and behaviour characterization of vehicle materials

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Abstract
In this paper the authors discuss three issues of structural crashworthiness of rail vehicles which are in correspondence with the questions enquired by the reviewers for our two previous publications [1,2]. The three issues are as follows: (1) the robustness of a crashworthy design in the scenarios different from the design conditions; (2) the correlation of structural crashworthiness to passenger safety; and (3) behaviour characterization of vehicle materials in train collisions. The purpose for processing these issues is for an increased understanding of research conclusions gained from different conditions towards integrative descriptions. Targeting the development requirements, an appropriate treatment of these three issues could generate a promotion on crashworthiness applications and bring an increased confidence in progressing crashworthiness of rail vehicles.

Keywords
Crashworthiness of rail vehicles, robustness of crashworthy designs, passenger impact safety, materials of rail vehicles, behaviour sensitivity of train collisions

1 Introduction

During the period 1980-2000 a variety of development programmes on the crashworthiness of rail vehicles were conducted by different organisations in the railway industry. The pioneers included the European Railways' Office of Research and Experimentation (ORE) (through B165 Committee) [3], British Rail (BR) [4] and French Rail (SNCF) [5]. This was followed by a series of research programmes organised by the EU, including SAFETRAIN, TRAINSAFE, SAFETRAM, SAFE INTERIORS, and numerous research activities run in the US [6]. These research activities included an understanding of the mechanism of train collisions and facilitated the design principles of crashworthiness of rail vehicles which are now widely accepted. The European and the US research projects led to the formulation of new crashworthiness standards [7-9] which sees the emergence of a new era in crashworthiness of rail vehicles. New application designs in energy absorbers, structural implementations and material applications bring distinct progress. On the academic side, theoretical investigation brings a good implementation to industrial practices and promotes advent suggestions for further development.

Train crash events usually occur in two successive impact phases and these tend to occur sequentially. In the first phase, targeted by primary structural crashworthiness, the kinetic energy of impacting train(s) is absorbed by structural collapse and deformation of the vehicle structures. In the second phase, targeted by secondary interior crashworthiness, passengers impact with vehicle interiors as a response to the inertial force generated in collisions. Unlike the automotive sector, structural crashworthiness of rail vehicles was more densely investigated than interior crashworthiness in the early development stages. This probably reflects the fact that the railway rolling stock assets were publically owned and they are easier to control than the passengers, whereas in the automotive sector private owners consider passenger protection to be the priority. When considering transferring technology from one mode to the other it should always be emphasised that the impact scales are very different between the two modes. In the rail scenario the masses are much higher and results in very high energy levels and a high energy absorption demand. Additionally for passenger impacts, the mobile and unbelted states of passengers in rail vehicles lead to far more complex scenarios of passenger impacts than automobiles. Prior to dealing with passenger impact safety, the influence of structural crashworthiness on interior crashworthiness is worth discussing.

The impact response of rail vehicles is a dynamic process with diverse responses and a great variation in failure modes. There is therefore a concern for how reliable and robust a crashworthy design is in different crash scenarios, i.e. how sensitive rail vehicle behaviour is to impact conditions. Impact scenarios addressed here are determined by three variables as follows: (1) *impact severity* related primarily to impact speed and the impacted interfaces, e.g. impacts rather than head-on; (2) *structural characteristics* the rail vehicles, referring to the layouts, configurations and structural integrity; and (3) *dynamic performance* affected by crashworthiness designs, energy absorption management systems and integrity levels. Moving on rails, structural collision scenarios of trains are heavily dependent on velocity and obstacle, whereas passenger collision scenarios are established on the consequent basis of structural collisions. Therefore, passenger collisions of the secondary impacts are more complex than structural collisions of the primary impacts in terms of impact scenarios. This leads to the following two characteristic features of train collisions: (1) simple impact scenarios, as train collisions are always originated along the track direction and guided on rails, and (2) complex variable responses, as collision consequences are strongly affected by the numerous degrees of freedom contained in couplers, bogies and wheels-rails. Consequently, the influence of impact velocities and impacted interfaces on train collisions has attracted a great deal of attention from researchers and customers.

Different materials have been used for rail vehicles. In the early stages modern rail vehicles were generally built as thin-walled steel structures. The structures were replaced by aluminium extrusions in recent years whose light density permits the adoption of complex sandwich structures in building vehicle panels. More recently rail vehicle structural design is seeing the emergence in the use of composite materials following on the great success in composite passenger airplanes and race cars. An investigation of the influence of materials in crashworthiness behaviour would benefit the development of crashworthiness of rail vehicles.

The three aspects mentioned above, i.e. robustness of crashworthy designs, correlation of structural crashworthiness on passenger safety and influence of vehicle materials on impact behaviours, are discussed in the current paper. Focusing on development issues, this paper is an effective supplementary to our two previous publications [1,2].

2 Robustness of crashworthy designs in different impact scenarios

This section targets the two types of questions from the reviewers of the previous two papers [1,2] on the effects of the parameter variations of vehicles and scenarios. One is the robustness of the simulation result when vehicle configuration is changed. The other is the validation of the simulation result obtained at a higher close speed to the scenarios at lower impact speeds. The selection of 80km/h for the collision speed in our modelling comes from two considerations. On the one hand, the collision at 80km/h can produce sufficient structural collapse, so that the deformation over all the range of the crushing zone could be examined. On the other hand, structural deformation at higher speeds is more unstable than at lower speeds and thus the conclusion obtained at the speed of 80km/h can suit a wide range of impact cases. Readers who are interested in this matter can refer to a previous publication of ours [1] for a more detailed discussion. Robustness here refers to the ability of a system to fulfil assigning functionalities when behaviours and conditions vary from design situations. The variation of behaviours and conditions show probabilistic features and the range of the variation or fluctuation permitted for convergent behaviours refers to the robustness of the system. This section focusses on the robustness of a predictable crashworthy design affected by changes from vehicle configuration and impact velocity.

In collisions, rail vehicles may show regular or irregular responses. Regular responses are the essential requirement for crashworthiness behaviour and irregular responses often lead to unstable or irregular consequences. Crashworthiness refers to the response under certain conditions and thus a crashworthiness design or response may show unpredictable events as soon as the impact goes beyond crashworthiness conditions. From a mechanical point of view, the above two consequences inform the different ways in dealing with the kinetic energy involved in the collision, reflecting the ability of a rail vehicle to perform the crashworthy design endorsed. It is worth noticing that crashworthiness designs are generally based on the scenario cases of head-on or end-on collisions under limited impact speed [8, 9]. While this is the usual case in impact events and has nominal information, other collisions on different interfaces, e.g. side impacts and level crossing or obstacle impacts, and on high impact speeds contribute a large share of fatalities in railway accidents. Collision behaviours of crashworthy vehicles in different cases illustrate the robustness of rail vehicles and affect the confidence of customers and industries on crashworthiness designs. Figure 1 depicts the two types of responses of rail vehicles, i.e. robust and scattering, as well as the energy transmissions in train collisions.

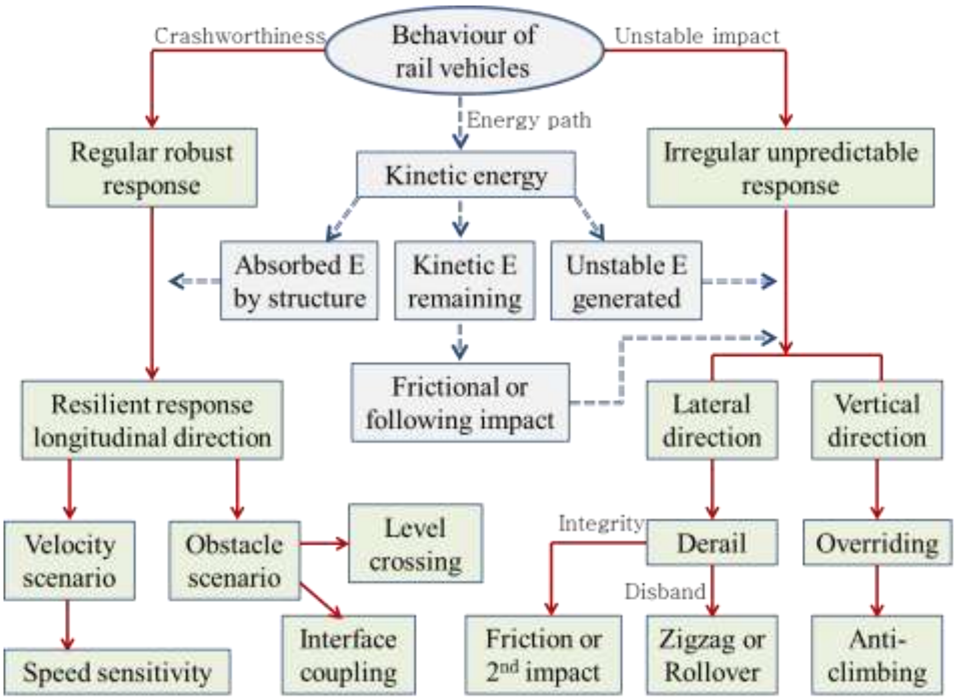

Figure 1: Structural responses and energy distribution in rail vehicle collisions

Energy transmission is the physical principle behind impact events while controlling the absorption of kinetic energy is the fundamental principle behind crashworthy design. In a railway collision, the huge kinetic energy of the impacting train(s) needs to be managed and is either absorbed by structural deformations or transformed into other forms, e.g. dynamic interactions. As demonstrated by Fig.1, in collisions the kinetic energy is dissipated along the following three routes: (1) absorbed by structural deformations, (2) remains as kinetic energy if vehicles keep moving after the impact and (3) transformed to unstable kinetic energies as vehicles leave the track. The unstable energies refer to the diverse energies, e.g. frictional, heat, sound, vibration and irregular deformations. The remaining kinetic energy after the collision may be dispersed through frictional work between the track and vehicles if the vehicles retain their original coupling states. It would be converted to unstable energy if the train hits another train or obstacle or if the train is derailed in the collision with subsequent rollover, overriding or jack-knifing. In both cases, as long as the impacting train keeps the regular connective states with couplers and bogies, the promoted interactions may increase the dispersion rate of the kinetic energy. In instances, when a derailed train with normal coupling state hits a wagon and pushes it, the wagon is able to dissipate some of the kinetic energy, resulting in an increase of energy dissipation. Therefore, increasing the amount of structural deformation work is a key feature in crashworthy designs, whereas keeping the regular coupling state of the train can reduce the damage in the post stage of a collision.

Structural crashworthiness is provided by progressive deformations made up of a series of discrete deformations. The frequencies and magnitudes of these discrete deformations are related to the materials, structures and loads. For crashworthiness, deformations should be within the same area and deform one by one based on their locations. This enables the total deformation to be maintained and avoids global collapses. This is a design challenge, as it is influenced by the ratio of the length to the cross sectional area of the structure, the dynamics of impact loads, the nonlinearity of materials and the stability of boundary conditions. Variation from progressive deformations may lead to buckling and poor crashworthiness performance. Therefore, crashworthiness requires the structure to be designed in such a way that the deformation is encouraged or enforced to follow the progressive route. The measures may include geometric parameter and a strengthened region of the structure ensuring it crushes in the weaker orientation.

The robustness of a crashworthy design depends on how resilient the design is by retaining convergent performances in different scenarios. The robustness of rail vehicles in different cases is comparably discussed as follows.

1. *Between crashworthy and non-crashworthy rail vehicles*, as stabilised resilient behaviour is a major target of crashworthiness, a crashworthy design can tolerate a wider range of scatterings and thus behaves more robustly in impacts than conventional ones.
2. *Between crashworthy designs based on different scenarios*, a vehicle design based on a strict scenario can ensure the vehicle to behave healthy in the scenario with lenient requirement, whereas a vehicle design based on lenient scenario cannot exclude the possibility of appearing divergent behaviour in the scenarios with strict requirement. Therefore, the design based on the scenarios with strict requirements results in higher robust performances than that based on lenient requirements. On this case, the design built after taking into account different impact interfaces, e.g. side impacts and impacts with obstacles or automobiles, shows increased integrity among scenarios and behaves more robust than the design built under the regular head-on impacts.
3. *Between high and low impact velocities*. A change in impact velocities produces two different consequences. One consequence is that impacts with higher impact velocities lead to higher impact energy and longer crushing distance than impacts with lower impact velocities. Correspondingly, crashworthiness design of high speed impacts requires the involvement of large regions in which stepped deformation patterns with a series of substructures are often adopted to increase the stability of structural deformations. The other consequence is that

impacts with higher impact velocities result in higher strain rates on the structure, leading to more difficulties for progressive deformations than lower impact velocities. This is evidenced by the case of quasi-static impacts, an extreme scenario of low speed impacts, where progressive deformations are easier to form than high speed impacts.

For structural crashworthiness of rail vehicles, the purpose is to ensure the responses, deformations and displacements to be converged in the longitudinal direction. For this purpose, the instable responses in the vertical and lateral directions should be controlled within relevant ranges, including the resilient mechanisms for anti-climbing and anti-overriding, the prevention measures for coupler bending and bogie dismantling from the vehicle body. Couplers play an important role in impact stability and, depending on their location on the train, may affect vehicle behaviours in two different ways. For couplers that experience structural collapse in advance of crushing an essential requirement is to shear off the coupler when the impact force reaches a certain predetermined magnitude. This prevents the influence of irregular coupler deformation. A discarded coupler could be a problem and create a derailment risk. It is therefore important that there is a strategy for coupler retention. For the couplers between intermediate vehicles, the important requirement is to provide a certain connective stiffness to increase the integrity between vehicle ends so that irregular responses of individual rail vehicles, a main cause for zigzags, can be constrained or retarded. In terms of connective stability, articulated trains have an advantage over conventional non-articulated trains [10].

3 Correlation of structural crashworthiness and passenger impact safety

The main purpose of crashworthiness of rail vehicles is for passenger/occupant safety. In the respect of structural crashworthiness, collision impulse generated in structural impact of rail vehicles by inertial effect is a key parameter for an evaluation of interior crashworthiness. In the respect of interior crashworthiness, due to the unbelted status of occupants and varying layout of seating regions, the impact scenarios are complex. Relevant studies understandingly fall into the two parties involved in the impacts, i.e. occupant responses and interior designs. Occupant responses need to consider their seating directions, standing status, driver activities and injury consequences from different collisions. Interior designs on layouts, structures and materials focus on seats and bay tables for the case of seating and luggage rakes and hand supports for the case of standing. For an integrative investigation, the different combinations of interior details and occupant responses require to be analysed and evaluated in designs, tests and validations before recommending for standard procedures. A number of research programs have been carried out in the EU and the US. On the EU part, the major activities and developments on interior crashworthiness up to 2009 was extensively reviewed by literature [11]. The updated research progresses can be acquired from the EU project SafeInterior which was completed in 2010 and introduced by literature [12]. On the US part, relevant researches on occupant safety have been associated with a series of ambitious FRA projects [7, 13] which were programed in the last two decades and involve the impact tests of single vehicles, two vehicles and train to train, respectively. The focus of this paper is put on the correlation between structural and occupant crashworthiness, which is informed by the fundamental conclusions in the past studies and assisted by relevant concepts.

This section deals with the issue of the correlation of structural crashworthiness on interior crashworthiness. Different from the structure-structure impact in structural crashworthiness, interior crashworthiness concerns the passenger-structure impact. Due to the different physical behaviours, structural and interior crashworthiness are generally classified into two different domains for research. However, resourced from the same collision event, the relationship between structural and interior crashworthiness requires an integrative description. Note that, mechanically, a deformable object in collisions, e.g. the train or passengers, would illustrate two types of responses, a dynamic response of the object as a whole and a deformation response of the object in relevant regions subject to stresses. The dynamics and deformation responses promoted from structural and interior impacts in rail vehicle collisions are shown figure 2. The behaviours of stability and integrity are focused by dynamic response. The damages generated on the contact surface and by inertial effect are targeted by deformation response. Figure 3 depicts the detailed terms related to dynamic and deformation responses in interior impact. The terms are grouped into three stages based on collision phrases, i.e. primary impact, secondary impact and biomechanical response, to show the cause-effect correlation between different stages of impacts.

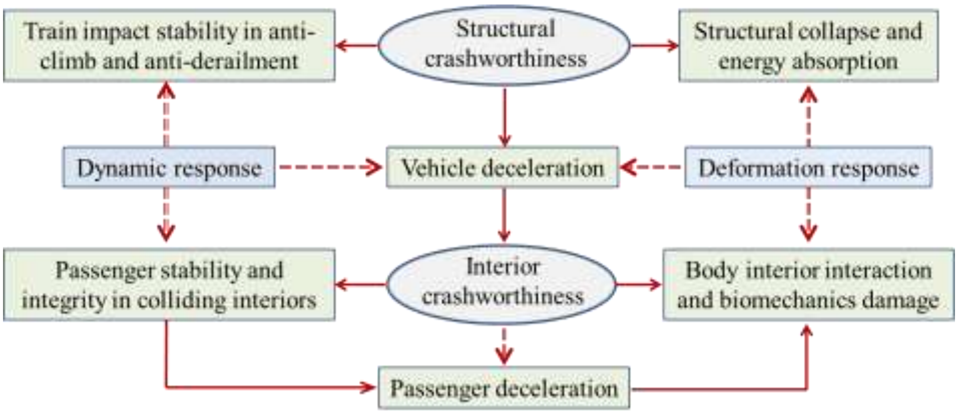

Figure 2: Dynamic and deformation responses associated with structural and interior impacts in rail vehicle collisions

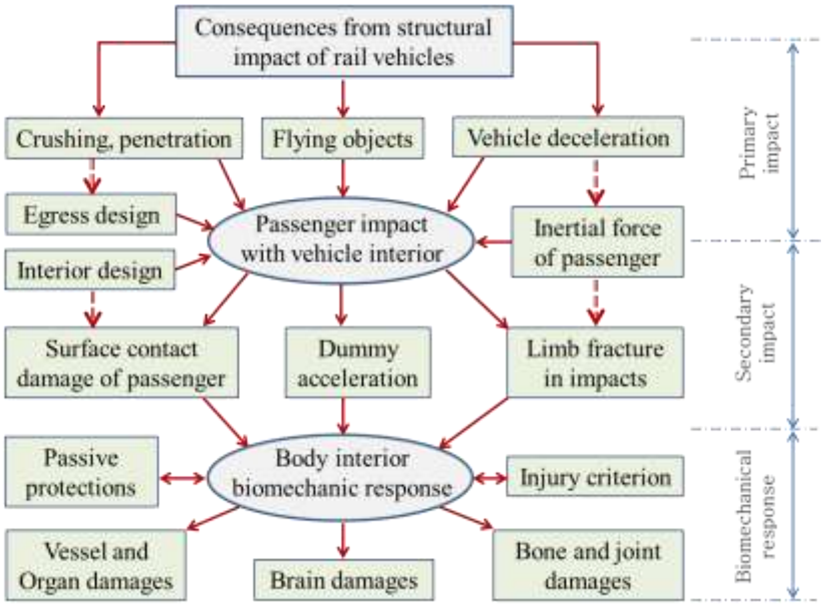

Figure 3: Relevant terms in the two responses from passenger impact with vehicle interiors

Figure 3 shows the relevant factors corresponding to dynamic response (termed as passenger impact with vehicle interior in the figure) and deformation response (termed as body interior biomechanic response in the figure) in passenger interior impacts. All the responses of passenger impact are promoted by the primary structural impact, as shown in the top cells in figure 3. In respect of structural deformation, structural impact often leads to space crushing, object penetration and flying debris, resulting in direct injury or fatality of occupants due to a loss of survival space. Closely relevant to structural behaviour, this issue is generally categorised as being in the domain of structural crashworthiness along with the control of structural collapses in unoccupied regions and providing safety cells or shields for drivers and passengers. In considering acceleration effect, structural impact generates the deceleration of the entire vehicle which promotes an acceleration pulse corridor to occupants. A secondary impact will then occur between occupants and vehicle interiors in the compartment. The progress and consequence of the secondary impact depends on the following two factors: (1) the crash pulse transferred from the deceleration of the impacting vehicle which generates the inertia force on all the objects and passengers, resulting in free moving passengers whilst causing some objects to be projected and (2) the mechanical interaction of free moving passengers and the interior. The secondary impact can result in damage and injury to the passengers. Injury criteria are used to determine the mortality and injury levels, for example Head Injury Criteria (HIC). Impact biomechanics also looks at the face, neck, chest, (rib deflection), abdomen, upper leg (femur and knee) and lower leg. Biomechanics employs various measuring and test devices and software simulations such as MADYMO. The crash pulse is a matter of impact cause, requiring actively controlling vehicle deceleration within a permissible level, whereas vehicle interiors are a matter of surrounding environments of passenger impacts, requiring passive measurements for reduced consequences.

In vehicle collisions, there are three stages of object movements relative to their surroundings, i.e. vehicle to vehicle or to the track, occupants to the compartment and organs/liquids in occupant bodies. The inertia effect and relative movements lead to impacts occurring in these three stages, including vehicle impact on the primary stage; interior impact of passengers with vehicle interiors on the secondary stage and organ impact inside passenger bodies on the third stage. The classification of the three stages shows the impacts can be structurally described by the internal impact response within each stage and the external interactions between adjacent stages. These three stages of impacts show a series of topological correlations of cause and effect: the impacts on previous stages provide the cause and environment to subsequent stages and the impacts on subsequent stages show the effect and consequence of previous layers. With this topological division, the impact at each stage is determined by three aspects: (1) *the impact source*, transferred from previous stages and enforced by inertia effect; (2) *the boundary constraints and impact interfaces*, provided by the current stage; and (3) *the physical response*, of the object itself. Among the three terms, term 1 emphasises inherited conditions, term 2 targets safety measures and term 3 examines damage consequence. For passenger safety, all the manoeuvre factors for designs come from term 2, which is however based on a clear understanding of term 3 and an accurate representation of term 1.

In short, the interactive correlations between different stages are illustrated by the impact transmissions from the previous to subsequent stages, in which the inertia effect is transmitted by setting-up decelerations and the environment is transmitted by applying boundary conditions. The impact responses inside each stage are determined by the surrounding environments as the boundary conditions and the degree of freedom (DOF) possessed by the impacting objects. The relevance is discussed as follows.

1. *On the stage of structural impact*, the responses of deformations and movements of rail vehicles should be constricted along the longitudinal direction, whereas the responses in the vertical and lateral directions should be effectively constrained within the ranges required by stability. As the deceleration generated in structural impact is the cause for the crash pulse executed on passengers in impacts, vehicle deceleration should be controlled within the safe range but be high enough for effective energy dissipation.
2. *On the stage of interior impact*, passenger damages come from the interactions between passengers and surrounding interiors as a result of surface contact impacts. Hence, impact damage at this layer is closely related to the layouts and materials of interiors. Specific

occupation characteristics in rail vehicles face very different challenges compared to other transportation means. For example, the use of seat belts as in automobiles would be unsuitable as is comparing passenger occupation characteristics to coaches and airplanes where passengers generally remain seated, unlike on trains where frequently moving passengers lead to far more complex scenarios of passenger impacts. In addition, while an increase of the softness of interior materials in regions surrounding passengers in intercity trains could assist passenger impact safety, they bring other concerns or difficulties such as fire safety, equipment cost and repair convenience. As a result, passenger safety faces two challengers in terms of the differences between theoretical requirement and realistic existence. One is the conflicting design requirements on vehicle interiors between impact and fire safety. The other is the practice that crashworthy designs have to be established on the basis of existing structural patterns and material provisions.

3. *On the stage of impact biomechanics*, while injuries and damages related to blood leakage, organ damage and airway blockage can be roughly informed by relevant criteria [8.9], e.g. criteria of head (HIC), neck (NIC) and chest (VC), the biomechanical reasons and biomedical progresses can only be obtained through biomechanical studies based on physical explicit description. A clarification of relevant details of physical responses could give a concrete support to tailored measures. The challenge for dealing with biomechanics damages is that early diagnosis and treatment by professional hands are often unavailable in remote accident sites. As a result, some medical symptoms which are required for a quick treatment in accidents tend to be delayed. On this aspect, portable diagnostic devices using emerging micro-sensor and wireless technologies could assist doctors to do some remote diagnoses and treatments before the arrival of rescuing forces, reducing relevant damage due to the delay in responses.

4 Behaviour characterizations of materials

As a ground transport carrier, rail vehicles are required to provide sufficient space inside the container and satisfy the operational requirements on dynamics and mechanics. As dynamic response and power consumption are proportional to the weight of the train, lightweight is an objective characterisation of rail vehicles. Consequently, modern rail vehicles are built as thin-walled structures using materials with good plane behaviours and cost-efficient production. Figure 4 shows the three common materials used for rail vehicles and their behaviour characterizations which are discussed in detail below.

1. *Steel*. Steel was used for the first generation of modern rail vehicles. With plentiful resources of steel and the wide availability of manufacturing techniques, steel could be flexibly fabricated into different shapes providing great convenience for the creation and modification of products. Consequently steel rail vehicles were an assembly of individual beams and shells, easy to supplement and modify. A distinct weakness of steel vehicles was, however, the heavy density of the material and this lead to the pursuit of applying thin sheets of steels in rail vehicles. As a result, very thin-walled structures are now used in rail vehicles following design optimisation. This is an issue faced by most of the designs using optimisation, as optimised structures tend to reduce the safety margins for the conditions which are not taken into account in optimisation processes. This brings concerns for reliability behaviours, such as defects at local regions and responses in extreme events, e.g. fatigue, vibration resonance, collision stability.
2. *Aluminium*. Aluminium extrusions are the second generation of modern rail vehicles. A distinct advantage of aluminium is its low density, though the low elastic modulus means the low density cannot bring a benefit unless complex structural patterns are adopted by aluminium vehicles. At about a third of the density of steel, aluminium can be built as double

layered sandwiches embodying re-enforcement scaffolds. With the use of advanced techniques, the poor welding quality weakness has been appropriately solved with more reliant joint techniques. Furthermore structural integrity is largely increased by extrusions. Thanks to the extrusion technique, aluminium vehicles possess the unique feature of high reliability with simple assembling structures produced from complex manufacturing techniques.

3. *Composites*. With the advantages of lightweight and high corrosion resistance, composite materials have been used for interiors of rail vehicles for many years. The successful application of composite materials in commercial airplanes, e.g. Boeing 787 Dreamliner built with 50% composite materials, has boosted the potential of using composite materials not just in the interiors but also in the structures of rail vehicles. One of the advantages of composite materials is the variation of composite type available for different applications, e.g. structure embodied sandwich for plates, carbon FRP for high loaded shells and glass FRP for low loaded shells. Fabricated by adhesive technique, composites provide a convenience for setting up phase density and distribution based on different requirements. The mixture manner of composites however also brings concerns to the bonding strength and interaction on the interfaces. Finding a solution to the brittle behaviour of composite materials and establishing a manufacturing technique for mass production are the two key issues associated with increasing the use of composite materials in rail vehicles.

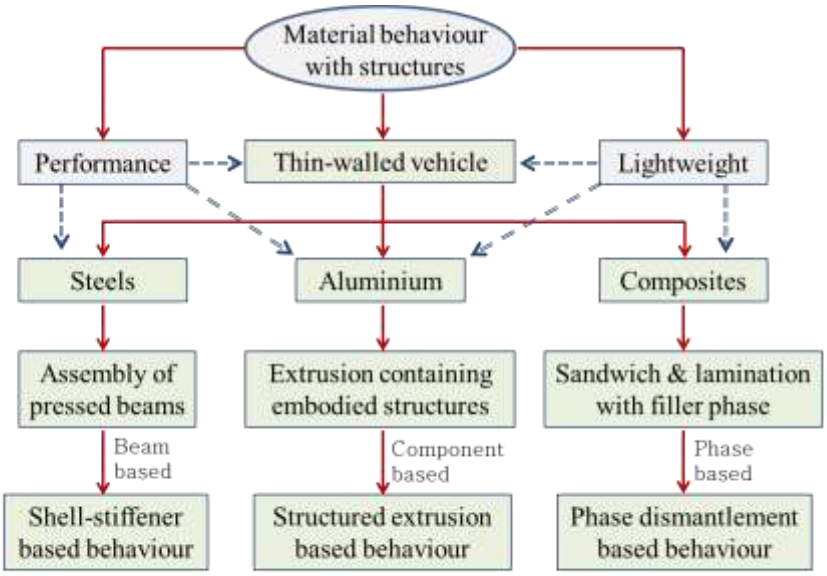

Figure 4: Material behaviours by structural enhancement and flexibility in crushing

To date, most crashworthiness designs have been incorporated into steel rail vehicles or steel energy absorption measures equipped in the end regions of aluminium vehicles. The popularity of steel devices in crashworthiness applications is relevant to the assembling manner of steel vehicles and the inheritance habit in railway manufacturing. Assembled in a bottom-up manner, steel vehicles are easily modified from a component level, offering convenience for the implementation of crashworthiness designs. The strong feature of inheritance in railways due to the scale of manufacturing means that steel devices or structures tend to be considered as the first option for crashworthiness designs, following the initial practice of crashworthiness measures conducted in steel vehicles. In contrast, the extrusion technique used in aluminium vehicles means that structural modifications on aluminium extrusions need to change the composition of extrusions, a complex practice involving manufacturing processes. Although steel is widely used for energy absorption, the application potential of aluminium materials (including aluminium foam fillings and thin-walled aluminium tubes) in energy absorption has started to attract much attention. The filled aluminium foams increase the stability of tube collapse and the amount of energy absorbed, favourably illustrating the potential use of aluminium foam in energy absorbers.

The progressive deformation required by structural crashworthiness corresponds to a series of local collapses from the impact end to the rear end, discussed as follows.

1. *The homogeneity of the structural materials* may affect the progressive deformation, due to the presence of stress concentrators in heterogeneous materials such as composites among adjacent regions. Metals such as steel and aluminium are more homogeneous and are more predictable in their response and easier to model.
2. *The Geometry and stability of the structure* has an effect on progressive deformation. The influences of geometry and structural patterns come from two aspects. For individual plates, the thickness and simplification of the plate affect progressive deformation. For a structure comprising a number of plates, the bending stiffness of the structure affects structural stability, for example, using the same material, a symmetric tube has better compression properties than a square channel. Steel beams and aluminium extrusions have structures that reduce the buckling tendency during crushing. Buckling would lead to complex bending interactions in the local regions. Aluminium extrusions have larger cross sections than pressed steels and this results in aluminium extrusions being stiffer than the equivalent steel beam.
3. *The failure behaviour of composite materials* is very complex and comprises a number of mechanisms including; delamination, matric failure, fibre breakage, interface cracking etc. This means that predictable crushing is very difficult to achieve and often fragmentation occurs as the composite energy absorber collapses [14,15].

Progressive deformation which is favoured by structural crashworthiness requires local material collapse based on plastic hinges and local structural constraining collapse confined by structural formations. Based on the three points discussed above, on the material aspect, both steel and aluminium possess even homogeneous properties and can generate plastic hinges for local collapses. On the aspect of structural constraining, however, as local constraining collapse depends on stiffener beams and plate thicknesses, thin-walled structural panels of steels could offer easier local collapse than thick aluminium extrusions which hold complex double-faced sandwich plates. Therefore, aluminium extrusions would face more challenges than steel materials in designing and performing crashworthiness behaviours.

Possessing two or more material constituent, composite materials show different behaviours from steel and aluminium. On the aspect of structural constraining of local collapses, composites need to control delamination. On the aspect of material local collapses, composites need to deal with the interaction between filler phase and the matrix. Therefore, composite materials need to show convergent behaviour when dismantling two material constituents and debonding ply interlaminars. As the reinforced material constituents show line shape and orientated towards different directions, it is difficult to promote progressive deformations along one direction. As such, fragmentation is a reasonable consequence for composite behaviour in crushing. Therefore, the work on composite structures should concentrate on progressive collapses based on phase separations, which often results in brittle disassembling consequences due to the macro sizes of the filler phase used in rail vehicles. Experimental and numerical investigations are demanded for understanding damage mechanism. Modelling is increasingly used to determine the crashworthiness of rail vehicles [1,2,16].

5 Conclusions

Train collisions concern a dramatic mechanical phenomenon in which multidisciplinary behaviours are presented in their extreme conditions. Excessive behaviours and fierce interactions among different behaviours are the two distinctive features illustrated in train collisions. The extraordinary process suggests that many traditional approaches focusing on stable and deterministic consequences require tailored extensions before they are used for collision analysis. This paper discusses three typical topics concerning extreme ranges and interactive responses as follows: (1) Robustness of crashworthy designs, concerning behaviour sensitivity to parameter variations; (2) Correlation of structural crashworthiness to passenger safety, concerning coupled interactions between different impact scopes; and (3) Material behaviour in crushing processes of structures, concerning constitutive evenness of material distributions and structural integrity due to material bonding status. Targeting the above three development issues, this paper offers an extending discussion from our pervious publications [1,2]. The following conclusions are highlighted.

1. Robustness of a crashworthy design is related to the convergent ability of rail vehicles when design variables vary among different impact scenarios. Robustness is thus used to measure the validation range of simulations or tests. With regards to the impact velocity specified in this paper, due to strain rate sensitivity of materials, impact scenarios at higher impact velocities result in more conservative consequences than those at lower impact velocities. By contrast, the results obtained from impacts at lower velocities can only give guided rather than confirmed conclusions to impacts at higher velocities. On this aspect, an extreme case of low velocity is quasi-static results where impact velocity is close to zero. Therefore, when using conclusions obtained from quasi-static or lower impact velocities to the cases at higher impact velocities, the ranges of suitability require to be investigated.
2. Passenger impact safety is related to a series of cause-effect impact consequences presented in train collisions. Collisions are a phenomenon occurring between any moving objects which are encountered in the course and possess relative velocities. Correspondingly impact interactions in train collisions fall into three types, including structural impact of rail vehicles, passenger impact with vehicle interiors and biomechanical impact of organs, vessels and bones. The influence of structural impacts on passenger impacts is by means of inertia effect which transmits vehicle decelerations to the crash pulse applied on passengers. In the respect of vehicle decelerations, crashworthy vehicles show stable force-displacement characteristics which can effectively reduce vehicle deceleration by evenly extending deformation period and diminish impact scale by dissipating energy through structural deformations. Passenger impacts in rail vehicles have some unique specifications, e.g. without safe-belt and protection measures and mobile states of passengers. The effect of the above specifications on impact biomechanics requires relevant investigations closely integrated with rail vehicles.
3. Rail vehicles built with steels, aluminium and composite materials show different behaviours in vehicle collisions, as a result of the substantial differences on structural patterns and material properties among these three materials. From the point of view of potential and constraining, material property concerns the natural possibility or opportunity possessed by materials for promoting different types of deformations. By contrast, structural bonding refers to constraining measures enforced on materials to assemble materials into a functional system. Crashworthiness design thus refers to a practice for guiding the progress of structural deformations so that the natural behaviour of materials could be effectively released in collisions. One of the challenges for behaving crashworthiness is that the existing structural patterns of rail vehicles were formed in early development stages when crashworthiness was not an essential requirement. As a result, while design principle and standard are based on

crashworthiness requirement, the basic patterns of the components, except for specifically supplemented energy absorbers, retain their original shapes for manufacturing reasons.

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