Crashworthiness Simulation of Urban Rail Vehicles
Based on ASME Standard

Hai-yang YU\textsuperscript{1}, Yang-yang YU\textsuperscript{1}, Peng LIN\textsuperscript{1} and Li-yang XIE\textsuperscript{2}

\textsuperscript{1}CRRC Qingdao Sifang Locomotive & Rolling Stock Co. Ltd., Qingdao 266111, China
\textsuperscript{2}Key Laboratory of Vibration and Control of Aero Propulsion Systems, Northeastern University, Shenyang 110819, China

Keywords: Braking simulation, Collision simulation, Stiffness design, Carbody.

Abstract. Based on ASME standard and technical conditions of vehicle bidding document, the crashworthiness of an urban rail vehicle is simulated by software HyperMesh and LS-DYNA. The collision simulation model applies braking force through beam elements to simulate the emergency braking status of the vehicle during the collision. The longitudinal stiffness gradient design evaluation of the carbody structure is realized by simulation analysis of the overall longitudinal impact. The crashworthiness of the train is evaluated from the aspects of energy absorption, longitudinal acceleration of the vehicle, climbing and derailment, longitudinal stiffness of the carbody structure, etc. The simulation results show that the crashworthiness of the urban rail vehicle meets the corresponding technical requirements. At the same time, a simulation method of vehicle braking behavior and the verification procedure of longitudinal stiffness gradient design of carbody structure are proposed.

Introduction

Operation safety of rail transportation, especially the safety of vehicle collision accidents, is receiving more and more attention. A. Erskine \cite{1} summarized research data on the crashworthiness of rail vehicles around the world, conducted comparative analysis to current British operation, the latest viewpoints and development worldwide. S. Bounds \cite{2} described principal findings in the project of Whole Train Dynamics (WTD), investigated the factors affecting the dynamic stability and general crashworthiness in event of an end on collision. W. Wang et al. \cite{3} proposed a joint simulation analysis method for train crashworthiness analysis based on nonlinear finite element method and one-dimensional multi-rigid dynamics technology. H. Zhou et al. \cite{4} studied the climbing phenomenon during the collision of rail trains based on the nonlinear finite element method and three-dimensional multi-rigid dynamics joint simulation method. S. Xiao et al. \cite{5} proposed a simulation method for analyzing the characteristics of couplers and buffers based on the discrete beam in LS-DYNA. Yang et al. \cite{6} simulated train colliding with a static train at a speed of 25km/h on curved and linear tracks based on LS-DYNA.

At present, Chinese institutes and vehicle design manufacturers carry out the design and evaluation of the crashworthiness of rail vehicles \cite{7-10} based on the EN 15227 standard \cite{11}. Research on vehicle crashworthiness against the corresponding US standards is rare. H. Liu \cite{12} and F. Luo \cite{13} analyzed the elastic-plastic deformation law of the collision post and the crashworthiness of the end structure for a North American urban rail vehicle based on the American subway carbody design standard ASME RT-2:2014 \cite{14}, but the vehicle collision calculation model construction, vehicle braking simulation, and longitudinal stiffness gradient design of the carbody structure were not involved.

Based on ASME RT-2:2014 standard and technical conditions in the employer's bidding document, this paper takes urban rail vehicle as the object, establishes a detailed train collision simulation model according to the design variable such as cars-formation, structural characteristics of the carbody,
braking requirement, and energy absorption characteristics of the end structure of the carbody by the software HyperMesh and LS-DYNA to evaluate the crashworthiness of urban rail vehicles.

**Crashworthiness Simulation Model**

According to the multi-body collision response behavior, the finite element collision simulation model of 12-group trains is constructed using HyperMesh and LS-DYNA. Vehicles No.1 and No.2 are detailed modeled presenting vehicle structure, bogie, suspension system and other vehicle substructures. Vehicles No.3 to No.8 are simplified as mass points, the inter-vehicle hooking device, suspension system and braking force are simulated by the force elements. The whole train model is treated as a symmetric semi-vehicle model to improve the calculation efficiency.

**Train Conformation**

The urban rail train is formed with 12 cars as shown in Fig.1, the train is flexibly formed with 2 cars as basic units.

![Figure 1. The formation of the train.](image)

where, A, B refer to car type, = refers to automatic coupler, - refers to semi-permanent drawbar.

**Carbody Structure and Material Characteristics**

The urban rail vehicle is made of steel, composed by cab, underframe, side wall, roof, and end wall as shown in Fig.2. The components and their internal substructures are mostly connected by seam and spot welding.

![Figure 2. Overall view of Carbody structure.](image)

There are five kinds of materials used for the carbody structure, the mechanical property of the materials are shown in Table 1.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Density /kg·m³</th>
<th>Elastic modulus /MPa</th>
<th>Poisson ratio</th>
<th>Yield strength /MPa</th>
<th>Tensile strength /MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>301L 1/16H</td>
<td>7860</td>
<td>200,000</td>
<td>0.33</td>
<td>345</td>
<td>690</td>
</tr>
<tr>
<td>301L 1/8H</td>
<td>7860</td>
<td>200,000</td>
<td>0.33</td>
<td>415</td>
<td>760</td>
</tr>
<tr>
<td>301L 1/4H</td>
<td>7860</td>
<td>200,000</td>
<td>0.33</td>
<td>515</td>
<td>825</td>
</tr>
<tr>
<td>301L 1/2H</td>
<td>7860</td>
<td>200,000</td>
<td>0.33</td>
<td>690</td>
<td>930</td>
</tr>
<tr>
<td>A588</td>
<td>7860</td>
<td>200,000</td>
<td>0.33</td>
<td>345</td>
<td>495</td>
</tr>
</tbody>
</table>
Finite Element Model of Vehicle

For the vehicle finite element model, mainly used are 4-node shell elements to construct the car body. The element size of the passenger area in the middle of the car body is set to 20mm. Since the end structure of the car body will be plastically deformed during collision, the element size of the corresponding area is set to 10mm ~ 15mm. The 1-D discrete beam element is used to simulate the spot welding relationship of the car body, the material model is MAT100. The 1-D discrete beam element is used to simulate the inter-vehicle coupler and buffer and the end deformation energy absorption characteristics of the car body, and the material model is MAT119, the performance parameters of the coupler and buffer are taken from the design parameters provided by the supplier, the end deformation energy absorption characteristic parameters of the car body are taken from the simulation results of the corresponding end structure collision. Rigid element is used to construct the bogie-frame, the bolster, and the spring, damping element are used to simulate the connection between the frame and the bolster and the vehicle body. Shown in Fig.3 is the composition of the train vehicle collision finite element model.

![Figure 3. Schematic of train collision calculation model.](image)

For the braking behavior of the vehicle, this paper calculates the corresponding braking force based on the vehicle braking deceleration and the vehicle impact mass, and the 1-D discrete beam element is used to simulate the braking and is applied to the bogie-frame, as shown in Fig.4 of the green marking line.

![Figure 4. Schematic illustration of vehicle braking simulation.](image)

**Definition of Contact**

In the process of train collision, physical contact may occur at some areas. After the frontal collision between two trains, the coupler of the head car first contacts, the coupler force increases rapidly, causing the coupler to shear, and then the anti-climb device is deformed and contacted with the structure of car body end. When the collision energy flow is transmitted to the interface of the intermediate vehicle, part of the intermediate coupler will shear and the end of the car body will
contact. Therefore, according to different contact relationships, type of contact is automatic single-surface contact (car end structure) and surface-to-surface contact (contact between car end structures, contact between wheel-set and rail, etc.).

**Design Scenarios of Crashworthiness**

**Train Crashworthiness Scenario**

According to the technical conditions of the vehicle design, the crashworthiness design shall meet the requirements of scenario 1 in Table 2 of ASME RT-2:2014 standard, i.e. two servicing trains, one train collides with the other stationary train at a speed of 24km/h, both trains apply emergency braking. The scenario is shown in Fig.5.

![Figure 5. Train collision scenario at 24km/h (15mph).](image)

**Design Scenario of Carbody Structure Stiffness**

In order to ensure the space integrity of passenger in carbody, it is necessary to ensure that the deformation of the carbody structure in the collision process gradually collapses from the front end to the middle of the carbody. Therefore, in the longitudinal structural stiffness design process of the carbody, the structural strength between the bolster beam (C in Fig.6) is set to be more than 40% higher than that between the anti-climb teeth and the coupler mounting seat (A in Fig.6), and the structural strength between the coupler mounting seat and the bolster beam (B in Fig.6) is set to be more than 20% higher than that between the anti-climb teeth and the coupler mounting seat. In order to meet the longitudinal stiffness design requirements of the carbody structure, this paper designs corresponding verification scenario based on the overall plastic buckling load gradient design concept of the carbody structure, as shown in Fig.7.

![Figure 6. Division of Longitudinal Stiffness Gradient of Carbody.](image)
Crashworthiness Simulation Analysis Results

The energy absorption of trains, longitudinal acceleration of vehicles, climbing and derailment of vehicles and structural stiffness of carbodies are analyzed according to the crashworthiness design requirements of urban rail vehicles.

Scenario of Train Collision at 24km/h

**Energy Change.** Under condition "3.1 train collision scenario", when two trains collide with each other at speed 24km/h, the overall energy and time curve of collision system is shown in Fig.8. Due to the existence of braking force, the collision energy of the system is not only dissipated in the form of plastic deformation of the carbody end structure, but also dissipated due to friction caused by braking, i.e. the kinetic energy of the system eventually tends to zero, which does not generate a stable platform stage in which the kinetic energy and internal energy of the system are formed due to the common speed of the two trains in the collision process. The speed and time curve of each train can better reflect this phenomenon, as shown in Fig.9.

![Figure 7](image_url)

Figure 7. Design Scenario for longitudinal stiffness verification of Carbody.

![Figure 8](image_url)

Figure 8. Energy and time curve of train collision system.

![Figure 9](image_url)

(a) The moving train  (b) The stationary train

Figure 9. Speed and time curve of each train.
For the calculation object, the energy dissipated by plastic deformation of the carbody end structure and the energy dissipated by braking account for 44% and 56% of the initial kinetic energy of the system, respectively. Among them, the deformation and energy absorption of the carbody structure are mainly concentrated in the structures such as the anti-climb device at the end of the carbody and the energy absorption tube. Due to the effective engagement of the anti-climb teeth at the end of the carbody, the passenger area of the carbody remains intact, as shown in Fig. 10 and Fig. 11.

**Figure 10. Maximum deformation status of head car of colliding train.**

**Figure 11. Plastic Deformation Status of End Structure of Head Car of Colliding Train at Main Moments.**

**Vehicle Acceleration and Speed.** The change of vehicle acceleration directly reflects the response degree of the vehicle during the collision. The response value of acceleration directly affects the intensity of the secondary collision between the crew and the internal structure of vehicle. Therefore, the design standards for the crashworthiness of rail vehicles all stipulate the vehicle collision acceleration index. The ASME RT-2: 2014 standard stipulates that the average acceleration of vehicles shall not exceed 7.5g. According to the speed and time history curves of each vehicle in chapter 4.1.1, the maximum acceleration of the head car of the colliding train is about 3.5g, which is less than the standard specified value, as shown in Fig. 11.
Risk of Vehicle Climbing and Derailment. When rail vehicles collide, the climbing behavior has an important impact on the casualties of passengers. Therefore, the vertical displacement caused by the vehicle-to-vehicle interface should be limited to effectively reduce the risk of vehicle climbing in collision accidents. Among them, compared with EN 15227 standard, ASME RT-2: 2014 standard not only specifies the lifting amount of wheel rim, but also requires the vertical displacement of underframe in two adjacent vehicles, and the limit for both is 101.6 mm.

Fig. 12 is the lifting amount of each wheel-set of the head car of colliding train, which is less than the standard required value of 101.6mm, in which the wheel-set number gradually increases from end 1 to end 2. Figure 13 shows the vertical displacement of the underframe of the head vehicle of colliding train, which is also less than the standard required value of 101.6 mm. in accordance with chapter 4.1.1, due to the effective engagement of the anti-climb device at the vehicle end, the vertical displacement of the carbody structure is obviously lower than the standard required value, i.e. the risk of climbing the vehicle can be effectively reduced by installing the anti-climb device.

Longitudinal Stiffness Analysis of Carbody Structure

For the longitudinal stiffness distribution characteristics of the carbody structure, the calculation results show that under the scenario in 3.2, the carbody structure presents progressive crushing buckling deformation from the end to the middle, and the overall deformation is controllable, as shown in Fig. 14. The Fig. shows the areas A, B and C of the carbody in 3.2. The structural buckling
load gradient of each area is obvious. The specific value is shown in Fig. 15, and the structural buckling load of each area meets the design requirements of the corresponding ratio.

![Figure 14. Schematic of progressive buckling deformation of Carbody structure.](image)

![Figure 15. Buckling load and time curve of Carbody structure.](image)

### Conclusion

Through the simulation analysis to the crashworthiness of the urban rail vehicles, the following conclusions can be drawn:

1. The energy absorption of the vehicle is orderly and controllable under the 24km/h collision scenario, the average longitudinal acceleration of the vehicle is less than 7.5g, no vehicle climbing or derailment occurs, and the requirements of ASME RT-2:2014 standard are satisfied.

2. Using discrete beam element to apply braking force to simulate the emergency braking of the vehicle during collision, the braking behavior of the vehicle is well reflected.

3. The analysis of the risks of climbing and derailment at the end of the vehicle shows that by installing an anti-climb device at the end, the vertical displacement of the carbody structure is lower than the standard value, thus effectively reducing the risks of climbing.

4. Obstaining plastic buckling loads of carbody section at different longitudinal position by the overall longitudinal impact simulation of car body structures, the evaluation of longitudinal stiffness gradient design is realized.

### References


