Study on side impact responses of suspension module in trams

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Abstract

The finite element models (FEM) of a 5-module 100% low-floor tram and a city bus are established to study the responses of trams under side impact scenarios. The model is a low-floor tram impacted vertically on the side wall of its suspension module. The simulation is conducted under two scenarios, one is the tram impacted by a Movable Deformable Barrier (MDB) with the velocity of 50 km/h, and the other one is the tram impacted by the city bus with the velocity of 30 km/h respectively. The result shows that three main responses of side impact are the lateral traverse, rolling and yawing displacements of the tram body. There are also failure of lateral stop, wheelset uplift of bogie and plastic deformation of sidewall on the impact side. The responses of tram in the latter collision scenario were more severe than those in the former. Rational explanations may concern that the kinetic energy of the city bus is bigger than the MDB, and the height of the impact point of the city bus is higher than that of the MDB. The result also indicates the damage in tram accident with large and medium automobiles, such as buses and trucks, is more severe than smaller cars. By analyzing the side impact problems of trams, the result can contribute to the development in side crashworthiness designs and the establishment of side impact standards for trams.

Keywords: Tram; Side impact; Crash responses; Crashworthiness

1. Introduction

At present, the relevant standards of vehicle crashworthiness are mainly aimed at the longitudinal impact response of the vehicles, including multi-level energy absorption, overriding, deceleration, survival space assessment etc. This representative evaluation covers most of the impact scenarios of railway vehicles on lines. However, low-floor trams, is easier to have a collision with cars because of their lack of independent road rights [1]. One of the collision scenarios beyond the research on longitudinal impact of vehicles is that the side of tram is impacted by a car. Relevant standards in the aspect of side impact are inadequate. For instance, EN15227 (Railway applications Crashworthiness requirements for railway vehicle bodies) [2], which was issued by the European Standards Committee defines trams as C-IV classification. The standard provides two collision scenarios. One is a front end impact between two identical tram units with the relative velocity of 15 km/h. The other one is a tram impacting a rigid obstacle in the angel of 45° with the relative velocity of 25 km/h. However, side impact scenario of trams is not involved.

Concerning side crashworthiness of car body, most relevant standards specify only the static strength requirements: The UIC566 published by International Railway Union requires that the connection between sidewall and underframe have the certain ability to resist lateral shearing [3]. In addition, the side beam is expected to bear a certain lateral force and have the ability of anti-rolling in standard 49CFR238 provided by the US Federal Railways (FRA) [4].

Below are some studies on the safety of the tram operation. In 2008, a project Transit Cooperative Research Program initiated by FRA and the Transport Development Corporation included a lot of simulation calculation on the crashworthiness of light rail vehicles. Based on the side wall construction of the light rail vehicles, 2 scenarios that a SUV car impacts a static light rail vehicle on the side face with respectively two velocities of 25 mile/h and 35 mile/h are designed to investigate the deformation of the side wall and intrusion of survival space [5]. By establishing a three dimensional multibody dynamics model, Ling, Dhanasekar and others investigated the derailment mechanism of railway train after side impacted by heavy truck on railway grade crossing and the sensitivity of derailment risk to side guard rail mechanism parameters [6-7].

In summary, it's necessary to investigate collision dynamics of tram on its side structure. In this paper, in order to investigate side impact response of the trams, the low-floor tram suspension module is used as the research object with its side impact as a key study point, a collision dynamic model is es-
tablished by using the LS-dyna explicit dynamic simulation method.

2. Finite element model for collisions

2.1. Finite element model of a low-floor tram

The module number and the joint devices of a low-floor tram model are illustrated in Fig. 1. The tram is composed of 5 modules, and the modules are represented by A1 to A5. The modules A1, A3 and A5 are endowed with bogie, A2 and A4 are suspension modules. A1-A2 means the interface between A1 and A2, and the rest can be done in the same manner. The joint devices which provide connections and transfer forces between two modules consist of fixed joints, rotary joints and free joints. The fixed joint j1 only provides three rotational degrees of freedom. The rotary joint j2 only possesses one rotational degree of freedom around the vertical axis. The free joint j3 only limits the lateral translational motion.

![Figure 1. FEM model of low-floor tram](image)

The underframes of motor and trailer modules are made of the steel Q355. The side wall, end wall and roof are made of 6000 series. The components are connected through welding, riveting and other ways. The car body of the suspension module is made of aluminum alloys. The service mass of the tram is 59 ton.

2.2. Finite element model of a movable deformable barrier

The movable deformable barrier model is the Advanced European Movable Deformable Barrier Model V1.0 (AE-MDB) [8] provided by the Livermore Software Technology Corp. The barrier shown in Fig. 2 is about 4355 mm in length, 1723 mm in width, 835 mm in height. The mass of AE-MDB is 1.3t.

![Figure 2. Finite element model of AE-MDB](image)

2.3. Finite element model of city bus

The bus model established in this paper is a classic city bus as shown in Fig. 3. It is about 12 m in length, 2.5 m in width, 3.4 m in height and the curb weight is about 12 ton. The bus wheelbase is 6 m and the body frame is an integral bearing structure composed of thin-walled rectangular beams with different sections.

![Figure 3. Finite element model of city bus](image)

3. Design of collision scenarios

The design of collision scenarios in any standard is based on accident statistics. Though it cannot include every accident scenario, it has a relatively strong representativeness. Therefore, the design of collision scenarios plays an important role in impact simulation.

In view of the randomness and diversity of on-road accidents, the speed, impact angle, relative position and occupant load of the vehicle are relatively uncertain when the collision accident occurs. It is not only difficult but also time-consuming to calculate for each accident scenario. The design of the collision scenarios in this paper is appropriately simplified based on the New Car Assessment Program (NCAP) and follows below 5 principles:

1. The low-floor tram velocity is set to 0 km/h in order to reduce investigated variables. Only the deformation and motion responses of one side of tram, instead of both sides, are taken into account.

2. The effect of passenger mass on the response of collision is neglected. Thus total mass are calculated as the sum of curb weight of the low-floor tram and city bus.

3. The velocity orientation of city bus is vertical to the trams, that is, the collision angle is 90°.

4. According to the standard NCAP [9], the velocity of the MBD in the collision scenario is set to 50 km/h.

5. Considering the bus operation limited by the traffic flow, traffic lights, road scenarios and other factors, the bus needs to accelerate and decelerate frequently. The velocity of bus is generally lower than cars which is usually between 20–40 km/h [10]. In this paper, 30 km/h is taken as the initial velocity for bus when it impacts the tram.

After determining the coordinate system of the simulation model, this paper designs the following two collision scenarios based on the above 5 principles:

Collision scenario 1 (C-A2) is shown in Fig. 4. The side face of module A2 of a static low-floor tram paralleling to x-axis is impacted by a movable deformable barrier under $V_I=50$ km/h in the positive orientation of y-axis. The center line of barrier coincides with A2s.
Figure 4. Collision scenario 1

Collision scenario 2 (B-A2) is shown in Fig. 5. The side face of module A2 of a static low-floor tram paralleling to x-axis is impacted by a 12 ton bus with a velocity \( V_B = 30 \text{ km/h} \) in the positive orientation of y-axis. The center line of bus coincides with A2s.

Figure 5. Collision scenario 2

4. Results and analysis

4.1. Motion attitude of trambody

Fig. 6 shows the change of contact force between the movable deformable barrier and the tram in Scenario 1. The peak contact force is 430 kN.

Figure 6. Contact force of the impact interface in Scenario 1

As shown in Fig. 7, the module A2 had displacement along the y-axis and the maximum lateral displacement of its underframe center is 102mm. Besides, the modules A1 and A3 which are adjacent to the module A2 rotate around the joint devices and revert to the initial position after collision. The wheels are not separated from the track during the collision.

Figure 7. Deflection of tram in Scenario 1

Fig. 8 shows the change of contact force between the bus and the tram in Scenario 2. The peak contact force is 1120 kN which is greater than that in Scenario 1. The impact time is also longer than that in Scenario 1.

Figure 8. Contact force of the impact interface in Scenario 2

Fig. 9 shows the side rolling (around x-axis), lateral, and yawing displacement of tram body in Scenario 2. Each module rotates around joint significantly. The maximum lateral displacement of the underframe center of module A2 is 306 mm. The bogies of Modules A1 and A3 derail after wheel lifting, and cannot go back to the initial position. The tram shows an irreversible Z-shaped posture at the end of the collision.

Figure 9. Deflection of tram in Scenario 2

4.2. Survival space and lateral stop deformation

Different from the traditional longitudinal collision of vehicles, the side structure of tram is impacted without multi-level energy absorption system. The plastic strain and the deformation of the side wall of module A2 are shown in Fig. 10. The impacted position is at the lower part of the side wall of the suspension module and the side wall have some plastic deformation, and the survival space is invaded slightly. The main reason is conjectured that the side wall structure bears all impact force from the movable barrier due to lacking of bo-
gies in the suspension module. In addition, the suspension module has low strength for its aluminum alloy structure.

The intrusion of survival space of the tram side wall in Scenario 1 is shown in Fig. 11. The maximum intrusion value reaches 117 mm. After rebound, the side wall plastic intrusion value remains in 53 mm, accounting for 2.0% of the width of the tram body.

The motion of module A2 is transferred to the A1 and A3 by joint devices. The car bodies of A1 and A3 are in contact with the lateral stops of the bogies. Slightly plastic deformation occurs. The deformation of lateral stops of A1 and A3 are shown in Fig. 12 and Fig. 13.

As shown in Fig. 15, the maximum intrusion of the side wall is 318 mm during the collision process. The side wall plastic intrusion value of the side wall remains in 238 mm. The obvious deformation of suspension module may be caused by the side impact of bus due to its inherent characteristics including the structure and boundary scenarios. Thus, the survival space of the suspension module should be taken into account as one of the side crashworthiness evaluation indexes.
The motion of module A2 is transferred to the A1 and A3 by joint devices. The car bodies of A1 and A3 are in contact with the lateral stops of the bogies. Significant plastic deformation leads to the failure of limiting lateral displacement of tram body. The deformation of lateral stops of A1 and A3 are shown as Figs. 16 and 17.

Consequently, the lateral stop deforms slightly without failure in Scenario 1 while the one completely loses its function in Scenario 2.

4.3. Energy

The collision process is also the process of energy conversion. Fig. 18 shows the change of the energy over time during the whole collision process in Scenario 1.

It is observed that the initial kinetic energy of the system is 125 kJ. The absorbed energy is 108 kJ, of which about 96 kJ is converted into internal energy. It is mainly absorbed by the structure of the tram and the MDB. The internal energy accounts for about 88.8% of the total absorbed energy. The energy of 12 kJ is dissipated by friction between car bodies during the collision process. The remaining kinetic energy is 17 kJ, which is the rebound kinetic energy of the MDB.

Fig. 19 shows the change of energy over time during the whole collision process in Scenario 2. It is observed that the initial kinetic energy of the system is 416 kJ. The absorbed energy is 389 kJ, of which about 330 kJ is converted into internal energy. The internal energy absorbed by structure deformation of tram and bus, accounts for 84.8% of the total absorbed energy. The energy of 59 kJ is dissipated by friction between the vehicle bodies. The residual kinetic energy, 27 kJ, is the rebound kinetic energy after the collision. It is worth mentioning that, 147 kJ out of 196 kJ, the converted internal energy is provided by body deformation, and the remaining 49 kJ is from the damper.

5. Conclusion

The finite element models of the tram and bus, and design two kinds of collision scenarios were built. The dynamic responses, the survival space and energy change of the tram are studied based on the model and the scenarios. Several sugge-
tions are proposed for the side impact softy of the trams according to the results. The main conclusions are as follows:

(1) The side impact responses of the tram are mainly the lateral rolling, yawing displacements of the tram body, the bogie lifting, the deformation of the impacted side wall and the failure of lateral stop etc.

(2) The responses of the Scenario 1 are less severe than those in the Scenario 2. The possibility that occupants get hurt in the tram is much smaller when a side impact happens between a car and a tram. If the tram is impacted by large transport vehicles, the result tends to be more severe.

(3) Trams are lack of side crashworthiness design, and the impact force is directly applied to its side structure. The collision energy is mainly absorbed by the deformation of its side wall structure and the head structure of road vehicles.

In this paper, the side impact responses of tram are investigated by means of simulation. The result shows the necessity of the researches on side collision softy. The design of collision scenario should refer to the regulations and related researches of automotive industry.

References


