Research for Ensuring Safety in the Event of a Train Collision

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The Railway Technical Research Institute has conducted various types of research and development aimed at ensuring safety in the event of a train collision. These studies encompass two types of collision, namely, primary collisions and secondary collisions. Primary collisions refer to the impact between an obstacle and a carbody. Secondary collisions occur between interior fixtures and passengers (and drivers). For Primary collisions, an analytical method was developed to evaluate deformation behavior and amount energy absorbed by the carbody, following several fatal accidents. In the case of secondary collisions, a quantitative analysis was made of injuries to the driver, which was used to draft a set of guiding principles for carbody-structure design, geared to improve crashworthiness. Finally, this paper presents a method devised to accurately evaluate passenger injury using a FE model.

Keywords: train collision, vehicle body strength, ergonomics, simulation, crashworthiness

1. Introduction

Of the 300 plus research and development projects conducted or being conducted by RTRI during FY2015, the largest number by theme are related to enhancing safety. Some projects related to vehicles look at improving running safety, measures against strong winds and reliability assessment of high-strength members. In addition to these topics, improving crashworthiness is also very important for railways.

RTRI classifies collisions into two categories in its R&D, in terms of passenger and crew safety. The first category are primary collisions that occur between the carbody and another train, a car or an obstacle. The most important aspect related to this category is understanding the shrinkage of survival space caused by extreme impact acceleration and damage to carbodies. Clarifying carbody deformation behavior is also important as the deformation of related parts play a critical role in absorbing massive impact energy. The second category of collisions are secondary collisions which occur following the primary collision, between passengers and crew and interior fittings and between the passengers and crew themselves. The primary themes in this category are quantitative analysis and mitigation of injuries.

In its R&D projects on cars over the past 20 years, RTRI has looked primarily at the mechanisms involved and damage mitigation in primary collisions. In recent years, RTRI has been working and making proposals on the quantitative evaluation and mitigation of passengers/crew injuries in secondary collisions. This report will briefly look at these activities.

2. R&D on primary collisions and achievements

Primary collisions occur between a rail carbody and another train, car or obstacle which enters and blocks the

track. RTRI has been working on the clarification of carbody damage characteristics and the development of damage mitigation measures for each type of primary collision.

2.1 Mitigation of damage in vertical and lateral offset collisions [1]

Figure 1 shows a derailed car being hit by an oncoming train. In extreme lateral offset collisions like this, the impact is usually concentrated towards the corners of both carbodies involved. In a vertical offset collision in which a derailed carbody sinks, there will be a vertical gap between the relatively stronger underframes of both carbodies involved and the car hitting the derailed car may climb over the car being hit. The Hibiya Line derailment accident in 2000 led to lateral and vertical offset collisions being placed under closer scrutiny because of the resultant greater damage to the carbodies involved. RTRI has since been working more actively on mitigating damage from offset collisions.

Impact tests were conducted using rigid blocks representing corner body shells in order to clarify how carbodies are damaged in vertical and lateral offset collisions. Figure 2 shows a comparison between a test block damaged in a lateral offset collision and another test block damaged in a collision with both vertical and lateral offsets. In the lateral offset collision, only the inner top edge of the underframe became

Fig. 1 Lateral offset collision between the corners of the cars involved

Fig. 2 Damaged rigid blocks in impact tests

clearly deformed while neither the skin nor the corner post became severely deformed. On the other hand, in the collision with both vertical and lateral offsets, the end skin and the corner post sustained a shear failure and the side skin became deformed while the underframe was deformed only slightly. The maximum impact load was 280 kN in the lateral offset collision and 120 kN in the collision with both vertical and lateral offsets, which indicates that a significant reduction in deformation resistance results when the underframes of the colliding cars are not aligned.

A finite element model capable of accurately reproducing the deformation behavior of impact test pieces was developed. By applying the model to full-scale cars, a response analysis was then conducted to identify best ways to mitigate damage. It was found that the impact energy of a collision with both vertical and lateral offsets could not be absorbed sufficiently only through the deformation of body corners, but could be effectively absorbed by adopting a structure designed to prevent the colliding cars from biting into each other.

2.2 Characteristics of carbody damage in front- and rear-end collisions

In a primary front-end collision, adjoining cars of the same train set involved in the collision can collide with each other. In such a collision, whether the colliding cars become vertically offset through vertical buckling or not can make a great difference in the characteristics of damage done to the carbodies as well as the amount of impact energy that is absorbed. With a rear-end collision in 2002 on the Kagoshima Line serving as a catalyst that saw similar offset collisions in the same train sets involved, RTRI was able to identify the characteristics of damage to car ends of the same train set that occurs in similar end collisions and developed a method capable of accurately estimating the amount of impact energy that is absorbed.

In that identification and development process, quasi-static compression tests were conducted using test pieces (about 4 m in size) cut from actual cars. In a full-wrap test, shown in Fig. 3 (a), the end and center beams of the underframe became severely deformed. On the other hand, in an offset test shown in Fig. 3 (b) in which a block was installed on the rigid flat plate facing the end of the test piece, the underframe sustained no damage while the end body shell became significantly deformed and broke where it joins the end beam.

Fig. 3 Quasi-static compression test on test pieces cut from actual cars

Fig. 4 Load and deformation characteristics

In the next step, a finite element model of the carbody was developed and, using the model, a plastic deformation analysis equivalent to the static compression test was conducted to reproduce similar deformation behavior. Figure 4 shows the deformation caused in response to the static compression load in the above tests and analyses. The maximum static compression load was 2.4 MN in the full-wrap trial and 0.9 MN in the offset trial. The amount of energy absorbed ($\delta \leq 230$ mm) in the offset trial was only around 40 % of that in the full-wrap trial.

2.3 Characteristics of carbody damage in side collisions [2]

Where a train derails and deviates, hitting wayside structures on the side, or where falling rocks, vehicles or other obstacles hit a train on the side, it is important to secure survival space to minimize injuries. After that importance was raised as an issue following the Fukuchiyama Line train derailment accident in 2005, RTRI developed a method for analyzing carbody damage in side collisions that is capable of estimating damage in detail, using an index of survival space reduction.

In the development process, the strength of the carbody's side was evaluated by conducting quasi-static compression and falling weight tests on full-scale body shells. Figure 5 shows a falling weight test in which a 4.8 ton loading plate was dropped at a rate of about 10 m/s onto a test body shell placed on its side. As shown on the left-hand side of the figure, the cross beams of the underframe buckled at the ends and the spot weld between the side beams and the cross beams and between the cross beams and the floor board, fractured. The right-hand side of the figure shows the bulged roof and the fractured spot weld between

Fig. 5 Scene from the falling weight test (State of deformation 80 ms after impact)

Fig. 6 Example of side collision analysis

the rafters and the cant rails.

In the next step, a finite element analysis method capable of accurately reproducing the deformation of body shells in quasi-static compression and falling weight tests was developed and, using the method, injuries from side collisions were estimated using an index of survival space reduction. Figure 6 shows an example of analysis in which a carbody hits a 3 m-wide rigid wall on its side at 30 km/h (roughly the same conditions as the falling weight test in Fig. 5). The result was that the survival space shrank about 10 % based on the cabin width, a measurement between the inner posts of the door pockets on both sides, indicating that severe injuries can be caused in the secondary collision.

3. R&D on secondary collisions and achievements

3.1 Response analysis of level crossing accidents and mitigation of crew injuries [3]

RTRI has been developing and improving the accuracy of methods for analyzing carbody damage from primary collisions at level crossings. In recent years, RTRI has also been developing a method for both analyzing and evaluating carbody damage and crew injuries at the same time using a detailed finite element model of a lead car with a reproduced cab complete with internal framing and a rigid driver dummy. The method enables both the primary and secondary collisions to be analyzed at the same time.

Using this method, major level crossing accidents from the past were analyzed. In the analysis, the amounts of the end body shell deformation and the toppling statuses of the gangway bellows and corner posts closely reflected the actual data from the accidents. The computed injury levels of the dummy's head, chest and thighs from the analysis roughly agreed with the actual injuries sustained by the crewmembers in the accidents.

Furthermore, typical level crossing accident conditions were identified based on the results of analysis of past major level crossing accidents. These conditions were then analyzed using the method mentioned earlier (Fig. 7), from which the following items were selected for review aimed at mitigating crew injuries in secondary accidents and, for each of the items, guidelines on the structural design of cars for effective injury mitigation were proposed.

- Mitigation of injuries to the head, chest and knees
Guidelines: Installation of buffer members in areas of expected collisions with interior fittings
- Prevention of injuries to the legs
Guidelines: Measures to prevent the cab from falling over
- Measures to prevent the head from hitting the front window
Guidelines: Measures to keep the cab and the front window apart

Fig. 7 Response analysis example of typical level crossing accident conditions (Lead car hitting a large trailer at 54 km/h)

3.2 Sophistication of dummy and interior fitting models

Going forward, RTRI aims to propose targets for mitigating passenger injury in secondary collisions using indices, including for carbody impact acceleration and survival space reduction. That, however, requires improved accuracy of injury estimation in various types of collisions and clarification of the correlation between these indices and injury levels.

In order to improve the accuracy of secondary collision injury analysis, RTRI has been introducing a finite element analysis model for human bodies and interior fittings which were previously simulated using combinations of rigid elements. Figure 8 shows analysis examples of seated passengers hitting the transverse seat in front of them. It was verified that, by using the finite element model for human bodies and seats, dummy behaviors and injury data from collision tests could be reproduced accurately.

Fig. 8 Analysis examples of secondary collision injuries from hitting a transverse seat

4. Actions for the future

As part of the new approaches being taken for collisions, the behavior of train sets is being clarified as described below. In primary collisions of long train sets, it is difficult for the impact energy to be absorbed only by the lead car. In addition, Japan primarily uses a distributed traction system whereby each car in the same train set is equipped with a cabin and the equipment is distributed throughout the train set, making every car of the train set almost equal in specification. Based on these circumstances, it is difficult to lessen injuries from primary collisions by substantially increasing the body strength of the lead car and/or adding impact absorbing features. Given this context, in order to help contribute to related efforts including guidelines on the structural design of carbodies, RTRI has been developing a method capable of analyzing and evaluating the process of energy absorption and dissipation while taking into account various factors including the deformation of not only the lead car but also the other cars in the train set as well as the effect of buffers. The following are some of the examples of related calculations.

With the method mentioned above whereby time-series responses of a multi-degree-of-freedom system consisting of a series of coupled bogie car models are analyzed, the model's damage characteristics are applied to areas of the

carbodies subject to impact while the coupling devices' buffer characteristics are applied to the car joints. Figure 9 shows the deformation-load and energy absorption characteristics, obtained by finite element analysis, of the end of a stainless steel carbody that was pressed onto a rigid wall. As the car end deformed about 280 mm, the static compression load peaked at 1.8 MN while the energy absorption peaked at 400 kJ, which is more than 40 times the values obtained with a rubber buffer shown in the same figure.

Figure 10 shows an analysis example of a 10-car suburban train colliding at 20 km/h with another stationary 10-car train. It shows the relative time-series longitudinal displacement (the moment of collision $t = 0$) of the adjoining cars consisting of Cars 1 to 10 of the train hit and Cars 11 to 20 of the train colliding. The carbody model characteristics of Fig. 9 were applied to the areas (shown in orange) of direct impact and to the immediate front and rear cars (shown in green), assuming that these carbodies would deform. As shown in the figure, following the initial damage, the direct impact areas were displaced closer to each other by 400 mm, followed by Cars 9 and 10 moving closer to each other by 70 mm and Cars 11 and 12 by 220 mm. During that process, the rubber buffers between the cars were sequentially compressed, sending a wave of collision impact throughout both train sets within a second.

RTRI will continue to upgrade the analysis method as part of an attempt to develop techniques capable of

Fig. 9 Car end deformation characteristics applied to areas of collision

Fig. 10 Example of response waveforms representing longitudinal displacement of adjoining carboodies (10-car suburban train collided at 20 km/h with another 10-car train)

processing both vertical buckling and vertical offset at the same time.

5. RTRI's research and development for collision safety

RTRI's R&D concepts of collision safety are shown in Fig. 11. By building on the methods thus far developed, estimation is made on the impact acceleration of carbody and the reduction in survival space from the primary impact and on the injury levels of passengers and crews from the secondary impact, for each of the various modes

Fig. 11 R&D concepts of collision safety

of collision impact. In the next step, the relationships between these estimated subjects are clarified and targets are proposed for the mitigation of injuries from the secondary collision using indices such as impact acceleration and survival space reduction.

The results of that process are utilized in the subsequent reviewing of the collision safety structures and specifications of carbodies and interior fittings. The process can also be applied for evaluating the safety of any structure or specification that may be proposed based on the process. Through these exercises, RTRI will continue contributing to improving safety in case of collision.

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