Evaluation of Carbody Strength against Side Load

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It is a regretful fact that fatal accidents sometimes still occur despite ongoing efforts to reduce accident risk and ensure the safety of railways. At the Amagasaki accident in April 2005, one carbody was severely damaged due to side impact. Static and dynamic compression tests were performed to evaluate the carbody side strength using full-size partial carbodies followed by FE analyses under the same loading conditions as in the empirical tests. The numerical results obtained by FE analyses were consistent with the empirical results in terms of the load-time characteristics as well as deformation of carbodies. A method was developed to evaluate the impact deformation behavior of a carbody subject to side loads by using FE analysis.

Keywords: carbody strength, side load, strength test, finite element analysis

1. Background

One of the worst train crashes on record occurred in Amagasaki near Osaka, about 500 km west of Tokyo, Japan, on 25th April 2005. A seven-car EMU rake, part of the morning rapid commuter service to the centre of Osaka, derailed in a tight curve with a radius of about 300 m. The two leading coaches overturned and hit a building that was beside the track. The side of the second coach hit a corner of the concrete building and its body structure were severely damaged. At RTRI, estimations were made of the fundamental structural characteristics of existing typical light-weight stainless-steel body structures in order to investigate their current vulnerability against side impacts and to identify paths towards improvement in crashworthiness under such impacts. Most recently built Japanese EMUs for commuter and suburban services consist of light-weight car bodies made from stainless steel or aluminium [1]. The cars involved in the accident were made from stainless steel. Therefore, the stainless-steel car bodies were made a first priority.

1.1 Structural standards for Japanese rolling stock

A carbody's structural strength is defined by its integrity under static loads, according to general requirements for the design of rolling stock for Japanese railways, such as standard JIS E7106.

JIS E7106 shows different cases for loading the body structure, for example vertical load distributed onto the floor structure, longitudinal load at couplers, torsion moment at bolsters supported by bogies, and means to test fatigue strength in some cases. The vertical load represents the weight of passengers in an overcrowded car, and the longitudinal load represents the coupler load. However, JIS E7106 provides no quantitative definition for crashworthiness. Furthermore, in the current Japanese standard, neither static nor dynamic load cases include examples considering application of side loads.

2. Static compression tests

2.1 Carbody structure for the test

Actual-size partial carbody structures were used for the static compression tests. The intermediate carbody structures between two bogies (2.95 m in width, 6.5 m in length and 2.9 m in height) were cut out from the stainless-steel car bodies of commuter EMUs. The test specimens are as shown in Fig. 1.

Fig. 1 Carbody structure for compression tests

2.2 Static test conditions

The test carbody was placed up against a stable, large, rigid wall and compressed by another moving rigid wall powered by hydraulic servo actuators.

Several loading conditions were applied for the compression tests; the width of the moving rigid wall and the direction of compression were altered. The test conditions are as shown in Fig. 2 and the parameters for the loading cases are listed in Table 1.

Four synchronized actuators were placed at each corner of the moving rigid wall during the test using a 3 m wide wall. For the test with the 1 m wide moving rigid wall, two actuators were used, one placed at roof struc-

Fig. 2 Test conditions

Table 1 Loading condition parameters

Test case	A3	B3	B1	A3S
Test carbody	Seating section	Door section	Door section	Seating section
Width of moving rigid wall [m]	3.0	3.0	1.0	3.0
Direction of compression	Level	Level	Level	15° inclination

ture height of the carbody and the other at floor structure height. These actuators controlled the displacement of the moving rigid wall.

Two different directions were chosen to apply the compressive loads. For normal cases, the test car bodies were placed with their floor structures parallel to the ground. For other cases, the test carbody was inclined to 15°. In the latter cases, the compression load first acted at the corner between the side panel and the roof panel. This easily deforms the cross section of the carbody into a parallelogram.

2.3 Static test results

The static compression tests provided information on the deformation characteristics of the carbody structures. Figure 3 shows the permanent deformation of the test car bodies. Figure 4 plots the compression load versus deformation under the various loading conditions. There is no significant difference between results for A3 and B3 in terms of the maximum compression load. On the other hand, results produced different load-versus-displacement curves among cases with different wall widths. This is due to the different number of main cross beams under-

Fig. 3 Examples of deformed body structures

Fig. 4 Load-versus-deformation characteristics

neath the floor structure of the carbody which resist the lateral load.

2.4 Numerical simulation of static compression tests

Numerical simulations were also carried out in order to validate the empirical results. Explicit FE analysis was applied instead of the usual implicit FE solver for calculations with static loading condition cases. The regular size of FE mesh is about 25 mm and isotropic thin shell elements were mainly selected for building the numerical mesh. The total number of nodes for each model was about 320,000 and the total number of elements was approximately 260,000. Rupture characteristics for spot welds connecting most structural parts were also taken into account for these numerical models. On this occasion commercial software, PAMCRASH, was used for the series of simulations. Figure 5 shows the results of the deformed FE mesh for each loading condition. Figure 6 shows numerical results of the relationship between compression load and deformation in each simulation case.

Resulting deformation shows that the most significant deformation modes of the roof structure, side structure and under-floor structure were bending and buckling. It was found that FE analysis allowed adequate simulation of the empirical deformation modes for cases A3 and B1. In case B3 however, deformation mode differences appeared between the empirical results and the numerical results especially around the under-floor structure including side beams and cross beams, as shown in Fig. 7. The load versus deformation curves, in Fig. 6, also describe the disagreement revealed in case B3 after the appearance of large deformation exceeding the deformation stroke by as much as 200mm, whereas the load versus deformation characteristics in cases A3 and B1 could be cross-validated between empirical and numerical results. It was also clarified that spot-weld ruptures around under-floor structures in both cases A3 and B1 were adequately calculated, whereas the numerical result for case B3 shows a different distribution of ruptured welding points. The abovementioned outcomes demonstrate that spot-weld ruptures are critical for determin-

Fig. 5 Numerical results for the deformation of carbody structures

Fig. 6 Numerical results for compression load versus deformation curves

Fig. 7 Deformation shapes around the under-floor structure for the case B3

ing deformation modes and load-deformation characteristics, while larger deformation occurs at the main structural parts i.e. side beams and cross beams of the under-floor structures. Concerning the case A3S, FE analysis made it possible to validate the empirical results in terms of both of deformation modes including rupture of spot welds and load versus deformation characteristics.

3. Dynamic compression tests

3.1 Dynamic test condition

The dynamic compression test was setup as shown in Fig. 8. The specimen equivalent to the static test speci-

men was mounted sideways on the base, the loading plate was installed so that the distance to the specimen side was 5 m, it was then released to fall freely and collide with the specimen at a speed of about 10 m/s. The loading plate was about 3 m wide by 3.7 m in length and about 10 tons in weight. The load was measured using load cells mounted on the base, and deformation of the specimen was recorded with high speed cameras.

Fig. 8 Dynamic test setup

3.2 Dynamic test results

The test was carried out twice in order to check reproducibility. The collision speed of the first test was 9.87 m/s, and the 2nd was 9.95 m/s. Figure 9 shows the deformation of the specimen 80 ms after impact in the 2nd test, and Figure 10 shows the relationship between the load and the time for each of the tests. Results obtained from tests carried out twice were almost the same, validating reproducibility of the test method.

The end of the cross beams on the side of the loading plate mainly underwent compression buckling, and un-

Fig. 9 High speed camera image of dynamic test (80ms after impact)

Fig. 10 Load – time relation

der compression the roof buckled up as shown in Fig. 9. As apparent from Fig. 10, the maximum load reached about 2000 kN at 30 ms after impact.

3.3 FE analysis equivalent to dynamic tests

A numerical simulation using an explicit FE analysis equivalent to dynamic tests was carried out. The FE model for dynamic analysis was based on the model with verified accuracy in the static tests, and included the effect of strain rate.

Figure 11 shows the deformed FE model by calculation at 80 ms after impact, and Figure 10 shows the relationship between load and time. The numerical results obtained through FE analysis are consistent with the empirical data in terms of deformation such as the buckling in a section of the cross beams and the load-time relationship.

Fig. 11 FE model of deformation (80ms after impact)

4. Evaluation of carbody strength against side load impact

The FE model, which can duplicate each test result, was created by comparing static and dynamic test results. Trials utilized a partial carbody of 6.5 m in length, a whole car was obtained for the FE model by extending this test model.

As an example of impact deformation behavior evaluation of a carbody subject to side load impact using the whole car FE model, a numerical simulation using an explicit FE analysis was carried out where the carbody was hit sideways (including the weight of the two bogies) with a 3m wide rigid wall at a speed of 30 km/h (8.33 m/s). Figure 12 shows the deformation of the FE model obtained through calculation. As shown in Fig. 12, when defining interior width as the distance between the inner door surfaces, this distance is crushed after impact to about 90 % of the original width from before the collision. Under these collision conditions therefore, evaluating the impact behavior of passengers knocking into equipment inside the car becomes more important than the reduction in survival space.

Fig. 12 Strike with rigid wall travelling at 30km/h

5. Conclusion

The authors carried out static and dynamic empirical compression tests on cut out sections of full-size carbodies and performed FE analyses under matching conditions in order to acquire the fundamental carbody side strength property data. Numerical results were then verified through FE analysis to ensure consistency with the empirically obtained data in terms of load-time characteristics and carbody deformation. A method was developed to evaluate the impact deformation behavior of carbodies subject to side load impact using FE analysis. An example was produced using this method.

Future work will aim to identify courses for improvement in crashworthiness by applying this new method to

verify carbody strength under various side load collision conditions.

Acknowledgment

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References

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