Crashworthiness Investigation of Railway Carriages

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Serious railway accidents in recent years in Japan were surveyed in order to clarify the target of railway crashworthiness. From the result, it was found that level crossing collision accidents were one of the most important targets of the crashworthiness of railway carriages. Both numerical simulations and empirical method to analyze crushing behaviour of railway carriages in Japan were applied in this research work. As the empirical methods, quasi-static compression tests for carbody sections were used to understand crushing behaviour of the carbody. Using the crushing characteristics obtained from the test, one-dimensional lumped mass numerical model was built and calculated to evaluate impacting behaviour of the trains at collision accidents. Three-dimensional FE analysis and real size train crash test were also included in this research program. The results of both numerical method and experimental tests were compared.

Keywords *: crashworthiness, vehicle structure*

1. Introduction

The safety of train operation is one of the most important issues for the railway industry. Development of safety equipment to prevent railway accidents is no doubt an issue of the first priority. In Japan, such "active safety" equipment has been developed successfully. However, it is also important to develop "passive safety" equipment to reduce damage of passengers and crews at collision accidents.

Since the 1960s, mainly in the later 1980s, a lot of research projects [1)2)3)] about railway crashworthiness have been developed in Europe and America. On the other hand, the crashworthy program for railway carriages has not necessarily been focused in Japan.

In order to clarify the target of railway crashworthiness, recent railway accidents in Japan were investigated and both numerical simulations and empirical method to analyze crushing behaviour of railway carriages in Japan were applied in this research work. Both results of numerical simulation and experimental tests were compared.

2. Recent railway accidents in Japan

In order to prevent the same types of railway accidents from occurring again, accident data have been collected and analyzed by the office related to railway safety in Japan according to the policy to clarify the responsibility for accidents, in other words, to make clear who is directly responsible. This means that these data have not necessarily contained sufficient items for the purpose of crashworthiness investigation.

In this paper, using statistic data of "serious railway accidents" defined by the Ministry of Land Infrastructure and Transport, the recent tendencies of railway collision accidents in Japan were studied, then the target of crashworthiness for railway carriages in Japan and the issue were investigated.

2.1 Serious railway accidents in Japan

The most important and serious accidents are defined as the "serious accident" by the Ministry of Land Infrastructure and Transport in Japan. The definition of the serious railway accident is as follows.

- A case with more than 10 casualties
- A case with more than 10 derailed vehicles
- Any other most serious and worst cases

As mentioned above, the definition by the Ministry is based on the number of casualties and derailed vehicles. This shows that only derailment is focused on to measure damage of railway vehicles, that is, crashworthiness itself is not taken into account.

2.2 Recent serious railway accidents

The serious railway accidents from April 1991 to December 2001 were reviewed.

The number of these serious accidents categorized in terms of the types of accident and train operating company are shown in Table 1.

Derailments of freight trains or cases where only pedestrians on the ground or people boarded on road vehicles had been killed or injured were omitted from the

Table 1 Number of serious railway accidents (April 1991 - December 2001)

	JR	Private Railways			Total
		Sub-urban	Provincial	Other	
Head-on collision	1	0	5	3	9
Level crossing collision	5	2	2	0	9
Collision to natural obstacles	2	1	0	0	3
Side-on collision	1	1	0	0	2
Buffer stop collision	0	0	2	0	2
Over turning	2	0	0	0	2
Derailment	1	0	0	0	1
Total	12	4	9	3	28

data because the main purpose of this investigation was to improve the safety for passengers on trains at accidents.

From this Table, both the head-on collision and the level crossing collision happened nine times in these ten years. For JR companies and sub-urban private railways, the level crossing collision seemed to be at the highest risk. The collision to natural obstacles (i.e. huge rock falling down onto railway tracks) was second. On the other hand, for small provincial private railways, head-on collisions and buffer stop collisions were relatively at higher risk.

This is because JR lines and sub-urban private railways have already completed equipping sophisticated signaling and protection systems such as the Automatic Train Protection system. Therefore there can be a lesser risk of train-to-train collisions, whereas several small provincial private railways have not been able to equip newer protection systems and some have to operate older and decrepit railway vehicles and ground equipment, which may cause collision accidents by the lack of reliable protection system.

Then casualties from serious railway accidents were surveyed in terms of the types of railway accident. See Table 2.

Only casualties of passengers and crews boarded on trains are taken into account here, with the number of people on the ground or road vehicles omitted since the purpose of this study was to investigate the safety of passengers and crews on trains.

From this Table, head-on collisions are the worst in terms of both fatalities and injured, largely affected by the "Shigaraki Railway accident" case on May 1991, with 42 fatalities and 614 injured, 656 casualties in total.

The Shigaraki accident case is regarded as a very unusual and rare accident here. Except the Shigaraki accident case, it is found that level crossing collision, buffer stop collision and side-on collision are also serious and important targets.

Table 2 Number of casualties by serious accidents (April 1991 - December 2001)

	Fatalities	Injured	Total casualties
Head-on collisions	43	854	897
Level crossing collisions	1	586	587
Collision to natural obstacles	0	54	54
Side-on collisions	5	141	146
Buffer stop collisions	1	467	468
Over turnings	0	54	54
Derailments	0	16	16
Total	60	2172	2232

From the above, keeping level crossings safe for JR lines and sub-urban private railways may be one of the most important safety targets and crashworthiness against heavy lorries on level crossings might be an effective countermeasure to improve railway safety. For provincial private railways, crashworthy railway carriages against head-on collision and buffer stop collision might be effective as well as signal system improvements.

3. Evaluation method for crushing behaviour of railway carriages

Although proof load of carriage carbody structures for static compression had been defined in the design standard, it had not been supposed as crushing behaviour of carbody structures at collision accidents in Japan. As a result, mechanical characteristics over the defined proof compression load for the carbody structures had not been evaluated sufficiently. Crushing behaviour of carbody structures was investigated using both experimental and numerical methods in this study.

3.1 Static compression test for carbodies

In order to understand the basic characteristics of mechanical behaviour, quasi-static compression tests for partial carbody structures were carried out.

The quasi-static compression tests have been common in European and British railway industries [4)5)6)] to verify crashworthiness of carriage end structures. About railway carriages in Japan, deformation around the center area of the carbody happened in some accident cases, so it was necessary to check the crushing characteristics not only of the end structure but also of the center door area and passengers' seat area.

Passenger's door section, seat section, cab end section and intermediate coupling end section were used as the test pieces. These parts are representative structures of carriage carbodies.

Two types of load condition were used for the tests.

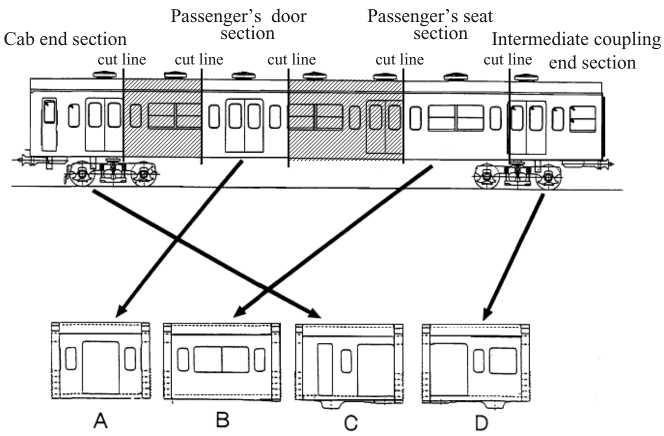


Fig. 1 Partial carbody structures for quasi-static compression tests

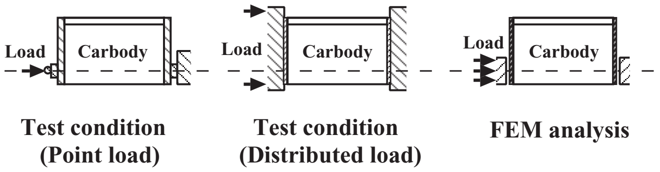


Fig. 2 Loading condition used in quasi-static compression tests and FE analysis

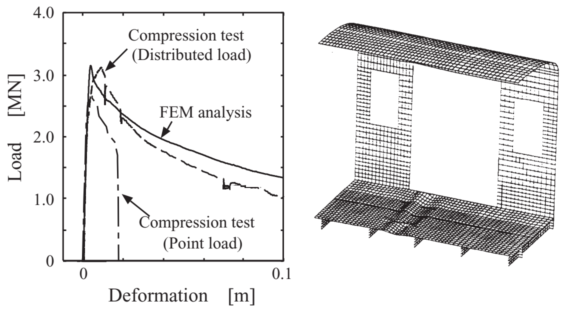


Fig. 3 Compression load and deformation relation for the door section

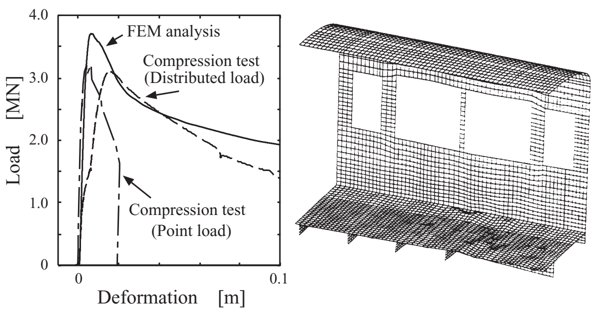


Fig. 4 Compression load and deformation relation for the seat section

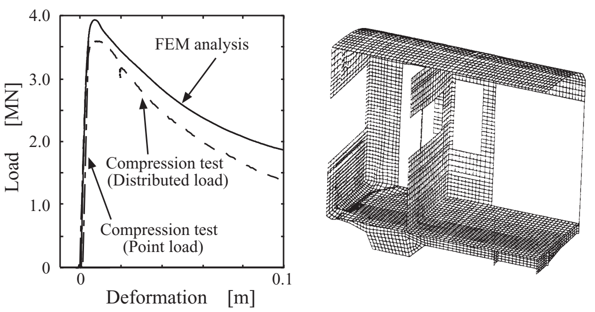


Fig. 5 Compression load and deformation relation for the cab section

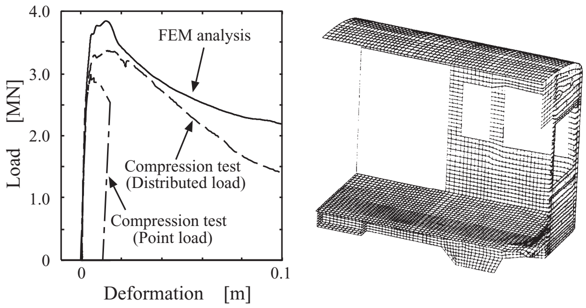


Fig. 6 Compression load and deformation relation for the coupling end section

Table 3 Results of maximum compression load

Case	Point load MN	Distributed load MN	FEM analysis MN
A	2.67	3.12	3.16
B	3.21	3.10	3.70
C	3.65	3.59	3.94
D	2.93	3.37	3.84

One was the point-load condition and another was the distributed load condition which allowed us to compress carbodies with both loading faces kept in parallel.

FE models were produced according to the experimental testing conditions. The numerical models were calculated under quasi-static conditions corresponding to those for the experimental method.

Deformed FE models and macroscopic mechanical characteristics (compression load and deformation relation) are shown in Fig. 3 to 6. Values of maximum compression load for the carbody sections are shown in Table 3.

The results of experiments and numerical simulations basically corresponded to each other in terms of deformation mode and compression load-deformation relation.

3.2 Numerical simulation

3.2.1 FEM analysis

By combining FE models for the partial carbody sections, whose accuracy was already checked by the results of quasi-static experiments, a full car FE model was built and used for the crash analysis. The FE code "PAM-CRASH" was used for the simulation.

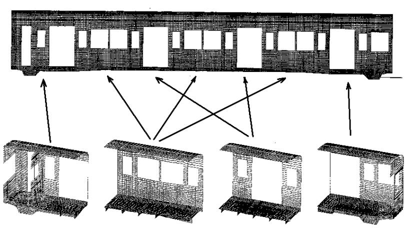


Fig. 7 Three-dimensional FE model for a leading carriage of commuter EMU

3.2.2 One-dimensional lumped mass analysis

In order to represent railway carriages, a one-dimensional lumped mass model was proposed, which included lumped masses and springs with non-linear deformation characteristics. This numerical model was light and easy to calculate impacting behaviour of rakes involved in accidents.

The load and deformation relation from the results of experiments and FE analysis was introduced in the non-linear characteristics of spring elements. For example, a numerical model with seven springs and seven masses per each carriage is shown in Fig. 8.

3.2.3 Results

The results of lumped mass analyses and FE analyses were compared. The tendencies of the deformation from these two different numerical models were basically coincident. This showed that the one-dimensional lumped

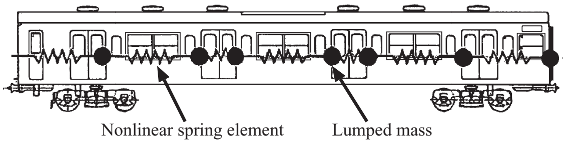


Fig. 8 One-dimensional lumped mass modeling for a leading carriage of EMU

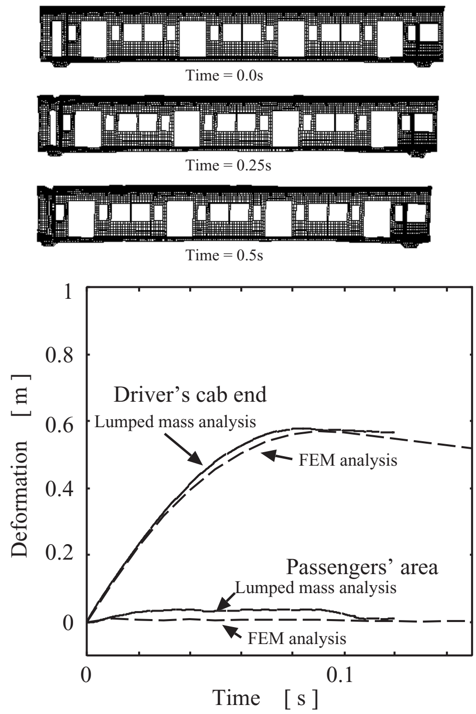


Fig. 9 Comparison of the results of both lumped mass analysis and FE analysis

mass model was adequate to evaluate the behaviour of train sets at a collision accident as well as the detail analysis by the FE model.

3.3 Evaluation method for carbody structure

The one-dimensional lumped mass analysis was applied in order to evaluate vehicle safety at a collision accident.

The impacting behaviour of four-car commuter train set, with each car having seven representative sections, was calculated. The model was calculated in several collision cases with its train formation and carbody structure changed.

To simplify the numerical model, the carbody structure was supposed to be composed of such basic four sections as the door section, seating section, driving cab end section and intermediate end section.

(1) Case of changing front structures of the leading carriage

The behaviour of four-car commuter train running at 50km/h on hitting a rigid obstacle was calculated. Such cases of changing structures at driver's cab were also calculated as the case of the cab end structure with a stiffness twice that of ordinal structure, the case of the cab end structure with a strength twice that of the ordinal structure and the case of the cab end structure with a strength half that of the ordinal structure.

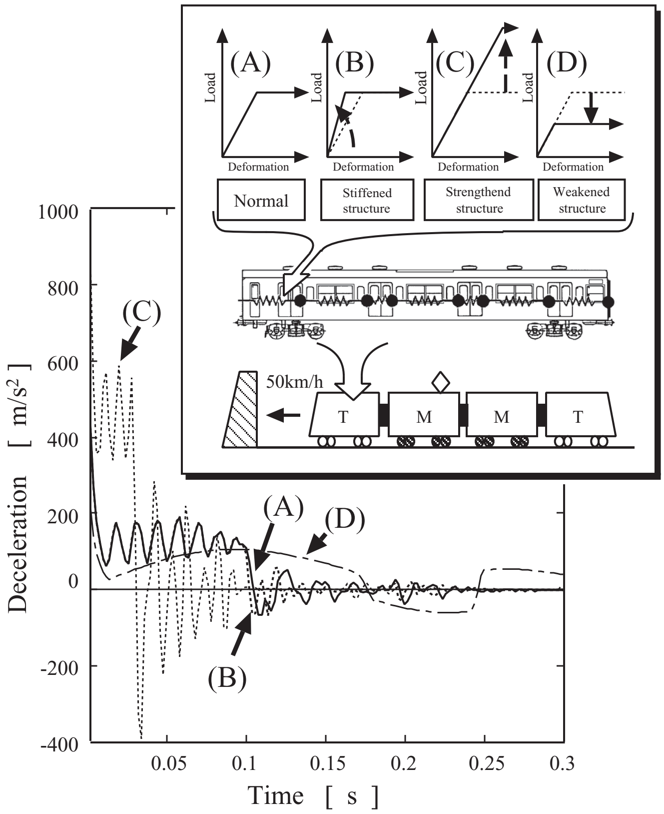


Fig. 10 Evaluation of the impacting behaviours in changing the cab end structure

Figure 10 shows the calculated results in terms of the time history of deceleration at the center of the leading carriage for each simulation case. The result showed that the impacting behaviour of the train set depended on the crushing characteristics of the vehicle carbody structures especially collapsing load rather than stiffness of the carbody from these simulation cases, lower strength carbody structure, such as "the crumble zone, "might be advantageous to the impacting deceleration which was related to the safety of passengers and crews on the train.

(2)Case of changing the train formation.

Three types of the train formation colliding with a rigid obstacle, such as head motorized driving carriage case, head driving trailer carriage with motorized intermediate carriages case and motorized tail carriage pushing trailer carriages case, were calculated as shown in Fig. 11. This meant that numerical results were variable depending not only on the structural strength of carbodies but also on the distribution of weight in the rake.

From the result, heavier leading carriages might contribute to lower impacting deceleration at the center of leading carriages compared with other cases with the same weight of the train formation.

As mentioned above, one-dimensional lumped mass analysis was useful to calculate the impact behaviour of train formations in collision accidents at variable situa-

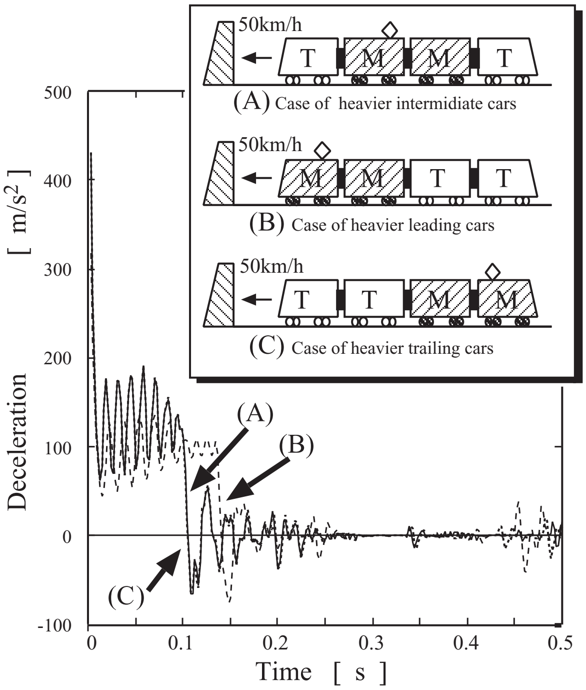


Fig. 11 Evaluation of impacting behaviours in changing the train formation

tions and to find optimised mechanical characteristics of crashworthy carbody structures.

4. Train crash test

4.1 Testing method

In order to understand train crash behaviour and verify numerical simulation, train crash tests were carried out. The impacting rake consisted of a test carriage and a coupled trailer carriage was pushed off by a shunting locomotive at about 30km/h and hit the obstacle. The test carriage of the impacting rake was mainly observed in the test.

4.2 Test carriages

Steel-made commuter EMUs were used for the test. The test carriage was a driving trailer of the class and the carriage was coupled with the next carriage as a deadweight. The impacted rake consisted of two carriages which were expected to behave like an obstacle. These two carriages in the impacted rake were connected at the end section and fastened by steel wire tightly.

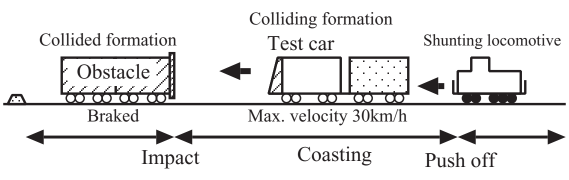


Fig. 12 An outline of train crash test

4.3 Measuring method

4.3.1 Compression load in carriage carbodies

Compression load acting on the carbody structure was supposed by measuring strain at points on the main constructive sills in certain sections near the impacting end for both impacting and impacted carriages shown in Fig. 13.

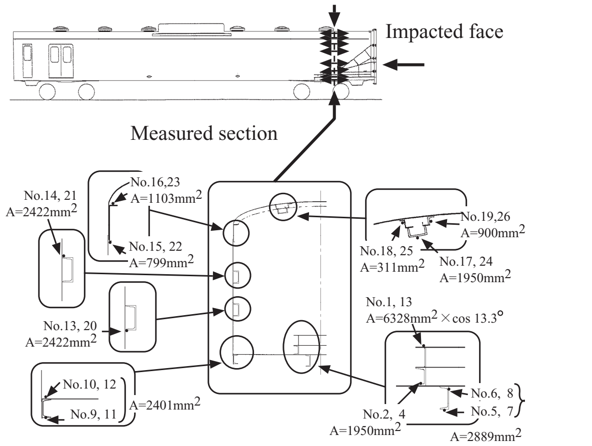


Fig. 13 Measuring points of strain in the carbody sections

Here the compression load in the carbody was calculated by the next equation.

$$P = \sum_n \varepsilon_n \cdot A_n \cdot E \quad (1)$$

In the equation, P means the calculated compression load; ε_n means the strain at point No. n; A_n means the cross section for No. n's constructive sill; E means Young ratio for each constructive sill.

As the verification of this measuring method, a preliminary test was carried out. The coupler between the leading test car and deadweight trailing carriage had been calibrated before setting between carriages in order to use the coupler as a load cell. When the test rake was pushed against the obstacle rake by the shunting locomotive, the strain in the carbodies were observed and those data were used for calculation of compression load. The calculated compression load was compared with the load measured at the coupler between carriages in the test rake as shown in Fig. 14. As a result, it was found that this measuring method was satisfactory to grasp the compression load in the carbody.

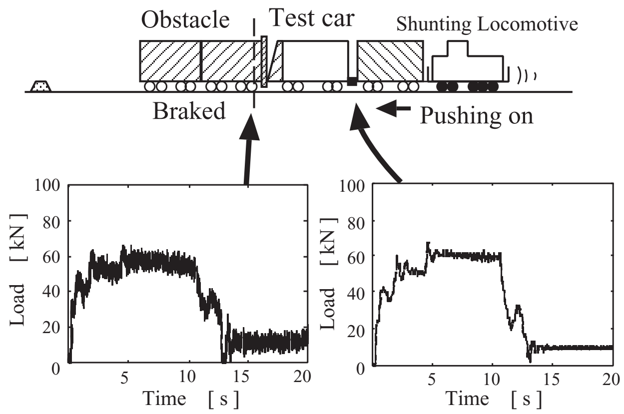
4.3.2 Deformation in carriage carbodies

Certain points along the side sill on both side structures of the test car were measured using a three-dimensional digitizer before and after the crash test in order to calculate deformation in carbodies. Deformation of the driver's cab section was also measured.

4.3.3 Impacting deceleration

Accelerometers were put on the floor of test carriages and bogies to measure the impacting deceleration of these carriages. The data were also checked to investigate occupants' safety.

4.3.4 High speed video filming



(a)Calculated reaction force (b)Measured coupling load

Fig. 14 Comparison of the compression load calculated from measured values of strain of carbody structures and measured at the coupler between carriages in the impacting rake

In order to record the behaviour of both impacting and impacted rake during the collision, high speed video films were taken toward both sides of carriages at the scanning speed at 400 pictures per second. Marked points on the side of the carriage were followed in each picture and the displacement of the points at each time step was checked. The data could be used to find the velocity of the carriages and calculate the progress of the deformation in the carriage carbodies.

4.4 Testing results

The compression load calculated by the equation (1) and longitudinal deformation in the carriage carbodies checked on the high speed video pictures were used together in order to lead compression load to deformation relation of the carriage carbodies. The result of compression load to deformation characteristic of the carbody at the crash test is shown in Fig. 15. The result of dynamic FEM analysis is also shown in Fig. 15. Deformed shapes of the carbody structure in both crash test and numerical simulation were also compared. See Fig. 15.

When these results were compared, the deformation mode in the experimental result from train crash test and the numerical result from FE analysis were similar to each other in terms of the appearance of shear band on the upper side structures around driver's cab area and buckling on the floor in the carriage carbody. The tendencies of compression load - deformation characteristics from both the train crash test and numerical simulation were coincident but the numerical result showed lower values than those from the crash test. The value of compression load at quasi-static compression test was also lower than the value of the result from the crash test.

5. Conclusion

In this research, the target of railway crashworthiness in Japan was considered and the impacting

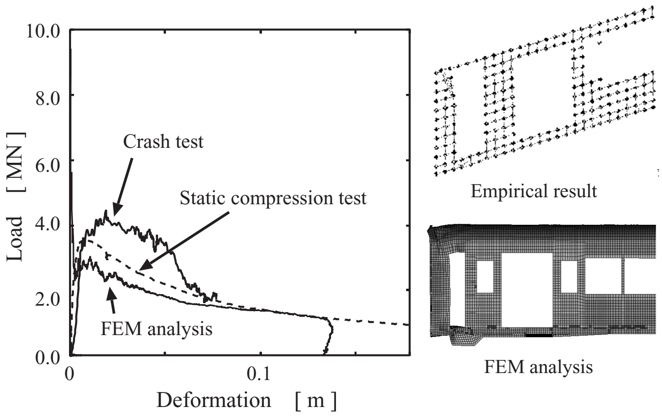


Fig. 15 Comparison of the result from the train crash test and FE analysis

behaviour of carriages at a collision accident was investigated. Carbody sections were tested under quasi-static compression load in order to understand crushing characteristics of carbody structures. The results of quasi-static compression tests were introduced in one-dimensional lumped mass analyses, which were used to evaluate the behaviour of trains involved in a collision accident. Three-dimensional FE analyses of the carriage and train crash tests were also carried out. Those results were compared with each other.

In the future plan, improvement of numerical simulation method and evaluation of the crushing behaviour in types of carbody structures made of different materials will be treated. Investigation of carriages according to certainly defined targets of railway crashworthiness using the established numerical methods will also be carried out.

This research project was supported by the subsidiary of the Ministry of Land Infrastructure and Transport in Japan.

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