Proposal of Simulation Method for Behaviour Analysis of Passengers on Longitudinal Seating in Railway Collision

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Abstract In railway collisions, passengers are thrown from their seats and translate long distances because they are not restrained by a seatbelt. This creates the possibility of serious injury caused by collision with interior components at high velocity. It is important, therefore that passengers' behaviours are estimated. This study focuses on a passenger seated on longitudinal seating away from a bench-end partition. They translated and then pitched over with its head leading any other physical part. Sled tests for imitating a situation where a passenger collides with the bench-end partition were conducted. Then, numerical simulations for reproducing the sled tests were performed with MADYMO. The dummy's behaviours of the numerical simulations, which are collision position and collision velocity, were almost equivalent to those of the sled tests. On the other hand, the head accelerations of the simulations were different from those of the sled tests greatly. Thus the joints of the dummy model's neck were improved. The head accelerations of the simulations after the improvement almost corresponded with those of the sled tests.

Keywords behaviour analysis, longitudinal seating, multi-body dynamics, seated passenger, railway collision.

I. INTRODUCTION

It is important that severe injuries are prevented when a railway collision happened. Since the railway passengers do not have a seat belt, they are thrown from their seat by the acceleration of collision and collide with interior components. The collision between the vehicle and external objects is called "primary impact" [1] and the collision between passengers and interior components is called "secondary impact" [2]. This study focuses on the secondary impact.

There has been a great discussion about the secondary impact on a railway vehicle. Severson (2000) conducted a full-scale collision test and numerical simulations to evaluate occupant protection strategies [3]. Wang (2011) analysed secondary collision injuries to occupants and influence factors of railway vehicle interior impact injuries using the software MADYMO [4]. Li (2007) carried out numerical simulations using the software PAM/CRASH [5]. Hecht (2005) conducted experiments and numerical simulations to improve the crashworthiness of tramcars and light rail vehicle [6]. Some studies have shown the head injury value as a function of secondary impact velocity. Tyrell (1998) analysed secondary impact against a seat back with MADYMO [7]. Simons (1999) researched the survivability for a general high-speed train system when a passenger strikes a forward seat back [8]. Xie (2013) investigated the secondary impact of a passenger faced with a table in a compartment [9]. In bus crashes, McCray (2001) simulated frontal rigid barrier test [10]. Elias (2001) evaluated potential of safety restraints on large school buses and indicated that seat spacing could affect dummy kinematics and responses [11]. Elias (2003) discussed relative performance of compartmentalization, lap belt restraints and lap/shoulder belt restraints, as well as the effects of seat back height and seat spacing on the performance of these safety restraint strategies [12]. Mitsuishi (2001) focused on passenger protection in frontal collisions and showed the limitations of lap belts in preventing head impacts and the potential of reducing passenger injuries by optimizing seat spacing [13]. In this way, although there has been extensive study of train and bus crashes, they focus on transverse seating layout. In the United Kingdom, the standard for safety assessment of transverse seating passengers exists [14], in which methods for sled tests using a dummy has been prescribed. On the other hand, there is no standard for longitudinal seating passengers. The longitudinal seating is typical as a commuter vehicle in Japan and can been seen in a European subway. Safety assessment in such a layout is also important.

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The secondary impact velocity is important for safety assessment in railway collision because passengers are thrown from their seat by the acceleration. The secondary impact velocity depends on the vehicle acceleration and initial position of the passengers. It is necessary to conduct case studies with these parameters for considering safety measures. If a simulation is able to predict passengers' behaviours, it is possible to identify the vehicle acceleration for suppressing the secondary impact velocity within an upper limit value. Therefore the purpose in this study is to propose the simulation method to estimate the passengers' behaviours. The error rate of the secondary impact velocity by the proposal simulation method was 3%.

II. METHODS

Sled tests using a dummy were conducted and numerical simulations reproducing the sled tests were performed.

Methods of the Sled Test

Sled tests were conducted to reproduce the secondary impact of a passenger. A side impact dummy (ES-2) was used in the sled tests because the movement of a passenger on longitudinal seating is mainly lateral in the event of head-on collision. Figure 1 shows the ES-2 dummy. Figure 2 shows the layout on the sled. The mock interior consists of a floor, a longitudinal seating and a bench-end partition. The longitudinal seating was what was used for commuter vehicles in Japan. A feature of the longitudinal seating was the shape of the bucket seating (figure 3).

Fig. 1. ES-2 dummy.

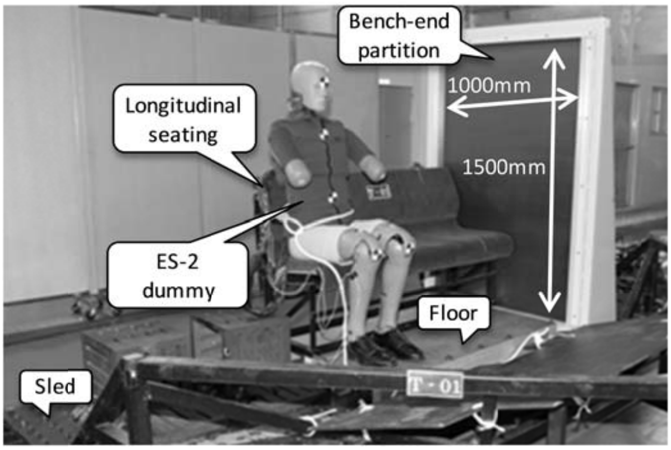
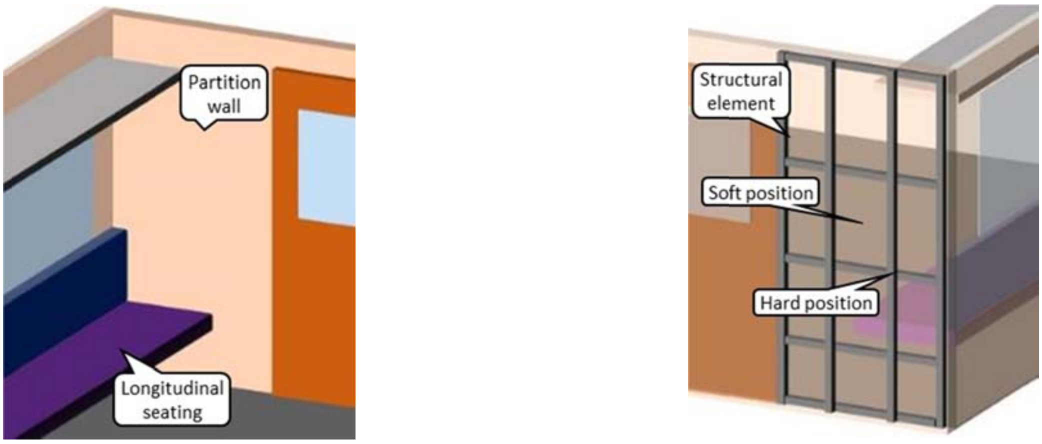


Fig. 2. Layout on the sled.

Fig. 3. Longitudinal seating.

Existing interior equipments, such as divider or partition, were not used for the bench-end partition. A steel plate (Height: 1500 mm, width: 1000 mm, material: SS400) was used as the bench-end partition, which is utilised in actual railway vehicles. A reason of choosing the steel plate is to avoid that a structure of the bench-end partition influences the severity of the injury. The severity of the injury depends on stiffness of collision position. Difference of collision position affects the severity of the injury in the case of using an existing vehicle partition because the existing vehicle partition has hard position and soft position (Figure 4).

Component experiments using a partition wall and a window, which are interiors a head of sitting passenger can collide with, were conducted in order to measure their stiffness. An impactor, imitating passenger's head, collided with them (Figure 5). Since the stiffness of the partition wall varies at the positions, the stiffness at two positions, which were hard position and soft position, were measured. Impact velocity was set at 5.0 m/sec which was approximately the same as secondary impact velocity of the dummy's head. Figure 6 shows the data measured and the stiffness defined. Horizontal axis represents replacement and vertical axis represents force. The deflection was measured with displacement gauge using magnescale. The force was calculated using acceleration measured by accelerometer in the impactor. The slope was defined as the stiffness in this study. The stiffness of the soft position of the partition wall, the hard position of the partition wall and the window was 350 N/mm, 1100 N/mm and 2300 N/mm, respectively.



(a) Interior fitting. (b) Back side of partition wall.

Fig. 4. Existing component in the train vehicle.

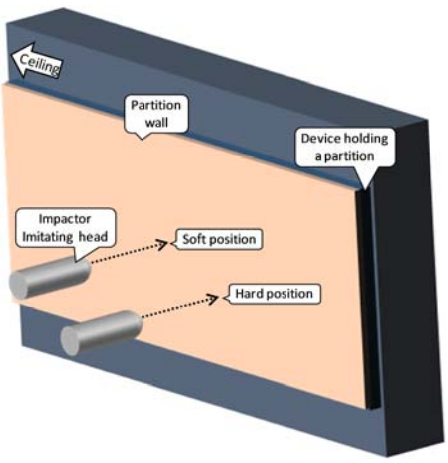
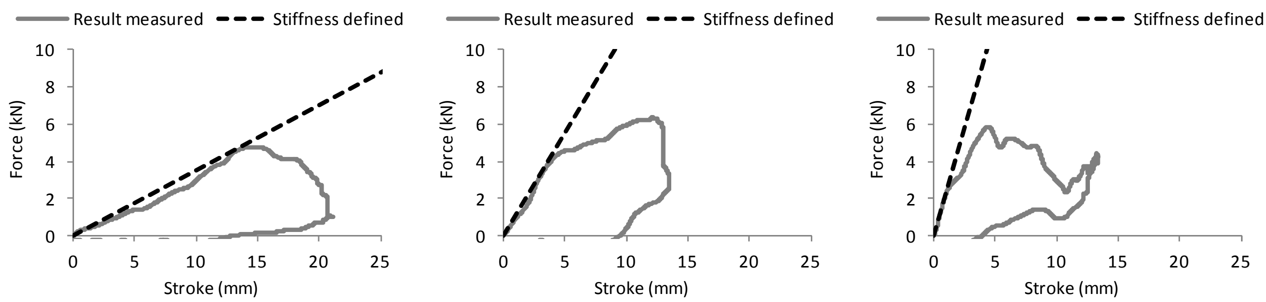


Fig. 5. Appearance of the partition wall experiment.



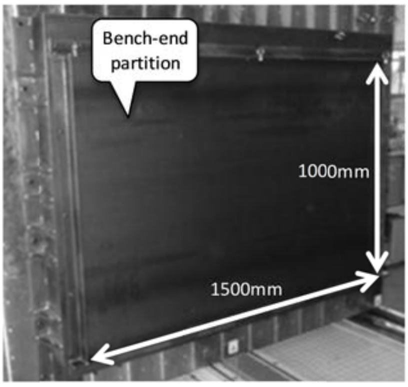
(a) Partition wall (Soft position). Stiffness: 350 N/mm

(b) Partition wall (Hard position). Stiffness: 1100 N/mm

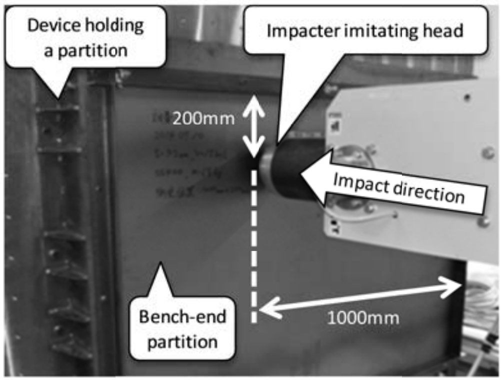
(c)Window. Stiffness: 2300 N/mm

Fig. 6. Results of the component experiments.

The same experiments were conducted by using SS400 (Thickness: 1.6 mm, 3.2 mm and 4.5 mm). Figure 7 shows the appearance of the steel plate component experiments. Four sides of the bench-end partition were held by a device. The impactor collided with the bench-end partition at 200 mm from the long side and 1000 mm from the short side. Impact velocity was set at 5.0 m/s. The stiffness value was defined by the relation between stroke (mm) and force (N). The stiffness value of 1.6 mm was 400 N/mm, 3.2 mm was 1200 N/mm and 4.5 mm was 2250 N/mm, respectively. Figure 8 shows the comparison of the stiffness. The stiffness of SS400 almost covered a range of the stiffness of the interiors. It is found that SS400 of 1.6mm, 3.2mm and 4.5mm was valid to imitate the stiffness of existing interior components.



(a) Condition of holding a partition



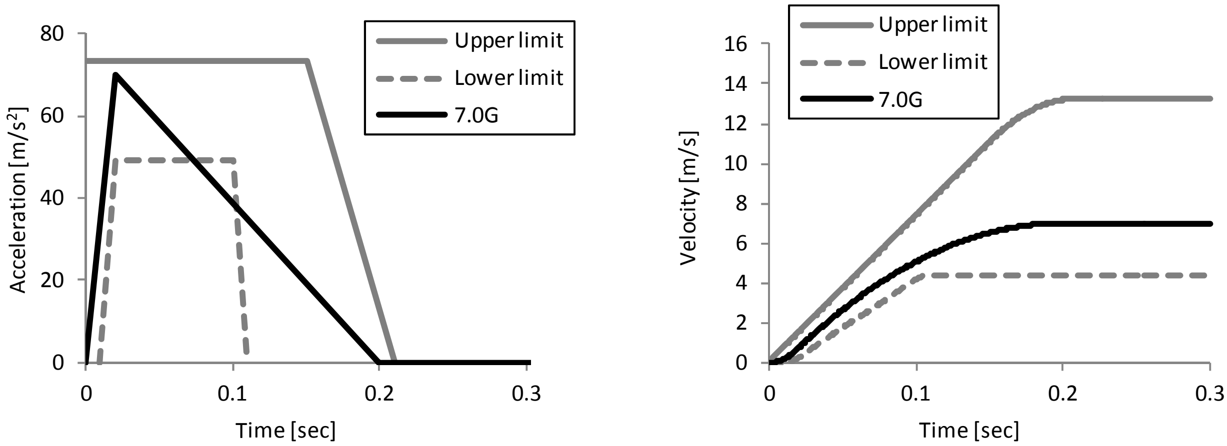
(b) Impactor colliding position

Fig. 7. Appearance of the steel plate component experiment.

Fig. 8. Comparison of the stiffness.

A corridor of the acceleration to evaluate crashworthiness of transverse seating passenger is provided in the RGS [14]. An acceleration impulse of 7.0 G was made in reference to an upper limit value of the corridor. It was difficult to reproduce the plateau part of the corridor in the performance of the test device. The velocity of the sled was within the corridor (Figure 9). An acceleration impulse of 6.0 G, 5.0 G and 4.0 G were made in reference to 7.0 G pulse (Figure 10). Figure 11 shows the initial position of the dummy. It is a hypothesis that the dummy initially translated, then pitched over with its head leading any other physical part.

Dummy's behaviour and head injury were evaluated. The collision position from the floor and the secondary impact velocity of the dummy's head (SIVH) were used to evaluate the dummy's behaviour. The collision position from the floor is important to evaluate the dummy's behaviour because it indicates the degree of leaning of the dummy. The degree of leaning of the dummy influences the SIVH. The velocity of dummy's head was measured using a high-speed camera whose frame rate was 1000 frame per second. Velocity data just before the velocity of dummy's head decreased suddenly was defined as SIVH because the secondary impact causes the rapid deceleration of dummy's head. As for head injury indexes, there are no requirements for the sled test with ES-2 dummy on the longitudinal seating. The dummy used in the RGS is Hybrid III which is different from ES-2 in structure. The head performance criterion (HPC) is used to indicate the likelihood of head injuries arising from the lateral impact, which is used in the field of automobile crash test. The HPC calculation method is the same as the head injury criterion (HIC) calculation method in the RGS.



(a) Relation of acceleration (b) Relation of velocity

Fig. 9. Comparison between pulse 7G and RGS corridor.

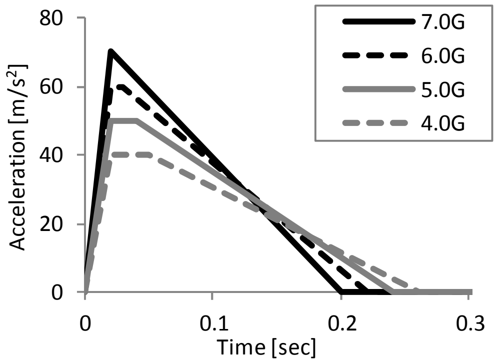


Fig. 10. Test conditions of acceleration pulse.

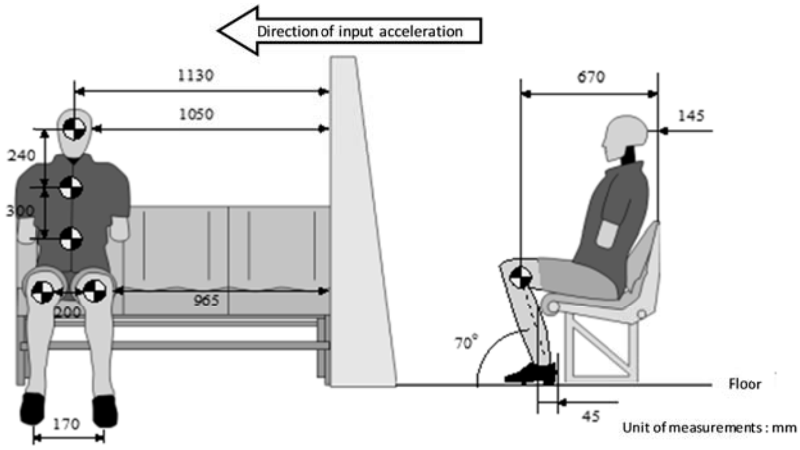


Fig. 11. Initial position of the dummy.

Methods of the Numerical Simulation

Numerical simulations under the same conditions of the sled tests were performed with MADYMO (Version 7.4.2). MADYMO is used widely in the field of the automobile crash simulation. ES-2 facet dummy model (Version 3.1) was used as the passenger. Figure 12 shows the ES-2 facet dummy model. Figure 13 shows the layout of the interior component model which consists of a floor model, a longitudinal seating model and a bench-end partition model. The longitudinal seating was modelled with an ellipsoid. The bench-end partition and the floor were modelled with a plane. They were rigid bodies. The results of the steel plate component experiments were substituted for contact characteristics of the bench-end partition model.

Although the longitudinal seating used in the sled test was bucket seat shown in figure 3, it was modelled with ellipsoid because of difficulty of modelling such a shape. Since the shape of the bucket seat influences the dummy's behaviour, the influence was simulated by varying the friction coefficient from 0.3 to 1.0.

Fig. 12. ES-2 facet dummy model.

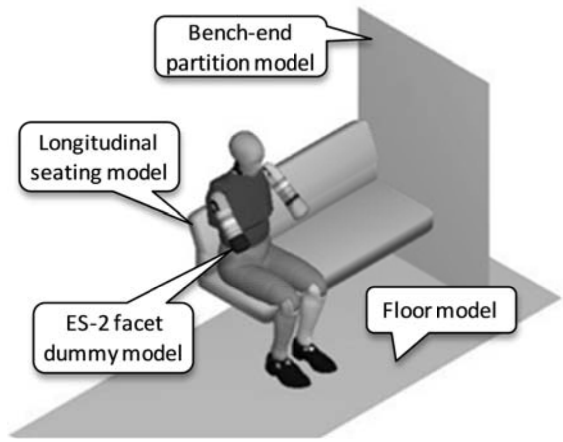


Fig. 13. Layout of the interior component model.

III. RESULTS

Comparing the results of the numerical simulations with those of the sled tests, the precision of the numerical simulations was inspected.

Results of the Sled Test

The actual acceleration of the sled was compared with the target acceleration. Figure 14 shows the time history of the sled acceleration (Acceleration pulse: 5.0G, Thickness: 3.2mm) and the target acceleration. The sled acceleration almost corresponded with the target acceleration. In the other conditions, similar tendencies were observed.

Figure 15 shows the dummy's behaviour in the sled test in the same case. The left side (a) was the initial position (0.000 sec), and the right side (b) was the time of secondary impact (0.214 sec). Figure 16 shows the measurement procedure of the collision position from the floor. The collision position from the floor was 1020mm in the case. Table 1 shows the results of the collision position. The higher the acceleration pulses, the higher the collision positions. The dummy pitched over largely in the case of the low acceleration pulse. In the condition of the same acceleration pulse, the collision positions were almost the same.

Figure 17 shows an example of the velocity change of the dummy's head over time during the test. SIVH was determined as shown in figure 18, since secondary impact causes a sudden deceleration of the dummy's head. Figure 18 shows relation between SIVH and HPC. In the case of the same thickness, the higher the SIVH, the larger the HPC. In the case of the almost same SIVH, the thicker the thickness, the larger the HPC.

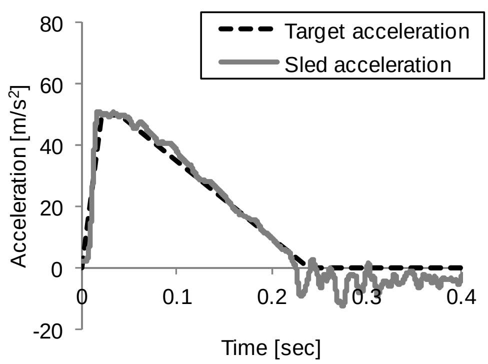


Fig. 14. Time history of the target acceleration and the sled acceleration.

(a) Initial position (0.000 sec) (b) Time of secondary impact (0.214 sec)

Fig. 15. Behaviour of the dummy.

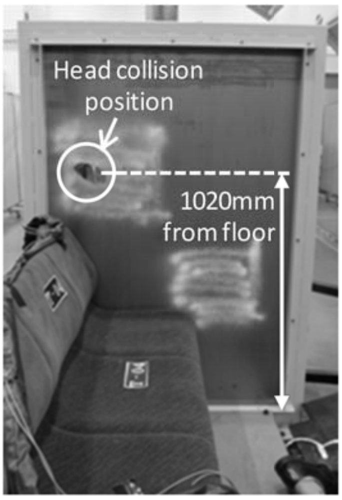


Fig. 16. Measurement of collision position from the floor.

TABLE 1
RESULTS OF THE COLLISION POSITION

		Stiffness		
		1.6mm	3.2mm	4.5mm
Acceleration	4.0G	-	960	990
	5.0G	1040	1020	1070
	6.0G	1153	1140	-
	7.0G	1155	-	-

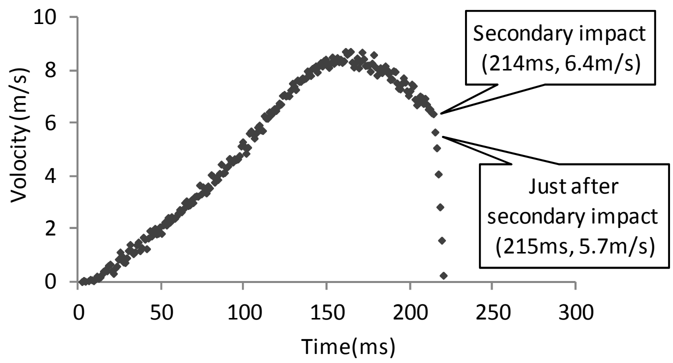


Fig. 17. The velocity change of dummy's head over time during the test.

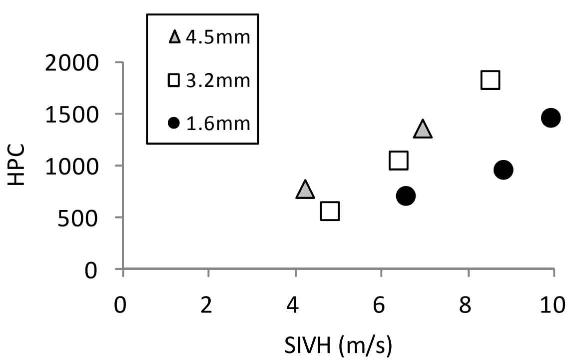


Fig. 18. Relation between SIVH and HPC.

Results of the Numerical Simulation

The results of the dummy's behaviours and the head accelerations in the simulations were compared with those of the sled tests. First as for the dummy's behaviours, error rates between the sled tests and numerical simulations were measured in the case of varying the friction coefficient between the dummy model and the longitudinal seating model. Figure 19 shows the error rates of the collision position and figure 20 shows those of SIVH. In the collision position, the error rate was 19% when the friction coefficient was 0.3. The error rate was decreased with increasing the friction coefficient. The error rate was minimum 3% when the friction coefficient was 0.9. In the SIVH, the error rate was 21% when the friction coefficient was 0.3. The error rate was decreased with increasing the friction coefficient. The error rate was minimum 3% when the friction coefficient was 0.9. From the results, it was found that the dummy model's behaviours of the simulations almost corresponded with those of the sled tests in the condition that the friction coefficient was 0.9. Figure 21 shows relation between SIVH and collision position in the sled tests and the simulations. Horizontal axis represents SIVH and vertical axis represents collision position. In the sled tests, the higher the collision position, the higher the SIVH. The simulations reproduced a similar tendency. Figure 22 shows examples of the dummy model's behaviour in the numerical simulation (Acceleration pulse: 5.0G, Stiffness: 1200N/mm, Friction: 0.9). The left side (a) was the initial position (0.000 sec), and the right side (b) was the time of the secondary impact (0.215 sec). The difference of the time of the secondary impact between the sled test and the simulation was only 0.001 sec. In comparison with the results of the dummy's behaviour in the sled test, the posture of the dummy model at secondary impact was almost the same.

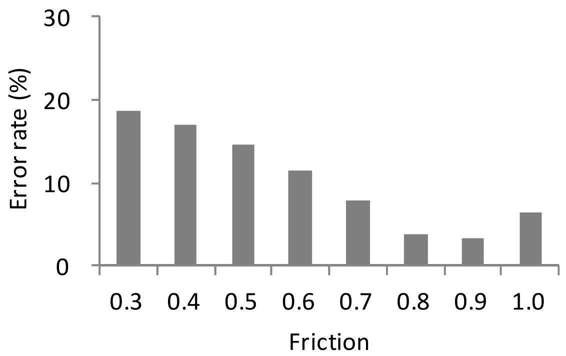


Fig. 19. Error rates of collision position.

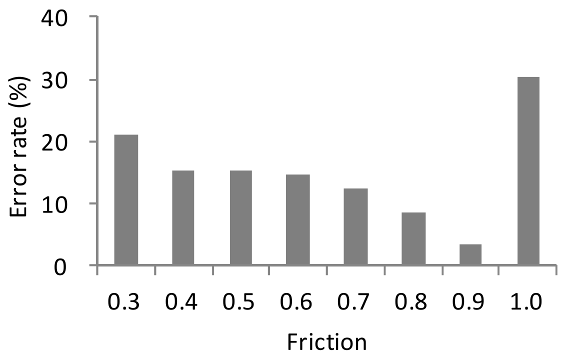


Fig. 20. Error rates of SIVH.

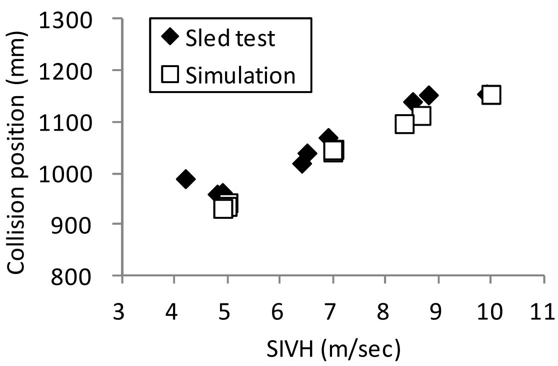
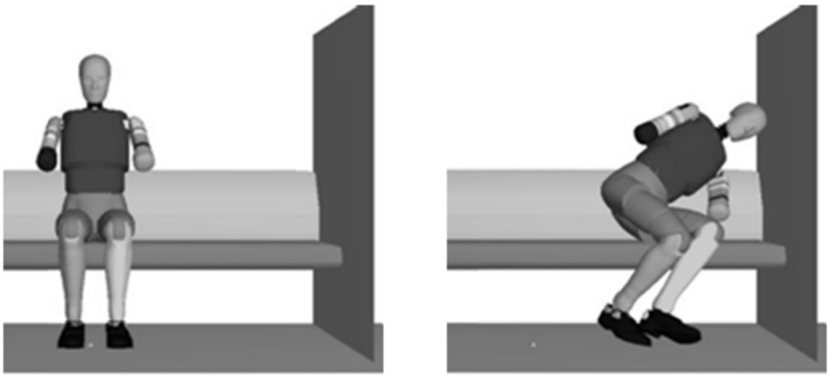


Fig. 21. Comparison of SIVH and collision position.



(a) Initial position (0.000 sec). (b) Time of secondary impact (0.215 sec).

Fig. 22. Behaviour of the dummy model.

Next, head acceleration was investigated. Figure 23 shows examples of the head G versus time plot comparing test to simulation (Acceleration pulse: 4.0G, Thickness: 4.5mm). In the sled test, maximum value was 182G and HPC was 781. In the simulation, maximum value was 708G and HPC was 5676. Vibrations of the head acceleration were observed which is not observed in the sled test. The HPC of the simulation was more than seven times that of the sled test. A completely different tendency was provided in the head acceleration.

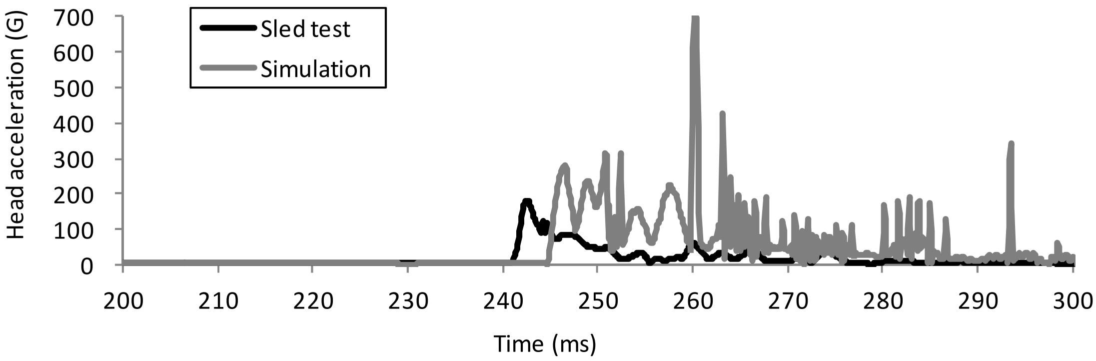


Fig. 23. Head G versus time plot comparing test to simulation.

IV. DISCUSSION

Characteristics of neck's joints were considered as the reason of the low precision of the head acceleration. Although the characteristics of the joints simulate those of the dummy's neck, head acceleration did not vibrate in the sled test. Therefore the characteristics of the neck's joints were improved. Figure 24 shows appearance of the dummy model's neck. ES-2 has five joints at its neck. Examinations to control movement of the joints were conducted in order to improve the characteristics of the five joints. The neck's joints were controlled one by one. Relations between status of the neck's joints and the head acceleration were examined. Figure 25 shows the error rates of the maximum value of the head acceleration. The horizontal axis represents the status of the neck's joints. "D" means "default" and "C" means "controlled". The error rate was 75% when all five joints were default. Controlling the joints one by one, error rate was 21% in the status that all joints were controlled and error rate was 19% in the status that only the bottom joint was default. Considering the average and the standard deviation of the error rates, the status that all joints were controlled was adopted. Figure 26 shows an example of the head acceleration in the status that all joints were controlled. In the simulation after improvement, maximum value was 227G and HPC was 1146. Although HPC in the simulation before the improvement was seven times that of the sled test, the error rate after the improvement was decreased significantly. By the results, it is difficult to evaluate the injuries of passengers in the railway collision with the default dummy model. The precision of the simulation was improved by controlling the characteristics of the neck's joints.

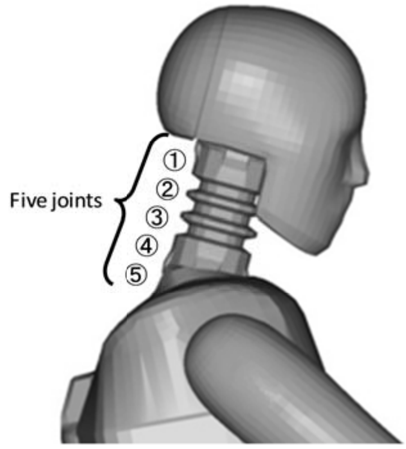


Fig.24. Five joints of the dummy model.

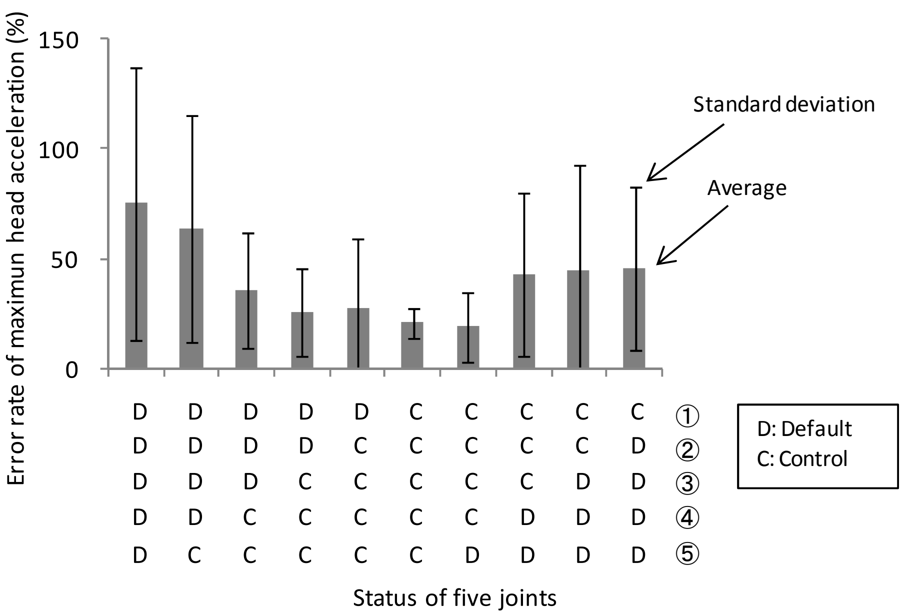


Fig. 25. Error rates of maximum head acceleration.

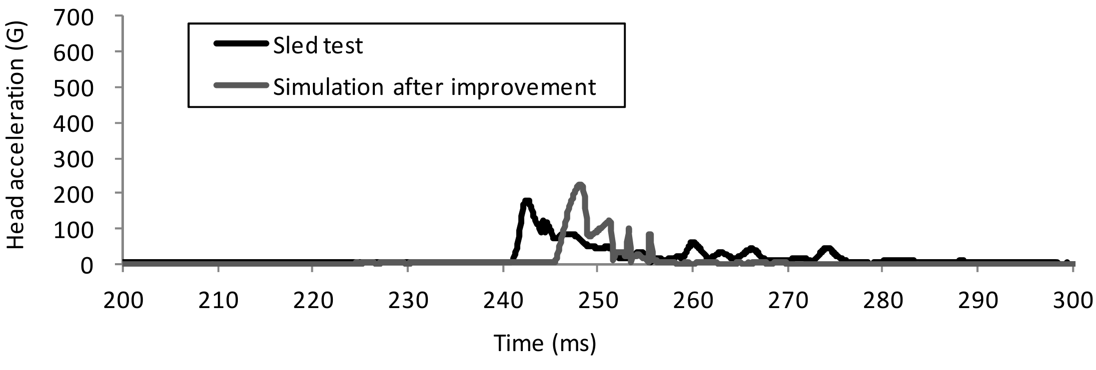


Fig. 26. Head G versus time plot comparing test to simulation after improvement.

For more improvement of the precision, a simulation analysis was conducted by varying the friction coefficient between the dummy model and the bench-end partition model from 0.86 to 0.95. Ranges of the maximum and the minimum value of the error rates of the HPC were investigated in order to extract the condition that reproduces the results of the sled test thoroughly (figure 27). When the friction was from 0.85 to 0.90, the ranges of the error rates were almost 40%, respectively. When the friction was 0.91, the range was 28% which was minimum. When the friction coefficient was more than 0.91, the ranges were more than 35%. Figure 28 shows relation between SIVH and HPC in the condition that the friction coefficient was 0.91. The results of the simulation showed the tendency same as that of the sled test

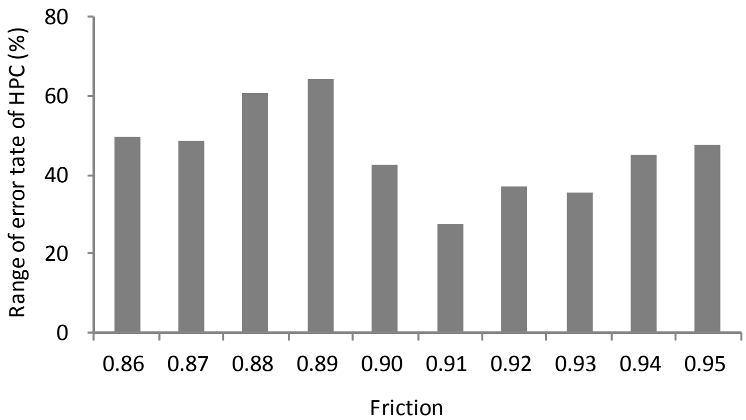


Fig. 27. Range of error rate of HPC.

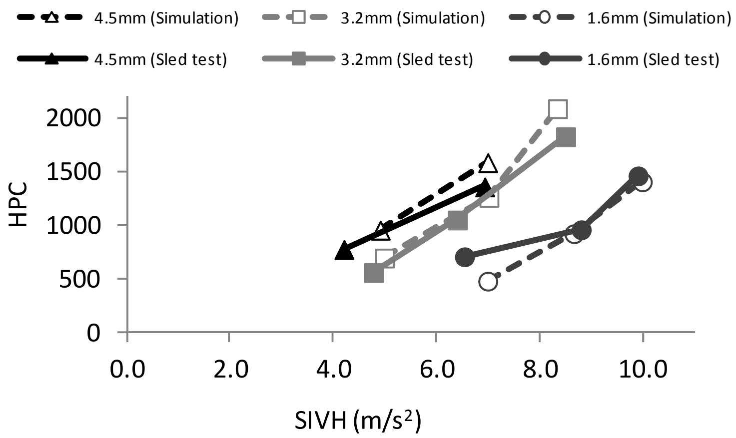


Fig. 28. Relation between SIVH and HPC.

The simulation method in this study has a limitation on the precision of the HPC. Although the error rate of the SIVH was only 3%, the error rate of the HPC was almost 20%. Two reasons are considered. One is the characteristics of the neck's joints of the dummy model. Since the ES-2 model was developed for automobile crash simulation, the default model was not able to evaluate the head injury in the railway collision accurately. The other is that the bench-end partition model, which was the steel plate, was the rigid body. Actually the steel plates deflect due to the impact. It is necessary to model them with FE.

V. CONCLUSIONS

This study focused on a passenger seated on longitudinal seating at the time of the railway collision. The purpose was to propose the simulation method to estimate the SIVH. In order to confirm the situations of the secondary impact, the sled tests were conducted. Numerical simulations reproducing the sled tests were also performed. The results of the SIVH in the numerical simulations almost coincided with those of the sled tests. As for the head acceleration, the results of the simulation were different from those of the sled tests greatly. It was found that the dummy model of the default is not usable for the evaluation of the head injury in the railway collision. Controlling the characteristics of the neck's joints, the precision of the head acceleration was improved. In the future, conducting parametric studies with various accelerations, relation between the vehicle acceleration and the secondary impact velocity is going to be clarified.

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