Basic Research on Standing Passenger Injury Response in Urban Rail Train Collision

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I. INTRODUCTION

In recent years, due to the extensive use of rail vehicles, the passenger safety has become a focus of attention. Because urban rail vehicles usually run in cities with large populations, once a car accident occurs, it will lead to serious casualties. For example, on November 17, 2017, a subway rear-end collision in Singapore caused more than 25 people to be injured. Therefore, the passenger injury response in urban rail vehicles is worth studying.

In the train collision accident, the secondary collision between the passenger and the vehicle body is the main cause of casualties when the vehicle deformation is small [1,2]. Compared with seated passengers, the number of standing passengers is higher, and the space for movement is larger, so the risk of injury is higher when collision occurs. Reference [3] found out that the head was the most commonly injured for standing passenger and 80% of the standing passenger were injured by the floor, handrails or other passengers. Reference [4] found that the shape of bench-end partitions and length of baggage racks played a role in safety for standing passenger. Reference [5] showed that horizontal handrail was the type of handrail with the least head injury. The results of Reference [6] suggest that the shape of a vertical handrail has a significant impact on the injuries to passengers standing backward and sideways .

Based on the injury standards and specifications of passengers in car collisions, researchers have developed a series of standards and specifications for passengers in rail vehicles. BS railway standards issued GM/RT2100 [7] specifies the structural energy absorption requirements of vehicles in collisions and the vehicle internal facilities requirements for passenger safety in secondary collisions. The Association of Train Operation Companies also put forward a standard ATOC AV/ST9001 to evaluate the train occupant injury [8], it also provided relevant basis for the design of train interiors.

At present, there are many studies on the collision of passenger with other passenger or object, but few studies on direct collision with floor. In this paper, a standing passenger in an unconstrained state was studied. In order to analyze injury of standing passenger, two kinds of impact acceleration in the above standards as boundary conditions compared with the velocity boundary condition in actual train collision.

II. METHODS

The methods of passenger secondary collision mainly include experiment and numerical simulation, Experiments are reliable but expensive. By contrast, numerical simulations are cheap and repeatable, therefore, the numerical simulation method is adopted in this paper.

Finite element model

As shown in Fig.1, the Hybrid III 50th finite element dummy model established by Livermore Software Technology Corporation (LSTC) was used, the dummy model is 177 cm tall and weighs 86 kg.

The bone of dummy does not deform, so *MAT_RIGID is used for it. The muscles were simulated with *MAT_ELASTIC, and the abdomen, buttocks and the softer parts of knees were simulated with *MAT_LOW_DENSITY_FOAM. Most of the elements are hexahedron and the elements size is about 40mm.

At present, most urban rail train made of aluminum alloy, so the * MAT_PIECEWISE_LINEAR_PLASTICITY material model is used. Parameters are set according to the mechanical properties of aluminum alloy.The contact between the passenger and the floor is simulated by * CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. The friction coefficient between the shoes and the floor is set to 0.49, the friction coefficient between the body of passenger and the floor is set to 0.3.

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Boundary conditions

There are two kinds of acceleration commonly used in research as mentioned in the introduction section. In tests to evaluate injury to railway passengers, the impact acceleration used by U.S. department of transportation Volpe Center is a triangular pulse, as shown in Figure 1. The impact acceleration defined by the British Standard ATOC AV/ST 9001 is shown in the Figure 2, the upper limit of acceleration has been selected as the boundary condition. The maximum of both is 8g.

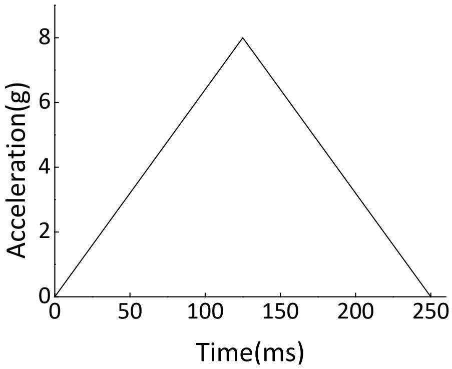

Fig. 1. Acceleration of Volpe.

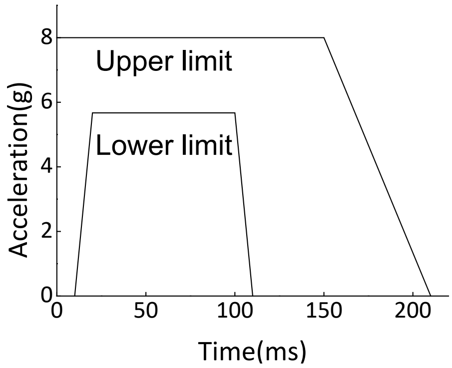

Fig. 2. Acceleration of ATOC.

The longitudinal velocity of the stationary head carriage in a 25 km/h collision condition is shown in Fig. 3. By contrast, the velocity obtained by the above two accelerations is significantly larger and more stable. In order to study the injury of passengers in the actual collision, the velocity in the actual collision was also taken as the boundary condition of the model. It can be seen in Fig. 4 that the longitudinal velocity is obviously greater than the other two directions velocity. In order to study the effect of vertical velocity and transverse velocity on injuries, the three directions velocity was taken as the boundary condition.

Because the passengers and vehicle had the same velocity before collision, the boundary conditions were only given to the floor.

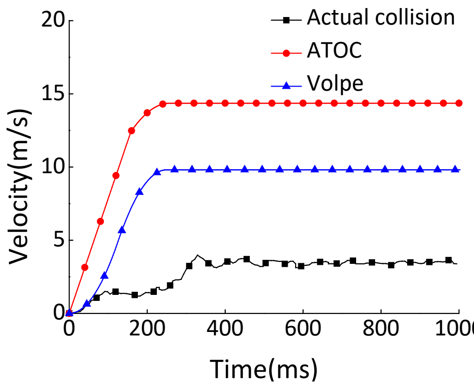

Fig. 3. Different velocity - time curves.

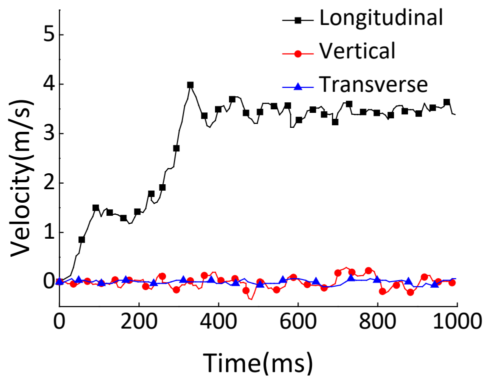

Fig. 4. Velocity - time curves in three directions.

III. INITIAL FINDINGS

In the process of collision tests or simulations, we can obtain the force, displacement, velocity, and acceleration parameters of the dummy model. However, these parameters cannot reflect the degree of injury directly. The researchers established relevant injury evaluation indexes to facilitate the determination of passenger injury. These indexes are mainly for the head, chest, neck and legs of humans. In order to protect the passive safety of passengers, injury evaluation indexes are specified in the above two standards, and the loss value is limited, as shown in Table 1.

TABLE I

INJURY LIMIT VALUE OF PASSENGER IN TRAIN COLLISION

	HIC	Neck moment		Clip3m	CC	FF	TF	TI
		Flexion	Extension					
AV/ST9001 [8]	500	190Nm	57Nm	/	30mm	4kN	/	0.75
GM/RT2100 [7]	500 (HIC15)	310Nm	135Nm	60g (3ms)	63mm	4kN	8.0kN	1.0

Where HIC is the head injury evaluation index, Clip3m is the chest injury evaluation index, CC is the chest compression, FF is the femur force, TF is the tibial force and TI is the tibial index. There is another neck injury evaluation Nij that is not described in the standard, but is often used in research, this value is usually required to be less than 1.In order to comprehensively evaluate the injuries of passenger, the weighted injury evaluation index is introduced, and the calculation formula is as follows. The larger the WIC value is, the greater the injury to passengers.

$$WIC=0.6(\frac{HIC}{1000})+0.35(\frac{Clip3m}{60}+\frac{THCC}{0.0762})/2.0+0.05(FF_{left}+FF_{right})/20.0$$

Dynamic response

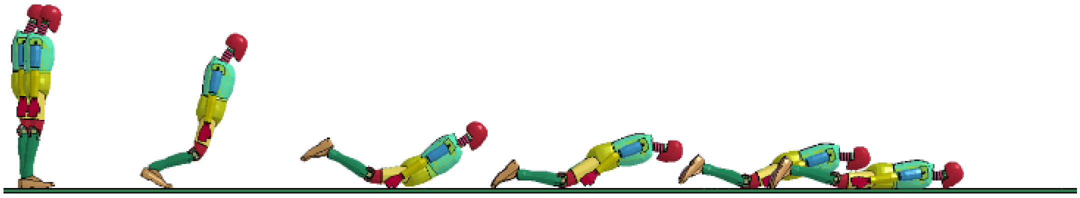

Fig. 5. Postures of standing passenger under acceleration of Volpe.

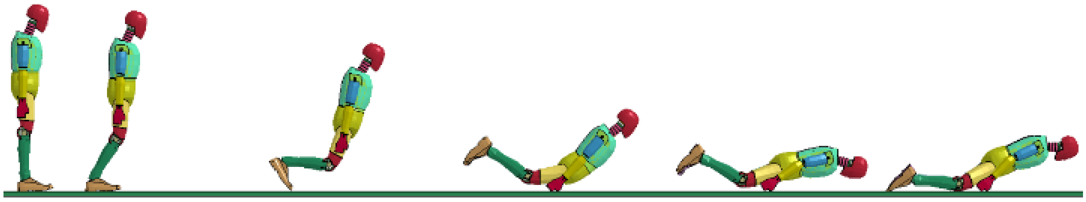

Fig. 6. Postures of standing passenger under acceleration of ATOC.

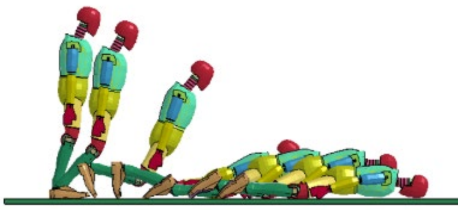

Fig. 7. Postures of standing passengers under longitudinal velocity.

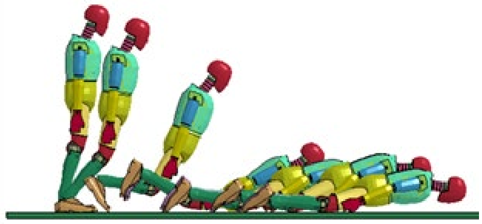

Fig. 8. Postures of standing passengers under velocity in three directions.

The dynamic responses under the above two acceleration impacts are shown in Fig. 5 and Fig. 6. Under accelerations, the centre of gravity of a standing passenger moves forward and slides on the floor, the knee bends under gravity and then comes into contact with the floor. Due to the reaction forces of the knees and the floor, the occupants were threwn upwards and then landed again causing injuries.

The dynamic responses of a standing passenger under actual collision velocity are shown in Fig. 7. and Fig. 8. Compared to the results of the above two accelerations, the distance the passenger is thrown forward is significantly shortened. The results also show that the transverse and vertical velocity of the vehicle body had little effect on passengers.

Injury assessment

In order to study passenger injury more intuitively, according to standards, injury values of the head, chest, neck and lower limbs were extracted. The injury values of unconstrained passengers under the above four different boundary conditions are shown in Table II.

TABLE II
INJURY INDEX UNDER DIFFERENT BOUNDARY CONDITIONS

	HIC36	Clip3m (g)	CC (mm)	Neck force (kN)		Neck moment (Nm)	
				Tension	Compression	Flexion	Extension
Volpe	**7158**	**68.8**	40.77	**8.72**	5.29	135.17	23.37
ATOC	**4586**	**66.5**	40.55	**7.07**	6.16	134.21	34.87
longitudinal velocity	**4273**	59.0	38.91	**8.42**	5.09	132.87	25.90
three-directions velocity	**5918**	**60.3**	38.71	**9.13**	5.08	132.93	30.57

	Nij	FF (kN)		TI		WIC
		Left	Right	Left	Right	
Volpe	**1.35**	3.34	2.94	0.36	0.67	4.60
ATOC	**1.43**	3.34	3.39	0.33	0.33	3.06
longitudinal velocity	**1.31**	3.54	3.55	0.25	0.33	2.84
three-directions velocity	**1.40**	2.34	2.37	0.29	0.32	3.83

IV. DISCUSSION

For the validity of the dummy model, according to literature [9], the model was verified in two situations, one falling forward, the other falling backward. As shown in Table III, the results obtained by finite element simulation are within the test range, so the model can be used for this study, the results are reliable.

TABLE III

HEAD RESPONSE VALUES OF TEST AND SIMULATION

		F_{max} (N)	Amax (g)	V (m/s)
Falling forward	Test	21155 ± 6775	421 ± 121	6.89 ± 1.22
	Simulation	18098	345.07	5.97
Falling backward	Test	22767 ± 2107	451 ± 38	6.75 ± 0.27
	Simulation	23517	479	6.64

From the injury values in the table II, it can be seen that head injury of standing passengers is the most serious. The injury was mainly caused by the head hitting the floor, the stiffness of the floor causes a large head acceleration. Head injury value HIC36 is much larger than standard, this can lead to death of passengers. Similar to the head injury, a large chest acceleration occurs when the chest hits the floor. This caused chest injury values Clip3m to exceed or approach standard values. The neck injury values Nij all exceed the standard value, which is mainly because the axial tension of the neck is too large. Although the lower limbs of passengers were injured, the damage value did not exceed the standard value. In summary, for the unconstrained passengers in a train collision, head and neck injuries are the most serious, followed by the chest, and the least affected are the lower limbs. At the same time, compared with the data under the longitudinal velocity, the reduction of the boundary velocity does not reduce passenger injury too much. This indicates that the boundary velocity is not the main factor affecting injury to standing passengers, and that the posture response under different boundary conditions is the main factor.

By comparing the dynamic response under the above four boundary conditions, we can clearly see that the passengers are thrown further under the acceleration boundary, and the passenger response at actual collision velocity is more realistic. So instead of using the acceleration in the standard as the boundary condition, it is better to use the actual collision velocity. In addition, compared with the injury values under longitudinal velocity, the value of HIC36, Clip3m, Nij, WIC increased by 38.50%, 2.20%, 6.87% and 34.86%, respectively, when considering the three-directions velocity. This shows that the vertical and transverse velocity will increase the injury of the passenger. It is best to consider three-directions velocity when choosing boundary conditions.

V. REFERENCES

[1] Evans, A.W. Fatal train accidents on Europe's railways: 1980-2009. *Accid Anal Prev*, 2011. 43(1): p. 391-401
[2] Silla, A. and Kallberg, V.P. The development of railway safety in Finland. *Accid Anal Prev*, 2012. 45: p. 737-44
[3] OMINO, K., SHIROTO, H., and SAITOH, A. Behavior Analysis of Passengers on Bench Seats in a Train Collision. *QR of RTRI*, 2008. 49(1): p. 47-52
[4] NAKAI, K., OMINO, K., SHIROTO, H., and SUZUKI, D. Simulation of Passenger Behavior on Board a Commuter Train in the Event of a Level Crossing Accident. *QR of RTRI*, 2012. 53(4): p. 235-240
[5] Peng, Y., Xu, T., Hou, L., Fan, C., and Zhou, W. An Investigation of Dynamic Responses and Head Injuries of Standing Subway Passengers during Collisions. *APPL BIONICS BIOMECH*, 2018
[6] Yao, S., Li, X., Xiao, X., Xu, P., and Che, Q. Injuries to standing passengers using different handrails in subway train collision accidents. *Int J Crashworthiness*, 2019
[7] "GM/RT2100: Structural Requirements for Railway Vehicles". London. 2010.
[8] "ATOC Vehicle Standard AV/ST 9001 Vehicle Interior Crashworthiness". London. 2002.
[9] Seidi, M., Hajiaghamemar, M., and Caccese, V. Evaluation of effective mass during head impact due to standing falls. *Int J Crashworthiness*, 2015. 20(2): p. 134-141