High-speed train occupant impact injury analysis in post-derailment collisions: methodology framework and initial results

Gongxun Deng, Yong Peng, Ciaran Simms

I. INTRODUCTION

The International Union of Railways reported that train derailments caused 37% of passenger casualties in 2019 [1]. Reinforced concrete (RC) containment walls are the most common countermeasure to reduce derailment-related losses, particularly in China's high-speed railways that are often built on viaducts. Nonetheless, this results in derailment-induced collisions with the adjacent RC wall. Previous train occupant impact injury studies have focused on full-frontal collisions [2-3], while there has been little evaluation of occupant injury in post-derailment collisions. This paper proposes a methodology framework for occupant crash analysis during train post-derailment collisions and assesses the effect of seating positions on occupant responses.

II. METHODS

A combination of finite element (FE) simulations, impact tests and multibody (MB) simulations was utilised (Fig. 1). First, FE models of the high-speed train and RC wall were established and respectively validated against single vehicle derailment test (30 km/h), eight-car marshalling train-to-train full-scale impact test (36 km/h), and RC beam drop tower tests (6.86 m/s) [4]. The eight-vehicle marshalling train post-derailment crash simulation on a curve of 400 m radius under 150 km/h was then performed using LS-DYNA [4]. Secondly, the rail vehicle motions were extracted from the LS-DYNA predictions and used as input for the MADYMO simulations. Thirdly, the train seat MB model was developed and verified against dummy sled tests [5], while the contact characteristics of the train's side-window glass were obtained via a drop tower test at 7 m/s (6.16 kg hammer close to the head-neck mass). Finally, injury risks for passengers seated in three positions in the head car were estimated in the MADYMO environment using injury risk curves for the head, neck, chest and femur [6]. Additionally, a combined injury probability metric was calculated to assess the passengers' total injury risk.

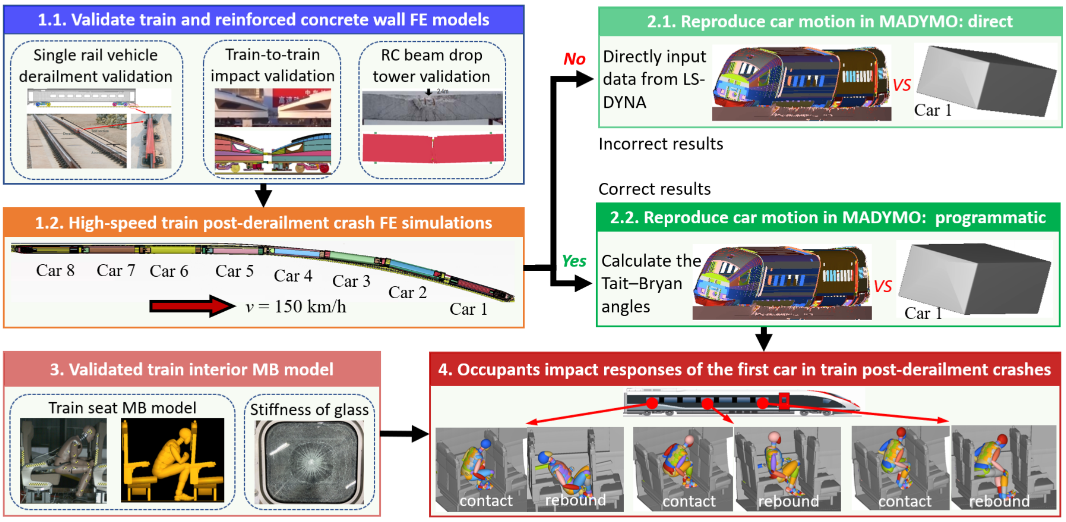

Fig. 1. Overall methodology for occupant injury analysis in train post-derailment collisions.

Three key points need to be noted. (1) The LS-DYNA output data were not directly compatible with MADYMO and initially resulted in inaccurate reproduction of the train motion (Fig. 1). Although the deformation of the train body was not significant during post-derailment collisions, the train exhibited obvious six-degree-of-freedom (6DOF) rigid body motion. In this study, the coordinates time histories of nodes that make up the local coordinate system of the vehicle were first output using LS-DYNA. Subsequently, the vehicle Tait–Bryan angles were calculated via calculating the rotation matrix using the nodal coordinates in MATLAB and this correctly reproduced the rigid body train motion as input in MADYMO. (2) The Hybrid-III 50th percentile Ellipsoid Q dummy model was employed here instead of the Facet active human model, as the Facet model was found to be

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G. X. Deng is a PhD candidate and Y. Peng (e-mail: yong_peng@csu.edu.cn; tel: +86-073182655374) is a Professor in the School of Traffic & Transportation Engineering at Central South University, China. G. X. Deng is also a joint PhD candidate in Biomechanics at Trinity College Dublin, Ireland. C. Simms is a Professor in Biomechanics at Trinity College Dublin, Ireland.

unsuitable for such high-speed collisions due to significant mesh distortions during high-velocity (>25 m/s) simulations. The root cause of this phenomenon is currently unclear. (3) To simulate passengers gripping the handrails in such long-duration but low-intensity crashes, the dummy's hands were re-established with the fingers. The fingers-handrail contact failure was defined to simulate the maximum grip force of the hand at 450 N [2].

III. INITIAL FINDINGS

In train post-derailment collisions, the occupant generally first hits the seat in front and the surrounding vehicle side wall (including the side-window glass) when the train strikes the RC wall (Fig. 1). The coupling effect between multiple cars in a train then leads to a rear-end collision between the cars, causing the occupant to rebound and potentially suffer from significant neck motion. Passengers seated in the rear seats in the head car are particularly vulnerable to this phenomenon (Fig. 1) because they are closer to the rear-end impact area and therefore more vulnerable to the effects of the rail vehicle-to-vehicle collision.

Table I depicts the detailed occupant injury criteria predictions and associated injury probabilities for three different seating positions. The head, neck and femur outcomes are serious, while the chest injury risk is negligible. The combined injury risk of the passenger seated in the rear of the head car is highest (92%).

TABLE I

PREDICTED INJURY MEASURES IN TRAIN POST-DERAILMENT COLLISIONS

Seating position	Head		Neck		Chest		Femur		Pjoint
	HIC 15	P (AIS3)	Nij	P (AIS3)	D (mm)	P (AIS3)	F (kN)	P (AIS2)	
Front	509	5%	0.90	19%	1.67	0%	6.26	7%	29%
Middle	761	13%	0.42	8%	0.17	0%	6.24	7%	26%
Rear	574	7%	0.73	14%	1.02	0%	15.253	89%	92%

IV. DISCUSSION

Train derailment is one of the most common major train accidents, which results in collisions with surrounding infrastructure and exhibits significant 6DOF motion. However, this is different from automobile rollover. Although automobile rollovers also involve 6DOF motion, previous research focused on the roof-to-ground collision phase, with only the initial position and velocity of the car body being input into MADYMO, and not considering the entire motion of the vehicle (such as the airborne rolling phase) [7]. However, as train passengers lack restraint systems and sufficient grip strength on handrails, very significant kinematic motion occurs after derailments. Thus, long-duration simulations are necessary to assess the influence of the entire 6DOF motion of vehicles on passenger responses. In addition, there is substantial vehicle crash acceleration noise as output from the FE models, especially for long-duration collisions. This necessitates inputting the complete vehicle's 6DOF displacements into MADYMO, as simply inputting the initial position and velocities of the vehicle is inadequate. Due to the different definitions of rotational motion between the two software programs, LS-DYNA results cannot be accurately replicated in MADYMO by directly inputting the kinematic curves. Hence, the rotation matrix must be calculated to determine the vehicle's Tait–Bryan angles.

The kinematic and injury responses of train occupants vary significantly among the three seating positions, emphasising the significance of passenger position in evaluating train occupant crash safety. Passengers seated at either end of the vehicle have higher injury risks because they are closer to the collision area. Head and femur injuries are severe due to direct contact, while chest injury is negligible as the foldable table is closed in these simulations, which prevents direct contact. However, the neck motions resulting from a rear-end collision by the following vehicle require further investigation to evaluate the risk of neck injury. Train derailments are complex and may present various scenarios that depend on surrounding infrastructures (e.g., derailment in a tunnel). Besides, occupants in different carriages may sustain varying injuries, which necessitates further study in the future.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

[1] UIC, 2020.
[2] Deng, G., *et al*., *Accid Anal Prev*, 2022.
[3] Suzuki, D., *et al*., *IRCOBI*, 2015.
[4] Deng, G., *et al*., *ICCES*, 2023.
[5] Deng, G., *et al*., *IRCOBI*, 2022.
[6] Eppinger, R., *et al*., *NHTSA*, 1999.
[7] Parent, D., *et al*., *SAE*, 2011.