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Original article

Finite element simulation of lower limb injuries to the driver in minibus frontal collisions

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ABSTRACT

Purpose: This study aims to explore the biomechanical mechanism of lower limb injuries to the driver by establishing a finite element (FE) simulation model of collisions.
Methods: First a minibus FE model was integrated with a seat belt system. Then it was used to rebuild two collisions together with the total human model for safety (THUMS) provided by Toyota Motor Corporation: a rear-end collision between a minibus and a truck and a head-on collision of a minibus to a rigid wall. The impact velocities of both collisions were set at 56 km/h. The vehicle dynamic response, vehicle deceleration, and dashboard intrusion in the two collisions were compared.
Results: In the minibus rear-end truck collision, the peak values of the von Mises equivalent stress at the tibia and the femur were 133 MPa and 126 MPa respectively; while in the minibus head-on rigid wall collision, the data were 139 MPa and 99 MPa. Compared with the minibus head-on rigid wall collision, the vehicle deceleration was smaller and the dashboard intrusion was larger in the minibus rear-end truck collision.
Conclusion: The results illustrate that a longer dashboard incursion distance corresponds to a higher von Mises equivalent stress at the femur. The simulation results are consistent with the driver's autopsy report on lower limbs injuries. These findings verify that FE simulation method is reliable and useful to analyze the mechanisms of lower limb injuries to the driver in minibus frontal collisions.

Introduction

According to the road traffic safety report released by the Ministry of Public Security Traffic Management Bureau, by the end of 2013, the number of motor vehicles nationwide has exceeded 250 million, indicating that China has been a leader in the automobile industry. Although the road safety situation is generally stable, people's awareness of road safety remains inadequate. The report also pointed out that in recent years; the market demand for minibus has been increasing. In 2013, the nationwide number of minibuses reached 14.38 million, 53.7% of which were used in rural areas. Meanwhile, the rate of minibus accidents has been rising annually, often causing serious casualties.[1] Based on the Communications in Computer and Information Science database, Pattimore et al[2] studied the type and region of the lower limb injuries of 2080 occupants who were bounded in the front-seat in 1991. The study revealed that, of the lower limb injuries, 76.5% was located below the knee area, and 92% was located in the thigh region. Recently, Li et al[3] conducted data collection and in-depth investigation of minibus head-on collision accidents in China and found that thigh injuries were involved in a large proportion of minibuses rear-end truck collisions. To clarify the mechanisms of the driver's lower limb injury, we constructed a finite element (FE) simulation model to analyze the injury mechanisms and the vehicle dynamic response process.

Materials and methods

In this study, a seat belt system was further built on a pre-built minibus FE model that has been verified by a real vehicle collision

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test using the HyperMesh software. Thereafter it was integrated with the total human model for safety (THUMS) provided by Toyota Motor Corporation to establish a complete minibus occupant restraint system. A real car crash test to the minibus has been conducted previously,[4] the results of which showed that the vehicle deformation mode, impact force, and B pillar acceleration[5] were highly consistent with the FE simulation results. Besides, the hourglass can be controlled below 5% of the total energy. These findings verify that FE model and numerical simulation are effective. On this basis, we reconstructed the rear-end collision between a minibus and a truck and the head-on collision of a minibus to a rigid wall under the same boundary condition and load. The simulations were calculated by LS-DYNA ls971s R5.1.1 with the hardware being a HP-Z820 workstation and the operating system being Windows7 X64.

A real case

In 2015, a minibus rear-ended a truck in the Chongqing Expressway section, in which the minibus driver died (Fig. 1). According to the autopsy report, the driver's lower limbs had open laceration with irregular wound edge and visible subcutaneous & muscle tissue. Epidermal exfoliation and subcutaneous hemorrhage were observed in the upper section of the left thigh at which fracture was palpable. These symptoms were more severe at the left interior knee joint and multiple fractures were found in the lower limbs. According to the appraisal report provided by an accident forensic center in Chongqing, when the accident occurred, the speed of the minibus was 56 km/h.

FE model of the occupant restraint system

Driver FE model

The selected driver model was the THUMS (version 4.0, seating posture) FE model, which was jointly developed, designed, and verified by the Toyota Motor Corporation and the Toyota Technical Center (Japan).[6] The element quantity of this FE model was more than two million, and the definitions of its materials and properties met the basic need of crash regulations. We adjusted the model's position to ensure that the model was placed on the seat accurately and ideally.

Fig. 1. Image of the traffic accident scene.

Seat belt FE model

The minibus has no airbags, so the seat belt is the most important occupant restraint system. Seat belt has 4 main types: shoulder belt, lap belt, three-point and four-point seat belts. We built a three-point seat belt model by using the Primer software. The model consisted of 324 elements and 396 nodes, including a retractor, a slipring, a webbing (500 mm wide and 1.2 mm thick),[7] a buckle, and other components. The retractor contains a pre-tightening device and a force-limiting device. The belt can effectively simulate its sliding on the driver's body surface during collision.[8]

Full vehicle FE model

The minibus model was provided by an automobile manufacturing company in Chongqing, China, which includes the car body, windshield, seating systems, steering systems, instrument panels, pedals, etc. It was modeled with 727,826 elements. The materials and properties met the basic need of crash regulations. In addition, the dynamic characteristic was successfully verified through head-on collision experiments. The truck model was downloaded from the US national crash analysis center, which included 36,539 elements. The cargo floor is 110 cm from the ground and the bottom of the back anticollision barrier is 60 cm from the ground, highly consistent with the real accident vehicle.

Setting of contacts

During collisions, a lot of contacts occur between road and vehicle, between vehicles, and between vehicle and driver. The contact type between THUMS model and components in the vehicle can be defined as Automatic-Surface-To-Surface. The ground was simplified as a rigid wall since it was not deformed.[7] The road property of the real crash described above was asphalt, so the friction coefficient between the road and the vehicle was set as 0.70, that between the human and the vehicle was 0.65, and between the minibus and the truck was 0.6.[9]

Boundary condition and load

The truck did not move obviously in the real crash. Thus, the translation and rotation in the directions of X, Y and Z were strictly limited. The acceleration of gravity imposed on the vehicles and THUMS models was 9.8 m/s^2. In the two simulated collisions, the impact velocities were set at 56 km/h. Fig. 2 shows the rear-end collision between the minibus and the truck (Fig. 2A) and the head-on collision of the minibus to the rigid wall (Fig. 2B).

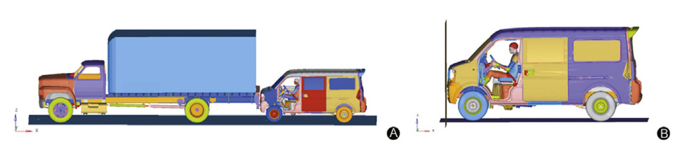

Fig. 2. Two collision models. A: The rear-end collision between the minibus and the truck. B: The head-on collision of the minibus to the rigid wall.

Results

Vehicle dynamic response

Fig. 3 shows the dynamic response process of the rear-end collision between the minibus and the truck. At 9 ms, the front of the minibus began to contact the truck tail and the seat belt began exerting pre-tightening effect on the driver. At 45 ms, the driver's lower extremity started to contact the dashboard. At 63 ms, the