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Numerical Simulation of Side Impact Crashes

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Abstract: Side impact collisions are the second most frequent cause of serious motor vehicle accidents after frontal impact. To reduce the severity of human injury through improved automobile design and designing protection devices, the dynamic response and injury of occupants in collisions must be analyzed. This study investigates the development and validation of a vehicle, movable barrier and dummy FEM model for studying interaction. Based on the Federal Motor Vehicle Safety Standard No. 214 (FMVSS214), the numerical crash test model was developed to simulate a side impact accident. The crash simulations were conducted using the LS-DYNA finite element code. The numerical models were found to be able to predict the severity of the driver's injury in impacts. The proposed methodologies can then be used to study the dynamic behavior of occupants and analyze injuries in side impact accidents. Moreover, the simulated models obtained herein give design guidelines for the vehicular structure and safety equipment needed to protect occupants.

Key words: Side impact, injury analysis, occupant, FMVSS214, LS-DYNA

INTRODUCTION

Statistics of the NHTSA (National Highway Traffic Safety Administration) have indicated that lateral and oblique side impact collisions are the second most frequent cause of serious motor vehicle accidents after frontal impact. In the US, nearly 10,000 people die in side impact crashes every year (http://www.nhtsa.gov). Side impact collisions differ from frontal impacts, in that the occupant interacts directly with the vehicle structure. The occupant has very little protection from the striking vehicle in such collisions. Neither bumpers nor engines help absorb the energy of the impact. Traffic accidents are a danger to human safety and health, causing significant loss of human life. Injury prevention is therefore necessary to improve the happiness of individuals and families. Hence, side impact airbags, sidebars and other protection equipment have been developed. To confirm the effectiveness of protection equipment installed in vehicles, studying the degree of impact is fundamental to understanding the effect of automobile collisions on the human body. Therefore, the dynamic response of the human body to traffic accidents should be analyzed to reduce the level of occupant injuries.

Crash testing is a necessity. Generally, the dynamic response and injury to human bodies involved in crash tests can be analyzed in two ways by experimental and numerical simulation. For the vehicle sample, the experimental method can be further divided into real car collision tests (Berg *et al*., 2001) and sled experiments (Watanabe *et al*., 2000; Yoganandan and Pintar, 2005; Dehner *et al*., 2007). Although real car collision tests can achieve results closely resembling a real accident, this method is complex and expensive. However, even a sled experiments are costly. Additionally, practical and ethical concerns limit the use real occupants in collision tests. Research and development tests using dummies can now simulate human responses in a car collision (Bostrom *et al*., 2000; Yoshida and Tsutsumi, 2001; Croft and Philippens, 2007; Kapoor *et al*., 2008). Recently, rapid advances in computer technology have allowed applied mathematicians, engineers and scientists to solve previously intractable problems. The simulation tools for predicting occupant kinematics and calculate injury criteria include MADYMO, Pam Crash and LS-DYNA (Teng *et al*., 2010; Kapoor *et al*., 2006; Gong *et al*., 2008; Teng *et al*., 2007; Zaouk and Marzougui, 2002; Croft *et al*., 2002; Kirkpatrick, 2000; Deshpande *et al*., 1999). Numerical crash simulations provide a valuable tool for automotive engineers. To optimize the protection for various situations, finite element modeling is necessary for investigating dynamic behavior of occupants and also in injury analysis.

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To reduce the severity of human injury through improved automobile design and designing protection devices, the dynamic response and injury of occupants in collisions must be analyzed. This study investigates the development and validation of a vehicle, movable barrier and dummy FEM model for studying interaction. Based on the Federal Motor Vehicle Safety Standard No. 214 (FMVSS214), the numerical crash test model was developed to simulate a side impact accident. The crash simulations were conducted using the LS-DYNA3D finite element code. The dynamic response of the human body to crashes is discussed herein. Additionally, the injuries of occupants were measured. The simulated models obtained could help evaluate vehicle crash safety and guide the future development of safety technologies.

DYNAMIC SIDE IMPACT REGULATION

Regulation: The safety standards are regulations written in terms of minimum safety performance requirements for motor vehicles or items of motor vehicle equipment. These standards are specified such that the public is protected against unreasonable risk of crashes occurring as a result of the design, construction or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur. Side impact protection standards have been adopted in both the United States and Europe. FMVSS 214 (U.S.) and ECE R95 (European) dynamic side impact regulations are quite different, especially with respect to their concerns about occupant injury. In this study, a side impact test was performed according to the FMVSS 214 specification.

FMVSS 214 specifies performance requirements for protection of occupants in side impact crashes. The aim of this standard is to reduce the risk of serious and fatal injury to occupants of motor vehicles in side impact crashes by setting vehicle crashworthiness requirements in terms of accelerations measured on anthropomorphic dummies in test crashes. For the physical test, the procedure was simplified with the struck vehicle stationary and the Moving Deformable Barrier (MDB) striking the target vehicle. The wheels of the deformable barrier were crabbed at an angle of 27 degrees from the longitudinal direction of the barrier. Figure 1 shows the test setup. Dummies in vehicle must satisfy requirements of FMVSS 214 when stationary vehicle is impacted by MDB at 54 km h^{-1} (33.5 mph). This test was intended to simulate an intersection crash involving two moving vehicles. Dummy injuries to the thorax and pelvic area were assessed along with vehicle structural damage.

Injury criterion: The thorax and the pelvis are mainly injured by side impact. The SID dummy response measurements consisted of the thorax and pelvic accelerations. The protection criterion based on the tolerance of the human body are given as follows:

The thoracic trauma index: The Thoracic Trauma Index (TTI) was measured as an indicator of side impact injury risk. The TTI is the average peak acceleration of the thorax and takes considers equally the acceleration in the ribs and in the spine. The SID thorax response data included accelerations measured at the upper (T1) and lower spine (T12) spines and the upper (UR) and lower

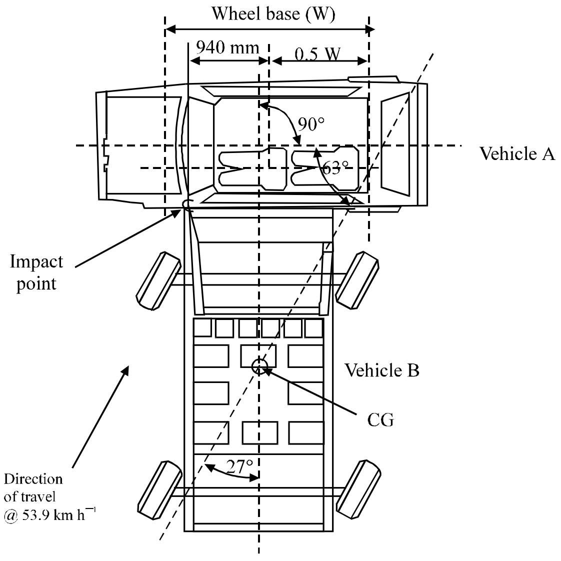

Fig. 1: The test setup of FMVSS 214

(LR) ribs on the impacted side of the dummy rib cage. The TTI was calculated by the formula:

$$\mathrm{TTI} = \frac{\mathrm{Peak\,(T12)} + \mathrm{Max\,(LU,UR)}}{2}$$

where, Max (LU,UR) denotes the larger of the peak accelerations of either the upper or lower rib, expressed in g and Peak (T12) denotes the lower spine (T12) peak acceleration, expressed in g. The FMVSS No. 214 specification stipulates that the TTI shall not exceed 85 and 90 g for a passenger car with four side doors and with two side doors, respectively.

The pelvic acceleration: The FMVSS No. 214 specification requires that the peak lateral acceleration of the pelvis shall not exceed 130 g for all vehicles.

THE NUMERICAL MODEL OF DYNAMIC SIDE IMPACT

The finite element side impact test model was conducted according to the FMVSS 214 specification and procedure. The model was consisted of three systems combined into one FE model: (a) the side-impact vehicle model; (b) the MDB model and (c) the SID model. The overall models of side impact test are validated according to the FMVSS No. 214. The validations are described by Teng *et al.* (2003).

Full-vehicle model: In this study, a Ford Taurus model was analyzed in a dynamic side impact test. EASi Engineering for the National Highway Traffic Safety Administration (NHTSA) developed the full-vehicle FE model. The FE model of the Ford Taurus has 171 parts, represent the vehicle components. Of the 171 parts, 149 were used with shell elements to model the sheet metal components, 21 were assigned beam elements to represent the steel bars and one part was modeled with brick elements to denote the radiator. The full-vehicle FE model for the side impact simulation, consisting of 49453 nodes and 5327 elements was used.

MDB model: The MDB, weighing 1367 kg, is designed to represent an average midsize vehicle in the US market. The FE model of the MDB was originally developed by NHTSA. The model is composed of seven components, 8908 nodes and 5848 elements.

SID model: The SID FE model used in the simulation is based on the Hybrid III50% dummy. The model includes the head, neck, upper spine, lumbar spine, pelvis, upper legs, lower legs, feet, jacket and ribcage. The geometry of the different components of the dummy was obtained from design drawings of the Hybrid III50% dummy. The model is shown in Fig. 2. The model is composed of 69 components, 43874 nodes and 57032 elements. The overall mass and the mass and inertia of each component of the dummy, match those of the Hybrid III50% dummy. All parts in the SID were modeled using different materials, including (1) Elastic, for simulating soft tissue and skin; (2) Rigid, for simulating the large parts of human body; (3) Fu-Chang Form, for simulating the muscles and (4) Mooney-Rivlin rubber, for simulating body parts characterized by extension, contraction and bending. The joints at the knees, hips and thorax were modeled with revolving, spherical and cylindrical joints. Each joint was assigned properties that simulating those of the real dummy.

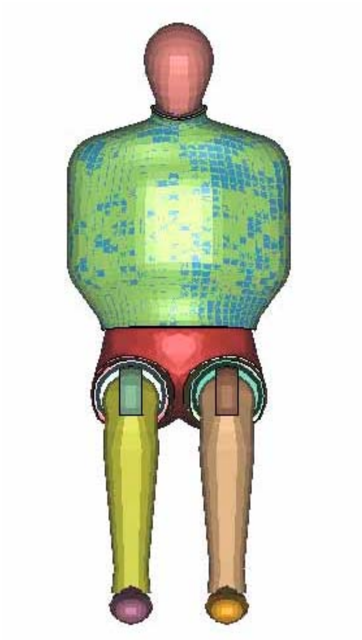
Fig. 2: Finite element model of SID (Side Impact Dummy)

RESULTS AND DISCUSSION

According to the FMVSS 214 specification, the side impact test is performed by running an MDB into the stationary vehicle side at a 54 km h^{-1} velocity impact. The wheels of the MDB are at an angle of 27 degrees relative to its axis to represent the relative motion of the two vehicles. Figure 3 shows the finite element model of the dynamic side impact test. The SID was seated on the

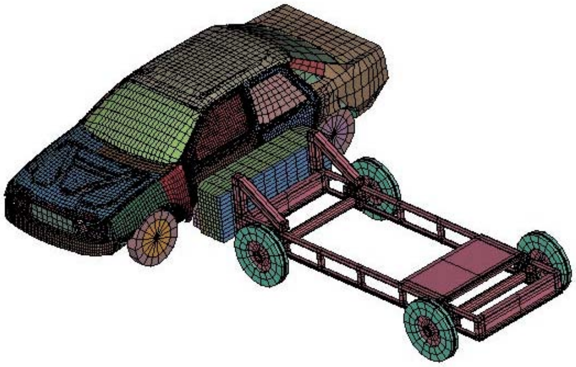

Fig. 3: Finite element model of the dynamic side impact test

struck side of the vehicle. For a 60 ms simulation, the CPU time on the IBM SP2 parallel system and LSDYNA3D 960 SMP version was about 8 h. The dummy response measurements consisted of the thorax and pelvic accelerations. The severity of injury analysis in the side impact can also be determined from the dummy response. The analytical results were compared with experimental results taken from Hultman *et al.* (1991).

Figure 4 shows a simulated impact sequence from the model, showing that the door was bent due to the impact force of the MDB in 0.016 sec. Since the MDB barrier face was located at about the dummy pelvis height, the armrest initially came into contact with the dummy pelvis. Hence, the dummy would leave the seat and its head hit the side window at 0.046 sec. Figure 5-7 present the upper rib,lower rib and lower spine accelerations used to analyze

Fig. 4: A simulated impact sequence of side impact test (a) t = 0.011 sec, (b) t = 0.016 sec, (c) t = 0.023 sec, (d) t = 0.033 sec, (e) t = 0.046 sec and (f) t = 0.06 sec

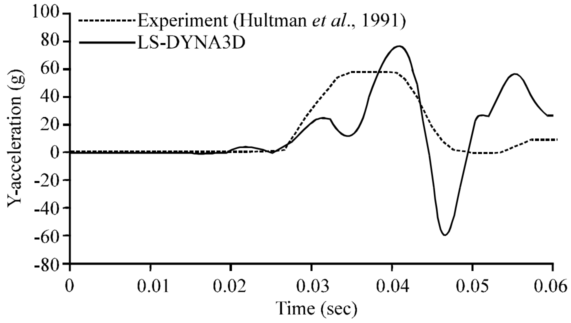

Fig. 5: Upper rib acceleration of the dummy

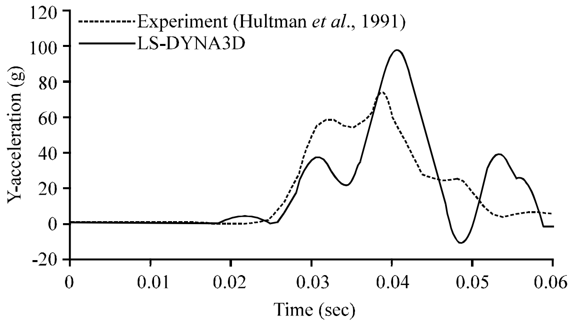

Fig. 6: Lower rib acceleration of the dummy

the behavior of the dummy's thorax during side impact simulation and test. The peak acceleration of upper rib, lower rib and lower spine for the simulation is 74.5, 93.3 and 75.8 G, respectively. With the test, the peak acceleration of upper rib, lower rib and lower spine is 59.2, 70.5 and 83.5 G, respectively. Figure 8 presents the pelvic acceleration to represent the behavior of the dummy's pelvis during side impact simulation and test. The peak acceleration of pelvis is 108 and 115.2 G, respectively. Simulation results indicate that this combination yielded the lowest number of injuries for both the pelvis and the TTI, as shown in Table 1. Since six Ford Taurus vehicles were used in a crash test experiment. The experimental results in Table 1 are the average results of six vehicles. As Table 1 indicates, the TTI and pelvic acceleration calculated using numerical analysis is 84.2 and 108 g, respectively. According to the injury criterion of human body in side impact, the acceleration of TTI and pelvic do not exceed 85 and 130 g, respectively, showing that the vehicle meets the FMVSS 214 specification. The motor vehicle occupant does not induce fatal injury in side impact crashes. Since, the finite element crash simulation models differ slightly from those in Hultman's crash test (Hultman *et al*., 1991). The difference between test and simulation in TTI and pelvic acceleration is 6-8%. However, the finite element analyses can help the engineers to study different design concepts and evaluate safety of vehicles at an early stage of research and development.

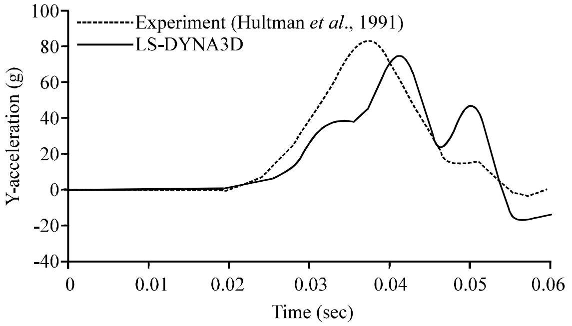

Fig. 7: Lower spine acceleration of the dummy

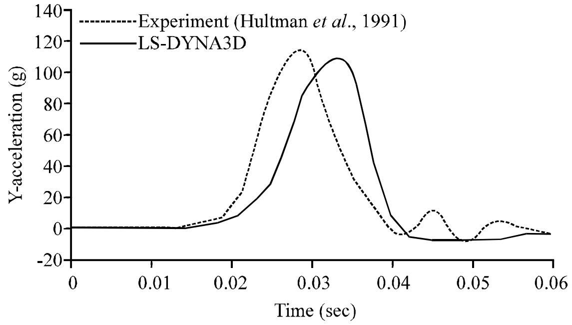

Fig. 8: Pelvic acceleration of the dummy

Table 1: Injury risk comparison between the test and the simulation

	Method	
Areas of occupant	Experimental results* (g)	Numerical simulation (g)
Lower spine	83.5	75.8
Upper rib	59.2	74.5
Lower rib	70.5	93.3
Pelvis	115.2	108.0
TTI	78.0	84.2

TTI: Thoracic trauma index, *: Hultman *et al.* (1991)

CONCLUSIONS

This study proposes a simulation method and its application which allows the establishment and satisfaction of side impact design requirements. Numerically measuring human responses in the side impact accidents is useful. In this study, a finite element side impact test model was developed and validated for crashworthiness analysis. The numerical models were found to be able to predict the severity of the driver's injury in impacts. The proposed methodologies can then be used to study the dynamic behavior of occupants and analyze injuries in side impact accidents. Moreover, the simulated models obtained herein give design guidelines for the vehicular structure and safety equipment needed to protect occupants.

These crash analyses form the numerical crash test model which has a complex nature involving large plastic deformations, non-linear material properties and contact surface, etc. To determine precisely the simulation results, accurate finite element models of the dummy, MDB and the vehicle must be established and examined. The simulation model needs further improvements. For instance, the dummy's sitting position on the seat should be examined. A model based on real material should replace the rigid material used for the seat.

Side impact means the direct interaction of the occupant with the vehicular structure. The injuries caused by side impacts are more serious than those caused by front and rear impacts. The occupant's head hits the side window and the door initially contacts with the dummy pelvis during collisions. The occupant bears the largest risk of fatal injury. Therefore, the door improvements and protection devices such as side bars, foam padding and side airbag can be used to reduce the risk of injury. These devices are placed in between the occupant and the vehicle structure to raise the duration of contact and reduce the peak forces acting on the occupants.

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