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Crashworthiness Evaluation of Side-Door Beam of Vehicle

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Side-impact collisions are the second leading cause of death and injury in the traffic accidents after frontal crashes. Side-door beams were developed to reduce the velocity and depth of door intrusion into the passenger compartment in side impact crashes. Assessing the effectiveness of side-door beams is significant for reducing occupant fatalities and serious injuries. In this study, full-scale side-impact test finite element models were presented. The test numerical models are based on the FMVSS-214. The crash simulations utilized the LS-DYNA finite element code. The capability of impact energy absorption of side-door beams is discussed herein. Analyses on the performance of beams in side crashes include displacement and intrusion measurement of door and injury analysis of dummy. This study results indicate that the side-door beams have considerable potential for reducing occupant injuries. These results and procedures can be applied as a reference for the optimal design of the side-door beams.

1 Introduction

The traffic accidents are one of the leading causes of mortality in modern society. Car safety became the most important issue immediately in the development of the automobile. Injuries due to road accidents are a problem that can be controlled considerably if adequate attention is given to accident and injury prevention strategies. Therefore, car manufacturers now incorporate a wide range of passive safety devices and features into their vehicles, including airbags, energy-absorbing steering columns, side door beams, etc. Notably, side-impact collisions are the second leading cause of death and injury in the traffic accidents after frontal crashes. Unlike a frontal collision, side-impact collisions are particularly dangerous; that is, the space between an occupant and the side of the vehicle is minimal. There are no bumpers, engines and so on to help absorb the energy of the impact. Hence, the occupant has very little protection when a vehicle is struck on its side. To develop a safe and effective passive safety devices are essential for reducing occupant injuries in a side-on crash.

To minimize this danger in a side-on crash, most new cars have sturdy airbags, side-door beams, cells, padding or other protection within the door structure. This provides a solid energy-absorbing barrier, while the safety cage helps to divert forces away from the occupant. Whatever, assessing the effectiveness of protective equipment is crucial during the design stage. Researching the degree of impact aimed at a better understanding of effectiveness of protective equipment during vehicle crashes is a fundamental and very important issue. Generally, the crash tests for analyzing dynamic response of and injury to human bodies have two ways: experiments and numerical simulations. For example, Yonezawa et al. (1996) analyzed total energy absorbed during impact in terms of the energy consumption process including the kinetic energy of the car and the energy absorbed both by the side structure and the loading device. The effect of side structure reinforcement on energy consumption in each process is also discussed. Adam et al. (1998) presented the testing methodologies for self-supporting car side doors made from FRP based on different conceptual design. Zhu et al. (1993) investigated the pelvic biomechanical response and padding benefits in side impact based on 17 cadaveric tests. Miller et al. (2002) developed a compact sled system for linear impact, pole impact and side impact testing. Vaidyaraman et al. (1998) developed a detailed and state-of-the-art modeling methodology to numerically simulate the folding and unfolding of a head/thorax side airbag system. The occupant response with side airbags in side collisions is also evaluated. T. Tsuchida and Y. Shibuya (2003) performed crashworthiness evaluations by CAE using orthotropic damage & fracture model. H. Lanzerath and R. Schilling (2003) presented the validation approach for aluminum foam and for polymeric structural foam in vehicle development. Ito et al. (1997) studied the relationship of the door inner material crush characteristics and the rib deflection of EuroSID-1 using MADYMO simulation. The crush characteristics are optimized using the sensitivity analysis method. Gandhi and Hu (1996) developed uncoupled lumped parameter models for the automobile structure and the test dummy based on the study of distribution of crash energy.

Side-door beams were developed to reduce the velocity and depth of door intrusion into the passenger compartment in side impact crashes. Assessing the effectiveness of side-door beams is significant for reducing occupant fatalities and serious injuries. In the evaluation methodologies for automobile side impact development, real car crash tests can achieve results closely resembling a real accident. However, this method is complex and expensive. CAE methodologies can increase product development process efficiency. Therefore, numerical crash simulations were used widely for automotive engineers. In this study, full-scale side-impact test finite element models were presented. The test numerical models are based on the FMVSS-214. The crash simulations utilized the LS-DYNA finite element code. The capability of impact energy absorption of side-door beams is discussed herein. Analyses on the performance of beams in side crashes include displacement and intrusion measurement of door and injury analysis of dummy. This study results indicate that the side-door beams have considerable potential for reducing occupant injuries. These results and procedures can be applied as a reference for the optimization design of the side-door beams. Furthermore, the full-scale side-impact test numerical models obtained could help evaluate vehicle crash safety and guide the future development of safety technologies.

2 Side Impact Regulation

2.1 FMVSS 214 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 (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.

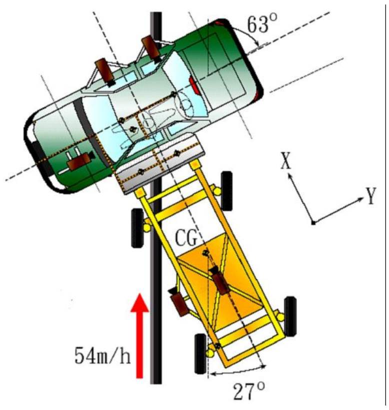


Figure 1. The test setup of FMVSS 214

2.2 Injury Criterion

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

(1) 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 dummy thorax response data included accelerations measured at the upper (T1) and lower spine (T12) spines and the upper (UR) and lower (LR) ribs on the impacted side of the dummy rib cage. The TTI was calculated by the formula:

$$TTI= [Peak(T12)+Max(LR,UR)]/2$$

where Max(LR,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 G and 90 G for a passenger car with four side doors and with two side doors, respectively.

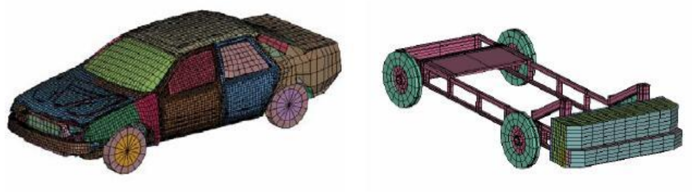
(2) The pelvic acceleration

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

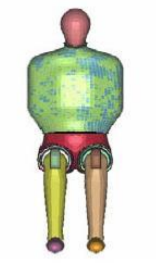
3 Finite Element Models of Full-Scale Crash Test

3.1 Finite Element Side Impact Test Model

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 moving deformable barrier (MDB) model; and (c) the side impact dummy (SID) model, as shown in Figure 2.



(a) Vehicle model (b) MDB model



(c) SID model

Figure 2. Finite element side impact test model

In this study, a Ford Taurus model was analyzed in a dynamic side impact test. The full-vehicle FE model was developed by EASi Engineering for the National Highway Traffic Safety Administration (NHTSA). The FE model of the Ford Taurus has 171 parts, represent the vehicle components. The full-vehicle FE model for the side impact simulation, consisting of 49453 nodes and 5327 elements, was used. 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. The SID FE model used in the simulation is based on the Hybrid III 50% 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 III 50% dummy. 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 III 50% dummy. The overall models of side impact test are validated according to the FMVSS No.214. The validations were described and presented by Teng et al. (2006).

3.2 Verification

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 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. The SID was seated on the struck side of the vehicle. The model is shown in Figure 3. For a 60 ms simulation, the CPU time on the IBM parallel processor and LS-DYNA 960 SMP version was about 8 hours. 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). 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 g and 108 g, respectively. The analytical results of numerical simulation achieved the best agreement with the experimental results. Clearly, finite element side impact model accurately calculates the acceleration of human body parts and assesses resulting injuries to an occupant.

Method Areas of Occupant	Experimental Results (Hultman et al., 1991)	Numerical Simulation
Lower Spine	83.5G (78~90G)	75.9G
Upper Rib	59.2G (57~81G)	58.5G
Lower Rib	70.5G (62~77 G)	80.1G
TTI	78G (73~83G)	78G
Pelvis	115.2G (101~126G)	114.7G

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

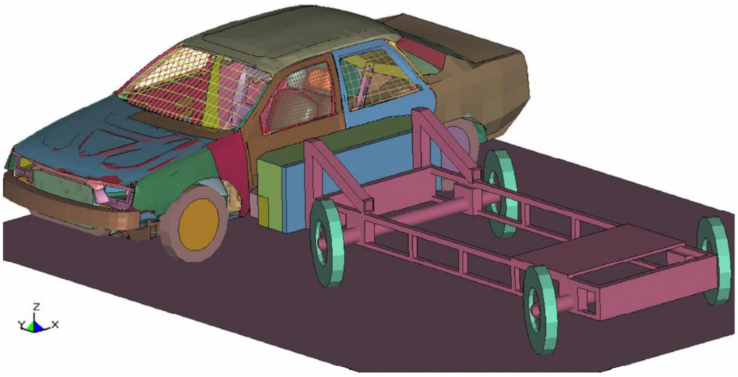
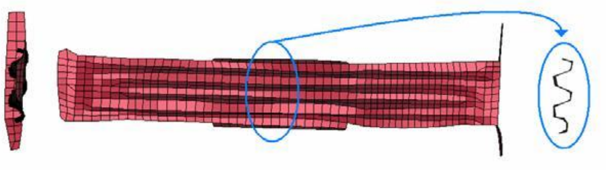


Figure 3. Finite element model of FMVSS214

4 Crashworthiness Evaluation of Side-Door Beam

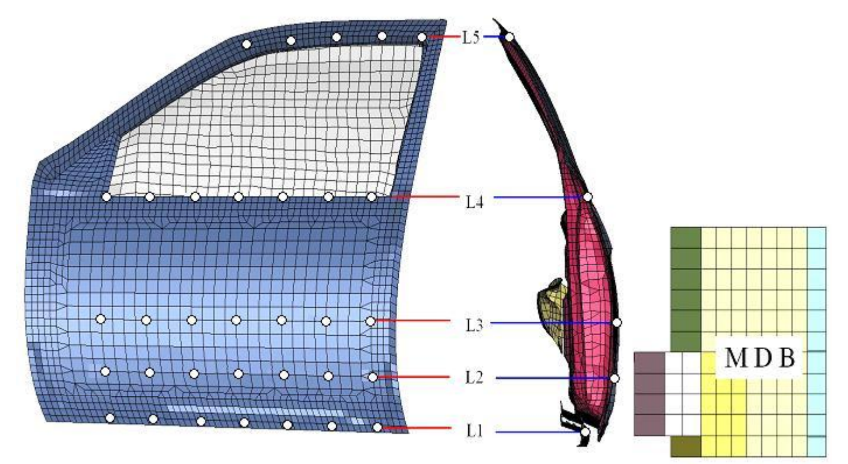
In order to assess the effectiveness of side-door beams, a vehicle with side-door beam model is analyzed in a dynamic side impact test based on the FMVSS-214. Figure 4 presents the finite element model of side-door structure. Analyses on the performance of beams in side crashes include deformation and intrusion measurement of door and injury analysis of dummy. The intrusion measurement of door is according to the vehicle exterior crush profiles. The deformation of the exterior side door of test vehicle was measured at five different vertical levels at incremental distances from the leftmost impact point, as defined by the FMVSS 214-D Test Procedure (1995). The position of measurement levels L1~L5 are shown as Table 2. To analyze the effect of intrusion on the occupant injury, the deformation and intrusion of door is measured after the crash. Furthermore, a comparison is made between the performance of vehicle with and without side-door beam model based on the dynamic side impact test.

(a) Side-door model



(b) Side-door beam model

Figure 4. Finite element model of side-door structure

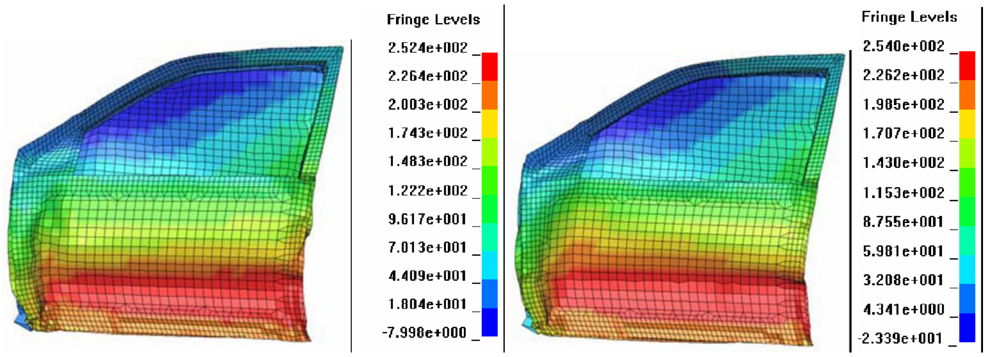


Measurement levels	Location	Distance away from the ground
L 1	Sill top	342 mm
L 2	Occupant H-point	497 mm
L 3	Mid-door	628 mm
L 4	Window sill	908 mm
L 5	Window top	1,301 mm

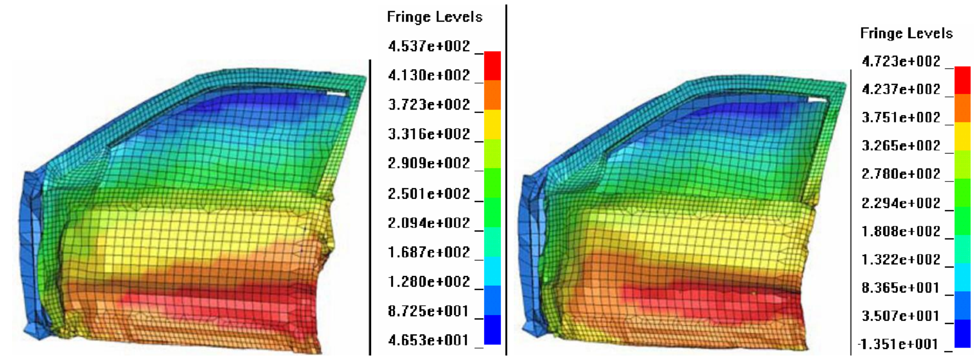
Table 2. The position of measurement levels L1~L5

4.1 Analysis of Deformation and Intrusion of Door

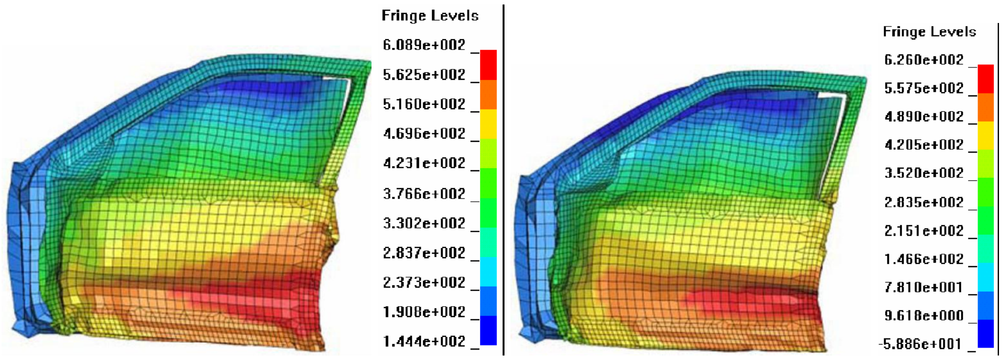
Figure 5 shows the displacement of side-door structure in the side impact test. The barrier face of MDB struck the side-door at the impact point. Consequently, the maximum displacement occurs on the level of mid-door at t = 0.02 sec. And the majority strike energy concentrates on this position. For the side-door with beam, a large deformation occurs near the B-pillar and strikes energy disperses upward along the B-pillar at t = 0.04 sec. For the side-door without beam, a large deformation also occurs near the B-pillar and concentrates on the bottom of the door. At t = 0.06 sec, a large deformation area occurs near the A-pillar for side-door without beam. Obviously, the side-door beam can effectively disperse strike energy to the A-pillar and B-pillar. The occupant injury can then be reduced by the side-door beam.



(1) t = 0.02 sec



(2) t = 0.04 sec



(3) t = 0.06 sec

(a) Door with side-door beam (b) Door without side-door beam

Figure 5. Displacement of side-door structure in the side impact test

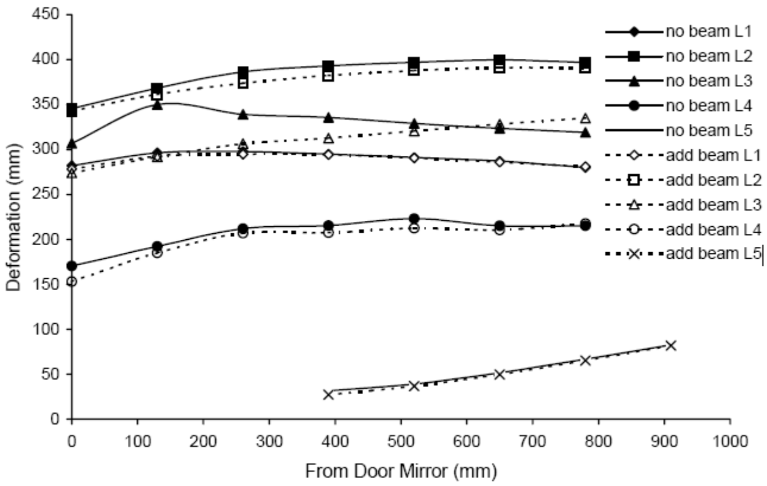


Figure 6. Intrusion of side-door structure in the side impact test (t = 0.06 sec)

The intrusion deformation for the test vehicle is shown in Figure 6 at each measurement level. This trend is thought to be quite important for designing the location of side-door beam. As figure indicates, the maximum intrusion overall was at the occupant H-point level (L2). The main reason for this is due to the "bumper" section on the MDB. And the intrusion deformation of level L1 on the door is less than position of L2 and L3. Owing to the position of L1 is near to the chassis, consequently most strike energy transfer to the chassis. Position of L2 and L3 are relatively far from the chassis. The strike energy can not disperse to the vehicle. Therefore, side-door beam must be considered and located on the higher intrusion levels. Figure 6 also present and confirm the effectiveness of side-door beam. The deformation of higher intrusion levels L2, L3 and L4 has obviously improved for side-door with beam. Especially, the side-door beam can effectively reduce the intrusion of location where is relatively near to A-pillar for the L3.

4.2 Injury Analysis of Dummy

(a) t=0.011s

(d) t=0.033s

(b) t=0.016s

(e) t=0.046s

(c) t=0.023s

(f) t=0.06s

Figure 7. A simulated impact sequence of side impact test

Figure 7 presents a simulated impact sequence in a vehicle with side-door beam 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.

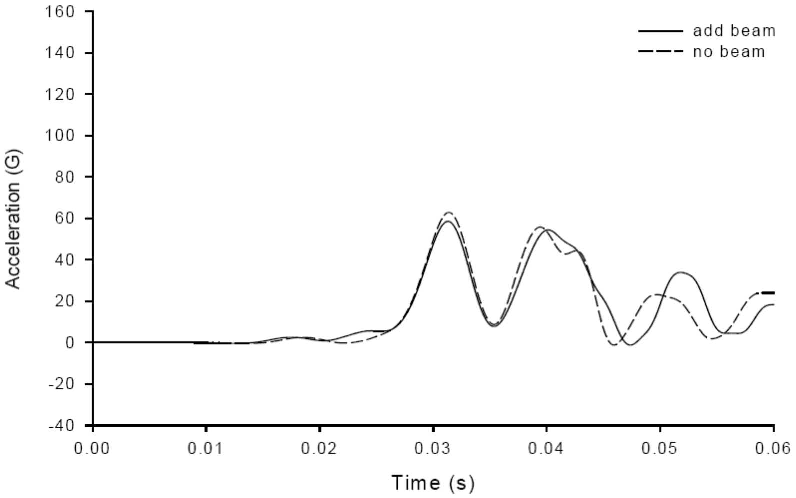


Figure 8. Upper rib acceleration of the dummy

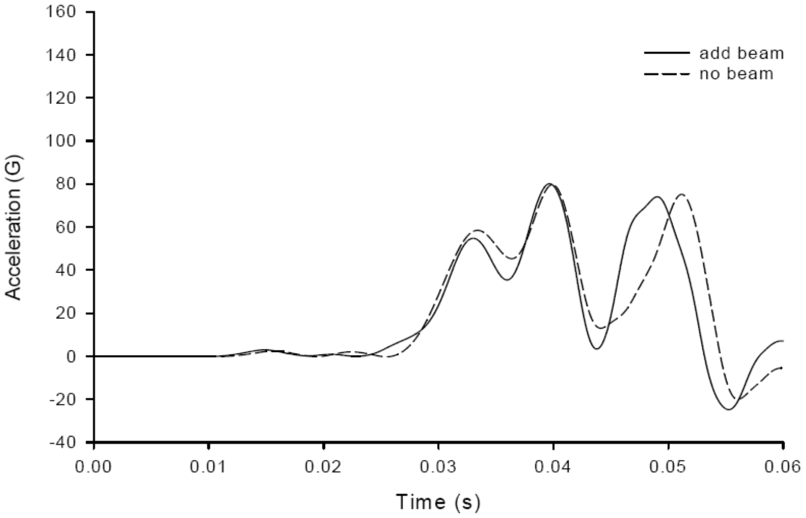


Figure 9. Lower rib acceleration of the dummy

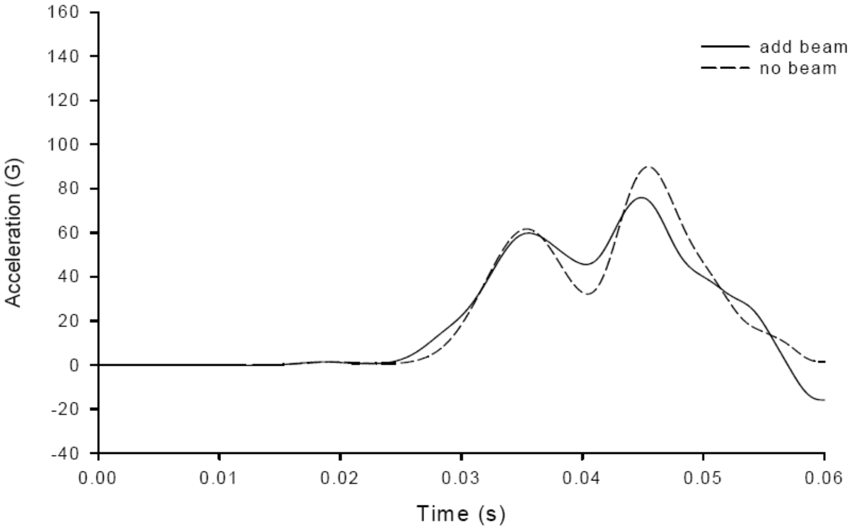


Figure 10. Lower spine acceleration of the dummy

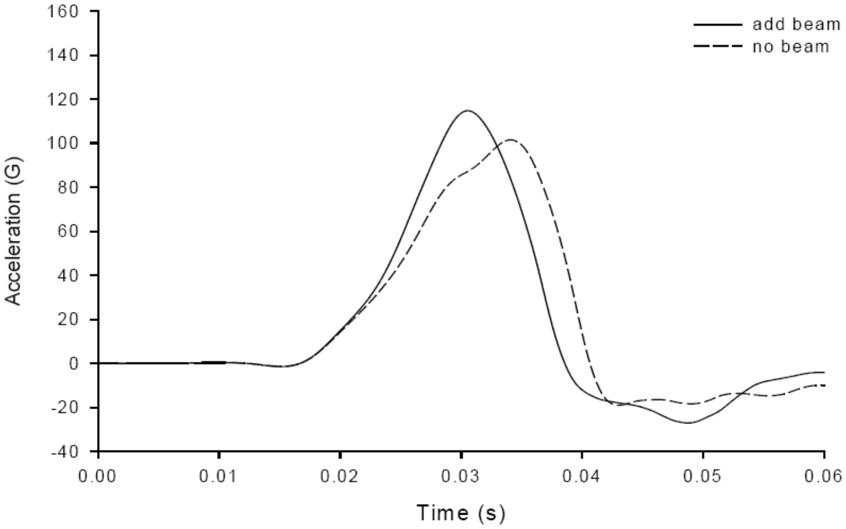


Figure 11. Pelvic acceleration of the dummy

(1) Thorax Injury Analysis

Figures 8–10 present the upper rib, lower rib and lower spine accelerations used to simulate the behavior of the dummy's thorax during side impact simulation. The peak acceleration of upper rib, lower rib and lower spine for side-door without beam is 62.9 G, 79.7 G and 89.9 G, respectively. With side-door beam, the peak acceleration of upper rib, lower rib and lower spine is 58.5 G, 80.1 G and 75.9 G, respectively. Simulation results indicate that this combination yielded the lowest number of injuries for the TTI, as shown in Table 3. For the side-door with beam or not, the TTI calculated by regulations were 78 G and 84.8 G, respectively. From the comparison of computational results, the improvement is seen in the TTI with the side-door beam. It appears that the side-door beam provides benefit for reducing TTI and the safety level of passengers greatly increased.

Consideration / Areas of Occupant	With side-door beam	Without side-door beam
Lower Spine	58.5 G	62.9 G
Upper Rib	80.1 G	79.7 G
Lower Rib	75.9 G	89.9 G
TTI	78.0 G	84.8 G
Pelvis	114.7 G	101.5 G

Table 3. Injury risk comparison of side-door with beam and without beam

(2) Pelvic Injury Analysis

Figure 11 presents the pelvic acceleration to represent the behavior of the dummy's pelvis during side impact simulation. For the side-door with beam or not, the peak acceleration of pelvis is 114.7 G and 101.5 G, respectively. Even though the acceleration of pelvis increased, the peak value still does not exceeded the injury criterion specified by regulations. Owing to the beam is mounted above the side impact point on the door, consequently the door regard beam as the rotation axis and invade in the counter-clockwise direction, as shown in Figure 12. The impact forces focus on the bottom of the door and strikes to the pelvis of human body. It is the reason why pelvis caused a large acceleration.

5 Conclusion

This paper investigates the effectiveness of using the side-door beam of apassenger car by means of computational simulation of its behavior under FMVSS 214 test specification. Based on the results in this study, we conclude the followings:

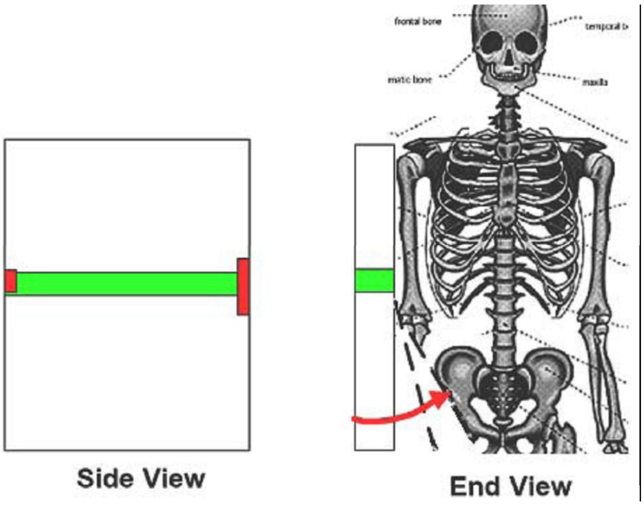


Figure 12. Behavior of the dummy during side impact

1 - The impacting force to the dummy pelvic area by the intruding side structure is potentially the most injury causing factor. Likewise, the intrusion at the mid-door and window sill levels would potentially influence the thorax area of the dummy.

2 - In accordance with the injury criterion specified by regulations for a human body during side impacts, numerical results for the acceleration of thorax and pelvis areas did not exceed 85 G and 130 G, respectively. It confirms that the side-door beam can effectively prevent an occupant from sustaining fatal injuries during a side-impact accident.

3 - From the comparison of computational results, the peak acceleration of pelvis increases for considering a side-door beam when side impact point is below the beam mounted on the door. However, the thorax injury can be effectively reduced by at least 8%. Generally speaking, the side-door beam has been adequately demonstrated to be reasonably available for reducing the injuries of occupant in side-impact accident.

4 - Placement, shape and material are factors that dominate the effectiveness of protection afforded by side-door beam. To minimize damage to the individuals involved, optimal design of side-door beam will be the future driving force in passive safety of research.

6 Acknowledgments

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References

Adam, H.; Patberg, L.; Philipps, M.; Dittmann, R.: Testing of new composite side door concept. *SAE Paper* No.980859, pp.1388-1395, (1998).

Gandhi, U. N.; Jack Hu, S.; Data based models for automobile side impact analysis and design evaluation. *Int. J. Impact Engineering*, Vol.18, No.5, pp.517-537, (1996).

Hultman, R. W.; Laske, T. G.; Chou, C. C.; Lim, G. G.; Chrobak, E. I.; Vecchio, M. T.: NHTSA passenger car side impact dynamic test procedure-test-to-test variability estimates. *SAE Paper* No.910603, (1991).

Ito, T.; Masuda, I.; Sakamoto, M.; Moriyasu, I.; Tsukamoto, H.; Watanabe, M.: Optimization of the crush characteristic of door inner material for occupant injury in side impact. *JSAE review*, Vol.18, No.2, pp.197, (1997).

Laboratory test procedure for federal motor vehicle safety standard 214D, side impact protection. *NHTSA* (TP-214D-04), (1995).

Lanzerath, H.; Schilling, R.: Crash simulation of structural foam. *SAE Paper* No.2003-01-0328, (2003).

Miller II, P. M.; Nowak, T.; Macklem, W.: A compact sled system for linear impact, pole impact and side impact testing. *SAE Paper* No.2002-01-0695, (2002).

Teng, T. L.; Wu, C. H.; Wang, S. W.: The injury analysis of occupant in side impact collisions. *Journal of Science and Engineering Technology*. Vol.3, No.1, pp.33-41, (2006).

Tsuchida, T.; Shibuya, Y.: The application of the damage & fracture material model to crashworthiness evaluations for aluminum cars. *SAE Paper* No.2003-01-2776, (2003).

Vaidyaraman, S.; Khandelwal, H.; Lee, C.; Xu, J.: State-of the art side airbag modeling and its application in occupant safety in lateral collisions, *SAE Paper* No.980915, (1998).

Yonezawa, H.; Toyofuku, Y.; Irie, Y.; Yasuhiko; Mizuno, K.: Absorbed energy of structure of passenger cars by 90-degree side impact test. *JSAE review,* Vol.*17*, No.1, pp.95, (1996).

Zhu, J. Y.; Cavanaugh, J. M.; King, A. I.: Pelvic biomechanical response and padding benefits in side impact based on a cadaveric test series. *SAE Paper* No.933128, pp.223-233, (1993).

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