796. Impact of anti-intrusion beam effectiveness on reducing fatalities and injuries of vehicle occupants

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Abstract. Side impact of vehicles is the second leading cause of fatalities and serious injuries in the traffic accidents after frontal collisions. The paper deals with the evaluation of effectiveness of anti-intrusion beam in vehicle side door. The presented analysis aims to determine the influence of the considered passive safety device on reduction of occupant fatalities and injuries. Results of dynamic numerical investigation are presented. The analysis of estimated deflection indicates the potential for reduction of the depth and velocity of door intrusion.

Keywords: traffic accidents, passive safety, side impact, anti-intrusion beam.

Introduction

In solving issues faced during vehicles design, currently the main research direction is safety analysis of the vehicle and passengers. For this purpose more complex models of major vehicles assemblies and systems are under development, increasingly moving away from the established guidelines. Recently, the increasing safety requirements for vehicles essentially changed the design standards that were well established for decades [1].

Vehicles bearing structural strength, stiffness and determination of energy absorbency during the accident, could be ensured in two ways [2]: a) using approximate methods and large safety factors; b) using accurate numerical methods and minimum factors.

The first option in this case is not acceptable, as it is widely applicable to various slow speed machines and static structures, to which own weight of the structure is not relevant. The second option allows reduction of structural weight ensuring the required operational security, but requires assessment of any possible structural features as accurately as possible.

In addition to functioning opportunities, the main factor is behavior of the optimal structure, sufficiently strong and reliable, exposed to external forces. Modern structures are designed by computer-aided methods using the most advanced software products. Almost all programs of engineering analysis both the applied and educational ones are based on the finite element method (FEM). As we know, this is only an approximate mathematical method for solving most engineering tasks. Therefore, usually we cannot rely on results obtained by programs that are based on FEM. In order to ensure reliability of engineering analysis programs, different approaches to the specific tasks are needed. These challenges are particularly relevant to the preparation of modifications, especially when held unit or small-production versions with limited opportunities of detailed studies and complex research.

In modern vehicles there is the tendency to combine two groups having conflicting requirements - increase in vehicle efficiency, reducing its weight and thereby increasing its reliability and durability. Therefore, efforts have been made to evaluate the existing loads more accurately, reduce safety factors and look for new solutions both using new technologies and more rationally dealing with design issues. This requires revision of design methodologies of individual vehicle units and the whole vehicle.

With increasing number of vehicles and their speeds, one of the most dangerous collisions in urban areas is the side collision. Safety of a car user is one of the main tasks set out for manufacturers. Protection of the whole car as a monolithic armor is not possible. It is necessary to find a compromise between vehicle weight and safety requirements. Car side door is a complex structural combination. In terms of safety the most important structural components are anti-intrusion beams and upper and lower crossbars (Fig. 1).

Fig. 1. Car side door design: a - anti-intrusion beam, b - upper and lower crossbars

Anti-penetration beams in side doors are very important components in terms of safety.

The purpose of this work was to develop numerical models to enable quick and fairly reliable assessment of side door protection beams impact on dummy injury criteria during impact of two vehicles. While the simulation task is quite large and time-consuming, it allows addressing and evaluating considerably more questions in comparison to the real side impact tests made under the regulations [3].

Differences in regulations on side impact testing. Side impact injury criteria

Safety standards and regulations describe the minimum requirements for motor vehicles safety and equipment.

The first side impact tests were carried out in laboratories of Mercedes and Volvo manufacturers in the 60 s. Modern side impact tests in US started after Federal Motor Vehicle Safety Standard (FMVSS) 214 protocol came to force, according to which cars have to withstand the impact of a trolley weighing a 1.5 ton, moving at 53 km/h, with the deformable barrier mounted on the front and made of aluminum frame. The trolley wheels rotate at 270° angle – an impact occurs at angle (Fig. 2). Tests in accordance with the National Highway Traffic Safety Administration (NHTSA) are even tighter: the trolley's speed is 62 km/h, mass is 1367 kg. The protocol FMVSS 214 also provides the quasi-static test. Press is pushing the door with a cylindrical punch with a diameter of 305 mm until 450 mm deflection is reached.

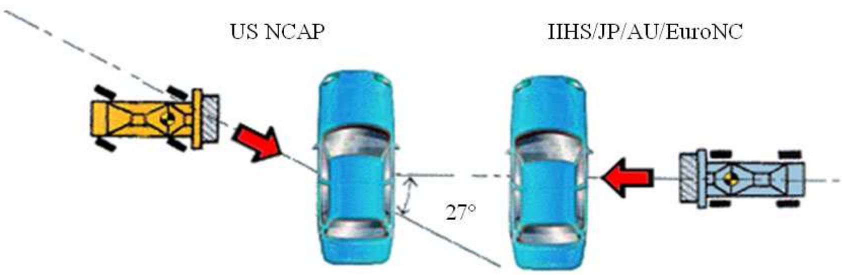

Fig. 2. Side impact test according to different safety requirements. *R*-point equal for hit point for 95th percentile male

Reaction force at such load must be greater than 10000 N. U.S. and Europe has different side impact safety regulations. In accordance with European New Car Assessment Program (EuroNCAP) a trolley moving straight at 50 km/h, having mass of 950 kg, with deformable barrier mounted on it hits the vehicle (Fig. 2). The same test is conducted in Japan, but the trolley is moving at 55 km/h. Recently under the EuroNCAP program an additional pole test was initiated. A car fixed onto special trolley runs at speed 29 km/h and in sideways strikes a solid metal pole with diameter of 254 mm. The driver's head area and the pole axes of symmetry must coincide. In this case, an influence of the side airbags to the driver's head injuries is closely monitored.

Vulnerability criteria for side vehicle collision with obstacles are quite different from those for frontal collision [4-6]. While using many criteria, predicting serious chest injuries, all of these methods quantitatively evaluate chest injuries with force, acceleration and speed applied, or with chest compression. In the U.S. standard tests, in case of side impact, using USSID, thoracic trauma index (*TTI*) is the most important criteria for describing both the chest and ribs injuries. *TTI* index can be calculated by:

$$TTI = (G(R) + G(LS))/2\,, \tag{1}$$

here $G(R)$ - maximum acceleration of an upper or lower rib in g, $G(L)$ - lower spine (T12) acceleration in g.

USSID dummy must meet the following requirements:

– *TTI* for 4 door passenger vehicle and other multi-purpose vehicles and buses does not exceed 85*g*.
– *TTI* for 2 door passenger vehicle does not exceed 90*g*.
– Maximum longitudinal acceleration of pelvis should not be greater than 130*g*.
– To comply with safety regulation, vehicle side structure must meet the following requirements:
– After the deformable barrier impact, side door should not completely detach from the vehicle.
– Side door should not detach from the lock mechanism.
– The lock mechanism should withstand impact and should not automatically fail.
– Hinges and their components should not detach from the door or their attachment points on the struts.

In [7] it is noted that the *TTI* index is usually calculated in the first milliseconds of an impact, but more serious thoracic lesions usually occur much later. There we make an assumption that the criterion which is based on body acceleration, cannot fully describe in detail the mechanisms of injury to the chest. Viscous Criterion widely used to assess soft tissue injuries is based on chest compression and compression ratio measurements. *VC* is pretty good for description of soft tissue injuries when strain rate is less than 3 m/s, however, it is not to be used at strain rate more than 30 m/s, resulting in very serious bodily injuries.

Car-to-car crashworthiness. Analysis of dummy injury at side impact

Vehicle models are presented in public National Highway and Transport Safety Authority library (FHWA/NHTSA National Crash Analysis Center, 2000). In the library there are models designed for LS-DYNA program. General MotorsGeoMetro finite element model (Fig. 3) has been chosen for numerical experiments.

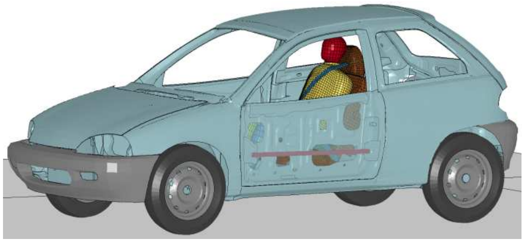

Fig. 3. General Motors GeoMetro FEM

The model was modified. Type of elements of main side parts contacting during impact were changed from the Belytschko-Tsay to the S/R co-rotational Hughes-Liu element to ensure numerical stability during the analysis. Full integrated shell elements of 16 type with 8 hourglass formulation has been chosen for Geo Metro shell structures.

Door structure has been changed in the model. Door was mounted to the body elements on three hinges, resulting in the door distortion like the real behavior of the side door in case of the vehicle side collision. The protective beam of round cross-section and 2 mm thickness was fitted in the door to protect passengers in case of side impact when a foreign body penetrates into the cabin area. The beams were mounted inside the vehicle door cavity at external plane and attached to the front and rear door struts. In this way, shock deformation energy absorbed is primarily directed to the door sides which lean against the body struts.

Accelerometers are mounted in the model beams, which calculate acceleration values in three coordinate directions. Mechanical characteristics of materials of protective beams are presented in Table 1.

Table 1. Mechanical properties of side anti-intrusion beam materials

	AISI 1060	AISI 1018	Stahl20 GOST	AA 2024	AA 6061
Young's Modulus (MPa)	205	205	205	73.1	69
Poisson's ratio	0.28	0.29	0.28	0.33	0.33
Density (kg/m^3)	7860	7865	7865	2780	2700
Yield strength (MPa)	430	315	288	332	262

For all variants of calculation the same LS-DYNA material strain model of type 24 was chosen and for beams Belytschko-Tsay shell elements description was selected in accordance with Mindlin shell theory - elements of 2 type in LS-DYNA program. A public domain version of an US side impact dummy (SID), made by NHTSA and especially regulated for side impact tests (Fig. 4) has been chosen in this work. Accelerometers are placed in the USSID at locations of primary interest are as follows: upper rib, lower rib, lower spine (T12), pelvic. The accelerometers were modeled using *SEATBELT_ACCELEROMETER function in LS-DYNA.

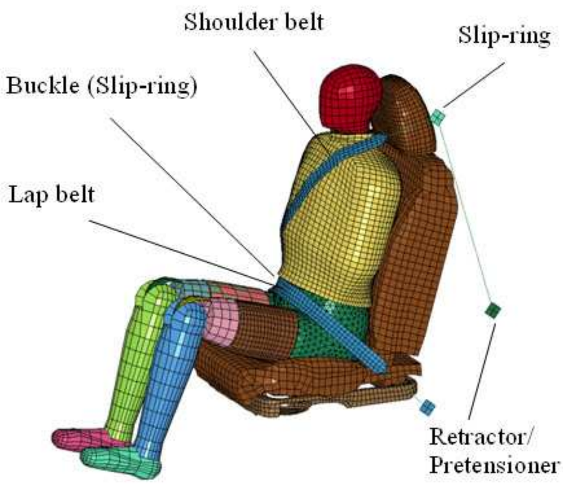

Fig. 4. Belted USSID model

Dummy restraint safety belt and seat modeling task is very important and significantly affecting the results. Car seats typically have the structural frame, rod elements, springs and nonstructural elements, polyurethane foam, covers. To model the seat structural frame *MAT_RIGID has been selected and for polyurethane foam modeling MAT_LOW_DENSITY_FOAM materials have been selected.

To restrain dummy in a seat, a safety belt was designed, it consisted of a shoulder belt and a lap belt (*MAT_FABRIC), slip-rings, buckle, retractor, and a pretensioner. The lap belt and shoulder belt were begirt on the dummy using LS-PrePost "Belt-fit" function. This function allows the user to select a number of points to define the seatbelt path, by picking dummy nodes. Slip-rings allow continuous sliding of the belt through a sharp change of angle. The retractor element has two states: unlocked and locked. When unlocked the seatbelt elements at paid out or taken in at a constant fixed tension and locking after a user defined fed length has been paid out.

Pretensioners are active devices which allow tightening of the belt during initial onset of collision by pyrotechnic activation. Load curves defined to control the seatbelt elements were selected from public domain sources.

This investigation stage deals with vehicle and dummy kinematics and criteria of dummy injuries during side impact (Fig. 5). The following computation case is analyzed: a car moving at 50 km/h speed and 70° angle hits a stationary car with the same weight of 900 kg along with USSID dummy belted with safety belt. The car striking in sideways with the bumper end hits the stationary car at the centre of side door protective beam. The crash results are presented in Fig. 5.

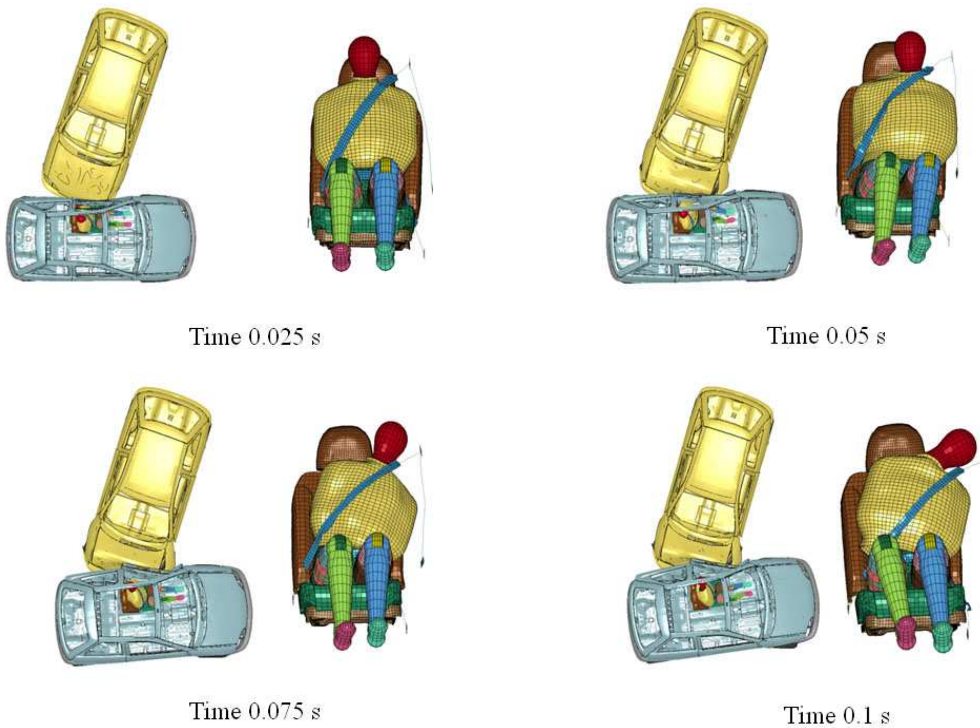

Fig. 5. Vehicles and dummy kinematics during side impact

It was determined that in the initial stages of the collision the impact deforms only the door. With increase in vehicle deceleration, the total vehicle deformation increases. In this stage of collision moving vehicle dos not change its direction. Initially stationary vehicle after a while begins to rotate around its vertical axis. From Fig. 5 we can observe that the kinematics of the dummy movement is close to geometric properties of the movement testing.

Dummy vulnerability criteria, with the acceleration results filtered by SAE 100 filter and calculated using the LS-DYNA program postprocessor, are presented in Table 2. While examining influence of beam of different types of materials on dummy main vulnerability criteria, two assumptions were confirmed. The first, the door beams alone are not enough to reduce the depth of intrusion into the other vehicle and reduce injuries. In addition, the calculation results obtained in the work confirmed predictions that the structural elements with higher yield strength absorb much more energy. Energy absorbed by the protective beam of AISI 1060 steel makes up 0.83 kJ, while the beams made of aluminum alloy AA6026 absorb 0.5 kJ. The difference between yield strengths of these materials makes 39 %, and between absorbed energy reaches 39.8 %, but the difference between main injury criteria is not large and only a slight increase is with assessment of fracture strain in the model.

Table 2. Numerical tests of side impact

Moveable car	Beam material	TTI, *g*	Pelvis, *g*
50 km/h, 70°	AISI 1060	35.8	59.5
	AISI 1020	38.5	62.7
	Stahl20 GOST	40	63.3
	AA 2024	36.9	61.4
	AA 2024 with failure strain	44.5	72.1
	AA 6061	42.1	63.4
50 km/h, 70°	without side beam	66.6	82.2
50 km/h, 70°, not belted dummy	AISI 1060	67.8	57.5
50 km/h, 90°	AISI 1060	42.8	59.1

Studies performed have demonstrated that lack of protection beam in a vehicle changes both the *TTI* criteria and pelvic acceleration, and the safety belt has the greatest influence on the chest vulnerability. Small gap between the passenger and the door creates problematic energy dissipation and an inevitable contact between the door and the passenger. In the computing variant without the safety belt, the dummy bumps into the door, resulting in significantly increased criterion for assessing thoracic vulnerability. From diagram given in Fig. 6 we can observe that absence of side beams on the vehicle door has the largest influence on pelvic deceleration – in the studied model forces concentrate at the bottom of the door and hit onto the dummy pelvis.

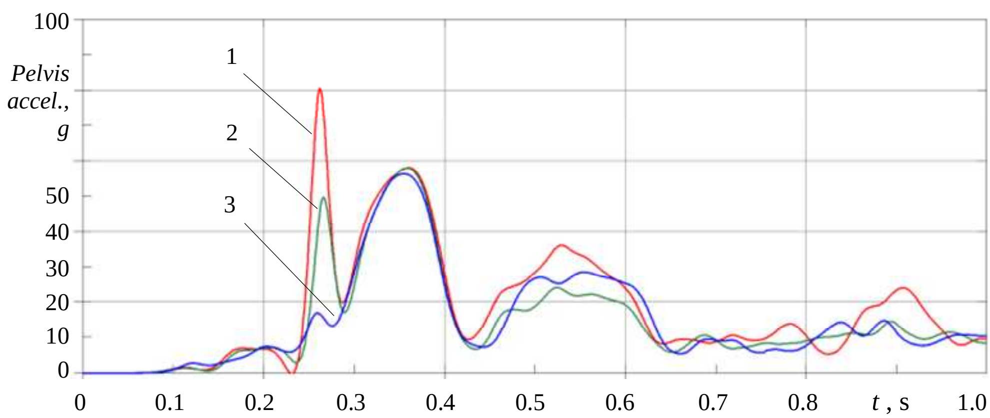

Fig. 6. Pelvis acceleration:
1 - without beam, 2 - AISI 1060 beam and car moving at 50 km/h, 70°, 3 - unbelted dummy

Recent studies were carried out using a simplified numerical model of the door. While clarifying solutions it is necessary to assess the additional parameters of interaction between the dummy and the seat. This would require further investigation of mechanical characteristics of material of the belt and the seat, provide rigidity and friction characteristics of the dummy and the seat, develop more detailed FE model of the door, more accurately describe interaction between the dummy and vehicle, to model side door hinges, locks and windows in detail.

Conclusions

Collision of two vehicles was studied in this paper. Software package LS-DYNA was used for the computations. FE model of a vehicle side door was developed and vulnerability criteria were defined at different collision situations. The most important advantage of the numerical solutions is the possibility to describe and analyze crashworthiness in sufficient detail, which is a challenging task when using conventional analytical methods.

Numerical models reveal that the results are highly dependent on mechanical characteristics of the anti-intrusion beams. In order to analyze side impact and overall side structure behavior more specifically with the developed FE models, it is recommended to carry out more detailed numerical modeling of beam materials and experimental studies to determine mechanical characteristics, analyze characteristics in the LS-DYNA mathematical models.

Influence of beams and other factors on dummy injuries was defined in the presented study. In the calculations the analyzed vulnerability criteria in all cases do not exceed those given in the acceptable regulations. From the we may observe that the beam is an important safety element but it is unable to provide full passenger protection during side impact.

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