INVESTIGATION OF PASSIVE SAFETY ASPECTS FOR VEHICLE SUBJECTED TO MINE BLAST

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Summary

A blast load of vehicle, especially the Under Body Blast (UBB) case is the specific kind of thread for occupant safety. The risk of injury is caused by great amount of energy transferred in a short time to a vehicle structure and further to a body of passenger. In the paper, similarity and differences between road collision and blast load of vehicle is discussed. The dynamic load of the occupant's body was presented and evaluated with the use of biomechanical criterion Dynamic Response Index (DRIz). The load intensity determined with DRIz was compared for a few points on the loaded vehicle structure and the body of the occupant simulated by an Anthropomorphic Test Device (ATD). An examples of numerical investigation of the blast load of the vehicle were presented.

Keywords: passive safety, Under Body Blast, numerical simulation, FEM

1. Introduction

Passive safety is usually referred to in the context of road traffic accidents. Such accidents are connected with a dissipation of significant energy in a short time, and safety is evaluated with the use of biomechanical criteria. In case of a blast load, the most dangerous case is the Under Body Blast (UBB), when a vehicle is loaded by a blast of exploding mine or Improvised Explosive Device (IED). The whole loading process is similar to a road collision (fig. 1).

The blast energy is rapidly released in detonation process. For buried charges, gaseous products of detonation transfer energy to the ground. The ejected soil with blast wave traveling through air impact the bottom part of vehicle (fig. 1).

The effects for the occupants are similar to a road collision too. As a result of rapid change of the vehicle velocity, a human body is rapidly accelerated, with significant risk of injury. There are some differences between road collision and the Under Body Blast case. First one is the direction of impact, which is in case of blast generally vertical, quite unusual for

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a traffic collisions or impacts of a military vehicle into a barrier [1]. As a consequence of this difference, the injury mechanisms and criteria are different as well.

Fig. 1. Crash test of the passenger car (left), full scale blast test of vehicle (right),

Second difference is the process of the energy transfer itself, described below. Means of counteract and minimize of an occupant injury risk can fit in definition of the passive safety, which can be defined as the practice of taking measures to reduce the consequences of accidents.

2. Energy transfer for the under body blast

The energy transfer process can be divided into three phases, presented in figure 2. In the first phase after blast wave impact, the elastic waves propagate with the speed of sound in the vehicle structure, resulting in high amplitude and high frequency vibrations. Because of high speed of wave, duration of this phase is a few of millisecond [2].

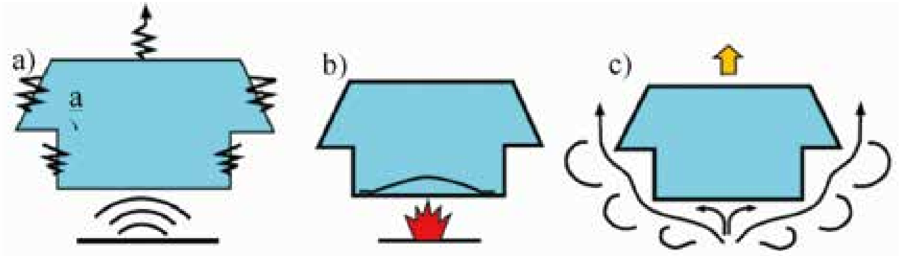

Fig. 2. The phases of the energy transfer after Under Body Blast: a) elastic wave propagation, b) local deformation of bottom, c) global movement of vehicle [3]

In second phase, a local deformation of the vehicle bottom occurs as a result of plastic strain and elastic vibrations in direction perpendicular to the floor plane. This phase is connected with risk of the lower extremity injury. Last phase of the process is the global movement of the whole vehicle. The part of transferred blast energy is transformed into kinetic energy of the vehicle body. This phase is connected with the risk of the spine injury caused by rapid vertical acceleration of the seat.

The difference in energy transfer between a road collision and a blast load is in form of the energy. In case of a road collision, the source of energy is difference of kinetic energy of impacting and impacted vehicle. The masses of both vehicles are usually the same order of magnitude, and the energy is dissipated in process of plastic deformation of the structure of both vehicles.

An impact of blast wave can be treated as elastic impact of very light, and fast object, the velocity of the blast wave at impact can reach velocity of a few Mach. For maximum explosive mass described in STANAG 4569, equivalent to 10 kg of TNT [4], the input energy is practically unlimited, because only a few percent of total energy in transferred to the vehicle structure. The captured energy is inversely proportional to the mass of the vehicle.

3. Injury criteria

For blast load events passive safety assessment, the commonly used approach is the use of biomechanical criteria. The structure of vehicle itself in not taken into consideration, except for maintain if the body integrity to prevent intrusion of the detonation products and blast wave to the interior of the vehicle.

Because of different direction of load and injury mechanisms, used criteria are different than in case of a road collision. Currently used criteria are described in NATO Standardization Agreement STANAG 4569, Annex B [4].

The spine injury is checked against the biomechanical criterion. As stated in [5], the best available model for thoracolumbar spine injury assessment is the Dynamic Response Index (DRI) introduced by Stech and Payne [6]. The primary purpose of this model was the evaluation of the risk of injury during the ejection of a seat from a plane. The similar direction and profile of the load acting on the human body allows adopting this model to evaluate effects of mine blast load. The evaluation of the human body response to the dynamic load is based on the simple mass-spring-damper system shown in figure 3. The Dynamic Response Index calculated only for vertical acceleration is described as DRIz.

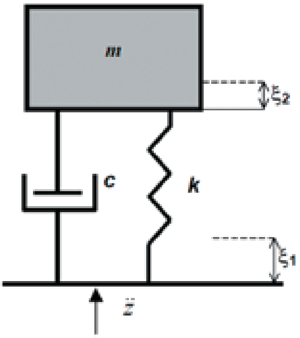

Fig. 3. DRIz model structure [5].

The equation of the motion for this model is:

$$\ddot{z}(t) = \ddot{\delta} + 2 \cdot \zeta \cdot \omega_n \cdot \dot{\delta} + \omega_n^2 \cdot \delta \qquad (1)$$

where

$\ddot{z}(t)$ – vertical acceleration at the seat

δ – compression of the system, $\delta = \xi_1 - \xi_2$

ζ – damping coefficient, $\zeta = \dfrac{c}{2 \cdot m \cdot \omega_n}$

ω_n – natural frequency, $\omega_n = \sqrt{\dfrac{k}{m}}$

The value of DRIz is calculated as a function of maximum compression δ_{max} of the system during full load process, natural frequency ω_n and gravity acceleration g:

$$DRIz = \frac{\omega_n \cdot \delta_{max}}{g} \qquad (2)$$

The values of damping coefficient ζ = 0.224 and natural frequency ω_n = 52.9 rad/s were selected by Stech for the model as values for a representative population of Air Force pilots with a mean age of 27.9 years [6]. The value of the DRIz parameter at the level of 17.7 refers to a 10% risk of AIS (Abbreviated Injury Scale) 2+ injury, defined in [7]. Criterion DRIz applied to a blast test is intended to use with acceleration measured with pelvis vertical accelerometer Anthropomorphic Test Devices (ATD) Hybrid III.

The injury to the passenger of a vehicle subjected to a blast load has been analyzed in numerous works. The spine loading was investigated in [8] and [9] with the use of LS-DYNA [10] and MADYMO codes. The transmission of the energy from a blast wave to the vehicle structure was presented in [11], [12] and [13]. It was reported that for various load profiles applied to the seat base, the main parameter influencing the spine injury is the maximum velocity of the blast-accelerated base of the seat.

Second important criterion is the axial force in lower extremity applied by impacting floor. In this case, the biomechanical criterion is defined as a maximum axial force equal to 5.4 kN, connected with the 10% risk of injury on the level of AIS2+ [5]. The criterion is intended to use with the force cell mounted in the leg of ATD.

4. Simulation and results

The numerical investigation of the passive safety for blast loaded vehicle was carried out with the use of LS-DYNA numerical solver based in explicit method [10]. The structure of 12.5t armored vehicle was modelled with shell elements, and directly loaded by blast wave pressure. Time and spatial varied field of pressure was modelled by Kingery-Bulmash blast load model implemented in LS-DYNA as a *LOAD_BLAST_ENHANCED function for surface blast. Because the buried charge detonation effects strongly depend on the depth of burial, type and condition of soil, and incident angle of the blast wave [9, 11], the blast pressure model was calibrated by full scale blast test on the simply mock-up resembling the shape of the vehicle. The calibration process was described in [9].

In the vehicle, the model of the blast attenuating seat was located, equipped in 5-point belts and a special damping device to mitigate the vertical acceleration, based on the aluminum foam, an excellent energy absorbing material [14]. The model of the seat-occupant system was initially checked on separated models with simplified vertical velocity profiles. The influence of the different types of the seat cushion foams were investigated. For the purpose of simulation, the stiffness characteristics of the two type of seat cushion foams uses in a real military vehicle seats were measured. The mechanical characteristics of the foams were presented in figure 4.

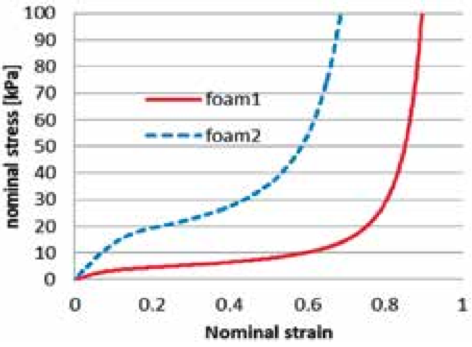

Fig. 4. The stiffness of the foams used for the cushion foam investigations

The result of simulations with a different cushion foam stiffness showed a negligible influence on the movement of the body and DRIz parameter. The resultant velocities and DRIz profiles are presented in figures 5 and 6. With the high acceleration level generated during a blast load, stiffness of the seat foam is too low to accelerate the body before contact with a steel seat structure. The usage of the cushion foam with much higher stiffness would decrease the comfort of the passenger.

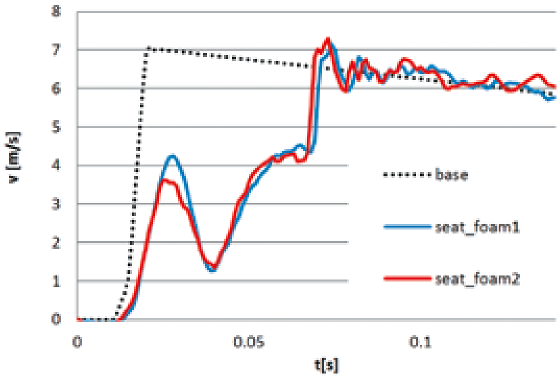

Fig. 5. The vertical velocity of the base of seat (wall of vehicle) and attenuated part of seat for two types of the foam

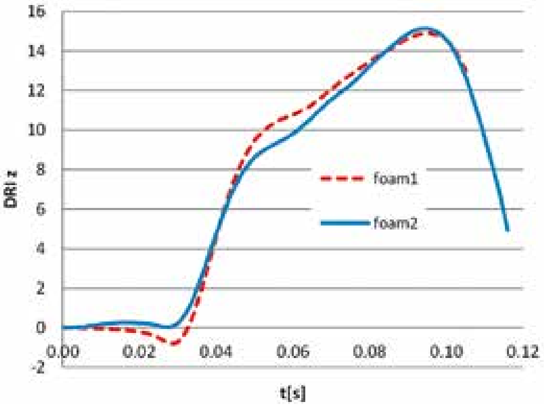

Fig. 6. The influence of cushion foam density on the value of DRIz parameter

In figure 7, the typical vertical velocity profiles of the base of the seat, attenuated part of seat and center of gravity of the HIII are presented. The body is accelerated, but because of elasticity of the cushion and seat structure, it does not follow strictly the movement of the attenuated part of seat. The shock wave reaches the seat base at point **A**. At point **B**, the cushion is fully compressed and the acceleration of the body starts. At point **C**, velocity of the movable part of the seat and the body reaches the velocity of the seat base. The elastic energy accumulated in a seat structure ejects t body in the direction of a roof. At point **D** the safety belts stop the body acceleration, and at point **E** the process of shock attenuation is finished, and the body follows the movement of the vehicle.

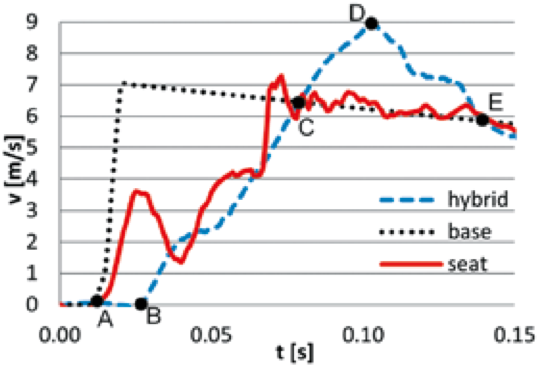

Fig. 7. The vertical velocity of the base of seat (wall of vehicle), attenuated part of seat and Hybrid model for 7 m/s maxi-mum vertical velocity of vehicle and damping force 10kN

The velocity of the body at point **D** is 35% higher than the velocity of the vehicle. It emphasizes the role of the seat belts, which should stop the body in upward movement to minimize the risk of head and neck injury. Additionally, compression of the cushion between points **A** and **B** develops a clearance between the body and the belts, which increases the distance between points **C** and **D**, so the body is stopped later.

For the full blast test simulation, the numerical model containing the vehicle, the seat and occupant were used. The view of the vehicle model was presented in figure 8a.

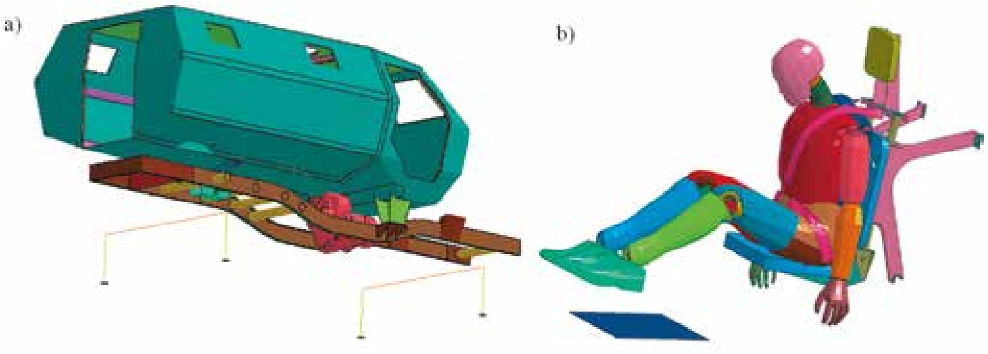

Fig. 8. The simulation model: a) the view of the vehicle model,
b) the view of the Hybrid III model seating in the blast attenuating seat

Last element of the model was the Hybrid III ATD deformable model, equipped with the acceleration and force sensors for measures the dynamic biomechanical parameters during the blast event. The view of the Hybrid III model seating in the blast attenuating seat was shown in figure 8b.

The simulation results provide useful information necessary for the vehicle shape and structure optimization. From the biomechanical point of view, the vertical acceleration of the pelvis can be checked as an input for DRIz model.

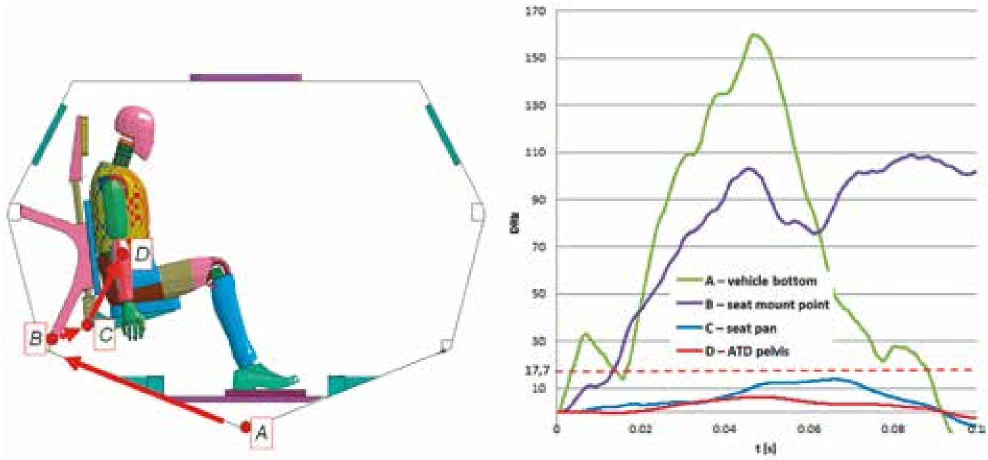

Fig. 9. The responses of DRIz model for the vertical acceleration at selected points of vehicle and on pelvis of the occupant

In analyzed cases, the acceleration of pelvis was very low, because the blast shield is placed above the frame of vehicle. Such structure decrease the amount of energy captured from the blast wave. Comparison of both concepts were discussed in [9]. The second reason was the blast attenuating device based on open cell aluminum foam Alporas, which significantly decreased the level of acceleration.

The acceleration profile itself, particularly the maximum acceleration, cannot be used to assess the risk, because the injury risk strongly depends on the duration of load. The DRIz model can be used for comparison of the acceleration profile measured at different point of vehicle structure. In figure 9, the responses of DRIz model on vertical acceleration at selected points of vehicle and on pelvis of the occupant were shown.

When energy is traveling through the vehicle structure, the DRIz profile is flattened. The most significant decrease in the DRIz level is visible between point B (seat mount point) and C (seat pan) as a result of the blast attenuating device engagement, which is assembled in the seat structure. Additional damping between the points C and D (ATD pelvis) is an effect of seat pan cushion and ATD structure elasticity. Final level of DRIz (point D) used as a biomechanical criterion of the spine injury risk is well below the level of 17.7 corresponding to a 10% risk of AIS 2+ injury.

Fig. 10. Loosen shoulder and lap belts as the result of the seat cushion compression during a blast event

Interesting effect of the seat beat loosening was observed during blast simulation. Despite of carefully fitted seat belts, after initial impact, the ATD inertia cause the full compression of the seat cushion. As a result, the shoulder and lap belts are loosen (fig. 10). This effect indicates, that the seat belts pretensioners could be necessary to keep the occupant body in proper position and to avoid the clearances in the restrain system. Despite of the vertical direction of the load, pretensioners in the UBB event are equally important as for the horizontal acceleration in the road traffic accidents [15].

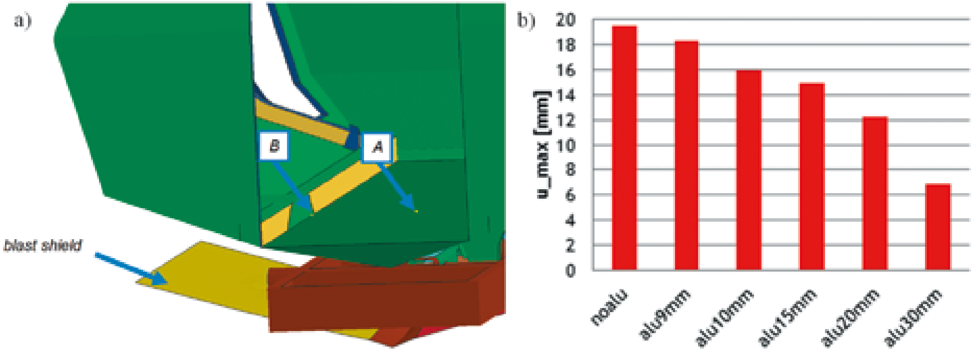

Fig. 11. Results of the numerical simulation: a) points used for measurement of deflection of the floor, b) the influence of the blast shield thickness on deflection of the floor

The structural stiffness of the floor panel has significant influence on the lower extremity load [5]. After the blast wave impact, the floor start to vibrate. Numerical simulations allow to examine a various configurations of the floor structure and additional blast shields placed between the vehicle bottom and detonation point. An example results of such analysis for various thickness of the blast shield were presented in figure 11b. As a measure of deflection of the floor, the relative deflection u_{max} of the floor center (point A, fig 11a) according to the hard point of the floor (point B, fig. 11a) was used.

Fig. 12. The mine resistant armored vehicle Germaz G-10 (left) and the prototype of the blast attenuating seat (right)

Fig. 13. Full scale blast test of the Germaz G10 mine resistant vehicle.

Results of the simulations were applied in the design of the mine resistant armored vehicle presented in figure 12. The vehicle structure and the blast-attenuating seat was developed with the use of presented methodology. The blast attenuating seat was designed and adjusted for specific stiffness of this vehicle.

The passive safety level of the crew in case of an Under Body Blast event was tested in the full scale blast test carried out according to the STANAG 4569 [4,16]. The example view of the blast test was presented in figure 13.

5. Conclusions

The passive safety in case of the Under Body Blast event can be successfully investigated by numerical simulation approach. While the acceleration load is similar to the road collision conditions, the significant differences in the simulation approach and biomechanical criteria exists. The biggest challenge in modeling is reliable definition of the blast load. Process of the explosive detonation especially for the buried charges, in much more complex than simply kinetic energy transfer in case of the road collision. In the paper, the Kingery-Bulmash surface blast load model calibrated by the full scale blast test was used.

Flexibility of numerical model allows to check numerous aspects of the passive safety, like the vehicle structure strength and integrity, or the efficiency of the blast attenuating seat cooperating with the deforming vehicle. Beside of standard check of the biomechanical criteria defined in STANAG 4569 Annex B, it is possible examine in details whole process of the occupant acceleration, work of the seat structure, and to observe unexpected phenomena like the loosen seat belts. The most interesting result of the simulation of the Under Body Blast is the significance of the seat belt pretension. Absence of the seat belt pretensioner leads to developing of a clearance between the belts and the body as a result of the seat cushion compression.

The results of simulation are extremely useful for improving the passive safety of the occupants of the vehicles endangered by the mine or Improvised Explosive Devices detonation. Usage of this tool can significantly decrease the cost of a full scale blast test of a mine resistant vehicles.

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