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# NUMERICAL ANALYSIS OF THE INFLUENCE OF BLAST WAVE ON HUMAN BODY

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### *Abstract*

*Threats for military personnel during combat missions nowadays are of different sources. Further development of methods for neutralization of mines or improvised explosive devices (IED) explosions must be preceded by identification of the impact phenomenon on crew of the military vehicle. Large accelerations cause injury to a person located in the interior of the vehicle and may lead to permanent disability exempting soldiers from the battlefield. Information about overload coming from the explosion of IEDs on humans are difficult to access or not sufficiently detailed. Therefore, the basis for their acquisition is conducting experimental research and modelling. The paper is presents finite element analysis of blast wave effects on a human body simulated by a numerical 50th percentile HYBRID III dummy. Coupled Euler and Lagrange (ALE) formulations are used in the finite element analysis of such problems to accurately represent the detonation phenomenon. Numerical model was developed in LS-PrePost software. All the computational analyses were carried out using an explicit LS-DYNA solver on multiprocessor cluster. Data such as hip and knee moment of inertia, femoral force, and foot acceleration are collected from the numerical dummy, which simulates the occupant's response. These data are then compared to injury threshold values from various references to assess survivability.*

***Keywords:*** *improvised explosive devices, blast wave, survivability, numerical study*

## 1. Introduction

Threats for military personnel during combat missions nowadays can have different sources. The improvised explosive device (IED) and anti-tank mine have been the most deadly weapon used by terrorists worldwide and are leading cause of injuries and death for soldiers operating in Afghanistan. To date, there have been more than 50,000 coalition soldiers injured or killed by explosive devices [1, 2]. Companies producing armoured vehicles for military applications constantly search for better materials with enhanced ballistic performance and energy absorbing capabilities that can provide maximum safety level against IED and mine threats [3]. During explosion under vehicle large accelerations cause injury to any person located in the interior which may lead to permanent disability or death. In such case, the crew is eliminated from further actions in the battlefield. Common injuries to vehicle occupants from IED are the result of:

- load transmission through floor,
- vehicle overturning and instability,
- blast pressure,

- fragments.

Common injuries caused by global and local acceleration of the vehicle:

- energy transmitted through floor,
  - lower extremity injuries (foot and ankle, tibia/fibula, knee joint),
  - many requiring amputation,
- vehicle overturning,
  - spinal injuries (lumbar spine compression and shearing, cervical spine (neck) compression and shearing),
  - head injuries (skull fractures, Traumatic Brain Injury – TBI).

## 2. Physical model

The paper presents numerical results of IED blast wave impact on side of special vehicle according to developed standardization. The experiment is based on NATO STANAG 4569 and NATO AEP-55 guidelines for determining response of structures under blast.

Among all available methods for numerical analysis, Finite Element Method (FEM) was chosen with explicit scheme of integration implemented in LS-DYNA software [4, 5]. In such an algorithms, the equilibrium equation (1) is solved by direct integration over time. Those equations are coupled which raises numerical cost and demands considerable memory resources.

Due to short duration of the phenomenon, damping can be omitted. Basic equation in explicit method is [4]:

$$[M]\{\ddot{x}\}_n = \{F\}_n - \{F_{\text{int}}\}_n , \tag{1}$$

where:

$[M]$ – mass matrix,

$\{F\}$ – external forces matrix,

$\{F_{\text{int}}\}$ – internal forces matrix.

Assuming that the mass matrix is diagonal, equations of motion can be solved using explicit Euler method. In that case, nodal acceleration vector $\{\ddot{x}\}$ can be found as [4]:

$$\{\ddot{x}\}_n = [M]^{-1}(\{F\}_n - \{F_{\text{int}}\})_n . \tag{2}$$

Equation (2) can also take into account damping, however, only in diagonal form. The main advantage of such an approach is uncoupling differential equations of motion that allows their solving.

Velocity $\{\dot{x}\}_{n+1/2}$ and displacement $\{x\}_{n+1}$ vectors for subsequent time steps are obtained by integration [4]:

$$\{\dot{x}\}_{n+1/2} = \{\dot{x}\}_{n-1/2} + \{x\}_n \Delta t_n , \tag{3a}$$

$$\{x\}_{n+1} = \{x\}_n + \{\dot{x}\}_{n+1/2} \Delta t_{n+1/2} . \tag{3b}$$

Unfortunately, the method is only stable when time step of integration is limited (4):

$$\Delta T \le 2/\omega_{\max} , \tag{4}$$

where $\omega_{\max}$ is the highest natural frequency of discrete model. It means that the time step has to be shorter than time of sound wave propagation through the smallest element in entire model. As a consequence, the more accurate model is used (smaller elements) the shorter time step becomes and time of computation increases. Numerical description of material must also take into account specific properties such as physical state, ductility, brittleness and hardness. All the experimental data were obtained from literature and experimental reports from Department of Mechanics and Applied Computer Science.

## 3. Simulation of the blast load

Simulation of the blast load is possible at different levels of approximation in the LS-DYNA package. The simplest way is to use the familiar CONWEP approach, which has been implemented in LS-DYNA code as LOAD_BLAST. This allows for a full Lagrangean simulation of the problem and certainly generates the fastest solution. However, CONWEP seems highly reliable for the simulation of explosives at a rather large distance from the target and somewhat less suitable for simulating mine blasts. Therefore verification should at least be done using a full MMALE simulation of the blast load involving full modelling of air and detonation gases and coupling with the Lagrangean model of the vehicle. This analysis is much CPU-intensive but only a few first milliseconds of the simulation are needed to compare with CONWEP results.

## 4. Simulation of occupants, seat and restraint systems

The main goal of the simulation is to obtain acceleration levels in the dummy pelvic area. Therefore, a rigid body dummy model can be considered sufficiently accurate. We have chosen to use a rigid body model of the hybrid-3 automotive dummy which is implemented into LS-DYNA as the *COMPONENT_HYBRID_3 option. This is the simplest approach to modelling vehicle's occupant with the LS-DYNA package. The use of full finite element deformable dummy models is not considered in this paper but could represent the next level of accuracy in the simulations if more detailed injury criteria are to be investigated. The seat and seatbelt components were modelled from drawings using HYPERMESH software and fixed to the M113 model with CONTACT_TIED options.

## 5. Numerical analysis

The aim of the analysis was to determine the results of land mine explosion under vehicle's bottom and to measure and reduce overloads affecting crew. First step was the verification of simplified numerical model with literature data. The most important task was to find peak values of accelerations and forces in characteristic points. Analysed system is presented in Fig. 1. The model consisted of anthropomorphic dummy and vehicle's bottom. Vehicle weighted 12.5 t. No local effects were taken into account such as bottom deformation due to blast.

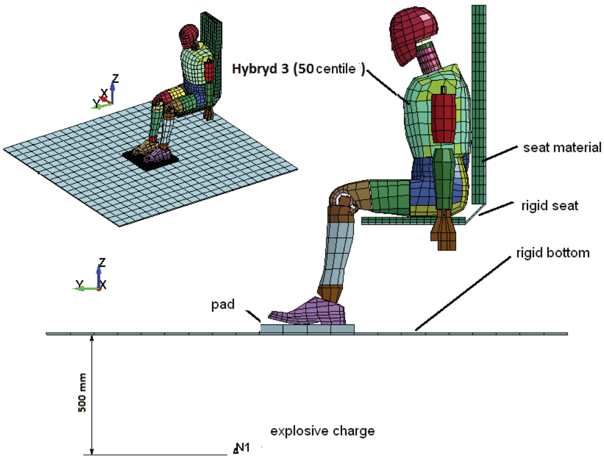

*Fig.1. Discrete model used in FE analysis*

The dummy was positioned on rigid seat with thin layer of elastic material. Impulse generated by explosive charged loaded rigid vehicle bottom. The impulse was generated using CONWEP function for charges 6 kg, 8 kg and 10 kg. Weights of explosives were chosen according to NATO

STANAG 4569 and their position was based on mean distance between ground and MRAP vehicles bottom. In presented study, bottom has dimensions 2000×2000×10 mm. The pad under dummy's feet is also modelled as rigid body. It was introduced to provide fixed position of dummy in further analyses. Mass of entire system was modelled by assigning appropriate densities to rigid elements.

Figure 2 presents accelerations versus time plots for different charges. Intersection points of cuts and ordinates was moved to 0.009 s in order to visualize difference in impulse peak value for each case. Duration of an impulse was around 0.7 ms.

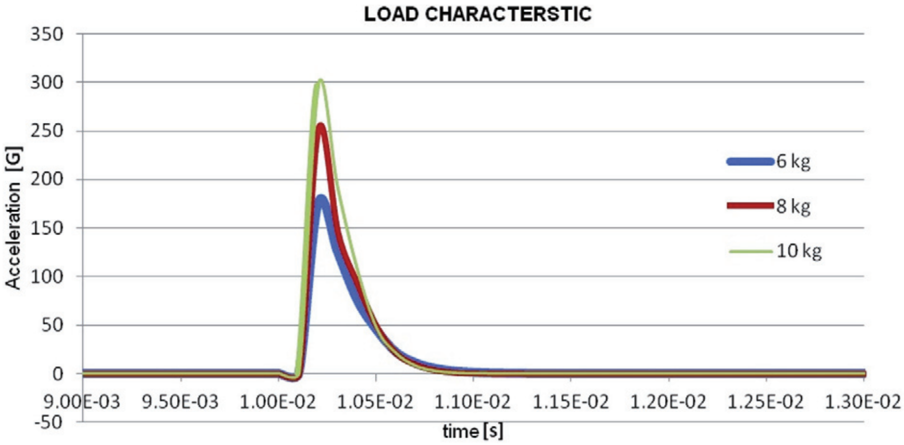

*Fig. 2. Accelerations vs. time for different charges*

Acceleration values in Fig. 2 are multiplies of gravity accelerations. As a result of previously made assumptions, in presented model accelerations are applied to vehicle's centre of gravity. In case of 6 kg charge, maximum acceleration was 176 G, for 8 kg charge – 252 G and for 10 kg – 297 G.

Another important factor is velocity of vehicle's bottom, which is related to amount of absorbed energy. Fig. 3 presents velocity as a function of explosive charge mass.

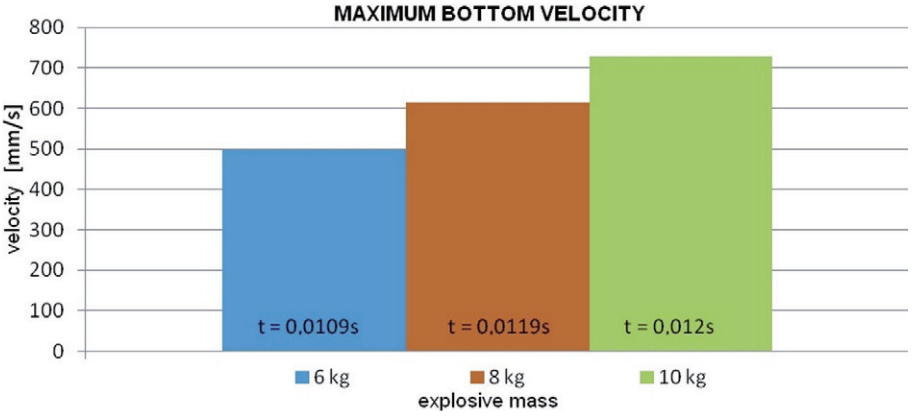

*Fig 3. Bottom velocity vs. charge mass*

Conducted analyses allowed determination of forces loading tibia of dummy. In Fig. 4, there are plots of forces versus time for different charges. There are visible peak values of forces and damping of vibrations in lower limbs system. In all cases, peak values greatly exceed safe level of force for lower limbs. For 10 kg charge maximum value was 94 kN, for 8 kg – 68 kN, and for 6 kg - 27 kN.

Further analyses were conducted with modification of pad under dummy's feet. The modification was adding 2 mm steel plate and 28 mm energy-absorbing Impax foam layer. Material properties used for modelling of foam layer are presented in Tab. 1. Foam was modelled using MAT_LOW_DENSITY_FOAM material in LS-DYNA.

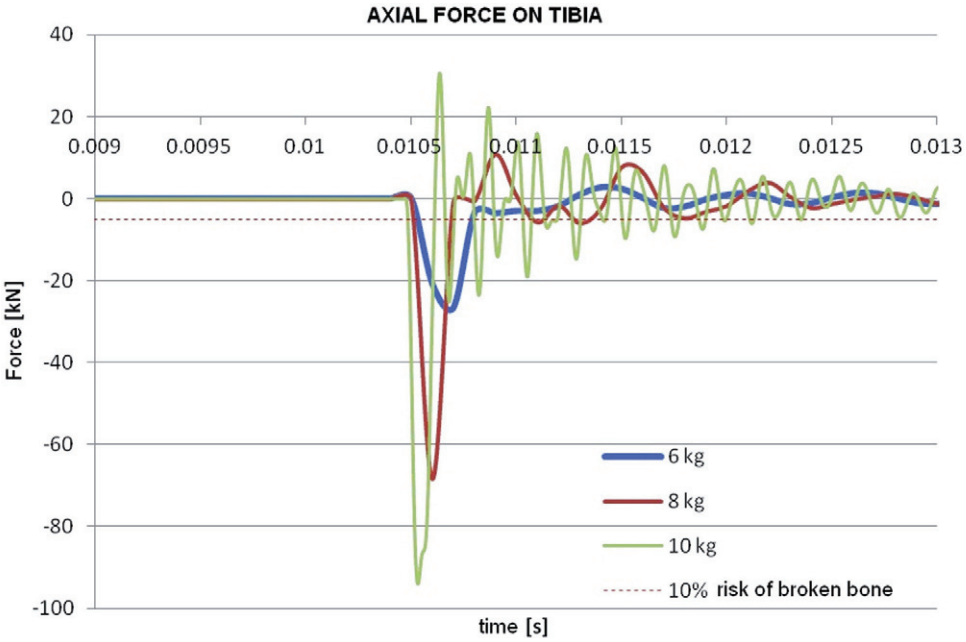

*Fig. 4. Axial force loading tibia for rigid vehicle's bottom*

*Tab. 1. Material properties of Impax700EA foam*

| density [Mg/mm$^3$] | Young modulus [MPa] | HU hysteresis coefficient (for unloading) | damping coefficient | shape coffined |
|---|---|---|---|---|
| 3.7E–11 | 10.5 | 0.101 | 0.2250000 | 15 |

Obtained results for the same load cases showed great improvement in energy absorption and justifies the use of additional protection. In case of 6 kg and 8 kg charges, peak axial force loading tibia was reduced to safe values. In case of 10 kg charge, maximum registered force was 6 kN. Fig. 5 presents the results of modified pad analysis. There are visible peaks of force for time $t \approx 0.011$ s. Later, the force decreased and increased again. This effect is caused by loss of contact between dummy's feet and bottom for a short period of time.

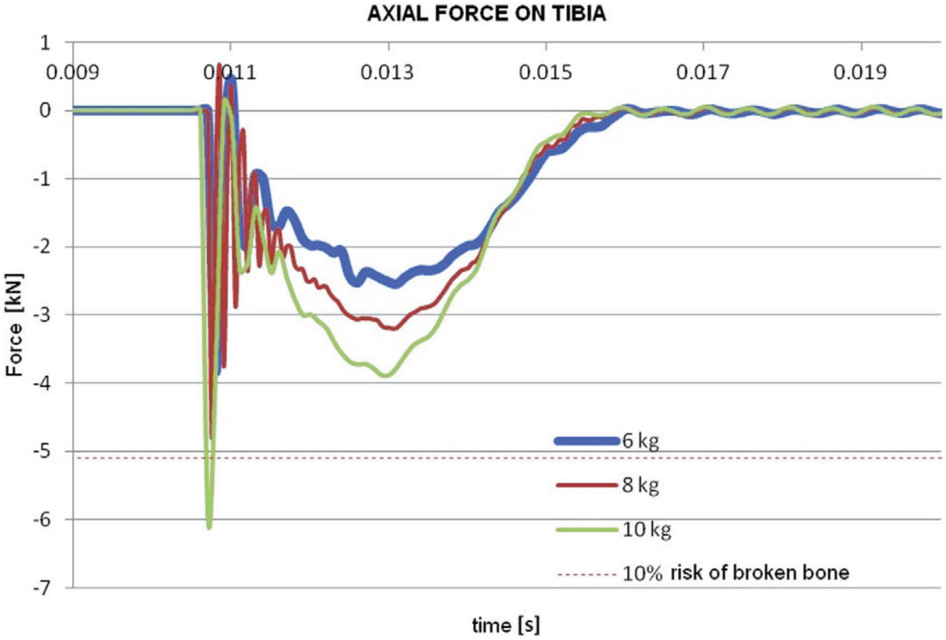

*Fig. 5 Axial force loading tibia for rigid vehicle's bottom with modified pad*

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