

## NUMERICAL SIMULATION OF MILITARY GROUND VEHICLE'S RESPONSE TO MINE-BLAST LOAD

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*One of the most present threats for military vehicles in today combat actions is the Improvised Explosive Devices (IEDs). The explosive threats complicate the process of vehicles design and increase the costs of proving. The current paper is concerned with the development of a numerical tool that can be used in the early design phase of a new armored vehicle concept. The adopted simulation strategy is based on several separate simulation models and data transfer (output/input) between these models. The studied scenario corresponds to a threat of Level 2b, according to NATO Standardization Agreement, STANAG 4569. The simulations results were assessed from the perspective of safety threshold criteria set out in the same standard.*

**Keywords:** numerical simulation, dummy model, mine-blast load.

### 1. Introduction

During peacekeeping missions or in tactical field, the military forces use vehicles that are potentially subjected to various threats: small and medium caliber projectile impact, shape charge ammunitions impact, mines and Improvised Explosive Devices (IED) detonation. Mines and IEDs use the chemical energy contained by the energetic materials able to detonate, also known as explosives.

When detonating an explosive charge, located on the ground under the vehicle, the chemical energy transforms into mechanical energy carried by a shock wave through air. The pressure acting on the vehicle floor has a dual effect: floor deformation by bulging and vehicle vertical acceleration due to reaction forces between the floor and the rest of the structure. Upon charge detonation the resulted gases trapped between ground and vehicle floor continues to act on vehicle structure up to environmental pressure value is reached. This phenomenon leads to an increase in vehicle transmitted impulse. Acceleration of the floor, closely followed by its deformation, ends into a sharp increase of pressure inside the vehicle, due to the acceleration of the air in contact with the floor. Over a certain limit, floor cracks leading to rupture and the high pressures gases leak inside the vehicle.

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If the explosive charge is buried, a directional effect occurs on vertical axis due to soil confinement, [1]. The soil layer laid on the mine is propelled vertically along with resulted gases. For an optimal depth, the impulse transmitted to the floor and vehicle is increased with a percent greater than 100% comparing to the situation when the explosive charge is laid on the ground surface, [1]. Occupant's injuries are induced by: floor acceleration (overloading inferior limbs bones), shock wave (action on the internal organs), throwing up and eventually rollover of the whole vehicle (overloading the spine) and by shrapnel that pierces the armor and hits the body.

Therefore, an effective protection system must have the following characteristics: to avoid penetration, to limit deformation and acceleration induced on the crew, and to reduce to a minimum the vehicle jumping height.

The complexity of the above described phenomenon makes impossible an analytic approach in designing and determination of the protection level offered by a vehicle to its occupants at detonation of an explosive charge under the vehicle. Typically, in order to determine the level of blast protection of a new vehicle, the prototypes are subjected to destructive field tests. This situation eventually led to the development of testing standards, like the one described in STANAG 4569 "Protection Levels for occupants of Logistic and Light Armored Vehicles", [2].

The above-mentioned standard "describes the threats definitions, the test conditions and the injury criteria for vehicle occupants to be used when determining the protection level" of armored vehicles exposed to effects of classical hand grenades and explosive mines.

Based on the protection offered for vehicle occupants, the armored vehicles are rated on levels of protection, [2]. Except the level 1, which correspond to threat defined by hand grenades, unexploded sub-munitions, and small anti-personnel explosive devices, all the other levels, from 2 to 4, are related to anti-vehicles buried land mines (known as anti-tank mines). The explosive charges that correspond to these threats levels are 6 kg, 8 kg and 10 kg of TNT. The surrogate mine specifications for these threat levels are defined in Appendix B3 of the standard. Specific mine detonation locations are chosen to correspond to the most dangerous situations for occupants. Procedures and positioning examples are described in Appendix D of the standard.

The assessment of the injuries risk for occupants when detonating a mine under the vehicle is based on the effects on the occupants of local deformations and the overall movement of the vehicle, [2].

The Hybrid III 50th Percentile Male Crash Test Dummy (ATD), better known as the crush dummy, developed for assessing car passenger safety, is used as a surrogate for occupants. The benchmarks for ATD Injury Assessment Reference Values (IARVs) are used to assess the risk of injury at mine detonation.

To assess the induced overpressures inside the vehicle, a tubular device with the dimensions specified in the standard or a pressure transducer mounted on the chest of the dummy may be used.

Mandatory IARVs are related to ATD response (section E5.2.1) and overpressure (section E5.2.2). Table 2 lists IARVs that are mandatory and used as passing criteria for the vehicle tested with a Hybrid III ATD (the 50<sup>th</sup> percentile man), [3].

The testing activity with real vehicles, under above-mentioned standard requirements, is both time consuming and costly. Moreover, does not ensure an optimized design. This is the reason why the development of a virtual environment used to assess optimized protective designs is considered as being crucial in reducing development costs and manufacturing of better vehicles, [4].

In the open literature there are many successful examples of using FEM software in numerical simulation of blast wave/structure interaction, [3-11]. The work covered by these papers deals with models of various degrees of complexity, starting with the deformation of a simple plane plate and ending with the assessment of potential damages on vehicle passengers, [8].

In the context of the above-mentioned considerations, the subject of the current paper addresses the possibility of using the numerical approach in the early design phase of a new armored vehicle concept as an alternative to the laborious activities and expensive equipments necessary to fulfill the steps and requirements like those imposed by NATO proving procedures.

## 2. Short description of adopted simulation strategy

The expected level of protection offered by the new vehicle concept is Level 2, according of the NATO standard. For tests with mines of Level 2 there are two main possible locations, [2]:

- (a) under deck/wheel with at least 50% of the charge inside – Level 2a;
- (b) under the occupants' compartment – Level 2b.

As long as Level 2b is the most challenging from the point of view of blast protection, this is the scenario used in simulation.

The adopted work strategy was based on the following fundamental elements:

- design of a simplified vehicle model that offers a balance between fidelity of the model and the necessary working time;
- adequate reproduction of surrogate explosive charge of Level 2;
- simulation of blast loading scenario Level 2b (the explosive charge is located under the occupants' compartment);
- loading of an existing dummy model with the vehicle seats displacements data obtained in the above-mentioned simulation;

- processing the data obtained with the dummy model in order to assess the safety of vehicle's occupants (IARV criteria).

AUTODYN and LS-DYNA software have been used for calculations. A synthesis of the information flow and of the work steps and data export is found in Fig. 1.

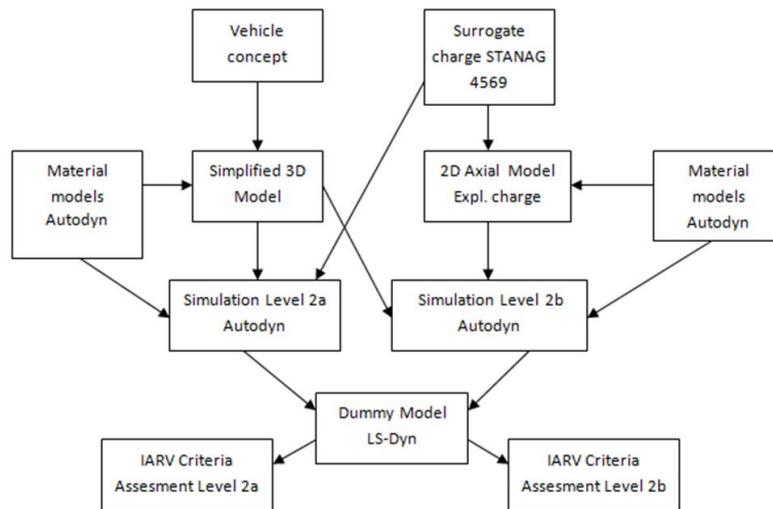


Fig. 1. The analysis steps

The decision to design a simplified model is supported by the fact that the reproduction of all vehicle parts or shape details leads to an overly large size of the model without a substantial change in vehicle response to mine-blast loading.

The structure of the vehicle has been modeled with SHELL triangular elements. This resulted in a total of 546,065 elements and 274,738 nodes, Figure 2. Several gauges were added to the model to track the movement of vehicle seats and the overpressure evolution inside the vehicle, Figure 3. To shell elements have been assigned thicknesses and material properties according to element position on vehicle structure.

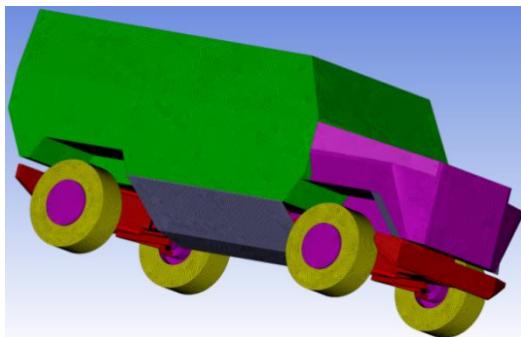


Fig. 2. Simplified vehicle model

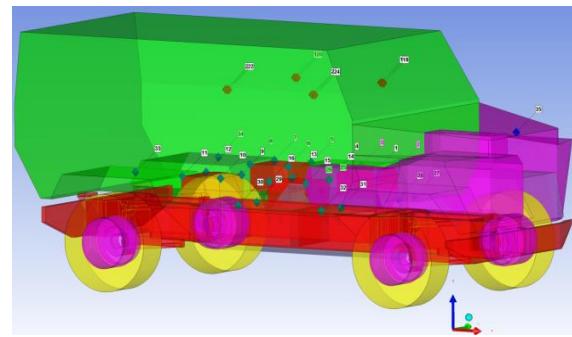


Fig. 3. Gauges positions in simplified vehicle model

The Level 2 surrogate charge detonation and blast wave propagation through air up to the moment of contact with vehicle structure was simulated in a separate model using the AUTODYN 2D - axial symmetric option. The axial symmetric option has allowed to model explosive charge and the surrounding environment with a fine Euler-type mesh of 1 x 1 mm elements.

For the explosive charge was used composition C4, that contains 90% RDX [12]. The used quantity of 5.4 kg C4 was calculated based on the TNT equivalency law and replaces the surrogate charge of 6 kg TNT.

The dimensions of the C4 charge and the metal container were calculated based on the imposed conditions, [2]. The axial-symmetric model is shown in Figure 4. The material models used for air and C4 explosive are presented in Table 1. The STEEL 4340 model, from the AUTODYN library, was adopted for the steel-pot part.

Table 1

Air and C4 models [10]

Material	Air	C4	C4
Ecuation of state	Ideal gas	JWL	Ideal gas
	$\gamma = 1,4$	Standard model	$\gamma = 1,35$
Initial data	$\rho = 1,225 \cdot 10^{-3} \text{ g/cm}^3$	$\rho = 1,63 \text{ g/cm}^3$	Obtained from detonation
	$E = 2,068 \cdot 10^5 \mu\text{J/mg}$	$E = 3,68 \cdot 10^6 \mu\text{J/mg}$	

According to procedures requirements, the charge was bottom initiated. Two material models were used for the explosive charge, as long as for pressure values under 1kbar, the JWL (Jones-Wilkins-Lee) equation of state fail to represent the real behavior of detonation gases [10].

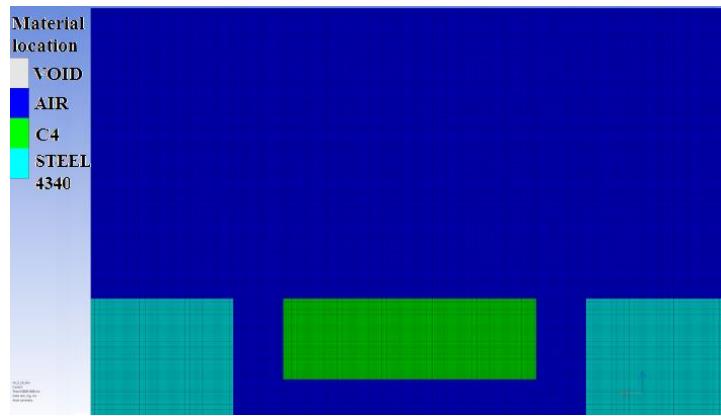


Fig. 4. Axial-symmetric model for surrogate explosive charge

The interaction of the shock wave with vehicle structure was modeled in AUTODYN 3D. To reproduce the level 2b testing conditions an Euler volume

that interacts with the simplified model has been modeled. The air volume considered is 2 m x 2 m x 2.2 m and was evenly meshed with 8,800,000 elements with a 10 mm x 10 mm x 10 mm size. The arrangement of the air volume relative to the simplified model is depicted in Fig. 5.

This arrangement allows that the data obtained in 2D axial-symmetric model for surrogate charge to be imported in a 3D model in the central area, under the vehicle's belly. Before the 2D axial-symmetric model data were imported, the defined air volume was loaded with air at the pressure of 1 bar. In this way, the initial moment of the numerical simulation is the same with the moment of interaction between the shock wave and vehicle's structure (Fig. 6). The boundaries of air volume (excepted the base's one) are defined so as to behave like permeable boundaries, which do not generate wave reflections.

A Lagrange part which defines the soil surface was also added. The Euler volume was kept active in the model until the vehicle's vertical acceleration is completed. The volume elimination reduces the time necessary for the calculations.

The numerical analysis was performed up to moment when the vehicle returns to the ground. The gauges were used to record the trajectories of the elements that reproduce the seats. This specific set of data was used to calculate the dummy response.

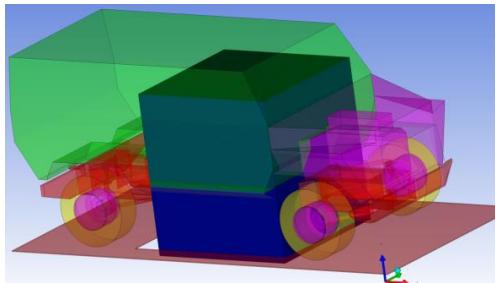


Fig. 5. Air volume position

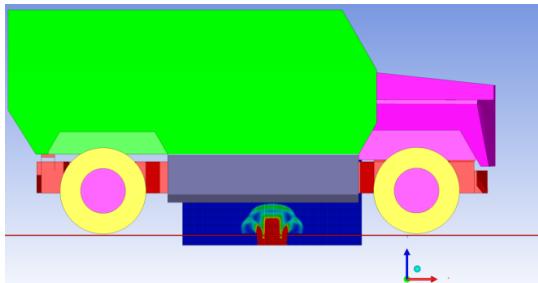


Fig. 6. Initial moment of shock wave/structure interaction

The dummy response to the loads generated by the Level 2b surrogate charge detonation was simulated using a model build in LS-DYNA software. The Hybrid III 50th Percentile Male Crash Test Dummy model was modified to extract the data required for the IARVs assessment. Thus, the nodes and elements having a similar position to the accelerometers and force transducers with which the dummy is equipped have been identified. These are tracked throughout the simulation and the resulted curves have been processed according to the instructions [2].

The model was completed with structural elements that schematically simulate the seat and floor of the vehicle. In addition, the model is also fitted with a 3-point seat belt.

To produce loads in the dummy model, a vertical displacement curve of seat was imposed in the model. This curve was obtained by processing the curve that describes the movement of the virtual transducers corresponding to the driver's seat position in the AUTODYN 3D simulation (Fig. 7).

For the simulation with the ATD III dummy, the most loaded seat position was considered. The selection was based on the accelerations supported by the elements that simulate the seats. For Level 2b the dummy simulation was performed for the driver's seat.

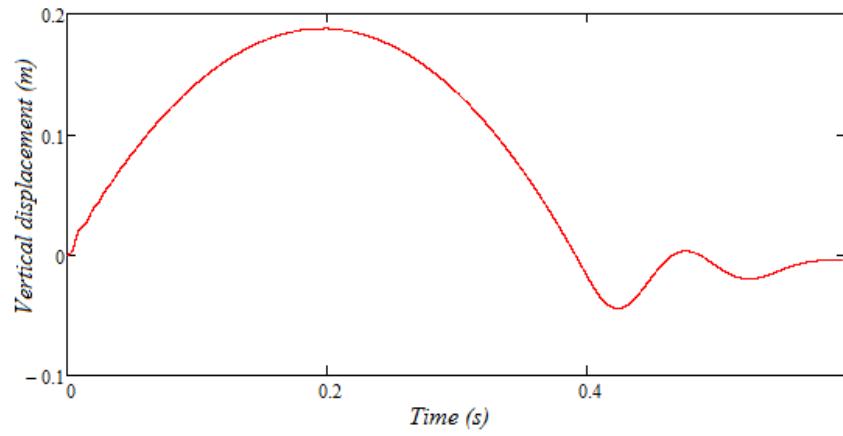


Fig. 7. The imposed curve for the seat in LS-DYNA dummy model (for Level 2b)

Fig. 8 and Figure 9 show the dummy during the ascension phase and, respectively, the descending phase respectively for the Level 2b simulation.



Fig. 8. Dummy model during the ascension phase in the simulation for Level 2b

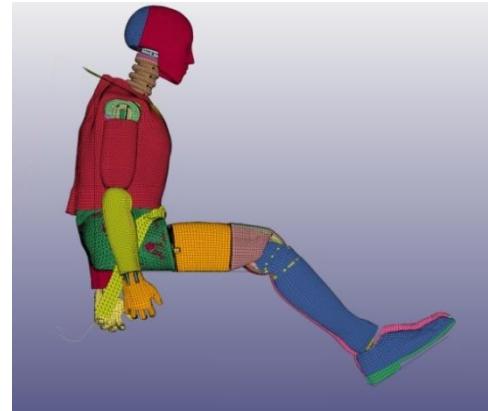


Fig. 9. Dummy model during the descending phase in the simulation for Level 2b

## 4. Results

For the dummy response simulation, the head accelerations, the pelvic acceleration, the forces exerted at the neck and the compressive forces from the femur and the tibia were extracted. These data were mathematical processed with digital filters according to the specifications [2]. Where required, the recorded data were processed according to the equations given in of STANAG 4569.

For each criterion specified in IARVs list, the data obtained by simulation were compared with the criteria limit values in Table 2. The values obtained for all criteria are lower than the pass/fail thresholds.

Table 2

Simulation results for level 2b - driver's seat

Body region	Criterion/ IARV	Pass/fail threshold	Simulation results
<b>Head</b>	Head Injury Criterion (HIC <sub>15</sub> )	250 g <sup>2.5</sup> ·s	12.905 g <sup>2.5</sup> ·s
<b>Neck</b>	Axial compression force (Fz-)	4.0 kN at 0 ms / 1.1 kN >30ms	1.783 kN at 7 ms
	Axial tension force (Fz+)	3.3 kN at 0 ms / 2.8 kN at 35 ms / 1.1kN >45 ms	0.454 kN
	Shear force (Fx+-)	3.1 kN at 0 ms / 1.5 kN at 25-35 ms / 1.1 kN >45 ms	0.21 kN/ -0.333 kN
	Shear force (Fy+-)	3.1 kN at 0 ms / 1.5 kN at 25-35ms / 1.1 kN >45 ms	0.017 kN/ -0.013 kN
	Bending moment (flexion) (M <sub>0c<sub>y</sub></sub> +)	190 Nm	5.63 Nm
	Bending moment (extension) (M <sub>0c<sub>y</sub></sub> -)	77 Nm	5.25 Nm
<b>Thorax</b>	Thoracic Compression Criterion (TCC <sub>frontal</sub> )	30 mm	6.79 mm
	Viscous Criterion (VC <sub>frontal</sub> )	0.70 m/s	0.148 m/s
<b>Spine</b>	Dimensionless Dynamic Response Index (DRI <sub>Z</sub> )	17.7	8.78
<b>Left Femur</b>	Axial compression force (Fz-)	6.9 kN	1.956 kN
<b>Right Femur</b>	Axial compression force (Fz-)	6.9 kN	1.94 kN
<b>Left Tibia</b>	Axial compression force (Fz-)	5.4 kN(HIII lower load cell)	4.72 kN
<b>Right Tibia</b>	Axial compression force (Fz-)	5.4 kN(HIII lower load cell)	4.7 1kN
<b>Non auditory pressure induced injuries</b>	Chest wall velocity predictor (CWVP)	3.6 m/s	0.05 m/s

Except the Axial compression force (Fz-) criteria for all the other Neck force criteria the maximal values correspond to the intervals where the duration of load is not any more important in pass/fail assessment.

The results reveal that the most exposed parts of body are the lower legs as long as the calculated value for Axial compression force (Fz-) for both tibia are around 87% of the threshold value.

## 5. Conclusions

The numerical study on the response of the vehicle concept at mine-blast load was done in order to assess the protection level. The simulations have reproduced the test conditions specified in STANAG 4569 for threat Level 2b. The analysis of the protection capability was carried out based on the IARV acceptance criteria mentioned in the same NATO Standard.

In order to simplify the numerical calculation model, the adopted simulation strategy was based on several separate simulation models and the data transfer (output/input) between these models.

The results of 3D simulations with the simplified model of the vehicle concept indicate that the floor of the cabin area, the armored carcass, does not fail under the specific load conditions of Level 2b.

Obtained data from the AUTODYN 3D simulation with the simplified vehicle model allowed the evaluation of the ATD H III dummy mechanical loads through a separate numerical simulation. The numerical results regarding accelerations and forces exerted on the dummy elements were compared with the standardized IARV criteria. The results of the simulations indicate that the proposed vehicle concept does not exceed any of the threshold values corresponding to the IARV acceptance criteria.

Successful completion of all steps of the proposed approach indicates that the proposed strategy, based on several separate models, offers the ability to analyze and to evaluate various prototypes for a broad spectrum of test conditions.

The used numerical approach represents a Simulation-Based Design (SBD) alternative to the testing activities imposed by NATO proving procedures in the early design phase of a new vehicle concept.

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