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Numerical Analysis of the Mine Blast Action on an Armored Vehicle for Different V-hull Geometries

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The main objective of this research is to develop a numerical model of vehicle damage caused by an explosion of a mine, as well as to find the most favorable case of V-hull geometry and to point out a possible solution for mitigating the effects of mine explosion on an armored vehicle. Seven different V-hull geometries were considered and structure damage analysis was performed for all seven options. Also, the mass change for different geometries was analyzed. The effect of the mine explosion on the target structure was analyzed using the overpressure function according to the empirical CONWEP model, using Abaqus / Explicit software. An example of an explosion of 8 kg of Composition B acting on a vehicle with a total mass of 8000 kg was analyzed. The vehicle has two main parts - the cabin with mass of 6 t and a V-hull of mass of 2 t. The V-shaped hull in all the examples shown is made of 10 mm thick plates of Hardox 400 steel. The position of the explosive charge is the same for all geometry examples and is 0.6 m below the center of the vehicle. After analysis of the obtained results the most favorable V-hull geometry is determined. The guidelines for the further work and model improvement are suggested.

Key words: **landmine, IED, detonation, blast, armored vehicle, V-hull..**

Introduction

SINCE the World War II more military vehicles have been destroyed by mines than by all other threats combined [1]. Anti-tank (or more general anti-vehicle) mines can disable heavy vehicles or completely destroy lighter vehicles. The most common form of anti-tank mine is an explosive mine that uses a large amount of explosives to directly damage the target. In conventional military applications, mines are used as a powerful multiplier to limit the movement of enemy forces and to protect against attack. They have a relatively low price and are affordable, so they are a powerful weapon in the fight against enemies [2]. The detonation of an anti-tank mine causes an exothermic explosive reaction, which results in the formation of a shock wave due to the rapid expansion of gases. Unlike standard mines, improvised explosive devices (IED) can be of different sizes, shapes, types, and different technical solutions, and therefore the problem of their description and modeling increases [3].

The blast is the result of an explosion - a process characterized by extremely rapid release of energy. Demolition effect is a very complex phenomenon, which involves, on the one hand, determining the time variable of pressure on the considered structure and, on the other hand, modeling the deformation of the structure itself under conditions of large deformations and high rates of deformation, that is, nonlinear behavior of the material. Calculation of the structure under these conditions is only possible by applying numerical methods [4]. As experimental testing is financially disadvantageous, appropriate engineering computer analyses and simulations are increasingly being used. Regardless of the origin and cause of the explosion, there is a general need to develop an explosion-resistant structure. In order to accelerate the development process, a computer-aided analysis technique (CAE) is used to test structure protection [5]. In the last few decades, great progress has been made in modeling of detonation, dynamic behavior of materials, and ballistic interactions between detonation products and the structure of a vehicle. These models are usually created by coupling the Eulerian and Lagrangian approach in treatment of computational mesh [6].

When a vehicle comes in contact with a mine, an explosion occurs. Detonation is a process in which a shock wave propagates within an explosive and initiates a rapid exothermic and explosive chemical reaction. Local pressures are usually of the order of 20 ÷ 40 GPa, while temperatures are of the order of 2000 to 6000 K. An explosion is an extremely complex process, because changes of physical quantities take place quickly in space and time [7].

To achieve greater passenger survival by minimizing the vehicle damage and reducing the acceleration that affects them, much effort has been made to direct the blast wave further away from the vehicle. To achieve this, most modern armored vehicles have a V-shaped hull. Geometry of V-shaped hull allows more explosion energy to be routed away from the vehicle, and therefore a lower vertical impulse is transmitted to the vehicle [8]. The hull of the vehicle must be able to withstand the intense load resulting from the explosion. Immediately after the hull is damaged, passengers are exposed to the dangers that can result in fatal injuries. In the case where it is not possible to simply introduce a V-shaped hull, it is possible to introduce "double V-shape". In this case, instead of blasting exclusively on the exterior of the vehicle, one part of the explosion is directed towards the center of the explosion. A flat hull offers a high degree of

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mobility and load capacity, but does not provide enough blast protection [9]. This subject received significant attention recently.

The goal of the present research is to investigate influence of V-hull geometry on the level of its stress, strain and damage.

Definition of the problem and numerical model

The analysis can be summarized as follows: A vehicle of a total weight of 8000 kg is exposed to the explosion action of 8 kg explosive Composition B, which consist from 60% hexogen (RDX) and 40% trinitrotoluene (TNT). The vehicle has two main parts – the cabin with mass of 6 t and a V-hull of mass 2 t. The V-shaped hull is made of 10 mm thick plates of Hardox 400 steel. The position of the explosive charge is 0.6 m below the center of the vehicle. The characteristics of the Hardox 400 are shown in Table 1. Besides the elastic properties, the Johnson-Cook plasticity model [10] and Johnson-Cook damage model [11] are employed in order to describe the response of material to dynamic loading.

Principles of numerical approach to the problem of mine blast loading of a vehicle will be demonstrated using a representative example illustrated in Fig.1. Typical vehicle structure is comprised of a V-shaped hull and the upper structure which will be termed as the “cabin“.

Table 1. Main characteristics of Hardox 400 steel [12,13]

	Density (g/cm^3)	7850
Elastic properties of materials	Young’s modulus (GPa)	209
	Poisson coefficient	0.3
Plastic behavior, Johnson-Cook model parameters	A (MPa)	1350
	B (MPa)	362
	n	1
	C	0.0108
	$\dot{\varepsilon}_0$	0.0005
	m	1
Damage model of Johnson and Cook, non-dimensional parameters	d1	0.0705
	d2	1.732
	d3	-0.54
	d4	-0.015
	d5	0

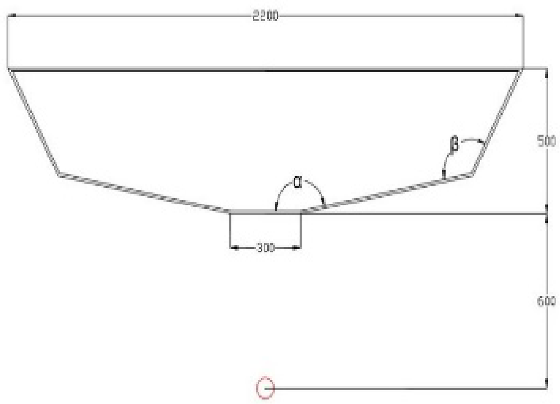

Figure 1. Geometry of the V-shaped hull used in numerical model

In all analyzed cases, we will consider a vehicle with the following fixed parameters: hull width (2.2 m), hull height (0.5 m), width of the lower flat surface of the V-hull (0.3 m), distance from the center of explosion (0.6 m), plate thickness and material (10 mm, Hardox 400), vehicle cabin (mass, material, dimensions) and type and mass of explosive substance. During the analysis, the angles α and β that define the hull geometry were changed in order to find the best solution.

Numerical simulation was performed using FEM - based software Abaqus/Explicit [14]. The simulation time of 10 ms is found to be enough for capturing all relevant parameters. The continuous 3D hexahedral element with reduced integration (C3D8R) is selected for the cabin and the continuum shell element SC8R is used for the V-hull. Depending on the geometry, the total number of elements ranges from 262000 to 401600. Significant model enhancements are possible in terms of material behavior, explosion simulation, and fluid-metal interaction (FSI) [15].

The effect of the mine explosion on the target structure was analyzed in a simplified way using the overpressure function according to an empirical model, known as “CONWEP“. To use this approach, one needs to know the following information on explosive charge: mass, position and TNT equivalent (TNT mass that will give the same explosion performance as the real mass of the explosive used). For the explosive used, the relevant data are shown in Table 2.

Table 2. The main properties of Composition B used in the numerical model [10]

Explosive	Density (g/cm^3)	Detonation velocity (m/s)	TNT equivalent factor, q_{TNT}
Composition B, 60% RDX + 40% TNT	1.751	8000	1.148

The equivalent mass of TNT W corresponding to the mass of used explosive M_E is determined as:

$$W = q_{\mathrm{TNT}} \cdot M_{\mathrm{E}} \quad (1)$$

Based on eq. (1) and data from Table 2, the equivalent mass of explosive substance Composition B can be simply calculated:

$$W = q_{\mathrm{TNT}} \cdot M_{\mathrm{E}} = 1.148 \cdot 8 = 9.184\,\mathrm{kg} \quad (2)$$

Very important parameter for calculation of the blast effect is scaled distance from the center of explosion, which is defined as:

$$Z = \frac{R}{W^{1/3}} \quad (3)$$

where R is the actual distance from the center of explosion.

For example, if a real distance from the center of explosion is assumed to be 1 m, it is obtained that the scaled distance from the center of explosion is 0.478 $\mathrm{m/kg^{1/3}}$, according to the eq. (3).

The maximum overpressure produced by the rapid expansion of detonation products can be determined by different empirical relationships. One of empirical formulas that is excessively used is Henrych’s equation [9]:

$$p_{\max} = \begin{cases} \dfrac{14.072}{Z} + \dfrac{5.540}{Z^2} - \dfrac{0.357}{Z^3} + \dfrac{0.00625}{Z^4}, & 0.05 < Z \le 0.3 \\ \dfrac{6.193}{Z} - \dfrac{0.326}{Z^2} + \dfrac{2.132}{Z^3}, & 0.3 \le Z \le 1 \\ \dfrac{0.662}{Z} + \dfrac{4.05}{Z^2} + \dfrac{3.288}{Z^3}, & 1 \le Z \le 10 \end{cases} \quad (4)$$

For previously scaled distance of 0.478, it can be calculated from eq. (4) that the value of the overpressure in free air is 49.2 bar.

In the presence of a rigid obstacle, it can be shown that the value of overpressure behind reflected normal shock wave can be expressed as:

$$p_r = 2p_{max}\frac{7p_0 + 4p_{max}}{7p_0 + p_{max}} \quad (5)$$

where p_0 is atmospheric pressure.

All previous CONWEP model relationships have been implemented in Abaqus/Explicit software.

Analysis of the influence of angle change α on damage to the target structure

In order to find the most favorable geometry of the V-hull, four different geometries will be analyzed in terms of the angle change α. This angle has dominant influence on pressure distribution, load and the damage of the hull. After discovering the most favorable solution with a given angle α, angle β will continue to change, while angle α will remain unchanged. The effect of changing the angle β will be shown for four different cases. The effect on the equivalent plastic strain as well as on the distribution of von Mises stresses for 5 different moments after detonation was analyzed. Equivalent plastic strain (PEEQ) is a parameter indicating the level of irreversible deformation of a structure [12, 13, 16].

- For the starting geometry, the example presented in [10], which has been improved from the aspect of material properties, was used. In this case, α=170° and β=130°. Fig.2 shows the geometry of the V-hull as well as the finite element mesh for the case of the given angles.
- As a second case, the geometry of the V-hull for which α = 160° is analyzed, while the angle β, as well as all other parameters except mass, remains unchanged. In this case the weight of the V-hull is 11.8% less than in the first case. The geometry of the V-hull and the finite element mesh are similar to those shown in Fig.2.
- As a third case, the geometry of the V-hull for which α = 165° is analyzed, while the angle β, and all other parameters except mass, remains unchanged. In this case the mass of the V-hull is 1.1% less than in the first case. The geometry of the V-hull and the finite element mesh are similar to those shown in Fig.2.
- As a fourth case, the geometry of the V-hull for which α = 155° is analyzed, while the angle β, and all other parameters except mass, remains unchanged. In this case the weight of the V-hull is 11.9% less than in the first case. The geometry of the V-hull and the finite element mesh are similar to those shown in Fig.2.

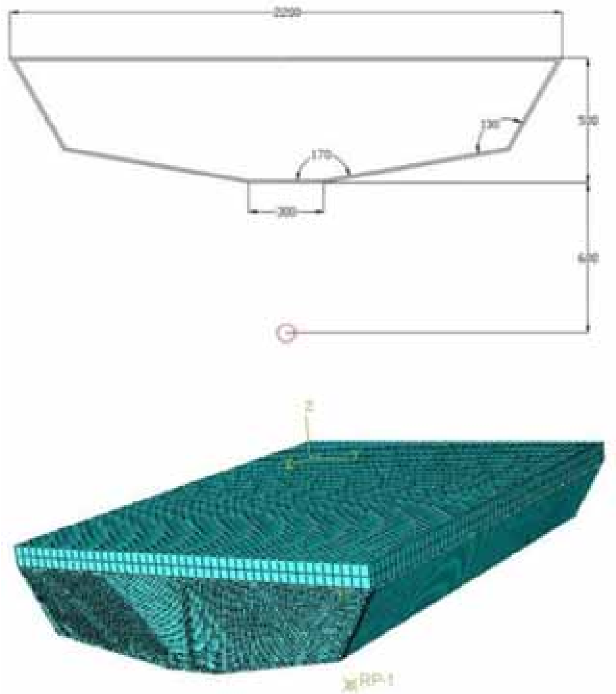

Figure 2. V-hull geometry and finite element mesh for the numerical model and the FEM vehicle model and the position of the explosive charge when α=170° and β=130°

Table 3 shows a comparison of the results for four different values of the angle α.

By comparing the obtained results, it is concluded that the most favorable results in terms of minimum values of equivalent plastic strain (PEEQ) and equivalent von Mises stress (S) are obtained for the case of V-hull when α=155° and β=130°. Also, this case is most favorable from the point of the mass of the V-hull.

Fig.3 shows the equivalent plastic deformation (PEEQ) for 4 different cases at the moment 10 ms after detonation. Fig.4 shows the distribution of von Mises stress for 4 different cases at 10 ms after detonation.

Table 3. Comparative presentation of equivalent plastic deformation (PEEQ) and equivalent von Mises stress (S) for four different angle (α) values

	α=155°		α=160°		α=165°		α=170°	
Mass (kg)	1795		1797		2015		2037	
Results								
Time (ms)	PEEQ	S (MPa)	PEEQ	S (MPa)	PEEQ	S (MPa)	PEEQ	S (MPa)
2	9.778e-04	845.3	2.462e-02	1066	1.494e-04	729	0	1229
4	3.396e-03	1460	3.550e-02	1525	5.846e-03	1497	3.428e-03	1526
6	3.396e-03	1066	3.708e-02	1512	1.883e-02	1481	1.610e-02	1520
8	3.396e-03	1142	3.708e-02	1514	2.593e-02	1349	1.618e-02	1491
10	3.396e-03	866.4	4.102e-02	1517	2.593e-02	1290	1.618e-02	1141

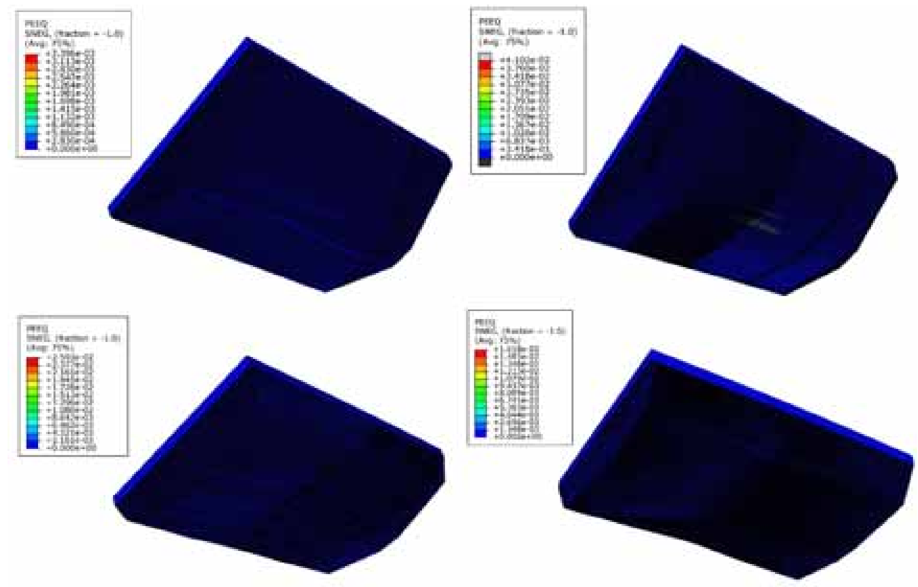

Figure 3. Equivalent plastic deformation (PEEQ) for 4 different cases at 10 ms after detonation

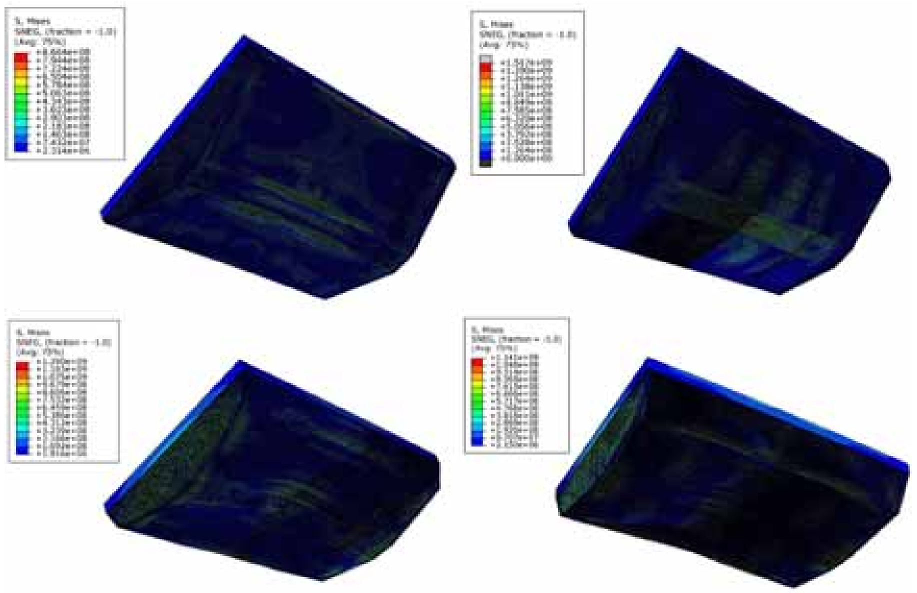

Figure 4. Von Mises stress in loaded structure for 4 different cases at 10 ms after detonation

Analysis of the influence of angle β on damage to the target structure

After the angle $\alpha = 155°$ was adopted as the most favorable solution from the aspect of influence of angle α, the angle β is further changed. The analysis has already been made for the baseline case when $\beta = 130°$.

- In the second case, the geometry of the V-hull for which $\beta = 120°$ is analyzed, while the angle α, as well as all other parameters except mass, remains unchanged. In this case the mass of the V-hull is 2.96% higher than the V-hull whose angles are 155° and 130°. Fig.5 shows the geometry of the V-hull as well as the finite element mesh for the case when $\beta = 120°$.
- As a third case, the geometry of the V-hull for which $\beta = 145°$ is analyzed, while the angle α, and all other parameters except mass, remains unchanged. In this case, the mass of the V-hull is 1.69% higher than the V-hull whose angles are 155° and 130°. The geometry of the V-hull and the finite element mesh are similar to those shown in Fig.5.

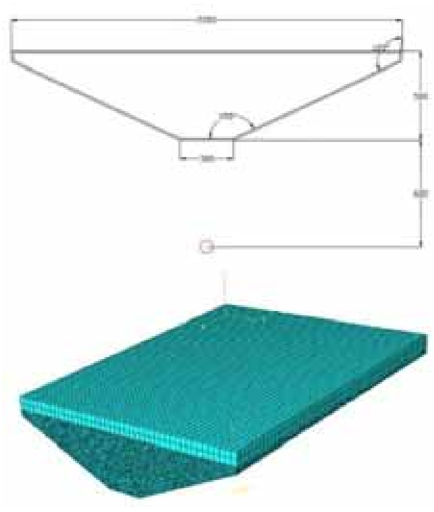

Figure 5. V hull geometry and finite element mesh for the numerical model and the FEM vehicle model and the position of the explosive charge when α=155° and β=120°

- As a fourth case, the geometry of the V-hull for which β = 160° is analyzed, while the angle α, like all other parameters except mass, remains unchanged. In this case, the mass of the V-hull is 0.27% less than that of the V-hull, whose angles are 155° and 130°. The geometry of the V-hull and the finite element mesh are similar to those shown in Fig.5.

Table 4 shows a comparative overview of the results for four different values of angle β.

Fig.6 shows the equivalent plastic deformation (PEEQ) for 4 different cases at the moment 10 ms after detonation. Fig.7 shows the distribution of von Mises stress for 4 different cases at 10 ms after detonation.

Table 4. Comparative presentation of equivalent plastic deformation (PEEQ) and equivalent von Mises stress (S) for four different angle (β) values

	β=120°		β=130°		β=145°		β=160°	
Mass (kg)	1802		1750		1779		1745	
Results								
Time (ms)	PEEQ	S (MPa)	PEEQ	S (MPa)	PEEQ	S (MPa)	PEEQ	S (MPa)
2	0	1084	9.778e-04	845.3	0	971.7	0	607.5
4	5.447e-03	1352	3.396e-03	1460	4.556e-03	1457	4.822e-03	1462
6	5.447e-03	1058	3.396e-03	1066	4.610e-03	1384	4.918e-03	1495
8	5.447e-03	1163	3.396e-03	1142	4.610e-03	1142	4.918e-03	1162
10	5.447e-03	736.4	3.396e-03	866.4	4.610e-03	634	4.918e-03	600.5

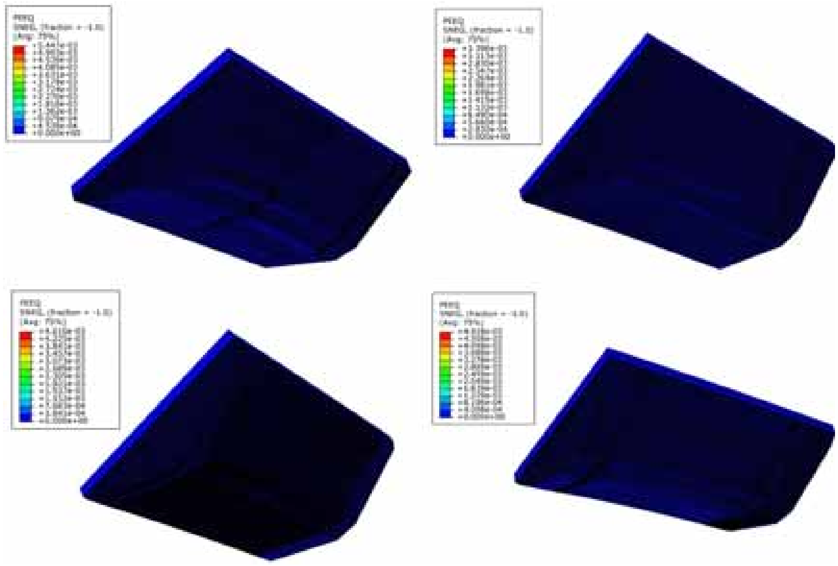

Figure 6. Equivalent plastic strain distribution (PEEQ) for 4 different cases at 10 ms after detonation

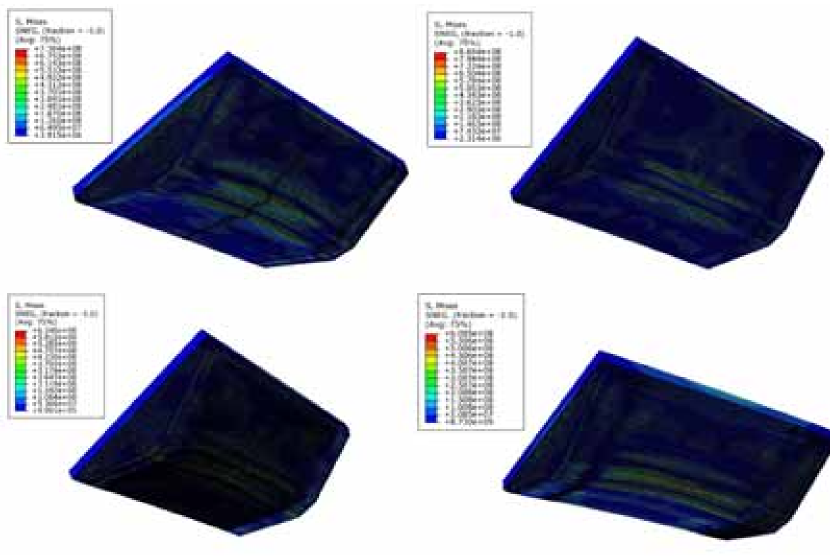

Figure 7. Equivalent of von Mises stress distribution in loaded structure for 4 different cases at 10 ms after detonation

Concluding remarks

By comparing the obtained results, it is concluded that the most favorable results are obtained for the case of V-hull geometry when α = 155° and β = 120°. Fig.8 shows the equivalent plastic deformation (PEEQ) for 5 different moments after detonation. Fig.9 shows the distribution of von Misses stress for 5 different moments after detonation, for the most favorable case. The obtained results refer to a specific example, but the metodology can be applied to other examples with different mass and geometry of the vehicle, as well as different characteristics and position of explosives.

The main objective of this paper is to point out a possible solution for mitigating the effects of mine explosion on a combat armored vehicle. In the introduction, a brief overview of the impact of anti-tank mines on a vehicle is presented.

The following section describes the problem that is being analyzed and shows the relations used for the CONWEP model. The properties of the explosive used for the analysis are given. Also, the model for calculating overpressure is shown, and typical values are presented.

The next section presents the vehicle FEM and V-hull geometry models that are considered in terms of the impact on equivalent plastic strain as well as the von Mises stress distribution. By comparing the obtained results, it is concluded that the most favorable results are obtained for the case of V-hull geometry when design geometry is defined by the angles $\alpha = 155°$ and $\beta = 120°$.

The analysis shows that in the case of any analyzed geometry and explosion of 8 kg of Composition B, there will be no fracture of the V-shaped hull, and that the most favorable result is obtained in the case when the angles $\alpha = 155°$ and $\beta = 120°$.

This important conclusion should be tested with an improved numerical model, and finally by an experimental approach. Significant model enhancements are also possible in terms of material behavior, explosion simulation, and fluid-structure interaction (FSI).

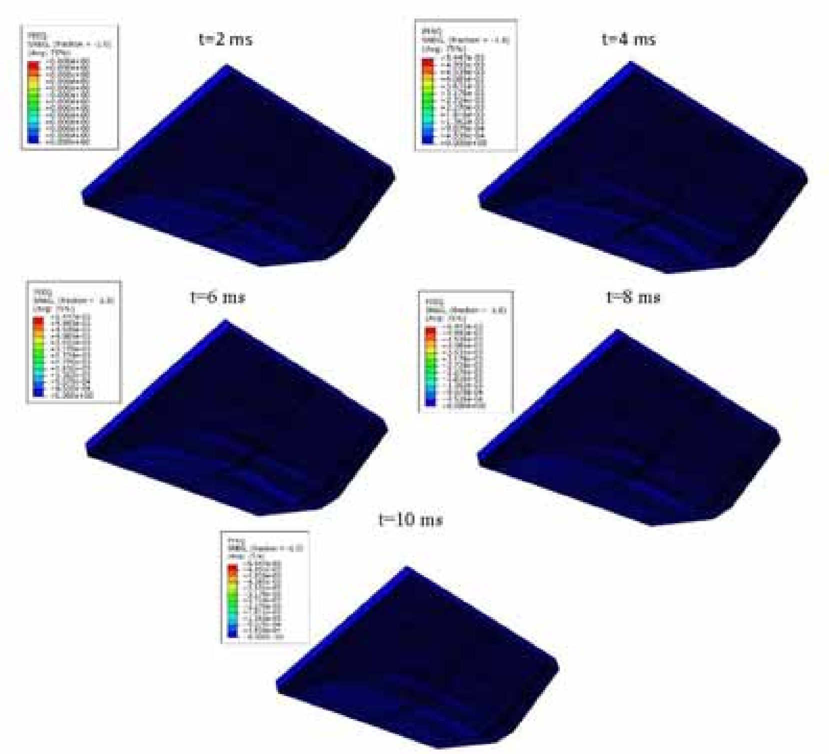

Figure 8. Evolution of equivalent plastic deformation (PEEQ) for 5 different moments after detonation for the case when α=155° and β=120

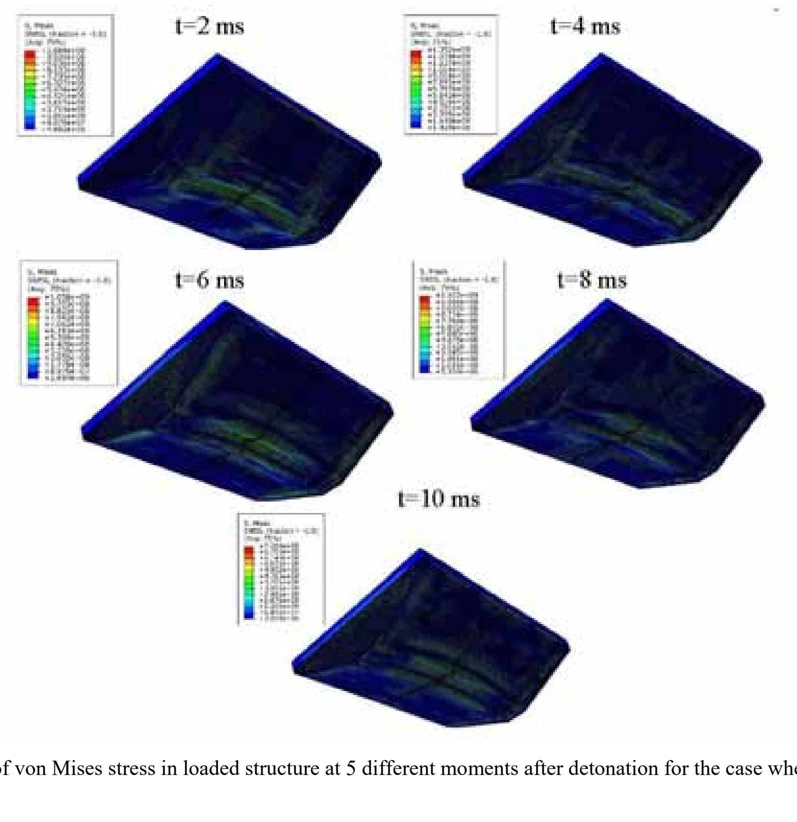

Figure 9. Evolution of von Mises stress in loaded structure at 5 different moments after detonation for the case when α=155° and β=120°

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Numerička analiza uticaja eksplozije na oklopno vozilo za različite geometrije V-trupa

Osnovni cilj ovog istraživanja je izrada numeričkog modela oštećenja vozila pod dejstvom eksplozije mine, kao i pronalaženje najpovoljnijeg slučaja geometrije V-trupa i ukazivanje na moguće rešenje za ublažavanje efekata eksplozije mina na oklopno borbeno vozilo. U obzir je uzeto sedam različitih geometrija V-trupa i izvršena je analiza oštećenja strukture za svih sedam mogućnosti. Takođe, analizirana je i promena mase za različite geometrije.

Efekat eksplozije mina na ciljnu strukturu analiziran je korišćenjem funkcije natpritiska prema empirijskom modelu CONWEP, korišćenjem programa Abaqus/Explicit. Analiziran je primer eksplozije 8 kg eksplozivne materije Kompozicija B koja deluje na vozilo ukupne mase 8000 kg. Vozilo se sastoji od dva glavna dela – kabine mase 6 t i V-trupa mase 2 t. Trup u obliku slova V je u svim prikazanim primerima sačinjen od ploča debljine 10 mm izrađenih od čelika Hardox 400. Položaj eksplozivnog punjenja je za sve primere geometrije isti i nalazi se 0.6 m ispod centra vozila.

Nakon analize dobijenih rezultata utvrđena je najpovoljnija geometrija V-trupa i ukazano je na mogućnosti daljeg unapređenja numeričkog modela.

Ključne reči: **protivoklopne mine, IED, eksplozija, rušeće dejstvo, oklopno vozilo, V-trup.**