



## Analysis of vehicle bottom structures in terms of blast protection using LS-DYNA

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**Abstract.** This paper is about the current military situation in the World, which is specific with asymmetric warfare. In this specific warfare, improvised explosive devices situated under or near a road are often used. The paper describes formation and spread of a shock wave after blast of an explosion. It specifies negative effects of the blast of an explosive device directly situated under a vehicle, vulnerabilities for the occupants or the vehicle structure. The main goal of this paper was aimed at the numerical simulations of different types of vehicles bottoms. The Simulations are made by a finite element method in program called LS-DYNA, based on the conditions from STANAG 4569 and AEP-55 Volume II. In the end to sum the paper up there are some specific comparisons of the solutions for the safety of the occupants, which include the solutions of the vehicle bottom.

**Keywords:** mechanical engineering, vehicle bottom, finite element method, blast protection

### 1. Introduction

A command of ground forces during current conflicts places great demands on mobility of forces with frequent usage of vehicles. Nowadays, the war takes place in an asymmetrical warfare, where insurgents use IEDs to eliminate the occupants of vehicles. This weapon is very dangerous and effective. It also has to create the atmosphere of terror and fear. In this case it is important, that the vehicles used in international operations should provide a high level of ballistic protection, but also anti-mine blast protection. In the figure bellow there is an example of IED that has been recovered in Iraq.

The protection against IEDs is a new sphere of international research. To achieve good results, both experimental study and modelling of potential situations by



Fig. 1 Anti-Tank mine encased in concrete and command detonated via remote control [2]



Fig. 2. Destroyed vehicle after contact with IED [1]

different software are necessary. Numerical simulations provide useful information about types, sizes of the loads and ways of a vehicle structure deformation. They are effective in application to design a new protection system.

## 2. Theory of the blast

A shock wave is caused by large dynamic explosive transformation of detonating agent (especially solid or liquid phase) to great volume of gases with high temperature. At the moment, when the gases and the steams are released, they compress surrounding air. Volume of explosive products is enfolded by a layer of the compressed air. External limit of this layer is simultaneously the shock wave front. In the first stage, the velocity of the explosive products is approximately equal to the velocity of the shock wave, but later the velocity of the explosive products declines rapidly whereas velocity of the shock wave declines very slowly. Therefore, the pressure of the explosive products has destructive effects only in short distance [6].

In larger distance from a charge, the destructive effect is caused by a shock wave. The shock wave spreads similarly as physical environment. When it impacts a rigid obstacle (for example armour of a vehicle), the pressure is rising. We can compare this action with the pressure of wind impact, of course with less power. In this case, the shock wave acts on the obstacle with increased pressure and dynamic forces. Stopping of a fast moving physical environment causes this effect as a consequence [6].

The shock wave has the most destructive effect on vehicles. Less destructive effect on vehicles have: high temperature, pressure of gases and steams, and flying fragments. Movement of the shock wave gives the elements large kinetic energy and that creates shrapnel effect.

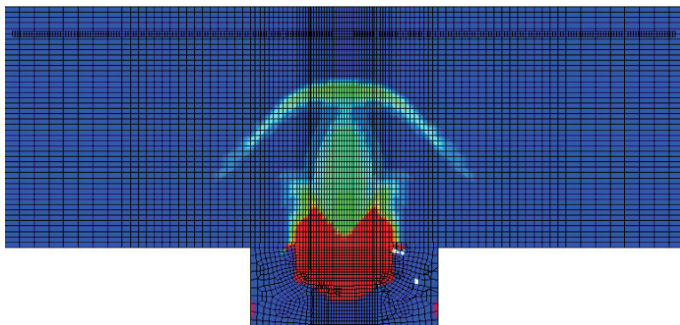


Fig. 3. Pressure analysis of a moving shock wave

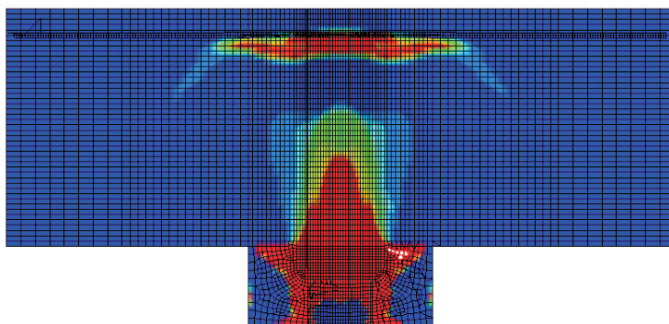


Fig. 4. Pressure analysis of a shock wave, which impacts an armor plate

### 3. Vehicle bottom structures

Vehicle protection against landmines in terms of its bottom structure in general includes: a shock wave and fragments deflection, explosion energy absorption, penetration of infiltration of a pressure, toxic substances and substances with a high temperature.

The bottom structure of most military vehicles is made by only one armour layer. Mentioned structure is called „single bottom”.

The structure of „double bottom” consists of two parallel armour layers. The space between layers can be filled with air, ceramic or other materials, which are able to absorb a part of explosion energy. Properties of „double bottom” partially depend on a distance between the armour layers.

The angle of impact of a shock wave is very important to design a bottom structure, therefore the bottom structure in the shape of „V” (so called „V-shape bottom”) has been shown as especially effective one. The concept of this protection originated in the South Africa. It effectively deflects much of the shock wave. The problem is to joint this type of the bottom with a classic request for low vehicle profile and good mobility.

In this paper, three types of vehicle bottoms: „single bottom”, „double bottom”, and „V-shape bottom” are analysed and compared. Figure 5 shows schematic drawing of analyzed bottom types, its primary parameters and distances from explosive charges.

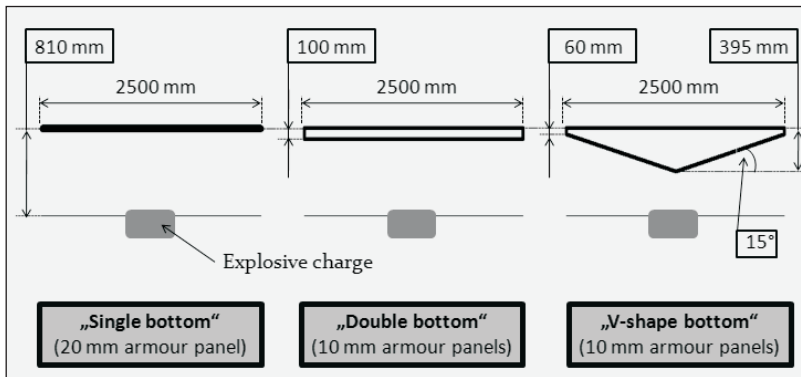


Fig. 5. Schematic drawing of comparison between bottom models

While thickness of the armour plates of „double bottom“ and the „V-shape bottom” is 10 mm, „single bottom” is made from the armour plate with a thickness of 20 mm. It means that each bottom type has the same total thickness of the armour, which separates a crew from a mine explosion. The only difference is in the way of material configuration into layers.

The selected bottom types are modelled and analysed using simulations conducted in the program called LS-DYNA. It is the explicit and implicit finite element software designated to analyze nonlinear dynamic response of structures. This program offers a lot of the possibilities of analysis of explosion problems. LS-DYNA accurately predicts vehicle’s behaviour as a reaction to a mine blast and the effects of the mine blast upon the vehicle’s occupants.

#### 4. Conditions of simulations

The numerical simulations’ models are based on the conditions, which are used to define the protection levels for occupants of logistic and light armoured vehicles. These conditions are written in Slovak defence standard SOŠ 4569 AEP-55, which is based on STANAG 4569 and AEP-55 Volume II.

STANAG 4569 describes four levels of threat that a crew can be exposed to. These levels are shown in Table 1. There are also types and weights of munitions and places, where the munitions are situated.

TABLE 1  
Protection levels for occupants of logistic and light armoured vehicles against grenades and landmines [8]

Level	Grenade and mine blast threat		
4	4b	Mine Explosion under centre.	10 kg (explosive mass) Blast AT Mine
	4a	Mine Explosion pressure activated under any wheel or track location.	
3	3b	Mine Explosion under centre.	8 kg (explosive mass) Blast AT Mine
	3a	Mine Explosion pressure activated under any wheel or track location.	
2	2b	Mine Explosion under centre.	6 kg (explosive mass) Blast AT Mine
	2a	Mine Explosion pressure activated under any wheel or track location.	
1	Hand grenades, unexploded artillery fragmenting submunitions, and other small anti personnel explosive devices detonated under the vehicle.		

The numerical simulations, which are analysed in this paper, are modelled based on 3b level. It means that the threat is caused by an anti vehicle landmine (commonly known as an anti tank mine) with explosive power of 8 kg TNT. During the tests, a real landmine is substituted by a landmine simulator, which consists of an explosive charge and a steel confinement (steel pit). The explosive charge should constitute plastic explosive PETN-B. This explosive contains 86% of PETN and 14% of wax. Weight of the explosive made from PETN-B is calculated on the formula [7]:

$$m_{\text{TNT}} = 1.19 \cdot m_{\text{PETN-B}} [\text{kg}],$$

where:

$$m_{\text{TNT}} - \text{TNT mass [kg]},$$

$$m_{\text{PETN-B}} - \text{PETN-B mass [kg]}.$$

Explosive charge weight for level 3 calculated by the above formula is 6.72 kg. The explosive charge has short cylindrical shape with height to diameter ratio of approximately 0.33. The diameter of cylinder is given and according to SOŠ 4569 AEP-55 it has parameter  $X = 245$  mm. An initiation point lies on vertical axis of the explosive charge and the distance between the point and a lower side is 16.7 mm.

Because of the absence of information about the plastic explosive PENT-B, this explosive is replaced by plastic explosive C4 in the numerical simulations. Properties of both plastic explosives are very similar.

In the model there should be an air gap between the charge and the confinement.

Minimum outer parameters, which are recommended for the steel pit, are: length  $\times$  width  $\times$  height = 700  $\times$  700  $\times$  300 mm. [7] Geometry specification of the charge and the steel pit is depicted in Figure 6. It is the basis to create the landmine simulator that is used in analysis.

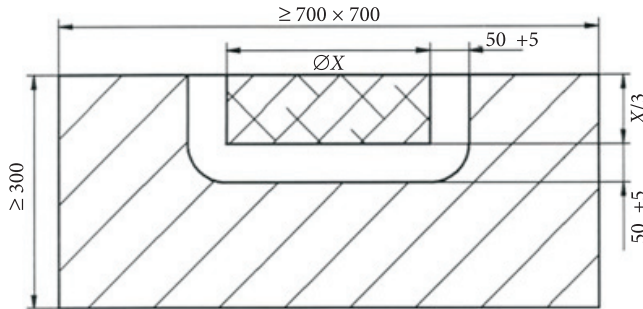


Fig. 6. Geometry specification of the charge and the confinement [7]

### 5. Creating of the model

Each analysed model consists of four parts: a vehicle bottom, an explosive charge, a steel pit and air. Figure 7 illustrates configuration of these parts. Every part used in the simulations is created and meshed in LS-PrePost. They are modelled with eight node solid elements. The vehicle bottoms and the steel pit are using constant stress solid elements, but the air as well as the explosive charge is modelled by 1 point ALE multi-material elements.

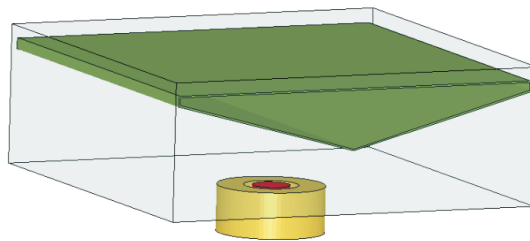


Fig. 7. Model of an explosive charge in a confinement with surrounding volume of air and vehicle bottom

#### 5.1. Modelling of a vehicle bottom

Vehicle bottoms contain Lagrange elements. Length of each element edges is approximately 10 mm. The material of bottom models is common rolled homogeneous armour (RHA), which properties are defined by material model

003-MAT\_PLASTIC\_KINEMATIC. The material model that was mentioned includes plasticity and kinematic hardening. Table 2 shows material parameters of rolled homogeneous armour.

Material parameters of RHA [5]

TABLE 2

Parameter (MAT_PLASTIC_KINEMATIC)	Value in consistent units [mm, kg, ms, kN]
Mass density	$7.85 \times 10^{-6}$
Young's modulus	197.5
Poisson's ratio	0.33
Yield stress	1.32
Tangent modulus	1.81
Hardening parameter	1.0
Failure strain	1.0

The width of the bottom is 2500 mm. This value represents approximate width of a real bottom. Length is adjusted to speed up calculation to the value 2500 mm. The results are not affected by shortening the length, because maximum values of monitored parameters are evaluated. Primary blast simulations showed that the highest values occur around the centre of plate (directly above the explosive charge) and towards the edges of the plate the values considerably decrease.

The nodes on edges of bottoms have removed all degrees of freedom, so the bottoms are anchored. Disadvantage of the bottoms anchoring is the distortion of results against real situation, but this way of anchoring is suitable for making a comparison between various bottom types.

## 5.2. Modelling of a mine simulator

A mine simulator consists of an explosive charge, which is placed in a steel pit. These two parts are divided by an air gap.

The steel pit is created with Lagrange elements as well as the vehicle bottoms. Their material properties are defined by the material model 003-MAT\_PLASTIC\_KINEMATIC. Table 3 contains the material parameters of steel that is used in the mine simulator confinement.

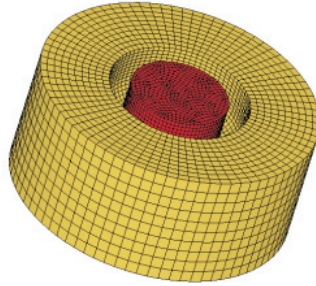


Fig. 8. Finite element model of an explosive charge placed in a steel pit

TABLE 3

Material parameters of steel pit [3]

Parameter (MAT_PLASTIC_KINEMATIC)	Value in consistent units [mm, kg, ms, kN]
Mass density	$7.86 \times 10^{-6}$
Young's modulus	206
Poisson's ratio	0.3
Yield stress	1.0

The explosive charge is modelled with Euler elements. The material properties of the plastic explosive C4 are defined by the material model 008-HIGH\_EXPLOSIVE\_BURN and Jones Wilkins Lee equation of state (\*EOS\_JWL). Table 4 contains material parameters of the plastic explosion C4.

TABLE 4

Material parameters of the plastic explosion C4 [3]

Parameter (HIGH_EXPLOSIVE_BURN)	Value in consistent units [mm, kg, ms, kN]
Mass density	$1.60 \times 10^{-6}$
Detonation velocity	8040
Chapman-Jouget pressure	28.1
Beta burn flag, BETA	2
Bulk modulus	6.8
Shear modulus	3.0
Yield stress	0.0011

### 5.3. Modelling of air

Air is represented by a large block, which is created with Euler elements. A gap between an explosive charge and a steel pit is also filled by the air. Block proportions depend on size of a bottom model and distance between the bottom model and

a mine simulator. It has to account for the way of shock wave spread. If block would not be large enough, results of simulations will be distorted.

The proportions of elements close to the central axis are approximately  $9.5 \text{ mm} \times 9.5 \text{ mm} \times 20 \text{ mm}$ . The elements size is increasing towards the block sides.

The properties of air are defined by the material model 009-NULL and LINEAR POLYNOMIAL equation of state. Table 5 contains material parameters of air.

TABLE 5

The material parameters of air [3]

Parameter (NULL)	Value in consistent units [mm, kg, ms, kN]
Mass density	$1.2047 \times 10^{-9}$
Viscosity coefficient	$1.95 \times 10^{-11}$

Lagrange elements are connected to the Euler elements of air with the \*CONSTRAINED\_LAGRANGE\_IN\_SOLID card.

Interaction between the explosive charge and the air is provided by the connection of parts meshes in the nodes on boundary.

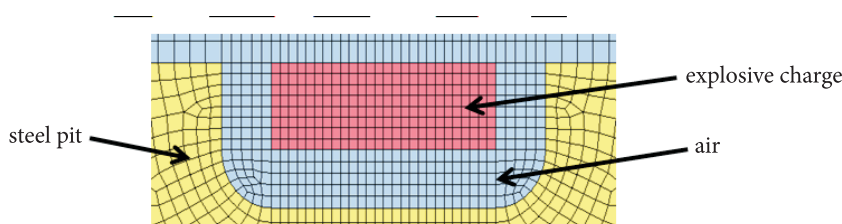


Fig. 9. Connection of parts meshes in nodes

## 6. Results

On analysed bottom types, the chosen parameters were monitored, which reflect a capability of various bottom structures to protect a crew. The values of these parameters are measured on armour plate surface, which represent crew compartment floor.

### 6.1. Deformation

Material displacements give information about size of deformation, which can be elastic or plastic. The largest deformation was detected on the floor of „single bottom“. The maximum value of displacement is 51 mm.

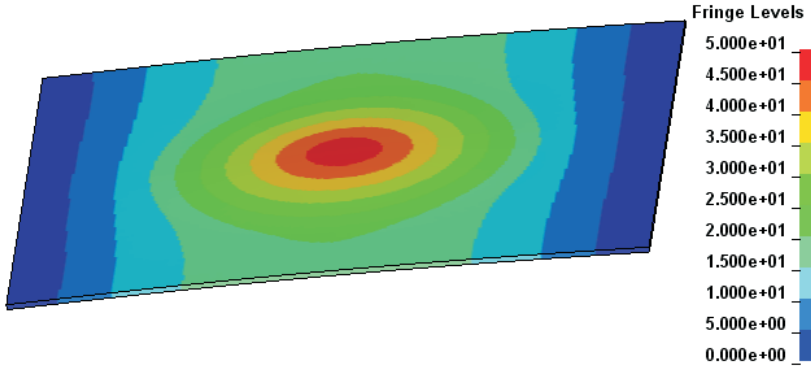


Fig. 10. Displacement on „single bottom”

Maximum displacement on the floor of „double bottom” has the value of 25 mm. In Figure 11, it is possible to see greatly less deformations than on the floor of „single bottom”.

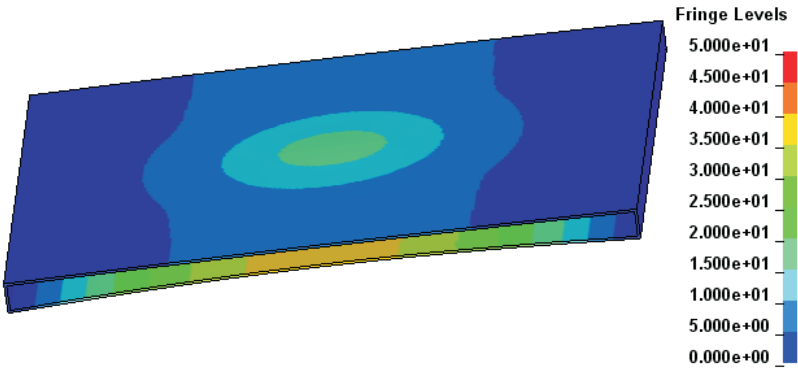


Fig. 11. Displacement on „double bottom”

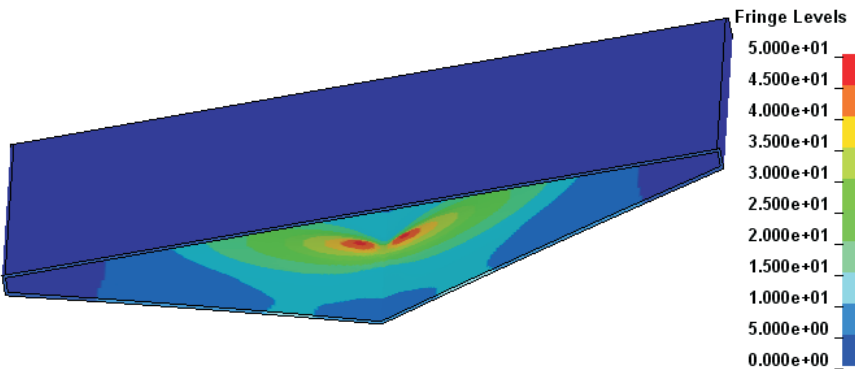


Fig. 12. Displacement on „V-shape bottom”

Maximum material displacement on the floor of „V-shape bottom” is only 3 mm. The deformations are very low in comparison with other two bottom types.

## 6.2. Acceleration and velocity

When a shock wave impacts a vehicle bottom, mechanical vibrations are developed in a vehicle structure. The vibrations spread in the structure and consequently are transferred to feet of occupants or to pelvis and thoraco-lumbar spine through a seat.

The values of local acceleration and velocity are measured on armour plate surface, which represent a crew compartment floor. Specifically these are the values in a vertical direction. The vertical direction is considered as the main direction of the spread of the vibrations. Mentioned vibrations cause the most frequent and the most serious injuries.

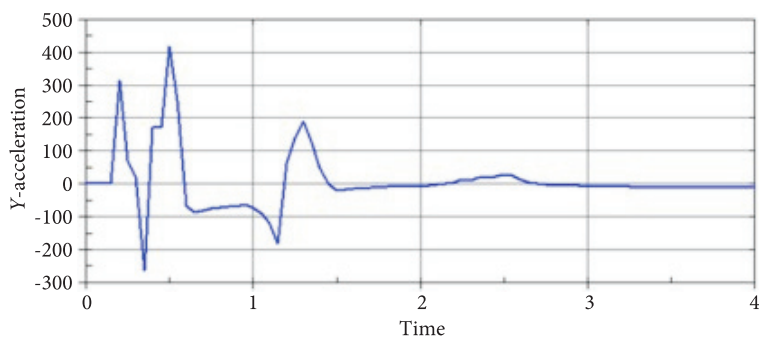


Fig. 13. Curve of acceleration on „single bottom”

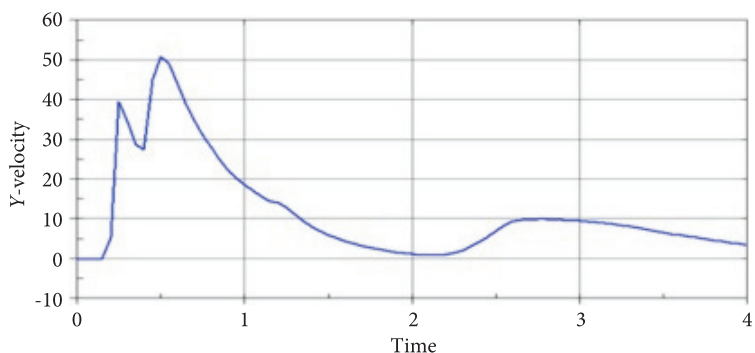


Fig. 14. Curve of velocity on „single bottom”

The highest acceleration as well as velocity was measured on the floor of „single bottom”. The maximum measured acceleration is  $410 \text{ mm.ms}^{-2}$  and the value of

maximum velocity is  $51.1 \text{ m}\cdot\text{s}^{-1}$ . After being hit by the shock wave, the armour plate was wobbled.

In case of „double bottom”, the accelerations and the velocities are lower than these parameters measured on the floor of „single bottom”. Maximum acceleration is reduced by 89% and maximum velocity by 84.5%.

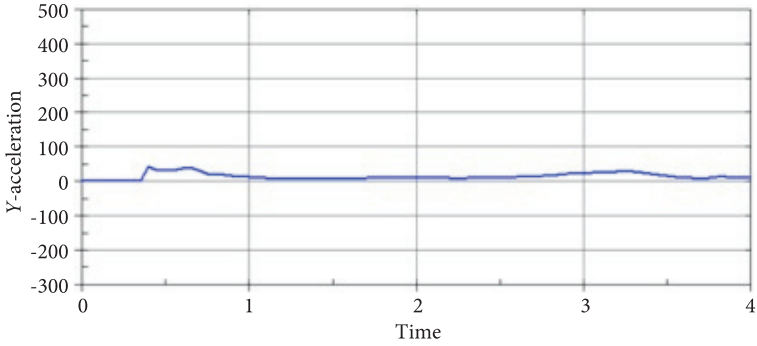


Fig. 15. Curve of acceleration on „double bottom”

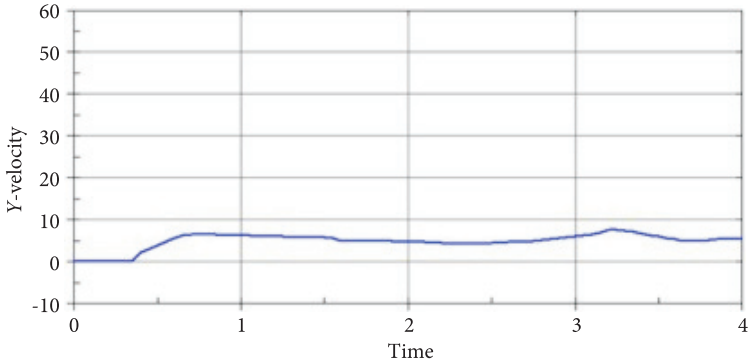


Fig. 16. Curve of velocity on „double bottom”

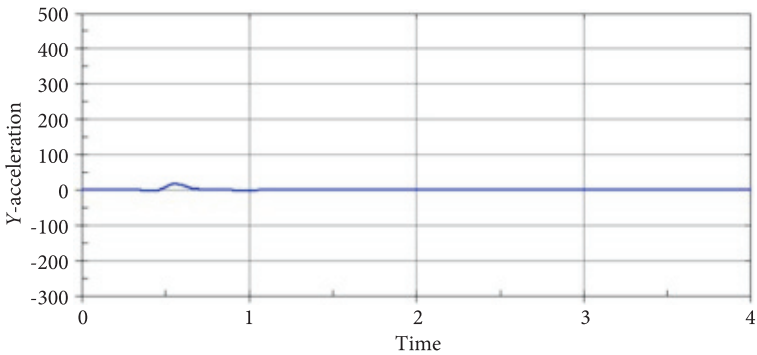


Fig. 17. Curve of acceleration on „V-shape bottom”

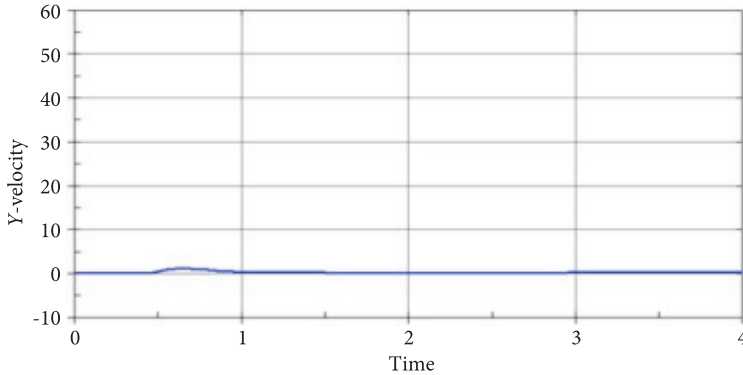


Fig. 18. Curve of velocity on „V-shape bottom”

The lowest values were measured on the floor of „V-shape bottom”. Compared to „single bottom”, the maximum acceleration is reduced by 95% and maximum velocity by 97.6%.

### 6.3. Fluid flow

An explosion causes fluids to flow. In this case: these are gasses and steam, which are the detonation products. When a solid is situated in the flow, it causes drag. More energy from the fluid is transferred to the solid, which offers greater drag than to the solid that offers lower drag. The transferred energy can cause the solid to move, its deformation, heating or this energy can be transferred further. In case of vehicle’s bottom, this energy is transferred to the occupants. Figures 19 and 20 illustrate the behaviour of the fluid in a contact with a flat bottom and a „V-shaped bottom”.

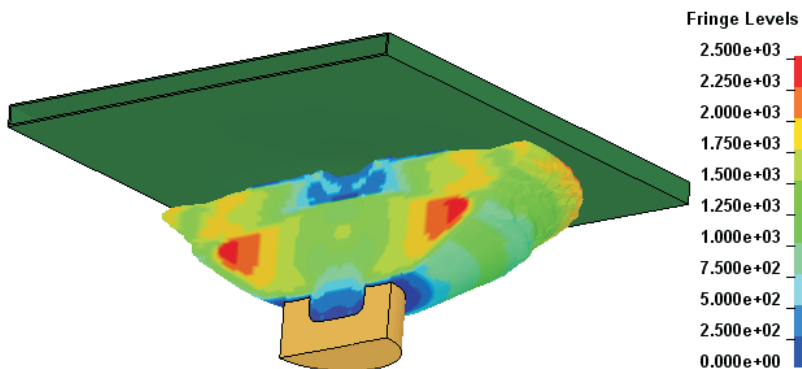


Fig. 19. Behavior of the fluid in a contact with a flat bottom

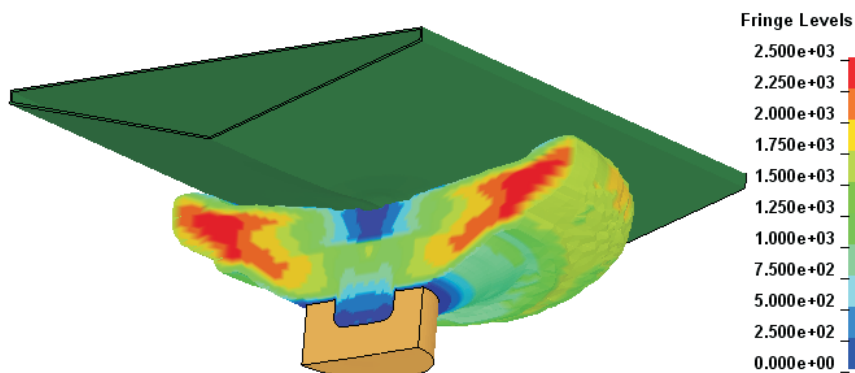


Fig. 20. Behavior of the fluid in a contact with a „V-shaped bottom”

Various colours give an overview about speed of fluid flow. Both scales illustrate velocity in  $\text{m}\cdot\text{s}^{-1}$ . The flat bottom offers great drag for the fluids flow. On the other hand, the fluid is flowing around the shaped bottom with high speed. It means that a great quantum of fluid energy is taken away from the bottom.

## 7. Conclusion

Deformation of a crew compartment floor causes injuries of a lower leg and thoraco-lumbar spine. As well as that, local vibration with high acceleration and velocity causes same injuries and death of occupants.

Based on the results it is possible to say, that the highest load will act on the occupants of the „single bottom vehicle”. In this case, local deformation of the crew compartment floor is very large. The maximum acceleration is  $410\,000\ \text{m}\cdot\text{s}^{-2}$  and the maximum velocity is  $51.1\ \text{m}\cdot\text{s}^{-1}$ . The „double bottom” model gives lower maximum floor deformation than a „single bottom” model. Acceleration is reduced by 89% and velocity by 84.5%. The best protection of occupants judged by the monitored parameters is provided by „V-shape bottom”. The floor deformation is minimal. Maximum acceleration is reduced by 95% and velocity by 97.6%. Mass of V-shape bottom model is only by 45.6 kg greater than double bottom model and by 84.8 kg greater than single bottom model.

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**Analiza struktur podwozi pojazdów pod względem zabezpieczenia przed skutkami wybuchu przy pomocy programu LS-DYNA**

**Streszczenie.** W pracy przedstawiono obecną sytuację militarną na świecie dotyczącą asymetrycznych działań wojennych. W tych działaniach często stosowane są improwizowane urządzenia wybuchowe sytuowane pod drogą lub w jej pobliżu. W artykule opisano tworzenie się i rozprzestrzenianie fali wybuchowej powstałej po wybuchu. Określono negatywne efekty wybuchu usytuowanego pod pojazdem, możliwość zranienia ludzi lub uszkodzenia struktury pojazdu. Celem pracy była numeryczna symulacja różnych typów podwozi pojazdów. Symulację wykonano przy użyciu metody elementów skończonych w programie LS-DYNA, bazując na warunkach STANAG 4569 i AEP-55 Volume II. Porównano różne rozwiązania zapewniające bezpieczeństwo żołnierzy, w tym dotyczące podwozia pojazdu.

**Słowa kluczowe:** budowa maszyn, podwozie pojazdu, metoda elementów skończonych, zabezpieczenie przed wybuchem

