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METHOD OF EVALUATING THE STIFFNESS OF A VEHICLE WITH RESPECT TO THE RISK OF EXPLOSION

METODA OCENY SZTYWNOŚCI POJAZDU POD KĄTEM ZAGROŻENIA EKSPLOZJĄ*

This article describes a new method of evaluating the stiffness of structure of a vehicle with respect to its resistance to mine explosion. This method allows for the assessment of the structure of a wide range of tracked and wheeled vehicles in the early stage of the construction process, considering such factors as mass and stiffness of the hull and ground clearance. By applying this method it is possible to assess the risk of lower limb injury for every vehicle occupant, caused by local deformation of the vehicle.

***Keywords**: military vehicles, risk of explosion, IED, stiffness of structure.*

W artykule przedstawiono nową metodę oceny sztywności struktury pojazdu pod kątem odporności na eksplozję miny. Metoda ta umożliwia ocenę konstrukcji szerokiej gamy pojazdów gąsienicowych i kołowych na wczesnym etapie procesu konstruowania pojazdu uwzględniając takie czynniki jak masa i sztywność kadłuba oraz prześwit pod pojazdem. Wynikiem zastosowania metody jest ocena zagrożenia kończyn dolnych wskutek lokalnej deformacji pojazdu dla każdego członka załogi.

***Słowa kluczowe**: pojazdy wojskowe, zagrożenie eksplozją, IED, sztywność struktury.*

1. Introduction

The use of military vehicles in areas where landmine or Improvised Explosive Devices (IEDs) are used is highly hazardous to military vehicle occupants. The task of evaluating the resistance of such vehicles to explosions is complex and is often possible only after the vehicle has been constructed [2]. This problem is particularly important in relation to military vehicles; however, in the era of terrorist threat, there is often a need to analyze the safety of civilian vehicles in this respect.

Occupant safety should be evaluated on many aspects related to different types of threats [11]. The most dangerous and difficult to combat are threats related to injury of lower limbs [8] and spine [3, 7].

$$I = \int_0^t p\, dt \quad (1)$$

where t is the time of the pressure impulse and p – the instantaneous average value of pressure of gases acting on the loaded surface.

The energy transmitted to the structure can be regarded as two energy streams. One of them is dissipated through permanent deformation of the structure; the second is transmitted to the structure as kinetic energy. The kinetic energy may, in turn, be divided into the energy of elastic deformations, which are excited by wave impact in the form of vibrations consistently with its natural frequencies, and into global structure motion. The latter is understood as the change in the velocity vector of the vehicle's center of gravity in relation to the environment, resulting from the explosion.

The diagram in figure 2 depicts the phases of blast energy transmission. The high-frequency vibrations excited in the first stage by the wave impact propagate at the speed of sound in the entire structure, which can lead to temporary damages of less resistant elements. Due to the high velocity of the elastic wave, this stage is very short, in the range of several milliseconds.

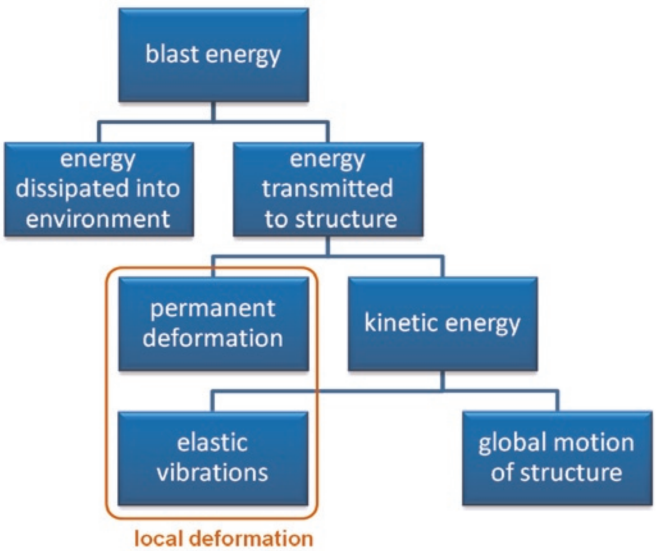

Fig. 1. Diagram depicting the process of transmitting blast energy to the vehicle structure

The diagram in figure 2 depicts the phases of blast energy transmission. The high-frequency vibrations excited in the first stage by the wave impact propagate at the speed of sound in the entire structure, which can lead to temporary damages of less resistant elements. Due to the high velocity of the elastic wave, this stage is very short, in the range of several milliseconds.

In the second stage, local deformation occurs in the lower part of the vehicle, which includes permanent deformations and elastic vibrations, whose proportions depend on the strength of the structure. Permanent deformations dominate in vehicles of low structural strength, whereas elastic deformations may dominate in vehicles structurally resistant to explosion under the vehicle.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

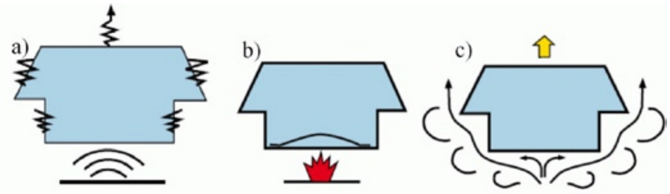

Fig. 2. Load to vehicle caused by landmine explosion: a) propagation of elastic waves, b) local deformation of structure, c) global vehicle motion [6]

In the third stage of explosion the whole structure accelerates. This stage is longer than the second stage due to significantly larger inertia of the whole vehicle than the inertia of the vehicle floorplate. It should be noted that the global motion of the structure caused by the explosion can overlap the motion of the structure prior to the explosion, e.g. the advance velocity of a vehicle which is moving when the landmine explodes. If the advance velocity is significant, the vertical height of the vehicle leaping over an exploding explosive charge may be so high that the pressure impulse distributes over a larger area of the floorplate. In terms of safety, such a phenomenon is advantageous as it decreases the concentration of energy and local deformation. This effect intensifies with the increase in burial depth of the explosive charge, which lengthens the time of energy transmission. In the case of surface detonation, or detonation of shallow buried explosives, the transmission of energy to the hull is too short for the velocity of the vehicle to impact the blast load to the structure surface.

The threat to lower limbs is related to the second stage, i.e. the local deformation of the structure. The load to lower limbs is a result of the vertical motion of the floorplate, in which case the key parameters related to the threat of lower limb injury are the vertical velocity and maximum deflection. Figure 3 shows an example graph of the vertical velocity of the floorplate during explosion.

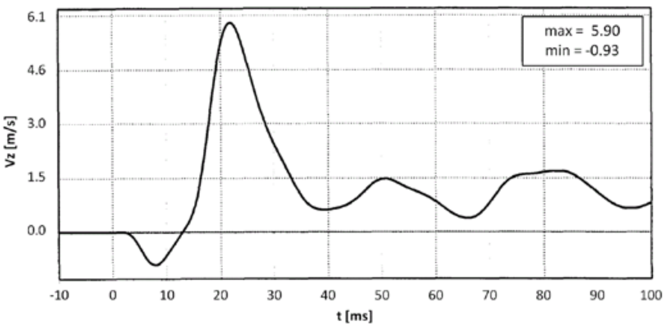

Fig. 3. Example graph of the vertical velocity of the floorplate during explosion. [1]

The figure shows a large increase in the floorplate velocity in the initial stage of loading, which is a result of the plastic and elastic deformation of the vehicle floor (second stage in figure 2). This is followed by a series of elastic vibrations of the floor near average velocity, which correspond to the global vertical velocity of the vehicle (third stage, figure 2).

The basic parameters which determine the deflection of the floorplate are the load mass, distance between the charge and the floor of the vehicle, mass of vehicle and the stiffness of vehicle structure. Whereas the mass of the vehicle has significant influence on the global motion of the vehicle (figure 2c), the stiffness in connection with the mass determines the degree of local deformation to the structure (figure 2b). The diagram in figure 4 shows the relation between mass, stiffness and threat of injury to lower limbs.

By using an additional deflectors under the vehicle it is possible to decrease the local deformation, but this also decreases the distance to the explosive charge. This is exceptionally disadvantageous in vehicles with low ground clearance.

	low mass	high mass
low stiffness	high global velocity high local deformations (HMMWV)	low global velocity high local deformations (heavy tracked vehicle)
high stiffness	high global velocity low local deformations (armored wheeled vehicle)	low global velocity low local deformations (MRAP)

decrease in threat of injury

Fig. 4. Relation between mass, stiffness of vehicle and threat of injury to lower limbs

The assessment of the level of threat of injury to lower limbs is possible by performing costly tests on firing grounds using anthropomorphic manikins [12]. The biomechanical criterion in such a case is the maximum axial force in the lower leg Similar tests can be performed by simulation, however such calculations are complex and are not suitable for evaluating the vehicle in the design stage [4]. Full simulation of the threat of injury requires the modeling of the detonation process of an explosive charge buried in the ground, the propagation of the shock wave with the products of detonation and soil ejected into the air. Figure 5 shows an example simulation of a detonation of a 10 kg TNT charge buried in the ground at a depth of 100 mm using the MM-ALE method.

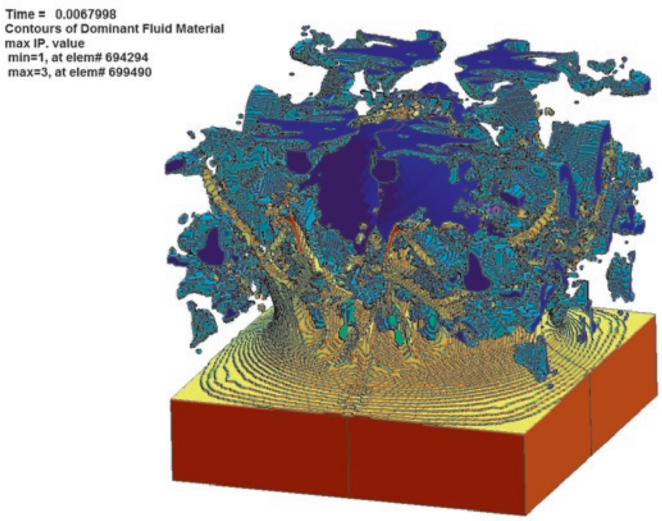

Fig. 5. Simulation of an explosion of an explosive buried in the ground using the MM-ALE method

In the existing literature there is no method for assessing the local deformation in a vehicle as a result of landmine of IED explosion under the vehicle, without performing a full simulation of the explosion. Such a method, which takes into consideration the key safety-related parameters of the whole system, including the detonating explosive and the structure of the vehicle, would allow for a preliminary analysis of the vehicle with respect to such events.

3. Method

The local deformation of the vehicle floorplate is determined by the mass of the vehicle and the stiffness of the floorplate in vertical direction. The maximum force acting statically on the vehicle floor at a given point is limited to the force which lifts one or two wheels off the ground. Therefore, maximum force may be exerted by pressing on the floor directly under the vehicle's center of gravity, which is illustrated in the diagram in figure 6. This point is also considered the most dangerous point of detonation under a vehicle[12].

The surface subject to the action of products of detonation and the soil ejected by the explosion is frequently located at some distance from the feet of the passenger. This could be due to a double floor, elastic mats which separate the feet from the vehicle floor or additional shields under the floor of the vehicle.

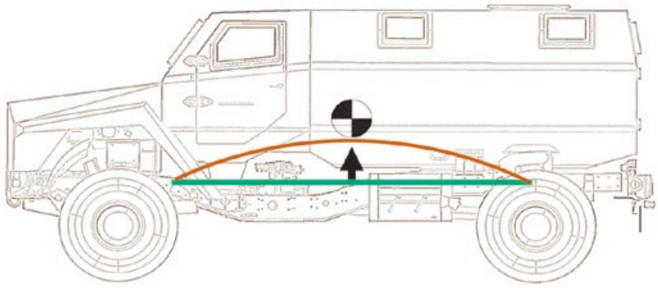

Fig. 6. Local deformation to the floorplate of the vehicle caused by explosion

As the direction of wave incidence on the surface deviates from the perpendicular direction, the pressure and pressure impulse decrease. The relation between the impulse of incident pressure I_s, impulse of reflected pressure I_r, and the angle of wave incidence θ can be defined as the formula described in [9]:

$$I_{r\theta} = I_r \cos^2(\theta) + I_s(1+\cos(\theta) - 2\cos^2(\theta)) \quad (2)$$

The impulse of reflected pressure I_r exerted on the vehicle floor can be defined using the equation described in [5], which is based on experimental surface tests of detonations of explosive charges. The value of the impulse is determined by the scaled distance Z expressed by the Hopkinson-Cranz formula:

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

which relates the distance from the center of the explosive device R [m] with the mass of the explosive W [kg]. The relationship between the value of the impulse of incident and reflected pressure and the scaled distance may be expressed by the formula:

$$I_{s,r} = \exp(A + B\ln(Z) + C\ln(Z)^2 + D\ln(Z)^3 + E\ln(Z)^4)W^{1/3} \quad (4)$$

where Z is expressed in [m/kg$^{1/3}$], whereas I_s, I_r in [Pa s]. The values of parameters A, B, C, D and E for the impulse of incident pressure I_s are given in [10]. The values of reflected pressure I_r were calculated on the basis of the formula in [5]. The numerical values of parameters are presented in table 1.

*Table 1. Values of parameters describing the impulse of incident pressure **I_s** and reflected pressure **I_r** as a function of scaled distance **Z** [10]*

	A	*B*	*C*	*D*	*E*	Remarks
I_s	5.522	1.117	0.6	-0.292	-0.087	for *Z* in the range 0.2÷0.96
I_s	5.466	-0.308	-1.464	1.362	-0.432	for *Z* in the range 0.96÷23.8
I_r	6.775	-1.346	0.102	-0.0112	0	for *Z* in the range 0.2÷100

Let us define the measurement of threat of lower limb injury as parameter S, which is proportional to the ratio of vertical deflection Δh of the surface loaded with shock wave pressure and the initial distance h of that surface from the feet of the passenger. The proportionality factor is the pressure impulse of reflected wave $I_{r\theta}$, which includes the inclination of the surface loaded with pressure in relation to the direction of wave incidence.

$$S = I_{r\theta}\frac{\Delta h}{h} \quad (5)$$

This parameter enables the assessment of threat of injury resulting from local deformation of vehicle floor for different classes of vehicles without the necessity to perform full simulations of the explosion. It includes such factors as ground clearance, mass of the explosive charge, geometry and stiffness of the vehicle floor and the initial distance between the feet and the impact point of the shock wave.

An attempt to statically deflect the vehicle floorplate in selected points causes elastic or elastic and plastic deformation of the vehicle structure. In order to measure the static deflection Δh it is necessary to adopt a measurement base connected to the vehicle. Due to the fact that the threat of feet injury is related to the motion of the floor relative to the vehicle , the nearest points with high stiffness in vertical direction, e.g. the lower parts of the vehicle's side walls, should be used as the base for measuring the deflection. Figure 7 presents a diagram of the measurement method.

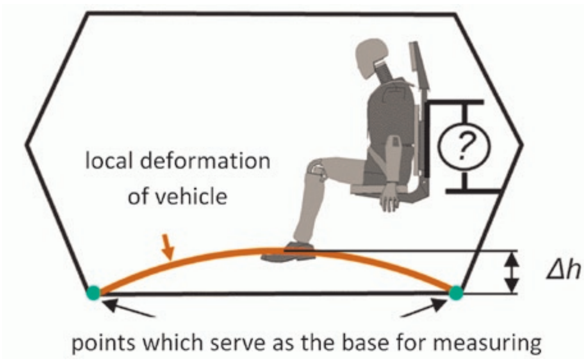

Fig. 7. Method of static measurement of the vehicle floor deflection

4. Results

The measurement of static deflection may be performed on a real vehicle or using a numerical model. Figure 8 presents an example measurement of the vertical stiffness of the floor of a Ford F250 vehicle. The static deflection in this case is 132 mm and the plastic deformation of the floorplate is significant.

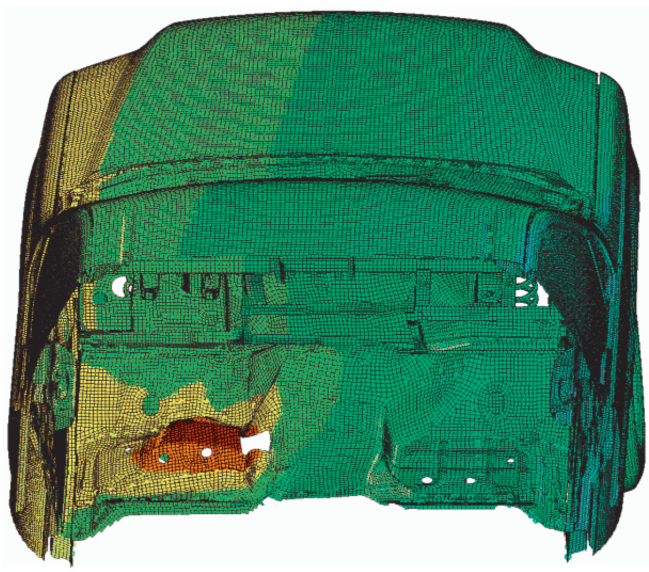

Fig. 8. Local static deformation of Ford F250 vehicle under the driver's feet, maximum static deflection (marked red) equal to 132 mm, large plastic deformations

Fig. 9. Analyzed vehicles

Table 2. Results of calculations for selected vehicles

vehicle type	pickup	tracked	wheeled	wheeled with deflector
M [Mg]	2.6	33	12.5	12.5
Δh [mm]	132	7	3	11
h_s [mm]	25	175	170	520
R [m]	0.65	0.57	1.17	0.82
W [kg]	0.5	6	10	10
Z [m/kg$^{1/3}$]	0.65	0.31	0.54	0.38
Θ [degrees]	0	0	17	17
***S* [Pa s]**	**4735**	**332**	**68**	**139**

The values of parameter *S* were calculated for several vehicles. Calculations were performed for a pickup-type vehicle (Ford F250), a tracked vehicle with a mass of 33 Mg and an armored wheeled vehicle with a mass of 12.5 Mg both with and without an additional deflector under the chassis frame. Figure 9 depicts the analyzed vehicles. The results of calculations and the basic parameters of vehicles are presented in table 2.

Calculations were performed for different masses of explosive charge. Results indicate that a detonation of a 0.5 kg TNT explosive charge under a pickup vehicle is much more dangerous than the detonation of 10 kg under a mine-resistant wheeled vehicle. A tracked vehicle, due to its large mass and flat floor with relatively low stiffness, is less resistant to detonation of 6 kg TNT than a significantly lighter wheeled vehicle with a much higher ground clearance. The value of parameter *S* for a wheeled vehicle with an additional V-shaped deflector is higher, because it receives a higher pressure impulse and the deflector has lower stiffness. These factors are so unfavorable that they are not compensated by the significantly larger distance between the loaded surface and the passenger's feet.

Figure 10 illustrates how the change in the ground clearance impacts the value of parameter *S*. One can observe that the impact of ground clearance is significant, especially in the range below 0.5 m characteristic of tracked vehicles.

Figure 11 illustrates how the distance between the feet and the impact point of the wave influence the value of parameter S. One can see that in the neighborhood of 170 mm the change in the distance *h* has significant influence on the threat of lower limb injury.

The presented method enables the evaluation of the threat caused by local deformation at different locations within the same vehicle, e.g. threat to individual passengers. To this end, the abovementioned method should be used to measure the local stiffness of floor under the

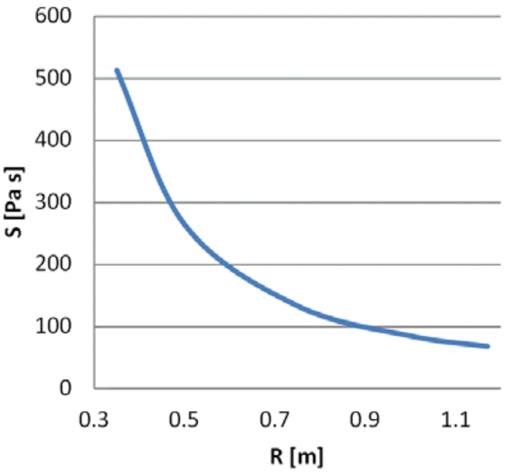

Fig. 10. Influence of ground clearance R of wheeled vehicle on the value of parameter S for a charge of 10 kg TNT and inclination angle of 17 degrees

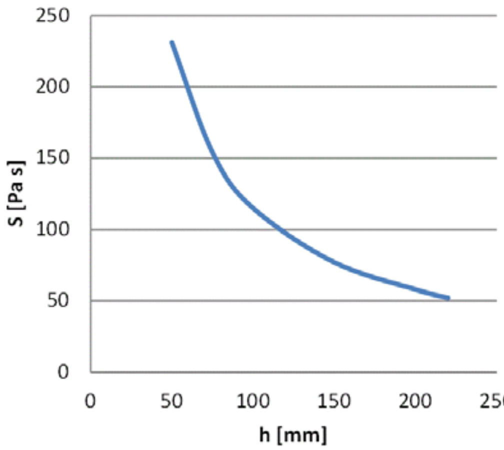

Fig. 11. The influence of the distance h between feet and the impact point of the wave on the value of parameter S for wheeled vehicle, charge of 10 kg TNT and inclination angle of 17 degrees

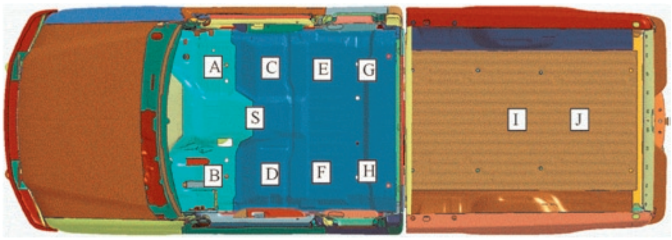

Fig. 12. Location of measurement points for local deflection of floor, Ford F250

*Table 3. Values of parameter **S** for detonation of 500 g TNT charge under Ford F250 vehicle, location of points in parentheses as depicted in figure 12*

left side [mm]	center [mm]	right side [mm]	description
4735 (B)	-	2475 (A)	feet in front
	4232 (S)		center of vehicle mass
2116 (D)	-	1721 (C)	seats in front
2690 (F)	-	3192 (E)	feet in back
1542 (H)	-	1470 (G)	seats in back
-	1112 (I)	-	bed
-	1040 (J)	-	bed

feet of individual occupants. Figure 12 presents an example of such analysis performed at different points for the Ford F250 vehicle. Table 3 presents the values of parameter *S* for detonation of 500 g of TNT, calculated on the basis of stiffness measurements in selected points.

Local deflection, and thus the level of threat of injury, is significantly different at different points of the vehicle. Despite the fact that the largest loading force occurs under the center of gravity, higher deflection values were recorded under the driver's feet, where there are gaps in the floorplate, which consequently reduce its stiffness. Figure 8 shows the distribution of deformations for this case.

This example illustrates the capability of the method of assessing the vehicle structure with respect to its resistance to local deformation resulting from an explosion under the vehicle. This assessment may apply not only to the vehicle as a whole, but also to selected areas of the structure.

5. Conclusion

The presented method enables the assessment of stiffness of a projected or existing structure with respect to its resistance to local deformation caused by explosion under the vehicle. In order to compare the resistance of different vehicles, the parameter *S* may be used, which, to a certain extent, defines the threat of lower limb injury. In the case of other methods, it is necessary to perform full analyses with explosion simulation or exceptionally costly tests on firing grounds. The possibility to assess structures in the early stage of design offers the opportunity to increase structural resistance of vehicles to explosion. An additional advantage is the possibility to assess the resistance of the vehicle at any point, which allows for the estimation of threat of lower limb injury for each vehicle occupant individually.

In its current form, the method allows only for the comparison of the level of threat between different vehicles or between individual structural solutions for the body and deflectors. To assess the threat directly, it is necessary to analyze the entire vehicle-occupant system with the use of biomechanical criteria.

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