MECHANICAL RESPONSE OF V-SHAPED PROTECTIVE PLATES WITH DIFFERENT ANGLES UNDER BLAST LOADING

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Abstract

The effective design of armored personal vehicles requires an evaluation of the structural response of blast-resistant constructions such as Infantry Fighting Vehicles (IFVs), known as Mechanized Infantry Combat Vehicles (MICVs), or Armored Personal Vehicles (APVs), or Mine-Resistant Ambush-Protected (MRAP) vehicles. These structures' rigid designs will transmit blast forces into the troop's cabins, while their softer designs will result in excessive structure deformation that is hazardous to the troops. The troops in the cabin should experience the least amount of vibration and the least amount of blast-loading energy transmission in an ideal configuration. In this paper, the efficiency of different angled V-shaped plates under blast loading is examined. This study focuses on blast modeling for STRENX700 (S690QL) armor steel, which is utilized for blast protection in Anti-Landmine (ALM) Vehicles, using the Conventional Weapon (ConWep) method. The Johnson-Cook material model is applied to define the plate as a deformable solid. The V-shaped protective structure is subject to significant elastoplastic deformation as a result of landmine detonation within 4 milliseconds of the explosion. Blast-wave is associated with large deformation, erosion, high strain rate, dependent nonlinear material behavior, and fragmentation. In this paper, the results of numerical simulation for failure in V-shaped plates subjected to localized blasts at different included angles (from 145 to 180 degrees) are presented. The parameters chosen to represent the results were the maximal value of the vertical displacement of the central node on the protective plate and the maximal value of the von Mises equivalent stress.

Keywords: V-shaped plate, blast load, structural response, finite element method, explicit dynamic analysis.

1. Introduction

The threat posed by blast loading to both public and military infrastructure is severe. The soldiers in armored vehicles are seriously at risk of death due to the blast loading caused by landmines and improvised explosive devices (IEDs). For structural components like columns and plates, blast loading has the potential to cause significant damage. Because there are so many factors to consider, like the angle of the V-shaped plate, the position, and shape of the charge, etc., it is challenging to determine how the armored vehicle will respond to a blast loading.

Examining the effects of the blast wave on the vehicle and its systems is vital to limit the deformation of the vehicle [1] and hence increase troop safety within the armored vehicle. The use of numerical simulations, which require fewer prototypes and take less time to develop, is validated in the paper [2] as a strategy for designing armored vehicles. In numerical simulations, FE models can be modeled with different types and with different sizes of finite elements. In order to achieve convergence, the floor and protective plates of the armored vehicle are modeled with five different mesh densities [3]. The body of the vehicle is covered with armored steel plates to protect it from explosions, making it an armored vehicle. The explosion protection plates can have different geometries [4]. Geometries that are investigated in papers [5-7] are V-shaped. Determining the ideal angle for the V-shaped protective plates is vital to ensure that the armored vehicle sustains the least amount of damage acceptable.

Levels 2, 3, and 4 of the NATO AEP-55 STANAG 4569 standard were followed in the research for this paper [8].

Determining the ideal angle for the V-shaped protective plates is the main objective of this paper. It is vital to ensure that the armored vehicle sustains the least amount of possible damage in order to protect troops and armored vehicles from the blast wave generated by ALM.

2. Problem description and FE models

A V-shaped protective plate is one of the best possible geometries to provide adequate protection to the troops, armored vehicles, and military equipment from the anti-landmine blasts. The hull is made of a metal plate that is installed beneath the floor of the armored vehicle and bent into a V shape. In order to determine the best angle, eight geometries of the V-shaped hull were developed (Fig.1). The explosion originated from an anti-landmine that is located directly under the V-shaped hull at a distance of 500 mm as shown in Fig.1. The protective plate is 2 m wide and 3 m long.

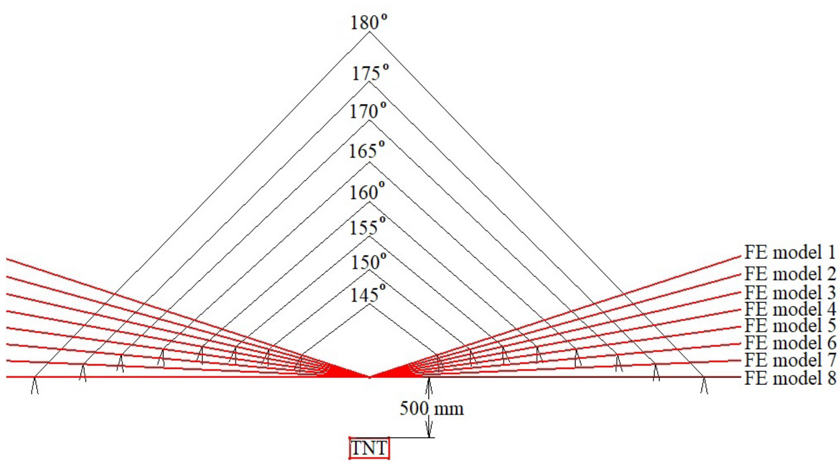

Fig. 1. Angles for V-shaped protective plate

All four edges of the plate are fixed to the floor of the armored vehicle. The material chosen for the protective plate is an appropriate type of steel. The V-shaped protective plates were numerically tested in order to resist 6 kg, 8 kg, and 10 kg of trinitrotoluene (TNT) exploding directly under the V-shaped hull. Many variables affect the parameters of the explosion: depth of burial, the composition of sand, the shape of the explosive, etc., but for this research, a simplified model of the explosion is used.

In this paper, the significance of the V-shaped protective plate angle in the reduction of incident explosion waves is examined. The clearance value for all analyzed models is the same. The mass of TNT explosives corresponds to levels 2, 3, and 4 of protection according to the NATO standard [8] and their mass is 6 kg, 8 kg, and 10 kg. The V-shaped protective plate thickness for all FE models is 12 mm. The input file for the LS-DYNA software [9] was exported after the FE model was created in the FEMAP v2021.2 program [10] using the CAD model. All other settings of the FE model for explicit dynamic analysis were performed in LS-DYNA software. FEMAP v2021.2 software was used for pre-processing and post-processing. All protective plates were exposed to a hemispherical incident wave. The floor of the vehicle is modeled with 3D hexahedral eight-noded finite elements, while the four-noded plate elements were used to model the V-shaped protective plates as shown in Fig. 2.

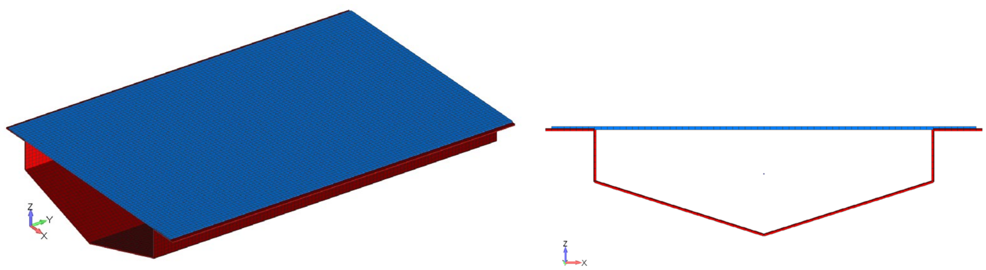

Fig. 2. FE model

The size of 3D hexahedral eight-noded finite elements is 30 mm x 30 mm x 15 mm, and the size of the four-noded plate elements is 30 mm x 30 mm.

3. Material model

Armor steel was chosen as the material for the V-shaped protective plate. When subjected to high strain rates, the material suffers plastic flow, temperature increase, and final possible failure as a consequence of the blast wave. In numerical simulations, the Johnson-Cook material model is frequently used to perform simulations that use temperature and high strain rate effects. The von Mises flow stress is expressed as:

$$\sigma = \left[A + B\varepsilon^n \right]\left[1 + C \ln \dot{\varepsilon}^*\right]\left[1 - T^{*m}\right] \tag{1}$$

the reference strain rate. T^* is the homologous temperature defined as $T^* = \dfrac{T - T_0}{T_{melt} - T_0}$. T is the material temperature, T_{melt} is the melting point temperature of the material, and T_0 is the reference temperature (room temperature). The material constants A, B, C, n, and m can be calculated using the tests suggested by Johnson and Cook (1985) or by fitting the flow stress data based on static and dynamic tests. The Johnson-Cook material model can also be used to simulate the material damage beginning and its development. The material damage is calculated using the value of the parameter D, which is defined as:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \tag{2}$$

where $\Delta\varepsilon$ is the equivalent plastic strain and ε^f is the equivalent strain to fracture. The fracture occurs when the parameter D reaches the value 1. The basic form of the fracture strain is given as:

$$\varepsilon^f = \left[D_1 + D_2 \exp D_3 \sigma^* \right]\left[1 + D_4 \ln \dot{\varepsilon}^*\right]\left[1 + D_5 T^*\right] \tag{3}$$

where $\sigma^* = \frac{\sigma_m}{\bar{\sigma}}$ and σ_m is the average normal stress and $\bar{\sigma}$ is the von Mises equivalent stress. $D_1 - D_5$ are material damage parameters.

A number of armored steel varieties with differing degrees of ductility and strength are available. Steel with a moderate amount of ductility and enough strength is chosen for the analysis because ductility is a key factor in the energy dissipation caused by blast loading. Young's Modulus (E=228 GPa), Poisson's ratio (ν=0.3), and density (ρ=7850 kg/m^3) of S690QL steel are equal to mild steel, but because of its increased strength, S690QL steel is substantially stiffer when loaded (σ_y=750-800 MPa). In the Table 1 are shown Johnson-Cook material characteristics for S690QL steel.

Parameters	Values
Density ρ (t/mm^3)	7.85E-9
Young's Modulus E (MPa)	228368.9
Poisson's ratio v	0.3
Yield stress A (MPa)	767.38
Proportionality coefficient B	445.13
Reinforcement exponent n	0.5075
Strain rate Impact parameter C	0.0265
Temperature Impact parameter m	1.354
Damage parameter D_1	-0.066
Damage parameter D_2	3.028
Damage parameter D_3	-1.408
Damage parameter D_4	-0.00851
Damage parameter D_5	0.633

Table 1. Johnson-Cook material parameters for S690QL steel

The material parameters shown in table 1 were experimentally obtained on the split Hopkinson tension bar (SHTB) and validated using the finite element simulations in LS-DYNA.

4. Results and discussion

In order to decide which geometry would be the best to use as anti-mining protection, the results of explicit dynamic analysis of all eight FE models were compared. All FE models were tested with a simulated TNT weight of 6 kg, 8 kg, and 10 kg which corresponds to levels 2, 3, and 4 of the NATO AEP-55 STANAG 4569 standard.

The maximum value of the vertical displacement of the central node on the protective plate, which is located on the longitudinal plane of symmetry in the direction perpendicular to the protective plate, and the maximum value of the von Mises equivalent stress, has been chosen as the parameters to compare the results of each model.

The maximal value of vertical displacement of the central node on the protective plate and the maximal value of von Mises stress for all eight FE models are shown in Table 2.

FE model	TNT – 6 kg		TNT – 8 kg		TNT – 10 kg	
ID	Vertical	von Mises	Vertical	von Mises	Vertical	von Mises

	displacement (m)	stress (MPa)	displacement (m)	stress (MPa)	displacement (m)	stress (MPa)
ID 1 - 145°	0.10	977.79	0.15	1029.2	0.23	1108.37
ID 2 - 150°	0.13	987.78	0.21	1079.18	0.27	1124.09
ID 3 - 155°	0.18	1026.2	0.24	1076.77	0.27	1095.68
ID 4 - 160°	0.20	1024.29	0.23	1048.53	0.26	1065.86
ID 5 - 165°	0.19	993.64	0.22	997.88	0.25	1012.47
ID 6 - 170°	0.17	957.35	0.20	977.83	0.24	992.86
ID 7 - 175°	0.14	959.1	0.18	988.97	0.23	1004.57
ID 8 - 180°	0.12	957.76	0.16	1007.79	0.21	1048.41

Table 2. Results of numerical analysis for all eight FE models

Maximal values of the vertical displacement of the central node on the protective plate which is located on the longitudinal plane of symmetry in the direction perpendicular to the protective plate for a TNT mass of 6 kg are shown in the diagram in Fig. 3.

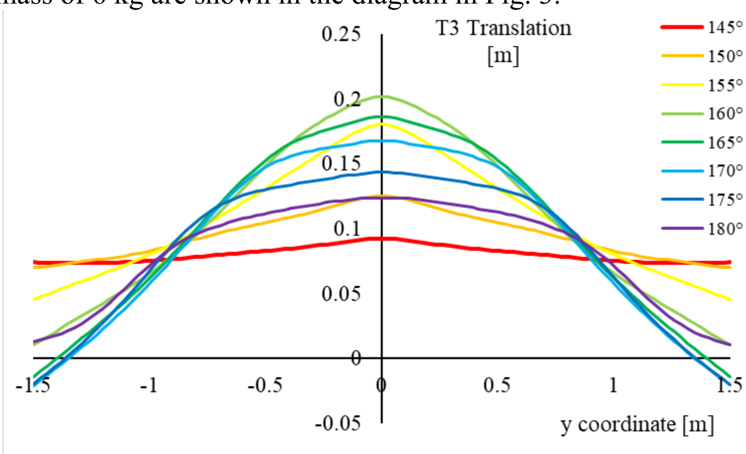

Fig. 3. Values of vertical displacement of the central node on the protective plate for all eight FE models under blast loading for a TNT mass of 6 kg

Based on the obtained results, which are shown in Table 2 and the diagram in Fig. 3, it can be concluded that FE models with the smallest (ID 1 - 145°) and the largest (ID 8 - 180°) angle have the smallest vertical displacement (highest stiffness). As can be seen from Table 2 FE models (ID 2 - 150°) and (ID 7 - 175°) also have high stiffness. The lowest values of von Mises stress have FE models (ID 1 - 145°), (ID 6 - 170°), (ID 7 - 175°), and (ID 8 - 180°). The smallest value of von Mises stress has an FE model (ID 6 - 170°) 957.35 MPa.

Maximal values of the vertical displacement of the central node on the protective plate which is located on the longitudinal plane of symmetry in the direction perpendicular to the protective plate for a TNT mass of 8 kg are shown in the diagram in Fig. 4.

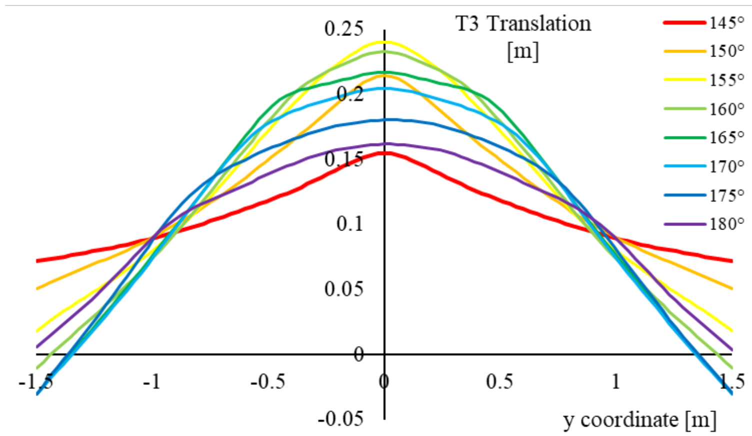

Fig. 4. Values of vertical displacement of the central node on the protective plate for all eight FE models under blast loading for a TNT mass of 8 kg

Based on the obtained results, which are shown in Table 2 and the diagram in Fig. 4, it can be concluded that FE models with the smallest (ID 1 - 145°) and the largest (ID 8 - 180°) angle have the smallest vertical displacement (highest stiffness). As can be seen from Table 2 FE model (ID 7 - 175°) also have high stiffness. The lowest values of von Mises stress have FE models (ID 5 - 165°), (ID 6 - 170°), (ID 7 - 175°), and (ID 8 - 180°). The smallest value of von Mises stress has an FE model (ID 6 - 170°) 977.83 MPa.

Maximal values of the vertical displacement of the central node on the protective plate which is located on the longitudinal plane of symmetry in the direction perpendicular to the protective plate for a TNT mass of 10 kg are shown in the diagram in Fig. 5.

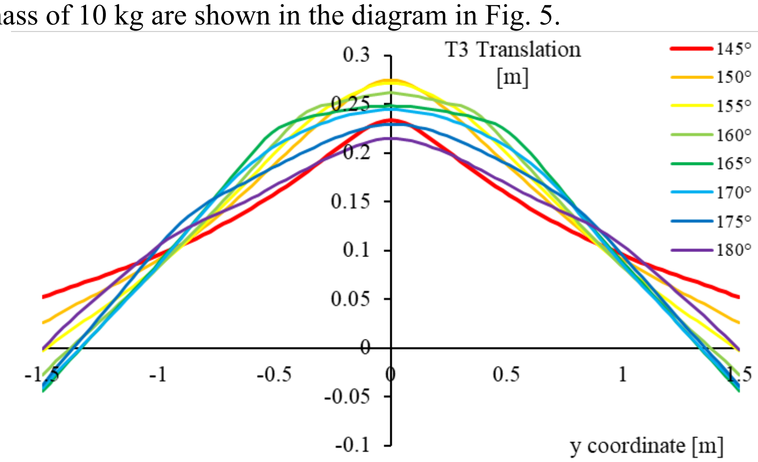

Fig. 5. Values of vertical displacement of the central node on the protective plate for all eight FE models under blast loading for a TNT mass of 10 kg

Based on the obtained results, which are shown in Table 2 and the diagram in Fig. 5, it can be concluded that FE models with the smallest (ID 1 - 145°) and the largest (ID 7 - 175° and ID 8 - 180°) angle have the smallest vertical displacement (highest stiffness). The highest value of vertical displacement has FE models (ID 2 - 150°), and (ID 3 - 155°). The lowest values of von Mises stress have FE models (ID 5 - 165°), (ID 6 - 170°), and (ID 7 - 175°). The smallest value of von Mises stress has an FE model (ID 6 - 170°) 992.86 MPa.

An example of vertical displacement of the central node on the protective plate for FE model 6 with a simulated TNT weight of 8 kg is shown in Fig. 6.

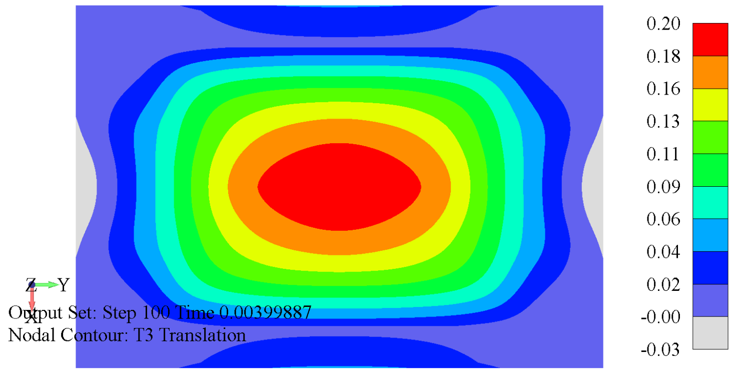

Fig. 6. Vertical displacement distribution

Von Mises equivalent stress distribution for FE model 6 with a simulated TNT weight of 8 kg is shown in Fig. 7.

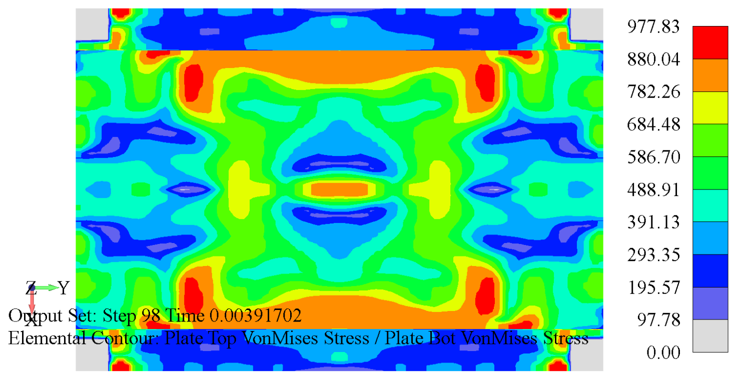

Fig. 7. Von Mises equivalent stress distribution

5. Conclusions

This study uses numerical simulation to analyze the mechanical response of V-shaped protective plates with different angles subjected to blast loading. The focus of this study is to determine the optimal angle of the V-shaped protective plate which can be used for Infantry Fighting Vehicles (IFVs), known as Mechanized Infantry Combat Vehicles (MICVs), or Armored Personal Vehicles (APVs), or Mine-Resistant Ambush-Protected (MRAP) vehicles. From the analysis using FEM, the following conclusions, which are based on the maximal value of the vertical displacement of the central node on the protective plate and the maximal value of the von Mises equivalent stress, are reached:

- In general, the maximal value of the protective plate vertical displacement increases with the increase of the TNT mass;
- Maximal value of the von Mises equivalent stress increases with the increase of the TNT mass;
- The smallest vertical displacement of the central node on the protective plate, i.e., the highest stiffness has a protective plate in the FE model (ID 1 - 145°) and (ID 8 - 180°).
- The smallest value of von Mises stress has an FE model (ID 6 - 170°) for all three load cases (6 kg, 8 kg, and 10 kg of TNT).
- In order to achieve a more efficient configuration of protection, developing anti-mining protection should be a major step in the process of developing a complete vehicle.

Further study will concentrate on the use of various protective plate geometries, as well as various types of high-strength steels, sandwich constructions, and composite materials to protect troops, armored vehicles, and military equipment from the effects of ALMs and IEDs.

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