Numerical Simulation and Optimization of an Off-Road Vehicle Floorboard for Mine Blast Damage Reduction

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ABSTRACT: This paper studies numerically the response of V-shaped hull subjected to mine blast load using finite element analysis package ABAQUS. The V-shaped plates are made from Domex700 steel folded along the centre to provide different angles and a constant area of $300 \times 300$ mm for each plate. Different masses of explosive are used to provide results ranging from large inelastic deformation of the plate to tearing. A general trend of increasing permanent mid-point deflection is observed for an increase in charge mass at a constant stand-off distance. The results showed that smaller angles deflect more blast energy resulting in lower mid-point plate deflection.

Keywords: V-shaped plate, mine blast load, finite element analysis, mid-point deflection

INTRODUCTION

According to the Landmine Monitor Report 2011, Iran has been significantly contaminated with mines, primarily as a result of the 1980–1988 conflict with Iraq, affecting particularly the western region of country. In 2010, the number of casualties among humanitarian clearance operators was double that recorded for 2009. There were 131 deminer casualties (36 deminers killed; 95 injured) recorded in 15 states/areas in 2010, compared to 67 deminer casualties in 2009. The large increase can mainly be attributed to the availability of casualty data from Iran, where there were 47 demining casualties recorded in 2010 and for which there was no data on demining casualties in 2009. The use of landmines and Improvised Explosive Devices (IED) highlights the need for better mine resistant vehicles, especially for peace-keeping forces and the demining effort. Accordingly, the investigation on the use of plated structures as a means to deflect the resultant blast pressure wave from an explosion becomes more significant. Protection against mine explosion is a key and unsolved problem related to the safety of vehicle and occupants. How to design the protective structure to minimize the damage from outburst and explosion is always a concerned problem. The purpose of special kind of vehicle design is to increase the vehicle and crew survivability by deflecting an upward blast from a landmine (or IED) away from the vehicle, while also presenting a sloped armour face. New combat vehicle designs emphasize weight reduction for increased fuel efficiency and airborne transportation; therefore, a significant effort must be invested in order to ensure that the vehicle’s survivability is not compromised (Kania, 2009).

The design of the vehicle plays a vital role in the blast propagation. The flat hull gives more face area to the blast and so gives more space to propagate the blast. The shape of the bottom hull should be kept in such a way as to cause minimum blast propagation and minimum damage to the occupants. Quite a few studies have been done in the past to analyze the response of vehicle floor plates subjected to blast loading. Genson (2006) explored the effect of geometry on floor plates subjected to buried blast loading. He performed experiments for different depths of burial in soil, stand-off distance and plate geometries on the transferred impulse. Failie (2002) did a 2D and 3D numerical study of mine blast loading on a circular plate using AUTODYN and also compared results with experimental measurements by calculating momentum transferred to a horizontal pendulum from a mine blast. Benedetti (2008) carried out experiments with similar variables to Genson with a view to investigate methods for mitigating the blast effects on the floorboard. The use of foam to either fill the gap between the floorboard and the hull or to isolate the floorboard from the hull was investigated. He found that the use of foam did not have positive mitigation effects. Gurumurthy (2008) developed simplified two-dimensional and three-dimensional computational models to investigate the blast effects on vehicular structures, which were not validated with any experiments. The effect of the vehicle hull shape on net impulse loading was analyzed and optimized over varying blast intensities. It was found that the V-shape hulls provided the best performance in reducing the peak head-on impulse. Further analysis on
the V-shape hull suggested that head-on impulses were nearly constant and minimum for a range of stand-off distances. Yuen et al. (2012) experimentally and numerically investigated the response of V-shaped plate to the detonation of a disc of explosive placed in the central position of the plate using ABAQUS. They showed that while the measured impulse does not significantly change, an increase in mid-point deflection is observed with a decrease in stand-off distance for a constant mass of explosive. They also showed that smaller inclusive angles deflect more blast energy resulting in lower mid-point plate deflection.

From these studies, it can be seen that the effect of floorboard shape has not been given due importance in these analyses. In the present study, effects of plate geometry, stand-off distance and charge mass are investigated on stress and deformation of the V-shaped plate using commercial code ABAQUS.

**V-Shape Hull**

The V-shaped hull is superior to a flat-bottom hull in resisting load transfer from an explosive blast (Fig. 1). Under a flat bottomed hull the blast wave will reflect and coalesce with the resultant pressures many-fold higher. Conversely, the V-shaped hull would allow for the blast wave and the detonation products to be directed away from the passenger (Baker et al. 1983, Ramasamy et al. 2011). The effectiveness of the V-shaped hull to direct the detonation products away from the passengers was related to the angle of the hull; the more acute the angle, the better the energy dissipation (Fig. 2). However, a more acute hull reduced the carrying capacity of the vehicle as well as potentially making the vehicle more unstable and more likely to overturn. The cross sections of the studied V-shaped hulls are shown in Figs. 1 and 3.

![V-shaped hull](image1)

**Figure 1.** A cross-section view of the V-shaped hull of the crocodile vehicle (Ramasamy et al. 2011)

![Schematic illustration](image2)

**Figure 2.** Schematic illustration showing the effectiveness of the V-shape hull to deflect blast wave (Yuen et al. 2012)

![Cross-section view of the twin V-shaped hull of the TMV vehicle](image3)

**Figure 3.** A cross-section view of the twin V-shaped hull of the TMV vehicle

**Geometric Scaling**

Geometric scaling is used to determine the parameters such as plate dimensions, load diameter and stand-off distance, based on the dimensions of the ¾ ton vehicle hull and a 2.5 Kg TNT weighted anti-tank mine. The width of the vehicle is scaled to the width of the V-shape plate specimen (300 mm) resulted in a
ratio of 6.66:1. This geometric scale ratio is then applied to the ground clearance and load diameter of the charge. The vehicle ground clearance of 400 mm scales to an initial test stand-off distance of 60 mm. The stand-off distance is later reduced to 30 mm because the 60 mm stand-off distance produced negligible deflections for the charge mass used. The plates made from Domex 700 Steel, are 2 mm thick and folded along the centre line of the plate to provide the $120^\circ$ included angles and a constant projected area of $300 \times 300$ mm. The Hopkinson-Cranz scaling is also used to scale 2.5 Kg TNT detonated under the belly of the vehicle (Uddin 2010).

**Finite Element Modelling**

**Model geometry**

The ABAQUS software package is used to build and analyze the solid model and finite element mesh of the $120^\circ$ V-shape plate. The V-shape plate is modelled taking advantage of symmetry, using 54716 linear tetrahedral elements of type C3D4. The mesh is biased towards the centre of the plate where the explosive is detonated and most deformation occurs. All degrees of freedom are fully constrained at the flat section of the plate to simulate the clamped boundary conditions.

**Material properties of V-shape plate**

The Johnson and Cook material model is used as shown in Eq. (1) (Yuen et al. 2012). The model describes the material flow stress as a function of strain, strain rate, and temperature. The model assumes the strength of the material is isotropic and independent of mean stress.

$$\bar{\sigma} = \left[ A + B(\bar{\varepsilon}^p)^n \right] \left[ 1 + C \ln(\bar{\varepsilon}^p) \right] \left( 1 - \frac{T}{T_{\text{melt}}} \right)$$  \hspace{1cm} (1)

$$\bar{\varepsilon}^p = \frac{T - 300}{T_{\text{melt}} - 300}$$  \hspace{1cm} (1)

where $\bar{\sigma}$ is the yield stress at non zero strain rate, $\bar{\varepsilon}^p$ is the equivalent plastic strain, $\bar{\varepsilon}^p$ is the normalized equivalent plastic strain rate, $T$ is the material temperature (K) and $T_{\text{melt}}$ is the melting temperature of the material. The constants $A, B, n, C, \varepsilon^0$ are material dependent parameters and may be determined from an empirical fit of flow stress data. Table 1 lists the material dependent parameters used in the model (Yuen et al. 2012).

<table>
<thead>
<tr>
<th>Material properties of the V-shape plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Mpa)</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>818</td>
</tr>
</tbody>
</table>

**Properties of air**

The air and post-burning gas product media are assumed to behave as an ideal gas. Hence, the default equations of state are used.

$$P = \rho (\gamma - 1) E^v_0$$  \hspace{1cm} (2)

$$\gamma = \frac{C_p}{C_v}$$  \hspace{1cm} (3)

$$E^v_0 = C_v T$$  \hspace{1cm} (4)

where $C_v, C_p, \rho$ are the specific heat at constant volume and pressure and the density of the gas respectively, whilst $T$ is the gas temperature. The air model is depicted in Table 2.

<table>
<thead>
<tr>
<th>Properties of air</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
</tr>
<tr>
<td>1.225</td>
</tr>
</tbody>
</table>
Properties of explosive

The explosive behaviour is modelled using the Jones-Wilkins-Lee (JWL) equation of state (Eq. (5)).

\[
P = A \left(1 - \frac{\omega P}{R_p \rho_v}\right) e^{-R_1 (\rho_v / \rho_p)} + B \left(1 - \frac{\omega P}{R_e \rho_v}\right) e^{-R_2 (\rho_v / \rho_p)} + \omega P E_0^0
\]

where \(P\) is the pressure, \(\rho_p, \rho_v\) are the density of the explosive and explosive products respectively, \(A, B, R_1, R_2, \omega\) are material constants that are empirically derived and \(E_0^0\) is specific internal energy of the explosive. The material constants used are shown in Table 3.

### Table 3. Material properties of explosives

<table>
<thead>
<tr>
<th>(\rho_v) (kg/m(^3))</th>
<th>A (Gpa)</th>
<th>B (Gpa)</th>
<th>(R_1)</th>
<th>(R_2)</th>
<th>(\omega)</th>
<th>(V_{\text{ax},\text{SN}}) (m/s)</th>
<th>(C - J) energy/vol (kJ/m(^3))</th>
<th>(C - J) pressure(Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>609.8</td>
<td>12.95</td>
<td>4.5</td>
<td>1.4</td>
<td>0.25</td>
<td>8193</td>
<td>9\times10(^4)</td>
<td>28</td>
</tr>
</tbody>
</table>

![Figure 4. Blast modelling in ABAQUS](image)

**Figure 4. Blast modelling in ABAQUS**

### Table 4. Predicted mid-point deflection.

<table>
<thead>
<tr>
<th>Varied charge mass 120(^0) stand-off distance: 30mm</th>
<th>Charge mass (gr)</th>
<th>Mid-point deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>19.3</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>33.3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Varied V angle mass 25 gr stand-off distance: 30mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>120</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>180</td>
</tr>
</tbody>
</table>

![Figure 5. Transient response of the 120\(^0\) V-shaped plate at constant stand-off distance](image)

**Figure 5. Transient response of the 120\(^0\) V-shaped plate at constant stand-off distance**
showed almost identical response to the blast. It was found that the angle of V should be optimized in order to further deflection of the blast wave and maintenance of vehicle stability. Moreover, both V-shape and twin V-shape plates showed almost identical response to the blast.

RESULTS AND DISCUSSION

The blast model made in ABAQUS is depicted in Fig. 4. Table 4 gives the simulated results of mid-point deflection for the various parameters investigated. Generally, encouraging correlation is obtained for the mid-

CONCLUSIONS

In this paper, finite element analysis of a V-shaped plate was conducted using ABAQUS. The results showed that the V angle, stand-off distance and charge mass have considerable effect on the deformation of the V-shaped plate subjected to mine blast load. It was found that the angle of V should be optimized in order to further deflection of the blast wave and maintenance of vehicle stability.
point deflection. The numerical results indicate a general trend of increasing permanent mid-point deflection with increasing mass of explosive for constant stand-off distance and decreasing stand-off distance for constant mass of explosive. Figs. 5 to 8 illustrate the transient response and Von-mises stress distribution of $120^\circ$ V-shaped and twin V-shaped plates at constant stand-off distance, respectively. As can be seen, deformation is initiated in the central area of the plate with buckling type failure along the ridge of the V-shaped plates. The deformation progresses with an increasing damage area in the central area of the plate. Furthermore, both V-shape and twin V-shape plates demonstrate almost identical response to the blast.

REFERENCES


