Finite element analysis of response of v-shaped hull plates under blast loading

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Abstract. Armoured vehicles usually employ shaped plate for protection from blast loads arising from landmines. In most of the cases the plates deflect a part of the load away from the vehicle thus protecting the crew. Important parameters which affect the design of the plates include the included angle of the V shaped plate and standoff distance between the explosive and plate. In this study Finite Element (FE) analysis is carried out to estimate energy absorbed by the plates and the impulse transmitted to the superstructure. A validated numerical procedure with ABAQUS is used to conduct the parametric studies to compare and estimate the effectiveness of two different configurations. Guidelines for selecting the required plate angle and location of the plate could be developed based on the suggestions of the numerical study.

Keywords: Blast loading, Finite element method, Parametric study, V-shaped plates.

1. Introduction

Blast loading is considered to induce major threat to the life of soldiers and civilians in war affected areas. The only option for mobility in war affected areas could be with armoured personal vehicles (APV). The response of the vehicles to the blast loads is difficult to predict as the number of variables involved are large. Hence evaluating the design parameters of the vehicle during the blast loading becomes important in the design of APVs. Both flat and shaped plates have been used for protection of the vehicle hulls from blast loads. Among the shaped plates V shaped plates becomes important due to its superior response characteristics as reported by Sahu et al. [1].

The flat plates being simple in construction have received considerable attention [2,3]. On the other hand, shaped plates like V shaped plates have received very little attention. APV like South African CASSPIR has been using V shaped plates under its hull for protection from mine blasts. The effectiveness of the flat plates is lower due to the reflection of the blast wave from its surface. This leads to considerable magnification of the blast wave leading to the failure of the protective plates [4]. The V shaped plates on the other hand deflects a considerable part of the blast wave away from it, reducing the load intensity.

Literature review shows that certain features of the V shaped scaled down plates have been investigated. Genson [5] has conducted experimental studies on scaled down plate models by
considering the effect of mass of the charge, standoff distance and included angle (θ) of the V shaped plate. He has reported the optimum value of the plate angle as 75° to 85°. A coupling effect between the standoff distance and V included angle was also seen during the blast wave mitigation. Similar study was conducted by Benedetti [6] with a reported optimum angle of 78°. Literature review shows that scaled down models have been used in the experimental and numerical investigations [5,6]. Adequate number of experimental and numerical results are available for flat plates. The experiments on the V shaped plates are focused on the deformation and impulse transmitted. It is seen that the V shaped hull is capable of mitigating the blast load to a larger degree, compared with other shapes (like flat, parabolic or convex). Still studies are not available which can be used as references for understanding its performances when it is used as part of vehicle structure.

A review of the available literature directly indicates that a plate with lesser value of the included angle is better. It also indicates that larger standoff distance is preferable to reduce the impact. For an APV the height of the vehicle floor is usually fixed. Hence it is not possible to simultaneously implement the two options mentioned above namely maximum standoff and minimum included angle. A V plate with large value of included angle has the advantage of getting a larger stand-off distance. While a V plate with lesser value of included angle suffers from a lower value of standoff. These cases are illustrated in Figure 1 and Figure 2. This study is conducted with the objective of making a direct comparison of these cases and helps in making the right decision for structure design.

In the present paper the objectives are;
1) To develop validated a numerical model that would simulate the mechanical response of scaled down V-shaped hulls.
2) To use the numerical models developed above for performing a parametric study on the V shape hull subjected to variation in parameters.

The mechanical response parameters monitored in the study are a) transmitted impulse at the supports b) acceleration and of the hull and c) energy calculations involved in the blast loading of the plates. The design parameters that are varied in the study are a) plate included angle and b) standoff distance of the charge.

2. Methodology
The APV CASSPIR employs a V shaped hull to provide adequate protection to its crew from the land mine blasts. Details of the material used and the geometry like V angle are missing in the open literature. The vehicle is designed to resist 14kg of TNT exploding directly under the V shaped hull and 21kg of TNT under each wheel. The standoff distance is assumed as 410mm and width as available in literature [7] is 2500mm. The APVs are fitted with the V shaped hulls for blast resistance as seen in Figure 1. This study uses scaled down version of the full-scale plates mentioned above. A numerical study is conducted with ABAQUS Explicit for evaluating the combination of V angle and standoff distance, which gives maximum blast mitigation.

The dimensions of the full-scale model and the scaled down model used for the validation purpose are given in Table 1. The variables which affect the explosion may be many like a) depth of burial, b) composition of the sand, c) shape of the explosive and d) reflection from surroundings. We model the explosion as a spherical free air burst that is, it is assumed to occur in open air without any surrounding interactions. The parameters under consideration are a) V-included angle of the plate, b) mass of the explosive and c) standoff distance. A detailed validation for the numerical model has been reported in Ref. [7]. It is felt that independent study of these variables may not make much sense for vehicle design as many combinations of these parameters turns out to be impractical. A numerical study was conducted to find the effectiveness of the plate under certain combination of these parameters under consideration during the vehicle design. The values for the mass of explosive, plate angle and standoff distance of the model for the parametric study is given in Table 2. The commercial software ABAQUS (version 6.14) has been used for pre-processing, analysing and post processing the results.
Figure 1. APV with a smaller value of included angle and standoff distance.  

Figure 2. APV with a larger value of included angle and standoff distance.

Table 1. Model dimensions, Ref. [8]

| Parameters of scaled down models | Parameters of the full-scale model |
|----------------------------------|-----------------------------------|
| Dimensions of projected area     | 300x300mm²                        |
| Standoff distance                 | 50mm                              |
| Plate thickness                   | 2mm                               |
| Material                          | Domex 700steel                    |
|                                  | 2500x2500mm²                      |
|                                  | 410mm                             |
|                                  | 16.66mm                           |
|                                  | Mild steel                        |

Table 2. Model parameters for the current study.

| Parameters of scaled down models | Value                        |
|----------------------------------|------------------------------|
| Dimensions of projected area     | 300x300mm²                   |
| Standoff distance                 | 50mm, 270mm                  |
| Plate thickness                   | 2mm                          |
| Material                          | Mild steel                   |
| Mass of explosive (PE4)           | 5gm, 14gm, 19gm.             |

Even though the blast loading can produce a combination of effects we focus on the shock loading effect of the blast wave. The generation of the blast wave produces shock front with strong gradients in velocity pressure and density of the surrounding gas. The shock wave exerts a pressure, $P_s$, which is much higher than ambient pressure, $P_a$, and the difference of these pressures is denoted by blast over
pressure, \((P_s-P_a)\). The shock wave has a positive and negative phase associated with it and can be represented as shown in Figure 3.

![Figure 3. Typical pressure time history of blast wave.](image)

\[ p(t) = (P_s - P_a) \left[ 1 - \frac{t-t_d}{t_d} \right] e^{-\frac{(t-t_d)}{\theta}} \] (1)

Here, \(t_a\) is the time of arrival, \(t_d\) is the duration of the positive phase and \(\theta\) is the decay constant. A convenient option for the modelling the free air blast problem is to utilize the built-in blast generation function CONWEP. CONWEP is an empirical equation for calculating the shock wave pressure acting on the surfaces. Adisak Showichen [9] has given a brief description about CONWEP. CONWEP loading on different structures like flat plates circular plates and honey comb structures have given results consistent with experiments [10].

The model geometry created with ABAQUS is discredited using Lagrangian elements. Lagrangian elements are preferred for studies with moderate mesh deformations. They are also better in tracking the material interfaces. Experimental results in literature used for validation studies have reported moderate deformation and hence Lagrangian elements have been selected here. The first order solid elements (C3D8R that is, continuum 3-dimensional 8 node reduced integration) which have minimal shear and volume locking effect has been used for calculations for both validation studies and the parametric studies. These are suitable for carrying out the nonlinear geometric analysis and have been used for accurately representing the stresses and strains for similar problem, as shown in Ref. [10]. A total of 33,975 C3D8R elements were modelled with hexahedral meshes. Thermal aspects have not been considered since the effect of thermal softening is not seen as a major factor affecting the simulations. The fixed boundary conditions have been used to represent a plate clamped to the main hull, at the boundaries.

Although armoured steel is preferred for the application mild steel is chosen for the current work due to the availability of parameters. The Johnson Cook (JC) model [11] is often used in literature to handle the simulations which employ high strain rate and temperature effects. The Von Mises flow stress as proposed by JC model is expressed as...
\[
\sigma = [A + B\epsilon^n][1 + Cln\dot{\varepsilon}^*][1 - T^m]
\] (2)

Here \(\epsilon\) is the equivalent plastic strain, \(\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\varepsilon_0}\) is the dimensionless plastic strain rate and \(\dot{\varepsilon}_0\) is the reference strain rate. \(T^*\) is the homologous temperature. The constants \(A, Bn, C\) and \(m\) in the equation may be determined by fitting the flow stress data, based on static and dynamic tests. The plastic flow beyond the yield strength \(A\) is assumed to depend on the strain, strain rate. Although temperature dependency is possible with this model it is not such problems. The temperature rise would weaken the material but it is compensated by the increase in strength during the high strain rate deformation. The parameters obtained by Iqbal et al. [12] was used by the authors for the study, and is given in the Table 3 below.

| Description                  | Notation | Numerical value |
|------------------------------|----------|-----------------|
| Yield stress                 | \(A\) (MPa) | 304.33          |
| Strain hardening constant    | \(B\) (MPa) | 422.007         |
| Viscous effect               | \(n\)    | 0.345           |
| Thermal softening constant   | \(m\)    | 0.87            |
| Reference strain rate        | \(\dot{\varepsilon}_0\) | 0.0001s\(^{-1}\) |
| Melting Temperature          | \(\Theta_{\text{mel}}\) (K) | 1800            |
| Transition temperature       | \(\Theta_{\text{transition}}\) (K) | 293             |

The blast wave exerts an impulsive pressure on the plate which results in the momentum transfer to the plate. This momentum is captured as the net impulse transferred \((I)\), to the plate and can be calculated as follows,

\[
I = \int_0^{t_d} Pdt
\] (3)

Here, \(P\) represents the applied pressure due to blast loading function CONWEP and \(t_d\) is the duration of loading.

3. Finite element results

The studies with numerical modelling are intended to assess the effectiveness of the shaped plates to mitigate the blast load. The developed numerical method was validated with results reported in literature. Simplified loading with CONWEP functions is always important in feasibility study as significant conclusions could be obtained without adopting the computationally intensive blast load modelling with gas dynamics equations. Here the spatial and temporal variation for blast loads were modelled with the blast function CONWEP. Numerical studies were conducted to assess the transmitted impulse while varying the mass of the explosive. A numerical model with 180\(^0\) and 150\(^0\) plate were subjected to blast loads generated from 5, 14 and 19gm of Plastic Explosive (PE4). The obtained values were compared with experiment results [7] as shown in Figure 4. It is seen that the best results are obtained with flat plate loading with a maximum error of 7.5%, while the V shaped plate with 150\(^0\) gives a maximum error of 26%. This is expected since the CONWEP function may not give the optimum results for non-uniform structures.

Suitable magnification factors need to be added for matching the free air blast results of CONWEP with experiments. The magnification factor in the above simulations has been fixed as 2.2. The results
of the numerical procedure are seen to be sufficient while considering the computational time and resource constraints. The overall impulse in the experiments has been calculated by integrating the values of the reaction force at the boundaries with respect to time duration of loading.

Numerical investigations were conducted to find the effectiveness of 60° plate and 150° plate. The 60° plate has a larger inclination with the incident load and a closer proximity with the load source. The 150° plate on the other hand has a larger distance with the source while the faces have a lesser inclination with the load. Thus, we have two options for protecting the vehicle hull from the blast loads while the overall height of the vehicle floor remains unchanged. These configurations need to be analysed numerically since straight forward solutions may not be sufficient for estimation of the impulse transferred. Figure 5 shows the effect of various explosive masses on the impulse transmitted for both the plates. It is seen that the 60° plates are better in deflecting the blast wave away although the explosives are located close by. The 150° plates on the other hand with a larger standoff distance is seen to be inferior due to the larger included angle. Figure 6 shows the effect of explosive mass on the acceleration imparted to the both the plates under consideration. It is seen that the accelerations are more or less matching for the different plates for the lower load range. For a higher load the 60° plate suffers more acceleration and hence inferior.

![Figure 4. Variation in predicted and measured value of impulses for (left) 180° and (right) 150° plate](image)

![Figure 5. Impulse transmitted with variation in mass of PE4](image)

![Figure 6. Acceleration imparted to the plates with variation in the mass of PE4.](image)
Figure 7 shows the variation of energy absorbed by the 60° plates for various explosive masses and compares it with the external work input due to blast loading. It is seen that almost the entire work input is absorbed by the plates which means that the fraction of the external work converted to kinetic energy is very little. Figure 8 shows the fraction of the internal energy to the external work input. It shows that the fraction of internal energy for the 60° plate goes on increasing for increasing mass of the explosive. At the same time the fraction shows a reverse trend for the 150° plate. This means that more work is converted to kinetic energy for 150° plates for an increase in mass of the explosive.

![Graph showing energy absorbed and work input for 60° plates.](image)

**Figure 7.** Internal energy (IE) and external work (WK) for 60° plate with variation in mass of the explosive.

![Graph showing variation in IE/WK ratio for 60° and 150° plates.](image)

**Figure 8.** Variation in the ratio of internal energy (IE) to work input (WK) for 60° and 150° plates.

### 4. Conclusion

A numerical study is conducted to ascertain the response of 60° and 150° plate under the blast loading. The study is conducted to ascertain and compare the performance of two separate configurations depending on the included angle and standoff distance. The study clearly shows that the configuration with lesser included angle is more favourable in blast mitigation. This highlights the importance of controlling the included angle for better blast mitigation. The energy-based analysis shows that the plates with lesser included angles are more effective in dispersing the external work in the form of internal energy. On the other hand, the plates with larger internal angles favours the dispersion of energy in the form of kinetic energy. It is also seen that this trend increases with increasing mass of the explosive. This could be unfavourable for the vehicle structural design. It is hoped that these findings would be helpful in designing the proper configuration of the blast resistant hull plates used in APV.

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