Polyurea Coated Steel Plates For Blast Mitigation In Armoured Vehicles

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Abstract. Increasing terror attacks and development of Improvised explosive devices (IEDs) has resulted in the development of protective structures for armored personnel vehicles (APV). These shaped plates either deflect or absorb the energy imparted to them. A well designed plate should absorb the energy as much as possible and transmit the least impulse to the vehicle structure. In this context the response of polyurea coated steel plates have recently been explored with the purpose of increasing the effectiveness of these shaped plates. Experimental studies have shown the capability of polyurea coated steel plates in mitigating the blast load. Hence there is scope for a numerical study on the polyurea coated V-shaped steel plates for finding its response. The objective of this study is to conduct FE based analysis of V-shaped steel plates coated with polyurea. The important parameters which affect the response of the plate are the mass of the explosive, the parameters of the V shaped plate and thickness of polyurea layer. The response variables under consideration are the deflection of the plate and imparted impulse. A numerical procedure validated for flat plates coated with polyurea, has been used for the above study. The results are helpful in identifying an optimal structure design for resisting blast loads.

1. Introduction
New and improvised explosive devices in the form of land mines are widely used in war affected zones. The armoured personal vehicles (APV) are the only means of transportation under such conditions. These APVs always uses shaped metallic plates as blast load resisting structures for effectively resisting blast loads. These coated metallic plates can deflect away and absorb a major part of the blast load. Hence specific impulse transferred to the vehicle crew is significantly reduced thus reducing the possibility of damage. APV like South African CASSPIR are known to use ‘V’ shaped plates as blast mitigation structures. Traditionally the plates are made from the armoured steel. Latest research has also highlighted the use of sandwich structures, using hyperplastic materials like polyurea for the above purpose as given in Ref. [4,6]. Polyurea is an elastic polymer formed by the rapid chemical reaction between isocyanates and amines. Polyurea coatings exhibit resistance to fragmentation and impact loads along with blast energy absorbing capability. These materials when applied as an external coating on the, metals plate are seen to improve the blast resistant property of the shaped plates.

The mechanical response of flat plates and beams has been extensively investigated by several researchers [1-3]. In these studies experimental and numerical procedures have been used for the analysis of circular and quadrangular plates under varying magnitudes of loads and with various boundary conditions. On the contrary few studies are available related to the response of the V shaped plates coated with Polyurea subjected to blast loading.
Investigators have conducted an experimental and numerical modelling of the response of the bilayer plate made of metal plate and polyurea, under shock loading as presented in Ackland et al. [4] as well as in Amini et al. [6]. Yuen et al. [5] has conducted exclusive studies on the response of the V shapes plates. The V shaped plates mounted on ballistic pendulum were subjected to explosive loading. Agesh et al. [7] has conducted numerical simulations on the response of full scale V plates and flat plates under blast loading.

In the present paper the objectives are as follows,

1. To develop a numerical model for simulating the response of metallic plates with polyurea coating and validate the published results.
2. To use the validated model to assess the effectiveness of polyurea coated test plates.

The response parameters simulated are the midpoint displacement and the force or impulse transmitted to the boundaries for varying coating thickness.

2. Problem description and numerical modelling.

APV like Casspir use V shaped metallic hull made from armored steel as protection against blast loading. These plates provide adequate protection to the vehicle and crew from land mines. A schematic diagram of the shaped plate used for the numerical simulation is shown in Figure 1.

![Figure 1](image)

**Figure 1.** Schematics illustrating V-shaped hull and the terminologies

Here we are considering the response of flat plate and scaled down model of hull plate under shock loading. The validation is done with the flat plates under explosive loading. The analysis is carried out for scaled down V plate undergoing shock loading. The dimensions of the models are given in figure 1.

There are broadly two sets of parameters which affect the response of the APV, the ones related to the blast conditions and which relate to the structure. The focus of our analysis is on the structural part and hence a simplified blast model is assumed. The parameter under consideration is the thickness of the coating. The 3d numerical study is conducted with Abaqus version 6.12.
Table 1. Model dimensions

| Parameters of Flat plate for validation | Parameters of scaled down Plate |
|----------------------------------------|---------------------------------|
| Dimensions of projected area           | 1000mm x 1000mm                 |
|                                        | 300x300mm²                      |
| Standoff distance                       | 10mm                            |
| Plate thickness                         | 4mm-6mm                         |
| Polyurea thickness                      | 7.7mm, 15.7mm                   |
| Plate material                          | Bluescope XLERPLATE Mild steel  |
|                                        | 350 grade                       |

2.1 Geometric and material modelling

The plate angle of 145° has been selected based on recommendation from the numerical study conducted by the authors as given in Ref. [7]. A plate of 1000mm x 1000mm has been selected for validation. The 3D model is created with Abaqus and discretized using lagrangian elements. The plate has been modelled with shell elements while the polyurea layer has been modelled with solid elements. Shell elements S4R (4 noded, reduced integration elements with hour glass control) has been used since the thickness is far lesser than the other dimensions and also due to its computational efficiency. First order solid element C3D8R (8 noded, 3 dimensional reduced integration element) has been used for modelling the hyperelastic material, polyurea. Similar elements have been used previously in Ackland et al. [4], for modelling these materials under impulsive loading. A schematic cross section of the coated V plate is shown in Figure 2 and FE mesh used in numerical analyses is shown in Figure 3.

![Figure 2. Schematic cross section of a coated V plate.](image)

![Figure 3. FE model of coated V plate.](image)

The Johnson Cook material model which is dependent on the strain rate has been used in calculation of finite deformations. The Von Mises flow stress given by Johnson et al. [8] is expressed as,

\[
\sigma = [A + B\varepsilon^n][1 + Cln\dot{\varepsilon}^*][1 - T^{*m}]
\]  

(1)
Here $\varepsilon$ is the equivalent plastic strain, $\dot{\varepsilon}^* = \frac{\varepsilon}{\varepsilon_0}$ is the dimensionless plastic strain rate and $\dot{\varepsilon}_0$ is the reference strain rate. $T^*$ is the homologous temperature. The constants $A, B, n, C$ and $m$ in the equation may be determined by fitting the flow stress data, based on static and dynamic tests. All the material parameters for steel in the Johnson-Cook elastoplastic model have been evaluated by Iqbal et al. [9].

The hyper elastic strain energy function can be expressed as a two parameter Mooney Rivlin model as

$$
\psi = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{d}(J - 1)^2
$$

Here $C_{01}$ and $C_{10}$ are material constants, $I_1$ and $I_2$ are the first and second invariant of the deformation tensor, $J$ is the determinant of the elastic deformation gradient and $d$ is the material incompressibility factor. The value of $C_{10} = 875.2$ kPa, $C_{01} = 6321.3$ kPa and $d = 4 \times 10^{-8}$ (kPa)$^{-1}$

### 2.2 Blast load modelling

The validation part of the analysis deals with the simulation of the plate which undergoes shock loading from a centrally placed explosive. The explosive charge upon detonation generates a shock wave propagating towards outer direction with a sudden jump in the field parameters (like particle velocity, density, pressure and internal energy) across the shock front. The difference of shock pressure over the atmospheric pressure is denoted by blast over pressure, ($P_s - P_a$). The shock wave can be represented as shown in figure 4.

![Figure 4. Typical pressure time history in blast wave.](image)

The pressure time history of the blast wave can be represented by the modified Friedlander equation, Ref [7].

$$
p(t) = (p_s - p_a) \left[ 1 - \frac{t-t_a}{\tau_d} \right] e^{-\frac{(t-t_a)}{\theta}}
$$

The second part of the analysis deals with a plate which is loaded centrally. Parameters for governing blast loading on V-shaped Plates are given below.

- Radius $r$ of Shock loaded area is 17.5mm.
- Loading region on V-Plate taken as circular region with radius $r$
• Peak pressure at centre of the plate is 250bar.

The equation suggested by Brode [10] was used to calculate the blast overpressure, in the near field as a function of scaled distance and is given as,

\[ P_{\text{pos}} = \left( \frac{6.7}{Z^{3/5}} + 1 \right) \text{bar for } (P_{\text{pos}} > 10\text{bar}) \]  

(4)

where \( R \) is the radial distance between the target and charge, \( W \) is weight of detonator charge in kg & \( Z \) is scaled distance expressed as \( Z = \frac{R}{W^{1/5}} \). \( P_{\text{pos}} \) represents the blast overpressure acting on the plate. The peak pressure values of 150bar, 200 bar and 350bar has been used in the simulation of the V plate.

Another convenient option for the analysis of this fluid structure interaction problem is to utilize the built in blast generation function Conwep. The time history of the loading and its variation with the angle of incidence \( \theta \) is given in Ref. [7]. The total pressure is given as

\[
P(t) = P_i(t)[1 + \cos \theta_i - 2 \cos^2 \theta_i] + P_r(t)\cos^2 \theta_i, \text{ for } \cos \theta_i \geq 0,
\]

\[P(t) = P_i(t), \text{ for } \cos \theta_i \leq 0 \]  

(5)

Here \( P_i(t) \) is a function of incident pressure, \( P_r(t) \) is a function of reflected pressure, \( \theta_i \) is the angle of incidence measured between point of intersection on the target surface and the straight line connecting the point with the explosive location.

The imparted impulse (\( I \)) is be obtained by integrating the pressure acting with respect to the time duration of the loading.

\[ I = \int_0^{t_d} P(t) dt \]  

(6)

Here \( P \) represents the applied pressure due to blast loading function Conwep and \( t_d \) is the duration of loading. The time evolution of pressure and calculation of impulses due to blast loading due to conwep loading has been demonstrated by Agesh et al.[7].

3. Results

In the first part of the study the parameters like deformation of the plate and polyurea layer was simulated and compared with the experimental result given in Ackland et al [4]. A mesh convergence study was conducted on the plates subjected to Conwep loading. The mesh size for the scaled down model was varied as .006, 0.003 and .001m. The mesh size for the scaled down model was selected as .002m based on the results.

Figure 5 shows the comparison between the deformation contours of 6mm flat plate where the numerical results are compared with experiments conducted on the same plates by Ackland et al. [4]. From the comparison, it is seen that the numerical model is able to capture the experimental trends fairly accurately for the uncoated plate. A comparison of the total force transmitted to the boundaries for the flat plate and V shaped plate with 4mm thick coating are presented in Figure 6. It can be seen that the flat plate transmits the maximum force while the V shaped profiling with a polyurea layer reduces the force significantly.
Figure 5. Deformation contour of 5mm thick coated steel plate.

Figure 6. Response of the flat plate and V plate with polyurea layer.

Figure 7. Force transmitted for 1mm plates with polyurea coating.

Figure 8. Deformation for the 1mm plates with polyurea coating.

The Figure 7 shows the variation of maximum force transmitted on the V shaped plates with the variation of coating thickness. Figure 8 shows a similar variation of maximum displacement with input pressure. It is seen that there is a reduction in both deformation and transmitted force with increasing value of coating thickness, for the pressure values under consideration. This reduction could be partly due to the increasing stiffness of the structure as a result of coating and also due to the viscoelastic energy dissipation in the polyurea layer.

4. Conclusion
The main findings were:
- The V shaped plate offers substantial reduction in the transferred reaction forces to the base structure.
- The polyurea layer is capable of reducing the deflection imparted to the structure.
- From the results it also seems that the thickness of the polyurea layer affects the final force transmitted and needs further investigation for proper quantification of results.
References

[1] Teeling-Smith RG and Nurick GN1991The deformation and tearing of thin circular plates subjected to impulsive loads Int. J. Impact. Eng. 11(1)77-91.
[2] Rudrapatna NS, Vaziri R and Oslon MD 1999 Deformation and failure of blast loaded square plates Int. J. Impact Eng. 22(4), 449-67.
[3] Jacob N, Chum Kim Yuen S, Nurick GN, Bonorchis D, Desai SA and Tait D, Scaling aspects of quadrangular plates subjected to localized blast loads – experiments and predictions 2004 Int. J. Impact Eng. 30(8,9), 1179-208.
[4] Ackland K, Anderson C and Tuan Duc Ngo 2013 Deformation of polyurea-coated steel plates under localised blast loading Int. J. Impact Eng. 51, 13-22.
[5] Chung Kim Yuen S, Langdon GS, Nurick GN, Pickering EG, Balden VH 2012 Response of V-shape plates to localised blast load: Experiments and numerical simulation Int. J. Impact Eng 46,97-109.
[6] Amini MR Simon J Nemat-Nasser S 2010 Numerical modeling of effect of polyurea on response of steel plates to impulsive loads in direct pressure-pulse experiments Mechanics of Materials 42, 615–627.
[7] Agesh M Rao CL 2017 Mechanical Response Of Vshaped plates under blast loading Thin walled structures 115, 12-20.
[8] Johnson GR Cook WH 1983 A constitutive model and data for metals subjected to large strain, high strain rate and high temperature In: Proc. of the 7th symposium on ballistics, Hauge , Netherlands 541-7.
[9] Iqbal MA Senthil K Bhargava P Gupta NK 2015 The characterization and ballistic evaluation of mild steel Int. J. Impact Eng 78, 98-113.
[10] Brode HL 1955 Numerical solutions of spherical blast waves J. App. Phys 26(6), 766-75.