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Failure analysis of V-shaped plates under blast loading

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Abstract

Shaped plates assume importance in the design of armoured personal vehicles (APV). These plates are used as blast mitigation structures against land mine blasts. These shaped plates deflect and absorb a certain part of the energy imparted to them. The blast mitigating capacity at a particular impulse level mainly depends on material and the geometric parameters of the plate under consideration. The objective of this paper is to conduct a finite element (FE) based failure analysis and parametric study on the blast mitigating capability of steel plates. The important parameters of interest are the mass of the explosive and the included angle of the V shaped plate. A numerical study on V-shaped plates is carried out with ABAQUS to predict the midpoint deflection and impulse transmitted. The verified simulation procedure is repeated for conducting the parametric study. The study may be used in setting up guide lines for the design of V shaped plates for protecting vehicles.

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Keywords: V- shaped plates; Blast loading; Numerical investigation; Structural response.

1. Introduction

Close range blast loads from land mines pose a severe threat to the military vehicles and civil infrastructure. In most of the cases the loads are difficult to predict since a large number of independent variables are found to affect the loading. Attaching shaped metal plates below the vehicle floor is the only means of mitigating the effect of the blast loads in vehicles. In military vehicles providing a V shape hull is the most commonly used method for mitigating the blast effects, as shown in Fig. 1. As compared to a flat plate the V shaped plate deflects a part of the blast load and absorbs the remaining part to ensure sufficient level of protection. Sahu et al. [1] analyzed the

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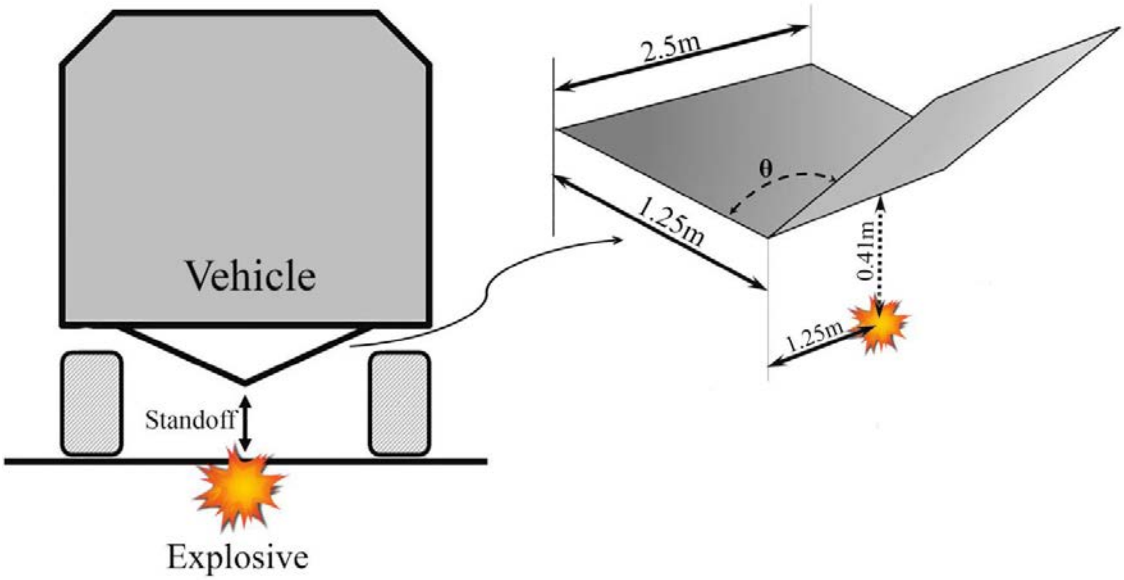
different shapes of the plate like flat shape, V shape, parabolic shape etc. and concluded that, V shape, provides the optimal protection. But the results of blast loading of V shaped plates or the details of optimum plate geometry are not easily available in open literature. But it is often used as the structural attachment in armored personal vehicles like South African Cassipir [2]. From the available literature shown in Refs. [3,4], it is seen that the plates with varying geometric parameters gives varying levels of protection against the blast loads. So it is desirable to find parameters of the V plate, which can provide the optimal protection. The objective of this present paper is to numerically analyze the blast loading response of V shaped plates. A parametric study is also conducted to find the effect of the key variables.



(Remark: Fig. 1 is attached separately in case of any formatting/resolution issues)

Fig. 1. Schematic illustrating the V-shaped plate and its terminologies.

2. Methodology

In this paper an attempt has been made to numerically simulate the blast loading response of V plate and correlate with available experimental data published by Yuen et al. [4]. A steel V plate with various included V angle (θ) is considered for the present study. These angles have been selected since plates with lesser included angles may be difficult to accommodate under the body of the vehicle. The material being considered is Domex 700 steel for which material data is readily available, Ref. [4]. The well-established Johnson -Cook model for the strain rate dependent plastic deformation is utilized. The numerical simulation is done in FE package ABAQUS . The geometry of the plate model is obtained by scaling down the dimensions of the APV, Cassipir. Here the effect of variation in mid-point deflection and the impulse transmitted with variation in parameters like a) Mass of the charge and b) V angle of the plate has been studied numerically. The results have been compared with the experimental data to ensure sufficient accuracy.

APV like Casspir have been proven to be safe for the occupants against a 14 kg TNT blast under V- shape hull, as reported in Ref. [4]. Blast loading experiments have been conducted on scaled down models of V shaped plate by Yuen et al. The geometric scaling factor used for generating the hull geometry from the actual dimensions of the APV Cassipir, has been used for obtaining other geometric parameters like stand-off distance and diameter of the explosive disc. The Hopkinson-Cranz blast scaling law, was used to scale down mass of the explosive charges for different stand-off distances. The experiments were conducted with an explosive mass range of 5g to 58g of PE4, angle range of 60 ^{0} to 180^0 and standoff distance range of 18 to 50mm. They have obtained the values of deformation, impulse transmitted and in certain cases failure patterns.

2.1. Geometry modelling

The geometric model of the V-plate is created with the inbuilt modeler in ABAQUS. The scaled down model geometry given in in the Ref. [4] is adopted here. The width of the APV, Cassipir is scaled to the width of the test plate in the ratio 8.33:1. The other geometric parameters like standoff distance and plate thickness are also scaled down in the same ratio. The dimensions of the full scale model and the scaled down model used for the validation purpose are given in Table 1. A mesh convergence study was done as the explicit analysis is sensitive to the mesh size. The mesh size of .002m was finally taken which gives error within the tolerance region. The quad type mesh is used which can give sufficiently accurate results under similar simulations. The simulations were conducted using the full plate geometry with solid elements for the calculation of impulses and deformations. The hull plate was modelled with fixed boundary along the clamped edges and utilizing the symmetry boundary conditions where ever applicable.

Table 1: Model dimensions as reported in Ref .[4].

	Parameters of scaled down model	Parameters of the full scale model
Dimensions of projected area	300x300mm^2	2500x2500mm^2
Standoff distance	34mm	410mm
Plate thickness	2mm	16.66mm
Material	Domex 700steel	Steel

2.2. Blast load modeling

Blast load is modeled by using the CONWEP blast loading function in ABAQUS. Adisak Showichen [5] has given a brief description about CONWEP. CONWEP is an empirical equation used for directly applying the blast load on any structural geometry. CONWEP takes into account a) the distance between the target and the charge, b) mass of the charge and c) inclination of the target, for calculation of the blast pressures. Although convenient, it is incapable of considering the effect of very near field loading and reflection from the nearby bodies. It helps to reduce the burden of explicitly simulating the progress of the shock wave and its interaction with structure. The pressure calculation using CONWEP function is based on experimental data and they can be used only by appropriately including the scaling parameters considering the actual explosion. The empirical model CONWEP has been implemented in the ABAQUS 6.10, and is used as such in the simulation.

2.3. Material modelling

The targets subjected to blast loading are subjected to shock loads which last for a few milliseconds and are subjected to high strain rates under these conditions. Material modelling under high strain rate is captured with Johnson – Cook model. The model describes the material flow stress as a function of strain, strain rate, and temperature. The associated Von Mises flow stress can be calculated as

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

Here ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}$ is the dimensionless plastic strain rate and $\dot{\varepsilon}_0$ is the reference strain rate. T^* is the homologous temperature. The constants in the equation namely A, B n, C and m may be determined from experiments. The dynamic simulation can be carried out with Johnson -Cook model with appropriate constants for Domex 700 steel. An explicit dynamic analysis with 3D elements was carried out. The material properties taken from Yuen et al. and shown in Table 2,

Table 2. Material properties of plate

$A(MN/m^2)$	$B(MN/m^2)$	$C(s^{-1})$	m	n	T^m (K)	$\dot{\varepsilon}_0$ (s^{-1})
818	1423	0.014	1	0.987	1793	1

3. **Finite element results**

The initial studies are aimed at establishing reliability of the numerical simulations using CONWEP blast loading function. Although fluid structure interactions can be carried out to capture the detailed simulation of the blast wave, it is more convenient to use the inbuilt loading function as a design tool due to the lesser computation time. Further it is seen from the Ref. [4] that errors for the numerical results using the fluid structure interaction calculations maybe even more than 20% in few cases, due to the non-linearity involved. Numerical simulations were conducted for finding the impulses when both mass of the explosive and the plate angle were varied successively. The mass of PE4 considered are 5, 14 and 19g. The effect of variation in mass of explosive on the imparted impulses for 180^0 and 150^0 plate is shown in Fig. 2. The experimental results reported in Ref. [4], for the above case is also shown for comparison. It is seen that the 180^0 plate gives a better fit as compared to the 150^0 plate. The maximum error can found for the flat plate is 7.5% while for the 150^0 plate it is 26.2%.

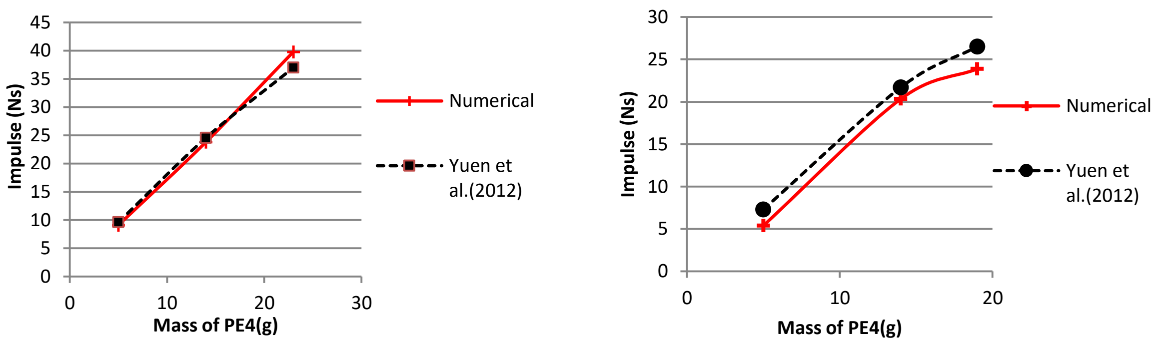


Fig. 2. Variation in predicted and measured value of impulses for (left) 180^o and(right) 150^o plate

Similarly study was conducted for finding the deflections of V shaped plates for variations in the mass of the explosive. Numerical simulations for finding the deflections were carried out and the results are compared with the experimental results, taken from Ref. [4], and shown in Fig. 3. The maximum error between the between the experimental and numerical values are found as 33%. The results show that the numerical method is sufficiently accurate and hence can be used for further parametric studies.

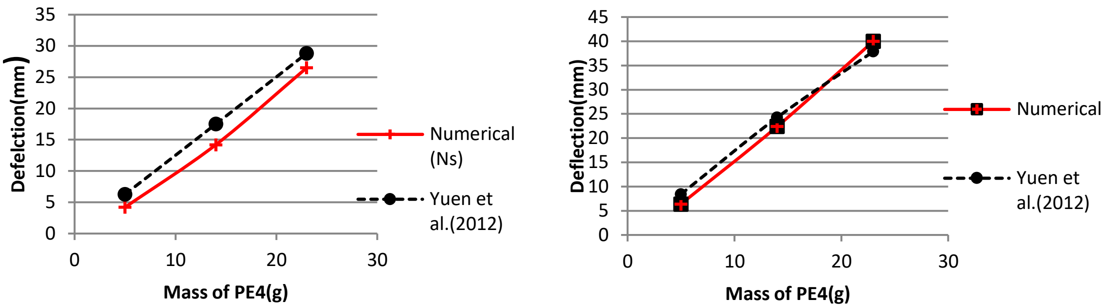


Fig. 3. Variation in predicted and measured value of midpoint deflections for (left) 180^0 plate and (right) 150^oplate

Numerical simulations were conducted for finding the impulse at various explosive masses that is 24, 30.5, and 36.3g of TNT which is very near to the fracture load of the plate. The standoff distance is now kept as 50mm instead of 34mm as this represents the geometrically scaled value. The effect of mass variation on the 150^0 V plate is displayed in Fig.4.a along with the experimental results reported by Yuen et al. for a lower range of load (that is 6.5gTNT to 18.85gTNT). The results show that higher value of loading results in higher values of impulse, but the rate of change impulse is much lower compared with response at lower mass values of the explosives. Similarly the impulse variation for plates with angles 145^0, 160^0 and 180^0 were investigated for a mass of 28gTNT at standoff distance of 50mm and is shown in Fig.4.b. The results are plotted along with experimental results from Yuen et al. for the angled plates for other values of explosive mass. It is seen that there is a general trend of increase in impulse with increase in plate angles for both experiments and simulation. It is seen from simulations that the 145^0 and 160^0 plates have little difference with respect to imparted impulse, while the flat plate transmits much larger impulse in comparison. This shows that the flat plate is inferior to the moderately angled plates especially at higher value of impulses.

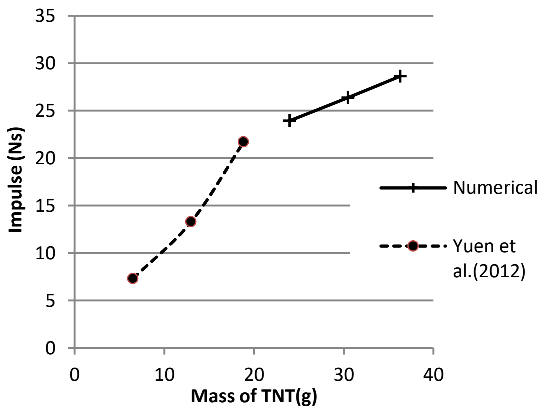


Fig.4.a. Predicted and measured value of impulses for 150^0 plate at different load ranges.

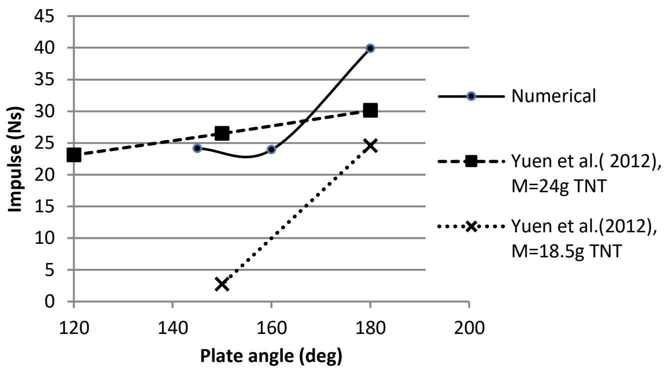


Fig.4.b. Predicted and measured value of impulses for plates with varying angles and load ranges.

The next parametric study was conducted to find the effect of variation of mass of the charge on the 150^0 V plate at the standoff distance of 50mm. Similar to the impulse simulations the mass of the explosive is varied in the range from 24g to 36.3g TNT, and the deflection values were found. A comparison is made with the experimental results obtained from Yuen et al. at lower mass ranges as shown in Fig.5.a. It is seen that the loading range is important factor affecting the final deflection. A higher loading range produces a higher rate of deflection even though the standoff distance is more as compared with the experimental results. Similarly the parametric study was also conducted to find the dependence between plate angle and midpoint deflection. The deflection of the plates with 145^0, 160^0 and 180^0 are plotted along with the data from experiments conducted by Yuen et al.[4] and shown in Fig. 5.b. The mass was selected as 28g of TNT placed at a standoff distance of 50mm. It is seen that the plates with angles of 145^o and 160^0 suffer almost the same kind of deflection. It is also seen that they offer considerably lesser resistance to the loading. It is seen from the reported experiments, in Ref. [4] that the overall trend indicates an increase in deflection with an increase in plate angle. But the trend of inverse relation between these variables at lower charge mass of 14.5g PE4 at plate angle of 150^o is also reported by Yuen et al. It is also seen from the simulation that the variation in deflections of the plates is higher for higher charge masses as compared to lower charge masses used in the experiment.

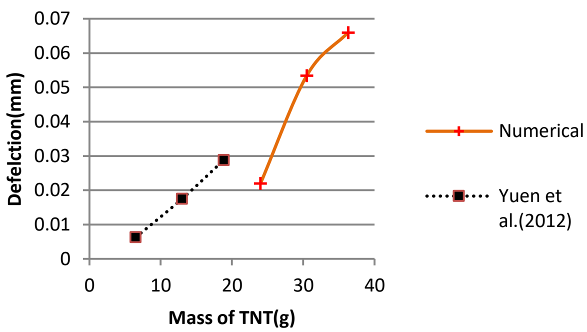


Fig.5.a. Variation in predicted and measured value of midpoint deflections for 150^o plate

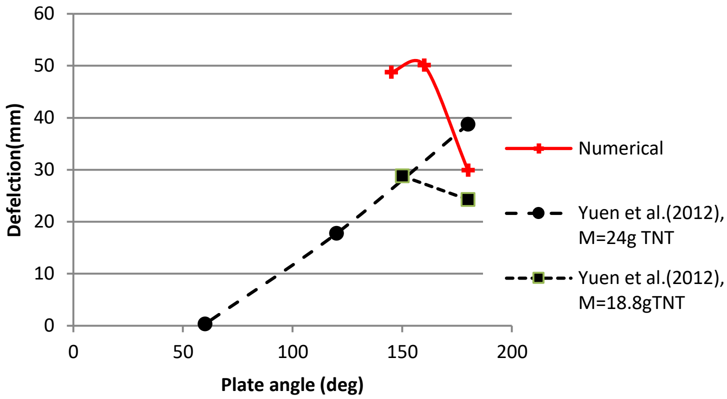


Fig.5.b. Variation in predicted and measured value of midpoint deflections for 150° plate.

4. **Conclusion**

In this paper we have presented a numerical simulation of the blast loading of V shaped plates by a spherical explosive placed directly under the center of the plate. The results indicate that there is a general trend of increasing values of transmitted impulses with the increase in mass of TNT and plate angle. The deflection pattern also shows an increase with increase in mass of the charge. Further it is seen from simulation that at angles close to180° the plates undergo considerable deformation while transmitting lesser values of impulses. It is anticipated that these guidelines may help in designing the hull of the blast resistant vehicles.

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