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Application of manifold method to punch loading tests for polymer bonded explosives

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ABSTRACT: Punch loading is a loading scenario to study the fracture mechanism of materials at low strain rates. In this paper, punch loading experiments of Polymer Bonded Explosives (PBXs) materials were simulated by manifold method. The flat and wedge shaped punch were used to investigate the difference of shear stress field and crack propagation mechanism. The predicted results are in good agreement with experimental results.

1 INTRODUCTION

Polymer Bonded Explosives (PBXs) are highly particle filled composite materials comprised of 90–95% by weight of powerful secondary explosive particles and 5–10% by weight of binder. They are used in both civil and military applications where very high performance is required. Energetic materials may be subjected to different external stimuli during handling, storage and transport, resulting in the change of microstructure and even mechanical failure. Damage influences not only the mechanical properties, but also the sensitivity, combustion and detonation behavior of explosives. Understanding the mechanical responses of PBXs is of great interest to the defense industry and commercial applications. Recently, different experimental methods, e.g., Brazil test, three-point bending test and punch loading test, have been developed to study the mechanical properties of PBXs (Kauly et al., 1998, Peterson et al., 2001, Chen et al., 2007). Punch loading is a loading scenario that a rigid object slowly penetrates the material at low strain rates. Prandtl firstly proposed a slip-line solution to the strain distribution on a semi-infinite, plastic body during impact and penetration by a rigid flat punch. Based on the digital image correlation technique, the punch loading test and Prandtl's theory have been used to investigate the deformation and fracture behavior of PBX materials (Chen et al., 2006, Zhou et al., 2010). In addition, different finite element software, including ANSYS/LSDYNA and ABAQUS, have been developed to study the macro and micro mechanical properties (Clancy et al., 1998, Wu et al., 2009). However, the finite element method is not good at the simulation of crack.

Manifold Method proposed by Shi is a new numerical method, which provides a unified framework for solving problems with both continuous and discontinuous media (Shi, 1984). By employing the concept of cover and two sets of meshes, manifold method combines the advantages of FEM and Discontinuous Deformation Analysis. It can not only deal with discontinuities, contact, large deformation and block movement as DDA, but also provide the stress distribution inside each block accurately as FEM can. The numerical model of the original MM possesses only the first-order accuracy, leading to dissatisfaction in simulating problems that need high accuracy in displacement and stress distribution. To overcome this and expand the applicability of MM, Zhang et al. (2008) developed the second order manifold method with six node triangle mesh. In this paper, the deformation and failure of PBXs under different punch loading test was numerically studied by using manifold method. The results may provide some further insights into deformation and failure mechanisms of explosives.

2 MM MODEL OF PUNCH LOADING TEST

Figure 1 shows MM model of flat punch loading test and wedge-shaped punch loading test respectively. The size of sample is 20 mm × 10 mm, the contact surface size of punch is 6 mm. The quasi-static displacement loading is applied to the punch and induce punch impacting PBX sample with a velocity of 2 mm/min. The punch is regarded as rigid and material parameters of PBX are listed in Table 1.

Different criteria are used in the initiation of new cracks and the growth of existing cracks. For the initiation of new cracks, a stress-based criterion, Mohr-Coulomb's Law with three parameters, is considered. It is assumed that new cracks initiate if: (a) the first principle stress is larger than the tensile strength of the material, or (b) the maximum shear stress is larger than the shear strength of the material. The failure criterion can then be expressed as

Tensile failure:

$$\sigma_1 = T_0 \tag{1}$$

Shearing failure:

$$(\sigma_1 - \sigma_3)/2 = C, \quad \text{if } (\sigma_1 + \sigma_3)/2 > 0 \text{ and } 0 < \sigma_1 < T_0 \tag{2}$$

$$(\sigma_1 - \sigma_3)/2 = C\cos\phi - (\sigma_1 + \sigma_3)\sin\phi/2, \quad \text{if } (\sigma_1 + \sigma_3)/2 < 0 \text{ and } 0 < \sigma_1 < T_0 \tag{3}$$

where σ_1 and σ_3 are the first and third principal stresses, T_0 is the tensile strength, C is the cohesion and ϕ is the friction angle.

For the existing cracks, the fracture toughness K_{IC} of the material is taken as the fracture criterion, and the maximum circumferential stress theory is adopted to determine the direction of crack growth measured from the current crack line θ.

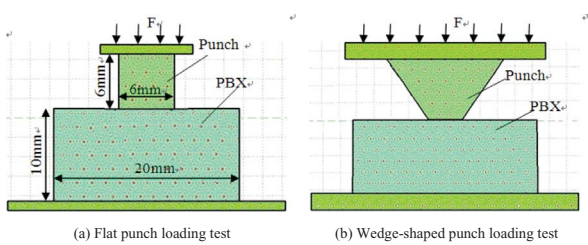
$$K_{\mathrm{I}} \sin\theta + K_{\mathrm{II}}(3\cos\theta - 1) = 0 \tag{4}$$

The fracture criterion for a mix mode problem takes the form as:

$$\cos(\theta/2)\left[K_{\mathrm{I}}\cos^2(\theta/2) - 1.5K_{\mathrm{II}}\sin\theta\right] = K_{IC} \tag{5}$$

3 RESULTS AND DISCUSSIONS

Figure 2 shows the shear strain distribution of PBX samples under loading of flat and wedge punch respectively. Strain concentration was both occurred in PBX samples under different



(a) Flat punch loading test (b) Wedge-shaped punch loading test

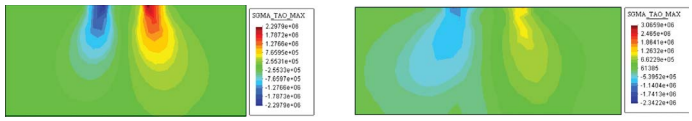
Figure 1. MM model of punch loading test.

Table 1. Material parameters of PBX.

Density (g/cm^3)	Young modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Cohesive strength (MPa)	Friction angle (°)
1.83	2	0.3	2	5	30

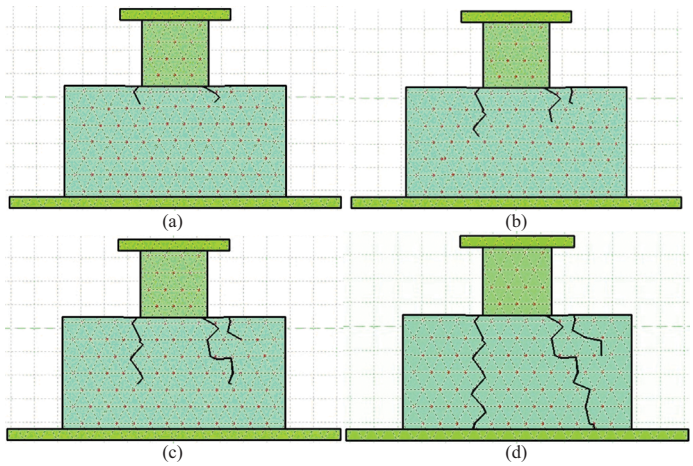
punch loading tests. Two shear strain concentration bands were underneath the punch and on two sides of the dead zone which proposed by Prandtl. The shear effect may induce initiation and propagation of cracks, and even failure of materials.

Figure 3 shows the simulation results of the failure process PBXs under quasi-static flat and wedge-shaped punch loading test by the manifold method. The corroding image of real fractured PBX sample (Li, 2009) is shown in Figure 4 for comparison. The results show that failure first initiates at the top boundary of PBX sample and forms initial cracks when the maximum shear stress reaches the shear strength of PBXs. With the increase of vertical load, the cracks propagate along the shear strain concentration band towards the bottom, finally form two long continuous cracks and result in the fracture of sample. The fracture region is different for flat and wedge-shaped punch loading test due to different shaped

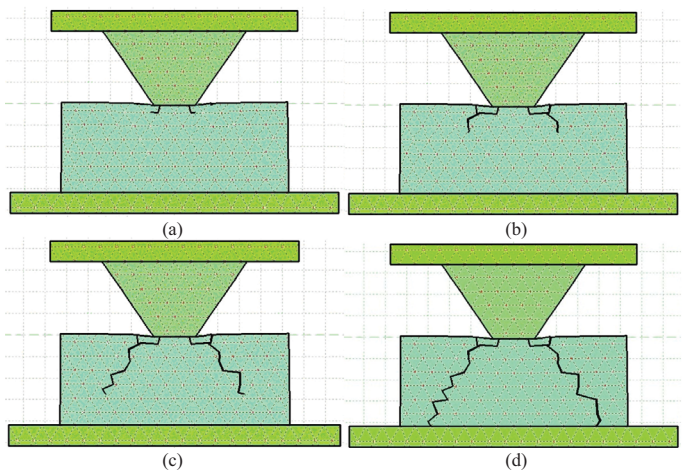


(a) Flat punch loading test (b)Wedge-shaped punch loading test

Figure 2. Shear strain distribution of PBX.



Flat punch loading test



Wedge-shaped punch loading test

Figure 3. Simulation results of failure process of PBXs under different shaped punch loading.

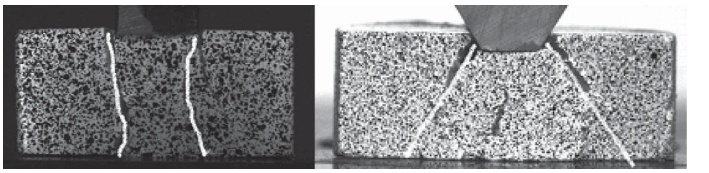


Figure 4. Experimental results for comparison.

punch resulting different shear stress distribution. It is noted that new crack occurs near the main crack during the propagation of main cracks. However, the crack does not obviously develop. For two kinds of shape punch loading, the simulation is in good agreement with the experimental results.

4 CONCLUSIONS

Different punch loading patterns including flat punch and wedge punch were applied to PBXs samples. The failure process of PBXs was studied by using manifold method. The shear strain distribution was obtained and used to analyze the fracture behavior and failure mechanisms of explosives. The simulation results show that the initial failure tends to start the top contact boundary of PBXs and propagate along the shear strain band. The punch shape influences the formation of shear strain band and fracture region. The predicted results are in good agreement with experimental results. Applicability of punch loading test and the corresponding computational techniques used to the study of the deformation and failure of PBXs is verified.

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