Modelling of the PELE fragmentation dynamics

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J Verreault
Weapon Systems, TNO, Lange Kleiweg 137, 2288 GJ Rijswijk, The Netherlands

E-mail: jimmy.verreault@tno.nl

Abstract. The Penetrator with Enhanced Lateral Effect (PELE) is a type of explosive-free projectile that undergoes radial fragmentation upon an impact with a target plate. This type of projectile is composed of a brittle cylindrical shell (the jacket) filled in its core with a material characterized with a large Poisson's ratio. Upon an impact with a target, the axial compression causes the filling to expand in the radial direction. However, due to the brittleness of the jacket material, very little radial deformation can occur which creates a radial stress between the two materials and a hoop stress in the jacket. Fragmentation of the jacket occurs if the hoop stress exceeds the material's ultimate stress. The PELE fragmentation dynamics is explored via Finite-Element Method (FEM) simulations using the Autodyn explicit dynamics hydrocode. The numerical results are compared with an analytical model based on wave interactions, as well as with the experimental investigation of Paulus and Schirm (1996). The comparison is based on the mechanical stress in the filling and the qualitative fragmentation of the jacket.

1. Introduction

The Penetrator with Enhanced Lateral Efficiency (PELE) is a type of ammunition that exhibits a larger lateral dispersion of its fragments upon perforation of a target plate compared with a more conventional ammunition (such as a kinetic penetrator). This behaviour was observed experimentally by Paulus and Schirm [1] and is illustrated schematically in figure 1. Also shown in this figure are the two main parts that compose a PELE projectile: a filling made of a relatively soft material (such as polyethylene or aluminium) and a jacket made of a brittle material (such as tungsten or hardened steel). In order to describe the origin of the PELE effect, figure 2 shows the shock and expansion waves that propagate in the target and the PELE projectile. Soon after the impact, shock waves travel in the filling and the target. Due to the fact that the filling’s material has a larger Poisson’s ratio than that of the jacket, there is a radial stress between the two parts. This radial stress causes the radial expansion and fragmentation of the jacket. At later times after the impact, radial and axial expansion waves travel in the filling and weaken the shock wave.

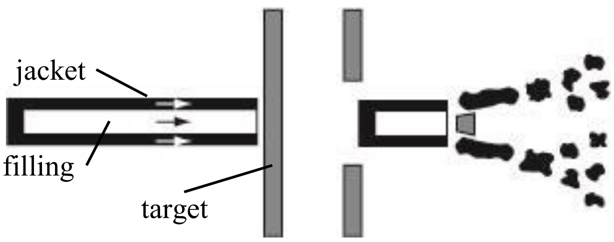

Figure 1. Schematic of the PELE fragmentation.

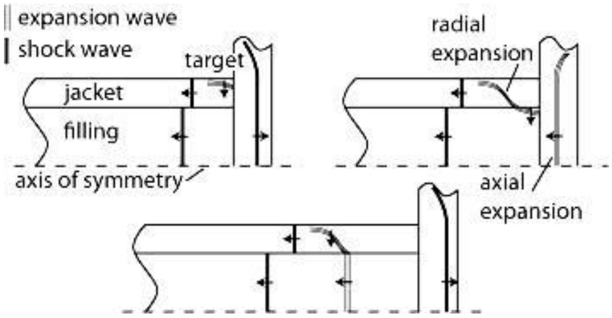

Figure 2. Schematic of the waves propagation in a PELE projectile and a target.

An analytical model based on shock and expansion wave propagation to describe the fragmentation of PELE projectiles was proposed by Verreault et al. [2]. This model assumes uniaxial strains in the filling. In general, a uniaxial strain state occurs in plate impacts, whereas a uniaxial stress state is commonly assumed for rod impacts. However, due to the brittleness of the jacket material, little radial deformation occurs in the jacket prior to fragmentation. Since the filling is constrained within the jacket, a uniaxial strain state can be assumed in the filling.

In this paper, the fragmentation process of PELE projectiles is explored via finite-element simulations. The results from the simulations are compared with the analytical model based on the mechanical stress in the filling and on the radial velocity of the jacket. This comparison assesses the uniaxial strain assumption used in the analytical model, while ensuring that the radial velocity of the fragments corresponds the experimental results of Paulus and Schirm [1]. In addition, a qualitative comparison of the fragmentation between the numerical and experimental results is provided.

2. Numerical model and impact conditions

2.1. Numerical model

The numerical simulations were conducted using the ANSYS Autodyn 14.0 software [3]. The 3D numerical model covered one quarter of the full domain using two perpendicular planes of symmetry, as shown in figure 3. An Euler – Lagrange coupling was used, since the jacket and target were simulated in Lagrangian volumes, whereas the filling occupied an Euler domain. The material models for the three parts are summarized in table 1. The failure model of the jacket, which was implemented as a user-defined subroutine in Autodyn, combined the Johnson-Cook failure model and a stochastic failure. In the Johnson-Cook failure model, the failure strain is related to three terms: the stress triaxiality, the strain rate and the temperature (see equation (1)), where the coefficients D_1 to D_5 are provided in table 2. These coefficients prevent failure in compression, which occurs at the impact with the target, and provide a failure strain of approximately 0.07 in pure shear and 0.03 in uniaxial tension, which occurs during the radial expansion. The cumulative damage of an element is given by the amount of plastic deformation divided by the failure strain, as expressed by equation (2). The stochastic failure, which is derived from the Mott distribution [4], is given by equation (3) and relates the probability of failure as a function of the cumulative damage (C and γ are provided in table 2).

2.2. Impact conditions

The geometric dimensions of the PELE projectile and the target in the numerical simulations correspond to those provided by Paulus and Schirm [1]. The filling diameter is 6 mm, the jacket outer diameter is 10 mm and the target thickness is 8 mm. Two impact velocities are considered in the next section; 1.3 and 2.4 km/s. In the simulation, the target is initially moving at the specified impact velocity, while the projectile is initially at rest.

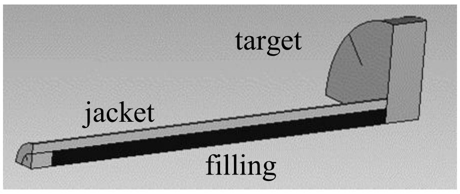

Figure 3. 3D numerical model.

Table 1. Material models used in the simulations.

	Filling	Jacket	Target
Material	polyethy-lene	tungsten alloy (3.5%Ni-1.5%Fe)	Al-6082
Equation of state	shock [5]	shock [5]	shock [5]
Strength	none	Steinberg Guinan [6]	Johnson-Cook [7]
Failure	none	Johnson-Cook (stochastic)	plastic strain
Erosion	none	geometric strain	geometric strain

$$\bar{\varepsilon}_f = \left[D_1 + D_2 e^{D_3 \sigma^*}\right]\left[1 + D_4 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{\mathrm{ref}}}\right]\left[1 + D_5 T^*\right] \tag{1}$$

$$D = \sum \frac{\Delta\varepsilon}{\bar{\varepsilon}_f} \tag{2}$$

$$P(D) = 1 - \exp\left[-\frac{C}{\gamma} e^{\gamma D} - 1\right] \tag{3}$$

Table 2. Parameters of the jacket failure model.

Johnson-Cook		Stochastic	
D_1	0.03	C	3.18e-6
D_2	0.05	γ	15
D_3	-10		
D_4	0.12		
D_5	0		

3. Results

3.1. Mechanical stress in the filling
Considering an impact velocity of 1.3 km/s, figure 4 presents the pressure evolution of particles initially located at 5 and 13 mm from the tip of the projectile. In this figure, the numerical results are compared with the analytical ones. The analytical profile shows an impact pressure of 3.5 GPa followed by a pressure decrease due to the arrival of the expansion wave. At increasing distance from the tip (see the profile for the particle initially at 13 mm), the duration of the impact pressure decreases. The numerical profile shows a similar trend, although fluctuations about the impact pressure are observed, which is due to the interaction between the jacket and the filling. The radial velocity of the fragments (originating from the jacket) is shown in figure 5, where the experimental result from Paulus and Schirm [1] is also included. The experimental measurements refer to the maximum radial velocity observed amongst all fragments, which occurred at the tip of the projectile. The analytical model predicts a final radial velocity of 145 m/s at the tip of the projectile and of 91 m/s

at an initial location of 13 mm from the tip. The numerical results follow closely the analytical profiles during the acceleration phase, but deviate from them at the end of the acceleration. At the tip of the projectile, the radial velocity is close to the experimental value 6 μs after the impact. At this time, the numerical element became excessively distorted and was numerically eroded. At 5 and 13 mm from the tip, the numerical results provide lower final velocities compared to the analytical results. This is due to the strain rate term in the failure model (second term in equation (1)), which was not accounted for in the analytical model. A comparison with experiments of the radial expansion of the fragments away from the tip is shown in the next section using X-ray photographs.

The pressure evolution in the filling for an impact velocity of 2.4 km/s is presented in figure 6. In this case, the impact pressure calculated by the analytical model is 8.8 GPa. The attenuation of the shock wave can be observed with the profiles for particles initially at 13 and 23 mm from the tip of the projectile. Considering the numerical results, the particle at the tip of the projectile was numerically eroded soon after the impact. However, the pressure evolution for the other two particles follows closely the analytical profiles. The corresponding radial velocity of the fragments is shown in figure 7. In this case, the analytical model predicts a slightly higher radial velocity at the tip of the projectile compared with the experimental result of Paulus and Schirm [1]. Similar to the 1.3 km/s impact velocity, the numerical results agree well with the analytical ones during the acceleration phase and the final radial velocity is slightly lower due to the strain rate dependency of the failure model.

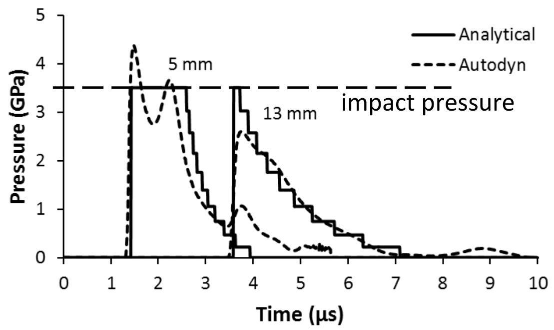

Figure 4. Pressure profiles at different axial locations for an impact velocity of 1.3 km/s.

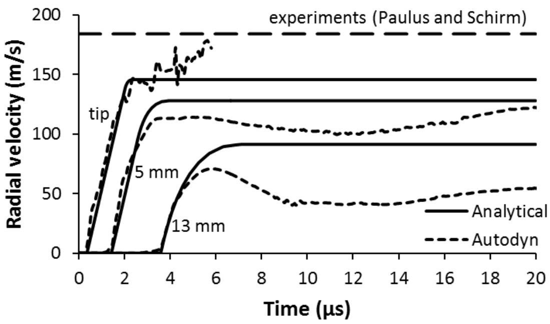

Figure 5. Radial velocity of the jacket for an impact velocity of 1.3 km/s.

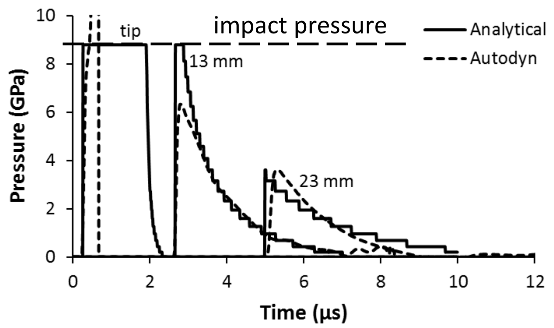

Figure 6. Pressure profiles at different axial locations for an impact velocity of 2.4 km/s.

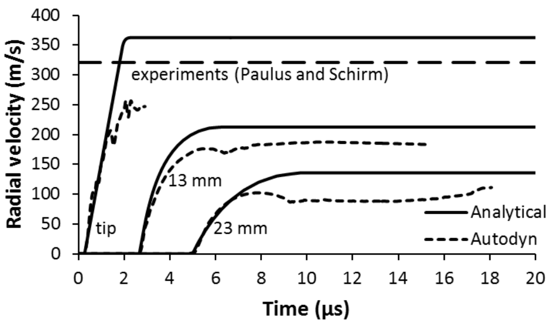

Figure 7. Radial velocity of the jacket for an impact velocity of 2.4 km/s.

3.2. Fragmentation of the jacket

Fragmentation of the jacket 13 μs after impact at 1.3 km/s is shown in figure 8, where the filling and the target are not shown for clarity. The cracks propagate in both longitudinal and circumferential direction. This is a result of failure under both shear and tension, as accounted for in the stress triaxiality term of the failure model (first term of equation (1)).

Fragmentation of the jacket at later times for impact velocities of 1.3 km/s is shown in figure 9 from the numerical simulation and from the experimental results of Paulus and Schirm [1]. The numerical simulations shows that only a portion of the jacket is fragmented. Far from the tip of the projectile, the radial stress between the filling and the jacket is insufficient for the jacket to fail. A target plug is formed and penetrates in the core of the projectile up to the point where the jacket is no longer fragmented. The experimental X-ray photograph shows that the jacket is fragmented over a longer distance than the numerical simulation and more fragments are generated. For the case of a 2.4 km/s impact velocity (figure 10) the jacket is fragmented along the complete length. In this case, the target plug has a sufficient inertia to provide additional stresses in the filling and the numerical simulation qualitatively agrees better with the experimental X-ray photograph.

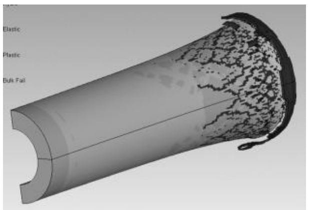

Figure 8. Fragmentation of the jacket 13 µs after an impact at 1.3 km/s.

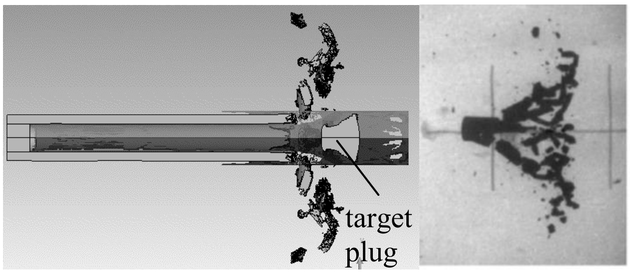

Figure 9. PELE fragmentation at 1.3 km/s (experimental X-ray photograph from Paulus and Schirm [1] used with permission).

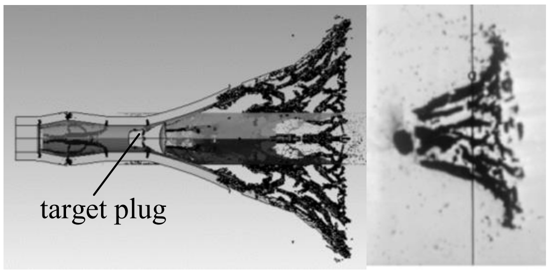

Figure 10. PELE fragmentation at 2.4 km/s (experimental X-ray photo-graph from Paulus and Schirm [1] used with permission).

4. Conclusions

Numerical simulations of the PELE fragmentation dynamics showed that the filling is subjected to a uniaxial strain state and is therefore a valid assumption for the analytical model, since the mechanical stresses are similarly reproduced in both cases. Furthermore, the radial velocity of the jacket obtained from the analytical and numerical models is in fair agreement with the experimental results of Paulus and Schirm [1]. The use of a Johnson-Cook failure model combined with a stochastic failure provided fragmentation of the expanding jacket upon perforation of the target plate. A qualitative comparison with experimental X-ray photographs showed that less fragments are simulated for an impact velocity of 1.3 km/s, while a fair agreement was obtained for an impact velocity of 2.4 km/s.

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