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THE INFLUENCE OF THE FRONT LAYER OF A REACTIVE ARMOR ON LONG ROD PENETRATOR DISRUPTION

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The main aim of this investigation was to study the complex interaction between the kinetic energy projectile and the Explosive Reactive Armor (ERA) module’s front plate including the edge effect caused by the simultaneous initiation of the explosive layer inside the armor module and the projectile’s penetrative motion. In order to gain a better understanding regarding the interaction mechanism between the long rod and the moving steel plate, we performed a series of 3D numerical simulations with the hydrodynamic codes of a generalized reactive armor module. The effect of impact point location on the reactive armor’s efficiency was investigated by means of a witness plate located at a specified distance behind the reactive armor. It was shown that the differences in rod shape distortion are due to the impact point location on the front plate and that the reactive armor’s ballistic efficiency is reduced when a witness plate is located in close proximity behind the reactive armor.

INTRODUCTION

The disruptive effect of a reactive armor sandwich on a long rod penetrator includes the possible action of both the front and rear plates on the projectile. As a consequence, the projectile's remains may be deflected and further fragmented. The few published papers on the subject refer to either the simultaneous action of both plates (the inverse scissor effect) or to the action of the back plate alone (ricochet), while neglecting the contribution of the front plate. However, in cases where the reactive armor is sufficiently energetic or the armor obliquity angle is large enough, mainly the front plate interacts with the projectile, while the rear plate is evacuated.
The interaction between stationary oblique armor plates and the long rod projectile, in the form of a direct impact with a moving projectile, has been previously investigated [1,2], however few published results are available. Wollmann et al [3] described a

method for accelerating single plates by means of electromagnetic forces and some results of direct impact tests with long rod projectiles were presented. Hou and Goldsmith [4] studied the penetration characteristics of an idealized small caliber projectile in direct impact with a rotating disc target. The penetration performance of a long rod penetrator may be considerably degraded when passing through a reactive armor sandwich. The defeating mechanism was already investigated by several authors both theoretically and experimentally. Held [5,6] studied the simultaneous motion of both the front and back plates which resulted in an inverse scissor effect, while Rosenberg & Dekel [7] focused only on the ricochet caused by the rear plate. The main aim of this investigation was to study the complex interaction between the kinetic projectile rod and the armor module's front plate, while taking into account the edge effect caused by the simultaneous initiation of the explosive layer inside the armor module. In order to gain a better understanding of the interaction mechanism prevailing between the long rod and the moving steel plate, we performed a series of 3D numerical simulations, with the Lagrangian Solver of the LS-DYNA hydrodynamic code. Several sets of numerical simulations were carried out incorporating a generalized reactive armor module. The effect of impact point location on the reactive armor's efficiency was investigated incorporating a witness plate located at a specified distance behind the reactive armor. The witness plate is used to evaluate projectile rod penetration efficiency.

NUMERICAL SIMULATION OF ERA PENETRATION

The numerical model contains a full generalized explosive reactive armor module comprised of front and rear steel plates and a middle layer of C4 explosive. The front and rear plates both have a length to width ratio of L/W=4 and the latter has a thickness which is half of the front plate's thickness. The oblique impact angle between the reactive armor module and the tungsten rod projectile is large. In our simulation the projectile rod length to diameter ratio is approximately L/D~30. The explosive layer is detonated in the simulation when the explosive initiation threshold criterion reaches its threshold value. Such threshold criteria are based upon projectile characteristics such as velocity and external diameter (v^2D) and a coupled combination of the pressure level and the time duration that determine the value of the P^2t explosive initiation criteria. The JWL equation of state (EOS) was used to define the pressure of the detonation products of the C4 explosive. This EOS is used mainly for determining the pressure of the detonation products in applications involving metal accelerations. Input parameters for this equation are given by Dobratz [8] for a variety of high explosive material. The unreacted explosive, projectile rod and the reactive module front and back plates were modeled using the Johnson Cook Material strength model. The Gruneisen equation of state with cubic particle velocity, which defines pressure for shock-compressed material, was used. A Lagrange approach was used to model the reactive module components and the projectile rod. The numerical simulation results are shown in Figure 1, which depicts several frames of projectile penetration into the reactive armor module at its center region.

The detonation products of the explosive generate a steep rise in pressure which cause the front and back plates of the reactive module to separate and move quickly in opposite directions. The moving front plate interacts with the projectile rod's original trajectory causing the rod to deviate from its original flight path. The rod is continuously tearing a narrow strip from the plate with which it is in contact. This strip serves as a contact point for the rod causing the large deflection seen in the projectile rod. As may be seen in Figure 1, there is no interaction between the projectile rod and the back plate of the reactive module during all of the penetration process. This is mainly due to obliquity angle of the reactive module relative to the penetrator and it's explosive energy.

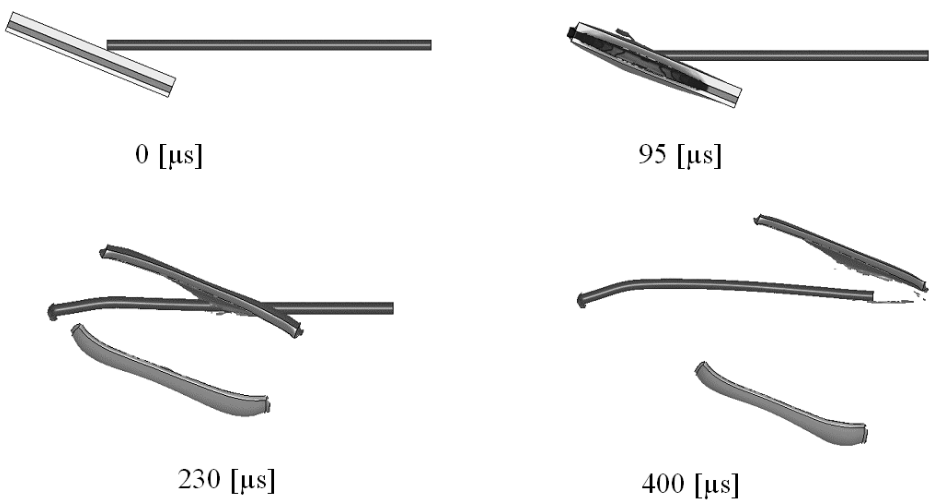

Figure 1. Projectile penetration processes into armor module cassette

The explosive initiation creates a very sharp blast of pressure which loads the front and rear plates of the reactive module. This abrupt shock deforms the plates plastically. This explosive effect, combined with the plates’ stiffness and the interaction of the projectile rod, caused different regions of the plates to move at different resultant velocities. For instance the difference between the front plate’s resultant velocity at its center and its upper section velocity, when the projectile rod impacts its center, could be approximately 100-150m/s. As mentioned previously, the projectile’s trajectory is deflected during penetration as a consequence of front plate interaction. The rear plate is evacuated backwards with a correspondingly larger velocity than that of the front plate's whose weight is twice as large. This effect is demonstrated in Figure 2.

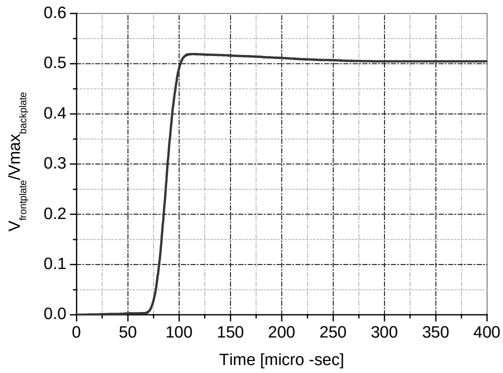

Figure 2. Reactive armor front and back plate velocity ratio

Experimental results showed that the projectile rod can impact the reactive armor front plate not only at its center. The projectile impact point at the front plate of the reactive armor module largely influences the resulting projectile shape and witness plate crater penetration depth characteristics. The general profile of the projectile rod after the penetration of a reactive armor module, is shown in Figure 3.

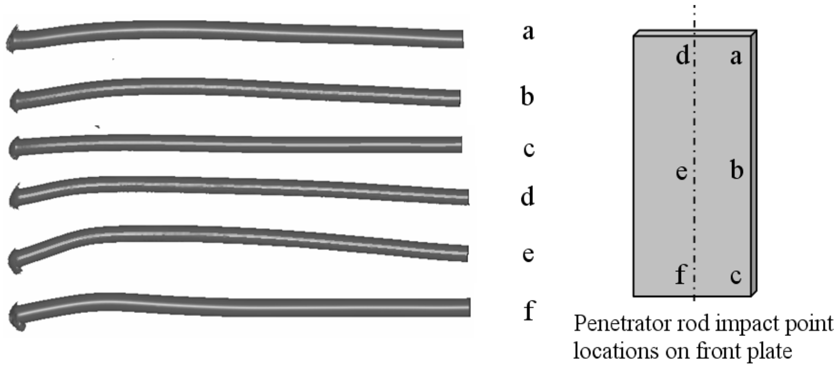

Figure 3. Projectile shapes after interaction with a reactive armor module at different locations on the front plate

The differences of the rod shapes are due to the interaction length between the rod and the front plate, and are a function of the impact point location. The closer the impact point is to the center of the plate, the larger the distortion of the penetrator rod, while the least damage is caused when impact occurs at the bottom of the plate. For the latter case, the rear portion of the projectile rod remains intact without any change of its initial curvature.

The interaction length between the projectile rod and the front armor plate can be estimated analytically. The analytical model is based on geometrical considerations without taking into account "edge effects", which are created as a result of the initiation of explosion. In actuality (and in our hydrodynamic simulation) the interaction process of the projectile with the front plate consists of two main stages. At first, the explosive material is uninitiated so the projectile is penetrating an oblique stationary front plate. The second stage, after initiation, consists of a simultaneous motion of the projectile (V_p) and the front plate (V_f). This results in an interaction length along the front layer. A rough estimate of the interaction length is obtained by viewing the problem as a purely geometrical one. The projectile and front plates are considered to be rigid bodies "with each one is moving through the other" without strength and energy considerations. Furthermore, a constant movement of the front plate immediately after impact is assumed. A simple calculation gives the following expression for the projectile interaction length, ℓ_p :

$$\ell_p = \begin{cases} h\left[\dfrac{(v_p/v_f)\cos\theta+1}{\sin\theta\cos\theta}\right] & \text{for} \quad h \le L\left[\dfrac{\sin\theta\cos\theta}{(v_p/v_f)\cos\theta+1}\right] \\ L & \text{for} \quad h > L\left[\dfrac{\sin\theta\cos\theta}{(v_p/v_f)\cos\theta+1}\right] \end{cases} \qquad (1)$$

and for the interaction length on the front plate:

$$\ell_f = \begin{cases} \dfrac{h}{\cos\theta} & \text{for} \quad h \le L\left[\dfrac{\sin\theta\cos\theta}{(v_p/v_f)\cos\theta+1}\right] \\ L\dfrac{\sin\theta}{1+(v_p/v_f)\cos\theta} & \text{for} \quad h > L\left[\dfrac{\sin\theta\cos\theta}{(v_p/v_f)\cos\theta+1}\right] \end{cases} \qquad (2)$$

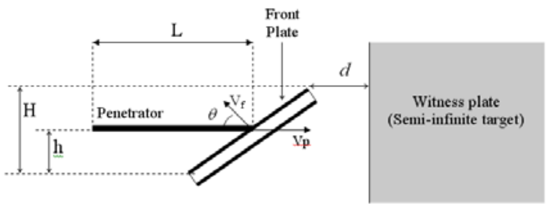

Figure 4. Armor configuration

Denoting by h_0 the minimal height of the projectile which gives full interaction, i.e. interaction length l=L, we found that $\frac{h_0}{L}=\frac{\sin\theta\cos\theta}{(v_p/v_f)\cos\theta+1}$ (see Fig. 4). The plot in Fig. 5 shows that generally this expression (as a function of θ) has a maximum which is the solution to the equation $\frac{v_p}{v_f}\cos^3\theta+2\cos^2\theta-1=0$. In case $\frac{v_p}{v_f}=4$, θ is 60^0.

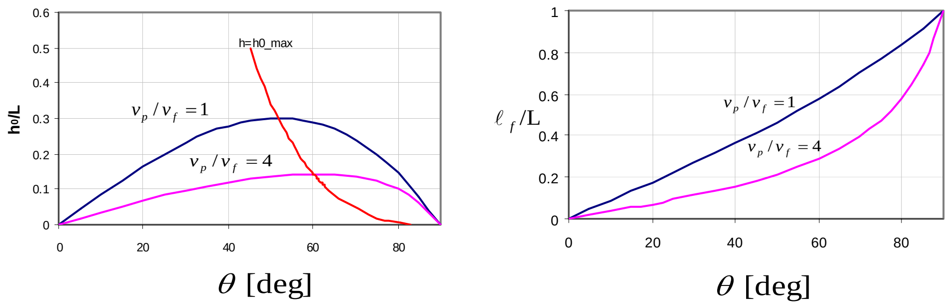

Figure 5. Minimal impact height for full interaction as a function of impact angle

The effectiveness of the ERA in disrupting the penetrator, as a function of its impact point location, can be estimated by measuring the penetration depth, *P*, in a witness plate located far away from the ERA. The interaction between the penetrator and the witness plate begins after the end of penetration into the ERA. Figure 6 presents the penetration depth due to the impact point height location along the ERA module.

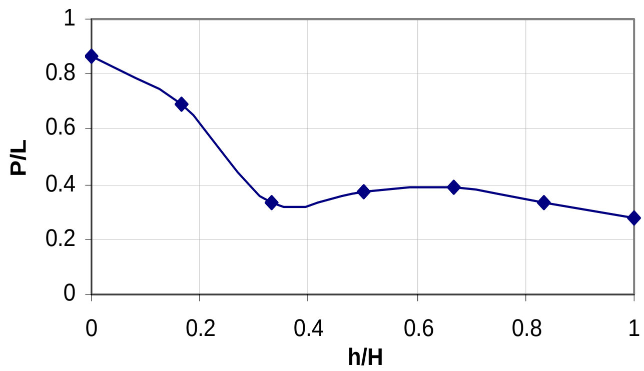

Figure 6. Penetration depth vs. impact height at ERA module

In a real life situation, the reactive module is assembled on an armored platform (vehicle, tank etc) which has its own existing armor shield. In order to assess the effectiveness of the reactive armor on the penetrative capability of the projectile rod, it's common to use the armor efficiency term. The efficiency may depend on various parameters such as material properties, impact angle, yaw angle, witness to armor distance etc. In this investigation, we are interested in its dependence upon the impact location on the front plate.

The numerical simulation contains a witness plate with large thickness that was located a distance *d* behind the reactive module. The impact scenarios differed not only in the locations of impact but also in the location of the reactive module relative to the witness plate's position. The shapes of the craters produced from the impact of the projectile rod vary considerably as the sidewall interaction between the projectile rod and the crater increases. The interaction time depends primarily on the projectile's shape after having been distorted by the reactive armor module.

Figure 7, depicts several frames of projectile penetration into the reactive armor module at its center region including a wide witness plate. The reactive armor penetration is similar to the case shown in figure 1 until 240μs. From that time there is interaction between projectile, the ERA and the witness plate.

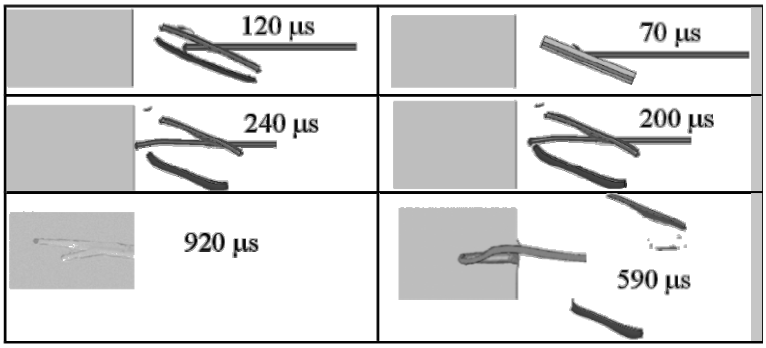

Figure 7. Projectile penetration processes into armor module cassette including witness plate

Figure 8 shows the simulated crater depth size and internal shape of the penetration channel due to projectile rod impact at different locations on the front panel of the reactive armor module. As may be seen from the figure, the penetration path depth and channel shape change with rod impact point position which affects both the rod's original line of flight and distorts its shape as it passes through the reactive armor module. When the impact point is located at the plate's center, the resulting crater within the witness plate bifurcates, indicating penetrator fracture as a result of penetrator-target crater interaction inside the target. Impact at the upper portion of the plate reveals that the penetration channel has the largest length of all the cases considered, indicating that only a low to moderate lateral penetrator-target interference force exists during penetration.

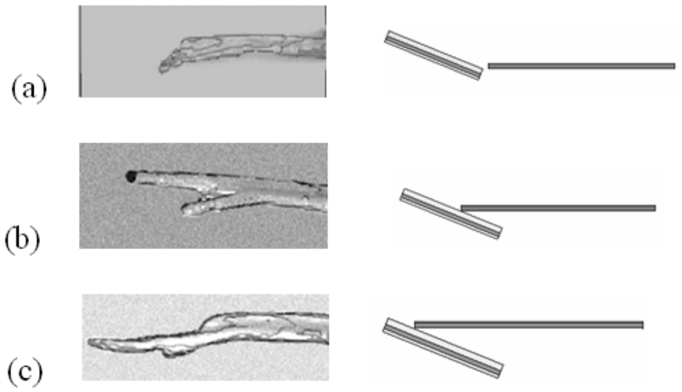

Figure 8. Crater channel shapes for different impact points after penetration into witness plate

The case shown in figure 8a was rerun, but the ERA module was placed contiguously to the witness plate as demonstrated in Fig. 9. The results emphasize the influence of the armor-to-witness plate distance on the effectiveness. The penetration depth is larger when the reactive armor module is in close proximity to the witness plate.

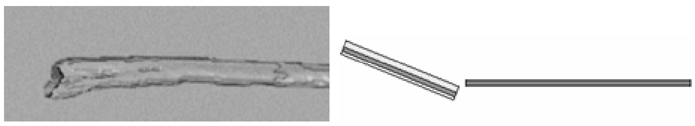

Figure 9. Crater channel shapes for different distances of ERA position

CONCLUSION

The main aim of this investigation was to study the complex interaction between the kinetic energy projectile rod and the ERA front plate including the edge effect caused by the simultaneous initiation of the explosive layer inside the armor module. A 3D numerical simulation was performed with the LS-DYNA hydrodynamic code. Several sets of numerical simulations were carried out incorporating a generalized reactive armor module. The effect of impact point location on the reactive armor's efficiency was investigated by means of a witness plate located at a specified distance behind the reactive armor. Simulations revealed that the projectile impact point on the front plate of the reactive armor module has a large influence on the projectile shape and on the crater channel penetration depth characteristics produced within the witness plate.

Furthermore, it was shown that the different rod shapes resulting from the rod's passage through the reactive armor module corresponds to the impact point location on the front plate. Another set of simulations included a witness plate located at varying distances behind the reactive armor, hence, resulting in a simultaneous interaction of the penetrator with both the moving front plate and the witness plate. It was found that the reactive armor's ballistic efficiency is reduced when a witness plate is located in close proximity behind the reactive armor.

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