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Subject review
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Analysis of the Behavior of a Penetrator Advancing Through a Guide Surface

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Abstract: The study concerns the transverse deformation behavior of a penetrator surrounded by sabot in a deformed gun barrel. In the gun barrel, transverse deformation occurs in the penetrator due to problems such as deflection by gravity, or geometric tolerance caused by the manufacturing process. This deformation causes structural instability problems and affects out-of-gun barrel movement. In addition, the deformation and structural safety of the penetrator is affected by the sabot supporting the penetrator. The finite element method was used to evaluate the effect of the sabot. Deformation and stress analysis were performed for the penetrator moving in the gun barrel, and the effect of the elastic modulus of the sabot on the deformation of the penetrator was studied.

Keywords: elastic modulus; numerical analysis; obturator; penetrator; sabot; von Mises stress

1 INTRODUCTION

Kinetic energy ammunition is being used as a countermeasure against the development of protection systems, such as tanks or light armored vehicles. Kinetic energy ammunition is being developed in the form of wing-stabilized armor-piercing (AP) ammunition using high slenderness ratio (L/D) penetrators to maximize penetration performance [1].

The AP consists of an obturator, fin, and sabot. The sabot is an important part and must withstand hundreds of MPa, and it transmits this pressure to the projectile. Fig. 1 [2] shows a schematic of such a kinetic energy projectile.

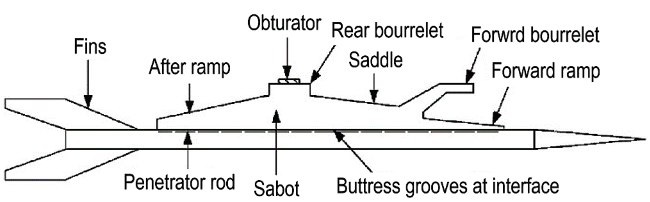


Figure 1 Components of a kinetic energy projectile

The sabot and the projectile both have interface buttress grooves that are used to transmit momentum. The projectile is pushed out of the barrel by high-pressure gas that is produced as the propellant burns on the sabot's rear ramp. A sealing device (seal) is installed on the rear barrel to prevent leakage of hot combustion gases. The projectile is supported throughout moving inside the barrel by a forward bourrelet, and the forward ramp is also utilized during the initial phases of separation to avoid separation failure brought on by obstruction behavior. Along the axial plane, various components make up the sabot. When the assembly of the projectile and the sabot exits the barrel, the sabot is no longer needed, and falls away.

Factors that affect the dispersion of AP [3] are uneven muzzle velocity, unevenness in warhead manufacturing, weather conditions, and the movement posture of flying bullets. In the case of wing-stabilized AP ammunition, the sabot is designed to be separated from the penetrator at the moment the warhead leaves the muzzle, so the function in the separation phase [2] will affect the dispersion of the bullet.

In AP, when the assembly of the projectile and the sabot exits the barrel, the sabot is not anymore required. Therefore, the separation of components, which must be done as quickly as possible, usually occurs in a barrel exit detonation. The most important consideration when designing a sabot that separates quickly is the balance between the aerodynamic force and the dispersion of the projectile [4] needed to separate the sabot quickly without compromising its ability to transmit force. The amount of destruction operating on the projectile during launch and free flight should be kept to a minimum for increased dispersion accuracy. To improve penetration, it is necessary to minimize aerodynamic drag [5], and move at a faster speed.

The existing sabot uses two bore riders [6, 7], a front part and a rear part, as shown in Fig. 1, so that the movement of the projectile is efficient with a high *L*/*D* ratio inside the bore [8]. The front bore rider of these two bore riders acts as an aerodynamic lifting surface to help the sabot disengage. Rotation of the sabot causes mechanical contact between the projectile and the sabot because the majority of the lift force is centered at the forward end of the sabot [9]. In general, asymmetric mechanical contact can make high yaw/pitch motion in the projectile [10], resulting in a loss of firing propulsion accuracy. Therefore, conventional sabots are known to have intrinsic problems of automated communication.

To overcome the shortcomings of the existing sabot, a solution to prevent non-uniform detachment due to pressure fluctuations of the sabot front bore rider has been proposed [11]. This design substitutes a web member for the front-bore rider, which also serves as a support to lessen turbulence in the entering airflow and lessen projectile impact.

If the projectile that is fired and progresses within the barrel vibrates [12] in the transverse direction, the firing condition of the projectile becomes unstable. The dynamic behavior of the projectile also becomes unstable, thereby reducing the accuracy of the projectile performance. The effectiveness of the projectile [13] is determined by the accuracy and consistency of hitting the target. The transverse behavior depends on the difference between the centerline of the barrel and the projectile. The symmetry of the propulsion pressure applied to the projectile also affects the transverse behavior.

Studies have been made of the effect of the barrel deformation on the projectile at the barrel exit [14, 15], and the effect of the bore-rider stiffness of the sabot on the propulsion behavior of the warhead [16, 17]. Such changes in the barrel centerline include vibration, non-uniformity of cooling, manufacturing defects, and non-uniformity of barrel wall thickness. By analyzing these factors and minimizing the occurrence factors, an optimal weapon system can be developed. Analysis of the transverse motion of the projectile is important in the development of the projectile [18].

Sabot prediction methodologies for projectile systems have been studied for several decades [19, 20]. The design of the sabot relies heavily on various types of propulsion systems, and it is performed in four forms: supporting the projectile during launch acceleration, guiding the projectile along the center of the barrel, sealing the encapsulation in high-pressure propellant gas, and smooth separation after disengagement from the barrel. The length of the sabot supporting the kinetic energy projectile [21] is an essential factor affecting structural integrity

As it is usually undesirable to modify the gun system to improve barrel exit speed and strike accuracy, it is preferable to modify the configuration of the sabot during the design of the gun system/projectile, and to select a sabot medium with a proper strength-to-weight relation. Regarding the formation changes, the structural integrity of the sabot cannot be cooperated, and designing a sabot with less weight and better structural performance becomes a difficult task. Meanwhile, within the barrel, the sabot affects the mechanical behavior of the warhead. According to the structure and material of the sabot, it is expected that the deformation and stress of the penetrator will be affected.

Vibration occurs when a transverse load is applied due to a variation of contact area between the sabot and the barrel. When the penetrator proceeds in the barrel, the deformation occurs in the penetrator according to the contact form between the sabot and the barrel, resulting in a change in the stress (σ_v) of the penetrator. As changes in the pressure within the barrel and the deformation of the projectile affect the accuracy of the strike and the structural stability of the projectile, analysis of such behavior is required. However, research on this is very limited. Since these weapon systems have various characteristics for each product, general standards cannot be applied, and individual research must be carried out according to individual target barrels and projectiles. In this study, we intend to conduct related research on a weapon system currently being developed by using the limited data collected.

The study aims to develop an analysis technique for the deformation of the penetrator that proceeds along the changing guide surface. Using this result, we intend to derive essential data to developing an optimized projectile by changing the projectile and sabot material.

2 ANALYSIS METHOD

The behavior of the penetrator moving in the gun barrel was analyzed using FEM. Fig. 2 shows that 8-node hexahedral elements were used. The analysis method is as follows: The barrel deflects due to gravity, and flexure occurs within the barrel under the influence of the manufacturing process, etc. The case where the barrel drooped due to gravity alone, and the case where bending was due to gravity and geometric tolerance overlap, were analyzed. The solid line indicates that the barrel is bent due to gravity alone (type G), and the dotted line shows the centerline shape of the barrel when the deflection due to gravity, and the deformation due to machining defects, are overlapped (type G+O) in Fig. 3.

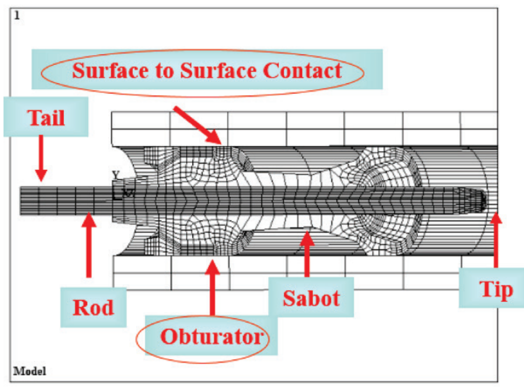


Figure 2 Analysis model

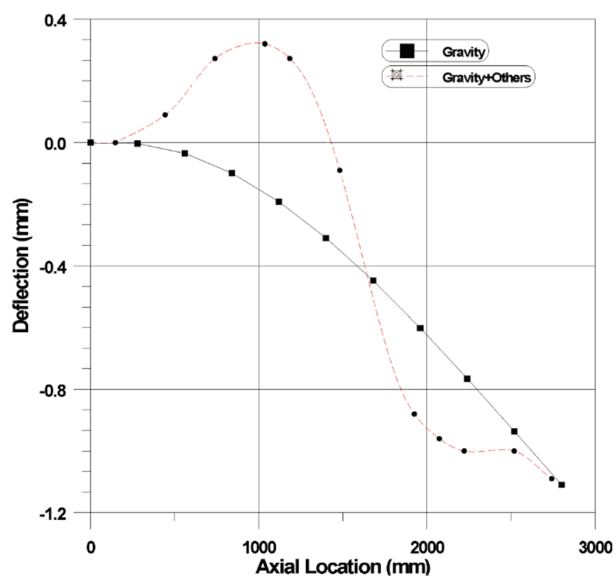


Figure 3 Gun tube profile for simulations

Table 1 Table title aligned centre

Type	AL-1	A	B	C	AL-2	D	E	F
Elastic Modulus (*E*) of Sabot (GPa)	72	49.2	47	48.5	72	49.2	47	48.5
Tube Centerline	Type G				Type G+O			

Tab. 1 shows the elastic modulus of the sabot and the deformation shape of the barrel. The elastic modulus of the sabot is (72, 49.2, 48.5, and 47) GPa, and the cases of behavior in 2 types of barrel are analyzed. Fig. 3 shows the propulsion force applied to the projectile, while Fig. 4 shows the pressure change curve with time that is used.

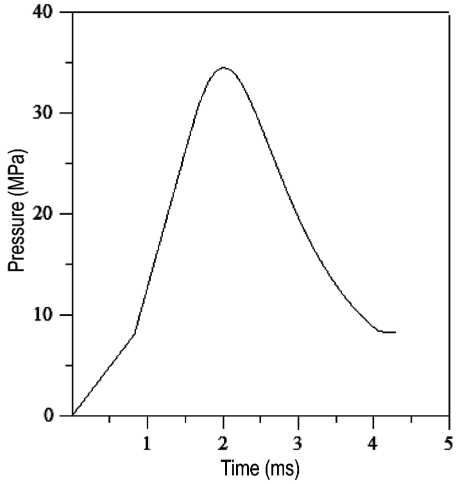


Figure 4 Breech pressure versus time

3 RESULTS AND DISCUSSION

3.1 Deformation of Penetrator

Fig. 5 and 6 show the deformation of the centerline of the projectile at (1 or 2) ms after firing. In the figure, the position represents the total length of the projectile, (0−40) mm represents the tail (fin tail) of the projectile, (40−160) mm is the part surrounded by the sabot, and (160−200) mm represents the front part of the projectile (warhead). When the sabot's modulus of elasticity is 47 GPa (△, ▲), which is the smallest at 1 ms, the deflection of the projectile was very small over the entire length of the projectile.

The difference in the amount of warhead deflection between the G case (●, ■, ▲, ◆) and the G+O case (○, □, △, ◇) when the projectile travels 2 ms is about 10^{-4} m. In addition, a sudden deflection occurs near the warhead

When the projectile movement time is 3 ms as shown in Fig. 7, this is a position where the primary inflection occurs in the barrel, in which the central trajectory of the barrel is inflected in two places. When the tube is deflected by its weight (●, ■, ▲, ◆), the transverse deflection of the entire length of the projectile is generally constant, and when E of the sabot is 72 GPa, the deflection of the warhead becomes larger than the other cases.

If there are two bends in the barrel (○, □, △, ◇), it can be seen that deformation of the entire length becomes larger than when the tube is drooping due to its weight only at the 3 ms point where the bending of the barrel is maximum. In this case, as E of the sabot decreases from 72 GPa (AL-2: ○) to 47 GPa (E: △), the difference between vertical deflection increases. From this result, it can be seen that the deformation of the warhead is affected by the bending of the barrel. If there is a bend in the barrel, the smaller the Young's modulus (E) of the sabot, the greater the difference of deflection between the warhead and the fin, as shown in Tab. 2.

Table 2 Deflection difference between tail and tip of projectile

Elastic Modulus (GPa)	$\Delta\delta$ only by Gravity (10^{-4}m)	$\Delta\delta$ by Superposition (10^{-4} m)
73	3	1.2
49.2	1	4.3
48.5	1.5	4.5
47	1.3	5.7

Tab. 2 shows the deformation difference between the tail and the warhead under each condition. In the case of superposing barrel deformation, when the sabot modulus of elasticity is 73 MPa, the difference in the amount of deformation is the smallest at 1.2×10^{-4} m. When it is 47 MPa, the difference in the amount of deformation is 5.7×10^{-4} m, which is the largest. It can be seen that the greater the elastic modulus of the sabot, the smaller the deformation difference between the warhead and the tail.

If the E of the sabot is 47 GPa in a projectile that travels when the barrel deflects with gravity, the deflection of the projectile according to the propagation time of the projectile is generally constant, and the difference between the deflection of the warhead and the tail is small. When the elastic modulus of the sabot is large as 73 GPa, the difference in deflection between the warhead and the fin is very large at the beginning of the launch. As time goes on, this difference in deflection gradually decreases; and just before the projectile leaves the barrel, this difference decreases considerably, and the deflection maintains a minimal shape.

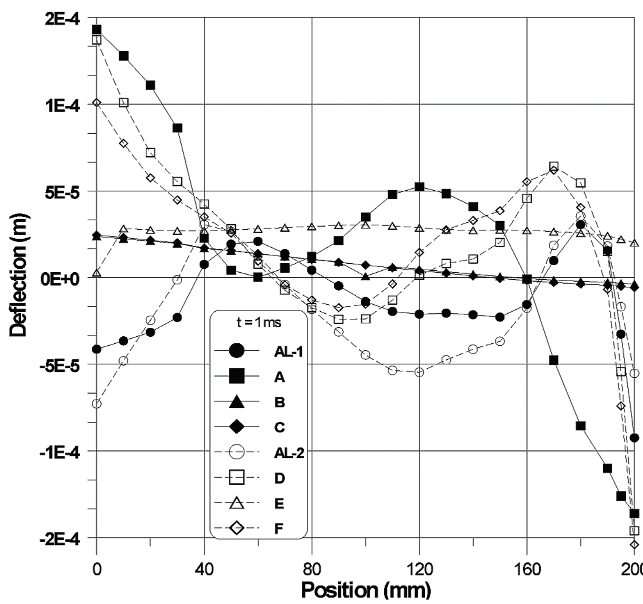


Figure 5 Deformation of penetrator centerline (t = 1 ms).

In the case where the barrel is type G+O, the overall fin is + deflection and the warhead is − deflection at the initial 1 ms of movement of the barrel, and the difference in deflection is large. At 2 ms, when the firing progress becomes stable, the warhead is directed in the + direction, and there is almost no bending deformation. The projectile in the barrel shows severe bending over its entire length. After some time has elapsed, the deflection of the total length decreases, and the stability of the deflection becomes stable.

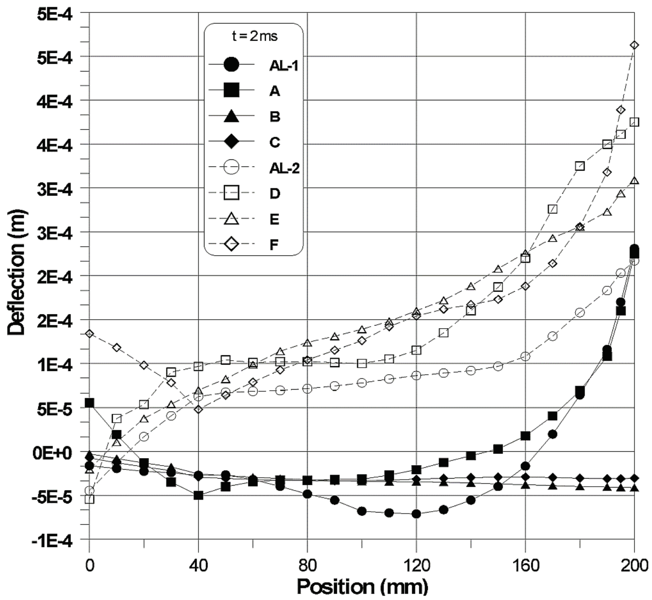


Figure 6 Deformation of penetrator centerline (*t* = 2 ms).

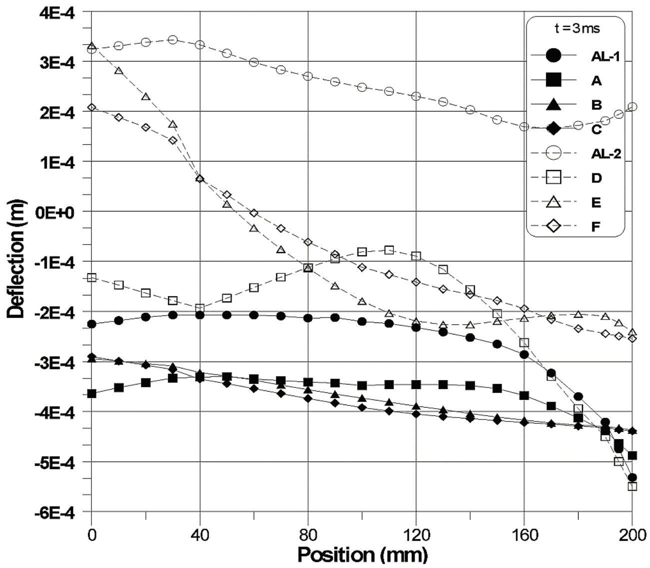
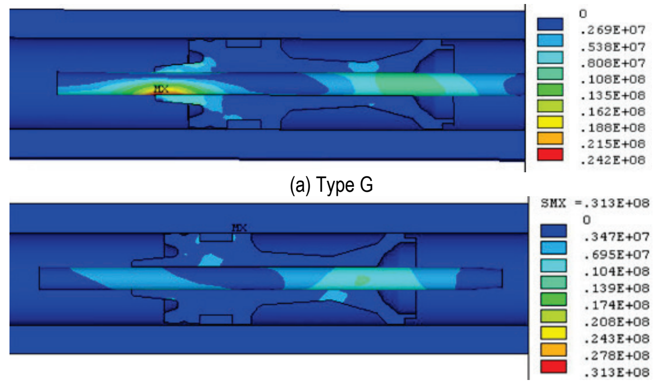


Figure 7 Deformation of penetrator centerline (*t* = 3 ms)

3.2 Stress of Penetrator

The stress at the point where the moving time of the projectile is about 3 ms for types G and G+O is presented in Fig. 8. In the case of type G, the maximum von Mises stress (σ_v) occurs in the front area between the sabot and projectile. The stress at this time is about 200 MPa. The reason for the difference in stress in the same moving time is as follows. The curvature of the barrel is constant in type G. However, in type G+O, it is judged that the barrel centerline is inflected in 3 ms.

The von Mises stress state in the warhead and tail during the entire process of the penetrator in the overlapped barrel shows in Fig. 9. The solid line indicates the stress state of the warhead according to the penetration time, while the symbol · indicates the stress state of the fin tail. The stress of the warhead gradually increases with time. The stress of the warhead increases greatly at the time of 3.6 ms, just before departure from the barrel. Comparing the results of the previous deflection with the results of Fig. 7, the deflection of the warhead is greater than that of the other parts.



(a) Type G

(b) Type G+O

Figure 8 von Mises stress distribution

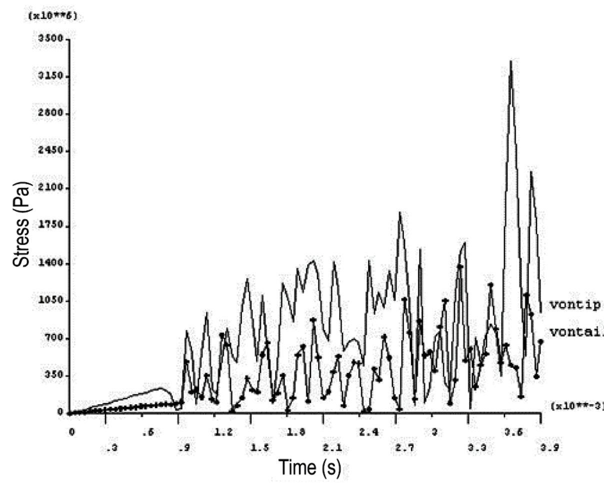


Figure 9 von Mises stress at full path (mixed centerline)

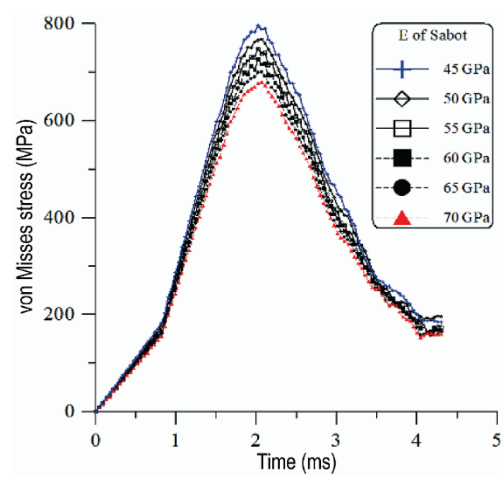


Figure 10 von Mises stress with the variation of elastic modulus of sabot

Fig. 10 shows the change in the maximum σ_v of the projectile according to the Young's modulus (E) of the sabot. The von Mises stress of the penetrator varies according to E of the sabot. The maximum stress occurs around 2 ms, and when the elastic modulus of the sabot is 70 GPa, the stress of the penetrator is 630 MPa. When the modulus of elasticity of the sabot is 45 GPa, the stress of the penetrator becomes 800 MPa; and as the modulus of elasticity of the sabot increases, the von Mises stress of the penetrator decreases.

4 CONCLUSION

Numerical analysis was performed on the deformation and stress of the penetrator in the barrel that is deflected only by gravity, and in the barrel where the deformations of gravity and machining error are superposed. The penetrator is surrounded by a sabot, and the sabot proceeds while in contact with the barrel. The deflection and stress in the penetrator were analyzed according to the change in the characteristics of the sabot. The obtained results are as follows.

In the case of bending due to only its weight, the degree of deflection in the entire length of the penetrator at each position within the barrel was generally minimal. The deflection degree of the small elastic modulus of the sabot was smaller than that of the large elastic modulus. If the elastic modulus of the sabot is large, the deflection of the warhead is greater than the deflection of the fin in most cases proceeding within the barrel.

The deflection of the penetrator is similar at the beginning, regardless of the bending shape of the barrel. As the penetrator pushes forward, the difference in deflection of the penetrator in the barrel where the deformation is superimposed becomes large. The difference in deflection between the fin and the warhead is greater than when the elastic modulus of the sealer is small in the stage just before the penetrator leaves the barrel. Considering the deflection of the projectile, the larger the modulus of the sabot the more stable for the penetrator behavior.

As E of the sabot increases, the stress generated in the penetrator decreases. When the results of stress and deflection are considered, it can be seen that the larger the E of the sabot, the better the structural stability of the penetrator.

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