Journal of Engineering Science and Technology Review 7 (2) (2014) 106 – 112

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Improvement and Simulation of THOR Formula with Yaw Angle

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Received 30 October 2013; Accepted 19 April 2014

Abstract

The THOR formula is widely used in the investigation of vulnerability and effectiveness of weapon system, however, its application was limited by the small slenderness ratio and limited materials of target. In order to investigate the damage effect of KE-rod warhead, this paper, basing on the classic THOR formula, focused on improving the formula of residual velocity and residual mass. The improved THOR model could predict the residual velocity and residual mass of KE-rod penetration in the complex conditions, and the predictions were found to be consistent with the experimental numerical results in the literatures. As the experimental data is limited, for the better validation of the improved formula, the paper investigated further research and verification of the improvement THOR formula with numerical simulation. Since the experimental data are limited for hypervelocity impact, comparisons of results between M-THOR with experimental and numerical data were widely preceded. The error is less than 4.8% for the predicted residual velocity while 5.4% for predicted residual velocity. The effect of yaw angle in the modified THOR formula was also found to agree quite well with the reference.

Keywords: penetration, projectile, target, KE-rod, yaw angle, improvement, calculation

1. Introduction

KE-rod warhead technology offers designers a novel warhead that can attack and destroy the ballistic missiles [1,2,3]. By contrast with the traditional projectiles and long rod penetrators, the KE-rod is well known of high density, great slenderness ratio, high flying velocity, etc. [3,4,5]. Researches on the residual velocity and mass of killing elements have found to be of great significance on the residual power and damage assessment.

Detailed analyses of the penetration characteristics of cylindrical projectiles have included the effect of the slenderness (L/D) ratio in the penetration models by Anderson et al. [6] and Chocron et al. [7]. In particular, the work done by Anderson et al. [8] revealed that numerical results tended to be in very good agreement with experiment data. Researches by Johnson and Cook [9] and by Gee and Littlefield [10] demonstrated that numerical simulations provided reasonably accurate results for impact events involving cylindrical projectiles, at various obliquities, yaw angles, and impact velocities. However, the range of obliquity and yaw angles used in their investigations is relatively limited.

Chen and Li [11] proposed an impact function and the geometry function of a projectile, two dimensionless parameters used to formulate the critical impact limit at the transition from non-deformable projectile penetration regime to semi-hydrodynamic penetration regime. They observed good agreement between experimental results and theoretical predictions using different materials in a broad range of impact velocities and projectile geometries.

Taylor and Tate [12] modified the material strength of projectile and target, and obtained the mass erosion law of long rod penetrators impacting on the target vertically with the fluid dynamics theory. Gunnar W. Recht and Yatteau [13] revised the traditional Light of Sight Model, and established the High Obliquity Model for long rod penetrator impacting on the plate obliquely. Furthermore, Gunnar W. Recht and Yatteau created the residual mass model of finite plate based on the improved Tate Model, which was used in the endgame analyzes procedure FATEPEN2 [14] and had better accuracy.

The THOR formula [15] was a statistical fitting of a large number of experimental data based on projectiles with various materials and shapes for the prediction of the ballistic resistance with projectile penetrating the armoured material, which was widely used in the analysis of vulnerability and effectiveness of weapon system as the high accuracy for prediction [16], however, its application is limited by the following conditions: (1) the slenderness ration of projectile is less than 3; (2) the projectiles don't broke up when penetrating; (3) the obliquity angle θ_R must be in the range of 70°; (4) the material of projectile should be in the Table 1.

Lu Y.-G., and Yang S.-Q. modified the THOR formula to apply in the condition of large slenderness ratio, great obliquity angle and high yaw angle. The paper focuses on the THOR formula in the work of literature [17]. The improved THOR formula could better reflect the real situation in term of the collision, and accurately calculate the relationships among the yaw angle and the residual mass, the yaw angle and the residual velocity.

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ISSN: 1791-2377

2. THOR Formula Model of KE-rod

2.1 Original THOR Formula Model

The basic formula of original THOR model contains: the residual velocity THOR formula, the protective velocity THOR formula of target and the residual mass THOR formula. The residual velocity THOR formula and the residual mass THOR formula concerned by the paper is [17]

$$V_r = V_R - 0.3048 \times 10^{c_{11}} \left(61023.75hA\right)^{c_{12}} \left(15432.1m_0\right)^{c_{13}} \left(\sec\theta_R\right)^{c_{14}} \left(3.28084V_R\right)^{c_{15}} \tag{1}$$

$$M_r = m_s - 6.48 \times 10^{c_{31}-5} \left(61023.75hA\right)^{c_{32}} \left(15432.1m_0\right)^{c_{33}} \left(\sec\theta_R\right)^{c_{34}} \left(3.28084V_R\right)^{c_{35}} \tag{2}$$

where V_r — residual velocity of projectile (m/s);
V_R — penetration velocity of projectile (m/s);
h — thickness of plate (m);
A — contact area of projectile and plate (m^2);
m_0 — initial mass of projectile (kg);
M_r — residual mass of projectile (kg);
θ_R —cross angle of velocity vector and the normal of plate (illustrated in Fig. 1);
$c_{11} \sim c_{35}$ —constants or coefficients of materials for target defined in the THOR formula (shown in Tab. 1 [18]).

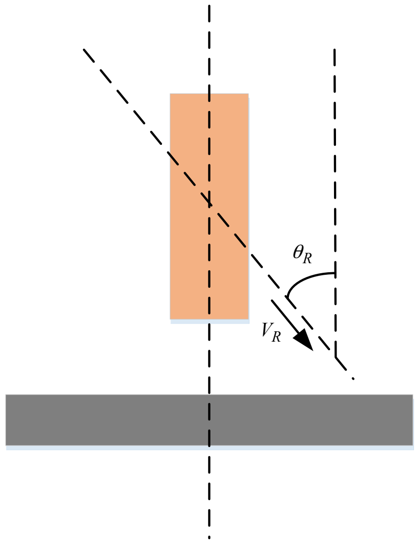


Fig. 1 Diagram of θ_R and plate

Table 1. Constants of material for THOR formula

Material	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{31}	c_{32}	c_{33}	c_{34}	c_{35}
Magnesium	6.904	1.092	-1.170	1.050	-0.087	-5.945	0.285	0.803	-0.172	1.519
Aluminum 2024-T3	7.074	1.029	-1.072	1.251	-0.139	-6.663	0.227	0.694	-0.316	1.901
Titanium	6.292	1.103	-1.095	1.369	0.167	2.318	1.086	-0.748	1.327	0.459
Cast Iron	4.840	1.042	-1.051	1.028	0.523	-9.703	0.162	0.673	2.091	2.710
Mild Steel	4.356	0.674	-0.791	0.989	0.434	1.195	0.234	0.744	0.469	0.483
RHA Armor	6.399	0.889	-0.945	1.262	0.019	-2.507	0.138	0.835	0.143	0.761
FH Armor	6.475	0.889	-0.945	1.262	0.019	-2.264	0.346	0.629	0.327	0.880
Copper	2.875	0.678	-0.730	0.846	0.802	-5.489	0.340	0.568	1.422	1.650
Lead	1.999	0.499	-0.502	0.655	0.818	-1.856	0.506	0.350	0.777	0.934
Tuballoy	2.537	0.583	-0.603	0.865	0.828	-3.379	0.560	0447	0.640	1.381
Nylon Unbonded	5.816	0.835	-0.654	0.990	-0.162	-7.538	-0.067	0.903	-0.351	0.717
Nylon Bonded	4.672	1.144	-0.968	0.743	0.392	-13.601	0.035	0.775	0.045	3.451
Lexan	2.908	0720	-0.657	0.773	0.603	-0.275	0.480	0.465	1.171	1.765
Plexiglass Cast	5.243	1.044	-1.035	1.073	0.242	-2.342	1.402	-0.137	0.674	1.324
Plexiglass Stretched	3.605	1.112	-0.903	0.715	0.686	-5.344	0.437	0.169	0.620	1.683
Doron	7.600	1.021	-1.014	0.917	-0.362	-10.404	0.215	0.343	0.706	2.906
Bullet Resistant Glass	3.743	0.705	-0.723	0.690	0.465	-5.926	0.305	0.429	0.747	1.819

As the THOR formula is obtained by fitting the experimental data, during the application of THOR formula in last decades, it is widely concluded by its uses that, application of THOR formula is limited in the following regions:

(1) The slenderness ratio of projectile is not more than 3;

(2) The materials of target offered by the experiment are limited, the other materials should be derived from the materials of experiment, that is to say, selecting the strength of material close to the material with experiment, then, modified the thickness of target by contrast of the density of unknown material and the material used in THOR formula;

(3) The THOR formula is used when the projectiles are not fracture in term of penetration;

(4) The oblique angle should be in the range of 0°-70°, the projectile is invalid when the oblique angle goes beyond 70°;

(5) The material of projectile should be in the Table 1.

2.2 THOR Formula for KE-rod Vertical Penetration on Target

Reference [17] finds that: the THOR formula is not applicable to calculate the residual mass of KE-rod when the slenderness ratio is more than 3, and the residual velocity is not affected by the limit of the slenderness ratio. The theoretical analysis and experiments of mass loss mechanism for long rod penetration on the target show that [17]: as the thickness of target and velocity of rod is constant, the mass loss of rod has a maximum value, that is to say, the mass loss increases with the slenderness ratio slowly, when the slenderness ratio reaches a certain value, the mass loss or rod reaches the maximum. On the other hand, according to the impact dynamics theory, the mass loss of rod is due to the plastic waves induced by the head of rod impact on target for the plate penetration, the effect begins from the time of rod touching the plate, and ends with the counteracting the plastic waves of rod impact on the plate and the rarefaction waves that reflected back from the plate bottom. So the thickness of rod and the elastic velocity of rod an plate have an important influence on the residual mass of the rod, the residual mass of the rod was modified, and the improved THOR formula is

$$V_r = V_R - 0.3048\times10^{c_{11}}\left(61023.75hA\right)^{c_{12}} \left(15432.1m_0\right)^{c_{13}}\left(\sec\theta_R\right)^{c_{14}}\left(3.28084V_R\right)^{c_{15}} \tag{3}$$

$$M_r = m_s - 6.48\times10^{c_{31}-5}\left(61023.75hA\right)^{c_{32}} \left(15432.1\cdot F_m m_0\right)^{c_{33}}\left(\sec\theta_R\right)^{c_{34}}\left(3.28084V_R\right)^{c_{35}} \tag{4}$$

$$F_m = \frac{2}{\pi}\arctan\left(\frac{l}{h}\right)\left(\frac{5C_{ep}}{C_{et}}\cdot\frac{h}{l}\right) \tag{5}$$

where C_{ep} — elastic velocity of projectile;
C_{et} — elastic velocity of target;
l — initial length of the rod.

3. Improvement of THOR Formula with Yaw Angle

The classical THOR formula considers the initial velocity, the obliquity angle, the mass of the projectile, the thickness of target and the contact area of penetration, ignoring the effect of the yaw angle, that is, the formulas is only capable of estimating the residual velocity and mass of KE-rod when the yaw angle is 0°. In practise, even if the above five factors are identical, the residual velocity will change with the yaw angle. Therefore, the effect of the yaw angle should be considered in the actual application, and it's necessary to modify the THOR formulas with the yaw angle. Fig. 2 shows the KE-rod penetration on plate with yaw angle β .

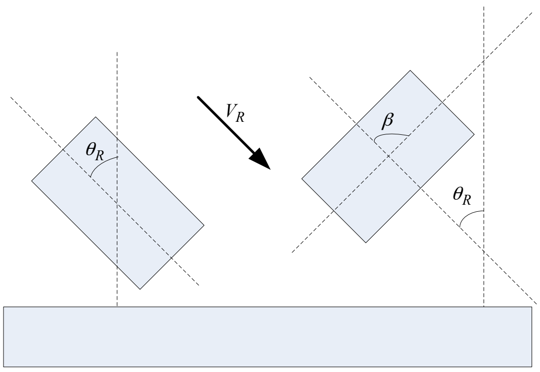


Fig. 2 Diagram of KE-rod penetration with yaw angle

We transform the model of KE-rod with the yaw angle into the projection area of KE-rod in the plate, the process of simplified model is shown in Fig. 3.

(1) As the rod is the cylinder, and the reference [17] takes the rod as the equivalent cuboid rod, so there are some errors of the equivalent area in the real situation. The paper takes the KE-rod as the equivalent elliptical rod, which meets the actual circs better, and ignores the width difference of the equivalent rod and the original, and supposes that the length of penetration is the same.

(2) The equivalent projection area contains two semi-ellipse areas and a rectangular area, which will lead to better accuracy comparing with the reference [17].

$$A' = \pi l_2\frac{d}{2} + dl_1 \tag{6}$$

$$l_1 = l\sin\beta \tag{7}$$

$$l_2 = \frac{d}{2}\cos\beta \tag{8}$$

where A' —projection area of KE-rod (m^2);
l —length of the KE-rod (m);
d —diameter of the KE-rod.

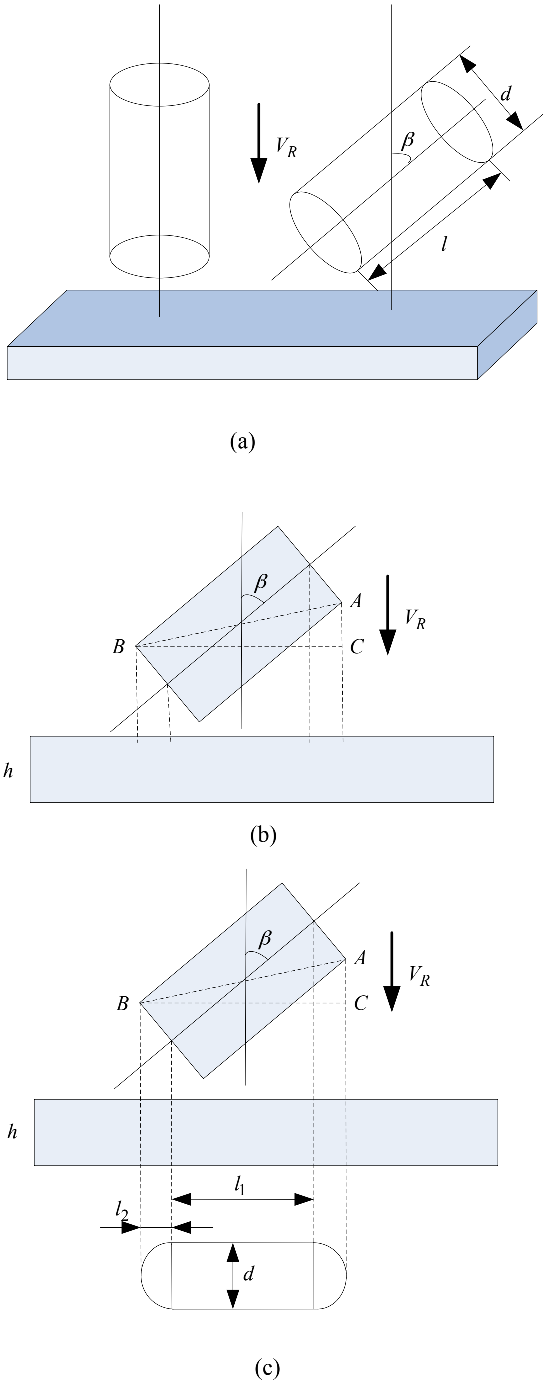


Fig. 3 Calculation of projection area for KE-rod

The residual velocity and residual mass of the modified THOR formulas with yaw angle are given by

$$V_r = V_R - 0.3048\times 10^{c_{11}}\left(61023.75hA'\right)^{c_{12}} \left(15432.1m_0\right)^{c_{13}}\left(\sec\theta_R\right)^{c_{14}}\left(3.28084V_R\right)^{c_{15}} \tag{9}$$

$$M_r = m_s - 6.48\times 10^{c_{31}-5}\left(61023.75hA'\right)^{c_{32}} \left(15432.1\cdot F_m m_0\right)^{c_{33}}\left(\sec\theta_R\right)^{c_{34}}\left(3.28084V_R\right)^{c_{35}} \tag{10}$$

4. Numerical Simulations and Discussion

4.1 Verification with Experimental Data

The paper simulated the relationship between yaw angle and the changes of mass loss with yaw angle based on the aforementioned modified THOR formula comparing with the experimental data in reference [14].

Fig. 4 shows the relationship between residual velocity and yaw angle, it can be found that the residual velocity decreases as the yaw angle increasing, and the residual velocity of modified THOR formula is marginally more accurate than the THOR formula; Fig. 5 reflects the changes of mass loss with the yaw angle that the mass loss increases with yaw angle and the mass loss of modified THOR formula is distinctly more accurate than the THOR formula obviously.

As the data of experiment is limited, the data couldn't verify the modified THOR formula comprehensively. According to the trend of changes of residual velocity and mass loss with yaw angle, the error of residual velocity and mass loss compared modified THOR formula with experiment is less than the THOR formula, in other words, the results of modified THOR formula is better than the original THOR formula.

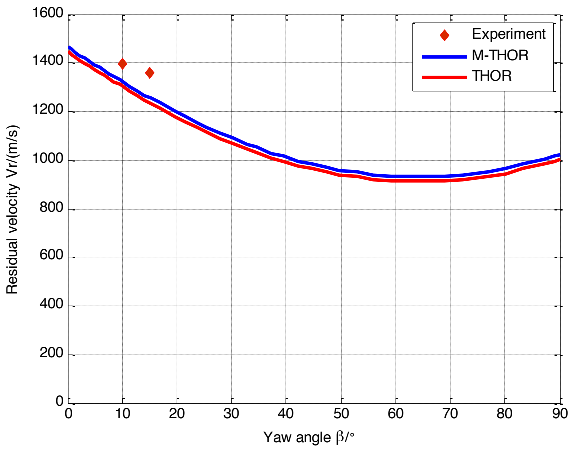


Fig. 4 Comparison of residual velocity with experiment

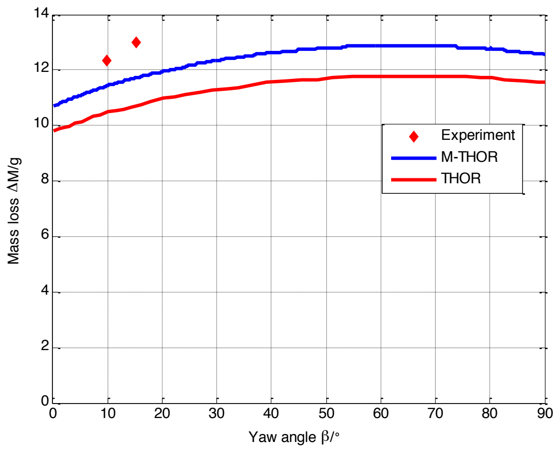


Fig. 5 Comparison of mass loss with experiment

4.2 Further Investigation of Modified THOR Formula

In order to validate the relationship among the yaw angle and the residual velocity and mass comprehensively, the paper verifies the modified THOR formula with numerical simulation. The initial penetration condition is the same as the reference [19,20]. The paper simulates the KE-rod penetrating on the plate with the software ANSYS/LS-DYNA to validate the modified THOR formula.

The rod material is 20# steel, diameter d is 0.01m, and the slenderness ratio l/d is 10, the initial mass is 61.7g; the plate material is duralumin, and the thick is 0.01m and 0.02m. The initial velocities of rod are 800m/s and 2000 m/s, the yaw angle β takes value 10°, 30°, 50°, 70°and 90°. The simulation model was established with the software ANSYS/LS-DYNA, the Johnson-Cook constitutive model [21] and Mie-Gruniesen equation of state [22] were taken into account thermal softening, strain hardening, and strain rate effects on the plastic flow regime for metals. The material parameters of rod and plate are shown in Tab. 2. The results of numerical simulations are presented in Tab. 3.

Table 2. Material parameters of rod and plate

Material	Yield stress/MPa	Hardening constant/MPa	Hardening exponent	Strain rate constant	Temperature exponent	Sound velocity/(m/s)	S_1	γ	A
Rod	245	426	0.36	0.014	1.05	5170	1.92	1.84	0.5
Plate	275	343	0.3	0.01	1.0	5090	1.34	1.68	0.5

The penetrations of KE-rods on plates with different yaw angles are presented in Fig. 6. The failure mode of plate is mainly due to the cutting effect and the penetration effect of KE-rod. At the same yaw angle and initial velocity, the bending of KE-rod and the damage of plate are more obvious as the plate is more thicker. And at the initial velocity of 800m/s and 2000m/s, the kinetic energy of the former is much smaller than the latter, at the same yaw angle and thickness of plate, the former is obvious in the bending of KE-rod, and the latter is obvious in the damage of pltae.

On consideration of analytical convenience and visualization, the contents of Tab. 3 are converted to Fig. 6, Fig. 8 and Fig. 9.

Fig. 7 shows the changes of residual velocity with yaw angle. As the initial velocity is 800m/s, the residual velocity decreases with the increasing of yaw angle, which reach the minimum value in condition of yaw angle 70°, and then the residual velocity increases slightly; when the thickness of plate is 0.02m, the residual velocity is almost the limit penetration velocity. As the initial velocity is 2000m/s, the residual velocity decreases as yaw angle increases. The reason is that when the rods penetrate on the plates with different yaw angles (except for $\beta = 90^o$), in a certain range, with the yaw angle increasing, the velocity decreasing, and the thickness of plate increasing, the attitude change rod is obvious, at the same time, as the initial veolocty is decreasing, the time of penetration is longer, then the effect on the residual velocity is greater.

Table 3. Results of numerical simulation for KE-rod penetration with yaw angle

β (°)	V_R (m/s)	V_r (m/s)	M_r/M_0	Deflectable angle (°)	V_r (m/s)	M_r/M_0	Deflectable angle (°)
		H=0.01m			H=0.02m		
10	800	760.3	0.945	4.6	689.7	0.891	7.3
10	2000	1972.6	0.922	1.4	1933.5	0.792	2.6
30	800	695.8	0.947	9.9	548.6	0.752	23.1
30	2000	1867.9	0.833	6.1	1720.2	0.543	11.2
50	800	621.5	0.831	9.5	279.4	0.755	17.9
50	2000	1719.4	0.657	7.8	1332.1	0.348	12.7
70	800	538.3	0.927	6.4	5.3	-	-
70	2000	1579.3	0.731	4.3	1112.5	0.273	10.7
90	800	539.2	0.956	-	126.3	0.846	-
90	2000	1564.1	0.658	-	1023.2	0.251	-

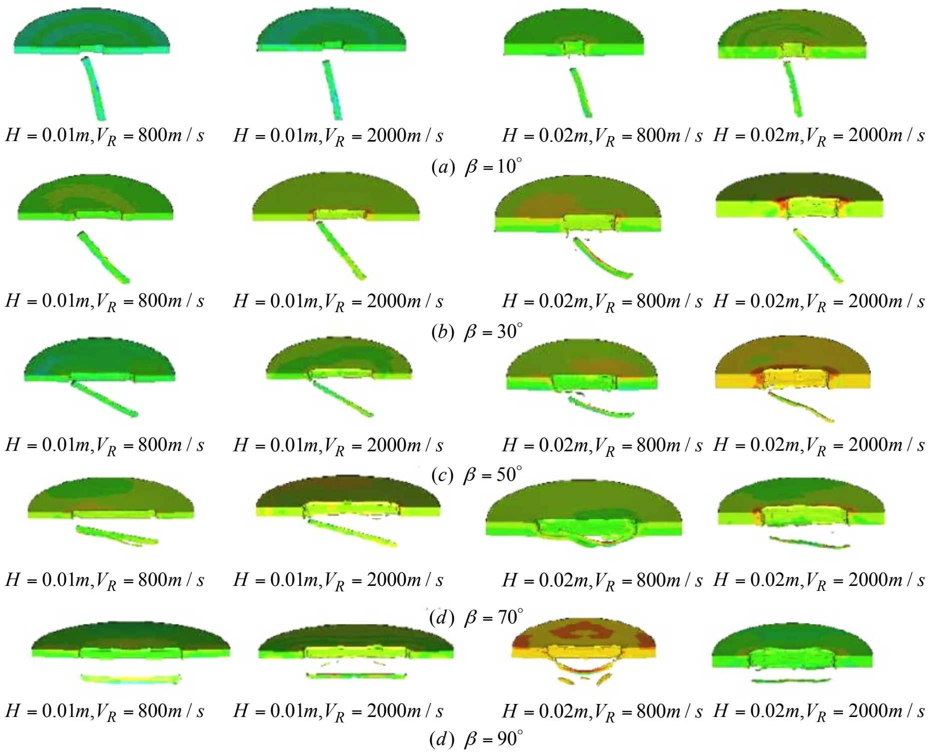


Fig. 6 Numerical simulation of KE-rod penetration with different yaw angles

The relationship between relative residual mass and yaw angle is shown in Fig. 8, the relative mass decreases with the increasing of yaw angle except the situation H =0.01 m, V_R =800m/s. As the thickness of plate is 0.02m, the yaw angle is 90°, and the initial velocity is 2000m/s, the destruction of KE-rod reaches the maximum, and the residual mass of rod is only about 14.1g, less than 25% of the initial mass of the rod. However, as the thickness of plate is 0.01m, the yaw angle is 90°, and the initial velocity is 800m/s, the destruction of rod is minimum, and the residual mass if 58.9g, the loss of mass is less than 5% of the initial mass of rod.

Fig. 9 reflects the relationship between deflectable angle and yaw angle, the deflectable angle increases with the yaw angle firstly, and reaches a maximum, then decreases with the increasing of yaw angle.

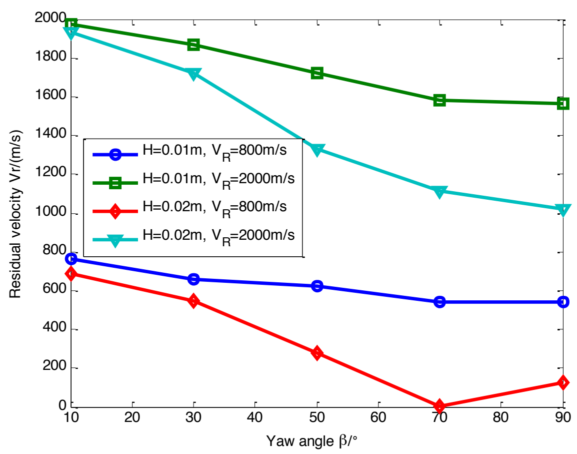


Fig. 7 Relationship of V_r and β

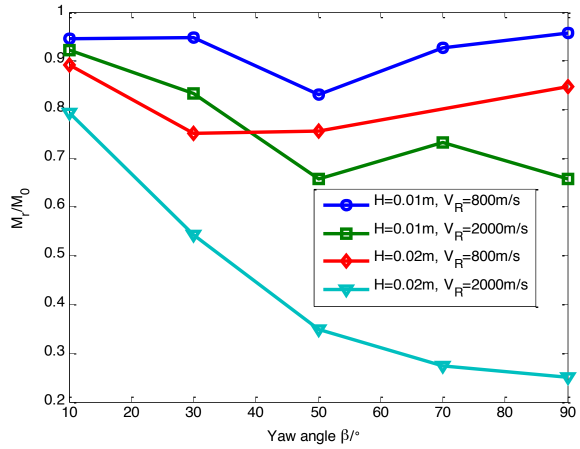


Fig. 8 Relationship of M_r/M_0 and β

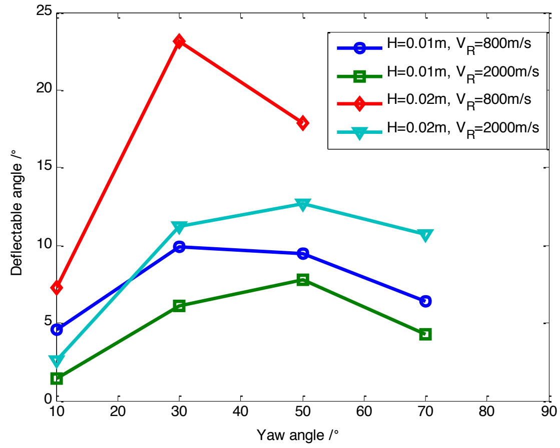
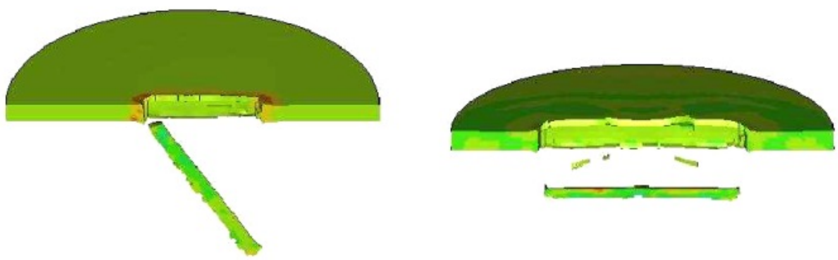


Fig. 9 Relationship of deflectable angle and β

4.3 Comparison between M-THOR Formula with Numerical Results

For the valid of modified THOR formula, the paper takes simulation for the initial velocity of KE-rod 2000 m/s, and the yaw angle 10°, 30°, 50°, 70°and 90° penetration on the plates respectively. Fig. 10 shows the numerical simulation of rod penetrating on the plate with the yaw angle β (30° and 90°). The results of residual velocity and mass from the modified THOR formula comparing with the data from the reference can be found in Fig. 11 and Fig. 12 [18,19].



$\beta = 30°, V_R = 2000 m/s$ $\beta = 90°, V_R = 2000 m/s$

Fig.10 Numerical simulation of rod penetrating on plate with yaw angle (30° and 90°)

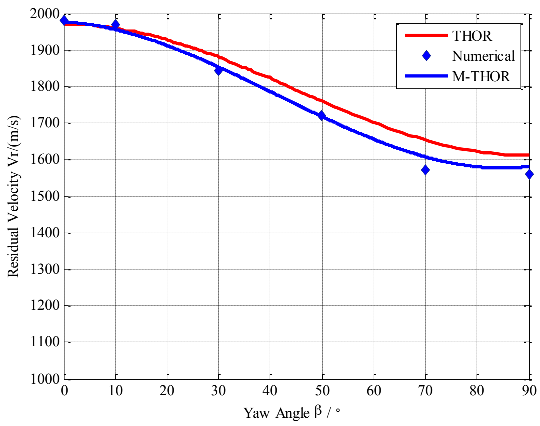


Fig. 11 Relationship of residual velocity and yaw angle

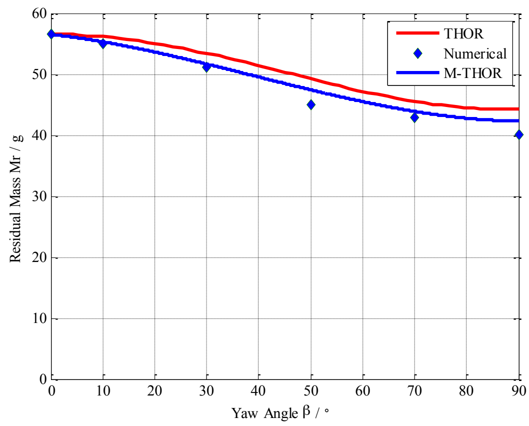


Fig. 12 Relationship of residual velocity and yaw angle

The cutting effect of rod penetration on the plate with high yaw angle is described in Fig. 10 , and the rod doesn't deform with high velocity penetration. The relationship between the residual mass and velocity changing with the yaw angle is illustrated in Fig. 11 and Fig. 12. It can be seen from Fig. 11 and Fig. 12 that the residual velocity and mass reduce as the yaw angle increases, and the changes are not obvious in the begin and end of the range of 10°. Comparing with the numerical results, the residual velocity and mass of the modified THOR formula are better than the THOR formula in reference [19], the error of residual velocity is less than 4.8%, and the maximum error of residual velocity is less than 5.4%.

The changes of yaw angle after penetration with the yaw angle are illustrated in Fig. 13, we can see that the changes of yaw angle increase with the yaw angle, then, reach the maximum, and decrease as the yaw angle increases. The maximum change of yaw angle is in the vicinity of 45°. The changes of modified THOR formula agree well with the reference [19].

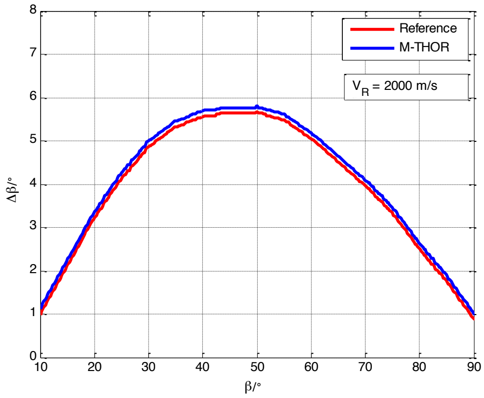


Fig. 13 Changes of yaw angle after penetration with β

5. Conclusion

The THOR formula is improved and calculated based on the reference [17], which contains the residual velocity and the residual mass. When the KE-rod impacts on the target obliquely with the yaw angle, the paper takes the rod as the projection area, and modifies the THOR formula. The modified THOR formula could reflect the relationship among the yaw angle, the residual velocity and the residual mass correctly from the numerical simulations. As the experimental data is limited, for the better validation of the improved formula, the paper investigated further research and verification of the improvement THOR formula with numerical simulation. Since the experimental data are limited for hypervelocity impact, comparisons of results between M-THOR with experimental and numerical data were widely preceded. The error is less than 4.8% for the predicted residual velocity while 5.4% for predicted residual velocity. The effect of yaw angle in the modified THOR formula was also found to agree quite well with the reference. The M-THOR formula could provide the reference for the damage assessment of the KE-rod warhead.

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