

Research on Damage Test Method of High-Speed Objects under Multiple Working Conditions

Jingliang Liu¹, Xinyu Chen¹, Qiang Luo², Ruobing Li¹, Ziqi Meng¹

¹ School of Physics, Changchun University of Science and Technology, Changchun, 130022

² China Weapons Industry Institute 203

Abstract. Aiming at the damage assessment and comprehensive test verification of high-speed objects impacting armored targets under multiple working conditions, the damage test method was studied. The vulnerability model of armored target is established. Based on this model, the damage of armored target under the action of damage elements such as armor rod, impact vibration and shock wave is analyzed, and the damage evaluation calculation result of armored target system is obtained. This method can effectively evaluate and calculate the damage effect, give the visual evaluation results, and provide guidance for the damage test of high-speed objects under multiple working conditions. Armored target 3D equivalent diagram and the key system of armor vulnerability of target is divided into three parts: front, middle and rear. The damage probability is estimated according to the angle.

Keywords: Damage assessment; vulnerability model; damage effectiveness; test method.

1. Introduction

With the development and progress of technology, various countries have completed the transformation from easily eroding aluminum alloy materials to resin based composite materials. This type of composite material can greatly reduce armor quality and manufacturing costs. Its structure is mostly sandwich structure, honeycomb structure, curved body structure, and the external panel is mainly made of high hardness steel. The sandwich is made of bulletproof ceramic body, and resin based composite materials are used to make composite armor. Due to its significant advantages, In line with the development of the technology era, it is possible to effectively reduce the reflection area of detection radar and achieve invisibility. Therefore, countries are accelerating the research process of applying composite materials to armored equipment^[1]. For this type of armored target, high-speed objects rely on the enormous kinetic energy of flight and utilize heavy metal armor piercing rod warheads to achieve effective strikes^[2]. The determination of the power of high-speed object warheads is based on the damage assessment of armor targets by damage elements such as armor piercing rods, shock vibrations, and shock waves, reflecting the damage capability of high-speed objects. Evaluation and verification of damage effectiveness are key issues that military equipment developers need to focus on^[3]. In 2009, Li Xiang rong and others from the Armored Forces Engineering college used shooting line technology to establish a damage model and studied the simulation evaluation of the damage effect of the shock wave of the explosive shell and the fragmentation warhead on the main battle armor^[4]. In 2014, Huang Jingwei from Nanjing University of Science and Technology established a penetration model of fragment warheads into infantry tanks from the aspects of warhead explosion, fragment penetration, and armor vulnerability. By calculating the damage probability of key components and the entire vehicle, the penetration effect of fragments on infantry tanks was studied^[5]. In 2018, Zhang Gao feng and others from Nanjing University of Science and Technology established a vulnerability assessment model for armor under the action of armor piercing shells by analyzing the key components of typical armor, and provided an analysis of the degree of damage to each surface of armor^[6]. In 2020, Song Jiaojiao and others from Nanjing University of Science and Technology established a projectile penetration model and a projectile target motion relationship model. Through theoretical numerical calculations, they provided a probability model for the damage of armored guns to armored targets^[7]. In 2022, Han Mengyan and others from Nanjing University of Science and Technology established a vulnerability model for armored targets and a probability

model for the rendezvous relationship between projectiles and targets by evaluating and analyzing the damage effectiveness of firepower strike plans. They provided a calculation method for the damage probability of armored targets^[8].

Based on the analysis of vulnerable components of armored targets and the target damage tree, a vulnerability model of target armor was established. Through the study of the damage efficiency of armored targets under the action of armor piercing rods, shock vibrations, shock waves and other damage elements, the damage assessment of high-speed objects to armored targets under multiple working conditions was analyzed. Visual evaluation results were provided, providing a reliable method for accurately verifying the damage judgment results of high-speed objects on armored targets.

2. Vulnerability model

Due to the complex structure and diverse functions of armor, in order to more accurately and reasonably reflect the damage situation of armor, key components necessary to achieve specific functions are defined as vulnerable components, and the damage level of tanks is classified as loss of motor function (M-level); Loss of firepower function (F-level); Destructive damage (K-level). M-level damage can cause armor paralysis, inability to control movement, and cannot be repaired by the crew on the spot. F-level damage refers to the loss of functionality of the primary armor weapon and its supporting equipment, resulting in the inability of crew members to repair on the spot, or the simultaneous death of gunners, loaders, and other crew members, leading to the loss of armor firepower. K-level damage refers to the destruction of armor, loss of mobility, and irreparable damage. Connect the damage events of vulnerable components with appropriate logic gates, establish an armored target damage tree through general deduction method, borrow the concept of reliability evaluation, start from the damage of system targets, analyze the subsystems and components that constitute the subsystems step by step, and use a tree structure to represent the interrelationships of each part and its impact on system targets^[9], As shown in Figure 1.

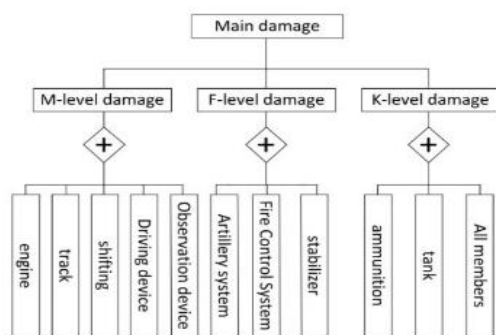


Fig. 1 Armored Target Damage Tree

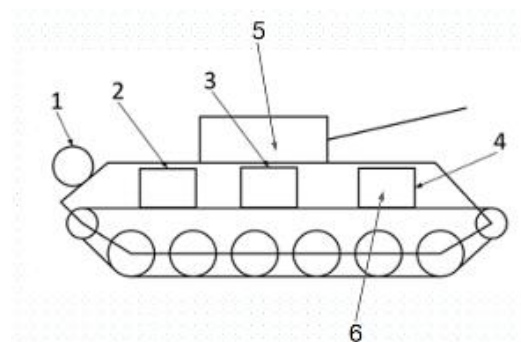


Fig. 2 Armor Damage Equivalent Model

The wheels/tracks, sighting devices, and F-level artillery systems in M-level damage can all be regarded as efficient targets for high-speed objects. However, to improve the overall damage capability of armor, a reasonable simulation model needs to be established. Analyzing the key components of the overall armor can classify them based on their distribution in the armor.

The general main battle armor mainly consists of fuel tank system, weapon system, crew system, walking system, power system, structural system, and fire control system. For the convenience of calculation, it is necessary to simplify the armor model. By combining the analysis of target functional structure and three-dimensional structural model, and analyzing the damage mechanism of armor, the corresponding relationship between component functional damage and structural damage is determined. Following the principle of functional and structural equivalence, establish a main battle armor damage equivalent model based on the three-dimensional structural model of the main battle armor target, As shown in Figure 2.

In Figure 2, 1 is the fuel tank, 2 is the entire crew, 3 is the middle compartment, 4 is the driving system, 5 is the artillery system, and 6 is the power system. It should be noted that the driving system

and power system are both located in the front of the armor, and side by side. Replacing vulnerable components with thick cubes can simplify the calculation process and improve calculation speed.

Table 1. Simplified Model Parameters of Target Armor

position	Armor thickness(mm)	normal angle(°)
top	7	60
bottom	19	57
side of turret	19	0
Turret face	23	0
Top of turret	10	0
Top of the vehicle body	6	0
side of the vehicle body	16	14
Underbody Side	18	0
tailstock	16	19

Table 1 above lists the armor thickness and angle with the normal of each key component in the simplified target armor model.

3. Damage assessment

3.1. Damage analysis of critical components

The main damage elements formed when high-speed objects strike armor are armor piercing rods, fragments behind the target, impact and vibration, shock waves, etc. Adopting the 0-1 damage law for the armor piercing rod, that is, if the key components can be penetrated on the penetration channel of the armor piercing rod, the key components will be 100% destroyed. If the jet trajectory intersects with various critical surfaces, the intersects are defined as Q_n , and n is the number of intersection points. Then, assuming O is the detonation point of the warhead, calculate the length from O to Q_n . If the length from O to Q_n is $\geq L$ (L is the ultimate penetration depth of the initial concentrated energy jet), then these critical components can be penetrated. If the critical component cannot be penetrated, the critical component has not been damaged. The kinetic energy damage criterion is adopted for the fragments which behind the target. It compares the kinetic energy of the impact fragments with the kinetic energy criterion that can cause mild, moderate, and severe damage to key components, and obtains the degree of damage caused by the fragments to key components. For shock waves, the overpressure specific impulse criterion is used to comprehensively compare the peak pressure and overpressure action time of the shock wave on the target, and obtain the degree of damage to key components caused by the shock wave.

3.2. Probability analysis of target armor damage

The classification of damage levels for infantry tank targets can refer to the classification method of armor damage levels: M-level, K-level, and F-level. The damage probability of different levels is determined by combining the damage probability of key components that contribute.

Due to the fact that infantry tanks are composed of various key components, damage to these components can result in varying degrees of damage to the entire vehicle. Therefore, to calculate the probability of damage to the entire tank, the first step is to calculate the probability of damage to each key component, and then summarize the results. Determine the probability of complete vehicle damage based on the contribution factors of each component damage. Assuming that the damage probabilities of each type of damage element to the target are not correlated, the overall damage probability of the target is:

$$P_K = 1 - [(1 - P_{K-FRAG})(1 - P_{K-PEN})(1 - P_{K-BLAST})] \quad (1)$$

In the formula: P_{K-FRAG} represents the probability of damage caused by fragments behind the target to the target; P_{K-PEN} represents the probability of damage to the target by the armor piercing rod; $P_{K-BLAST}$ represents the probability of damage to targets by shock waves.

The algorithm steps for calculating the probability of target damage under the action of each damage element are as follows: Calculate the intersection point between the damage element trace and the target component; Calculate the relationship between the damage element and the impact/breakdown of components which intersecting; Call the damage rate model which bound to the target component to calculate whether the component is damaged; Calculate the overall damage probability of the target based on the damage tree.

4. Damage determination method

The difference in jet velocity between the front and rear sections of a high-speed object, the stability of the tail wing, and the angle of the projectile's cone all affect the armor piercing effect and damage capability. To improve the damage effect, it is most suitable to use kinetic energy projectiles with medium distance, minimal rotational angular momentum, high tail stability, and small cone hole angles^[10].

The high-low frequency vibration and impact generated by high-speed objects penetrating armored vehicles cause a sudden change in the target mechanism and state, and the destructive effect varies with the magnitude and duration of external forces. Even if the armor structure itself can withstand such impacts, the components and devices installed inside the vehicle may still cause serious damage. At the same time, the impact wave overpressure inside the armored vehicle caused by the penetration of kinetic energy projectiles can cause damage to personnel, fire control devices, instrument panels, aiming systems, etc. The damage effect test of high-speed objects hitting advanced armored targets should include no less than three typical physical quantities, such as acceleration, shock wave overpressure, noise, strain, post effect temperature, etc; The comprehensive verification determines that there are no less than 16 testing locations, such as fuel tanks, armored personnel, ammunition, engines, and fire control systems.

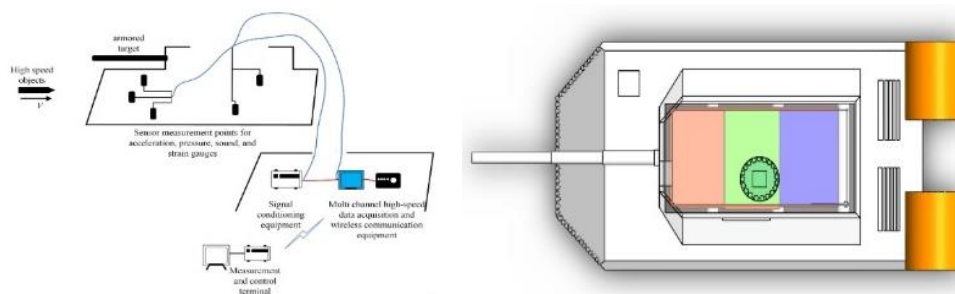


Fig. 3 Schematic diagram of destructive effect testing scheme

Fig. 4 Equivalent distribution diagram of key vulnerable systems for armored targets

The destructive effect testing scheme is shown in Figure 3, where acceleration sensors, shock wave pressure sensors, microphones, strain gauges, etc. are installed at appropriate positions in the armored vehicle. The sensor signal output is wired to the signal conditioning equipment outside the armored vehicle or directly connected to multi-channel high-speed data acquisition equipment. The data acquisition equipment can be controlled through remote measurement and control terminals, such as reset, fast data reading, equipment turntable monitoring, and so on. Remote measurement and control terminals can read real-time data from data acquisition equipment for signal analysis, processing, and report output. In Figure 4, the equivalent distribution of the driving system and power system, the equivalent distribution of the artillery system and the middle compartment, and the equivalent distribution of the passenger compartment and fuel tank are shown from left to right. The four modules are equipped with various judgment sensors and connected to the target external processing equipment for analysis.

The overall process is as follows: when a high-speed object hits the target armor at its initial velocity V , various sensors from inside the target armor first obtain data on armor damage caused by each facet, which is transmitted in the form of electrical signals to signal conditioning equipment,

multi-channel high-speed data acquisition, and wireless communication equipment for data analysis. The integrated data is then transmitted remotely to the measurement and control terminal, displaying various parameters and damage information in real time.

It should also be noted that the judgment can be divided into three groups, because the damage efficiency from the front, side, and back of the target armor is different.

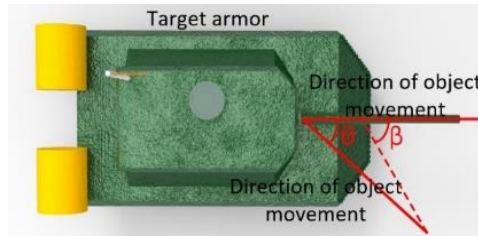


Fig. 5 Correlation diagram between armor and projectile movement

As shown in the above figure, assuming that the target armor moves horizontally at a velocity of V_1 and a projectile velocity of V_2 , with an angle of θ , according to the cosine theorem, the final velocity V acting on the armor and its angle with the direction of object motion can be obtained β , this angle can also be used as the penetration angle, when θ . The angle increases, The angle β also increases accordingly

Satisfy the following formula:

$$\begin{aligned} V^2 &= V_1^2 + V_2^2 - 2V_1V_2 \cos \theta \\ V_1^2 &= V^2 + V_2^2 - 2VV_2 \cos(\pi - \beta) \end{aligned} \quad (2)$$

According to Figure 5, it is not difficult to see that when θ is 0° , the projectile hits from the front; When $0^\circ < \theta < 90^\circ$, the projectile strikes from the angle between the front and a portion of the side front; When $\theta = 90^\circ$, the impact is directly on the side; When $90^\circ < \theta < 180^\circ$, the projectile strikes at a certain angle from the rear and side; When $\theta = 180^\circ$, the projectile is striking directly towards the rear.

Based on the above analysis, it can be roughly divided into three groups to calculate the comprehensive probability P , which is to strike from the front at an angle, from the side at an angle, and from the back at an angle

$$\begin{cases} P = \frac{\sum_{i=1}^n S_i \cdot P_{hi}}{\sum_{i=1}^n S_i} & (i = 1, 2, 3, \dots, n) \\ P_{hi} = \frac{b}{n} \end{cases} \quad (3)$$

In the formula, Φ is the probability of breakdown within the region, h is the armor thickness, and b is the penetration depth.

According to the analysis, it is easy to know that it is possible to directly penetrate or damage the frontal armor from $0^\circ < \theta < 90^\circ$. Below is a simulation of the relationship between the comprehensive probability and the angle.

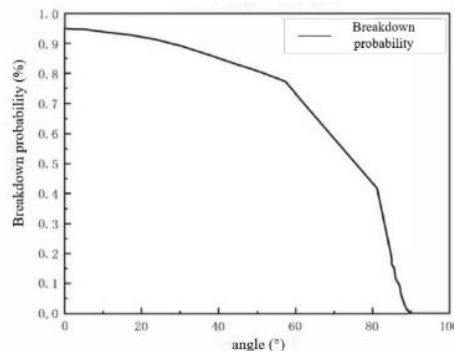


Fig. 6 Comprehensive Probability of Frontal Breakdown

From Figure 6, it can be seen that the smaller the angle, the greater the probability of armor penetration and the deeper the penetration depth for frontal armor. As the angle increases, the comprehensive breakdown probability P also decreases.

Same as above, the angle range that can damage or puncture the side is $90^\circ \leq \theta < 180^\circ$.

As shown in Figure 7, it can be seen that in the θ . When the angle is within the range of 50° to 125° , the comprehensive probability is the maximum $P_{\max}$ value.

From Figure 8 can be seen that when attacking armor from behind, the overall probability increases with θ . As the angle increases, When the angle is greater than 120° , the comprehensive probability is $P_{\max}=1$.

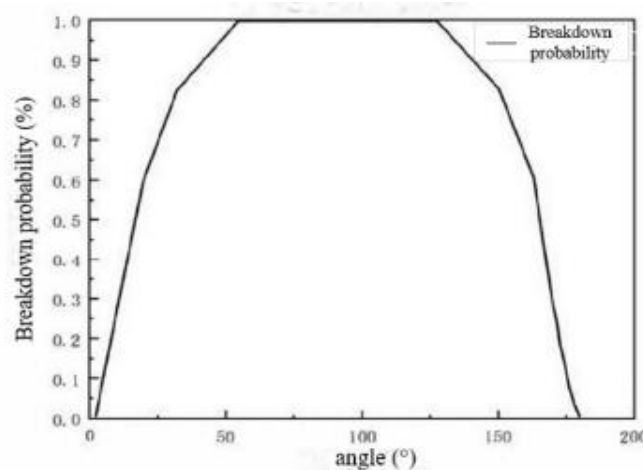


Fig. 7 Comprehensive Probability of Side Breakdown

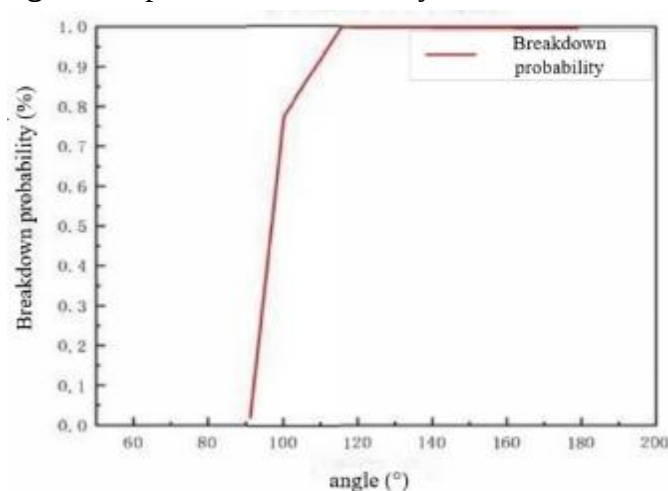


Fig. 8 the comprehensive probability of breakdown at the back

From a comprehensive analysis, the armor on the side and rear of the armor is more easily penetrated, with a significant effect and a high fault tolerance angle.

5. Summarize

By analyzing the armor structure and establishing a damage tree, vulnerability analysis was conducted on armored targets, and a vulnerability model for the target was constructed. Based on the damage criteria of armor piercing rods, target fragments, and shock wave damage elements, an algorithm for the overall damage probability of the target is provided. We have designed a destructive effect testing plan using various sensors and signal analysis instruments. This judgment method providing comprehensive visual evaluation results and technical support for achieving high-speed object damage judgment research under multiple working conditions.

References

- [1] Huabiao FU, Xinlong Tan. Application Analysis of Composite Materials in Tank Armored Vehicles [J]. China High-tech, 2018,25(2): 76-78
- [2] Yong Zou,Guohuai Hu,Yuhong Zhou,etc. Experimental Simulated Investigation on Armour-piercing Damage of High-speed Kinetic Energy Missile[J]. Journal of Projectiles, Rockets, Missiles and Guidance, 2019, 39(01): 35-37.
- [3] Haifu Wang, Jianwen Xie, Long Ji. Progress and Development Trend of Efficient Damage Technology [J]. Science and Technology Foresight,2022, 01(04): 113-124.
- [4] Xiangrong Li, Guohui Wang, Feng XU. Damage Evaluation Simulation of Blast Fragmentation Warhead to Main Battle Tank[J]. Journal of Academy of Amored Force Engineering, 2009,23(02): 44-47.
- [5] Jingwei Huang. Research on the Fragment Law of Fragmented Warhead and the Penetration Effect of Fragments on Infantry Fighting Vehicles [D]. NanJing University of Science and Technology,2014.
- [6] Gaofeng Zhang, Xiangdong Li, Lanwei Zhou, etc. Vulnerability Assessment of Typical Tank Under the Action of HEAT [J]. Journal of Ballistics,2018,30(02): 67-74.
- [7] Jiaojiao Song, Jun Wang, Yijia Gu. Simulation Research on Penetration Ability of Armor Piercing Shell Against Target Tank [J]. Fire Control & Command Control,2020,45(02): 97-101.
- [8] Mengyan Han, Yanyan Huang. A Method for Damage Evaluation of Fire Attack Schemes for Armored Targets [J]. Fire Control & Command Control,2022,47(09):66-72.
- [9] Hui Hu, Zhenyu Yuan, Chunsi Xie, etc. Research on Constructing Damage Assessment Model of System Target Based on the Function Tree [J]. Ship Electronic Eng ineering,2010,30(8):32-35,84.
- [10] Jia Xiong. The competition between armored and anti armored ammunition [J]. Tank and Amored Vehicle, 2016, 38(15): 53-58