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Comprehensive Review of Projectile Penetration Overload Research

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Abstract

This paper provides a comprehensive review of the research progress on the overload phenomenon during projectile penetration, systematically analyzing the topic from four aspects: theoretical research, simulation technology, experimental testing, and propagation laws. In the theoretical research section, the physical mechanisms and changing patterns of different materials during high-speed penetration are explored. The simulation technology section focuses on the advancements in numerical simulations that enhance the ability to replicate complex physical phenomena during penetration. The experimental testing section summarizes the work scholars have done on projectile load storage testing apparatus, including the design of testing systems, protective device design, and subsequent test data processing. The propagation laws section introduces the relationship between penetration overload and various factors based on previous studies and points out problems that urgently need to be addressed in penetration overload research.

Keywords

Penetration; Overload; Cavity Expansion Theory; Concrete Targets; Rock; Metallic Targets.

1. Introduction

The penetration-explosion warhead is a type of implosive warhead that combines both penetration and blast capabilities. It relies on the structural strength of the warhead casing and the delay mechanism of the fuse to penetrate protective structures such as reinforced concrete and detonate within, causing damage to the target. As the penetration depth increases, the requirements for penetration overload capacity have also escalated, posing significant challenges to the structural and explosive design of penetration-explosion warheads. During the design, development, and standardization of new penetration-explosion warheads, there are increasingly stringent requirements for target penetration depth and overload capacity, making previous penetration data inadequate for reference. Both research and application units urgently need feedback and validation of actual warhead overload and target response data, which necessitates advanced research on penetration overload. Therefore, in-depth studies on warhead penetration overload provide a critical foundation for safety assessments and the optimization of structural and explosive design.

This paper comprehensively reviews the research progress on warhead penetration overload from four perspectives: theoretical research, simulation technology, experimental testing, and propagation laws. By reviewing and summarizing existing research findings, it aims to provide references and insights for further research and application, thereby promoting the continued development of penetration-explosion warheads.

2. Current Research Status of Penetration Overload Theory

In the context of rapid advancements in modern military technology, the penetration process is a crucial aspect of studying the behavior of high-speed objects penetrating targets, making its theoretical research particularly significant. With the increasing demands for the precision strike capabilities and destructive effectiveness of weapon systems, understanding and mastering the physical mechanisms and changing laws of the penetration process under various conditions has become a core topic for enhancing the performance of weapon systems. In recent years, scholars both domestically and internationally have made significant progress in the theoretical research of penetration, deepening the understanding of the penetration process and providing a solid theoretical foundation for experimental studies on penetration overload technology.

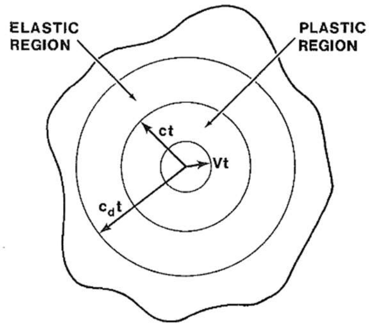

Figure 1. The theory of spherical cavity expansion in the response zone of elastoplastic materials [1]

Cavity expansion theory is one of the important theories for studying penetration issues, and extensive work has been conducted by researchers worldwide based on this theory. Deng Qiong et al.[2] found that the overload curves of projectiles calculated using the time discretization method based on the spherical cavity expansion theory(As shown in Figure 1) closely match the experimental overload curves in different media. This indicates that the cavity expansion theory can be approximately used for penetration calculations in multi-layered media. For concrete materials, Li et al. [3] derived theoretical expressions for the dynamic expansion response of spherical cavities using similarity transformation methods and proposed a spherical cavity expansion model for high-speed projectile penetration analysis. Given that penetration overload quantifies the target's resistance to projectile penetration during the process, the theoretical study of penetration resistance is key to exploring penetration overload. For concrete materials, Xue et al. [4] applied stress wave damage theory to analyze the penetration characteristics in the crater zone, establishing a new model for calculating the resistance on the surface of the projectile in the crater area,. Yang et al. [5] derived an expression for the resistance of conical projectiles during the penetration process and applied it to calculate the overload during projectile penetration in single-layer and multilayer media. Wang et al. [6] studied the entire process of rigid projectile penetration into power-law strain-hardening media and proposed a theoretical expression for the axial resistance of the projectile. By combining cylindrical cavity expansion theory with the projectile shape equation, they derived equations for the axial resistance of rigid projectiles and the changes in projectile velocity when penetrating semi-infinite thick power-law strain-hardening media and finite thickness target plates.

Regarding metallic materials, Jiang et al .[7] Using finite spherical cavity expansion theory and an equivalent tensile strain fracture criterion, they obtained numerical solutions for projectile penetration resistance, successfully predicting the penetration behavior of projectiles in metallic target plates of varying lengths and thicknesses. Wang et al. [8] utilized unified strength theory to derive expressions for the radial stress in the cavity wall of linear hardening target materials during the elastoplastic and plastic stages, provides a better description of the dynamic response of the projectile-target interaction

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during penetration and yields a series of analytical solutions for penetration resistance and depth based on different strength criteria.

For rock materials, numerous studies suggest that rock targets may exhibit two types of responses: (1) elastic-crack-plastic response; (2) elastic-plastic response. When the cavity expansion velocity is low, the target material responds according to the first type; conversely, when the cavity expansion velocity is high, the crack zone disappears, and the target material responds according to the second type. Based on these assumptions, Zhang and Lin [9] investigated the cavity expansion theory model used in the study of penetration into highly brittle rocks. They proposed a new response partition for target materials-complete failure, cracking, and elastic zones-based on experimental results and the fundamentals of geotechnical damage mechanics, employing a constitutive model for fractured materials in their calculations. By solving for stress and displacement in each partition, they established the relationship between radial stress in the cavity wall and cavity expansion velocity. Wei et al [10]. applied unified strength theory as the failure criterion for rocks and calculated the resistance experienced by the projectile during penetration, analyzing the effects of projectile shape and strength theory parameters on penetration depth.

3. Current Status of Penetration Overload Simulation Technology Development

With advancements in computer simulation technology, penetration overload simulation based on numerical computation methods has become an important research tool. Accurately simulating the complex physical phenomena during the penetration process of high-speed objects is crucial for enhancing the effectiveness assessment of weapon systems and the design of protective structures. However, the accuracy of numerical simulations is highly dependent on factors such as the selection of model parameters, mesh partitioning strategies, and contact algorithms.

Regarding the model parameters for medium materials, Ai et al. [11] combined the Johnson-Holmquist model and the crack softening model to conduct numerical simulations of impacts on rock targets at different velocities, successfully simulating the damage and strain caused by impacts, thereby providing new insights into the behavior of rocks under dynamic loads. Wei et al. [12] implemented a combination of the TCK model and the K&C model using AUTODYN software, modifying parameters to fit the scenario of kinetic projectiles penetrating concrete targets. By discussing the treatment of tensile damage, this method can better simulate the actual damage process. Shi [13] employed various experimental methods and concluded that the ratio of shear strength to compressive strength of concrete varies with different strengths, and that the splitting tensile strength of concrete is typically less than its shear strength. Dai [14] used experimental determination methods for HJC model parameters to obtain the constitutive model parameters for high-strength concrete and performed numerical simulations of impact compression tests on Hopkinson pressure bars using finite element simulation software. Meng et al. [15] utilized the HJC concrete damage constitutive model and fluid-solid coupling algorithms, recalibrating simulation parameters through experimental data fitting, with the calculated ballistic limits and residual velocities aligning well with experimental data. Wu and colleagues [16] employing different fitting methods to obtain various JC constitutive model and failure model parameters, concluding that without considering temperature softening, using a high strain rate as a reference strain rate for fitting can more accurately characterize the stress-strain relationship of materials under high strain rates. Zhang et al. [17] performed simulation analysis of the penetration process using LS-DYNA software, identifying several key parameters of the HJC model for ultra-high performance concrete (UHPC) under dynamic impact, with simulated penetration results closely matching real experimental data. Lin et al. [18] proposed a method for simulating the failure criteria and parameters of reinforced concrete penetration based on the HJC material model, modifying the failure control parameter FS in the HJC material model and combining it with three auxiliary failure criteria to address the deficiencies in failure definition within the HJC model.

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In terms of mesh parameters and parameter sensitivity, Chuang et al. [19] investigated the impact of target mesh on the numerical simulation results of high-speed projectiles penetrating concrete, finding that setting the target mesh edge length to one-sixth of the projectile radius meets accuracy requirements. Chen et al. [20] introduced orthogonal experimental design theory to configure, assess, and optimize penetration test schemes to determine the best parameter settings. Their research indicated that at a significance level of 0.05, the unit size and shape are the primary factors influencing simulation accuracy, while two-dimensional contact algorithms are secondary factors with minimal differences between them. Nie et al [21]. quantitatively calculated the contribution rates of different parameters in the RHT model for rock materials during the penetration process(As shown in Table 1), providing important guidance for determining material model parameters and precise simulation calculations based on sensitivity rankings for different evaluation metrics.

Table 1. Ranking of the overall contribution rates of different evaluation index parameters. [21]

Evaluation Indicators	Contribution Rate Ranking
Penetration Depth	$n_f > p_{co} > f_c > s > \xi > B > n > f_s^* > \rho_0 > f_t^* > g_c^*$ $> A > G > Q_0 > \alpha_0 > \varepsilon_p^m > D_1 > c_0^2 > A_f > N > g_t^*$
Projectile Mass Loss Rate	$n_f > c_0^2 > f_c > p_{co} > A > N > g_t^* > B > f_t^* > f_s^* >$ $\xi > G > \alpha_0 > A_f > g_c^* > \varepsilon_p^m > n > Q_0 > s > D_1 > \rho_0$
Target Damage	$f_c > \varepsilon_p^m > n > D_1 > \xi > f_s^* > \alpha_0 > \rho_0 > Q_0 > g_c^* >$ $p_{co} > f_t^* > c_0^2 > s > B > n_f > G > g_t^* > A > N > A_f$

Lin et al. [22] studied the effects of two tensile failure modes-hydrostatic pressure and principal stress-different mesh sizes of concrete target plates, and varying erosion strains on the calculated results of penetration depth and damage area on the front surface of the target plate, offering references for numerical simulations of concrete penetration. Ezzedin [23] examined the influence of erosion mechanisms on the numerical simulation of high-speed projectile impacts on reinforced concrete slabs, finding that erosion strain values and mesh size significantly affect the residual velocity of projectiles and the damage depth of concrete slabs.

4. Current Development Status of Penetration Overload Testing Technology

During the penetration of hard targets such as steel plates, concrete targets, or reinforced concrete structures, the warhead experiences immense impact forces, resulting in penetration accelerations reaching tens of thousands to hundreds of thousands of g. To accurately obtain empirical data on penetration overload, precise and reliable testing technologies are essential. The current primary method for testing penetration overload is based on onboard storage testing using high g-value accelerometers.

In recent years, significant advancements have been made in penetration overload testing technology, driven by developments in integrated circuit technology, sensor technology, and data processing techniques. Accelerometers serve as the foundation for testing overload during the penetration process. In the realm of high-range accelerometers, Zhou and colleagues [24] from North University of China designed a high-range accelerometer using a pair of double-ended cantilever structures, providing a reference for the realization of a single-chip integrated three-axis accelerometer with three independent mass blocks. Wang [25] proposed a temperature compensation scheme for the non-linearity in sensitivity of piezoresistive sensors by introducing polysilicon into the Wheatstone bridge.

Regarding onboard testing systems, Zhang and colleagues [26] developed a super low-power, compact device for testing high-impact overload during projectile penetration. Niu [27] employed storage testing techniques to study acceleration overload, structural stress and strain, and internal

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explosive pressure during the projectile's penetration of multilayer targets. Hang [28] designed a highly reliable control mechanism for the penetration overload testing system, effectively extending the system's operational duration and anti-interference performance. Zhang and colleagues [29] established a finite element model and conducted simulation analyses, which, when combined with field tests, indicated that the overload information recorded by the onboard storage testing device was closely aligned with the rigid body overload response when the rigidity of contact between the recording device and the projectile was minimal. Wei [30] researched common issues such as multilayer ceramic capacitor failures and lithium battery drift in onboard storage testing, providing theoretical support for the study of energy storage device failure mechanisms.

In terms of protective design for penetration overload testing devices, Wang Yan [31]conducted experimental research on various protective structures, providing a foundational basis for structural design of onboard testing systems. Zhang et al. [32] validated through numerical simulation and experiments the energy absorption, vibration reduction characteristics, and buffering mechanisms of foam materials, offering important references for the design of new fuze buffering components that meet high overload resistance requirements. Zhang and colleagues [33] from the Xi'an Institute of Electromechanical Information Technology proposed a composite encapsulation method for fuzes based on the theory of stress wave attenuation at interfaces, with experimental results (As shown in Table 2)meeting the overload protection requirements for fuzes penetrating multilayer hard targets.

Table 2. Experimental Results of Composite Encapsulation Method

Serial Number	Encapsulation Scheme	Encapsulated Device	Nominal Overload /g	Impact Failure Count/Occurrences
1	Silicone Rubber	DC/DC	50 000	7
2	Epoxy Resin			4
3	Electronic Potting Adhesive			4
4	Silicone Rubber - Epoxy Resin - Electronic Potting Adhesive			10
5	Epoxy Resin-Electronic Potting Adhesive-Silicone Rubber			5
6	Electronic Potting Adhesive-Silicone Rubber-Epoxy Resin			3

In the area of signal processing for measured penetration overload, Xie [34] proposed an adaptive optimized variational mode decomposition method for analyzing penetration overload signals. Wang et al. [36] introduced the concept of critical cutoff frequency, using low-pass filtering to obtain rigid body overload values that are similar to those obtained through semi-empirical methods. Zheng Hongliang and colleagues [37] proposed a method based on feedforward denoising convolutional neural networks (DnCNN), which can accurately estimate rigid body overload from penetration overload signals, demonstrating significant advantages in denoising capability and automation over traditional methods. Kang [35] and others proposed a synchronous analysis method for time and frequency information based on the fundamental theories of wavelets and wavelet packets.

5. Current Research Status on Penetration Overload Transmission Laws

In recent years, research on penetration overload has deepened, with scholars approaching the topic from various perspectives and utilizing multiple methods such as simulations, experiments, and data analysis techniques, yielding significant results. Ren et al. [38] combined dimensional theory with experimental research to perform regression analysis on the acceleration curves of projectiles penetrating concrete, resulting in specific formulas for engineering calculation models, which were validated by the measured overload characteristic parameters obtained during experiments. Wang et al. [39] conducted numerical simulations using ANSYS/LS-DYNA finite element software to analyze the penetration process of a 125 mm caliber explosive projectile into a finite thickness C35 concrete target, deriving empirical formulas for the maximum front overload during penetration under different conditions based on simulation data:

$$k_{\max} = \frac{V_0^2 - \frac{m}{m+m_1}\left(V_0^2 - \frac{1.63\times10^8 d^{1.5} b^{1.4}}{m}\right)}{(H+b)g} \tag{1}$$

Addressing the issue of penetration depth for different materials, Wang et al. [40] characterized the influence of key factors on penetration depth using a dimensionless impact index, establishing a new formula for calculating penetration depth:

$$h_{\mathrm{q}} / d = K_{\mathrm{p}} \lambda f(Z) \tag{2}$$

$$Z = 1.0\times10^{-3}\,\mathrm{NV}(1-9.091\mu)\left(\frac{P}{d^3 R}\right)^{0.5} \tag{3}$$

$$N = \begin{cases} 0.18 l_{\mathrm{r}} / d + 0.56 & (\textit{Elliptical projectile}) \\ 0.25 l_{\mathrm{r}} / d + 0.56 & (\textit{Conical projectile}) \end{cases} \tag{4}$$

$$f(Z) = 0.9355 + 0.4046Z + 0.05752Z^2 \tag{5}$$

Peng Yong et al.[41] conducted experiments to measure the deceleration of rigid projectiles during the penetration process and the structural vibrations, providing a theoretical model for the deceleration time of projectile penetration/perforation.

By analyzing large-scale model penetration test data of various media materials such as concrete and rock, the reasonableness of the formula was verified. Several scholars have established penetration depth equations for different materials. Shen et al. [42] studied the penetration effects of projectiles in rock masses, deriving overload characteristics and motion laws during the penetration process through experimental and theoretical analysis, and proposed a new formula for calculating depth in rock masses. For steel plate targets, Lu et al. [43] obtained the relationship between the penetration depth of the projectile core into the target plate and the impact speed and kinetic energy upon impact through numerical simulation, providing an important reference for the design and performance evaluation of armor-piercing projectiles.

The study of penetration overload and its influencing factors is also crucial. Several scholars have focused on the main influencing factors of penetration overload, including the geometric shape, speed, material properties of the penetrator, and the characteristics of the target material. Xiaodong et al. [44] found that factors such as projectile speed, mass, diameter, and CRH ratio significantly affect static resistance, proposing an empirical formula to predict static resistance. Zhang et al. [45] analyzed the relationship model between mass abrasion and CRH, concluding that the impact of CRH on penetration depth increases with speed. Zhou and Hui et al. [46]-[47] analyzed the effects of different shapes of warheads on penetration overload through numerical simulation and finite element analysis. Yan et al. [48] proposed a non-proportional scaling design method, experimentally validating a scaled model of a projectile penetration overload testing device, finding that this non-proportional scaling model effectively simulates the rigid deceleration characteristics of the prototype projectile.

6. Conclusion

The study of projectile penetration overload is a complex interdisciplinary field that has made significant advances in recent years in areas such as theoretical research, simulation technology, experimental testing, and transmission laws. These research findings have not only deepened the understanding of the physical mechanisms underlying the penetration process but have also provided crucial technical support for the design and optimization of explosive warheads.

Despite the notable progress in the study of projectile penetration overload, several pressing issues remain to be addressed:

In terms of simulation research, the response characteristics of different materials during high-speed penetration processes are complex and variable. Existing material models (such as the Johnson-Holmquist model and HJC model) perform well under certain conditions, but their applicability under other conditions still needs validation, particularly under extreme conditions (such as high temperatures and high strain rates), where the material constitutive relations and damage models exhibit considerable uncertainty.

In experimental research, the limitations of projectile-mounted storage testing methods become apparent when measuring ultra-high overloads exceeding 100,000 g, as the devices are prone to circuit failure under significant impacts; furthermore, the need to alter projectile structures also restricts the development of projectile-mounted storage testing. Future research could take an energy conversion perspective, transforming the energy of the target during the penetration process into directly measurable quantities such as target stress and vibration signals, thereby achieving more reliable ultra-high overload testing.

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