Investigation on anti-penetration performance of reinforced concrete targets based on ANSYS/LS-DYNA

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Abstract. Based on the perforation experiment carried by S.J.Hanchak et al, the finite element method (FEM) model of the reinforced concrete (RC) target was set up. After obtaining the residual velocities of a projectile, the feasibility of this model was verified. On this basis, the effects of the inclination angle and impact position on the penetration resistance of the RC target were analyzed by ANSYS/LS-DYNA. Besides, three targets compared their penetration resistance with the RC target according to residual velocities and target damages. Three main conclusions were drawn: (1) the plastic deformation of the first and third steel layer is intensified with the inclination angle increasing, and the projectile kinetic energy is dissipated more, which improves the penetration resistance of the RC target; (2) the penetration resistance of the RC target is aggravated by the impact position at a high reinforcement ratio (3%), especially when impacting at the crossing point of steel bars; (3) based on the same condition, the anti-penetration performance of four targets is listed as follows: SC target > RC target ≈ SSC target > Concrete target.

1. Introduction

Scholars all over the world have devoted themselves to the study of penetration effects on plain concrete and RC structures [1-3] for a long time. As regards how to effectively attack military objects and improve the protective capability of significant structures, it is worth noting that the penetration resistance of the reinforced concrete has always been one of the important measurement criterions. A large number of researches have indicated that the penetration resistance of projectiles impacting RC targets is affected by many factors, including the inclination angle and impact position. Guirgis S et al. [4] investigated the penetration process of a rigid projectile impacting concrete based on an energy method, and proposed a new method to improve the concrete penetration resistance. The typical experimental phenomena of an abnormal penetration for RC targets were summarized by Hai-Jun WU et al. [5], who elaborated a penetration theory considering the direct impact between steel bars and concrete. Jian-Feng L et al. [6] adopted AUTODYN to establish a FEM model of the projectile and target, which is used to analyze how impact positions influence the projectile terminal performance.
Peng.Y et al. [7, 8] conducted perforation tests on ultra-high performance steel fiber reinforced concrete (UHP-SFRC) targets, and derived a semi-analytical model for the residual velocity to evaluate the penetration resistance of composite targets, achieving a high accuracy in the prediction of the residual velocity for segmented concrete targets.

Unfortunately, current researches on the penetration resistance of RC targets have the following shortcomings: (1) the influence of the inclination angle on the target damage is lack of analysis from an energy consumption; (2) the effect of the impact position on the projectile terminal performance isn’t verified at a higher reinforcement ratio; (3) the comparison of the anti-penetration effect between monolithic targets and segmented targets hasn’t been investigated. Thus, the effects of the inclination angle and impact position on the penetration resistance of the RC target were analyzed by ANSYS/LS-DYNA. Moreover, three targets, including a concrete target, a steel-concrete (SC) target and a segmented steel-concrete (SSC) target, compared their anti-penetration performance with the RC target according to residual velocities and target damages.

2. Establishment and Verification of Numerical Model

2.1. Geometric, Finite Element and Material Models

The geometric model of the projectile and target were based on the penetration experiments carried by S. J. Hanchak et al. [9] and their size is shown in Figure 1(a). The Lagrange algorithm in ANSYS/LS-DYNA was used in this model. Considering the calculation symmetry and efficiency, a 1/2 model (1:1 setting model) was established. Solid164 element was adopted by the projectile and concrete while beam161 element was used by steel bars, both steel bars and concrete were managed by common joints. The mesh of 20 cm area in the target middle was densified, while that of other area was sparse. The symmetrical boundary constraint was set on the symmetrical surface and the displacement boundary constraint was applied around the target. The contact between the projectile and concrete was *CONTACT_ERODING_SURFACE_TO_SURFACE (ESTS). The FEM model is shown in Figure 1(b). A plastic kinematic material model was used for the projectile and steel bars, while a HJC cumulative damage model was adopted for concrete, which could meet the numerical calculation requirements. The material parameters for the projectile, steel bar and concrete were taken from Reference [10]. The specific parameters are summarized in Tables 1 and 2.

| Name       | Density (g/cm³) | Elastic modulus (GPa) | Poisson ratio | Yield stress (MPa) | Tangent modulus (MPa) | Hardening parameter | Failure strain |
|------------|-----------------|-----------------------|---------------|-------------------|-----------------------|---------------------|---------------|
| Projectile | 8.02            | 207                   | 0.3           | 1724              | 4220                  | 1                   | 1             |
| Steel bar  | 7.86            | 200                   | 0.27          | 310               | 760                   | 0                   | 0.9           |
### Table 2. Material model parameters of the concrete.

| Density (g/cm³) | Shear modulus (GPa) | A   | B   | C   | N   | Fc (MPa) | T (GPa) | EPS0 | EFMIN |
|----------------|---------------------|-----|-----|-----|-----|----------|---------|------|-------|
| 2.52           | 8.76                | 0.79| 1.6 | 0.07| 0.61| 48       | 0.004   | 0.001| 0.01  |

### Table 3. Material model parameters of the concrete.

| SFMAX | Pc (GPa) | Uc (GPa) | Pl (GPa) | Ul (GPa) | D1 | D2 | K1 (GPa) | K2 (GPa) | K3 (Gpa) |
|-------|---------|---------|---------|----------|----|----|----------|----------|----------|
| 7     | 0.016   | 0.001   | 0.8     | 0.1      | 0.01| 1  | 85       | -171     | 208      |

2.2. Feasibility Verification of FEM Model

Some penetration tests of S. J. Hanchak et al [9] are simulated with the above model. As shown in Figure 2, when the steel mesh is impacted by the projectile with different impact velocities, the experimental values of the residual velocity is in a good agreement with the calculated values, and the error between them gradually decreases with the impact velocity increasing. Figure 3 displays the steel damage when the projectile vertically impacts its crossing point with 746 m/s. Because of compressive stress waves, the deformation direction of the first steel layer is opposite to the projectile impact direction, while that of the third one is consistent with the impact direction caused by tensile stress waves, and the middle one expands mainly along the radial direction, which are similar to the experimental phenomena in Reference [9]. Thus, the above model is feasible by conducting a corresponding penetration calculation.

![Figure 2. Comparison of experimental and simulated results of projectile residual velocities.](image1)

![Figure 3. Damage of steel bars.](image2)

3. Numerical Analysis and Discussions

3.1. Effect of Inclination Angle on penetration Resistance

During the flight of a penetration warhead, the projectile is affected by the asymmetry interaction between the gravity and air resistance, and a certain inclination angle is produced when it impacts the
target, which has an important influence on the target penetration resistance. According to the functional relationship between the ultimate ricochet angle and impact velocity proposed by Jian-Feng X et al. [11], the inclination range of this section is adopted 0-45°. The impact position is assumed as the steel crossing point and the FEM model in 2.1 is used to analyze the inclination change how to influence the RC target penetration.

Figure 4 plots the steel damage under different inclination angles. When the projectile impacts the RC target with 746m/s, the plastic deformation of the first and third steel layer is intensified with the inclination increasing, while the middle one remains almost unchanged. The ratio between residual and initial kinetic energy ($E_r/E_0$) is used to measure the target penetration resistance, which is 66.31%, 61.57%, 59.2% and 58.54%, respectively, corresponding to 0°, 15°, 30° and 45°. Combining with the fitting curve in Figure 5 and Figure 4, the increasing inclination makes the projectile trajectory longer during the target penetration, and the projectile kinetic energy is consumed more because of the plastic deformation of steel bars, thus improving the penetration resistance of the RC target.

3.2. Effect of Impact Position on penetration Resistance

The effect of the impact position on the RC target penetration resistance is difficultly verified by experiments, because the projectile migration or slip is existed in the real tests. In this section, it is assumed that the impact position remains unchanged during the penetration, and there are mainly three typical locations as shown in Figure 6. The FEM model in 2.1 is still used to calculate the penetration of these locations at a low (1%) and high (3%) reinforcement ratio, respectively.

Figure 7 displays the deceleration-time curves at different positions when the reinforcement ratio is 1% and 3%. It can be seen that the time of three impacts between the projectile and steel bar is approximately 25, 150 and 275μs. The peak value of the projectile deceleration at Position 3 is the
largest and varies intensely, which indicates Position 3 has the strongest anti-penetration performance, while that at position 1 is the smallest and changes mildly, indicating Position 1 has the weakest anti-penetration performance. Moreover, the projectile deceleration is enhanced rapidly when the reinforcement ratio is 3%, especially at Position 3, which proves the influence of the impact position on the projectile terminal effect is aggravated at a high reinforcement ratio.

![Figure 6](image1.png)  
(a) Position 1  (b) Position 2  (c) Position 3

Figure 6. Three typical locations of the impact position.

![Figure 7](image2.png)

(a) Reinforcement ratio=1%  (b) Reinforcement ratio=3%

Figure 7. Deceleration-time curves of a projectile impacting different positions.

3.3. Comparison with penetration resistance of four targets

The above model was improved referring to the experiments in Reference [10]. The FEM models of the concrete target, RC target, SC target and SSC target were established respectively, as shown in Figure 8. Additionally, the steel bar in the RC target was 15 mm apart from the target back surface and the interval of the SSC target was 50 mm. Solid164 element was used for the steel plate in the SC and SSC target, whose material model was the same as the steel bar. The thickness of the steel plate was 1 mm, and the reinforcement ratio of three targets was 1% except the concrete target. It has been known that the anti-penetration effect of Position 3 is the strongest in 3.2, so the impact position of the RC target is at the crossing point of the steel bar, while others are at the target middle. The penetration calculation of four targets is carried out respectively.

As shown in Figure 9, the projectile impacts four targets with 310 m/s. At the penetration beginning, the impact compressive stress occurs instantaneously at the contact point between the projectile and target, which is much greater than the target resistance. Therefore, the velocity gradient of four targets along the penetration direction is particularly great and the projectile velocity decreases sharply. During the penetration, the concrete target is continuously squeezed by the projectile and the compressive stress wave is produced because of a single material. When the projectile reaches the target back, the compressive stress wave is weakened by a reflection, thus the projectile velocity remains unchanged. As regards the RC target, the steel bar is collided by the projectile, which also restrains the concrete spalling of the target back, hindering the projectile penetration. With regard to the SC target, the spalling concrete is more restrained by the steel plate compared with the steel bar. Concerning the SSC target, although the restraint effect of the steel plate is stronger than that of the steel bar, the target penetration resistance is weakened by the interval because the projectile damage
and deformation is locally recovered. Thus the residual velocity of the projectile is listed as follows: Concrete target > RC target ≈ SSC target > SC target, corresponding to the anti-penetration performance: SC target > RC target ≈ SSC target > Concrete target.

Figure 8. FEM model of four targets.

Figure 9. Velocity-time curves of the projectile for four targets.

Figure 10 plots the damage of four targets, where (a) ~ (d) is the concrete target, (e) ~ (h) is the RC target, (i) ~ (l) is the SC target and (m) ~ (p) is the SSC target. The damage of each target can be divided into three stages: the initial, middle and terminal penetration stage. During the initial stage, the target is crushed instantaneously because of the impact compressive stress. With the projectile continuously penetrating, the integral impact stress of the target can’t be homogenized because the impact time is very short. The target surroundings are broken and destroyed continuously, and the debris is ejected outward. Moreover, an inverted conical crater is formed in the RC target, SC target and SSC target. Their crater diameter and depth are approximately same, but the debris ejected by the SC target is extremely more than that of the RC and SSC target. As regards the concrete target, the formation of a front crater is not obvious. During the middle stage, a stable tunnel is formed in the middle of the target because the integral impact stress of the target tends to be uniform, and the projectile deformation is very small at this stage. Besides, some propagation cracks are also formed at both sides of the tunnel. Additionally, the cracks of the concrete target are the longest and extend to the rear crater, while those of the RC target are shorter because the further cracking is hindered by the steel bar. The tunnel length in the SC target and SSC target is the shortest, and no cracks are emerged, which shows the crack resistance of a rear steel plate is better than that of a rear steel bar. During the
terminal stage, with the penetration velocity decreasing, the crush failure of the target slows down. The compressive stress wave generated by the impact stress reaches the target edge, which is reflected as the tensile stress wave by the free surface, steel bar and steel plate. Thus a rear crater is formed by the tension damage. After perforating the concrete target, the diameter and volume of the rear crater is the largest, while the steel bar in the RC target breaks down along the penetration direction caused by the tensile stress wave, leading to a decrease of the crater size. With regard to the SC target, the rear steel plate protrudes along the penetration direction and cracks like petals. Although the diameter and volume of the rear crater are slightly larger than those of the RC target, the crater formation is slowed by the steel plate and the projectile kinetic energy is greatly consumed. On the other hand, the steel plate of the SSC target is only broken down and few cracks are subsequently formed.
4. Conclusion
The effects of the inclination angle and impact position on the penetration resistance of the RC target were analyzed by ANSYS/LS-DYNA. Then, three targets, including a concrete target, a SC target and a SSC target, compared their penetration resistance with the RC target according to residual velocities and target damages. The following main conclusions were drawn:

1) The projectile trajectory gets longer with the inclination angle increasing, if no ricochet occurs during the penetration. The plastic deformation of the first and third steel layer is intensified, and the projectile kinetic energy is dissipated more, which improves the penetration resistance of the RC target.

2) The penetration resistance of the RC target subjected to three impact positions is as follows: the steel crossing point (Position 3) > the steel single row (Position 2) > the steel mesh (Position 1). The influence of the impact position on the projectile terminal effect and the penetration resistance is aggravated at a high reinforcement ratio (3%), especially when impacting the crossing point (Position 3) of steel bars.

3) Based on the same condition, the anti-penetration performance of four targets is listed as follows: SC target > RC target ≈ SSC target > Concrete target. As regards the target damage, the rear steel plate or steel bars can restrain the propagation cracks and the concrete spalling, which provides a better penetration resistance. Moreover, the penetration resistance of the steel plate is stronger than steel bars to some extent.

References
[1] Luk V K, Forrestal M J. Penetration into semi-infinite reinforced-concrete targets with spherical and ogival nose projectiles [J]. International Journal of Impact Engineering, 1987, 6 (4):291-301.
[2] Beppu M, Miwa K, Itoh M, et al. Damage evaluation of concrete plates by high-velocity impact [J]. International Journal of Impact Engineering, 2008, 35 (12):1419-1426.
[3] Grisaro H, Dancygier A. A Modified Energy Method to Assess the Residual Velocity of Non-deforming Projectiles that Perforate Concrete Barriers [J]. International Journal of Protective Structures, 2014, 5 (3):307-322.
[4] Guirgis S, Guirguis E. An energy approach study of the penetration of concrete by rigid missiles [J]. Nuclear Engineering & Design, 2009, 239(4):819-829.
[5] WU Haijun, ZHANG Shuang, HUANG Fenglei. Research progress in penetration/perforation into reinforced concrete targets [J]. Acta Armamentarii, 2018, 39 (1):182-208.
[6] LOU Jianfeng, WANG Zheng, ZHU Jianshi, et al. Effects of reinforcement ratio and impact position on anti-penetration properties of reinforced concrete [J]. Explosion and Shock Waves2010, 30 (2):178-182.
[7] Peng Y, Wu H, Fang Q, et al. A note on the deep penetration and perforation of hard projectiles
into thick targets [J]. International Journal of Impact Engineering, 2015, 85:37-44.

[8] Peng Y, Wu H, Fang Q. et al. Residual velocities of projectiles after normally perforating the thin ultra-high performance steel fiber reinforced concrete slabs [J]. International Journal of Impact Engineering, 2016, 97:1-9.

[9] Hanchak S J, Forrestal M J, Young E R. et al. Perforation of concrete slabs with 48 MPa (7 ksi) and 140 MPa (20 ksi) unconfined compressive strengths [J]. International Journal of Impact Engineering, 1992, 12 (12):1-7.

[10] Abdelkader M, Fouda A. Effect of reinforcement on the response of concrete panels to impact of hard projectiles[J]. International Journal of Impact Engineering, 2014: 1-17.

[11] XUE Jianfeng, SHEN Peihui, WANG Xiaoming. Anti-penetration behavior of concrete and reinforced concrete and its equivalent relationship [J]. Journal of Building Materials, 2017, 20 (2):174-179.