Experimental Study on Ballistic Performance of Lateral Constraint Ceramic Structures

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Abstract. Thermal Bush restraint technology was used to control the thickness of the restraint layer by applying the restraint layer on the ceramic lateral. Different thickness of circular SiC ceramic was confined lateral with steel Bush of 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm and 3.5 mm thickness according to the characteristics of thermal expansion and cold contraction of steel bushing, and lateral restraint of which was calculated. Ballistic resistance of lateral constraint ceramic structure was studied by firing 105 mm armor-piercing simulated projectile with 25 mm ballistic gun. And it turns out: the greater the lateral restraint on the ceramics, the smaller the penetration depth of the projectile into the after-effect target the higher the ballistic resistance of the target with increase of thickness of lateral restraint layer. In the design of armor structure, thickness of lateral restraint layer should be reduced as much as possible considering requirement of light weight under the condition of achieving the required ballistic performance to improve the overall ballistic performance of lateral restraint ceramic armor structure.

1. Introduction

Ceramic materials have become one of the key materials of tank and vehicle protection system because of their advantages in high temperature resistance and hardness in field of bullet-proof ceramic application[1-2]. But they have insufficient toughness and poor brittleness when impacted by detonation wave and projectile, and they are easy to break, collapse and crack propagation in the impact zone which weaken its anti-multi-shot elastic performance[3]. In addition, increasing simply thickness and hardness of ceramic protective materials can not meet the growing needs of armor protection, which limits applications of ceramic materials to a certain extent[4-5].

Ceramic materials imposed on lateral restraint layer can improve the ballistic resistance obviously. Lateral restraint layer can prevent the side propagation and reduce dispersion of ceramic materiales penetrated by projectiles in the process of the projectile-target interaction. Inhibition of lateral movement of the ceramic fragments by lateral restraint enhance abrasion effect on the projectile body,
and ballistic performance of restrained ceramics improve remarkably, which gives full play to the high bullet-resistant function of ceramics.\cite{6-7}. The ceramic structure has lower crack propagation rate and higher dynamic strength under high strain rate, so as to improve the comprehensive ballistic performance of armored vehicles. Ballistic resistance of ceramic structure with lateral restraint layer was studied through controlling thickness of lateral restraint in this paper, and matching law between ceramic and lateral restraint layer is of great significance and urgent military requirement for armored vehicle protection and upgrade\cite{8}.

2. Method of calculation of binding force
Ballistic resistance of metal-confined ceramic is mainly related to thickness ratio, properties, position distribution, material, thickness and structure of the sandwich structure. Shape and size of ceramic affect crack propagation path and the formation of ceramic cone, which is one of the important factors influencing ballistic performance of ceramic armor. Different shapes of ceramic require different constraint structures.

The method of steel bushing restraint was used to restrain the circular SiC ceramic with a given size on the lateral in this paper. The steel bushing was preheated to a certain temperature by using characteristics of hot expansion and cold contraction of metal plate and the size of interference fit, then embedding ceramic into steel bushing at this temperature, and cooled at room temperature to realize integrated lateral constrained ceramic structure, obtaining lateral constrained force of this ceramic structure.

Lateral restraint force of steel bushing on ceramic was calculated by Equation (1).

$$ p_c = \frac{\delta E_1 E_2}{2 r_c} \left( \frac{1}{E_2} \left( \frac{1+k_1^2}{1-k_1^2} \right) \frac{1}{\mu_1} + E_1 \left( \frac{1+k_2^2}{1-k_2^2} \right) \frac{1}{\mu_2} \right) $$

(1)

Where, $p_c$—Binding force of a steel bushing on a ceramic; $\delta$—Interference fit; $r_c$—The radius or middle diameter of the joint surface between steel bushing and ceramic; $E_1$—Elastic modulus of steel bushing; $E_2$—Elastic modulus of embedded ceramic; $\mu_1$—Poisson's ratio of ceramic inlay; $\mu_2$—Poisson's ratio of steel bushing; $k_1$—Ratio of outer diameter of inlaid ceramics to $r_c$; $k_2$—Ratio of inner diameter of steel bushing to $r_c$.

Ceramic lateral binding force depends on material and size of ceramic and binding layer. The maximum interference fit is obtained according to the strength limit of steel bushing. When the calculated magnitude or value of the strength is exceeded, steel bushing itself will be destroyed, so binding force on ceramic will be weakened. Interference fit doesn’t change much in range of several mm thickness steel bushing, which varies with steel bushing material and thickness. Temperature of steel bushing should not exceed tempering temperature of steel, so as to prevent the damage of steel bushing from restraining ceramic.

3. Experimental method
Circular SiC ceramics with size of Φ100 mm× 30 mm were selected for experiments. And 45 # steel was used as lateral restraint layer with thickness of 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm and 3.5 mm respectively. TC4 titanium alloy with thickness of 30 mm was used as backing plate, and ceramic composite structure with lateral constraint was shown in Figure 1. Clearance between composite plate and appraisal plate was kept 20 mm. Surfaces of each component in this composite structure should be cleaned, with flat ceramic material and grounded back plate when necessary, which should be 7A52 aluminum alloy of 40 mm thickness. Target plate configuration is shown in Figure 2, test scheme is shown in Table 1, and the material parameters for experiment are shown in Table 2.

**Table 1.** Test scheme for 105 mm armor-piercing simulated projectile of ceramic composite structure with lateral constraint.

| Serial number | Plan | Experiment projectile | Structure configuration | Surface density (kgm⁻²) | Thickness of steel bushing (mm) | Binding (MPa) | Interference fit (mm) | Steel bushing material | Remark |
|---------------|------|-----------------------|-------------------------|--------------------------|---------------------------------|--------------|----------------------|-----------------------|--------|
| 1             | D-1# | 105 mm armor-piercing simulated projectile | 30 mmSiC+30 mmTC4 | 226.5                     | -                              | -            | -                    | -                     | -      |
| 2             | D-2# |                       | 30 mmSiC+30 mmTC4 | 226.5                     | 1.0                             | 5.0          | 0.12                 | 45# steel             | -      |
| 3             | 30-1# |                       | 30 mmSiC(1 mm steel) +30 mmTC4 | 232.0                     | 1.0                             | 5.0          | 0.12                 | 45# steel             | -      |
| 4             | 30-2# |                       | 30 mmSiC(1 mm steel) | 232.0                     | 1.0                             | 5.0          | 0.12                 | 45# steel             | -      |
| 5             | 30-3# |                       | 30 mmSiC(2.5)      | 234.7                     | 1.5                             | 7.3          | 0.12                 | 45# steel             | -      |

**Figure 1.** Lateral restraint ceramic composite structure diagram.

**Figure 2.** Schematic diagram of target plate configuration.
| Material components | Density(g/cm³) | Wave velocity (m/s) | Mechanical properties |
|---------------------|---------------|---------------------|-----------------------|
| SiC                 | 3.1           | About 8000          | Bending strength 399 MPa, HRA94 |
| TC4                 | 4.45          | About 4700          | Σb: 975 MPa, σ0.2: 922.5 MPa, HBW 328 |

**Table 2.** Structure and properties of armor target materials for testing.

Figure 3. Bullet core of 105 mm armor-piercing simulated projectile and 25 mm ballistic cannon.

Figure 4. Layout of target plates.
A 25 mm ballistic cannon was used to launch 105 mm armor-piercing simulated projectiles, and distance between target plate and muzzle was 10 m during tests. Bullet core of 105 mm armor-piercing simulated projectile and 25 mm ballistic cannon are shown in Figure 3, Layout of target plates is shown in Figure 4.

4. Experimental results and analysis
Experimental results of confined ceramic composite structure against 105 mm armor-piercing simulated projectiles are shown in Table 3.

| Bullet serial number | Scheme number | Target board structure | Bullet speed (ms⁻¹) | Back injury | Penetrated depth (mm) | Surface density (kgm⁻²) | Remark |
|----------------------|---------------|------------------------|---------------------|-------------|----------------------|--------------------------|--------|
| 1                    | D-1#          | 30 mm SiC+30 mm TC4     | 1399                | Through    | 30.4                 | 226.5                    | Ceramic fracture         |
| 2                    | D-2#          | 30mm SiC (1 mm steel) +30 mm TC4 | 1393                | Through    | 30.5                 | 232.0                    | Ceramic fracture         |
| 3                    | 30-1#         | 30 mm SiC (1.5 mm steel) +30 mm TC4 | 1391                | Through    | 22.2                 | 234.7                    | Ceramic fracture         |
| 4                    | 30-2#         | 30 mm SiC (2 mm steel) +30 mm TC4 | 1403                | Through    | 20.7                 | 237.5                    | Ceramic fracture         |
| 5                    | 30-3#         | 30 mm SiC (2.5 mm steel) +30 mm TC4 | 1397                | Through    | 21.7                 | 239.8                    | Ceramic fracture         |
| 6                    | 30-4#         | 30 mm SiC (3 mm steel) +30 mm TC4 | 1411                | Through    | 25.3                 | 242.2                    | Ceramic fracture         |
| 7                    | 30-5#         | 30 mm SiC (3.5 mm steel) +30 mm TC4 | 1395                | Through    | 18.2                 | 244.5                    | Ceramic fracture         |

Backboard and aftereffect damage of ceramic composite armor structure with no lateral constraints is shown in Figure 5. Backboard and aftereffect damage of ceramic composite armor structure with lateral constraints is shown in Figure 6.
Figure 5. Backboard and aftereffect damage of ceramic composite armor structure with no lateral constraints.

Figure 6. Backboard and aftereffect damage of ceramic composite armor structure with lateral constraints.

It can be seen from Figure 6 that steel bushing had a slight deformation after side-bound ceramic composite structure penetrated by 105 mm armor-piercing simulated projectile. Diameter of steel bushing at the start face of the ceramic had a large deformation, while diameter of steel bushing at the back end of the ceramic was unchanged basically. The relationship between thickness of lateral restraint layer and average penetration depth of the after-effect plate is shown in Figure 7 through analysis of experimental results.

Figure 7. Relationship between thickness of ceramic lateral restraint layer and average penetration of after-effect plate.
Penetration in after-effect plate of ceramic composite plate imposed lateral constraints is smaller than ceramic composite structure with no lateral constraints showed in Figure 7, because steel bushing to the ceramic produced corresponding binding through heat of round ceramic liner technique, and the ceramic pieces of projectile penetration generate a constraint and fixed effect which increased the ceramic pieces to the abrasive action of the projectile and limited lateral flying target function in the process of broken porcelain. This maintained stability of ceramic cone, thereby improved elastic resistance of lateral constraints ceramic armor structure. But penetration depth of after-effect plate decreases with increase of lateral confinement layer’s thickness. Because the thicker the lateral confinement layer is, the greater the lateral constraint on the ceramic is; the smaller the penetration depth of the projectile on the after-effect plate is, the higher the ballistic resistance of ceramic composite structure with lateral confinement is.

However, thickness of the lateral restraint layer should be reduced as much as possible to improve the overall elastic strength of lateral restraint ceramic armor structure while keeping the required elastic strength considering lightweight.

5. Conclusions
(1) Lateral constraints of the circular SiC ceramic with a given size were obtained by using characteristics of heat expansion and cold contraction of the steel bushing and control of the amount of interference fit. Size of lateral binding force of ceramic is related to the material and size of ceramic and confining layer.
(2) Diameter of steel bushing at the end of projectile face becomes larger, while the diameter at the back end of the ceramic is unchanged basically when ceramic composite structure with lateral constraint is penetrated.
(3) The thicker the lateral restraint layer is, the greater the lateral restraint on the ceramic is, and the smaller the penetration depth of projectile to the after-effect target plate is, which improves comprehensive ballistic resistance of ceramic armor structure.
(4) Thickness of lateral restraint layer should be reduced as much as possible to achieve the required elastic resistance considering lightweight in the design of armor structure, so as to improve the overall elastic resistance of lateral restraint ceramic armor structure.

6. References
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