Experimental research on explosion resistance of masonry structures reinforced with modified polyurea elastomer

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Abstract. In order to improve the explosion resistance performance of masonry structures during the terrorist attacks and accidental disasters, clay brick and concrete block walls are reinforced by modified polyurea materials. Explosion resistance tests of these two kinds of masonry wall structures are carried out to analyze the failure modes and anti-explosion effects of reinforced masonry walls under different thickness and reinforcement modes. The results show that modified polyurea elastomer not only has good spraying adhesion and compatibility with the base material surface, but also can effectively encapsulate the explosive debris generated by the back blasting surface of the masonry wall under explosive load, which reduces the deformation and displacement of the wall.

1. Introduction
The explosion caused by terrorist attacks and accident disasters forms a huge pressure shock wave, which leads to great damage to nearby buildings and objects, and even causes continuous collapse and casualties due to local damage. Therefore, it is urgent to study and analyze how to improve the explosion-proof and explosion-resistant ability of buildings.

Polyurea is an elastic block copolymer formed by the reaction of isocyanate and ammonia. Because of its excellent mechanical properties[1,2], high elastic modulus[3], high tensile strength, high ductility[4] and good impact resistance[5,6], polyurea has been extensively studied and applied in the materials mitigating explosive shock in recent years. In this paper, the brick wall and concrete block walls are reinforced with modified polyurea elastomer. Then explosion tests are carried out on these masonry walls with different thickness of polyurea elastomer, aiming to study and analyze the failure mode and anti-explosion effect of the wall reinforced with polyurea elastomer under different thickness and reinforcement modes, which provides a reasonable basis for practical application.

2. Modification and properties of polyurea elastomer
Polyurea elastomer materials with amino-terminated polyoxypropylene ether as the main component have poor adhesion and compatibility with the substrate surface, which limits the application of polyurea elastomer materials in engineering.

For amino-terminated polyoxypropylene ether polyurea elastomer materials, the research on their properties is mainly aimed at resin chain extender. It is prepared by the reaction of R component consisting of high active amino-terminated polyether and polyamine chain extender with A component consisting of polyisocyanate prepolymer. No catalyst is needed because the reaction speed between amino group and NCO group is very fast. In general, too fast film formation produces some fatal surface defects, sometimes even discontinuous coatings. In order to overcome these shortcomings, the
chain extender of primary amine with high activity is modified to reduce its reaction rate with isocyanate to achieve the protective effect of polyurea elastomer.

The modification methods of primary amine chain extender mainly include cyanoethylation of amine chain extender, addition with acrylate, ketoimidation of amine chain extender, etc. In this paper, primary amine chain extender is modified with hexamethylenediamine chain extender and glacial acetic acid to form amide chain extender, which reacts with polyoxypropylene ether of different concentration to form amino-terminated polyether R component, and then reacts with polyisocyanate prepolymer to form high performance polyurea elastomer materials with good adhesion and compatibility with the surface of the base material. According to ASTM D412 standard, the static tensile mechanical properties of the modified polyurea elastomer are tested, the physical and quasi-static mechanical properties of which are shown in Table 1.

### Table 1. Physical and Quasi-static Mechanical Properties of Polyurea.

| Density (g/cm³) | Poisson's rate | Elastic modulus (MPa) | Shear modulus (MPa) | Yield stress (MPa) | Fracture stress (MPa) | Fracture strain |
|----------------|----------------|----------------------|--------------------|-------------------|----------------------|-----------------|
| 1.12           | 0.4            | 161                  | 7.5                | 6.2               | 15.8                 | 1.6             |

3. Explosion resistance test scheme and specimen making of masonry structures reinforced by modified polyurea elastomer

The common filling parts in building structures are clay brick wall, concrete block wall and reinforced concrete, which are divided into load-bearing wall and non-load-bearing wall according to different structural forces. The projection of the damaged part of the wall and high-speed debris caused by explosive load are the main causes for indoor casualties. In this experimental research, clay brick wall and concrete block wall are chosen as the objects of this modified polyurea elastic reinforcement.

#### 3.1 Test Scheme

The failure modes of walls under external loads are different with different failure pressure and resistance limit of walls. The main purpose of the test is to investigate the failure mode and explosion resistance limit of the wall reinforced with polyurea elastomer under different thickness and reinforcement methods. To achieve this purpose, the test plan is drawn up as shown in Table 2. The shock wave load is obtained by the cylindrical TNT explosion in the experiment.

### Table 2. Test Scheme.

| Wall material | Number | Dimension (cm) | Spraying method | Coating thickness (mm) | Explosion mode |
|---------------|--------|----------------|-----------------|-----------------------|----------------|
| Clay brick    | 4      | 250×310×24     | Single side     | 3, 5, 8               | Contact explosion |
| Concrete block| 4      | 250×310×24     | Single side     | 4, 6                  | Contact explosion |

#### 3.2 Specimen making

Brick walls and concrete block walls are constructed on the test site. The process of spraying polyurea elastomer is strictly followed to ensure the quality of sprayed polyurea elastomer coating. Single-wall masonry is completed in 1-2 days as soon as possible. All walls are maintained for 28 days at the same time and under the same conditions. The process of specimen preparation is shown in Figs. 1 and Figs 2.
4. Experiment results and analysis of explosion resistance of masonry structures reinforced with modified polyurea elastomer

The influence of the thickness of polyurea elastomer on the explosion resistance of the wall is explored through the explosion test of brick wall and concrete block wall specimens reinforced with elastomer under different working conditions.

4.1. Brick wall

The explosion tests are carried out on the brick wall without sprayed polyurea elastomer (Z-0-0) and those with sprayed thickness of 3 mm (Z-0-3), 5 mm (Z-0-5) and 8 mm (Z-0-8) respectively. The phenomena of the clay brick masonry walls after the test are shown in Figure 3.

The brick wall unsprayed with polyurea elastomer collapses and spreads under the action of TNT explosive load with an equivalent amount of 2.17 kg and a detonation distance of 10.5 cm, and the damaged parts splash within the radius of 8 m on the ground of the back blasting surface of the wall.

When the thickness of sprayed polyurea elastomer is 3 mm, under the action of TNT explosive with an equivalent amount of 2.16 kg and a detonation distance of 10.5 cm, there are dislocation cracks in the central area of the wall, with ruptures in the reinforcement layer and a horizontal displacement of 12 cm. Though slight concave deformation appears, it is relatively intact and does not collapse compared with the non-sprayed wall.

When the thickness of sprayed polyurea elastomer is 5 mm, under the action of TNT explosive with an equivalent amount of 2.24 kg and a detonation distance of 10.5 cm, the horizontal displacement of the central area of the wall is 21 cm, without obvious rupture in the reinforced layer. The tension strain of the back blasting surface of the wall increases, which leads to the increase of the central displacement of the wall compared with those with polyurea elastomers 3 mm thick (Fig. 5).

Under the action of TNT explosive with an equivalent amount of 2.06 kg and a detonation distance of 10.5 cm, the brick wall with sprayed polyurea elastomer 8 mm thick has obvious cracks in the central area, with a horizontal displacement of 33 cm, and obvious ruptures in the reinforcement layer. Compared with other thickness of polyurea elastomer, there is increased response of concave deformation of back blasting surface of brick wall.

Compared with brick wall without sprayed polyurea elastomer, the explosion resistance of the brick wall sprayed with polyurea elastomer is obviously improved, which does not collapse entirely, only with cracks on the back blasting surface of the wall, the surface complete and relatively smooth. The encapsulation of polyurea elastomer can effectively reduce the spattering debris of the brick caused by blast wave and slow down the secondary damage.
The test results show that (Table 3) the brick wall sprayed with different thickness of polyurea elastomer has concave deformation response under explosive load, but polyurea elastomer can effectively reduce the displacement of the center of the wall. With the increase of the thickness of polyurea elastomer, the central displacement of brick wall becomes larger. Polyurea elastomer can effectively restrain the displacement of brick wall and reduce the concave deformation of the wall.

Table 3. Statistics of explosion test results of brick wall specimens.

| Specimen number | Coating thickness mm | Booster charge kg | Detonation distance cm | Distance from the ground cm | Result |
|-----------------|----------------------|-------------------|------------------------|----------------------------|--------|
| Z-0-0           | 0                    | 2.17              | 10.5                   | 90                         | building blocks spatter |
| Z-0-3           | 3                    | 2.16              | 10.5                   | 90                         | horizontal displacement of the center of brick wall 12cm |
| Z-0-5           | 5                    | 2.24              | 10.5                   | 90                         | horizontal displacement of the center of brick wall 21cm |
| Z-0-8           | 8                    | 2.06              | 10.5                   | 90                         | horizontal displacement of the center of brick wall 33cm |

The brick wall, which is sprayed with 3-mm-thick polyurea elastomer on the back blasting surface, remains relatively intact without damage or debris throwing under explosive load. The slight concave deformation indicates that the middle area is the plastic area under strong dynamic loads, and the boundary of the plastic area varies in the course of plate deformation. But under explosive load, cracks in the central area of the brick wall sprayed with polyurea elastomer almost coincide, the specific magnitude of impact of incident explosive load and magnitude of impact of back blasting surface on unloading wave can not be quantitatively analyzed, but it can be explained that spaying polyurea elastomer on the back blasting surface of brick wall significantly reduces the damage of explosive load on wall structure.

4.2. Concrete block wall

The explosion tests are carried out on concrete block walls unsprayed with polyurea elastomer (Q-0-0) and sprayed with thickness of 4 mm (Q-0-4) and 6 mm (Q-0-6) respectively. The phenomena of concrete block walls after explosion test are shown in Fig. 4.

Fig 4. Phenomena of concrete block masonry wall specimens after explosion test.

The concrete block wall without sprayed polyurea elastomer, collapses and disperses under the action of TNT explosive load. The damaged parts spatter within the radius of 16m on the ground of the back blasting surface of the wall.

When the thickness of sprayed polyurea elastomer is 4mm, under the action of TNT explosive with an equivalent amount of 1.2kg and a detonation distance of 20.5cm, the back blasting surface of the concrete block wall is smooth and complete, without rupture or tension damage in the reinforcement layer. The surface of some blocks of the front blasting face is broken. Compared with the wall without polyurea elastomer, the concrete block wall is intact and does not collapse.

The concrete block wall with sprayed polyurea elastomer 6 mm thick collapses, and the middle of the reinforcement layer cracks under the action of TNT explosive with an equivalent amount of 1.25 kg and a detonation distance of 10.5 cm. But there is no spattered damaged blocks.
Test results show that (Table 4) the concrete block wall without sprayed polyurea elastomer collapses and spatters under explosive load and the damaged parts of the wall are thrown into the ground of the back blasting surface, while the concrete block wall with sprayed polyurea elastomer is effectively encapsulated. Even if the wall collapses after being damaged, the debris of the back-burst surface of the wall is obviously decreased, restraining the concave deformation and failure of walls.

The explosion resistance performance of the concrete block wall with sprayed polyurea elastomer 4mm thick is obviously improved, and there is no concave deformation in the wall. Under the explosive load, the center of concrete block wall with sprayed polyurea elastomer with thickness of 6mm is broken and dislocates. The block wall collapses after being torn because of the strong adhesion of polyurea elastomer.

| Specimen number | Coating thickness mm | Booster charge kg | Detonation distance cm | Distance from the ground cm | Result |
|-----------------|----------------------|-------------------|------------------------|-----------------------------|--------|
| Q-0-0           | 0                    | 1.22              | 20.5                   | 70                          | block throwing, the longest distance from the wall 16.3m |
| Q-0-4           | 4                    | 1.20              | 20.5                   | 70                          | back blasting face smooth and complete, cracks on the front blasting face of the block |
| Q-0-0           | 0                    | 1.18              | 10.5                   | 90                          | block throwing, the longest distance from the wall 16m |
| Q-0-6           | 6                    | 1.25              | 10.5                   | 90                          | middle of the wall tore and collapsed, without spattered blocks |

It can be seen that wall response at the early stage under explosive load experiences the impedance matching of blasting face and the dispersion of shock wave. In the dynamic response of wall, the strain process of polyurea elastomer occurs, which leads to the dispersion of wall strain, and ultimately leads to the transformation of failure mode of the reinforced wall.

5. Conclusion
Through the explosion tests on brick walls and concrete block walls reinforced with polyurea elastomer under different working conditions, the influence of thickness of polyurea elastomer on the explosion resistance of the wall is analyzed. The main conclusions are as follows:

The brick wall sprayed with polyurea elastomer 3mm thick on the back blasting surface remains relatively intact under the action of explosive load, without damage or debris throwing, only with slight concave deformation, which can be considered for application in practical engineering.

The concrete block wall, which is sprayed with polyurea elastomer with the thickness of 4mm on the back blasting surface, shows good explosion resistance.

Polyurea elastomer can effectively reduce the debris generation of the back blasting surface of the wall, and decrease the deformation and displacement of masonry wall under explosive load, which, therefore, improves the explosive resistance performance of the masonry wall.

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