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Experimental studies on the local damage and fragments of unreinforced masonry walls under close-in explosions

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ABSTRACT

Most casualties and injuries resulting from a terrorist attack are caused by the fragments discharging from the failure structural components or building envelope systems. Unreinforced masonry wall, which is widely constructed as structural components or building envelope worldwide, tends to break into sharp fragments under terrorist explosions, especially when explosions are in the close range. Therefore, it is of great significance to study the local damage and fragments of unreinforced masonry walls under close-in explosions. In this paper, two unreinforced masonry walls were tested under blast loads generated by 1 kg and 6 kg of TNT charge separately to investigate their failure mechanism and fragment characteristics. The local damage such as spalling or punching damage of the masonry wall with fragments in different sizes and splash distances were observed, and the splashed fragments were categorized and weighted. The fragment size distribution was also analyzed and it was found that the size distribution of the fine portion of the fragments followed a Weibull distribution.

1. Introduction

Recent terrorist attacks not only targeted on government buildings, but also on some random civilian structures such as hotels, shopping centers and traffic stations. This imposes a great challenge on attack preventions since it is impractical to deny public access to these structures [1]. Once terrorist attack is not successfully prevented and occurs in the near field of the building structures, serious casualties are not the only result from the explosion itself, but also by the high-speed ejecting fragments discharging from the local damaged structural and building envelope. And owing to the ease of construction and low costs, clay masonry is commonly used in China and other countries as building envelope materials besides concrete masonry and glass. However, this clay masonry, which is made of clay bricks and mortar, tends to break into sharp fragments due to its brittle nature and low integrity under close-in explosions, inevitably causing casualties and injuries for occupants and severe damage to the equipment or furniture inside the room. Thus, there is an urgent need to study the behavior of local damage, as well as the fragment characteristic of unreinforced masonry wall under near field explosions for blast protection against such a hazard.

Recently the researchers worldwide have carried out studies on dynamic response analysis and damage assessment of masonry walls under blast loads, as well as protection measures. Great achievements have been made. For example, some researchers used the detailed three dimensional solid elements model, in which clay brick and mortar are separately modeled, to investigate the nonlinear dynamic behavior of masonry wall under blast or impact load [2–6]. This method is quite straightforward and could derive accurate results on the condition that the proper material model with accurate parameters is utilized and the interface between brick and mortar is considered. However, the detailed numerical model is very difficult to establish and it is also very time consuming to carry out such a numerical analysis. Thus, some researchers [7–10] proposed the homogenized models for clay masonry material which can be used to simulate the dynamic response of masonry wall under blast loading. The model is based on the assumptions that masonry damage is not necessarily governed by the weak interfaces because of the very short blast loading duration when masonry wall is under high-strain rate blast loads. Thus, homogenized dynamic masonry material properties could be used in modeling masonry damage to blast loads with high computation efficiency as compared with distinctive modeling. The interface model [11–13], mesoscale model and other modeling strategies [14–16] are also developed to improve the efficiency and accuracy of numerical simulations of unreinforced masonry walls under blast or dynamic loading.

Damage assessment methods of masonry wall under blast loading have also been studied. Wesevich and Oswald [17] proposed damage

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criterion and established empirical pressure–impulse curves to evaluate the damage degree of masonry walls under different blast loads. Wei et al. [18] conducted similar research based on numerical simulations. Some researchers also developed procedure [19,20] to assess the reliability of masonry infill walls subjected to blast loading.

As indicated, fragments from masonry walls due to blast loading imposes a great threat to the safety of building occupants, thus a series of studies on fragments from masonry walls to blast loads have also been reported in the literatures. For example, Knock et al. [21] carried out tests to investigate the bounce and roll of masonry fragments under blast loads. Ahmad et al. [22] conducted 6 field tests at large scale distance to investigate the response of unreinforced masonry under blast loads. Haberacker et al. [23] investigated the effects of near-, contact- and embedded detonations on masonry structures and presented the test results of fragment eject. Dennis et al. [24] conducted a series of experiments to determine the response of one-way 1/4-scale CMU wall to the detonation of an explosive charge. Besides the tests, Dennis et al. [24] also carried out numerical simulations to rebuild the results from the tests. Keys and Clubley [25] studied fragment distribution of masonry wall under blast loads through numerical simulation based on Applied Element Method (AEM), and good agreement between numerical results and test results has been achieved. Wang et al. [26] proposed a new approach based on the mechanics of continuum damage and micro-crack development of masonry material to predict the probabilistic size distribution and launch distances of fragments induced by blast loads. This method could reasonably predict the fragment size distribution from the statistic point of view; however, it might fail to predict the location of each fragment thus it might also give error results of ejecting distance.

Certain measures used for blast protection for masonry walls against blast loads were also put forward. Henderson et al. [27] carried out more than 700 static and dynamic tests in the laboratory and on existing structures to study the boundary influence on the behavior of unreinforced masonry wall under in-plane and out-of-plane loads. Abrams et al. [28] conducted a total of 8 tests in which unreinforced masonry infill panels were subjected to pressures normal to the panel plane. They found that the out-of-plane capacity of masonry walls could be enhanced by applying a rigid support steel frame or section at the top, bottom or the whole surrounding of the wall. Arching action (the wall acts as two rigid rotating segments after the cracks occur at the ends and the center of the wall therefore the in-plane resistance is enhanced largely until the masonry crushes) was utilized by Abou-Zeid et al. [29] to increase the blast resistant capacity of unreinforced masonry walls, and it was found that it could not only significantly improve the blast resistant capacity of masonry wall but also reduced the hazard resulting from ejecting fragments by increasing the frictional forces between the masonry courses. However, the disadvantage of the method is that the installation of extra fixed conditions to generate and enforce the arching action is quite difficult and money consuming. Steel wire mesh [3], carbon fiber-reinforced polymer (CFRP) [30], fabric, proxy and some other modern retrofit materials [31–40] have also been frequently used in the available literatures to enhance the capacity of masonry and reduce the hazard level of fragments under static and dynamic loads.

It should be noticed that the above achievements mainly focus on the overall dynamic response and damage of masonry walls under distance blast loading, which is important in the blast design of masonry wall. However, the research on the local damage and fragments of masonry walls under blast loads in close-in range is rare to find in the available literatures. At the same time, the damage mechanism of masonry wall under close-in explosions might be quite different from the case of distance explosions because of the following reasons: (1) the blast load is not uniformly distributed and usually localized in a small area; (2) the blast induced stress wave is so big that the spalling damage might be occurred on the rear face of the masonry wall therefore the stress wave propagation in masonry material cannot be ignored anymore. Therefore, it is of great significance to study the damage mechanism, as well as the fragments distribution of masonry wall under close-in explosions, for blast protection of building envelope against terrorist attacks.

In this paper, as a first step, experiment studies on the local damage of two unreinforced masonry walls under different close-in blast loads are carried out to investigate the characteristic of blast induced local damage, as well as the fragment distributions and ejecting distances. Two unreinforced clay masonry walls with a dimension of 1.2 m × 1.5 m × 0.24 m (width × height × thickness) are subjected to blast loads induced by 1 kg and 6 kg TNT charge separately at the 0.4 m standoff distance beside the center of the wall. The damage of the masonry walls under different blast loads are investigated, and the masonry fragments splashed behind the walls are collected and weighted. The fragment distribution characteristics, which can be used for blast protection design for masonry wall, are also analyzed accordingly. The achievements of this paper can also be used to verify the numerical method for fragment prediction of unreinforced masonry wall under close-in explosions.

2. Experiment setup

2.1. Masonry wall specimen setup

A one story reinforced concrete (RC) frame of 3.4 meters width, 3.2 meters length and 2.0 meters height was constructed previously to do the glazing tests. The RC block was built with two individual testing cells with a dimension of 1.2 m × 1.5 m × 0.24 m (width × height × thickness). The back wall of the frame is left open therefore it is possible to collect the ejecting fragments. The width of columns and beams for each test cell is 240 mm, which is exactly the same as the thickness of a typical masonry wall in China. Therefore, it is used in the experiments as the supporting system of masonry wall specimen.

Two unreinforced masonry infill walls are constructed with a dimension of 1.2 m × 1.5 m × 0.24 m (width × height × thickness) exactly in two individual testing cells (Fig. 1). Each wall is constructed in a Flemish bond and mortar is used to fill the gap between the masonry and the surrounding RC frame to be consistent with the masonry infill wall in a real construction practice. There is no tie bar built between the RC frame and the masonry wall, in which case the boundary conditions of masonry wall is simple for after test numerical analysis. The typical bricks in China with the dimension of 240 mm × 115 mm × 53 mm are used. The thickness of the mortar is 10 mm. The lateral sides of RC frame are completely sealed to make sure that the overpressure would not wrap around the frame and reach the back of the masonry wall to affect experimental results.

The unreinforced masonry infill walls are built at the test site, and each masonry wall specimen is allowed to cure at least 28 days before the field tests. The grade MU15 clay brick and grade M5 mortar are adapted to construct the masonry wall. Both the masonry bricks and mortar specimen are collected during the constructing process, and they are sent to the lab to do the static material property tests. Only the compressive strength tests of masonry brick and mortar were carried out. Five samples were tested according to the Chinese standard for each material. The results show that the average compressive strength of brick is 15.5 MPa with a CoV 1.36 MPa, while the average compressive strength of mortar is 4.9 MPa and the corresponding CoV is 0.16 MPa.

The TNT charges are formed into cylindrical shape with different diameter/height ratios. The density of the shaped TNT charge is 1630 kg/m^3. In each test, the cylindrical explosive is placed at a certain standoff distance to the wall (0.4 m), with the bottom facing the center of the masonry wall.