Engineering Structures 152 (2017) 901–919

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental and numerical study of basalt fiber reinforced polymer strip strengthened autoclaved aerated concrete masonry walls under vented gas explosions

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ARTICLE INFO

Article history:
Received 19 June 2017
Revised 26 September 2017
Accepted 26 September 2017

Keywords:
Autoclaved aerated concrete (AAC)
Basalt fiber reinforced polymer (BFRP)
Two-way masonry wall
Vented gas explosion
Field test
Numerical simulation

ABSTRACT

Ten full-scale field tests were conducted to study the performance of basalt fiber reinforced polymer (BFRP) strip strengthened autoclaved aerated concrete (AAC) masonry walls subjected to vented gas explosions. Three walls i.e. unstrengthened, rear-face strengthened and front-face strengthened wall specimens were prepared for blast tests. The testing data including overpressure time histories of vented gas explosions, displacement time histories, damage characteristics and fragment distribution of each wall specimen were recorded and analyzed. It was found that the rear-face strengthened wall specimen showed the best blast-resistant performances. Three wall specimens under vented gas explosions experienced damage modes of typical two-way flexural deformation along with shattering of AAC blocks at the latter stage of gas explosions. A detailed micro model for masonry walls was developed in LS-DYNA, incorporating material parameters obtained from material tests. The accuracy of numerical model in predicting the responses of masonry walls was validated with the testing data. Parametric studies were also conducted to explore the influences of BFRP strip layouts, strip thickness and fiber types on the performances of masonry walls. It is found that the BFRP strip layout, strip thickness and fiber types affect the resistance capacity of masonry walls significantly.

1. Introduction

Blast loads can be generated from various explosion sources (e.g. high explosive charges, vapor gas explosions, bursting pressure vessels, etc.) in industrial, civilian and military fields, and they impose great hazards to existing structures [1,2]. Masonry wall has been widely used in the constructions of masonry buildings as load-bearing components and in reinforced concrete (RC) frame buildings as non-load-bearing components. The unreinforced masonry wall is vulnerable to blast loads due to its low resistance capacity. The failure of masonry walls may claim lives and enormous loss of properties. Finding a cost-effective method to strengthen masonry walls is a necessity and draws attentions in recent decades [3–5].

Strengthening techniques by using different strengthening materials have been developed for masonry walls against blast loading. The masonry wall subjected to out-of-plane loads (static and high explosive loads) were studied by conducting field blasting tests, numerical simulations and theoretical analysis, as summarized in Table 1. Composite materials including fiber reinforced polymers (e.g. CFRP and GFRP) and spray-on polyurea, and steel wire mesh, have been used to strengthen concrete masonry unit (CMU), clay brick and AAC masonry walls. The composite structures made of composite material and masonry wall can make use the full advantage of their own characteristics. When the applied loading is not devastating leading to wall collapse, the existence of the composites enhances the equivalent section area of structures, increases the stiffness significantly and in turn reduces the deflection of structures. By means of absorbing strain energy, the failure of composites can mitigate the damage of main structures effectively. When intensive loading is applied, the composites can decrease the number of fragments and can also be a catching system to effectively mitigate the threats from flying debris.

As an 'ultra-lightweight' concrete material, autoclaved aerated concrete (AAC) has been used as an alternative to conventional normal-weight or lightweight concrete products [22,23]. The micro cellular structures of AAC bring excellent thermal and sound insulation properties, but also result in strength reduction and heterogeneity of the material. Currently, the performance of AAC

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https://doi.org/10.1016/j.engstruct.2017.09.055
0141-0296/© 2017 Published by Elsevier Ltd.

Table 1
Summary of previous studies on the masonry wall strengthening.

Researchers	Year	Structures	Strengthening material	Experimental	Numerical	Theoretical
Oswald and Wesevich [6]	2001	CMU walls	Aramid	Shock tube		
Crawford et al. [7,8]	2002, 2003	CMU walls	CFRP		DYNA3D	
Muszynski and Purcell [9]	2003	AEC walls	CFRP	Explosive		
Myers et al. [5]	2003, 2004	CMU walls	GFRP	Explosive		
Baylot et al. [4]	2005	CMU walls	GFRP	Explosive		
Davidson et al. [10]	2005	CMU walls	Polymer spray	Explosive	DYNA3D	
Urgessa et al. [11,12]	2008, 2009	CMU walls	GFRPs, CFRP	Explosive		
Hrynyk and Myers [13,14]	2007, 2008	Clay brick CMU walls	GFRP	Static		YES
Tan and Patoary [15]	2009	Clay brick walls	CFRP and GFRP	Explosive		YES
Irshidat et al. [16,17]	2010, 2011	CMU walls	Nanoparticle polymer	Explosive (blast simulator)	AUTODYN	YES
Chen et al. [3,18]	2013, 2014	Clay brick	CFRP, steel wire mesh, steel plate	Explosive	LS-DYNA	
Elsanadedy et al. [19]	2016	CMU walls	GFRP	Static		YES
S.H. Alsayed et al. [20]	2016	CMU walls	GFRP	Explosive	AUTODYN	
Wang et al. [21]	2016	Clay brick, AAC	Polymer spray	Explosive		

masonry walls strengthened with composite materials under blast loads is mainly studied by using experimental method. Muszynski and Purcell [9] conducted field tests on the air-entrained concrete (AEC) masonry walls strengthened with CFRP subjected to high explosive detonations. However, the test data were not reported in detail. Their study only concluded CFRP laminate strengthened AEC masonry wall exhibited less residual displacement than the bare walls. Wang et al. [21] performed field tests to obtain the dynamic response of spray-on polyurea reinforced AAC block masonry walls under TNT explosions. The results showed that the existence of ployurea layer improved the blast resistance of walls significantly, prevented the wall collapse and reduced the number of high-velocity fragments effectively. Yankelevsky and Avnon [24] carried out tests to study the localized responses of AAC under contact explosion and the effectiveness of surface treatment by gluing textile fabric on the ACC block performances. The test results showed that the surface treatment enhanced the tensile strength and ductility of AAC blocks, and contributed to higher resistance to tensile wave spalling. The above-mentioned studies focused on the performances of AAC blocks and strengthened AAC masonry walls under blast loads generated by high explosives. However, the study of AAC masonry walls subjected to gas explosions is very limited in the open literature. In the previous study [25], the responses of unreinforced AAC masonry walls under gas explosion loads were investigated by conducting experimental, numerical and simplified analytical studies. The behavior and failure mode of unreinforced AAC masonry walls under gas explosion loads were investigated and discussed in detail, which are not necessarily the same as the walls under blast loads from high explosives owing to the unique characteristics of gas explosion loads (such as lower amplitude, longer rise time, longer duration and possibly multiple peak pressures). No study of the responses of strengthened ACC masonry walls subjected to gas explosions has been reported in the open literature yet.

As compared with CFRP and GFRP, BFRP, which is made from basalt rocks through melting process, is a relatively new type of FRP composite. BFRP is usually inferior to CFRP in terms of the ultimate strength and Young's modulus and to GFRP in terms of the ultimate strain. BFRP also has good fire resistance and is cost-effective therefore a potential material for strengthening structures [26,27]. Limited studies were carried out to research the material properties of BFRP products under dynamic loads especially blast loads [28,29]. The static and dynamic tensile properties of BFRP strips were studied by Chen et al. [28] at the strain rate from $4.68\,e^{-5}\,s^{-1}$ to $259.0\,s^{-1}$. The dynamic enhancements on the strength, elastic modulus and failure strain of BFRP strips at different strain rates were well captured and the empirical formulae were proposed. Basturk et al. [29] investigated dynamic behaviors of laminated basalt composite plates under blast loads based on large deflection theory of thin plate. The theoretical result showed that the basalt fiber composite plate might serve as an alternative to composite structures. However, no study on the performance of BFRP strengthened masonry walls and other RC structures (beam, column and slab) under blast loads can be found in the literature. Therefore, it is necessary to investigate the performance of BFRP strengthened structures under blast loads.

In this study, a series of full-scale field tests on BFRP strip strengthened AAC masonry walls subjected to vented gas explosions were conducted. A detailed micro model was also developed to predict dynamic responses of strengthened AAC masonry walls by using LS-DYNA. The parameters of the material models for AAC blocks, mortar and FRP strips were obtained from material tests. The predictions from the numerical simulations were compared with the testing data to validate the numerical model. Parametric studies were carried out to evaluate the effects of strip layouts, strip thickness and fiber types on the response of strengthened masonry walls subjected to vented gas explosions.

2. Experimental program

A 3 m × 2 m × 2 m reinforced concrete (RC) chamber with two openings was built for the field gas explosion tests. The small opening of 0.8 m × 0.8 m was installed with vent covers and acted as a vent window. The larger opening with dimensions of 3 m × 2 m was used to place wall specimens for testing.

2.1. Preparation of wall specimens

Three wall specimens, including one unstrengthened specimen, one rear-face strengthened specimen and one front-face strengthened specimen were prepared according to the standard [30]. The wall specimens with dimensions of 3 m × 2 m × 120 mm were lumped with AAC blocks with dimensions of 590 mm × 120 mm × 240 mm and 5 mm-thick mortar in "Running" pattern, as shown in Fig. 1. The wall specimens were pre-built inside the RC frames for the convenience of installation. The RC frame made of C30 concrete has the internal dimensions of 3 m-high and 2 m-wide and cross-section area was 30 cm × 30 cm. To fasten the RC frame onto the RC chamber, a total of 24 holes with the diameter of 70 mm were predesigned and uniformly distributed along the edges of RC frame as shown in Fig. 1(b). Correspondingly, 24 steel bars with the diameter of 50 mm were pre-embedded into the RC chamber. The RC frames were fastened on the RC chamber by using 24 nuts. The right and left boundaries of wall specimens were bolted into the RC frames by using steel bars at an equal space of 25 cm. The