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Cyclic testing of unreinforced masonry walls retrofitted with engineered cementitious composites

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HIGHLIGHTS

- 6 1/2-scale reverse cyclic tests on 6 unreinforced and retrofitted brick masonry walls.
- Static cyclic in-plane shear behaviour of ECC-retrofitted masonry walls.
- Significant improvement of both masonry resistance and deformation capacity.
- ECC strips around the masonry wall can effectively provide a constraint for the wall.

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ABSTRACT

The results of in-plane static cyclic lateral loading tests conducted on unreinforced masonry walls retrofitted with trowelling engineered cementitious composites (ECC) are presented in this paper. Six 1/2 scale testing specimens including unretrofitted and retrofitted walls were constructed. The first and second unretrofitted masonry walls were control specimens. The third and fourth walls were retrofitted applying ECC with strip type and the other two walls were retrofitted with ECC coatings. Every batch of tested walls was constructed with two different mortar strengths. The failure modes, lateral strength, ductility, stiffness, and the energy dissipation capacity of the tested walls were examined and compared. Furthermore, the experimental envelope curves were idealized and reasonable overstrength factors of the retrofitted walls were obtained. The results indicated that these retrofit techniques can effectively improve the lateral strength and the displacement ductility of unreinforced masonry (URM) walls, convert the brittle failure mode to a more ductile one, and provide an effective constraint for the walls, resulting in preserved integrity of the wall at large lateral displacements. Finally, the calculation methods for each retrofitting scheme were proposed to estimate the ultimate lateral strengths of ECC retrofitted masonry walls.

1. Introduction

Unreinforced masonry (URM) buildings are most likely to suffer severe damage or even collapse during earthquakes due to their seismic vulnerability. This vulnerability is generally the result of their constituent materials, which are characterized by low tensile strength, high mass and limited ductility. In addition, many existing masonry buildings in China were designed and constructed in the absence of active seismic standards or do not meet any seismic building codes. Thus, there is a need for reinforcing techniques for retrofitting this type of building.

Different retrofitting techniques have been investigated and developed by researchers to improve the performance of masonry buildings. The most commonly applied in practice is shotcreting the wall on a single side or double sides in combination with conventional steel wire mesh [1]. Although the reinforced sprayed concrete layer can provide advantages in terms of seismic resistance improvement, 80–150 mm of concrete might add substantial weight to the structure, modifying the structural behaviour of the whole building and having a negative impact on the aesthetics of the structure [2]. An alternative retrofitting method investigated by numerous researchers that does not change the weight and stiffness of the walls is external bonding fibre reinforced polymer (FRP). FRP strips or laminates can effectively enhance the lateral strength and energy dissipation capacity of URM walls [3–5]. Moreover, out-of-plane loading tests have concluded that blockworks strengthened with FRP sheets maintain their integrity during tests [6] and that the performance of masonry walls subjected to blast loading can be improved through retrofitting

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with FRP composites [7,8]. In addition, some relevant numerical models developed to predict the structural behaviour compare well with experimental results [9,10]. However, FRP materials generally respond elastically up to the failure point and have anchorage or bond issues, resulting in brittle behaviour and potential debonding failure.

Other retrofitting methods include applying a reinforced plaster layer or utilizing textile reinforced mortar (TRM). Since the plaster layers generally have a thinner thickness (10–50 mm) and better physical compatibility with the masonry, these techniques can allow an easy and clean construction process without debonding of two different materials. The structural efficiency of this retrofitting technique has been confirmed to enhance the performance of structural members in terms of increased lateral strength and stiffness (e.g., the steel wire mesh reinforced plaster used by Altın et al. [11] and the steel fibre reinforced plaster used by Facconi et al. [12]). Utilizing inorganic matrices in which grids or fabric of dry or coated fibres are embedded, typically referred to as textile reinforced mortar (TRM), can overcome the challenge of application of FRP strips or laminates to retrofitting, which usually include incompatibility between the FRP and URM substrate material and poor performance in adverse environments. The application of TRM strengthens the structural members, such as reinforced concrete beams [13] and URM walls [14]. The TRM jacket can significantly increase the bearing capacity of these members, but the cementitious adhesives may be brittle, especially at high temperatures, due to spalling [15].

The retrofit technique presented in this paper utilizes engineered cementitious composites (ECC) as a strengthening material for improving the performance of URM walls. ECCs are a type of cement composite reinforced with synthetic fibres. When loaded in tension, ECCs exhibit a strain-hardening characteristic via the process of multiple cracking [16,17]. The strain-hardening characteristic of ECCs makes it an ideal material for earthquake strengthening of structural members. Some studies have investigated the effects of using this retrofitting method, such as for repairing infrastructures using a wet-mix shotcreting process [18], strengthening reinforced concrete beams [19–21] and retrofitting unreinforced masonry panels [22–24]. These experimental results have indicated that ECCs can significantly enhance the behaviour of these structures by adding both high tensile strength and ductility to the structural element.

The main structural elements of masonry structures that resist earthquake actions are URM walls which are designed to bear mainly gravity loads. Under in-plane earthquake actions, URM walls have multiple failure modes which generally include diagonal shear failure, sliding shear failure and rocking and/or toe-crushing failure. Yi-Wei Lin et al. [25,26] studied the effectiveness of ECC shotcrete or trowelling ECC overlays as a seismic retrofitting method to improve the in-plane response of brick URM wallettes and concrete URM wallettes. These wallette tests, which applied a diagonal compression load to the wallette, were conducted using a modified version of the ASTM E519-07 test method [27]. The ECC overlay system can significantly enhance the diagonal shear strength within a wide range, depending on the ECC layer thickness and the application method of this strengthening technique. However, there is little research on the behaviour of URM walls retrofitted with ECC overlays subjected to quasi-static cyclic lateral loading. The objective of the investigation described in this paper is to assess the in-plane cyclic behaviour of strengthened masonry walls with different ECC strengthening configurations including strips around the wall and coatings on both sides of the wall. The responses of the tested walls are compared based on the observations in the test and changes in the failure pattern of the walls. The efficiency of strengthening by ECC is quantified in terms of lateral strength, stiffness degradation and energy absorption capacity. The influence of the mortar strength on the behaviour of the walls was also discussed. Furthermore, idealized envelopes obtained from the test backbone curves are presented.

2. Experimental program

2.1. Specimen construction

In this research, a total of six approximately 1/2 scale test specimens were subjected to cyclic shear loads. The double-wythe brick walls had nominal dimensions of 2300 × 1250 × 240 mm (length × height × width). The dimensions of the specimen were chosen to obtain a height-to-length aspect ratio of approximately 0.5 to ensure that shear behaviour dominated the failure pattern of the walls. The walls were constructed on a bottom reinforced concrete beam with sectional dimensions of 440 × 400 mm (width × height). To prevent premature sliding between the wall and the base, the bottom beam was grooved at the centre of the top surface with dimensions of 2400 × 340 × 35 mm (length × width × height), and a 10-mm-thick cement mortar (1:3 ratio of cement to sand by weight) was paved on it to bond the bottom masonry course. When the brickwork was completed, the groove was grouted with high-strength cement mortar or the ECC material for control specimens and retrofitted walls, respectively. The 120-mm-deep and 240-mm-wide RC cap beam was placed on the top of the wall and was designed with deeper cross sections located at both ends of it to transfer the lateral load to the wall effectively. The masonry wall was constructed using 240 (length) × 115 (width) × 53 (height) mm solid clay bricks bonded with approximately 10-mm-thick head and bed mortar joints. The properties of the mortar used in the joints are reported in the following sub-section. The wall panels were built in a bond consisting of stretchers and headers that alternated in every course. The headers in the course were centred above and below the stretchers in the other course. Since dry clay brick has a high water absorption capacity, all bricks were pre-soaked before construction to improve the bond performance at the brick-mortar interface.

2.2. Specimen retrofitting

In the test walls, two walls were retrofitted with ECC strips around the wall, and two of the other walls were retrofitted with ECC coatings. The remaining two walls were tested as control specimens. For the first retrofitting scheme, the strip retrofitted wall was expected to demonstrate seismic behaviour similar to that of a confined masonry wall (masonry with tie-columns and an upper tie beam). The ECC was trowelled on both surfaces of the wall from one side of the wall to the wall thickness successively for all retrofitting schemes. This process avoids premature delamination and debonding of the ECC layer initiated at the side edges of the wall. The strengthening overlays of all retrofitted walls were extended to the bottom of the groove to enhance the connection between the overlays and their foundations. Table 1 summarizes the tested specimens. Details of the retrofitting configurations and the dimensions of the tested walls are shown in Fig. 1.

Prior to trowelling the ECC onto the surfaces of the walls, the walls were blasted with water to remove loose material and pre-wet the wall surfaces. This procedure can prevent rapid drying of the ECC, which can lead to a weak bond between the overlays for strengthening and the masonry substrate. The chosen thickness of the layer for strengthening was 15 mm which is convenient for trowelling application and levelling. Once trowelling was completed, the ECC layer was cured by spraying water once a day for one week.