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Pseudo-static cyclic loading comparison of reinforced masonry walls strengthened with FRCM or NSM FRP

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HIGHLIGHTS

- Reinforced masonry walls were strengthened with FRCM and NSM FRP and subjected to cyclic loading.
- Variables included type of strengthening technique, amount of fiber, and masonry bond pattern.
- Behavior was investigated in terms of ultimate capacity, energy dissipation, and mode of failure.
- Experimental results were compared to control specimen and the effect of parameters was reported.

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ABSTRACT

Fiber reinforced polymer (FRP) composites have demonstrated poor performance in high temperature environments where the glass transition temperature of the resin is exceeded and this justifies the need to examine alternative strengthening techniques such as near surface mounted (NSM) reinforcement with cementitious adhesive or fabric-reinforced cementitious matrix (FRCM) systems. Evaluation of pseudo-static cyclic performance of these strengthening systems is of high interest. In this study, twelve reinforced masonry walls were strengthened in out-of-plane direction using FRCM composite or NSM with cementitious adhesive that were built as a part of this study. FRCM strengthening composite materials consisted of one or two plies of carbon or PBO (polyparaphenylene benzobisoxazole) fabric embedded in cementitious mortar. The NSM technique consisted of carbon or glass bar(s) installed in slots that had been grooved into the masonry tension surface. For all these specimens, a constant mild steel reinforcement ratio (ρ) was used in fully grouted walls. These simply supported walls were tested under out-of-plane constant-amplitude displacement cycles. The key parameters for this investigation were bond pattern (stack and running) and the type and amount of fabric/NSM product. The behavior of the specimens is discussed with emphasis on the load deflection response, flexural capacity, energy dissipation, stiffness degradation, and ductility index. The test results indicated that the behavior of the slender (i.e. non-arching) reinforced masonry walls was significantly dependent on the type of fiber used. The maximum flexural enhancement was found to be 97% and 75%, and the dissipated energy of the specimen with stack bond pattern was increased by 38% and 62% for masonry walls strengthened with FRCM and NSM system, respectively, compared to the control specimen. Different modes of failure occurred in the strengthened reinforced walls, including crushing of concrete block, as well as a debonding of NSM bar or fabric sheet from the masonry substrate and slippage of fabric within the cementitious matrix.

1. Introduction

The majority of existing masonry buildings has been constructed as unreinforced masonry (URM) structures in the absence of mandatory seismic design requirements. These structures possess very limited ductility so that its seismic performance has been considered to be sensitive to strong earthquakes or ground accelerations [1]. Evaluation of out-of-plane stability of unreinforced masonry walls subjected to seismic excitation was conducted by Griffith, et al. [2]. A simplified procedure was assessed to evaluate this behavior by considering tri-linear curve as an idealization for nonlinear force displacement response. As a conclusion of this

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study, initial stiffness is not crucial in determining the occurrence of collapse. The stiffness of the second and third branches of idealized force displacement curve (i.e., maximum strength and ultimate displacement capacity) is an important parameter for determining seismic design action. Reinforced masonry is obtained by placing and grouting vertical steel reinforcement in the open cells of masonry units to increase seismic capacity by resisting the load generated from earthquake. There are a large number of reinforced masonry buildings around the world in need of strengthening to meet the current seismic standards [3]. Seismic strengthening of masonry structures reduces not only casualties and damage to buildings during earthquakes, but also the cost of first-aid activities, rescue, rubble removal, and permanent residential reconstruction [4]. Extensive studies of masonry structures in the past two decades have been focused on strengthening masonry structures with emphasis on FRP and epoxy adhesive as a strengthening technique [5–7]. These studies reported that the strengthening of masonry structures using FRP composite was very effective to increase out-of-plane capacity for non-arching walls. FRP was preferred in the field of strengthening due to its high strength-to-weight ratio, corrosion resistance, and ease of installation [6]. The NSM system has been proven as a viable option for strengthening in terms of applicability, practicality, and low impact on aesthetic. The behavior of near surface mounted (NSM) and carbon fiber reinforced polymer (CFRP) strengthened masonry walls in flexure was reported [8]. The experimental results of this study indicated that the spacing of FRP strips played an important role in upgrading the out-of-plane flexural capacity and increasing the displacement of specimens. Increased fiber reinforcement ratio resulted in higher strength capacity and a reduction in the displacement. For a constant fiber reinforcement ratio, close spacing resulted in improved wall strength and displacement response. The influence of NSM FRP on the out-of-plane behavior of reinforced masonry walls was investigated [9]. As a result of this study, the capacity of strengthened walls was increased by 231% compared to the control specimen, and two basic types of failure modes were identified: FRP debonding and shear failure within concrete block unit. Although epoxy adhesive was approved as an effective bonding agent in many structural applications for strengthening, it may not be an optimal choice for other applications due to some limitations. These include hazardous poor behavior of epoxy at and above the glass transition temperature, incompatibility with the masonry surface, inability to be applied on damp surface, emission of toxic fumes, moisture impermeability, and flammability [10,11]. When an FRP system is subjected to high temperature, the guidelines for the design of FRP-strengthened structures state that the contribution of FRP is neglected unless a fire protection system or insulation is used [12]. In order to overcome these drawbacks of FRP and an epoxy system, NSM with cementitious material adhesive, or FRCM, has emerged as an alternative technique. Cementitious material is less expensive and preferable as a bonding agent due to its compatibility with masonry substrate [13]. A few studies have considered cementitious material as an adhesive material. The flexural behavior of unreinforced masonry walls strengthened using NSM FRP with epoxy and cementitious material was compared [13,14]. In terms of capacity, almost similar results were achieved by using epoxy or cementitious paste as a bonding adhesive, but the specimens with cementitious material had gradual stiffness degradation and debonding failure. As a recommendation of these studies, improved performance for this system was observed when the size of the groove was approximately 2.25 times the diameter of FRP bar and the bond-dependent factor was recommended as 0.55 in the case of using circular FRP bars. Out-of-plane performance of URM walls using the NSM technique subjected to reverse cyclic load was investigated [15]. Using twisted stainless steel bars in this study helped to provide a bi-linear behavior of the strengthened walls. The flexural capacity of strengthened walls increased by 434% compared to the control wall.

FRCM, also known as textile-reinforced mortar is an alternative strengthening technique and complementary to FRP systems. An FRCM system has almost the same advantages of an FRP system, such as high strength to weight ratio, corrosion resistance and ease of installation, but also overcomes some FRP drawbacks, especially the elevated temperature issue and application on damp surfaces. The flexural capacity of the structural element strengthened with FRCM is affected by several factors. Increasing the number of FRCM layers increased the flexural capacity, but the relation was not one to one (non-proportional relation). Also, the type of fiber affected the flexural capacity due to mode of failure and bond strength associated with each type. Moreover, the anchoring of FRCM could help to improve the capacity and ductility by delaying the mode of failure [16]. Previous studies have investigated strengthening URM walls using an FRCM system focusing on ultimate strength without considering the seismic resistance. Retrofitting of URM concrete or clay brick walls with FRCM under uniformly distributed lateral load was conducted [17], and an enhancement in flexural capacity ranging from 2.7 to 7.8 compared to unstrengthened specimens was reported. The potential modes of failure for these strengthened specimens were identified, including flexure and shear failure, depending on fiber reinforcement ratio. The out-of-plane behavior of URM walls strengthened with FRCM under cyclic load was investigated by Ismail and Ingham [18]. Based on the result of this study, the behavior of the strengthened specimen was ductile until the failure, and the capacity increased by the range 575–786% compared to the control specimen with remarkable increment in displacement ductility.

Clay brick walls strengthened with carbon-FRCM and subjected to out-of-plane cyclic loading was tested [19]. The effectiveness of FRCM overlays was evaluated in comparison to that provided by FRP in the form of overlays or NSM reinforcement. It was concluded that FRCM overlays provide substantial increase in strength and ductility and comprise an extremely promising solution for the structural upgrading of masonry structures under out-of-plane loading. Compared with FRCM, NSM strips offer lower strength, but higher ductility due to a more controlled debonding. The inorganic matrix-grid composite was very effective in enhancing in-plane capacity and ductility ratio of masonry walls [20,21]. Diagonal compression tests on masonry specimens before and after the application of composite strengthening system were used to evaluate this system. Strengthening specimens from both sides produced further improvement in shear response, eliminating out-of-plane bending in the post-peak softening phase. The experimental results evidenced that the maximum resistance increment is about 350% compared with the control specimen.

Most strengthening design guides are limited to unreinforced masonry structures due to a lack of experimental studies related to RM structures. This work reports the outcomes of an experimental study on the strengthening of RM walls using FRCM or NSM with a cementitious material as the bonding agent. For the NSM phase of work, two types of fibers were used, either GFRP bars, or CFRP bars and strips. Fabric composed of either PBO or carbon was used in the FRCM system. The comparison of the specimens is discussed with emphasis on the load-deflection response, crack pattern, energy dissipation, stiffness degradation, and ductility index. The main objective of this investigation is to study experimentally the behavior of RM walls strengthened with FRCM composite or NSM with cementitious adhesive. This work also studies the contribution of fiber reinforced composite on improving the flexure strength and pseudo-static cyclic characterizations of reinforced masonry walls, in addition to identify potential failure modes of strengthened specimens. This study will develop and