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# Seismic capacity of masonry infilled RC frame strengthening with expanded metal ferrocement

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ABSTRACT

This research was to investigate the behavior of masonry infilled reinforced concrete frame strengthening with expanded metals under cyclic loading. In this study, a prototype frame was chosen from a three-story reinforced concrete building that was not designed for earthquake load. Three specimens were built to full scale of 1:1 ratio including, the reinforced concrete bare frame (BF), the brick masonry infilled frame (W) and the masonry infilled frame strengthening with an expanded metal sheet (W-SR). The specimens were tested under constant vertical load and cyclic lateral load. The infilled frame strengthening with expanded metal sheet (W-SR) provided the lateral strength, stiffness and energy dissipation capacity of 1.25, 1.26, 1.27 times those of the brick masonry infilled frame (W), respectively. An analytical model based on an equivalent strut was proposed for masonry infill panels. In this approach, the nonlinear behavior obtained from the masonry prism test results was employed to determine the lateral strength and stiffness of the masonry panel model. The hysteretic behavior of the infill panel and infilled frame was evaluated using a nonlinear structural analysis program, RUAUMOKO. The results of the hysteretic behavior were compared with the experimental results to validate the proposed model.

## 1. Introduction

In Thailand, many existing buildings are not designed for earthquake resistance, and most buildings are reinforced concrete frames with brick masonry infilled frames. Typically, the effects of infill frame under seismic loading are not considered in the design. During the 2014 Mae Lao earthquake, many school buildings were severely damaged due to insufficient in-plane strength and ductility of masonry infill panel [1]. It is recognized that masonry infill contributes significant strength to the reinforced concrete frame. Failure modes of infilled frame under in-plane loading are characterized into three principal behavior [2], i.e., (a) bed-joint sliding, if the mortar beds are weak compared to the masonry, (b) diagonal cracking, diagonal crack propagates from one corner to the diagonally opposite corner due to the excessive transverse tension strain, which is the common form of cracking in most infill panels, and c) corner compression, when infill panel is sufficiently strong in shear, high stress concentration at the corner causes crushing to the masonry and may induce the damage to extend to the concrete frame. Many studies on the strengthening techniques for masonry infill panels have been conducted to protect against these failure modes. Among these studies, Fiber Reinforced Polymers (FRP) is widely employed. For example, it was observed that the shear strength of mortar beds could be improved for masonry walls retrofitted with fiber-reinforced polymer (FRP) laminates [3]. In addition, the application of FRP laminates reduced anisotropic behavior for different bed joint orientation and maintained the specimen integrity. To improve the lateral strength and stiffness of the masonry walls, fiber-reinforced polymers (FRP) was employed to retrofit slender wall and squat wall [4]. It was found that the retrofitting technique improved both strength and stiffness; moreover, the FRP retrofits do not affect the fundamental frequency and the initial stiffness of the specimens. The effect of the presence of damage in the walls at the time of the repair was also studied [5]. Shear-dominant clay brick masonry walls, initially damaged by shear, were repaired by using externally bonded carbon fiber strips. It was observed that the maximum strength, deformation capacity, and the cracking pattern of the repaired walls were similar to that of undamaged walls. Diagonal strengthening of masonry infilled frames was investigated by using diagonal carbon fiber-reinforced polymer (CFRP) strips under cyclic loads [6]. CFRP strips were applied using various widths and arrangements to study the difference between the case of symmetrical and un-symmetrical retrofits of the infill panels. The test results indicated that the specimens with symmetrical strengthening showed higher lateral strength and stiffness than the other one. A similar study on CFRP grid was also conducted [7] to

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**Nomenclature**

| | |
|---|---|
| $f_a$ | is the permissible compressive stress of masonry prism |
| $f'_m$ | is the compressive strength of masonry prism |
| $f_t$ | is the permissible tensile strength of infill panel |
| $f_{ym}$ | is the yield strength of masonry prism |
| $h$ | is the center to center dimension of the height of the frame |
| $h'$ | is the height of masonry infill panel |
| $k_o$ | is the initial stiffness |
| $k_{sec}$ | is the secant stiffness |
| $l$ | is the center to center dimension of the length of the frame |
| $l'$ | is the length of masonry infill wall |
| $L_d$ | is the length of the equivalent diagonal strut |
| $M_{pb}$ | is the plastic moment of beam |
| $M_{pc}$ | is the plastic moment of column |
| $M_{pj}$ | is the minimum plastic moment between $M_{pc}$ and$M_{pb}$ |
| $R_{CC}$ | is the maximum lateral force of the corner compression resistance |
| $R_{DC}$ | is the maximum force of the diagonal compression strut force |
| $R_t$ | is the diagonal cracking strength of infill panel |
| $R_{ycc}$ | is the corresponding yield strength of the corner compression resistance |
| $t$ | is the thickness of masonry infill panel |
| $V_y$ | is the lateral yield strength |
| $V_m$ | is the maximum force |
| $\phi$ | is the strength reduction factor |
| $\theta$ | is the inclination of the diagonal strut |
| $\mu$ | is the coefficient of friction of the frame and infill interface |
| $r$ | is the aspect ratio of the frame |
| $\beta_c$ | is the reduction factor for column |
| $\beta_b$ | is the reduction factor for beam |
| $\Delta_y$ | is the yield displacement |
| $\Delta_m$ | is the maximum displacement |
| $\varepsilon_y$ | is the strain corresponding to the yield point value of masonry prism |
| $\varepsilon_m$ | is the strain corresponding to the maximum value of masonry prism |
| $\alpha k_o$ | is the post-yield stiffness |
| $\alpha$ | is the bilinear factor |
| $\alpha_b$ | is the normalized contact length of stress block at the beam infill interface |
| $\alpha_c$ | is the normalized contact length of stress block at the column infill interface |
| $\sigma_c$ | is the contact normal stress corresponding to the peak load at the loaded corner of column |
| $\sigma_b$ | is the contact normal stress corresponding to the peak load at the beam infill interface |
| $\tau_b$ | is the contact shear stress at the beam infill interface |
| $\sigma_{yc}$ | is the contact normal yield stress at the loaded corner of column |
| $\sigma_{yb}$ | is the contact normal yield stresses at the beam infill interface |
| $\tau_{yb}$ | is the contact yield shear stresses at the beam infill interface |
| $\rho_g$ | is the reinforcement ratio |

observe the effects of the number of strengthening layers, the type of grid, the type of bonding agent and the compressive stress level applied to specimens under in-plane loading. It was found that the use of externally bonded grids showed a promising solution for the structural upgrade of existing masonry structures. On the other hand, the strengthening of block walls with openings to resist extreme out-of-plane loads was studied by using CFRP [8]. The lateral load carrying capacity of the strengthened walls was found to be significantly higher than that of the un-strengthened walls. These upgrading techniques seem to be effective, however, FRP strips may debond at the ultimate load levels, and stress concentrations that were encountered at FRP anchorages may cause premature rupture failure. Moreover, other issues such as the need for surface preparation, relatively high cost of epoxies, incompatibility between epoxy resins and clay brick cause difficulty in applying FRP on the masonry infill panel [9].

To overcome these limitations, cement based composite materials are employed for strengthening masonry infill panel. These include shotcreting masonry infill panel [10], textile-reinforced mortars [11], high performance fiber reinforced cementitious composites [12], steel fiber reinforced mortars [13] and engineered cementitious composites (ECC) [14]. Among these methods, ECC is a widely used material to strengthen masonry panels [15–18]. ECC is a special kind of high-performance fiber-reinforced cement-based composite material which is typically reinforced with short fibers and micromechanically tailored to feature high tensile ductility and multiple cracking [19]. Experimental studies have shown that the ultra-high ductility of ECC can considerably enhance the behavior of the strengthened structural system resulting in high delamination resistance, high ductility and increased load-carrying capacity of the system [14]. However, the reliability of the composite material depends on the workmanship in the mixing process to achieve good workability and uniform fiber distribution, therefore, careful workmanship is required in the mixing process.

On the other hand, expanded metal which can be well bonded with mortar plastering may be an alternative method of retrofitting. Expanded metal panels are manufactured in a single process by using the expansion of partially slit metal sheets, which produce diamond like patterns [20]. This process leads to a lightweight mesh which is composed of strands connected in a continuous manner through nodes. Basically, expanded metal panels [21] are produced in two types: standard expanded metal (EMS) and flattened expanded metal (EMF). For the standard type, rhomb-shaped stitches are connected together by overlapping at the end of each bar. In contrast, there is no overlap between stitches in the flattened type. They are continuously connected together to form a completely flattened sheet. The EMF type undergoes additional cold work in which the EMS sheet is passed through a cold-roll reducing mill which increases the material yield strength. Several researches have been conducted on the seismic retrofit by using expanded metal. Dung and Plumier [22,23] investigated the shear strength of expanded metal panels under cyclic loading, and it was found that the hysteretic behavior is stable with a large displacement ductility ranging from 10 to 20. The stiffness degradation was caused by the pinching effects due to yielding in tension and buckling in compression of the panels. Teixeira et al. [20] also investigated the quasi-static shear response of both EMS and EMF panels. The experimental results showed that shear response depends mainly on cell geometry; cells oriented horizontally at 0° exhibit better performance than cells oriented vertically at 90°. Moreover, the EMF panels can withstand higher loads than the EMS ones but their load–drift behavior is more unstable. The shear response also increases with an increase of panel length, whereas the effect of the panel height is almost negligible. However, the results were examined only for the suitability of expanded metal panels for steel plate shear walls. Kazemi and Morshed [24] evaluated the shear strength of the strengthened RC columns with ferrocement jacket reinforced with expanded steel meshes. Three specimens with volume fractions of expanded metal of 0.008, 0.016, and 0.024 were tested under cyclic loading. The shear strength of the strengthened specimens could be increased with the increase of ferrocement reinforcement. A high ductility capacity factor was observed up