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Engineered cementitious composites for strengthening masonry infilled reinforced concrete frames

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ABSTRACT

The results of the second part of a comprehensive experimental program, aimed at investigating the behavior of masonry infilled reinforced concrete (RC) frames strengthened with fiber reinforced engineered cementitious composites (ECC) used as an overlay on the masonry wall, are presented in this paper. The proposed strengthening technique aims at increasing the lateral strength of infilled RC frames and maintaining the integrity of masonry infills during loading, which is an important seismic parameter for these elements. Material tests were conducted first for ECC in order to assess its distinctive mechanical properties such as tensile stress–strain behavior and multiple cracking. Thereafter, three 1/2 scaled one bay, one story RC specimens were constructed and tested under quasi-static lateral loading. The obtained results are presented and discussed in terms of the strength, stiffness, and the cumulative absorption capacity of the tested specimens. Furthermore, the obtained backbone curves are idealized and the drift limits usually considered in seismic design are specified. The obtained results indicate that the proposed ECC-strengthening technique can effectively increase the lateral strength and energy absorption capacity of the infilled frame, prevent brittle failure modes in the infill wall, and provide a reasonable system overstrength.

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1. Introduction and background

A large number of reinforced concrete (RC) structures with inadequate lateral strength and limited ductility exhibited weak performance during past earthquakes around the world due to various deficiencies, including soft story, weak column-strong beam connections, insufficient concrete confinement, and non-seismic reinforcement detailing. At the present time, lots of RC structures in use have similar deficiencies and need to be strengthened against seismic loads. Furthermore, the presence of infill walls in some of these structures is another serious challenge in retrofitting because of their potential vulnerability under in-plane as well as out-of-plane loading. Several research studies on the seismic behavior of infill walls (e.g. [1]) has shown that these elements generally exhibit a small plastic region on the stress–strain curve due to the significant decrease in stiffness, strength, and energy absorption capacity. On the other hand, the use of existing masonry panels in a strengthening scheme for RC structures is an interesting solution, because it can avoid the catastrophic failure modes of masonry panels and can simultaneously use the beneficial characteristics offered by infills such as increase in the lateral load resistance and stiffness of the system [2].

Generally, masonry infill walls interact with the structural frames and contribute to the seismic behavior of buildings. However, they are often ignored by structural engineers and are considered as architectural elements. By increasing the lateral stiffness of the structure, these elements shift the natural period of the structure on the earthquake response spectrum in the direction of a higher seismic base and story shears and direct earthquake forces to parts of the structures not designed to resist them [3]. During an earthquake, these infill walls increase the earthquake lateral load significantly and are often damaged prematurely due to diagonal tension and compression or out-of-plane failure.

One way to improve the seismic behavior of this kind of structures is to enhance the in-plane shear behavior of infill panels. Based on this concept, different techniques have been developed and some of them are applied in practice, such as utilizing monolithically cast or precast RC infill walls (e.g. [4,5]), applying reinforced plaster layers [6,7], and shotcreting masonry infill panels [8] to increase stiffness and lateral strength of infilled RC frames and reduce the lateral drift at the ultimate load. Despite being effi-

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cient, it seems that applying these techniques to the inhabited existing structures is not practical, because they require a great deal of preparation, the construction work may disturb the ongoing building functions, and the newly added structural elements may affect aesthetics of the building. These techniques also add considerable mass to the building resulting in higher seismic loads. An alternative technique proposed and tested by extensive experimental studies (e.g. [9–12]) is the use of fiber reinforced polymers (FRPs) to enhance the overall behavior of such systems. The experimental results have revealed that significant improvement in lateral strength and energy absorption capacity is achieved if adequate anchors are provided to attach FRP sheets to the masonry wall as well as the corners of the surrounding RC frame. However, FRP materials generally behave elastically up to the point of failure and potential debonding failure is likely to take place through FRP debonding from the masonry infill [13]. Furthermore, other issues can prevent FRP from being successfully applied on the masonry infill such as the need for surface preparation, relatively high cost of epoxies, incompatibility between epoxy resins and some substrate materials (e.g. clay), and difficulty in applying FRPs on wet surfaces or in low temperatures in practice [14].

In general, the compatibility between the substrate and repair material is a key parameter in the selection of the repair material type, which can insure a good composite action under different loading and structural component durability. Regarding this issue, cement based composite materials were proposed for strengthening concrete and masonry elements due to their mechanical and physical properties (e.g. coefficient of thermal expansion, fracture energy, and small shrinkage deformation after installation), as well as other important considerations such as cost, availability, constructability, and ease of installation [15]. For instance, the use of textile-reinforced mortars (TRMs) as an effective substitute for FRP used in the form of overlays or near-surface mounted (NSM) reinforcement were proposed [14,16] to strengthen masonry walls under in-plane as well as out-of-plane cyclic loading. In comparison to the resin-based systems, TRM resulted in reduced effectiveness for strength in the case of in-plane loading, while out-of-plane loading the effectiveness of TRM versus FRP depended on the failure mechanism [14]. Recently, TRM jacketing has been used to enhance the seismic behavior of infilled RC frames. It was shown that TRM jacketing increases both the stiffness and the lateral strength of the system [2]. Other examples of using cement based composite materials for strengthening RC frames are based on the application of high performance fiber reinforced cementitious composites (e.g. [17]) and steel fiber reinforced mortars (e.g. [18]).

The aim of this study is to utilize engineered cementitious composites (ECC) as a strengthening material to enhance the seismic behavior of infilled RC frames. ECCs are a special kind of high-performance fiber-reinforced cement-based composite materials (HPFRCCs) which are typically reinforced with short fibers and micromechanically tailored to feature high tensile ductility and multiple cracking [19]. Applying ECCs in different parts of the structure have been studied in the literature such as bridge deck link slabs, flexural elements, moment resistant frames, design of new framing systems, damping elements, coupling beams in high-rise buildings, and shear beam elements [20]. In an attempt to utilize new repair materials ECCs have been utilized by some researchers for repairing infrastructures using wet-mix shotcreting process [21], strengthening of concrete beams [22], making precast panels for retrofitting frame structures [23], and strengthening unreinforced masonry panels [24–27]. These experimental studies have shown that 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.

In the present study, the ECC strengthening technique which can be applied with minimum disturbance to the occupants is extended to the field of retrofitting brick-infilled concrete frames. In this paper the efficiency of ECC overlays is evaluated and the behavior of test specimens subjected to quasi-static cyclic lateral loading in terms of the strength, stiffness, and energy absorption capacity is discussed. Furthermore, the ideal backbone curves obtained are presented, which can be utilized in numerical simulation. Lastly, the drift limits usually considered in seismic design corresponding to initiation of significant damages are introduced.

2. Experimental program

The experimental program was conducted in the Structural Laboratory of the International Institute of Earthquake Engineering and Seismology (IIEES) in Tehran, Iran. The comprehensive experimental program consisted of two parts: a thorough investigation on the ECC material characteristics and small scale masonry elements retrofitted by ECC, the result of which has been published earlier [25], and the evaluation of seismic behavior of masonry infilled reinforced concrete frames strengthened using ECC which is the subject of current paper. The experimental tests in the second part of the study were conducted on three half scale RC frames subjected to reversed in-plane cyclic loading.

2.1. Prototype structure and test specimens

A five-story, three-bay reinforced concrete moment-resisting frame was selected as a prototype structure in which the height/length ratio for each bay was selected to be 3/4.4. Since the main aim of the study was to evaluate a strengthening procedure for existing deficient buildings, the specifications of the old version of Iranian Seismic Code were used to design the prototype structure. Gravity loads were taken from the Iranian Loading Code (Standard 519) [28] and the equivalent static lateral forces were calculated according to the Iranian Code for Seismic Resistant Design of Buildings (Standard 2800) [29]. The live load was taken to be 200 kgf/m^2 and the dead load was estimated to be 810 kgf/m^2. The designed structure represented existing RC frames which do not meet the detailing requirements of current seismic design provisions. As in standard design practice, the infill panels contribution in the structure response was ignored in the designing process.

The test specimens were 1/2 scale, one-bay, one story, representing the interior bay at the bottom story of the prototype frame. Reinforcement details and dimensions of the tested frames are shown in Fig. 1. The RC frames were detailed and constructed deliberately with common deficiencies observed in existing buildings in the country including inadequate lateral stiffness, weak column-strong beam connections, inadequate lap splice length in the columns' longitudinal reinforcements, insufficient confinement of concrete at the end of beam and columns, and lack of transverse reinforcements at the beam–column joints. Furthermore, the ties used in the tested frames had 90° hooks at their free ends. The columns' section was 200 × 200 mm with eight 12 mm diameter deformed steel bars as longitudinal reinforcement. The beam was 200 × 250 mm and six 12 mm diameter deformed bars were used as its longitudinal reinforcement. Plain bars with a diameter of 6 mm spaced at 100 and 125 mm were used as ties in the beam and columns, respectively. The test results of three specimens are presented and discussed in the current paper, namely the bare frame (BF), the masonry infilled frame (IF), and the strengthened infilled frame with 15 mm ECC layers on both sides of the infill wall (IF-DL15).

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