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SEISMIC RETROFITTING OF A THREE-STOREY MASONRY-INFILLED RC FRAME WITH TEXTILE-REINFORCED MORTAR (TRM)

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ABSTRACT

The effectiveness of using textile-reinforced mortar (TRM) as a means of improving the mechanical behaviour of reinforced concrete (RC) or masonry elements has been experimentally verified in the recent past. In this study TRM was employed for the first time in the case of substandard masonry-infilled RC frames representing structural detailing of the 60s-era in Southern Europe. For this purpose cyclic tests on two nearly full-scale three-storey RC frames were conducted. The structure was subjected to a linear pattern of cyclically alternating forces through servohydraulic actuators. The performance of the retrofitted specimen was compared to the performance of the unretrofitted companion specimen. The test results demonstrate that the proposed strengthening technique considerably enhances the lateral strength, the lateral stiffness and the deformation capacity of the frame. An analytical model to simulate the response of TRM retrofitted masonry-infilled RC frames is also provided.

1 INTRODUCTION

Past experience has shown that masonry infills in substandard reinforced concrete (RC) buildings play a key role in their behaviour under seismic excitations. This role can either be beneficial for the overall response of the structure, or can have catastrophic consequences. An overstrength is usually provided by the infills, given that they do not cause adverse effects on the frame members or on the structure as a whole. Nevertheless, masonry infills cannot be considered as reliable structural elements because they suffer damage even since early stages of strong earthquakes, shedding rapidly their strength and stiffness and becoming vulnerable to collapse. In this context, retrofitting masonry infills aims to convert them from non-structural to structural elements by applying external layers of reinforcement and by connecting them to the surrounding RC frame members.

Various retrofitting techniques have been proposed in the literature as alternative solutions to conventional ones that make use of steel-mesh reinforced shotcrete layers. The most recent techniques include the application of fiber-reinforced polymers (FRP) (e.g. [1, 2]) and sprayable ductile fiber-reinforced cementitious composites (e.g. [3]). The retrofitting technique proposed in this study is based on the application of textile-reinforced mortar (TRM), which is a composite material comprising high-strength open-mesh fiber textiles as reinforcement in combination with inorganic matrices (i.e. cement-based mortars). The concept of the technique relies on the application of TRM layers on the entire surface of the wall and their connection to the surrounding RC frame members. The effectiveness of TRM in retrofitting RC and masonry wallettes has been experimentally investigated in the past and has been found to be significant and in some cases higher than the effectiveness of FRP (e.g. [4-7]). In this paper the application of TRM in masonry-infilled RC frames is examined both experimentally and analytically. The developed analytical model is finally verified via numerical simulations of the tested frames.

2 CYCLIC TESTS

2.1 Specimens

A 2:3 scale model of a three-storey frame with detailing practices of the 60s-era in Southern Europe was selected. Two identical RC frames were built; their geometry is shown in Fig. 1a. One infilled-frame was tested without being strengthened and served as control specimen (SP#1), whereas the other was tested after being retrofitted with TRM (SP#2).

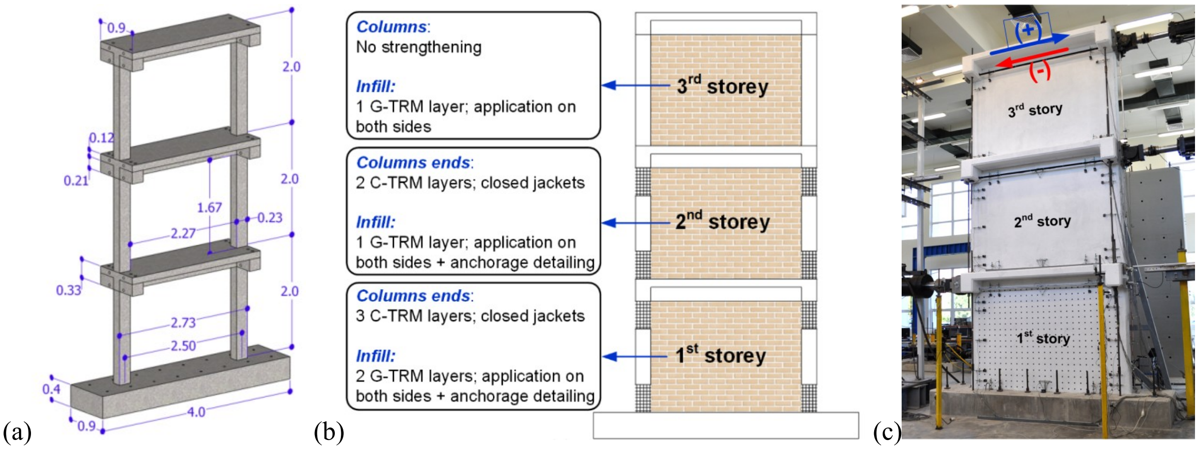

Figure 1 (a) Geometry of the bare frame (dimensions in m), (b) strengthening configuration, (c) test set-up

As illustrated in Fig. 1a, the clear height and length of each bay was 1.67 m and 2.27 m, respectively. Columns were of rectangular cross-section 170x230 mm (the long side parallel to the plane of the frame) with the longitudinal reinforcement comprising six 12 mm-diameter deformed bars. The beams were of T-section (170x210 mm with 120 mm-thick and 900 mm-wide flange). The transverse reinforcement both for columns and beams consisted of plain bars with 90-deg end hooks spaced at 130 mm. The concrete compressive strength on the day of testing was 27.2 MPa and 27.8 MPa for the SP#1 and SP#2, respectively. The yield stress of the rebars was 546 MPa and 289 MPa for the deformed and plain bars, respectively.

The infill walls consisted of two wythes with an internal gap of 60 mm (without any connection between them). Each wall was built by using perforated, fired clay bricks laid with the perforations running parallel to the unit's length. The total wall thickness (including the internal gap) was equal to 170 mm. The mean compressive strength of the bricks perpendicular to the perforations was 11.3 MPa. The mean flexural and compressive strength of the mortar was 2.6 MPa for both frames and 12.6 MPa (SP#1)/13.3 MPa (SP#2), respectively. The thickness of the bed and the head mortar joints was approximately 10 mm.

The strengthening scheme for the retrofitted specimen SP#2 was based on the response of SP#1 and on results obtained from tests on small-scale specimens conducted earlier [8]. It included strengthening of the infill walls via two-sided application of TRM layers and shear strengthening of the columns with closed TRM jackets. The infill at the 1st storey received two TRM layers, whereas the rest of the infills received one TRM layer (Fig. 1b).

The TRM layers were anchored to the surrounding RC members. The textiles were simply extended to the columns and bonded over their full height, whereas specially designed anchors were placed at the bottom of the 1st and 2nd storey infills. Details on the development of the anchors and their verification can be found in [8]. At the top of the infills the textiles were extended to the beam surfaces up to the point where the web of the beam meets the flange. At the 1st and 2nd stories an extra textile patch was applied over the beam-infill interface region, as a means of improving the connection between them. Only in the case the 1st storey's front side, instead of applying an extra textile patch textile-based anchors were used.

A commercial carbon fiber bi-directional textile was used for the columns strengthening (with a mesh size of 10x10 mm, weighting 348 g/m^2). The textile used for the masonry infills consisted of a polymer-coated E-glass bi-directional textile (25x25 mm mesh size, surface weight 405 g/m^2). A commercial fiber-reinforced cement-based mortar mixed with re-dispersible polymers was used as binding material. More details on the strengthening procedure can be found in [9].

2.2 Experimental setup and results

Both specimens were subjected to a sequence of quasi-static cycles with increasing amplitude under an inverted-triangular pattern of forces. As illustrated in Fig. 1c, the displacements/forces were applied at each floor level via three servo-hydraulic actuators, one per storey. The frame foundation was fixed to the laboratory strong floor via prestressing rods, while two transverse steel trusses prevented out-of-plane displacements of the specimen. The axial load varied from the top to the bottom of the frame in order to simulate the actual heightwise distribution of gravity loads. This was achieved by using different sets of prestressing bars per storey.

The strengthening scheme resulted in a significant increase of the lateral strength of the frame as well as in enhanced deformation capacity. In particular, the maximum base shear was increased by 55% in both directions of loading, whereas the top drift ratio at maximum base shear increased by 56%. At the instant of failure (conventionally defined as 20% load-drop) the retrofitted frame reached 78.1% higher drift ratio at the top compared to the unretrofitted frame.

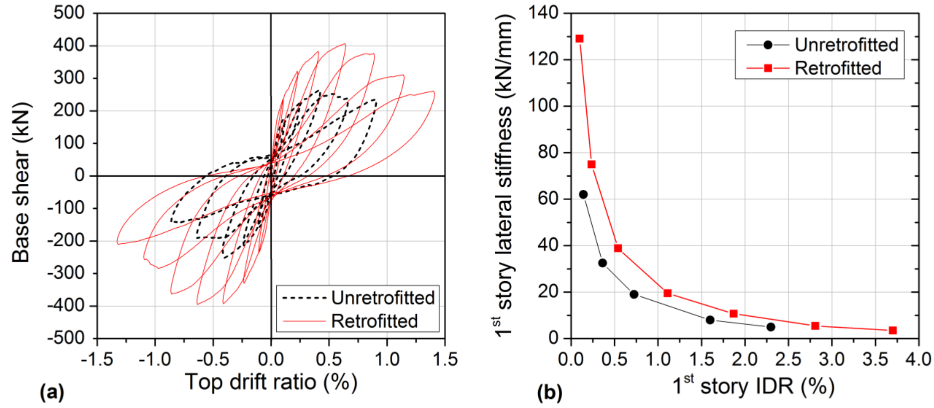

Figure 2 Comparison between the unretrofitted and the retrofitted specimen in terms of (a) base shear versus top drift ratio and (b) 1st storey's lateral stiffness.

As depicted in Fig. 2a, the behaviour of both specimens was almost linear elastic up to the first diagonal cracking on the body of the 1st storey's infill wall. The greater elastic stiffness of SP#2 compared to SP#1 is attributed to the presence of TRM layers and to the favorable masonry-concrete connection details. As illustrated in Fig. 2b the lateral stiffness of the 1st storey (secant stiffness of the storey force-displacement hysteresis loops) was almost doubled for the elastic range of response. The development of several diagonal cracks on the body of 1st storey's infill as well as of few minor cracks on the body of 2nd storey's infill resulted in gradual decrease of the lateral stiffness in both specimens.

The activation of the textile fibers in tension though, in the case of SP#2, enhanced the overall lateral strength of the infilled frame.

The retrofitting scheme managed to modify the heightwise distribution of the deformation demands. The lateral deformations in the case of SP#2 were better distributed, and thus the damage concentration at the 1st storey was significantly delayed. This favorable distribution, manifesting itself until the maximum base shear, affected the performance of the frame at the global level, implying that the present technique can be classified as a global intervention approach.

Failure of SP#1 was due to shear failure of a 1st storey's column, just below the beam-column joint, combined with progressive crushing of bricks. In the case of the retrofitted frame (SP#2), TRM debonding from the beam surface on the back side of the 1st storey and local crushing of the 1st storey's infill at the two upper corners led to the gradual lateral strength decrease. The connection details provided in SP#2 were proved to be effective in anchoring the TRM layers to the surrounding RC members. Only at large deformation levels of the 1st storey (IDR>2%) local debonding of the TRM layers was observed as a result of either rupture of anchors (at the top slab) or insufficient bond length. At these deformation levels the walls of the 1st storey partially disintegrated close to the top corners (with the debris falling inside the cavity between the two wall-wythes). It is also important to note that in specimen SP#2, column pre-emptive shear failure of the type observed in SP#1 (unretrofitted) was suppressed.

An interesting aspect of the behaviour of TRM was the capacity of the material to sustain high load even at large shear deformations without fibers rupture. This constitutes a further advantage of the TRM system: the structural integrity of the textile is maintained, rendering it capable of containing the masonry infill and reducing the risk of collapse.

3 ANALYTICAL MODELING AND NUMERICAL SIMULATIONS

An analytical model for TRM-strengthened masonry-infills RC frames is introduced, based on the use of a pair of strut and tie elements per infill diagonal. This model was implemented in OpenSees ([10]) and was employed to simulate the response of the tested 3-strory frames. The values of the physical parameters characterizing the response of the infills were derived from standard tests on masonry sub-assemblies, whereas the properties of the composite strengthening material were obtained through tensile tests on TRM dumbbell-type specimens. Numerical analyses were carried out to validate the analytical model.

The simplified approach of diagonal struts/ties simulating the response of retrofitted masonry infilled RC frames is based on the use of a pair of alternatively activated elements (a compression-only strut and a tension-only tie), placed along each diagonal of each portal (Fig. 3a). The strut element simulates the behaviour of the diagonal under compression, whereas the tie – which is employed only in retrofitted infilled frames - accounts for the behaviour along the opposite (tensioned) diagonal, relying on the externally bonded material to carry the developing tensile forces.

For the strut element the model of Fardis and Panagiotakos [11] was adopted. It consists of a multi-linear backbone curve with simple linear hysteresis rules (Fig. 3b). To account for the contribution of the externally bonded TRM layers to the response of the masonry infill under lateral cyclic loading, an equivalent tie element model was developed for the panel diagonal under tension. Based on the macroscopic behaviour of the TRM layers during the 3-storey frame test, the axial tensile force versus deformation (elongation) response of the tie was modelled as bi-linear with simple linear hysteresis rules (Fig. 3c). The concept of this model is that the fibers of the textile layers crossing a given crack pattern in the direction parallel to the strut develop tensile forces which are projected in the tie direction. As a result of the TRM behaviour during the test, the ultimate force carried by the fibers was limited to a value (the so-called effective force) which is lower than the one corresponding to fibers rupture. One of the objectives of this study was to calibrate the model in terms of the effective force and in turn of the effective strain value, with the experimental results. More details on the strut and tie-model parameters and how they were determined can be found in [12].

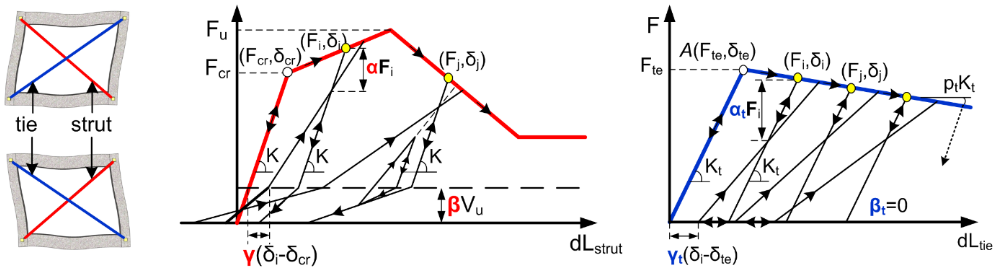

Figure 3 (a) Infill modeling scheme, (b) strut constitutive law, (c) tie constitutive law

A series of numerical analyses were carried out in OpenSees [10] in order to validate and calibrate the proposed tie-model. Some of the model parameters were experimentally determined, whereas the rest were calibrated with the test results. A sensitivity analysis was also conducted to investigate the effect of the several parameters to the global response. As a result, it was found that the crucial parameter was the effective strain of the TRM, which is related to the effective force. The best agreement with the test results was achieved for a value of effective strain equal to 0.8% for 1 TRM layer, whereas a change in the effective strain value of ±25% resulted in a ±7% variation of the base shear strength (Fig. 4a). The sensitivity of the model to the rest of the parameters was found to be limited. Even in the case of the parameters which control the shape of the hysteresis loops, a selection of extreme set of values did not yield significant changes in the results. Besides, for a specific set of these values the agreement achieved was quite favourable (Fig. 4b).

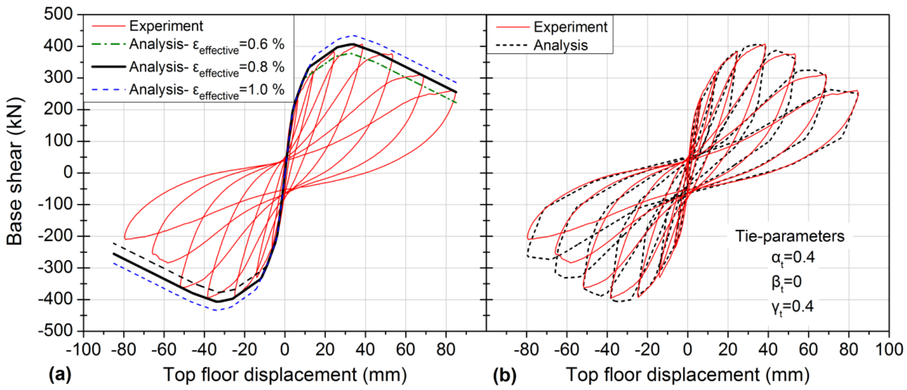

Figure 4 Comparison between experimental and analytical curves of the retrofitted frame: (a) sensitivity analysis on the value of the tie effective strain and (b) best agreement of the hysteretic loops for a specific set of values which control the hysteretic response of the tie

4 CONCLUSIONS

The paper presents a study on the seismic retrofitting of masonry infills in multi-storey RC frames with textile-reinforced mortar (TRM). The test specimens were two large-scale (2:3) three-storey masonry infilled frames; one was tested as-built where the other was tested after being retrofitted with TRM. The retrofitting approach was that of a global intervention, targeting to convert masonry infills into reliable structural elements. The main conclusions drawn are summarized as follows:

- The TRM retrofitting technique results in an enhanced global response of the infilled frame both in terms of lateral strength and deformation capacity (approximately 55% increase of the maximum base shear and 55% increase of the roof displacement at maximum load).
- Textile-reinforced mortar layers can accommodate large shear deformations by the ability of the textile to distort in shear sustaining at the same time its structural integrity.

- A modeling scheme that makes use of single strut and tie elements to model the behaviour of a retrofitted infill panel can adequately reproduce the response of the tested frames after proper calibration of few of the tie-model parameters.

This study is a first attempt to investigate at large scale the application of textile-based composites with inorganic matrices as a means of retrofitting infill walls in substandard multistorey reinforced concrete buildings. Future research effort could be directed towards optimizing the materials and anchorage details in the TRM system and investigating out-of-plane loading effects on the in-plane behaviour.

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