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Masonry infill construction and retrofit technique for the infill-frame interaction mitigation: Test results

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ABSTRACT

The paper describes the set-up and testing of an innovative construction technique for masonry infill, which can provide a flexible and predictable in-plane response to the infill inside the frame, together with a stable and reliable out-of-plane response. The design strategy is to downgrade the infill reaction inside the structural frame thanks to a dramatic reduction of the masonry in-plane stiffness. The infill is partitioned by vertical planks (or equivalent beams) into sub-panels, free to relatively slide and rock on their toes. The planks connected to the beams provide the necessary out-of-plane stability. The solution was tested for application in both new and existing infills and construction details are discussed. A comparison is also presented with the performance of two infills, one continuous and one with horizontal sub-panels, previously tested under the same conditions. The observed infill downgrade makes practically negligible the infill-frame interaction and the post-earthquake masonry damage.

1. Introduction

The research work here presented tries to address the well-known issues related to the infill-frame interaction in multi-story buildings. The paper describes the set-up and testing of an innovative infill construction technique, which can provide a deformable and predictable in-plane response to the infill inside the frame, together with a stable and reliable out-of-plane response. The design strategy is to downgrade the infill contribution to the building seismic response thanks to a dramatic reduction of its in-plane stiffness.

In fact, the uncertainty of the traditional masonry infills in- and out-of-plane response [1] and their possible irregular distribution in the structure jeopardize the building safety and resilience. The post-earthquake damage associated to a poor infill performance highly contributes to the cost and duration of the reconstruction process and activity recover [2,3], even after moderate intensity earthquakes [4]. Despite the possible detrimental effects of the infill-frame interaction, the post-earthquake damage survey showed also in some cases their contribution in preventing the collapse of poorly detailed buildings, not designed to withstand seismic actions; but this contribution is not always reliable due to the possible activation of undesired collapse mechanism in the structure. However, because of their efficiency in terms of construction ease, internal climate control and low building costs, traditionally constructed infills remain widely used, even if in the last decades, a large number of infilled frame buildings have performed poorly during earthquakes [5,6].

The increasing demand for post-earthquake damage control justifies the development of infill typologies for new buildings, capable to survive moderate to intense earthquakes without damage. In the last decade, several authors have proposed engineered masonry infill solutions to address this issue [7–11]). Mohammadi et al. [7] and Preti et al. [8] proposed the horizontal partitioning of the infill. Misir et al. [9] investigated the response of infills made of blocks without mortar, providing out of plane stability by a particular interlocking between blocks of adjacent rows (locked brick infill). Markulak et al. [10] proposed the use of weaker masonry blocks located close to the columns to accommodate the frame deformations. Vailati and Monti [11] substituted the mortar joints with plastic ones to be used with hollow blocks. Other ongoing research projects, aimed at optimizing the design of earthquake resilient infills, were presented in [12–16].

The construction technique here presented stems from the research work presented by Preti et al. [8,17], inspired by historical

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partitioned masonry structures [18] and recently updated towards industrialization by Morandi et al. [19]. The technique adopted the partitioning of the infill in masonry sub-panels connected to the columns for ensuring out of plane stability, but free to move relatively along horizontal planks, embedded in mortar beds. The performed tests showed a ductile infill response provided by the horizontal partitioning, without damage and with a significant stiffness reduction with respect to a traditional masonry infill. The innovation of the here presented solution consists in the configuration of the sliding planks (or equivalent beams), which have vertical instead of horizontal direction, and in their use as out of plane retaining elements. The main aim of the vertical configuration is to reduce the infill shear transfer to the columns of the surrounding frame. This need is justified by the parametric study described in [20,21], that quantified the significant increment of shear demand on the columns due to the interaction of the frame with the horizontally partitioned infills. Such shear increase occurs because of the concentrated frame-infill contact forces located at the masonry sub-panel corners and may affect the side elements of a possible opening (window or door), as well. In new structures, adequately detailed columns can support such shear action, even if a reduction of the demand will simplify the design. On the other hand, in existing buildings, for which the downgrade of infills could be beneficial [22], a reduced shear demand can prevent the columns shear failure, thus avoiding the need for their strengthening. Moreover, in existing buildings, the possible insertion of the sliding elements in vertical cuts operated in the masonry, makes possible their preservation and the consequent saving in terms of material disposal. The retrofit can be worked from the infill outside, limiting the building downtime.

The paper presents the test of two masonry infills built with vertical sliding planks and hollow clay blocks, and compares the results to previous tests on similar solid or horizontally partitioned infills. The first specimen (Specimen A) was tested in- and out-of-plane, proving the solution efficiency in reducing the lateral infill-frame interaction and in protecting the infill from the out-of-plane collapse. The feasibility of the solution for existing infill walls was studied on a second prototype (Specimen B). The in- and out-of-plane performance was tested under quasi static cyclic loading, also in this case, together with an operational procedure and the specific detailing for the insertion of the vertical planks in the existing infill.

2. Construction technique

The proposed construction technique consists in partitioning the infill wall by means of vertical elements, connected to the frame beams and working as sliding joints and retaining elements for out-of-plane actions. In the prototypes under testing, such vertical elements are made of shaped planks, pinned-end restrained to the frame beams by steel plates. Two vertical elements are also located adjacent to the columns and a gap remains between the infill sub-panels and the frame top beam. For thermal and acoustic performance, the gaps are meant to be sealed with a soft material. The planks stay in the thickness of the infill, so they can be covered by plaster to obtain a homogeneous facing. Additional internal or external insulating layers can be added, provided that they are sufficiently flexible in their plane.

2.1. In-plane mechanism

The vertical configuration of the joints imposes an in-plane deformation mechanism characterized by the alternate rigid rotation (rocking) of the masonry sub-panels around their toes, and the relative masonry sub-panels sliding along the vertical planks (Fig. 1a).

The free rocking of each masonry sub-panel produces their corner uplift, allowed by the top gap, and provides a limited resistance (R_R) to the infill deformation (in the order of few kilo-newtons), according to the mechanism schematically described in Fig. 1b-i. Such infill resistance can be quantified as the sum of the lateral overturning loads applied to each sub-panel. Assuming, in first approximation, the lateral load located at the top of the sub-panels, R_R is obtained with Eq. (1), where W_i, h_i, z_i and N are the weights, heights, internal lever arms and number of the sub-panels, respectively.

$$R_R = \sum_{i=1}^{N} \frac{W_i}{h_i} \cdot z_i \tag{1}$$

The most significant contribution to the in-plane resistance (R_F-Fig. 1b-ii) depends on the friction activated by the relative vertical sliding of the sub-panels on their lateral interfaces (of width t_i), which counteracts the sub-panels rotation. Assuming, for the sake of simplicity, a constant friction coefficient (μ) and average normal stress ($\bar{\sigma_n}$) on the sub-panel sides, the theoretical value of R_F can be evaluated according to Eq. (2):

$$R_F = \sum_{i=1}^{N} (\bar{\sigma_n} \cdot \mu) \cdot t_i \cdot b_i \tag{2}$$

However, such contribution is hardly predictable for the difficulty in quantifying the friction stresses in a such statically undetermined structure and because of: (i) the mortar shrinkage allows gaps between the sub-panels and the vertical planks, which may delay the contact and reduce the friction stresses intensity and modify their distribution; (ii) the sub-panel uplift and rotation induce, by compatibility, a geometrical interference between the masonry sub-panel and the windward vertical plank (Fig. 1c), which increases with the drift and tends to increase the normal (σ_n) and friction ($\sigma_n \cdot \mu$) stresses on the vertical sliding surfaces. In addition, the effect of the geometrical interference is reduced when the infill dilatation is not confined by the frame columns. Depending on the geometry of the sub-panels and the drift level, such geometrical interference, that would theoretically induce an interpenetration, can be quantified according to Eq. (3).

$$\Delta_{interference} = b \cdot (tan\alpha \cdot sen\alpha + cos\alpha - 1) \tag{3}$$

The interference grows with the width of the sub-panels (b) and their rotation (α), however it ranges in the order of decimals of millimeters and a small gap can completely change its effect, by delaying or nullifying the friction mechanism. Accordingly, for the aim of this structural application, a certain mortar shrinkage is desirable in order to limit the in-plane stiffness and strength of the infill, as it occurred in the experimental tests presented in the following.

To enlarge the scenario of the possible mechanisms of an infill with vertical sliding joints, Fig. 1b-iii describes a third resisting mechanism activated by the sub-panels, in the case their rocking mechanism is confined by the top beam (no top gap). The contribution to the infill resistance of the vertically confined rocking (R_V) would be given by Eq. (4), where F_v is the resultant of the confining stress acted by the beams and z_i' their lever arm.

$$R_v = \sum_{n=1}^{N} \frac{F_V \cdot z_i'}{h_i} \tag{4}$$

The investigation of the role of each mechanism in the infill response requires a detailed modeling, which is out of the scope of this paper, but it can benefit from the test here presented for calibration.