

Review Article

Recent Findings and Open Issues concerning the Seismic Behaviour of Masonry Infill Walls in RC Buildings

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The extension of the damages observed after the last major earthquakes shows that the seismic risk mitigation of infilled reinforced concrete structures is a paramount topic in seismic prone regions. In the assessment of existing structures and the design of new ones, the infill walls are considered as nonstructural elements by most of the seismic codes and, generally, comprehensive provisions for practitioners are missing. However, nowadays, it is well recognized by the community the importance of the infills in the seismic behaviour of the reinforced concrete structures. Accurate modelling strategies and appropriate seismic assessment methodologies are crucial to understand the behaviour of existing buildings and to develop efficient and appropriate mitigation measures to prevent high level of damages, casualties, and economic losses. The development of effective strengthening solutions to improve the infill seismic behaviour and proper analytical formulations that could help design engineers are still open issues, among others, on this topic. The main aim of this paper is to provide a state-of-the-art review concerning the typologies of damages observed in the last earthquakes where the causes and possible solutions are discussed. After that, a review of in-plane and out-of-plane testing campaigns from the literature on infilled reinforced concrete frames are presented as well as their relevant findings. The most common strengthening solutions to improve the seismic behaviour are presented, and some examples are discussed. Finally, a brief summary of the modelling strategies available in the literature is presented.

1. Introduction

The seismic vulnerability assessment of existing buildings that were not designed according to the recent and modern codes and the development of effective strengthening techniques are, nowadays, a paramount topic in the seismic engineering field. Over the last few years, it is visible a great interest regarding the study of the masonry infill walls and their influence in the response of reinforced concrete (RC) buildings when subjected to earthquakes, proved by the number of numerical and experimental studies available in the literature [1–4]. Their presence can be favorable or not for the seismic performance of the building, depending on several phenomena such as their plan and height distribution, existence or not of connection to the surrounding frame, boundary conditions, relative stiffness and strength

between the infill panel and the frame elements, and the infills' material and mechanical properties, among others.

Recent postearthquake survey damage assessment reports recognized that the infill masonry (IM) walls played an important role in the seismic response of the RC buildings [5–7]. The infill panels' seismic behaviour was also characterized by extensive level of damages and collapses, due to combined in-plane and out-of-plane loadings, as reported in [8, 9]. The collapse of many infill panels was responsible for several fatalities, direct and indirect economic losses [10, 11]. It is recognized that their in-plane (IP) behaviour affects with their out-of-plane (OOP) performance, since extensive damages caused by IP demands, such as the panel detachment, diagonal cracking, or shear failure, increase the infill panel OOP vulnerability [12, 13]. Different authors [1, 9, 14] reported that the masonry infill walls' OOP behaviour is

strongly affected by existence or not of connection between the panel and the reinforced concrete frame elements; existence or not of connection between leaves (in case of double-leaf infill walls); inadequate panel support width (very common constructive procedure adopted for thermal bridges' prevention); boundary conditions, panel slenderness, and inadequate execution of the upper bed joint; and lastly, the existence of previous damage. The infill panels' collapse can also result in plan and/or vertical irregularities, which can trigger global failure mechanisms such as torsion or soft storey.

Considering the number of experimental and numerical studies investigating the vulnerability issues of infilled RC frames, the missing of proper prescriptions by codes, and based on the well common masonry infill walls' presence in the RC buildings in the southern European countries, it is fundamental to carry out studies to characterize the seismic behaviour of these panels and to develop efficient strengthening strategies to improve their performance and prevent their collapse when subjected to earthquakes.

The present research work aims at presenting a global state-of-the-art review concerning the infilled RC frame seismic behaviour. First, a damage reconnaissance report from the last major earthquakes is presented. Observations of the RC structure performance during strong earthquakes represent a mean of teaching builders and engineers and proper and improper construction of earthquake load resisting systems. In regions that have long been inhabited, and which are subjected to relatively frequent strong ground shaking, design procedures have evolved, resulting in relatively good performance of engineered structures [15, 16]. Although such design procedures are not universally applicable because of regional differences in construction materials and techniques, structural engineers can learn much by studying such procedures. Additionally, the postearthquake damage reconnaissance highlighted the importance of the infill walls in the seismic performance of RC structures. Many authors pointed out that these elements (used to be called as "nonstructural") are very important and are responsible for a significant part of the human, material, and economic losses [7, 17].

Second, a deep state-of-the-art review of the experiments carried out on infilled RC frames is presented, where the major findings by each author are discussed. This section is very important to associate those findings with the damages observed in postearthquake scenarios. Finally, a brief presentation of modelling strategies of the masonry infill walls is provided, from the macromodelling approaches to micro-modelling approaches.

2. The Role of the Masonry Infill Walls in the Recent Seismic Events over the World

The RC structure behaviour depends on the strength and stiffness characteristics of the structural elements. The structural strength is provided by each of the structural members and by the interaction among them. Their response is controlled by the loading redistribution capacity that results in the failure of some members and/or in the

possibility of those members to be not able to suffer high levels of deformation demands until it fails. The insufficient strength capacity or incapacity of the structural elements to face seismic actions, which is several times higher than the value considered in the design process and results in shear loads higher than their strength capacity, is very common in existing low-standard buildings. The structures should be designed according to the seismic loading demand defined in the codes and to have stiffness, strength, and ductility balanced between the elements, joints, and supports. Similarly, the strength and stiffness contribution of the infill panels should be considered since these elements can significantly affect the whole structural behaviour.

This section aims at presenting the major learnings and findings concerning the typical damages from the last major earthquake in the Mediterranean area. They are presented and discussed, and a particular focus is dedicated to the masonry infill wall seismic behaviour and participation in the structural response.

2.1. Damage Typology Definition in Infilled RC Structures.

The Eurocode 8 [18] classifies the building elements as structural or nonstructural. Concerning the structural elements, they are subdivided into primary members (SP) and secondary members (SS). The primary members (SP) are considered as part of the structural system that resists to the seismic demands, modelled in the analysis for the seismic design situation, and fully designed and detailed for earthquake resistance. On the other hand, the secondary elements are members which are not considered as part of the seismic action resisting system and whose strength and stiffness against seismic actions are neglected; they are not required to comply with all the capacity design rules according to Eurocode 8 [18], but are designed and detailed to support gravity loads when subjected to the displacements caused by the seismic design condition. Last, nonstructural elements (NS) comprising architectural, mechanical, or electrical elements, systems, and components, whether due to lack of strength or to the way they are connected to the structure, are not considered in the seismic design as load carrying elements.

During the last major earthquakes all over the world, different types of damages, being the most representative ones listed above, affected the RC structures according to several authors and postearthquake survey damage assessments [5–8, 19]:

Damage Type 1: damages associated with stirrups and hoops (inadequate quantity and detailing, regarding the required ductility)

Damage Type 2: damages associated with detailing (bond, anchorage, and bond splitting)

Damage Type 3: damages associated with shear and flexural capacity of beam/column/wall elements

Damage Type 4: damages associated with the inadequate shear capacity of RC joints

Damage Type 5: damages associated with strong-beam weak-column mechanism

Damage Type 6: damages associated with short-column mechanism

Damage Type 7: damages associated with structural irregularities (in plan and/or in elevation: torsion, “weak storey,” and “soft storey”)

Damage Type 8: damages associated with pounding

Damage Type 9: damages in secondary elements (cantilevers, stair, etc.)

Damage Type 10: damages in nonstructural elements.

From the list, the first eight damages are related to primary members (SP), the ninth is related to secondary elements (SP), and finally, the tenth is related to nonstructural elements (SS). According to the after-earthquake damage survey assessment, it was concluded that there is an interaction among the last five types of damages. This interaction is related to the contribution/participation of the nonstructural elements or secondary elements in the global response of the infilled RC structure [20]. The existence of buildings with different (in plan or vertical) irregularities results in different responses than those expected; part of them are related to the disposition of the nonstructural elements [21]. Damages observed in postearthquake field missions highlighted that masonry infills, the main core of this work, cannot be generally regarded as nonstructural or secondary elements, as better discussed in Section 2.2, but should be considered as primary members, especially if they were built in full contact with the surrounding frame.

2.2. Most Common Damages in Masonry Infill Walls in Recent Earthquakes. Infills represent the external skin of the RC structures; they are generally used as interior partitions and to separate the inner spaces for the outside with constructive techniques that strongly depend on the construction practice typical of each country (double- or single-leaf infill, connection system between infill panel and surrounding frame, workmanship, etc.). This aspect can introduce a significant heterogeneity in the influence of the infills on the RC building seismic performance. Nevertheless, some similarities in the main vulnerability issues can be identified and observed in postearthquake reconnaissance field missions, especially if the more recent seismic events in the Mediterranean area are considered. The presence of infill panels generally leads to an increase of the IP lateral stiffness and strength, at least at low displacement demand, and a beneficial increase of the dissipated energy during a ground motion. Under higher displacement demand, infill panels, above all traditional (slender) panels, generally reduce their contribution to the lateral load and stiffness, thus producing a strength drop in the global lateral response of the whole infilled frame [22]. Some significant detrimental effects can be induced by the infill panels, certainly affecting the damage limitation performance level, but also potentially dangerous for the life safety, as discussed in the following remarks.

As well known, due to horizontal action parallel to their plane, infill panels generally exhibit a diagonal damage pattern, as shown in Figure 1. Such damage can be more or less diffused across the building and generally concentrated

at the lowest floors, where the relative displacement demand is generally higher. Such kind of damage is the clear evidence of the cooperation of infills in the seismic response of the building, so that their typical definition of “nonstructural” components can be considered as not appropriate. Additionally, as anticipated above, this damage, which is often particularly severe also under quite moderate seismic shaking, considerably affects the economic seismic losses for RC buildings [17], in terms of repair costs, downtime, and casualties, thus reducing the seismic resilience of the communities in seismic prone areas.

A structural irregularity can be induced by a nonuniform distribution of the infill panel along the height. As a matter of fact, due to severe seismic actions, a soft-storey collapse mechanism can be induced by the (quite common) absence of panels at the ground floor (see, for example, Figure 2(a)). Another kind of “irregularity” is the presence of frames with ribbon windows that are only partially infilled: such a situation generates very squat columns, which are extremely vulnerable to shear failures (see, for example, Figure 2(b)). These vulnerability issues clearly assume a crucial role since they are related to the life-safety performance level.

One of the big problems for life-safety purposes due to the infills is their OOP collapses (or overturning), which can be produced by the absence of proper connection systems between the “nonstructural” panel and the RC frame, as typical in existing buildings. In these cases, the problem becomes also more severe due to the typical high slenderness of the infills in existing buildings, generally realised in two (not properly connected to each other) leaves. As a result, the overturning of the infills is generally observed in post-earthquake field missions, as shown in Figure 3, enhanced by the combination between the damage due to in-plane actions and the transverse acceleration demand during a seismic event [6, 7].

A further issue affecting the life-safety performance level concerns the local shear interaction between the infill panels and the surrounding RC members. As well known, due to horizontal actions, an infill panel locally produces a shear action on the surrounding RC columns/beams concentrated in a squat portion of the RC member [26]. Such an action can lead to the shear failure of the RC structural members, especially in existing buildings, not designed according to capacity design principals, thus affecting the integrity and safety level of the whole building. Some examples of local shear interaction, from L’Aquila (Italy) 2009 [24] and Lorca (Spain) 2011 [7] earthquakes, are reported in Figure 4.

3. Literature Review on Recent Developments on Experimental Testing of Infilled RC Frames

The postearthquake damage analyses reported in the previous section highlight that a comprehensive knowledge of all the vulnerability aspects related to the seismic behaviour of infilled framed structures, of their nonstructural components, and of the phenomena related to the interaction between structural and “nonstructural” elements is

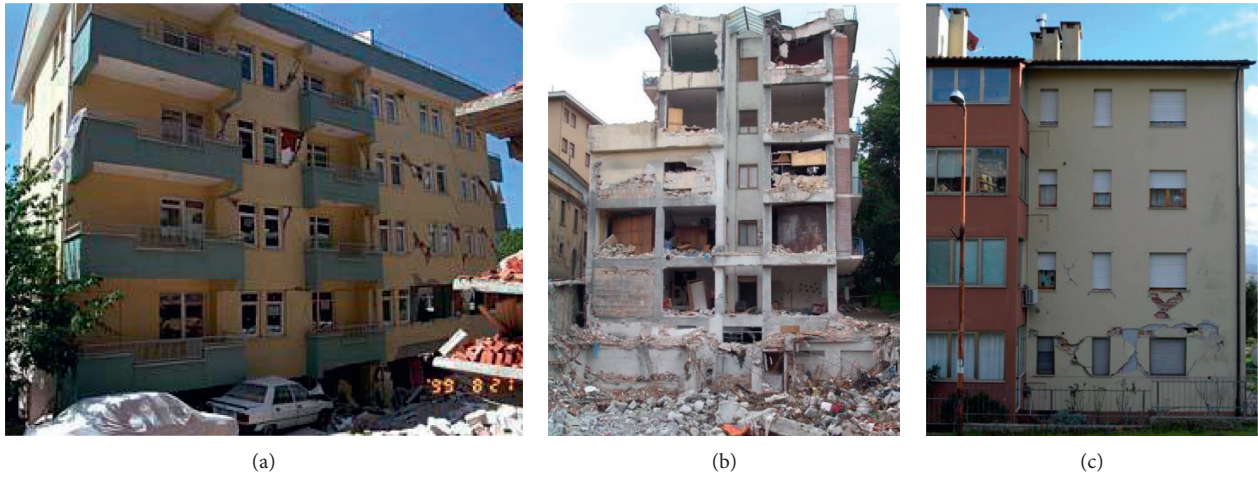


FIGURE 1: Example of medium-severe in-plane damage to infills (adapted from [23]). (a) Izmit (1999). (b) L'Aquila (2009). (c) Centre Italy (2016).

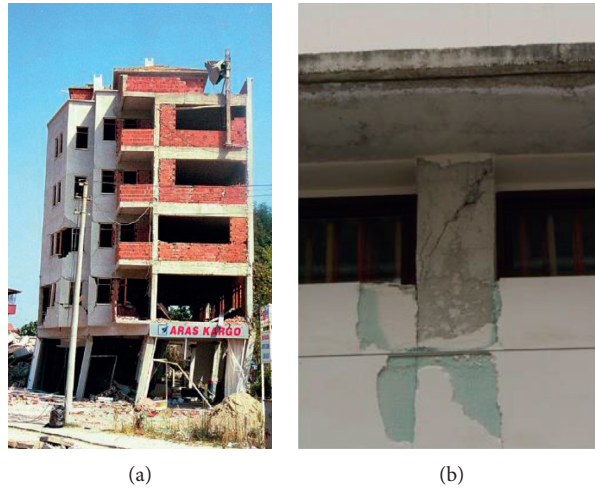


FIGURE 2: Example of structural irregularities induced by the infill panel (adapted from [7, 23]). (a) Izmit (1999). (b) Lorca (2011).

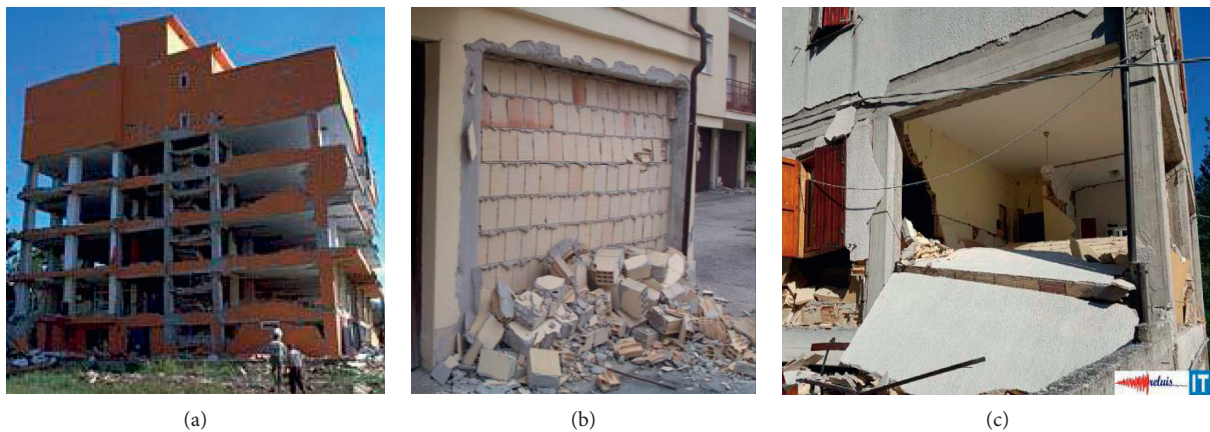


FIGURE 3: Example of out-of-plane collapses (adapted from [23–25]). (a) Izmit (1999). (b) L'Aquila (2009). (c) Centre Italy (2016).



FIGURE 4: Example of in-plane shear interaction between infill panels and RC frames adapted from [7, 24]. (a) L'Aquila (2009). (b) L'Aquila (2009). (c) Lorca (2011).

necessary. To this aim, the experimental testing allows understanding and characterizing the structural behaviour of given elements under different loading conditions reproducing the damage due to real earthquakes in lab. This is a key point to achieve the knowledge that is necessary to improve the codes with the capability of designing safer structures and with lower risk. Different types of experiments can be found over the literature concerning the infilled RC structures, which can be classified in in-plane (loading acting in the infill plane) and the out-of-plane (loading acting perpendicularly to the infill plane) testing of masonry infill walls. Section 3.1 presents a literature review about the in-plane (IP) tests, and Section 3.2 presents the out-of-plane (OOP) testing review and, lastly, a revision of strengthening techniques is presented in Section 3.3.

3.1. In-Plane Tests. Numerous tests have been performed in the literature to study the behaviour of infilled RC frames under in-plane actions in the last sixty years (see Table 1). Each experimental campaign investigated the influence of the infill panel on the lateral response of the whole frame depending on the brick typology (e.g., hollow or solid clay bricks, concrete or autoclaved aerated concrete (AAC) blocks, or other material typologies), on the infill-to-frame relative stiffness and strength, and on the presence of openings with different opening ratios and eccentricities, among other investigated parameters. Tested specimens were generally one-bay one-storey scaled infilled frames (e.g., [13, 34, 58] among many others—see Table 1). More rarely two- or three-storey frames (e.g., [29, 64]) or full-scale infilled frames [33, 40, 49] were tested in lab. Different typologies of test have been performed, by means of the application of monotonic or cyclic actions and pseudostatic or pseudodynamic actions or, more rarely, by means of shake table tests. Overall, about two hundred tests performed on RC frames with various typologies of infills can be collected from the literature [4, 65–67]. The main findings of these experimental campaigns on unreinforced masonry infills under in-plane actions are discussed in what follows.

A complete list of these campaigns can be found in Table 1 for infilled without openings (i.e., doors or windows).

For these tests, the experimentally observed failure mode has been different depending on the main geometrical and mechanical features of infills and frames. More in detail, the failure modes, specifically related to the infill panel, can be classified as follows [68]: (i) sliding shear failure, characterized by the horizontal sliding along mortar bed joints—typical in weak mortar infills and strong frame; (ii) diagonal cracking failure, characterized by cracks along the infill diagonals—typical of weak frame infilled with a strong infill; (iii) diagonal compression failure, characterized by the infill crushing in the centre of the panel—typical of slender infills; and (iv) corner crushing failure, characterized by the infill crushing in the corners—typical of weak masonry infills and frames with weak joints and strong members.

Although the significant heterogeneity of the tests is due to their differences in mechanical properties or material brick units (see Table 1), some general conclusions can be carried out.

From a phenomenological point of view, the evolution of damage affecting the infill panel under increasing in-plane lateral load goes from a hairline cracking along mortar bed joints or in bricks (“Slight Damage”), to more severe diagonal cracking and bricks crushing, often in the corners (“Moderate Damage”), until the complete “Collapse” of the panel [69], as shown in Figure 5. Starting from the analysis of the in-plane collected tests, the displacement capacity thresholds of the infills can be obtained for given Damage States (DS), from Slight Damage to Collapse, depending on their material typology, as recognized in Del Gaudio et al. [10]. It was found that, for infills with clay bricks, the median interstorey drift capacity is equal to 0.08%, 0.33%, and 1.6%, respectively, at Slight Damage level, at Moderate Damage, and at Collapse. Infills with concrete blocks showed a higher median drift capacity with respect to the infills with clay bricks, whereas, generally, a smaller drift capacity characterized infills with solid clay bricks with respect to infills with hollow clay bricks at more severe DSs [10].

TABLE 1: Literature review of IP experimental tests of infill walls depending on infill material typology: subset of tests on 1-bay 1-storey frames infilled without opening (adapted from [4]).

Author	Number of tests	Masonry unit	Scale factor
Aly and Mooty [27]	2	Solid clay unit	1:2
Akhoundi et al. [28]	1	Hollow clay unit	1:2
Al-Chaar et al. [29]	2	Solid clay unit-solid concrete unit	1:2
Angel et al. [13]	7	Solid clay unit-solid concrete unit	1:2
Baran and Sevil [30]	3	Hollow clay unit	1:3
Basha and Kaushik [31]	4	Solid fly ash unit	1:2
Bergami and Nuti [32]	2	Hollow clay unit	1:2
Calvi and Bolognini [33]	2	Hollow clay unit	1:1
Cavaleri and Di Trapani [34]	12	Hollow clay or concrete unit-solid calcarenite unit	1:2
Centeno et al. [35]	1	Hollow concrete unit	1:2
Chiou and Hwang [36]	2	Solid clay unit	1:1
Colangelo [37]	11	Hollow clay unit	1:2
Combesure and Pegon [38]	4	Hollow clay unit	2:3
Gazic and Sigmund [39]	10	Hollow clay unit-solid clay unit	1:2
Guidi et al. [40]	2	Hollow clay unit	1:1
Haider [41]	3	Hollow clay unit	1:1
Hashemi and Mosalam [42]	1	Solid clay unit	1:1
Kakaletsis and Karayannis [26]	2	Hollow clay unit-vitrified clay unit	1:3
Khoshnoud and Marsono [43]	1	Solid clay unit	1:4
Kyriakides and Billington [44]	1	Solid clay unit	1:5
Lafuente and Molina [45]	10	Solid clay unit	1:3
Mansouri et al. [46]	1	Solid clay unit	1:2
Mehrabi et al. [47]	11	Solid or hollow concrete unit	1:2
Misir et al. [48]	4	Hollow clay unit-solid AAC unit-hollow pomice unit	4:5
Morandi et al. [49]	1	Hollow clay unit	1:1
Parducci and Checchi [50]	6	Hollow clay unit	1:2
Pereira et al. [51]	1	Hollow clay unit	2:3
Pires [52]	6	Hollow clay unit	2:3
Schwarz et al. [53]	5	Solid AAC unit	1:2
Sigmund and Penava [54]	1	Hollow clay unit	1:2
Shing et al. [55]	1	Solid clay unit	2:3
Stylianidis [56]	11	Hollow clay unit	1:3
Suzuki et al. [57]	2	Hollow concrete unit	1:4
Verderame et al. [58]	2	Hollow clay unit	1:2
Waly [59]	2	Hollow clay unit	1:2
Yuksel and Teymur [60]	1	Hollow clay unit	1:2
Zarnic and Tomažević [61]	1	Semisolid clay unit	1:3
Zhai et al. [62]	1	Hollow concrete unit	1:1
Zovkic et al. [63]	3	Hollow clay unit-solid AAC unit	1:2

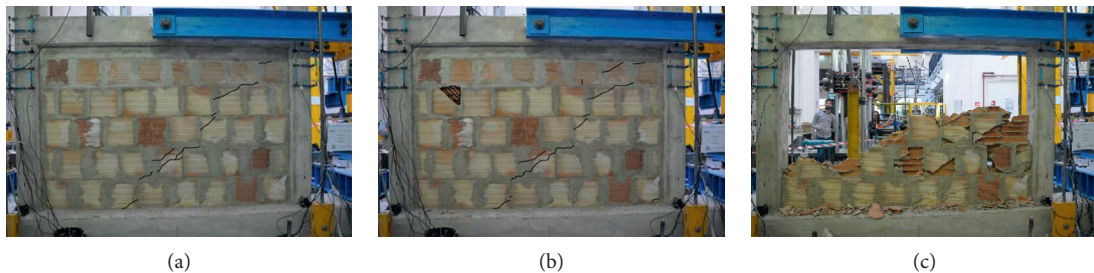


FIGURE 5: Example of damage evolution (adapted form De Risi et al. (2018)). (a) Slight. (b) Moderate. (c) Collapse.

Concerning the lateral response of the infilled frame, the analysed experimental responses for RC frames where the infill is well connected to the frame, under increasing lateral in-plane loading, generally showed an initial detachment of

the infill panel from the frame, until the born of a diagonal compressive stress flow—often reproduced in numerical analyses by means of one single- or multistrut (only resisting to compressive) [70], as better explained in Section 4. A high

initial stiffness until first cracking occurrence is generally observed, depending on the in-plane stiffness (thickness and material) of the infill panel. After the first macrocracking, a subsequent lateral stiffness degradation generally occurred up to the peak load. After the achievement of the maximum in-plane load, a degrading branch can be easily recognized until the residual strength of the frame, when the infill panel is no more able to contribute in terms of strength and stiffness [4]. The in-plane response and particularly the peak load and the subsequent softening branch were found to be dependent on the failure mode of the panel. Additionally, a significant portion of the experimental results indicated that, at least for one-bay one-storey frames under in-plane actions, (i) the presence of the infills can improve the lateral strength, stiffness, ductility, and energy dissipation capacity with respect to bare frames, and (ii) specimens with strong infills can exhibit a higher strength, stiffness, and energy dissipation capacity than those with weak infills [26].

Nevertheless, the estimation of the lateral load of the infill is important to define the shear action produced by the panel on the surrounding structural members. During the in-plane testing on infilled frames, some tests exhibited a shear failure in beams or columns due to their interaction with the infill panel. The analysis of the experimental campaigns revealed that such phenomenon, often observed also after seismic events as described in Section 2, was more likely for specimens with infills relatively strong with respect to the frame [68], as typical when the former is made up of strong concrete blocks or solid clay bricks and the latter is representative of existing low-standard buildings. Unfortunately, very few experimental studies [58, 71] are available from the literature to reproduce the local shear interaction between infill and frame, even less if masonry panels made of hollow clay units (typical of light nonstructural masonry in European and Mediterranean countries) are considered. More experimental tests on these units should be carried out to provide a useful support for a comparison with more or less simplified nonlinear modelling approaches [58], from FEM-based micromodelling to macromodelling, and the choice/proposal of a proper modelling tool.

Additionally, few tests exist in the literature about the study of the in-plane behaviour of infills with openings, taking into account their possible differences in void ratio, aspect ratio, or eccentricity (e.g., [26, 38, 54], among others). As expected, the presence of openings leads to a reduction in infill lateral strength and stiffness and energy dissipation capacity, mainly depending on the opening size [26]. Nevertheless, openings with an opening percentage (i.e., opening area divided by the whole frame area) lower than 40% can improve the lateral strength, stiffness, and energy dissipation capacity under in-plane actions with respect to bare frames [4, 25]. More frequently, the presence of openings is investigated only numerically (e.g., [2], among others), and therefore, additional real data should be provided by further experimental campaigns to be compared with the numerical results.

A higher number of experimental results should be still produced also to investigate about the effect of the level of restraint between the panel and the surrounding frame,

which can be strictly dependent on the construction practice adopted country by country, and which can strongly affect the in-plane response of the whole frame (as recently carried out by [72, 73]). Lastly, quite few tests from the literature studied the in-plane behaviour of infilled frame considering all the above-mentioned critical issues by means of shake table tests (as in [42]; or [74], one of the most recent study). It should be desirable to carry out new and further data from shake table tests to more realistically reproduce the ground shaking for the investigation of the seismic response of infilled frames.

3.2. Out-of-Plane Tests. Over the literature, few testing campaigns can be found where it was carried out the study and characterization of the OOP behaviour of infill panels in steel or RC frames, considering or disregarding their interaction with the IP loading demand [13, 33, 51, 75–86]. Part of these testing campaigns were based on shaking table tests of single IM panels or scaled infilled RC structures [87–94].

Dawe and Seah [76] started in 1989 the study of the OOP seismic behaviour of masonry infill walls surrounded by a steel frame. The authors performed eight full-scale infill panels made with concrete blocks. The loading on the wall was transferred with a system of airbags against a reaction frame, uniformly inflating to impose a displacement history. The objectives were to study the horizontal connections with reinforcement, other with mortar interface of infill frame, the influence of the wall's thickness, openings, among other parameters. Some of the conclusions were as follows: (1) the interface's reinforcement provided higher OOP deformation capacity of the system, (2) interface reinforcement sustained more OOP loading before appearance of the first crack, (3) higher thickness allowed the limitation of OOP arch mechanism, resulting in stronger loadings for collapse, (4) the opening did not reduce significantly the OOP capacity, and (5) the connections with reinforcement are introducing stress concentrations when connectors transmit in-plane loads. This causes premature damage to the infill, which reduces the infill's out-of-plane capacity. Thereafter, Frederiksen [95] tested fifteen scaled infill panels surrounded by steel frames under OOP loading using an airbag. Three types of brick were used in their experiment, and the main objective was to study the effect of infill-to-frame boundary condition by placing different materials in gaps between the infill and the frame at all boundaries instead of mortar. They concluded that the effect of bound type on the OOP strength and cracking pattern is negligible so long as the infill is in tight contact with the bounding frame. Angel et al. [13] performed thirteen full-scale infill walls made with concrete blocks and with brick masonry walls. They tested the combination of IP-OOP loading sequence. The OOP forces were applied with an airbag system following monotonic loading protocol. Some of the conclusions were as follows: (1) the OOP strength was affected by the thickness of the wall and by the compressive strength of the masonry, and (2) IP loading increased the OOP secant stiffness. Calvi and Bolognini [33] performed a set of tests in full-scaled RC frames infilled with

brick masonry. The tests were analysed for monotonic OOP loading after application of cyclic IP loading to introduce prior damage on the walls. The used systems were bare frame, unreinforced infills, horizontally reinforced, and reinforced with meshes. The authors concluded that the OOP behaviour was strongly improved by the reinforcement material.

Later, Lunn and Rizkalla [96] performed an experimental campaign comprising 14 full-scale specimens, four as-built specimens (reference specimens) and 10 strengthened specimens. The main aim of this study was to assess the efficiency of different strengthening strategies to improve the OOP behaviour. Varela-Rivera et al. [97] tested six confined walls made with vertical hollow concrete blocks to assess the effect of the boundary conditions in which the authors found that the panels with four and three supports reached similar maximum strength. Pereira et al. [51] carried out a testing campaign of scaled infill panels subjected to uniform OOP loadings applied by airbags to assess the effect of plaster and bed joint reinforcement. From the results, the authors concluded that the bed joint reinforcement provided higher strength and deformation capacity to the panel; however, it is not relevant when subjected to IP loading demands. Guidi et al. [98] developed an experimental campaign comprised of six panels with different thicknesses (large and thick) and tested with textile-reinforced mortar technique to assess the improvement of the OOP behaviour. Hak et al. [82] studied the OOP behaviour of strong infill panels in the context of the modern construction in the southern European countries. da Porto et al. [83] tested the efficiency of strengthening mortars to improve the seismic behaviour of infill panels subjected to IP and OOP loading sequence. Moreno-Herrera et al. [99] tested the influence of the masonry unit and aspect ratio on the OOP capacity of confined infill walls, from which it was concluded that (1) the maximum OOP displacements were larger for walls built with solid bricks; (2) the OOP strength depends highly on the masonry compressive strength; and (3) the OOP capacity decreases with the increase of the panel aspect ratio.

Recently, Akhoundi et al. [100] tested three scaled infill panels made with hollow clay horizontal bricks to study the effect of the workmanship and the effect of a central opening (window). From the results, the authors pointed out a variation of about 30% related to the workmanship and a reduction of the panel OOP strength and deformation capacity due to the opening.

Furtado et al. [84] studied the effect of the gravity load and the previous damage due to prior IP test and concluded that the gravity load modifies the cracking pattern and the previous damage (0.5% IP drift) reduced the OOP strength capacity of about 70% and the panel behaved as a rigid body. Later, the authors [101] studied the effect of the panel width support condition in which it was observed a reduction of the panel OOP strength capacity of about 60%.

Di Domenico et al. [14] carried out an experimental campaign comprised of three infill panels made with hollow clay bricks, with the same geometrical properties, construction materials, and workmanship. The major goal was to assess the effect of adopting different boundary conditions

to the confining RC frames; namely, it was tested a panel bounded along all edges to the surrounding frame (specimen OOP_4E), a panel detached from the confining frame at the upper edge (specimen OOP_3E), and a panel bounded to the confining frame only along the upper and lower edges (specimen OOP_2E). The authors concluded that the panel OOP_2E exhibited brittle failure and the remaining ones some displacement capacity for arching mechanism. Concerning the maximum strength, the panel with all edges bounded (OOP_4E) reached 1.6 times higher strength and the specimen OOP_3E reached 1.3 times higher strength than the value obtained by the panel OOP_2E.

Ricci et al. [12] performed OOP tests in scaled infill panels previously damaged due to quasistatic IP tests. Three different levels of prior IP drift were adopted, namely, 0.16% (IP + OOP_L), 0.37% (IP + OOP_M), and 0.58% (IP + OOP_H). Additionally, the results were compared with the one reference specimen OOP_4E (with no prior damage) that was tested by Di Domenico et al. [14] and described in the previous paragraph. The authors concluded that all the specimens reached an almost bilinear response behaviour with a pseudolinear response up to peak load and a softening branch after the maximum load. As expected, the specimens with medium-high in-plane damage exhibited lower strength capacity and lower stiffness. In fact, larger IP drift demands caused higher reduction of the panel OOP capacity.

Later, Ricci et al. [102] investigated the influence of the panel slenderness ratio and of the in-plane/out-of-plane interaction on the out-of-plane strength. To this aim, the authors tested three specimens with the slenderness ratio of 22.9 and compared with the results obtained by panels with the lower slenderness ratio of 15.2, tested in a previous testing campaign [12, 14]. From the results, the panels with the slenderness ratio of 22.9 reached larger peak loads (twice the results of the panels with slenderness ratio of 15.2). This result indicates that panels with larger slenderness ratio potentiate the development of arching mechanism, which can increase the panel OOP strength capacity. However, further experimental investigations must be developed to reinforce the conclusions and results obtained in this testing campaign. Finally, it was again observed the reduction of the OOP strength capacity with larger IP drift demands.

Lastly, De Risi et al. [71] carried out an experimental campaign on square infill walls in RC frames to investigate about the OOP behaviour of the masonry infills and about the IP/OOP interaction. Overall, four specimens were tested under OOP monotonic load. Three of them were firstly damaged due to cyclic IP actions, with different levels of demand. The remaining one was only subjected to OOP loading and thus was considered as reference specimen. The main purpose of the testing campaign was to assess the influence of the infill panel aspect ratio on the IP/OOP interaction through the comparison between the tests performed in this campaign and tests performed in the campaigns carried out by Ricci [12, 14] with nominally identical infills except that for the aspect ratio of the specimens. The authors concluded that, from the comparison between the square panels and the rectangular ones, it was observed that,

at roughly same drift demand, square and rectangular infills exhibit very different damage states, namely, the rectangular specimens reached higher levels of damage than the square ones. Obviously, at the same time, it was observed that, for the same IP drift, the square panels exhibited a strength reduction of 24% while the rectangular panel exhibited larger degradation of about 58%. A complete list of these campaigns can be found in Table 2 containing the variables under study, number of tests, loading approach, and masonry unit.

Recently, Butenweg et al. [103] carried out an experimental campaign of combined IP-OOP tests in full-scale RC frames filled with high thermal insulating clay brick. The main novelty of this experimental investigation is the simultaneous application of the IP and OOP loadings. From the testing campaign, the authors pointed out that boundary condition in the connection area between the infill panel and the frame is a crucial point for earthquake damage of the infill walls.

3.3. Retrofit and Strengthening Techniques. The retrofit and improvement of infill walls seismic behaviour is a complex subject, since it cannot be disconnected from their effect on the overall building response. It is paramount to take this coupled behaviour into consideration. In this context, two main approaches can be considered, as described below: (i) disconnection of infills from the structural system and (ii) effective integration in the superstructure and strengthening of the panel.

3.3.1. Disconnection of the Panel from the Structural System. Concerning this first assumption, three different strategies can be adopted: the use of sliding devices, energy dissipation devices, and assuming a disconnection using gap. From the literature, it is possible to find out that some authors tested the use of sliding devices to reach a good seismic performance of the panel. For example, Mohammadi et al. [104] carried out an experimental campaign to achieve engineered infilled frames in two stages. One of the techniques used on Stage 1 was the use of an infill “fuse,” in which some sliding layers were provided in the infill. In these techniques, some elements such as small parts of the columns or horizontal layers in infills (called “fuses”) are supposed to yield or slide before infill cracking. Two 2/3 scaled, 3 m-long and 2 m-high single-story single-bay infilled steel frames having an IPE-140 standard shape were tested under cyclic lateral in-plane loading. The specimens were used to check the efficiency of the mentioned technique in increasing ductility. The authors found in a previous experimental work that multilayer infill panels, composed of layers of masonry and concrete materials, are acceptable to be used in engineered infilled frames, as they have a better ductility in comparison with the single-layer ones, and their strength can be adjusted by changing the layer thickness and material [105]. The author concluded that supplying the infills with sliding fuses had the following advantages: (1) increasing the deformation capacity and consequently the ductility of the infilled frame; (2) avoid necking in cyclic load-displacement behaviour for

nonfused specimens; (3) preventing the panel from the occurrence of damage/cracking during seismic actions; and (4) high efficiency of the sliding fuse in increasing ductility of the infilled frames. Despite the advantages of the sliding fuse, simple configuration of the applied sliding fuse had two main shortcomings: (1) increasing the vulnerability of shear failure in some column zones and (2) creating a potential surface for OOP movement of the wall in the fuse area.

Two further testing campaigns were performed by Preti et al. [106] focused on the development of a similar engineered solution with sliding joints to reduce the infill-frame interaction and ensure OOP stability. The authors validated the potential of horizontal partition joints (embedded in few masonry mortar beds and acting as sliding joints) to ensure a ductile mechanism for the infill under IP loading; during the tests, it was prevented the development of the typical diagonal strut mechanism. Two additional works developed by Morandi et al. [107] and Verlatto et al. [108] can be found in the literature.

Some authors proposed solutions composed of energy dissipation devices that consist of the disconnection between the panel and the frame structure. Goodno et al. [109] proposed design criteria formulated in terms of energy, which provide optimal balance of stiffness and energy dissipation to the structure through appropriate cladding connection. Aliaari and Memari [110] tested a seismic IM wall isolator from the main envelope structure (SIWIS). The solution consisted in using subframes to be attached to the structural frame, and the infill wall then was constructed within the subframe. The OOP stability of the panel was provided through the top subframe member. The authors stated that the location of SIWIS elements showed that due to the fact of being located at the top of the wall, the frame will first contact the panel at that point under lateral drift and will tend to close the gap if there were no SIWIS elements. Later, Aliaari and Memari [111] carried out an IP test of a two-bay three-story steel frame with three different configurations: (i) bare frame, (ii) infilled braced frame, and (iii) pinned frame equipped with the proposed SIWIS device. The authors also tested a series of components on three different designs for the fuse element. From the tests, the authors pointed out that the response of the frame with SIWIS elements was significantly affected by the stiffness and strength properties of the SIWIS elements.

Finally, seismically active countries such as New Zealand, Japan, and some states in the USA adopted the practice of separating the infill walls from their frames by including a gap. This strategy was based on the poor seismic performance of the infill panels in past events. Additionally, the seismic design codes required that nonstructural elements are not damaged during earthquakes with low magnitude and do not affect the structural performance of the main structure in events with large magnitude. Due to that, the separation between the panel and the frame became the most common practice [112]. Separation gaps allow the frame to deflect freely without mobilizing the wall. However, this approach can result in serious consequences when the panel is subjected to some OOP loadings. Some approaches have been presented by different authors aiming to be effective for both IP and OOP loadings [107, 108, 113, 114].

TABLE 2: Literature review of OOP experimental tests of masonry infill walls.

Author	Number of tests	Loading approach	Masonry unit	Variables under study
Dawe and Seah [76]	8	Airbags	VHCB	Horizontal connections with reinforcement Slenderness Openings Boundary conditions
Frederiksen [95]	15	Airbags	HCHB SCB	Boundary conditions
Angel et al. [13]	13	Airbags	HCHB VHCB	Masonry unit IP + OOP IP + OOP
Calvi and Bolognini [33]	9	Airbags	HCHB	Bed joint reinforcement Meshes
Lunn and Rizkalla [96]	14	Airbags	CSB	Strengthening strategies
Varela-Rivera et al. [97]	6	Airbags	VHCB	Boundary condition
Pereira et al. [51]	7	Airbags	HCHB	Bed joint reinforcement Plaster
Guidi et al. [98]	6	4 points load	HCHB	Slenderness Strengthening strategies
Hak et al. [82]	5	4 points load	VCHB	Strong infills
da Porto et al. [83]	8	4 points load	HCHB VHCB	Strengthening mortars
Moreno-Herrera et al. [99]	8	Airbags	SCB VCHB	Masonry unit Aspect ratio
Akhoundi et al. [100]	3	Airbags	HCHB	Workmanship Opening
Furtado et al. [84]	3	Airbags	HCHB	Gravity load IP-OOP
Furtado et al. [101]	2	Airbags	HCHB	Panel width support Gravity load
Di Domenico et al. [14]	3	4 points load	HCHB	Boundary conditions
Ricci et al. [12]	3	4 points load	HCHB	IP-OOP
Ricci et al. [102]	3	4 points load	HCHB	IP-OOP Slenderness
De Risi et al. [71]	4	4 points load	HCHB	Aspect ratio
Butenweg et al. [103]	4	Airbag	VHCB	IP-OOP

VHCB: vertical hollow concrete block; SB: solid brick; CSB: concrete solid brick; HCHB: hollow clay horizontal brick.

3.3.2. Effective Strengthening of the Panel. The integration of the infill panels on the substructure and respective behaviour improvement and reduction of the OOP vulnerability can be achieved by using different strengthening techniques such as fiber-reinforced polymers (FRP) [115], engineered cementitious composites (ECC) [116], textile-reinforced mortars (TRM) [33], and bed joint reinforcement [33].

The knowledge and techniques to improve the way infilled RC buildings respond to earthquakes have been the object of several studies and tests. However, in parallel to these advances in the last years, and due to the concerns with thermal comfort, new bricks and new techniques have also been developed for buildings' façade walls with the main goal of reducing the cooling and heating losses. As a result of the innovation, new types of masonry units and construction technologies have been developed, being pushed by the market competition. The masonry industry improved the thermal properties of masonry units and developed new, faster, and cheaper technologies of construction [117]. The use of external thermal insulation composite systems (ETICS) is now common in the external walls with energy saving purposes. Distinct types of ties, generally from steel or

plastic and having different shapes and geometry (very dependent on the wall system), are usually adopted [118]. However, it cannot be found over the literature any study regarding the effect of the ETICS in the infilled RC frame seismic performance.

Backing to the FRP technique, Carney and Myers [119] tested two series of IM walls made with concrete blocks to be subjected to OOP loadings. A total of twelve walls with different strengthening schemes using FRP composite materials were tested. Two FRP strengthening techniques were adopted with anchorages for both techniques. The first method was composed by the application of externally bonded glass FRP laminates. This strategy includes a primer and a glass fiber sheet to form the composite material. The authors stated that glass fiber sheets are more economical and provide more compatible strength than the carbon fibers. The second method consisted in the application of near-surface-mounted (NSM) glass FRP rods. These rods were attached to the wall using an epoxy-based grout. The specimens strengthened with anchorage produced a system capable of carrying a load of approximately twice that of the reference one. Later, Hamid et al. [120] carried out an

experimental investigation to study the IP behaviour of face shell mortar bedded IM wall assemblages retrofitted with FRP laminates. Tests including specimens loaded in compression with different bed joint orientations, diagonal tension specimens, and specimens loaded under joint shear were carried out. The FRP laminate was selected according to an equivalent-stiffness-based approach, from which the laminate required was equated to the minimum steel reinforcement ratio of 0.2% (based on the gross cross-sectional area of the panel) according to the requirement of the Masonry Standards Joint Committee [121]. Lastly, Lunn and Rizkalla [96] carried out an extensive experimental campaign composed by 14 full-scale infilled RC frame specimens, which included four unstrengthened specimens and 10 strengthened specimens. Solid clay bricks were used to build the IM wall specimens. The strengthened specimens were reinforced with externally bonded glass fiber-reinforced polymer sheets applied in the exterior tension face of the external leaf of the panel. Different coverage ratios were adopted by the authors considering only unidirectional (vertical or horizontal) directions. Three different anchorage systems were used. From the testing campaign, the authors concluded that the externally bonded solution was effective if proper anchorage of the FRP laminate is guaranteed. Overlapping the FRP reinforcement onto the RC frame revealed to be very effective for double-wythe specimens, but less for single-wythe specimens. This strengthening technique requires the following steps to be applied: (1) application of primer; (2) smoothing of the surface with a layer of putty; (3) application of a first layer of epoxy resin; (4) positioning of the fibers; and (5) use of a small paint roller (FRP) to press the strip or a palette-knife (SRP), to allow proper impregnation of strands.

Moving to the ECC technique, in 2015, Kesner and Billington [122] studied the application of ductile fiber-reinforced mortar material referred to as engineered cementitious composites. The study was about the use of ECC to retrofit precast panels in lieu of a traditional reinforced concrete or masonry. From the testing campaign, it was observed that different levels of strength and stiffness increment can be achieved by varying the mix design of the ECC material and the amount of reinforcement in the panels. Kyriakides and Billington [44] studied the impact of a thin layer of ECC in IM wallets, made with solid clay bricks, subjected to flexure strength tests. The variables studied were the use of wall anchors to improve the ECC-masonry bond and alternate steel reinforcement ratios within the ECC layer in the form of welded wire fabric. From the tests, it was observed that the ECC retrofit increased the strength and stiffness by 45 and 53%, respectively. Billington et al. [123] proposed a thin layer of sprayable ECC applicable to retrofit an infilled RC frame subjected to IP loadings. From the 2/3-scale tests, the authors concluded that the ECC enhanced the performance of the infill walls in terms of both strength and deformation capacity. The authors also pointed out that the retrofit details need special attention to bond the ECC layer to the infill panel and to connect the ECC to the frame. Barros [124] carried out a testing campaign of

masonry wallets subjected to flexural strength tests parallel and perpendicular to the bed joints using hollow clay horizontal bricks. The objective of the experimental campaign was to assess the efficiency of the ECC strengthening technique to improve the OOP capacity and to evaluate the effect of different ECC thicknesses. For that, 30 specimens were built with geometric dimensions 600×600 mm made with 150 mm thick hollow clay horizontal bricks. For each type of tests were tested 5 as-built specimens (Group R), 5 retrofitted with 10 mm ECC thick (Group A), and 5 retrofitted with 20 mm ECC thick (Group B). From the flexural tests parallel to the horizontal bed joints, it was observed that the failure mode of the as-built specimens (Figure 6(a)) was characterized by the detachment of the first row of bricks from the adjacent row which according to the author was controlled by the mortar-brick adhesion. Regarding the retrofitted specimens, similar damages were observed in both groups, shear failure occurred most of the times due to the geometry of the panel (small distance between the OOP loading application and OOP restrains), and the remaining failures were characterized by the crushing of the bricks combined with one or two major horizontal cracks. It was observed that Group A and Group B specimens reached an average flexural strength of 0.43 MPa and 0.46 MPa, respectively. Therefore, it can be concluded that the double thickness of the ECC layer did not provide any significant effect in terms of strength (increase of around 6%). The authors pointed out that, due to the fragility of this type of masonry units, the ECC layer was too strong and the damages concentrated in the masonry. Regarding the comparison between the as-built specimens and the retrofitted ones, it was obtained an increase of the flexural strength of about 5.38 times and 5.75 times for the Group A and Group B specimens, respectively. The authors compared also the OOP displacement corresponding to the occurrence of the maximum OOP loading ($d_{f,oop,max}$). The $d_{f,oop,max}$ of the Group A and Group B specimens was around 1.86 times and 2.04 times higher than that of the as-built specimens. The double thickness of the Group B specimens contributed for a $d_{f,oop,max}$ 9% larger.

Finally, some studies were performed to study the efficiency of using textile-reinforced mortars (TRMs) to improve the OOP seismic behaviour of infill panels. Since 1980, the use of textile-reinforced mortar technique (TRM) started to be adopted. The most basic application is the fiber-reinforced mortar, which consists in a mixture of mortar with a percentage of fibers randomly distributed within its composition. It is generally used as shotcrete, which became widespread for tunnel reinforcements. Some of the factors that affect the effectiveness of this solution are fiber slenderness and length as well as the size of aggregates in the mortar matrix since they define the bonding properties and thus the capacity to behave as a composite [125]. More complex solutions using the same kind of material imply defining a direction for the reinforcement, according to the material requirements of the design of the structure; in this way, the fibers can develop their maximum capacity. The constructive solutions are unidirectional and bidirectional reinforcement meshes.

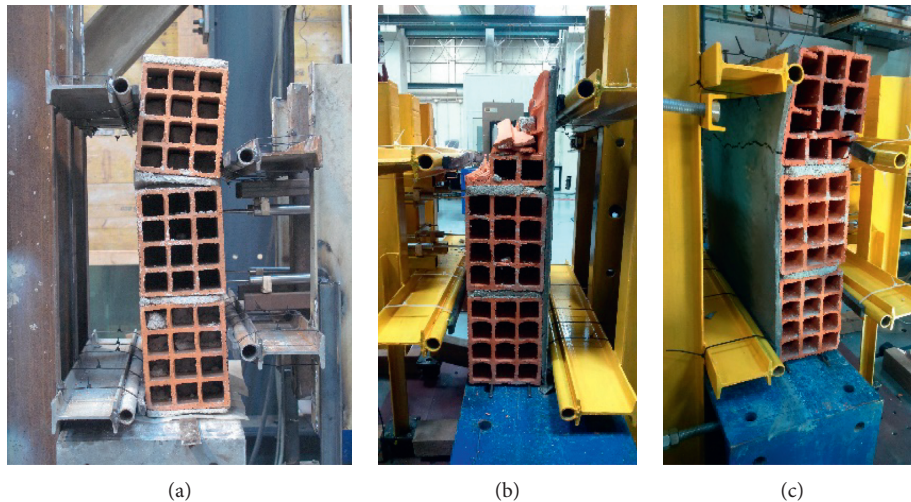


FIGURE 6: Test results obtained by Barros [124]: damages observed after the flexural strength tests parallel to the horizontal bed joints. (a) As-built specimens, (b) Group A, and (c) Group B.

The first investigations were related to the tensile properties of fiber-reinforced mortar and its application to retrofit RC structures that made it suitable for reinforcing beams (for both bending and shear) or jacketing and confining columns. The application as a method of retrofitting IM walls is a relatively new concept still under investigation, with many parameters still to be defined. Among the parameters that affect the performance of the reinforcement, there are some remarkable ones, namely: (1) density of the mesh, depending on quantity of fibers in each thread (defined by mass of textile-reinforced mortar) and the separation among them; and (2) mortar and textile surfaces properties, affecting the bond between the element and the reinforcement. Calvi and Bolognini [33] tested two different retrofit strategies, namely, bed joints steel reinforcement and external steel reinforcement combined with bed joint reinforcement. The external reinforcement was composed by mortar layer reinforcement. The design methodology was not provided by the authors. From the testing campaign, the authors observed that the presence of little reinforcement improved significantly the panel response, namely, by increasing the deformation capacity and by modifying the damage limit states for higher drift levels. Guidi et al. [98] carried out combined IP-OOP tests with the aim of characterizing the OOP behaviour of IM walls made with different types of masonry units, with and without reinforcement. Two specimens were unreinforced, and other two were made of reinforced masonry, having both horizontal and vertical bed joint reinforcement. The remaining two specimens were built with thin (120 mm) clay units with plaster layer, one of them was strengthened by means of a special quadriaxial net made with hybrid glass fibers that was casted in an extra fiber-reinforced plaster layer. From the test results, it was observed that the thick masonry systems tested (both reinforced and unreinforced) presented higher OOP strength, due to the development of an arch mechanism, even for higher values of previous IP drift. The thinner specimens, even when

strengthened, developed bending OOP failure that somehow limited the panel strength. The OOP strength of reinforced infill walls was higher than that of unreinforced walls, for higher IP prior drift. Strength decreased due to the increase of in-plane drift (or damage) was smaller in reinforced masonry (-6%) than in unreinforced masonry (-23%). Lastly, Koutas et al. [126] studied the development and performance of new textile-based anchors used to transfer tensile forces in models made of IM wallets and reinforced concrete prisms, to simulate the connection between infill walls and RC frames using TRM. None of these strengthening techniques has been tested under simultaneous IP-OOP loadings.

4. Numerical Modelling Approaches to Study the Seismic Behaviour of Masonry Infill Walls

In recent years, the study of the influence of infill panels on the seismic response of existing buildings has been deeply investigated. The contribution of the IM walls to the building's seismic performance can be favorable or not, depending on a series of phenomena, detailing aspects, and mechanical properties, such as the relative stiffness and strength between the frames and the masonry walls, and the type of connection between masonry and structures [5–8, 127–129].

For the assessment of infilled RC frame structures, the nonlinear behaviour induced by earthquakes should be considered [3, 70, 130, 131]. Different techniques are available in the literature to simulate the response of infilled frames, from refined micromodels to simplified macromodels [3, 131]. For the nonlinear analysis of complex structures when subjected to earthquakes, in many cases, it is not suitable to adopt refined models. Thus, for the simulation of the response of infilled frame structures, considering the IM walls and their interaction with the surrounding frame elements, the adoption of simplified models is unavoidable.

Different approaches are available in the literature to simulate the infill panels' seismic behaviour, which can be divided into two different groups, namely, micromodelling and simplified macromodelling approaches. The first of them involves models in which the panel is discretized into numerous elements to consider the local effects in detail, and the second includes simplified models based on a physical understanding of the behaviour of the infill panels. In the case of the last group, a small number of struts are used to represent the effect of the infill panels on the structural response of buildings when subjected to lateral loadings.

This section presents a review of the numerical modelling strategies to simulate the seismic behaviour of masonry infill walls. Comparison and discussion among the modelling strategies will be presented.

4.1. Detailed Micromodelling Approaches. The micromodelling is a refined/detailed strategy in which all the elements composing the wall are modelled, masonry units, mortar joints as volumetric elements, and boundary link models simulating the contact and friction conditions between the individual elements and frame. A simplified approach within the micromodelling may consist in reducing the number of elements by combining a brick with the surrounding mortar, which is connected to the rest by link models. These approaches are expensive both on the modelling phase and on computational demands, especially when applied to dynamic and nonlinear analysis. The detailed modelling allows obtaining results that help to understand the behaviour at local level and the panel cracking pattern, which can be very useful for calibration of global models and to perform parametric studies. This is an important advantage of the micromodels when compared with the simplified macromodels. This modelling procedure allows to assess and quantify the influence of each parameter on the seismic response of the infill panel [131].

From the literature, it can be observed that micromodelling was started in 1967 with the work carried out by Mallick and Severn [132], concerning the simulation of the IP behaviour of an infilled RC frame, with particular focus in the frame-panel interface. The authors' strategy was to model the wall by rectangular elastic elements with two degrees of freedom per node. The frame-wall interaction was provided by the consideration of frictional shear forces to simulate slippage.

A different approach was proposed by different authors such as Rots [133], Lofti and Shing [134], and Lourenço [135] with the introduction of the continuous-interface models' concept, which basically can be applied to bed joints by accounting for the interaction between the tangential and normal stress. Lourenço [135] proposed a model in which the Coulomb friction rule, tension cutoff, and compression strength are combined. From this, the obtained damages are concentrated in the IM wall bed joints and in the middle of the masonry units. One of the simplifications proposed is to simulate the IM panel as a three-phase material in which the units/mortar and their interfaces are modelled as continuous and discontinuous elements, respectively. For this purpose,

the assumption made by the author was to use a simplified modelling for two-phase material, where the units are simulated by continuous elements, but the mortar and interfaces were lumped to discontinuous elements.

Finally, a more simplified approach was proposed by assuming one-phase materials, in which units, mortars, and interfaces are combined into a continuum and homogeneous element. Chen and Liu [136] developed a finite element model to simulate the IP behaviour of concrete masonry infills bounded by steel frames with openings. The authors proved that the model had the capability of simulating the experimental tests with high accuracy. Mohyeddin et al. [137] developed a generic three-dimensional discrete-finite-element model that has been constructed for infilled RC frames using a commercial software to assess the in-plane and out-of-plane behaviour interaction. From the results, the authors found some differences between the behaviour predicted by the finite element model and the experimental results. The reasons behind these differences were justified by the authors as the combination of large coefficients of variation of masonry material properties and existence of weaker areas within the infill panel which were attributed to workmanship and that cannot be modelled.

Several other studies and efforts were carried out by other authors [68, 138–148]. Asteris et al. [131] present an extensive and in-depth state-of-the-art review concerning the infill masonry micromodelling approaches.

4.2. Simplified Macromodelling Approaches. The macromodelling with equivalent diagonal struts was originally developed to capacitate numerical analysis models of infilled frames with high shear stiffness. From its evolution with multistrut models, it was possible to integrate shear and tensile stresses within the contact length between wall and frame. Models have started to become more complex, with some considering the reduction of stiffness and strength under dynamic loads, or other equivalent approaches to consider the shear slip at the middle of the infill walls. One of the aspects yet to be developed is the OOP behaviour itself, an even more important issue when combined with the diagonal cracking created by IP demands on the masonry infill walls.

First, Polyakov [149] in 1956 proposed an equivalent strut model to simulate the IM wall behaviour. The proposal was based on experimental observation studies on steel frames with focus on normal and shear stresses on the infill walls, in which it was found that the stresses were only transferred by the compression corners of infill-frame interfaces from the structure to the nonstructural elements. From that work, the authors developed a numerical technique to estimate the load intensity to create diagonal cracking. Holmes [150] improved the previous concept, being the first author to propose a formulation for the diagonal strut. The proposed formula to calculate the equivalent strut width is a simplified approach, calibrated for steel frames with brickwork and concrete infill walls. It triggered several other studies to define the width more accurately. This simplified model considered deformation and ultimate strength of the global infill panel.

From these innovative works, successive authors have proposed improvements for the calculation method and a series of other modelling refinements, replacing the infill walls with additional diagonal struts. For example, El-Dakhakhni et al. [151] proposed a model with three diagonal struts on each direction, one in the diagonal of the panel and the other two nonparallel in off-diagonal. According to the researchers, it was better suited to compute the wall stiffness and describe the development of stresses along the frame elements when compared to other models with less diagonal struts. The frame was modelled with elastic elements with the nonlinearity lumped on the frame joints with springs. This simplified nonlinear model was capable of computing the frame-infill interaction and corner crushing failure mechanism.

Later, Crisafulli and Carr [152] proposed an improved strut model to compute the behaviour of infilled frame systems. For that, it was presented an integration of struts and spring to computing independently two phenomena: (i) diagonal cracking and corner crushing and (ii) shear sliding. The model considers six strut members using hysteresis rules. It consists in two diagonal and parallel struts in each direction, which carry the axial loads on the panel, and another pair to describe shear from the top and bottom of the panel, which are activated in each direction, depending on the activation due to axial compressive loads while the panel is deformed.

Crisafulli [153] compared different one-strut, double-strut, and triple-strut models, concluding that the double-strut model was the most balanced of the strategies, achieving accurate results without too much complexity in terms of calibration and computational efforts. According to the authors, the model finds its limitation on the connection to beam-column joints that avoids accurate development of bending moments and shear forces on the structural elements.

Recently, some advances have emerged regarding the strut models capable of simulating the combined IP and OOP behaviour. Kadyśiewski and Mosalam [154] proposed a model capable of simulating both in-plane and out-of-plane behaviour of the infill walls, with a single diagonal beam-column element with a node at the midspan having a concentrated mass to trigger the OOP inertia forces. A new macroelement model was also proposed by Trapani et al. [155] for the simulation of the IP-OOP response of infilled frames subjected to seismic actions. The model consists of two diagonals plus one horizontal and one vertical struts. Each strut is represented by two fiber-section modelling beam-column elements. The model can capture the arching action of the wall under an OOP load as well as the interaction between the IP and OOP actions.

5. Conclusions and Open Issues

This manuscript aims at presenting an overview regarding the seismic performance of infilled RC structures and with focus on the infill wall damages. A brief revision of the most common damages observed in this type of structures in the last major earthquakes was presented. From that, eleven

typologies of damages were defined concerning the infilled RC structures. From this revision, the main conclusions that can be achieved are that in the assessment of existing buildings and in the design of new buildings:

- Consideration of the masonry infill walls in the structural design (based on simple checking rules/procedures after the structural design) should be enforced

- Attention should be given to the stiffness differences between the 1st storey and the upper storeys (storey height, dimensions and position of openings, and distribution of masonry infill walls)

- Appropriate strengthening of the panel to the OOP loadings should be designed, with adequate connection of the reinforcement material to the RC elements

A state-of-the-art review concerning the testing of infilled RC structures was provided where the major aspects of each testing campaign were discussed. The analysed campaigns have investigated the influence of the infill panel on the lateral response of the whole frame, depending on the brick typology, on the infill-to-frame relative stiffness and strength, and on the presence of openings with different opening ratios and eccentricities, among other investigated parameters. The experimentally observed failure mode has been different depending on the main geometrical and mechanical features of infills and frames. Experimental results indicated that, under in-plane actions, (i) specimens with strong infills can exhibit a better performance than those with weak infills in terms of the observed lateral strength, stiffness, ductility, and energy dissipation capacity; (ii) the presence of the infills—even with openings—can improve the in-plane performance of RC frames; and (iii) a great attention should be paid to the shear load acting on RC members due to their interaction with the infill panel, especially if the infill is strong and the frame is nonconforming to the most updated seismic codes.

The out-of-plane tests of masonry infill walls available in the literature are still scarce, and the large number of variables such as the specimen geometries, masonry unit, loading protocol, among others, makes very difficult to achieve further and more robust conclusions and, thus, makes a step forward towards the reduction of the collapse risk for these panels. From those tests, it can be pointed out that the effect of previous damage caused by prior IP drift demand can highly reduce the OOP strength capacity of the infills and lead to fragile collapses due to the reduction of the probability of arch mechanism development. The slenderness and the reduction of the panel width support reduce the panel OOP capacity as well as the aspect ratio. An open issue is the testing of infill panels with openings (such as doors or windows) which represent mode adequately the buildings facades. The IP + OOP combination requires also higher efforts to reinforce the conclusions achieved until the present. The realization of tests with multiple loadings (IP and OOP) at the same time is one of the open issues for future research studies.

Regarding the strengthening of infill walls, two different approaches, which are commonly adopted in research

studies, have been presented. Looking for the sustainable solutions regarding the strengthening strategies is still an open issue as well as the development of guidelines to the design and application of these strategies. To this aim, many studies and experimental tests are needed, which allow assessing the efficiency of the techniques under both IP loadings and OOP loadings. Special attention should be provided to the connection of the reinforcement material to the surrounding frame. Without proper design and detailing, the retrofiting of the infill panels could result in an inadequate performance when subjected to earthquakes until the collapse.

Finally, simplified macromodels can be used and implemented by structural engineers nowadays with lower computational effort and easy implementation methodologies. Strut-based models with the capability of simulating the infills out-of-plane behaviour need further calibration based on experimental data. However, from the state-of-art review, there is a lack of enough results that covered the innumerable number of variables that are related to these nonstructural elements, which currently produce also the lack of proper code provisions to help practitioners in the design and assessment of infilled RC structures. This gap should be urgently filled.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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