Numerical investigation of the displacement incompatibility between masonry infill walls and surrounding reinforced concrete frames

Livio Pedone[1], **Stefano Pampanin**[1]

[1] Department of Structural and Geotechnical Engineering, Sapienza University of Rome
Via Eudossiana 18, 00184, Rome, Italy
{livio.pedone, stefano.pampanin }@uniroma1.it

Abstract. In the European building practice, masonry infill panels have been widely adopted as facade elements in Reinforced Concrete (RC) frames in order to provide architectural needs such as thermal and acoustic insulation. During seismic shakings, infill wall panels and the surrounding RC frame have a strong interaction, potentially leading to local brittle failures of both structural and non-structural elements or even to global collapse mechanisms (e.g., soft-story mechanism). In the past years, a significant research effort has been dedicated at the international level to better understand the seismic performance of infilled RC frame structures as well as to develop suitable and practical design/retrofit techniques to reduce the negative effects of infill-frame interaction. However, past numerical and experimental investigations mainly focused on the diagonal compression strut mechanism and associated stress path. On the other hand, a procedure to assess the local infill-frame displacement incompatibility (i.e., detachment due to the relative deformation mechanism) in terms of shape and values is still missing in the literature. Therefore, this paper investigates and discusses the seismic displacement incompatibility between infill walls and the RC frame structure as well as the key parameters affecting the infill-frame detachment. Specifically, the concept of shape functions is introduced and proposed to assess the seismic infill-frame displacement incompatibility, in line with and extending the state-of-the-art investigations on the relative deformation mechanism between seismic-resisting frames and precast flooring units. The proposed methodology can support a displacement-compatible design check of specific connection solutions, in the form of either shear keys and/or steel dowels, as part of either strengthening or decoupling seismic retrofit strategies, as well as of energy rehabilitation solutions, such as external thermal insulation systems, in order to protect these components during earthquakes.

Keywords: Infilled Frame Structures, Infill Walls, Displacement Incompatibility, Shape Functions, Reinforced Concrete Buildings.

1.INTRODUCTION

In the recent past, growing attention has been dedicated to enhance the overall performance of existing buildings, in order to meet recent structural/safety and sustainability requirements at the international level, e.g., Directive (EU) 2018/844 [2018]. In fact, recent catastrophic earthquakes have further highlighted the high seismic vulnerability of existing buildings, often designed for gravity loads only according to pre-seismic-code provisions. Moreover, the built environment is responsible for 36 % of global final energy end-use and 37 % of energy-related carbon dioxide emissions [IEA, 2021].

Focusing on Reinforced Concrete (RC) frame structures with masonry infills, which represent a large part of the European building practice, the overall performance of the facade "non-structural" elements plays a fundamental role in the seismic safety evaluation as well as in the energy consumption of buildings. Although masonry infill panels are typically designed to only provide other-than-structural functions such as thermal and acoustic insulation, it is well known that they have a strong interaction with the surrounding frame during an earthquake, potentially leading to local shear failures (Figure 1, left) or global failure mechanism (e.g., soft-storey mechanism) [Magenes and Pampanin, 2004]. Moreover, it is evident that earthquake damage to "non-structural" infilled facade elements can lead to loss of performance in case of recently implemented energy retrofit solutions such as External Thermal Insulation Composite System (ETICS), even for low-intensity seismic events (Figure 1, right). Therefore, recent works have pointed out that energy and seismic retrofitting should rather be designed and implemented through an integrated multi-performance approach [Calvi *et al.*, 2016; Marini *et al.*, 2017; Buornas, 2018; Di Vece and Pampanin, 2019].

Figure 1. (left) Shear failure of column (Bonefro, Molise 2002; Magenese and Pampanin [2004]); (right) damage to masonry infill panels and external thermal insulation after the Amatrice 2016 earthquake [Santarsiero *et al.,* 2016].

In the past years, the seismic behaviour of infilled RC frame structures has been widely investigated and significant research efforts have been dedicated to study and develop suitable and practical design/retrofit strategies and techniques to reduce the negative effects of infill-frame seismic interaction, based on either decoupling [Tasligedik and Pampanin, 2017; Morandi *et al.,* 2018b] or strengthening [Bournas, 2018; Facconi and Minelli, 2020] approaches. Both decoupling and strengthening retrofit techniques typically require specific construction details such as shear keys or steel dowels to prevent the out-of-plane collapse of infill (in the case of decoupling solutions) or realize an effective connection between the masonry panel and frame in strengthening solutions. It is worth noting that the seismic displacement incompatibility between masonry infill wall and surrounding frames (i.e., the well-known partial detachment between infill panels and the surrounding frame that occurs at the diagonally opposite corners during the seismic shaking) may affect the performance of these structural details (i.e., shear anchors and steel dowels), potentially leading to damage to facade components or results themselves damaged. Moreover, following an energy retrofit intervention comprising for example the use of external thermic insulation systems, the infill-frame displacement incompatibility can lead to damage to the insulation panels since the insulation materials (e.g., expanded polystyrene EPS) can exhibit a brittle failure when subjected to tensile stresses [Tang *et al.*, 2019]. However, past research efforts mainly focused on the diagonal compression strut load path and contact zones; on the other hand, a procedure to assess the local infill-frame displacement incompatibility (i.e., detachment due to the relative deformation mechanism) in terms of shape and values is still missing in the literature.

Therefore, this paper investigates and discusses the seismic displacement incompatibility between masonry infill panels and surrounding frames in terms of shape and detachment values by adopting the concept of shape functions, in line with, and extending, the state-of-the-art investigations on the relative deformation mechanism between seismic-resisting frames and precast flooring units. The paper is structured as follows. In Section 2, the adopted methodology is presented, including a brief review of the displacement incompatibility issue and the concept of shape functions. The description of the case-study structures as well as the adopted modelling strategy, involving two alternative macro-modelling approaches, is reported in Section 3, together with the results and discussion of the performed parametric analysis. Finally, conclusions are given in Section 4.

2. DISPLACEMENT INCOMPATIBILITY: METHODOLOGY

Past studies available in the literature have focused on the displacement incompatibility issue, mainly investigating the relative displacement between different structural members. For instance, Fenwick and Megget [1993] investigated the so-called "beam elongation" effect, i.e. the elongation that can occur in the plastic hinge zones of RC members due to the tensile yielding of the reinforcements and the cycling loads. Moreover, other studies [Matthews *et al.*, 2003; Vides and Pampanin, 2015] focused on the vertical displacement incompatibility between beams and precast flooring units. Yet, very few studies investigated the infill-frame seismic displacement incompatibility in terms of detachment shape and values rather than contact zones and stress path. As an example, quite recently Brodsky *et al.*, [2018] investigated the interaction behaviour in terms of the infill-frame contact regions and interfacial tractions in case of loss of a supporting column.

In order to assess the infill-frame detachment shape and values, this work proposes and adopts the concept of displacement incompatibility shape functions. This concept was introduced by Taylor [2004] and further developed and applied by Vides and Pampanin [2015] to investigate the vertical displacement incompatibility profiles between the seismic resisting frame and the precast flooring unit. Shape functions are defined as the envelope of the maximum (both horizontal and vertical) displacement incompatibility recorded along the interface with the surrounding structural frame. Figure 2 shows the adopted framework to carry out shape functions of displacement incompatibility.

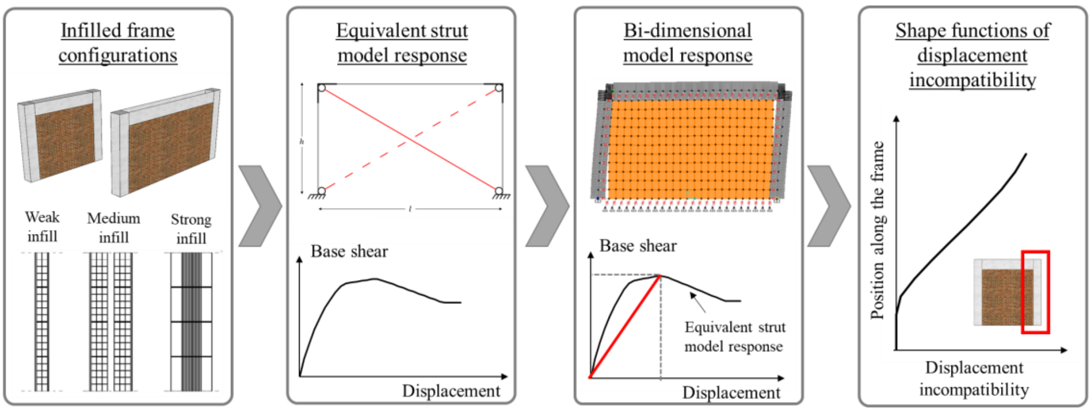

Figure 2. Adopted methodology to evaluate shape functions of displacement incompatibility.

Firstly, geometrical details and material properties of the considered case-study infilled frame structures are defined. Then the seismic behaviour of the structure is assessed by performing nonlinear static (pushover) analysis on numerical models. In order to evaluate the seismic displacement incompatibility through a numerical simulation, the best approach would be to develop a refined Finite Element Method (FEM) model following a micro-modelling approach. These methods allow to provide an accurate description of the structural behaviour of the system by modelling in detail both masonry units and mortar joints. On the other hand, these methods require a significant amount of data, resulting to be complex and time-consuming for their high computation effort [Tarque *et al.*, 2015]. In this research work, a more simplified modelling approach strategy is instead adopted to perform a preliminary investigation on the parameters that strongly affect displacement incompatibility. More specifically, the adopted modelling strategy involves two alternative numerical models of the structure, following the macro-modelling and the meso-modelling techniques. In the first method (i.e., the macro-modelling approach), the masonry infill panel is modelled by an equivalent diagonal strut, while in the meso-modelling approach the infill panel is idealized as a continuous linear bi-dimensional element without distinction between masonry units and mortar joints. Following the provisions reported in Cavaleri and Di Trapani [2015], the two numerical models can be considered as equivalent when they exhibit the same lateral secant stiffness under monotonic loading. Thus, by comparing the two numerical models, the nonlinear behaviour of the bi-dimensional model is introduced by iteratively reducing its stiffness (operatively, by reducing its thickness) until the same lateral secant stiffness of the equivalent strut model is reached for a fixed interstorey drift level. This concept is illustrated in Figure 3.

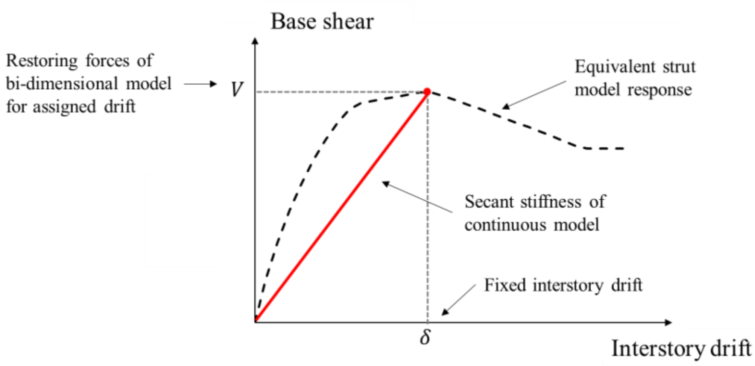

Figure 3. Theoretical representation of the adopted modelling strategy (after Cavaleri and Di Trapani [2015]).

Cavaleri and Di Trapani [2015] also proved that this modelling strategy can provide good accuracy in assessing the overall response of infilled frames as well as the local shear demands on frames. More details about the numerical models developed in this research work are given in Section 3.2. Finally, by evaluating the relative displacement (both in the horizontal and vertical directions) between the masonry infill and the surrounding frame, shape functions of the displacement incompatibility are derived.

In the following section, the proposed framework is applied to different infilled frame structures in order to carry out shape functions of displacement incompatibility and preliminarily assess which parameters strongly affect the infill-frame detachment.

3. PARAMETRIC ANALYSIS

3.1 DESCRIPTION OF THE CASE-STUDY STRUCTURES

Two single-story one-span infilled frame structures, characterized by beam span lengths of 3m and 5m, respectively, and an interstorey height of 3m, are considered to implement the study (Figure 4, left). The RC frame members are representative of a typical pre-1970s existing building in Italy, i.e. designed for gravity load only. Specifically, material mechanical properties, reinforcement and construction details are selected according to available data of an existing school building in Lucera, South Italy, as part of the UEFA/ELENA research project [Pampanin *et al.,* 2020]. Geometrical details of the structural members are shown in Figure 4 (left) and are assumed the same for both structural configurations. The beam-column joints have no stirrups and beam longitudinal bars are anchored with end-hooks. The mean concrete cylindrical strength is equal to 16 MPa, while the mean steel yield stress is equal to 400 MPa. Young's module is equal to 22.85 GPa and 200.0 GPa for concrete and reinforcement steel, respectively.

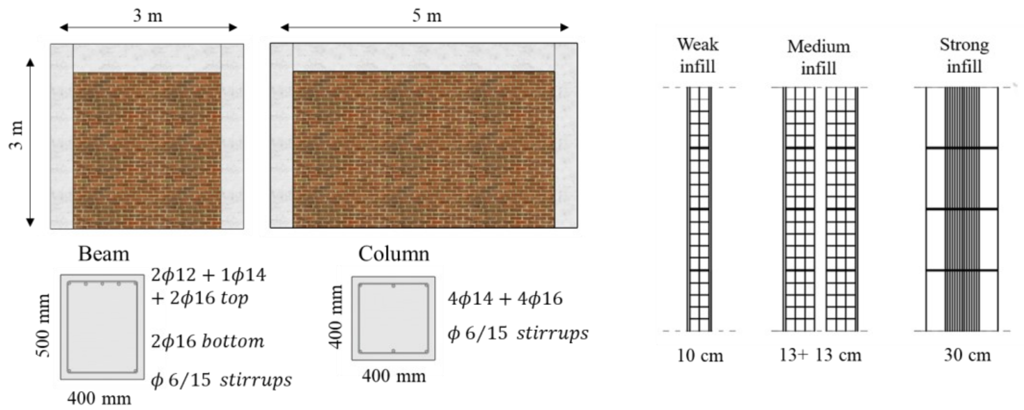

Figure 4. Geometric properties of (left) the infilled frame configurations and (right) the selected masonry infill panels.

For each structural configuration, three different masonry infills are considered: Weak Infill (WI), Medium Infill (MI) and Strong Infill (SI) (Figure 4, right). Specifically, the WI is a single-leaf masonry wall with horizontally hollowed brick; the MI is a double-leaf masonry wall with horizontally hollowed brick divided by an internal cavity; the SI is a single-leaf wall with vertically hollowed brick units. Mechanical proprieties of infill panels are selected according to Hak *et al.* [2012] (more details can be found in the cited paper). Moreover, three different axial load values are applied to the RC columns (i.e., N = 120kN, 270kN and 420kN) to simulate portal frames located at three different story levels in a low-rise building.

3.2 MODELLING APPROACH

As mentioned above, two alternative models are realized for each considered infilled frame configuration: an equivalent diagonal strut and a bi-dimensional model. Concerning the equivalent diagonal strut model, a non-linear lumped plasticity model is implemented in the structural software OpenSees (python library [Zhu *et al.*, 2018]). Details of the adopted modelling approach are shown in Figure 5.

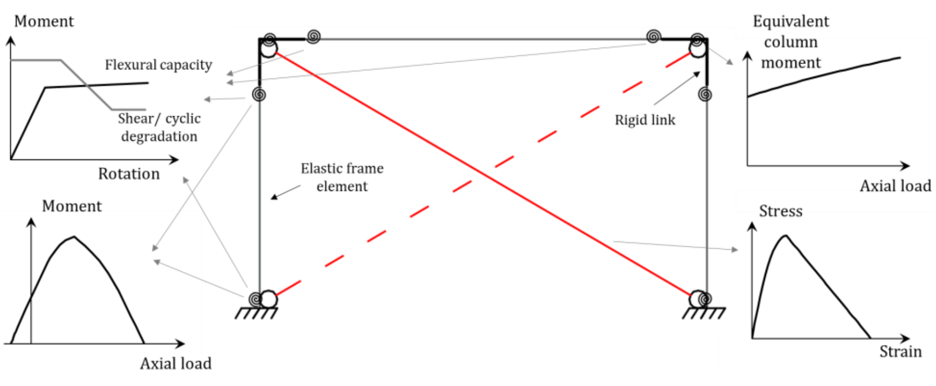

Figure 5. Adopted numerical modelling strategy for the equivalent strut model.

The soil-structure interaction contribution is neglected, and fixed base nodes are considered. Beams and columns are modelled by elastic elements with lumped plasticity at the end sections. Nonlinear behaviour of the plastic hinges is described using proper bi-linear moment-curvature relationships and accounting also for the shear failure mechanism. Panel zones are modelled using rigid arms with additional nonlinear rotational springs to capture the joint non-linear behaviour and failure mechanisms [Pampanin *et al.*, 2003]; these springs are characterized by equivalent column moment vs. joint shear deformation relationships. The infill panel is modelled by an equivalent diagonal strut. The strut properties (i.e., width, length, and thicknesses) as well as the ultimate compression stress are evaluated according to the procedure proposed by Bertoldi *et al.* [1993]. In this model, the thickness and the length of the infill are automatically defined by the panel geometry, while the width is evaluated as a function of the relative stiffness between the infill and frame, λ, obtained according to Stafford Smith [1967]. On the other hand, the ultimate compression stress is assessed considering four different failure mechanisms: 1) compression failure at the centre of the infill, 2) compression failure at the corners of the infill, 3) sliding shear failure, and 4) diagonal tension failure. The ultimate compression stress is defined as the minimum value obtained for the four failure mechanisms. More details about the mathematical formulations of this model can be found in Bertoldi *et al.* [1993]. A fibre section for the equivalent strut is implemented to define the nonlinear behaviour, considering the Kent-Scott-Park stress-strain law [Kent and Park 1971], as suggested by Di Tapani *et al.* [2018]. The ability of this model to provide a good description of the global seismic capacity of infilled-frame structures has been also tested by a comparison with experimental tests available in the literature (Figure 6).

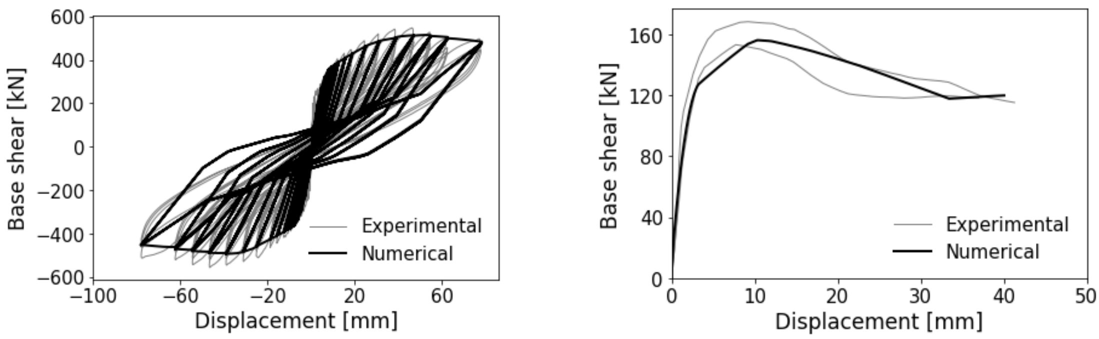

Figure 6. Comparison between experimental and numerical results: (left) cyclic response of the infilled frame tested by Morandi *et al.* [2018a]; (right) monotonic response of the infilled frame tested by Mehrabi *et al.* [1996].

Results show a good agreement between the experimental tests and the numerical results. The force-displacement behaviour is well captured, while the hysteretic behaviour of the numerical model slightly overestimates the energy dissipation of the infilled structure; however, it is out of the scope of this study.

Moving to the bi-dimensional model, beams and columns are modelled as reported previously, while the infill wall is idealized as a continuous element by using elastic orthotropic shell elements. This numerical model is implemented in the structural software SAP2000 [CSI, 2019]. The contact interface between frame and infill is modelled by using gap elements able to transfer compression stresses only. A similar modelling approach can be found also in Cavaleri and Di Trapani [2015] and Doudoumis [2007]. It is worth noting that friction phenomena are herein neglected in the numerical investigation. This choice is deemed reasonable in a preliminary assessment of the detachment mechanism since the definition of a realistic friction coefficient can be challenging, considering that friction stresses progressively vary in the case of cyclic loading. Moreover, past numerical investigations [Fiore *et al.,* 2012] have shown that friction phenomena do not influence the overall behaviour of an infilled frame. A qualitative illustration of the bi-dimensional model is presented in Figure 7.

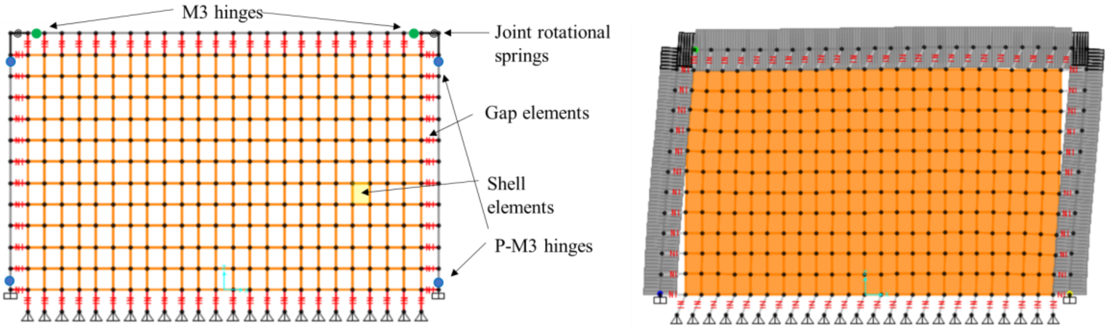

Figure 7. Qualitative illustration of the bi-dimensional model.

3.3 RESULTS AND DISCUSSIONS

Nonlinear static pushover analyses on the equivalent strut model are carried out for each infilled frame configuration. Figure 8 shows the results in terms of global capacity curves (i.e., base shear vs. top displacement).

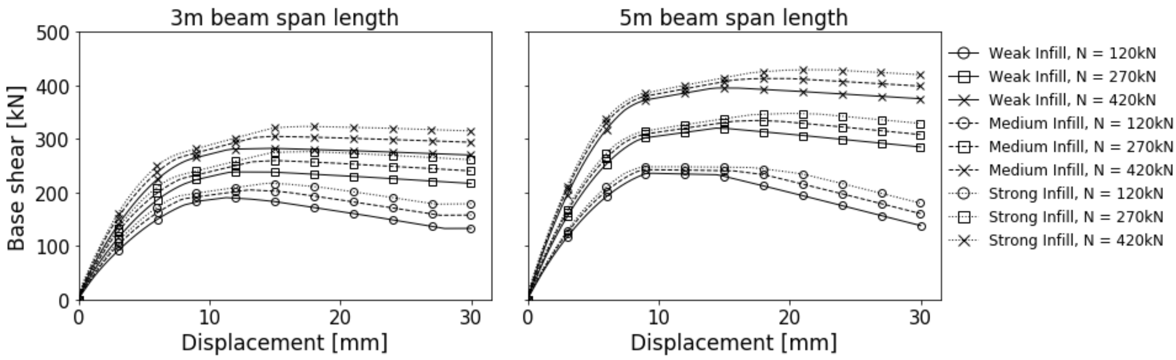

Figure 8. Force-displacement capacity curves for each considered infilled frame configuration.

Results highlight that the beam spam length as well as the axial load on the columns strongly influence the strength and stiffness of the infilled frame structure. Moreover, as expected, the strength and stiffness of the structure increase considering a stronger infill panel. It is worth noting that an ultimate displacement corresponding to an interstorey drift of 1.0% is considered for each configuration since the panel joint shows a critical damage level at this drift level [Pampanin *et al.*, 2002].

For each configuration, shape functions of displacement incompatibility are developed using the continuous bi-dimensional model. Displacement incompatibility is computed as the difference between the displacement of the frame and the infill panel edge both in the horizontal and vertical directions (namely, Horizontal Displacement Incompatibilities, HDI, and Vertical Displacement Incompatibilities, VDI). HDI and VDI are computed at two fixed interstorey drift values (i.e., ϑ=0.4% and ϑ=0.9%) representing the Damage Limit State (DLS) and Ultimate Limit State (ULS) of the infilled frame, according to past numerical and experimental investigations [Magenes and Pampanin, 2004; Hak *et al.*, 2012; Morandi *et al.*, 2018a]. Finally, shape functions are defined by the envelope of displacement incompatibility points. Figure 9 shows the obtained displacement incompatibility shape functions; for brevity, only results related to the HDI between the infill and the right column are reported. In Table 1 the maximum detachment values for both HDI and VDI are listed for each analysed configuration.

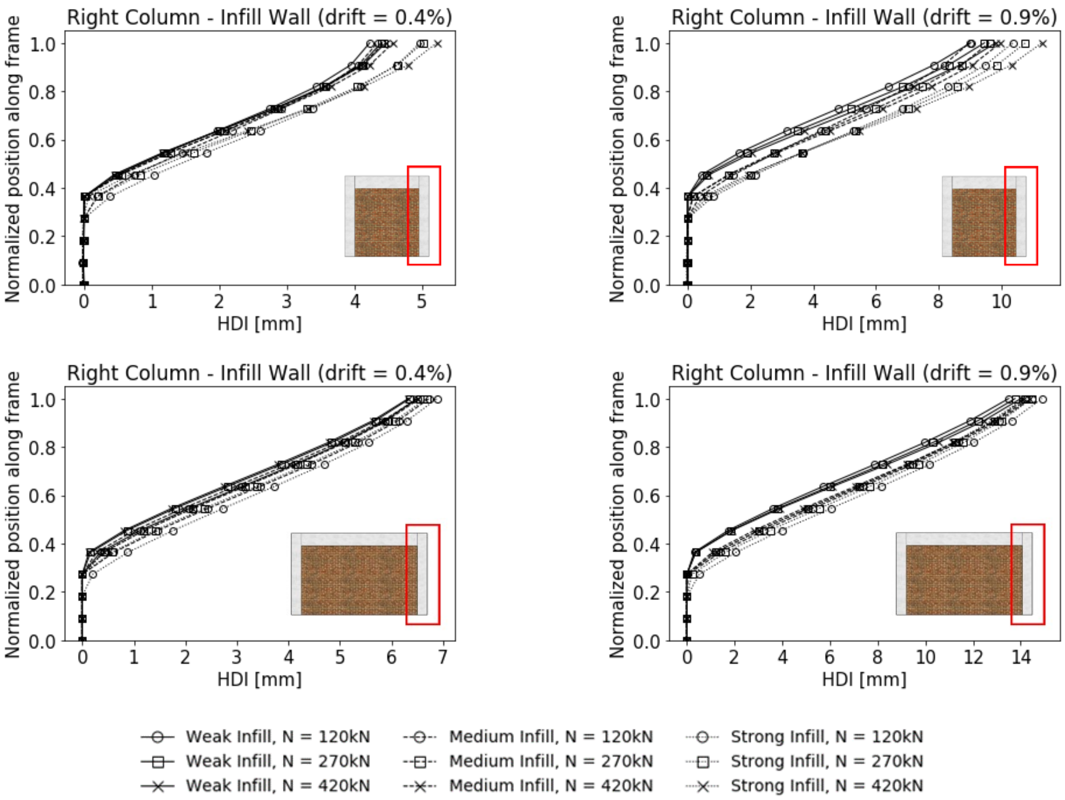

Figure 9. Shape functions of displacement incompatibility between infill wall and column.

Table 1. Maximum displacement incompatibility values for each analysed configuration.

Spec.	h	l	Infill type	N	Δ_{DI} drift 0.4% (mm)			Δ_{DI} drift 0.9% (mm)		
#	mm	mm	-	kN	Col_{sx}	Beam	Col_{dx}	Col_{sx}	Beam	Col_{dx}
1	3000	3000	Weak	120	-2.7	2.5	4.2	-7.1	5.3	9.0
2	3000	3000	Medium	120	-3.1	2.4	4.4	-6.9	5.2	9.5
3	3000	3000	Strong	120	-3.1	2.3	4.5	-6.9	5.2	9.8
4	3000	3000	Weak	270	-2.8	2.3	4.3	-6.5	5.1	9.0
5	3000	3000	Medium	270	-2.9	2.3	4.4	-7.4	5.0	9.6
6	3000	3000	Strong	270	-3.1	2.2	4.6	-7.3	4.9	10.0
7	3000	3000	Weak	420	-3.2	1.8	5.0	-7.7	3.8	10.4
8	3000	3000	Medium	420	-3.2	1.8	5.0	-8.2	3.8	10.8
9	3000	3000	Strong	420	-3.6	1.7	5.2	-8.9	3.7	11.3
10	3000	5000	Weak	120	-5.0	1.8	6.5	-13.2	2.7	13.5
11	3000	5000	Medium	120	-5.4	1.8	6.4	-13.0	3.6	13.8
12	3000	5000	Strong	120	-5.5	1.8	6.3	-12.7	4.6	14.0
13	3000	5000	Weak	270	-4.6	1.8	6.7	-11.2	3.9	14.4
14	3000	5000	Medium	270	-5.1	1.8	6.5	-12.6	4.4	14.2
15	3000	5000	Strong	270	-5.2	1.9	6.5	-12.4	4.6	14.3
16	3000	5000	Weak	420	-4.8	1.5	6.9	-11.6	3.8	14.9
17	3000	5000	Medium	420	-5.2	1.5	6.7	-12.8	3.6	14.5
18	3000	5000	Strong	420	-5.5	1.5	6.5	-13.6	3.6	14.1

Note: Col_{sx} = left column; Col_{dx} = right column; Δ_{DI} = maximum detachment values.

Table 1 shows that in general terms HDI (i.e., horizontal detachment between infill and columns) is more severe than VDI (i.e., vertical detachment between infill and beam). Considering the 5m beam span length, the seismic HDI increases while the VDI decreases when compared to the 3m beam span length. The main differences in the behaviour can be found for the strong infill when compared to weak and medium infills. In fact, generally weak and medium infills show similar behaviour, while strong infill leads to higher values of displacement incompatibility. Considering l=3m, the maximum detachment value is observed for the strong infill with the highest axial load on columns: Δs=5.2mm for interstorey drift ϑ=0.4% and Δs=11.3mm for ϑ=0.9%. Moving to l=5m, similar considerations can be made. The maximum value of detachment is recorded at the top corner in the horizontal direction (HDI), leading to Δs=6.9mm and Δs=14.9mm for interstorey drift ϑ=0.4% and ϑ=0.9%, respectively. As for the l=3m, displacement incompatibility generally increases when considering a stronger infill panel. However, axial load value has a strong influence in this configuration: higher axial load values lead to lower detachment in most of the configurations, especially for VDI and ϑ=0.9%. This is mainly due to the plastic hinges sequence of the structural frame. It is worth remembering that a pre-seismic-code frame structure is considered in this study; hence, the observed failure mode is a mixed sidesway mechanism because of a lack of capacity design principles. However, the panel zone capacity increases as the axial load on columns increases (as experimentally observed in Pampanin *et al.* [2002]), so when N=420kN plastic hinge occurs in the beam for positive bending moment, while when N=120kN shear failure of the panel zone occurs. For these reasons, it is not easy to identify a common behaviour for VDI. However, it is observed that VDI values are always smaller than HDI ones. and thus of lesser concern.

4.CONCLUSIONS

In this paper, a methodology to assess the seismic displacement incompatibility between masonry infill panels and surrounding RC frames has been proposed. The proposed framework involves the definition of shape functions of displacement incompatibility, in line with and extending the state-of-the-art investigations on the relative deformation mechanism between seismic-resisting frames and precast flooring units. A simplified modelling strategy has also been suggested and adopted, in order to allow one to analyse the local detachment mechanism without the need of implementing more refined, but more complex and time-consuming, FEM numerical models according to the micro-modelling techniques. The proposed framework has been applied to different case-study infilled-frame structures through a parametric investigation, to preliminarily evaluate which parameters strongly affect the infill-frame detachment as well as provide a preliminary range of detachment values and identify maximum detachment location along the frame. The proposed concept of shape functions can support the design of structural details such as shear keys or steel dowels, in order to avoid the out-of-plane collapse of infills or realize an effective infill-frame connection in strengthening retrofit techniques, preventing possible local failures. Moreover, shape functions can be used to design adequate construction details for energy efficiency retrofit solutions, such as external thermal insulation systems, since the infill detachment can lead to damage to these solutions.

It is worth mentioning that this research work represents a preliminary investigation of the infill-frame displacement incompatibility, and further research effort is needed to achieve a better understanding of this topic. Firstly, an extensive experimental program coupled with more refined numerical investigations (possibly based on micro-modelling approaches) is deemed necessary. Moreover, the proposed study could be improved by considering a wider class of infilled frame structures; further advancements would consist of developing tables and/or analytical formulations to quickly derive shape functions starting from the geometrical and material properties of the infilled frame structure. Finally, it is worth noting that when plastic hinges occur in the beam, the "beam elongation" effect may affect the infill-frame displacement incompatibility, leading to higher horizontal detachment values. Thus, also the influence of the "beam elongation" effect should be studied through both experimental and numerical investigations.

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