A NEW PROSPECTIVE TOWARDS OUT-OF-PLANE VERIFICATIONS OF URM INFILLS

Milanesi, Riccardo[1]; Morandi, Paolo[2]; Hak, Sanja[3] and Magenes, Guido[4]

ABSTRACT

The unreinforced masonry infills (URM) rigidly attached to the structures and built after the complete hardening of the structural member represent the "traditional" masonry infill, that is a commonly adopted non-structural member. Despite many studies have been accomplished in the last decades, the materials and the details utilized for masonry infills have been continuously changing to satisfy architectural, thermal and economic needs and, therefore, their interaction with the structure and their seismic performance needs to be furtherly investigated. Moreover, the recent post-seismic surveys have highlighted the out-of-plane vulnerability of traditional URM infills. Within this work, a new prospective towards the out-of-plane verification of traditional URM infills is presented. The study is based on the interpretation of experimental tests conducted on commonly adopted masonry typologies. The out-of-plane design procedure proposed addresses the out-of-plane resistance of masonry infills by also including its degradation due to in-plane damage. Additionally, the influence of the in-plane response in the modification of the out-of-plane stiffness, and therefore of the fundamental period of the URM infill, has also been considered to compute the out-of-plane seismic demand. Finally, although most of the current standards do not provide a path for out-of-plane verifications by including the in-plane/out-of-plane interaction in terms of out-of-plane strength and stiffness reduction, their inclusion could modify the safety check and lead to more realistic out-of-plane verifications.

KEYWORDS: *design implications, in-plane/out-of-plane interaction, out-of-plane seismic demand for infills, out-of-plane verifications, URM infills*

[1] Research fellow, Dept. of Civil Engineering and Architecture, University of Pavia, Italy. Via Ferrata 3, Pavia, Italy. riccardo.milanesi@unipv.it
[2] Senior Researcher, Dept. of Structures and Infrastructures, Eucentre, Via Ferrata 1, Pavia, Italy. paolo.morandi@eucentre.it
[3] Project Manager, Dept. of Structural Safety, Basler & Hofmann AG, Zurich, Switzerland. sanja.hak@gmail.com
[4] Professor, Dept. of Civil Engineering and Architecture, University of Pavia, Italy. Via Ferrata 3, Pavia, Italy. guido.magenes@unipv.it

INTRODUCTION

In many parts of the world, new and existing buildings are made of r.c. or steel frame structures with masonry infills. Although the seismic structural behaviour has been addressed through the years and it is scientifically covered in several aspects, the diversity of the masonry adopted for the infills, mainly due to the geographical and historical tradition and the thermal performance requested by the national codes, is still representing a challenging issue for the identification of the seismic in-plane and out-of-plane performance, moreover if it is defined for every masonry typology. Masonry panels are commonly built in full contact when the r.c. structural members are hardened, without the creation of any gap or connection around the boundaries. The current infill typology, constituted by single-leaf thick vertically perforated blocks (thickness of more than 25-30 cm), differs considerably from the previous ones, which were realized by single or double-leaf thinner horizontally perforated clay units (usually from 10 to 15 cm thickness) or by solid bricks. Such elements have been studied from many researches spread in different parts of the world to investigate specific issues that has been observed during the post-seismic surveys, where the high vulnerability of the infills became evident. The seismic studies related to infills have started in the mid-1950s (e.g. Polyakov, 1957 [1]), with the aim to identify the influence of the non-structural elements to the global behaviour of the structure. Subsequently, the research has been addressed into specific topics, such as the infill/structure global interaction (e.g. Hashemi and Mosalam, 2006 [2]), the local interaction with the structural members (e.g. Crisafulli, 2000 [3], Milanesi et al., 2018 [4]), the in-plane (e.g. Mehrabi, 1994 [5], Morandi et al., 2018 [6]) and the out-of-plane (e.g. Abrams et al., 1996 [7]) seismic performance of infills, the in-plane/out-of-plane interaction of infills (e.g. Angel et al., 1994 [8]), the economic evaluation of expected annual losses (e.g. Chiozzi and Miranda, 2007 [9]; Rossi et al., 2021 [10]), innovative infill solutions (e.g. Mohammadi et al., 2011 [11]; Morandi et al., 2018 [12]; Milanesi et al., 2020 [13], Preti et al., 2017 [14]), new strengthening techniques (Furtado et al, 2020 [15]), etc.

In present European seismic design codes (EC8 – Part 1, 2004 [16]), as well as in other national codes, masonry infills are considered as non-structural elements and must be verified accordingly. Although the importance to limit the expected damage of infills in the design of new structures is reflected in commonly adopted design procedures, recommendations and specific measures present several deficiencies in many aspects. In relation with the out-of-plane infill verifications, it is almost impossible to find a precise definition of the out-of-plane strength reduction and the out-of-plane stiffness changes due to the in-plane damage. Moreover, the evaluation of the out-of-plane resistance of undamaged infills specific for seismic verifications is missing in the norms, with few exception (e.g., the New Zealand Guidelines (2017) [17], which report a formulation based on the study conducted by Flanagan and Bennett (1999) [18]).

In the present paper, the out-of-plane verification of traditional URM infills is discussed, focusing on a new formulation to compute the out-of-plane resistance of the panel and a proposed strength degradation due to the in-plane damage. Moreover, the out-of-plane stiffness has been found to change due to the in-plane/out-of-plane interaction, consequently the fundamental period and the seismic action is expected to vary as respect to the undamaged situation.

Although most of the current standards do not provide sufficient indications for out-of-plane verifications considering the in-plane/out-of-plane interaction in terms of out-of-plane strength and stiffness reduction, their inclusion may significantly modify the safety check and lead to more realistic out-of-plane checks. The approach herein presented considers the out-of-plane strength and the modification of the demand as a function of the in-plane drift associated to different levels of damage. It has been based on the results of a wide experimental study conducted on robust modern masonry infills with a thickness of 35 cm but could in principle be adopted to every traditional masonry infill typology.

EXPERIMENTAL CAMPAIGN ON MODERN STRONG MASONRY INFILLS

A summary of the reference experimental campaign considered to develop the proposed approach is presented within this section. The tests have been conducted at the laboratory of the Department of Civil Engineering and Architecture of the University of Pavia.

Cyclic static in-plane and out-of-plane tests have been carried out on a bare r.c. frame and fully or partially infilled full-scale single-storey, single-bay 4.57 x 3.30 m r.c. frames (Figure 1), newly designed according to European code provisions. The dimensions of the infill panel are 4.22 x 2.95 m. After a detailed characterisation of all material components (i.e., concrete, reinforcing steel, mortar, masonry units, and masonry), the experimentation has been accomplished on seven frame specimens, as summarised in Table 1.

Details on the cyclic in-plane tests are reported by Morandi et al. (2018) [6]. The out-of-plane experiments have been carried out on the specimens called TA1, TA2, TA3 and TA4 previously damaged in-plane and are discussed in Morandi et al. (2021) [19], while the out-of-plane tests on in-plane undamaged infills (TA5 and TA6) are described in Milanesi et al. (2021) [20]. The specimens TA1 to TA5 were tested with out-of-plane displacement-controlled cyclic tests, where the control displacement is at the centre of the panel, whereas TA6 was tested under monotonic distributed load. The test setups, instrumentation and loading protocol are reported in the aforementioned publications.

Table 1: Performed tests and summary of maximum in-plane drift and out-of-plane displacement or force reached.

Specimen	TNT	TA1	TA2	TA3	TA4	TA5	TA6
In-plane max experimental drift	3.50 %	1.50 %	2.50 %	1.00 %	1.00 %	---	---
Out-of-plane max central displacement (or max force)	-	75 mm	75 mm	75 mm	75 mm	75 mm	max force
Configuration	bare frame	fully infilled	fully infilled	fully infilled	partially infilled	infill stripe	fully infilled

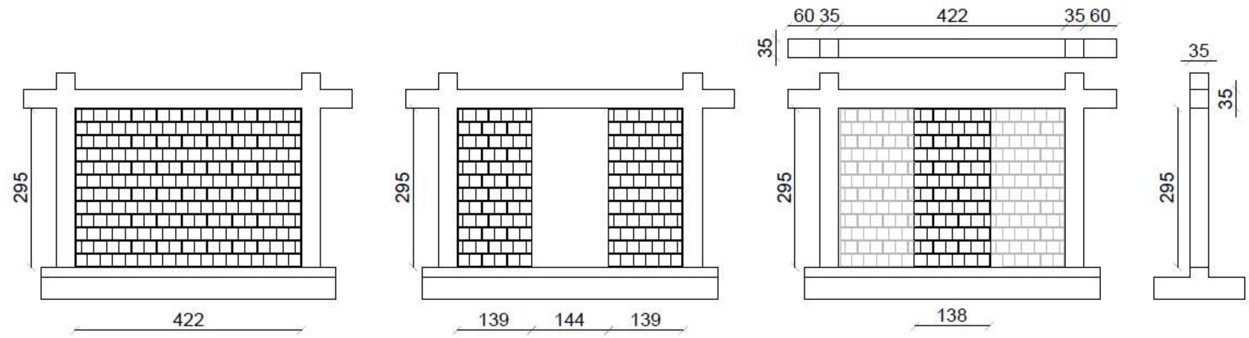

Figure 1: Fully infilled: TA1, TA2, TA3, TA6 (left); partially infilled: TA4 (center); (c) vertical infill stripe: TA5 (right).

The masonry typology tested represents a current common solution for traditional strong single-leaf unreinforced masonry infill. The masonry is 35 cm thick, and it consists of a vertically hollowed lightweight tongue and groove clay block units, having nominal dimensions of 235x350x235 mm and a nominal volumetric percentage of holes of 50% (Figure 2). The mortar selected is a general-purpose one, with a nominal compression strength of 5.0 MPa (M5 mortar type). The infills have been constructed after full hardening of the r.c. frame, adopting traditional bed joints, having a thickness of about 1.0 cm and dry head joints. Full contact between the infill and the surrounding r.c. members was assumed to be achieved filling the remaining vertical gaps on the two sides of the infill and the horizontal gap at the top of the infill with mortar.

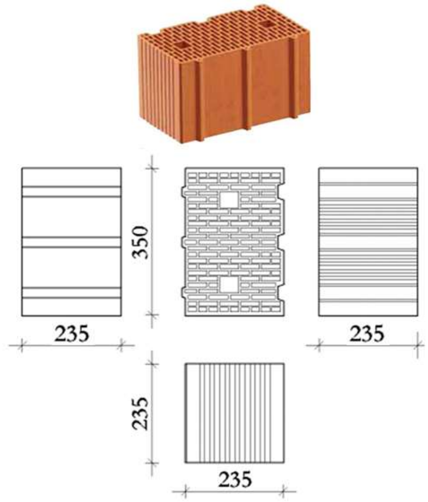

Figure 2: Masonry clay unit [21].

The results of the material characterization carried out on both the structural and infill materials including masonry, is reported in detail in Morandi et al. (2018) [21]. In the vertical direction (parallel to the holes), the masonry has an average resistance of 4.64 MPa and a stiffness of 5299 MPa, meanwhile in the horizontal direction the resistance and the stiffness are 1.08 MPa and 494

MPa, respectively. The initial shear strength of the bed-joints is equal to 0.359 MPa and the friction coefficient is 1.31.

IDENTIFICATION OF THE KEY PARAMETERS FROM THE IN-PLANE AND OUT-OF-PLANE TESTS

The reference experimental campaign was started with a series of in-plane cyclic tests up to the attainment of different in-plane drifts corresponding to specific limit states, as defined by Morandi et al. (2018) [6]. Subsequently, the out-of-plane tests were conducted with the aim of associating the out-of-plane response to the in-plane drift attained in the previous in-plane tests.

The experimental values of the out-of-plane resistance obtained following the in-plane tests (i.e., at 0.0%, 1.0%, 1.5% and 2.5% in-plane drift) are shown in Figure 4 and summarized in Table 2. The ratio of the corresponding value obtained in comparison to the undamaged panel, resulting in the experimentally evaluated out-of-plane strength reduction coefficient $\beta_{R,exp}$, are also reported in Figure 4 and Table 2. For each test, the considered force is the peak value of the maximum envelope reported in Figure 3.

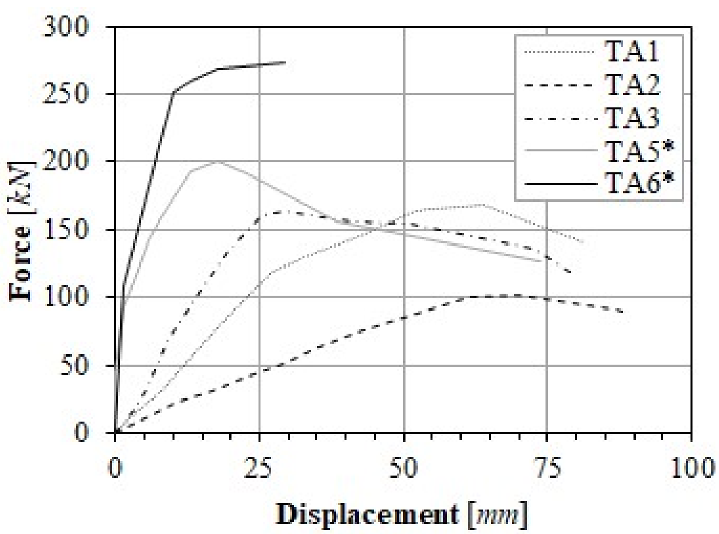

Figure 3: Out-of-plane experimental envelopes curves.

After a first reduction of the out-of-plane resistance as a function of the in-plane drift, the strength remains substantially constant between a drift of 1.00% up to about 1.50-1.75%, then followed by a soft degradation up to the maximum drift (2.50%).

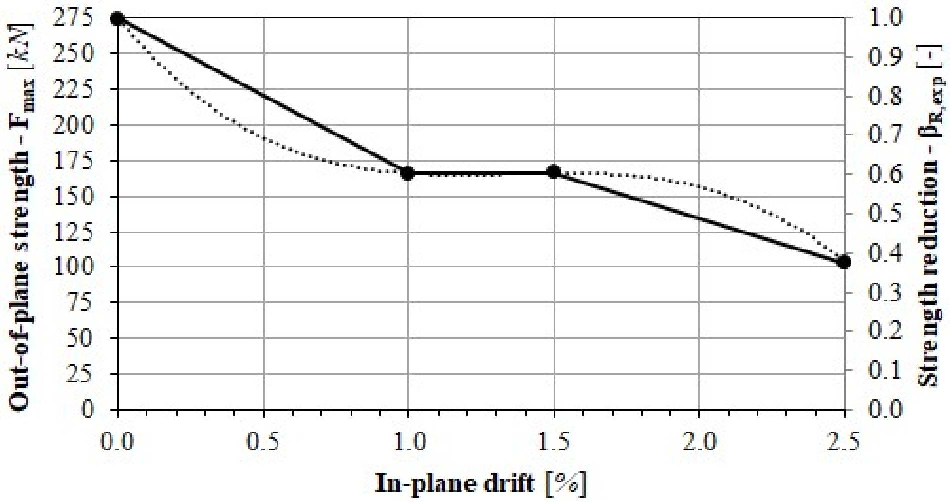

Figure 4: Experimental out-of-plane resistance and reduction coefficient $\beta_{R,exp}$ in function of previous in-plane drift.

Figure 5 and the values in Table 2 report the trend of the experimental out-of-plane elastic stiffness in function of the in-plane drift, along with the ratio of the corresponding value obtained for the undamaged panel, i.e., the out-of-plane stiffness reduction coefficient $\beta_{k,exp}$. The results show a sharp degradation from 0.0% to 1.0%, followed by a soft decrease, proving that the main loss of stiffness occurs at small values of in-plane drift, when the panel begins to be damaged and to detach from the frame. The variation of the elastic stiffness can strongly affect the seismic out-of-plane verification, since it modifies the fundamental out-of-plane period of the infill and, therefore, the pressure/force acting on the panel.

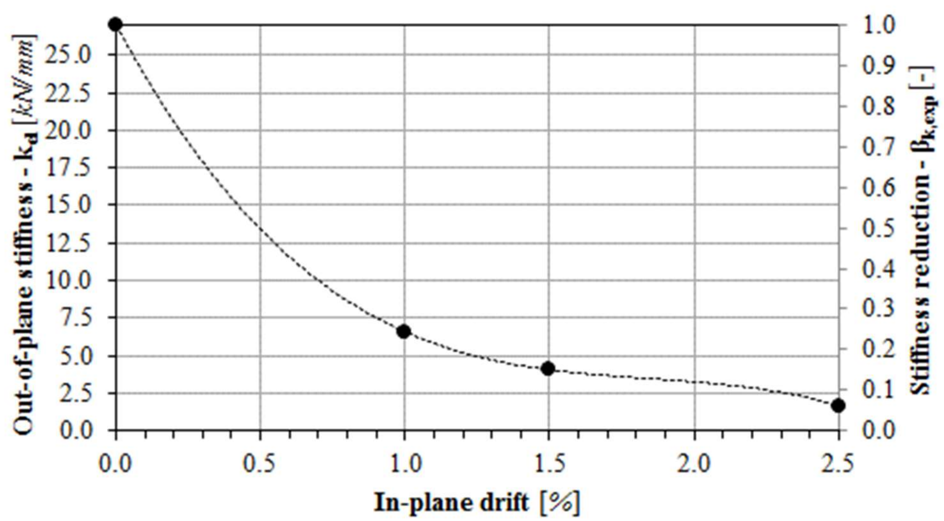

Figure 5: Experimental out-of-plane stiffness and reduction coefficient $\beta_{k,exp}$ in function of previous in-plane drift.

Table 2: Experimental out-of-plane resistance, stiffness and reduction coefficients $\beta_{R,exp}$ and $\beta_{k,exp}$ in function of previous in-plane drift for strong infill.

In-plane drift [%]	F_{max} [kN]	$\beta_{R,exp}$ [-]	k_{el} [kN/mm]	$\beta_{k,exp}$ [-]
0.00	274	1.00	27.0	1.00
1.00	164	0.60	6.61	0.24
1.50	168	0.61	4.06	0.15
2.50	103	0.37	1.67	0.06

The proposed relation between the in-plane drift and the out-of-plane strength reduction coefficient β_R cannot be taken as reference, unless a proper estimation of the out-of-plane resistance of the undamaged panel (i.e., at 0.0% in-plane drift) is provided, to avoid the risk to under- or over-estimate the actual strength, even if the reduction coefficient was consistently calibrated with the experimental results.

PROPOSAL FOR THE EVALUATION OF THE OUT-OF-PLANE RESISTANCE

The evaluation of the out-of-plane resistance of the considered strong undamaged infill (TA6) has been carried out in the study by Milanesi et al. (2021) [20]. It started from the ideal one-way vertical arching mechanism with reference to the model by Drysdale et al. (1999) [22], where a full contact between the infill and the surrounded frame is assumed and the lateral rise at mid-height of the panel is neglected. Proper reduction coefficients to consider the decrement as respect to the ideal case due to the effects observed in the tests, namely, the "second order effects" (deflection of the arch under the lateral load), the deformability of the frame (uplift of the beam) and the sliding of the panel at the frame/infill interface, have been introduced, along with an incremental coefficient to account for the contribution of the bi-axial bending in the case of infills supported on three/four edges (as TA6). Despite second order effects are usually overlooked in the calculation of out-of-plane resistance of thick panels, the deflection of the arch under lateral loads cannot be disregarded, being not always negligible for robust infills, as reported in Milanesi et al., 2021 [20], especially if the lateral displacement produced by the rotation of the two sub-panels activating the three-pinned arch mechanism is amplified by possible deformation of the surrounding frame (e.g., top beam).

Therefore, the expression of Equation (1), defined in terms of lateral pressure w_R, which modifies the common expression corresponding to a full vertical arching mechanism with the introduction of reduction coefficients accounting for the out-of-plane deflection ($k_{P\Delta 0}$), flexible supports ($k_{P\Delta g}$), and possible sliding of the panel (k_{SL}), is considered to be consistent with the experimental results and sufficiently conservative for design/assessment procedures, as reported in Milanesi et al., 2021 [20]. An increasing coefficient related to the bi-directionality of the out-of-plane response (k_{BD}) may be also included in the expression and can be estimated as the ratio between the vertical bending moment of a simple supported beam and the vertical moment of a plate calculated through the theory of the elastic orthotropic plates.

$$w_R = k_{P\Delta 0} k_{P\Delta g} k_{SL} k_{BD} 0.72 \left(\frac{t_w}{h_w} \right)^2 f_d \tag{1}$$

where t_w and h_w are the thickness and the height of the infill panel and f_d is the design compression strength of the masonry set as the ratio between the characteristic value (in the design) or the mean value (in the assessment) of the compression strength and the material safety factor γ_M for the seismic action combination. Values of $k_{P\Delta 0} = 0.95$, $k_{P\Delta g} = 0.95$, $k_{SL} = 0.80$ and $k_{BD} = 1.00$ and $\gamma_M = 1.0$ well-predict the TA6 experimental response, being the resisting lateral pressure w_R computed according to Equation (1) equal to 34.0 kPa, while the maximum experimental pressure equal to 36.2 kPa. A detailed discussion of such coefficients and their validation is reported in Milanesi *et al.* [20].

The proposed formulation reported in Equation (1) can be compared to the traditional one proposed by Drysdale et al. (1999) [22], that is reported in Equation (2). In Equation (2) the rotational equilibrium of the masonry panel can be computed accounting for a lever arm which is a fraction (γ) of the thickness of the wall. Eurocode 6 (CEN 2004) proposes to assume a value of γ equal to 0.9. The corresponding compression force can be computed as applied to the 10% of the thickness, hence being the thickness of the equivalent compressive area equal to $(1-\gamma)\cdot t$. Figure 6 shows the comparison between the experimental results and the resistance computed according to Equation (1) and to Equation (2), along with the influence of each reduction or amplification factor.

$$w_R = \frac{8M_R}{L_w h_w^2} = \frac{8\left(0.09 t_w^2 L_w f_d\right)}{L_w h_w^2} = \frac{0.72 t_w^2 f_d}{h_w^2} \tag{2}$$

In design procedures, the values of the coefficients in Equation (1) should be suitably defined according to the actual situation. For example, if the frame cannot deform, e.g., for the presence of infills at the upper and lower storey that limit the deformation of the beams and/or for beams heavily loaded, $k_{P\Delta g}$ can be taken equal to 1.0. Then, if the panel/frame interface joint is fully filled at the boundaries and/or suitable out-of-plane restraints are realized, the out-of-plane sliding at the panel/frame interface is unlikely or can be limited and therefore, it could be reasonable to assume values of k_{SL} larger than 0.80 (up to 1.00 if the sliding is completely inhibited). On the other hand, a reduction coefficient due to second-order effects $k_{P\Delta} = k_{P\Delta 0} \cdot k_{P\Delta g}$ at least equal to 0.90 is always strongly recommended for such thick masonry infills. Finally, the bi-directionality of the out-of-plane response can be conservatively neglected (k_{BD}=1.00), above all when the lateral restraints are not clearly effective or present or in case of full-height openings.

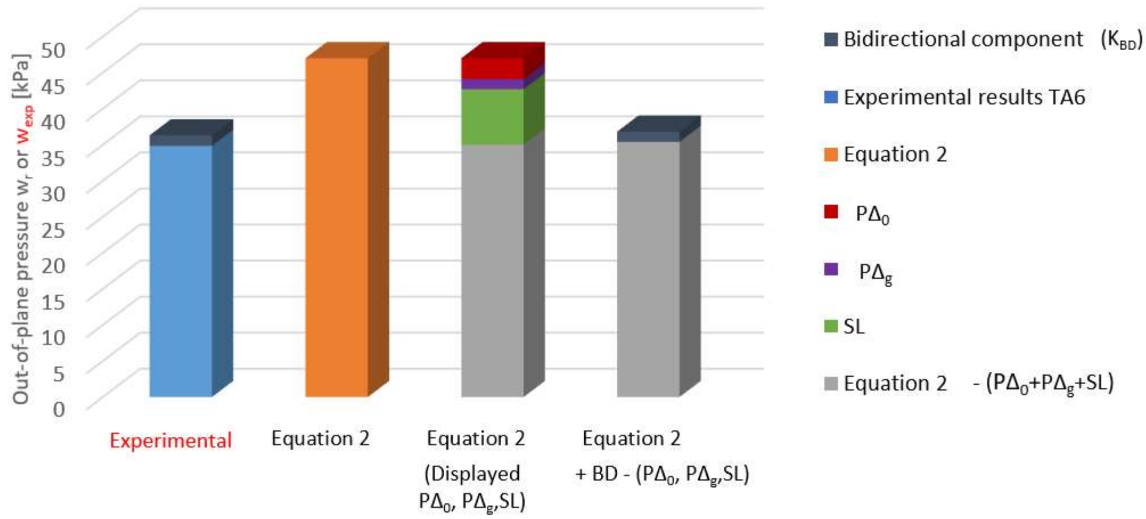

Figure 6. Comparison of the experimental out-of-plane resistance with the "weight" of each contribution.

As an alternative, Equation (1) can be modified into Equation (3), where the second-order effects are considered explicitly with the introduction of the central deflection of the arch Δ, that, for such strong masonry infill, can be conservatively taken as $0.10t_w$. Other values of Δ, to be expressed in terms of wall thickness ratio, can be derived for different masonry typologies.

$$w_R = k_{SL} k_{BD} \frac{0.8t_w\left(0.9\,t_w - \Delta\right)}{h_w^2} f_d = k_{SL} k_{BD} \frac{0.8t_w\left(0.9\,t_w - 0.1\,t_w\right)}{h_w^2} f_d \tag{3}$$

Therefore, once the strength of the undamaged panel (w_R) is evaluated, for example through the use of Equation (1) or Equation (3), the out-of-plane resistance of a damaged infill ($w_{R,\beta}$) can be computed from Equation (4), where w_R is lowered applying a reduction coefficient β_R.

$$w_{R,\beta} = w_R \cdot \beta_R \tag{4}$$

INFLUENCE OF THE IN-PLANE RESPONSE IN THE VARIATION OF THE OUT-OF-PLANE RESISTANCE AND STIFFNESS

Even though only limited data is currently available, resulting in three values of reduced strength and stiffness at three levels of previous damage, observations on the test results indicate that for the estimation of the out-of-plane resistance and stiffness an experimental reduction may be assumed, descending for increasing levels of previously imposed in-plane drift, as illustrated in Figure 4 and Figure 5 and resumed in Table 2.

Subsequently, considering the need to adopt for possible design applications a simplified approach, the out-of-plane strength reduction coefficient β_R may be defined as respect as the expected in-plane drift demand δ_w of the infilled frame. The simplified relations can be defined, for example, by a linear reduction by parts (trilinear) given in Equation (5) or by a polynomial interpolation, as represented in Figure 7. In the definition of β_R, the minimum between the values corresponding to the in-plane drifts at 1.00 and 1.50% has been assumed (=0.60).

$$\beta_R \begin{cases} \left(r_{R,1}-1\right)\cdot\dfrac{\delta_w}{\delta_{DLS}}+1 & \delta_w \le \delta_{DLS} \\ r_{R,1} & \delta_{DLS} < \delta_w < \delta_{ULS} \\ 0;\left\{\dfrac{\left(r_{R,2}-r_{R,1}\right)}{\left(\delta_{ULS}-\delta_{\max}\right)}\cdot\left(\delta_{ULS}-\delta_w\right)+r_{R,1}\right\} & \delta_{ULS} < \delta_w \end{cases} \tag{5}$$

Based on the same approach, on the basis of the results of Figure 5, the out-of-plane stiffness reduction coefficient β_k may be defined in function of the in-plane drift demand δ_w, following the bi-linear reduction of Equation (6) or the polynomial interpolation, as represented in Figure 7.

$$\beta_R \begin{cases} \left(r_{R,1}-1\right)\cdot\dfrac{\delta_w}{\delta_{DLS}}+1 & \delta_w \le \delta_{DLS} \\ \left\{\dfrac{\left(r_{k,2}-r_{k,1}\right)}{\left(\delta_{DLS}-\delta_{\max}\right)}\cdot\left(\delta_{DLS}-\delta_w\right)+r_{k,1}\right\} & \delta_{DLS} < \delta_w \end{cases} \tag{6}$$

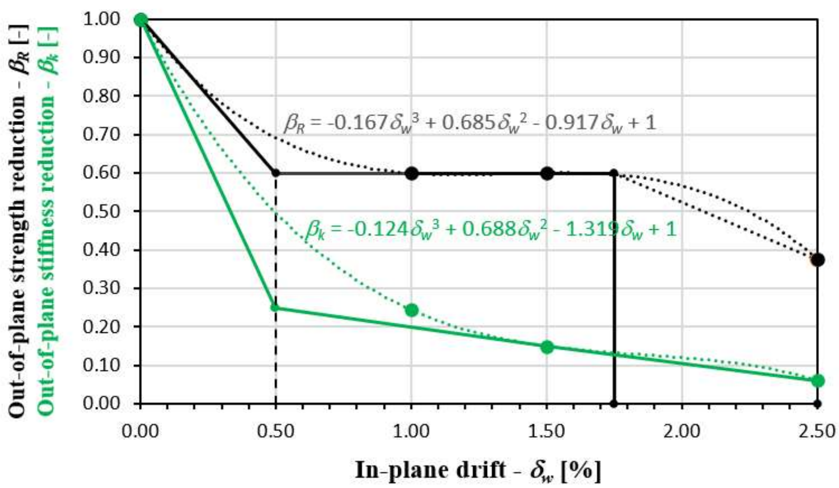

Figure 7: Out-of-plane strength and stiffness reduction coefficient β_R and β_k for strong masonry infill for design.

These simplified relations, derived from the available experimental data, depend on the values of in-plane drift δ_{DLS} and δ_{ULS}, which correspond to the attainment of damage limitation and ultimate limit state conditions (life safety/severe damage), and on the remaining fraction of out-of-plane strength and stiffness $r_{R,1}$, $r_{k,1}$ and $r_{R,2}$, $r_{k,2}$ corresponding respectively to δ_{DLS} and δ_{ULS}. The drift limits δ_{DLS} and δ_{ULS} have been estimated on the results of the in-plane tests according to the actual observed damage at the two performance states, as defined in Morandi et al. (2018) [6]. The aforementioned values, along with the maximum drift value attained during the tests δ_{max}, are summarized in Table 3. A similar interpretation of experimental results was previously accomplished for the case of unreinforced and lightly reinforced slender/weak clay masonry infills (Morandi et al., 2013 [23]).

Note that, after exceeding the drift corresponding to the achievement of infill ultimate limit state conditions δ_{ULS}, zero out-of-plane strength is assumed and therefore there is no need of performing any further safety checks in terms of in-plane drift at ULS in addition to the one at Damage Limit State already prescribed in the norms, because it is implicitly included in the out-of-plane verification. The residual out-of-plane stiffness could be also assumed as zero at the attainment of δ_{ULS}.

Table 3: Estimated drifts at damage δ_{DLS} and ultimate limit state δ_{ULS}, maximum attained drift δ_{max} and fraction of out-of-plane resistance $r_{R,1}$ and $r_{R,2}$ and stiffness $r_{k,1}$ and $r_{k,2}$.

δ_{DLS} [%]	0.50	$r_{R,1}$ [-]	0.60	$r_{k,1}$ [-]	0.25
δ_{ULS} [%]	1.75				
δ_{max} [%]	2.50	$r_{R,2}$ [-]	0.37	$r_{k,2}$ [-]	0.06

In Figure 8 the graphical representation of the key parameters needed for the proposed verification approach are shown without any values; if sufficient experimental information is available, such parameters may be obtained for any masonry typology using the same framework here presented.

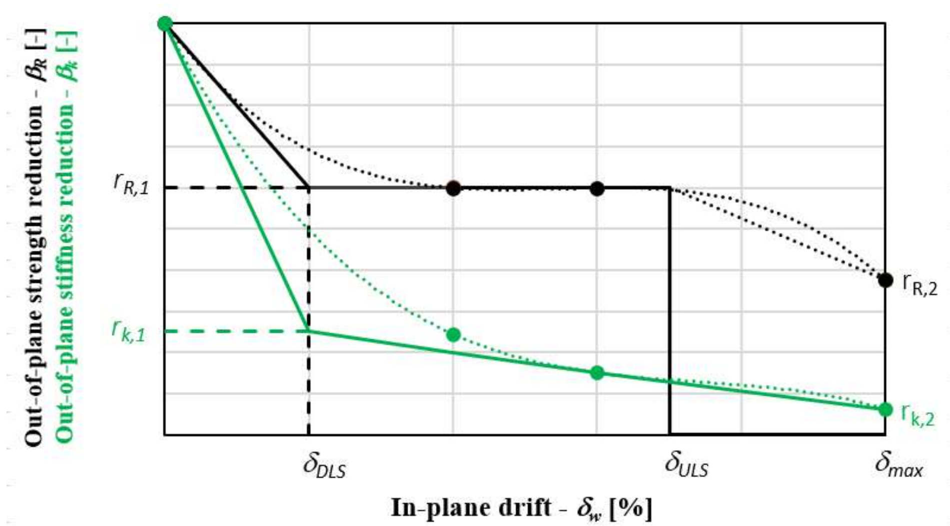

Figure 8: Main parameters for the evaluation of the out-of-plane strength and stiffness reduction coefficients β_R and β_k.

In order to carry out the out-of-plane safety verifications on masonry infills complying with seismic code regulations (i.e., the Eurocodes), the proposed out-of-plane strength and stiffness reduction coefficients β_R and β_k may be applied to estimate the reduced out-of-plane resistance and stiffness, accounting for a certain level of in-plane damage that is likely to be sustained by the infill. Given that the infill resistance verification is commonly carried out at the ultimate limit state (life safety/severe damage), the corresponding expected in-plane drift, δ_w, consequently needs to be evaluated. Since the design of masonry infilled RC structures is commonly carried out on bare frame structural configurations, the assessment of the related drift demands for the infilled structure may not be a straightforward task. In everyday design practice, the requirement to carry out detailed analyses on the infilled configuration may be rather demanding due to a series of complex issues, such as the nonlinear behaviour of the masonry and uncertainties related to the relevant material properties. However, in the case for the evaluation of the out-of-plane infill strength reduction the design drift of the bare frame configuration is assumed, the given procedure may be overly conservative since reduced drift demands are expected for the corresponding infilled frame. Hence, for the prediction of the expected drift demands of the infilled frame it may be convenient to apply the simplified procedure proposed by Hak et al. (2018) [24], that is based on the response of the corresponding bare configuration and considers a posteriori the stiffening effects of the infills in function of a simple parameter accounting from the structural characteristics and the properties and amount of the infills.

CONCLUSIONS AND FUTURE DEVELOPMENTS

Masonry infills rigidly attached to the structural elements are widely diffused in new and existing buildings in several regions of the world. A huge variety of different masonry infills exists and a proper identification of their seismic performance is a still ongoing challenge. Although the seismic vulnerability of such infills is well-known, the provisions in the Standards for the seismic verifications and design of masonry infills are anyway sometimes missing or partial.

In the present work, an approach to verify the out-of-plane seismic response of strong masonry infills has been proposed starting from the results of a wide experimental campaign conducted in the past. An equation to define proper design expressions for the evaluation of the out-of-plane resistance for infills has been presented. The development of such formulation has been derived starting from the ideal one-way vertical arching mechanism with reference to the model by Drysdale et al. (1999) [22], introducing reduction coefficients to consider the decrement with respect to the ideal case due to the complementary effects observed in the tests, namely the second order effects, *i.e.* the deflection of the arch under the lateral load, also due to the deformability of the frame, and the sliding at the frame/infill interface; on the other hand, an incremental coefficient has been included to consider the biaxial response in the case of infills supported on three/four edges. Moreover, the values of out-of-plane strength and stiffness have been related to levels of in-plane drift and simplified models describing the out-of-plane strength and stiffness reduction for the strong masonry infill have been proposed. The stiffness degradation, which has been observed to be relevant already from quite low in-plane drifts, significantly modifies the fundamental period and the force demand on the out-of-plane direction and, therefore, may not be neglected in the force-based safety checks.

The validity of the proposed formulation, in particular the evaluation of the reduction coefficient in the out-of-plane equation or for the strength and stiffness degradation, needs to further be verified against results of other out-of-plane tests on strong masonry infills, once they will be available. In principle, this approach can be also applied to other masonry infills typologies, for example slender/weak masonry, with a proper calibration of the reduction coefficients. Finally, the out-of-plane behaviour factor of the infill to consider the out-of-plane nonlinear behaviour of the masonry infills (Stavridis and Shing, 2010 [25]) represents one of the ongoing and future development of this study.

ACKNOWLEDGEMENTS
This work, conducted ad the Department of Civil Engineering and Architecture of the University of Pavia in Italy and the Eucentre Foundation, was funded by the ANDIL (Italian Association of Clay Brick and Tile Producers) and by the ReLUIS Projects 2018, and 2019-2021. The financial support received is gratefully acknowledged.

REFERENCES

[1] Polyakov, S.S., 1956, *Masonry in framed buildings*, Gosudalst-Vennoe Izdatel'stvo Literature po Straitel'stvu I Arkitectures, Moscow, 1956, Transl. G.L. Cairns, Building Research Station, Watford, Herts, UK.
[2] Hashemi, A, Mosalam K.M., 2006, Shake-table experiment on reinforced concrete structure containing masonry infill wall, *Earthquake Engineering and Structural Dynamics,* 35: 1827-1852.
[3] Crisafulli, F.J., Carr, A.J., Park, R., 2000, Capacity design of infilled frame structures, *Proc. 12th WCEE*, Auckland, New Zealand.
[4] Milanesi, R.R., Morandi, P., Magenes, G., 2018. Local effects on RC frames induced by AAC masonry infills through FEM simulation of in-plane tests, *Bulletin of Earthquake Engineering*, 16, 4053-4080.
[5] Mehrabi, A.B., 1994, Behavior of masonry-infilled reinforced concrete frames subjected to lateral loadings, *PhD Dissertation,* University of Colorado, Colorado, USA.
[6] Morandi, P., Hak, S., Magenes, G., 2018. Performance-based interpretation of in-plane cyclic tests on RC frames with strong masonry infills, *Engineering Structures*, 156, 503-521.
[7] Abrams, D.P., Angel, R., Uzarski, J., 1996. Out-of-plane strength of unreinforced masonry infill panels, *Earthquake Spectra*, 12(4): 825-844.
[8] Angel, R., Abrams, D., Shapiro, D., Uzarski, J., Webster, M., 1994. *Behaviour of reinforced concrete frames with masonry infills*, University of Illinois, Urbana-Champaign, Illinois.
[9] Chiozzi, A., Miranda, E., 2017, Fragility functions for masonry infill walls with in-plane loading, *Earthquake Engineering and Structural Dynamics*, 46: 2831-2850.
[10] Rossi, A., Morandi, P., Magenes, G., 2021, A novel approach for the evaluation of the economical losses due to seismic actions on RC buildings with masonry infills, *Soil Dynamics and Earthquake Engineering*, 145, 106722, doi 10.1016/j.soildyn.2021.106722.
[11] Mohammadi, M., Akrami, V., Mohammadi-Ghazi, R., 2011, Methods to improve infilled frame ductility, *Journal of Structural Engineering*, 136(6): 646-653.
[12] Morandi, P., Milanesi, R.R., Magenes, G., 2018. Innovative solution for seismic-resistant masonry infills with sliding joints: in-plane experimental performance, *Engineering Structures*, 176, 719-733.

[13] Milanesi, R.R., Morandi, P., Manzini, C.F., Albanesi, L., Magenes, G., 2020. Out-of-plane response of an innovative masonry infill with sliding joints from shaking table tests. *Journal of Earthquake Engineering*. DOI: 10.1080/11632469.2020.1739173.
[14] Preti, M., Bolis, V., Stavridis, A., 2017. Seismic infill-frame interaction of masonry walls partitioned with horizontal sliding joints: analysis and simplified modelling, *Journal of Earthquake Engineering*, 1-27.
[15] Furtado, A., Rodrigues, H., Arede, A., Varum, H., 2020. Impact of the textile mesh on the efficiency of TRM strengthening solutions to improve the infills walls out-of-plane behaviour, *Applied Sciences*, 10, 8745, doi:10.3390/app10238745.
[16] CEN, 2004. Eurocode 8 - *Design of structures for earthquake resistance*, Part 1: *General rules, seismic actions and rules for buildings*, EN 1998-1, European Committee for Standardisation, Brussels, Belgium.
[17] NZEE-2017, New Zealand Society for Earthquake Engineering, 2017. Structural Engineering Society New Zealand Inc. (SESOC), New Zealand Geotechnical Society Inc., Ministry of Business, Innovation and Employment, Earthquake Commission. *The Seismic Assessment of Existing Building (the Guidelines), Part C – Detailed Seismic Assessment*, www.eq-assess.org.nz
[18] Flanagan, R.D., Bennett, R.M., 1999. Bidirectional behaviour of structural clay tile infilled frames, *Journal of Structural Engineering*, 125(3), 236-244.
[19] Morandi, P., Hak, S., Milanesi, R.R., Magenes, G., 2021. In-plane/out-of-plane interaction of strong masonry infills: from cyclic tests to out-of-plane verifications, *Earthquake Engineering and Structural Dynamics*, under review
[20] Milanesi, R.R., Morandi, P., Hak, S., Magenes, G., 2021. Experimental-based out-of-plane resistance of strong masonry infills for codified applications, *Engineering Structures*, under review
[21] Morandi, P., Hak, S., Magenes, G., 2018. Mechanical characterization and force-displacement hysteretic curves from in-plane cyclic tests on strong masonry infills, *Data in Brief*, 16, 886-904.
[22] Drysdale, R.G., Hamid, A.A., Baker, L.R., 1999. *Masonry structures: behaviour and design*. The masonry society, Colorado, USA.
[23] Morandi, P., Hak, S., Magenes, G., 2013. Simplified Out-of-plane Resistance Verification for Slender Clay Masonry Infills in RC Frames, *Proc. XV ANIDIS*, Padova, Italy [in Italian].
[24] Hak, S., Morandi, P., Magenes, G., 2018. Prediction of inter-storey drifts for regular RC structures with masonry infills based on bare frame modelling, *Bulletin of Earthquake Engineering*, 16(1), 397-425.
[25] Stavridis, A., Shing, P.B., 2010. Finite-element modelling of nonlinear behavior of masonry-infilled RC frames, *Journal of Structural Engineering*, 136(3), 285-296.