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OUT-OF-PLANE EXPERIMENTAL RESPONSE OF STRONG MASONRY INFILLS

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ABSTRACT

In line with the current European building practice, clay masonry infills are commonly adopted for the construction of enclosures and partitions in RC frame structures. In order to improve further the understanding of the seismic response of masonry infills in newly designed RC structures, within the scope of a systematic numerical and experimental research program, the response of external masonry infills constructed with tongue and groove clay block masonry units has been studied. Particular attention has been devoted to the evaluation of the out-of-plane response of the infill, related damage propagation and failure mechanisms, as well as the evaluation of the out-of-plane strength in function of previous in-plane damage. This paper presents results of out-of-plane static cyclic tests on full-scale, single-storey, single-bay RC frame specimens with strong masonry infills designed following European seismic design provisions, carried out at the Eucentre and the University of Pavia.

INTRODUCTION

A significant number of investigations related to the performance of masonry infilled frames have been carried out in the past, see *e.g.* Calvi and Bolognini (1996), Crisafulli (1997); however, in particular with reference to certain infill typologies, the effective damage control of newly designed structures has not been sufficiently addressed in previous studies. Most importantly, the complex mechanism of correlated in-plane and out-of-plane infill damage has not received enough attention, even though the significance of the associated effects has been widely recognised and documented, in the light of post-earthquake damage assessment (*e.g.*, Vicente *et al.* 2012), as well as through experimental and numerical investigations (*e.g.*, Fardis *et al.*, 1999).

Based on field observations after earthquakes in European seismic regions during recent years, such as in L'Aquila (Italy, 2009), Lorca (Spain, 2011) and Emilia (Italy, 2012) examples of unsatisfactory masonry infill response have been reported (see Fig. 1), presented *e.g*. by Braga *et al.* (2011), Hermanns *et al.* (2013), Manzini and Morandi (2012), indicating that the damage of masonry infills may contribute significantly to economic losses and cause considerable threats to human lives. Importantly, extensive damage to masonry infills and enclosures has in some cases been observed on recently constructed RC buildings. Therefore, some significant problems related to the limitation of in-plane damage and the prevention of out-of-plane failure in the seismic design of new RC structures still need to be resolved, pointing also to the need for further improvements in the current approach to the verification and detailing of infills.

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Figure 1. Examples of combined in-plane and out-of-plane masonry infill damage (Emilia, Italy - 2012)

In present European seismic design codes (EC 8 – Part 1, 2004), as well as in national code provisions, *e.g.* in Italy (NTC08, 2008), masonry infills are considered as non-structural elements and have to be verified accordingly. Even though the importance to limit the expected damage of infills in the design of new RC buildings is to some extent reflected in commonly adopted design procedures, recommendations and specific measures in many aspects comprise significant deficiencies. In particular, the existing in-plane drift limitations have been found rather general; consequently, considering the variety of possible infill typologies, infill distributions and structural configurations, design choices resulting in a satisfactory response cannot always be ensured (Hak *et al.*, 2012). Furthermore, related to out-of-plane infill resistance verifications, the effect of a possible out-of-plane strength reduction due to previous in-plane damage is not accounted for in the design of new structures (Morandi *et al.*, 2013). On the other hand, in the assessment of existing buildings, the verification for combined in-plane and out-of-plane actions has been included in some of the existing recommendations (*e.g.*, FEMA-306, 1998; Al-Chaar, 2002).

Accordingly, the research interest in the seismic response of contemporary masonry infill typologies has increased notably in the last years (*e.g.*, Asteris *et al.*, 2011; Leite and Lourenço, 2012). However, until now only little experimental data needed for the explicit correlation of the out-of-plane resistance and previous in-plane damage is available (*e.g.*, Calvi and Bolognini, 1999). Investigations related to some types of building enclosures, such as unreinforced and reinforced strong clay block masonry infills, especially related to the combined in-plane and out-of-plane response, have been initiated only very recently (da Porto *et al.*, 2013; Verlato *et al.*, 2013).

In order to improve the current seismic design approach for new RC structures, masonry infill typologies commonly adopted in the present European building practise have been investigated within the scope of a systematic research campaign. In particular, the seismic response of rigid clay masonry infills, constructed in full contact with the surrounding RC frame structure, has been studied. A new experimental campaign has been programmed and carried out at the Eucentre and the University of Pavia in Italy, with the aim to investigate the in-plane and out-of-plane seismic response of a strong masonry infill typology, representing typical building enclosure systems, frequently adopted in European earthquake prone regions. As summarised by Morandi *et al.* (2014), within the framework of the experimental study, some of the principal research objectives were related to the in-plane response, specifically referring to the examination of infill damage patterns and failure mechanisms, the evaluation of the infill deformation capacity and the definition of related performance levels. Subsequent investigations, presented within the scope of this paper, included the evaluation of the out-of-plane response of the strong infill typology, the related damage propagation and failure mechanisms, as well as the assessment of the out-of-plane strength in function of previous in-plane damage.

SUMMARY OF THE EXPERIMENTAL CAMPAIGN

Within the scope of the experimental campaign, a series of cyclic static in-plane and out-of-plane tests has been carried out on bare and fully or partially infilled full-scale single-storey, single-bay RC frames (see Fig. 2), newly designed according to European (and Italian) code provisions. After a detailed characterisation of all material components (*i.e.*, concrete, reinforcing steel, mortar, masonry units and masonry), the experimentation has been accomplished on six frame specimens, as summarised in Table 1.

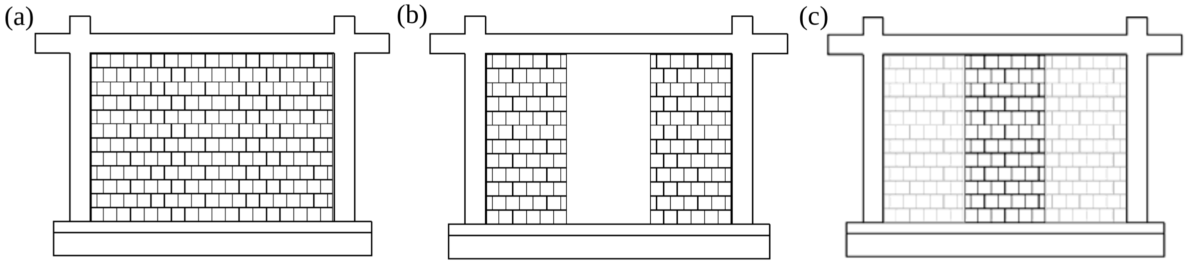
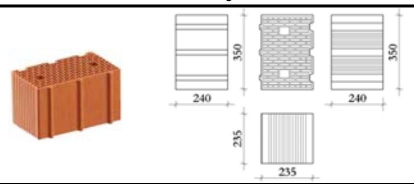


Figure 2. (a) Fully infilled: TA1, TA2, TA3; (b) Partially infilled: TA4; (c) Vertical infill stripe: TA5

Table 1. Summary of performed experiments and achieved maximum drift or displacement levels

Infilled Frame					**Bare Frame**	
No.	**In-plane**	**Out-of-plane**	**Configuration**	**Masonry unit**	**No.**	**In-plane**
TA1	1.50 %	75 *mm*	Fully infilled		**TNT**	3.50 %
TA2	2.50 %	75 *mm*				
TA3	1.00 %	75 *mm*				
TA4	1.00 %	75 *mm*	Partially infilled			
TA5	-	75 *mm*	Infill stripe			

Specifically, related to the cyclic in-plane tests, one RC frame was tested without infill (TNT), while three fully infilled specimens (TA1, TA2 & TA3) were tested at three increasing maximum levels of drift, equal to 1.00, 1.50 and 2.50 %. In addition, a partially infilled frame configuration with a 1.44 *m* wide full-height opening in the middle third of the span (TA4) was tested, reaching a maximum in-plane drift of 1.00%. The out-of-plane experiments have been carried out on the specimens previously damaged in-plane, in order to allow the evaluation of the related out-of-plane resistance reduction. Moreover, a 1.38 *m* wide stripe of the infill (TA5) was tested in the out-of-plane direction, with the aim to evaluate the out-of-plane strength of a previously undamaged specimen under vertical single-bending conditions. The in-plane infill performance at increasing levels of drift was aimed to approximately represent operational, damage limitation and ultimate limit state conditions, while in the out-of-plane direction the achievement of ultimate conditions was envisaged.

The selected typology represents a commonly adopted, traditional strong single-leaf unreinforced masonry infill of 35 *cm* thickness, consisting of vertically hollowed lightweight tongue and groove clay block units (*DANESI Poroton plan 700 TS*), having nominal dimensions of 235x350x235 *mm*, a nominal volumetric percentage of holes of 50% and a minimum thickness of webs and shells equal to 6.8 *mm* and 4.8 *mm*, respectively. The application of a general purpose mortar type M5 (*MM30 Fassa Bortolo*) was considered a suitable choice with respect to common construction practise. The infills have been constructed after full hardening of the RC frame, adopting traditional bed joints, having a thickness of about 1.0 *cm* and dry head joints. The bed joint mortar was applied in two stripes in the longitudinal direction of the wall with an intermediate cavity of about 2.0 *cm* (Fig. 3a). Full contact between the infill and the surrounding RC 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 (Fig. 3b).

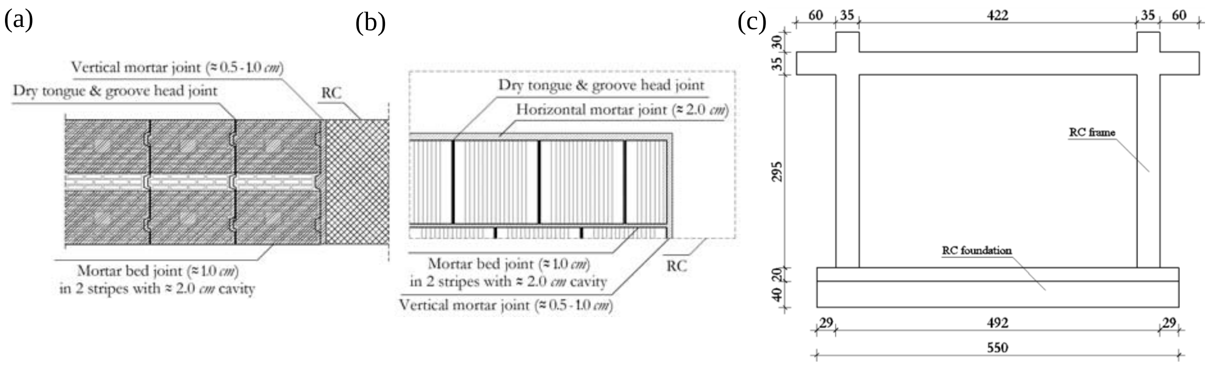


Figure 3. (a) Mortar bed joints; (b) Mortar joints adjacent to RC members; (c) Bare frame

Dimensions of the single-storey single-bay RC frame specimen to be tested have been chosen with the aim to realistically represent the part of a full-scale RC frame structure (Fig. 3c). The design of the specimen, described in more detail by Morandi *et al.* (2014), has been carried out following European code provisions (EC 8-Part 1, 2004; EC 1-Part 1-1, 2001; EC 2-Part 1-1, 2004), supplemented with the Italian national code (NTC08, 2008).

Furthermore, a complete characterisation of the relevant properties for all materials utilised for the construction of the specimens has been carried out, as reported by Hak *et al.* (2013), including the evaluation of unit, mortar and masonry properties for the selected infill typology, as well as compression tests on concrete cubes and tension tests on reinforcement rebars. The values obtained from vertical and lateral compression tests carried out on masonry wallets are reported in Table 2, resulting in a mean compressive strength, for the vertical and the lateral direction, of 4.64 *MPa* and 1.08 *MPa*, respectively. The related characteristic values are equal to 3.86 *MPa* and 0.85 *MPa*. The initial masonry shear strength in the plane of horizontal mortar bed joints has been evaluated based on a series of shear sliding tests on masonry triplets at three levels of compression in the direction orthogonal to the bed joints. As summarised in Table 3, a mean value of initial shear strength under zero compression f_{v0} equal to 0.36 *MPa* has been obtained with a corresponding friction coefficient μ of 1.31, while the corresponding characteristic values are equal to 0.29 *MPa* and 1.05, respectively.

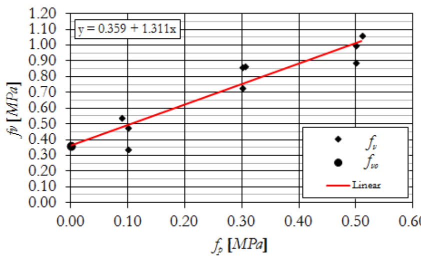
Table 2. Summary of horizontal and lateral compression test results on masonry wallets

Strength	**Vertical**		**Lateral**	
[*MPa*]	$f_{m,i}$	E_i	$f_{m,i}$	E_i
1	4.21	4780	1.29	310
2	5.96	5686	1.11	635
3	4.89	5278	0.85	488
4	3.96	4735	1.23	265
5	4.36	5311	1.11	550
6	4.44	6007	0.91	712

Strength	**Vertical**		**Lateral**	
[*MPa*]	f_m	E	f_m	E
Mean f_{mm}	**4.64**	**5299**	**1.08**	**494**
St. dev.	0.66	455	0.16	162
C.o.v.	14.1%	8.6%	14.5%	32.8%
Char. f_{mk}	**3.86**	-	**0.85**	-

Table 3. Summary of shear sliding test results on masonry triplets

Specimen	$f_{p,i}$ [*MPa*]	$F_{i,max}$ [*kN*]	$f_{v,i}$ [*MPa*]
1	0.10	55	0.34
2	0.30	142	0.87
3	0.50	163	1.00
4	0.51	173	1.06
5	0.50	145	0.89
6	0.30	120	0.73
7	0.30	141	0.86
8	0.09	87	0.54
9	0.10	78	0.48



f_{v0} [*MPa*]	f_{v0k} [*MPa*]	μ	μ_k
0.36	**0.29**	**1.31**	**1.05**

OUT-OF-PLANE TEST SETUP, INSTRUMENTATION AND TESTING PROTOCOL

The in-plane and out-of-plane cyclic static tests were carried out at the laboratory of the Department of Civil Engineering and Architecture of the University of Pavia. A detailed description of the in-plane test setup, the adopted instrumentation and the testing protocol is given by Morandi *et al.* (2014). Furthermore, for the needs of the experimental campaign, the construction of a newly designed steel reaction frame was accomplished, aimed to serve (i) as a reaction frame and as an out-of-plane restraint during the out-of-plane cyclic static tests, (ii) as an out-of-plane restraint during the in-plane cyclic static tests, (iii) as an out-of-plane restraint during future shaking table tests. The static out-of-plane tests needed to be carried out immediately following the in-plane experimentation, since they were performed on masonry infills that have previously sustained a certain level of in-plane damage. Hence, the out-of-pane reaction frame was constructed next to the in-plane setup, such that the specimens for the application of cyclic loading in both directions could remain connected to the strong floor in the same position. Therefore, the out-of-plane setup could be utilised also during the in-plane tests to prevent possible out-of-plane displacements of the RC frame. The steel setup was assembled on a 35.0 *cm* thick RC foundation slab in order to provide a sufficiently rigid support and to ensure a satisfactory transfer of forces to the strong floor. The steel structure was conceived consisting of a central reaction plane serving as a support for the actuator introducing the horizontal load on the masonry infill and two external restraining planes, as illustrated in Fig. 4.

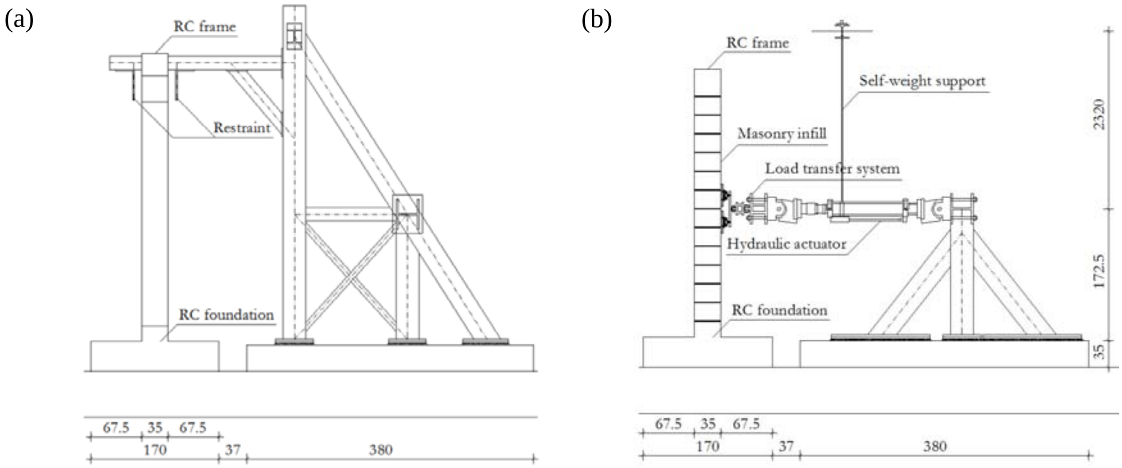


Figure 4. Layout of the out-of-plane test setup: (a) Restraining plane; (b) Reaction plane

The three structural planes were connected in the transversal direction with a steel beam allowing the attachment of the actuator. Additionally, above the actuator, the two restraining planes were connected with a steel profile that provided support for the self-weight of the actuator. In the restraining planes, the steel reaction frame was connected to the beam of the RC frame specimen. Specifically, L-shaped steel profiles attached to the cantilever beams reaching above the specimen were used as restraints to prevent the out-of-plane displacement of the RC frame and to allow the application of horizontal out-of-plane loads on the masonry infill. The load was applied at the mid-height of the masonry infill by means of a servo-controlled hydraulic actuator with an internal load cell, having a capacity of 650 *kN* and 450 *kN*, respectively, in push and pull directions. The length of the actuator at mid stroke was equal to 2534.0 *mm*, allowing ± 203.0 *mm* of displacement.

The design of the steel reaction frame was carried out assuming a maximum horizontal force of $F_{o,\max}$ = 600 *kN*, aimed to provide sufficient stiffness. The horizontal force resisted by the masonry infill was in part transmitted to the foundation of the specimen, *i.e.*, directly to the strong floor, while in part it was sustained by the out-of-plane restraints of the steel frame, counteracting the reaction of the actuator. Consequently, the obtained system was partially self-equilibrated, such that, ensuring adequate load transmission at the restrained points on the beam of the RC frame, the transfer of about 40% of the horizontal force through the restraints was assumed. In order to transfer the load from the actuator to the masonry infill, a system consisting of a series of hinged steel beams and plates was developed, allowing the introduction of the horizontal force in a relatively large number of discrete points, as illustrated in Fig. 5a. In particular, for the fully infilled frame specimens (TA1, TA2 and TA3) the forces were applied in two lines and eight points per line, reproducing an approximately linear load distribution at the mid-height of the panel. For the partially infilled configuration (TA4) the force was introduced through four points on each part of the infill, while for the infill stripe (TA5) the load introduction through eight central points was aimed to reproduce vertical single-bending.

For the evaluation of out-of-plane displacements of the tested masonry panel and with the aim to control possible displacements of the surrounding RC frame and the foundation of the specimen during the out-of-plane test, displacement transducers (linear potentiometers) have been adopted. In total, 30 potentiometers have been used for the fully infilled frame specimens (TA1, TA2 and TA3), 38 for the partially infilled configuration (TA4), and 28 for the infill stripe (TA5). The out-of-plane displacements of the masonry infill have been measured by means of 20 instruments for the fully infilled configurations (see Fig. 5b), 26 for the partial infill, and 18 for the infill stripe (see Fig. 5c), distributed symmetrically throughout the panel. For all infill configurations the out-of-plane displacements of the RC frame have been monitored using two potentiometers in the beam-column centreline intersections and one instrument at mid-height of each column. For the fully infilled frame three additional instruments were placed within the beam span, while one potentiometer at the centre of the beam was used for the partially infilled frame and the infill stripe. Vertical displacements of the beam were also measured, using six potentiometers for the partially infilled frame and two potentiometers for the infill stripe. The sliding of the foundation was monitored with three instruments for both types of infilled configurations and with one for the infill stripe.

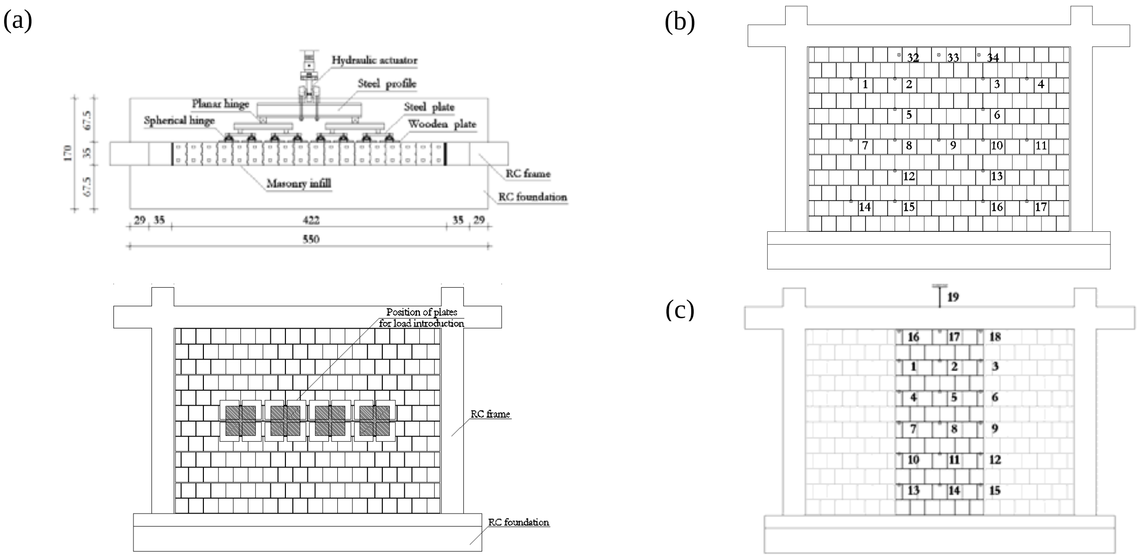


Figure 5. (a) Out-of-plane load transfer system; (b) TA1, TA2, TA3, and (c) TA5 instrumentation layout

The test in the out-of-plane direction has been accomplished using the steel structure designed to act as a reaction frame and to provide adequate restraining of the specimen, preventing out-of-plane displacements of the frame. In addition, a concentrated vertical force of 400 *kN* was imposed on each RC column and kept constant during the test. Therefore, two independent hydraulic jacks, each placed between the column and a rigid transversal steel beam tied down to the foundation with two steel bars, have been used, resulting in a self-equilibrated vertical load introduction system. At the beginning of the test the actuator and the out-of-plane restraints have been brought in position and the system for the horizontal load transfer has been placed in contact on the masonry infill. The cycles of horizontal out-of-plane load were imposed on the infill by means of the actuator, loading in one direction (push) and back to zero force. Firstly, two different levels of force-controlled loading were accomplished; subsequently, displacement-controlled loading cycles at increasing levels of maximum displacement at the centre of the panel were imposed. For each level of loading (*i.e.*, target force or displacement) three complete loading cycles have been carried out and the duration of load application has been kept approximately constant. During unloading, a minimum force of ca. 5.0 *kN* has been maintained in order to ensure complete contact between the loading system and the panel.

INTERPRETATION OF OUT-OF-PLANE EXPERIMENTAL RESPONSE

The results of cyclic out-of-plane tests for the fully infilled frame configurations (TA1, TA2 and TA3), carried out following the corresponding in-plane tests, and for the undamaged vertical infill stripe (TA5) have been evaluated in terms of hysteretic force-displacement curves. The control displacement, assumed to represent the cyclic response corresponds to the out-of-plane displacement at the centre of the panel, matching the centre-line of the actuator used to introduce the horizontal out-of-plane load. The largest target displacement imposed by the actuator on the load introduction system was set equal to 75 *mm* for all masonry infills, resulting, in function of the previous in-plane damage and the achieved resistance mechanism, in somewhat higher corresponding values of displacement at the centre of the specimen. The cyclic force-displacement response and the corresponding envelope obtained for specimens TA1, TA2 and TA3 is presented in Fig. 6a, b and c, respectively, while a comparison of the force-displacement envelopes is shown in Fig. 6d.

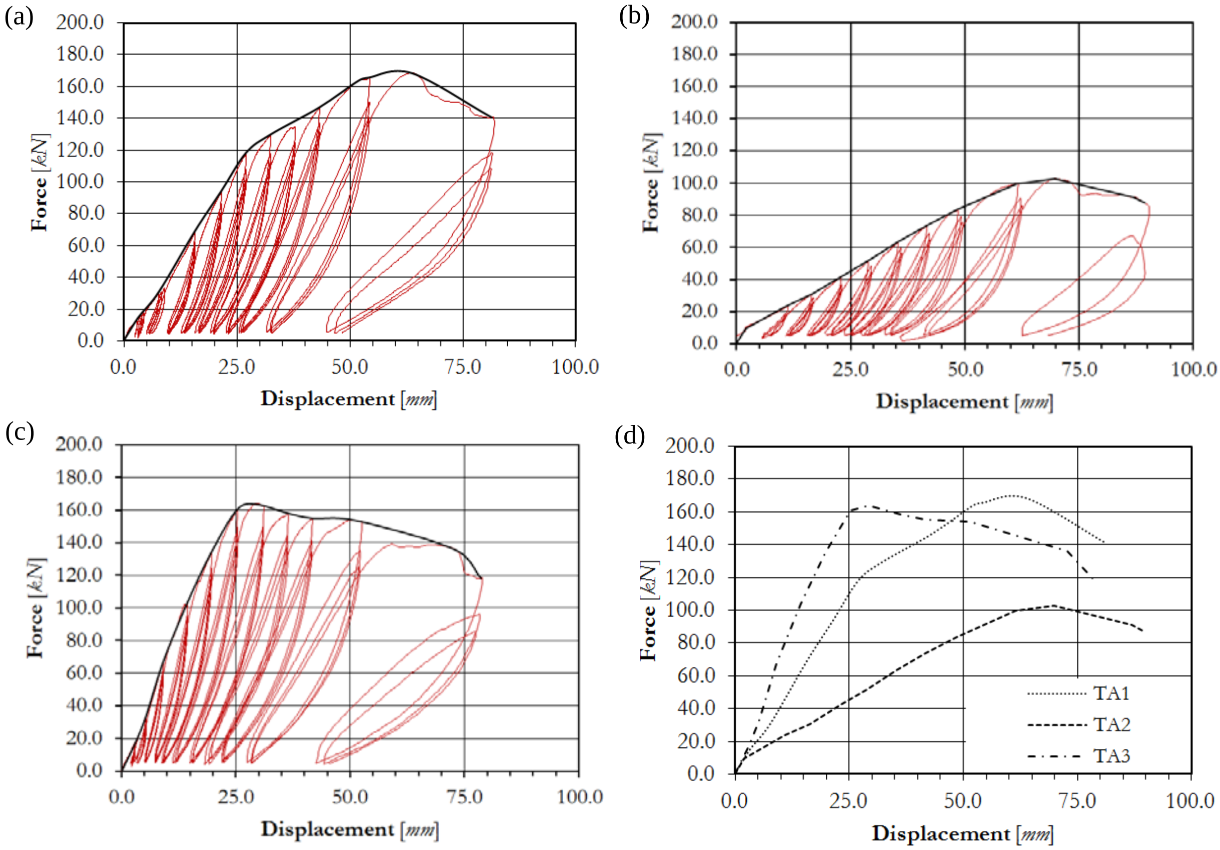


Figure 6. Force-displacement response: (a) TA1, (b) TA2, (c) TA3, (d) Comparison of TA1, TA2 & TA3

The results demonstrate clearly the significant degradation of stiffness and strength in the out-of-plane direction for increasing values of previous in-plane drift and related damage, in particular related to relatively high levels of drift and extensive preceding damage. Specifically, for specimens TA3 and TA1, which were previously subjected to in-plane drifts of 1.0 % and 1.5 %, respectively, similar values of peak resistance have been obtained (equal to 163.9 *kN* and 168.5 *kN*), but a significant stiffness degradation, equal to approximately 40 %, has occurred. For specimen TA2, which had sustained an in-plane drift of 2.5 %, the peak resistance has dropped to 102.7 *kN*, in addition to a reduction of stiffness equal to about 75 %, with respect to the stiffness of specimen TA3.

Referring to the damage propagation observed during the test on the fully infilled configurations, a more detailed description is firstly given for the infill that was subjected to the largest level of in-plane drift (*i.e.*, 2.5 %) prior to the out-of-plane test (specimen TA2). Specifically, first residual deformations of the infill occurred at a displacement of 10 *mm* and the creation of a crack at the joint between the masonry panel and the beam was observed. The initial behaviour of the infill indicated a cantilever wall response; however, at the following loading cycles, in particular once a target displacement of 20 *mm* was achieved, the formation of an arching action mechanism could be distinguished. Horizontal cracks in the mortar bed joints propagated further, in particular in the joint at mid-height of the panel. Subsequently, imposing a displacement of 25 *mm*, the arching action continued to develop and residual displacements became more pronounced. Some outer shells of masonry blocks previously damaged in-plane detached and fell off. Reaching a target displacement of 30 *mm*, the vertical boundaries of the infill started to separate from the adjacent columns. Cracking noise due to the repositioning of masonry blocks in the infill could be noticed and the crack between the infill and the beam increased substantially. Imposing the following displacement level (35 *mm*), the crack between the infill and the column widened progressively, the central horizontal crack at the centre of the panel opened further and diagonal stepwise cracks towards the corners of the infill, particularly in the bottom half of the infill, could be distinguished. Subsequently, during the loading cycles reaching a displacement of 40 *mm*, the infill bulged evidently and further masonry blocks were damaged. At a target displacement of 50 *mm*, the cracks in the region of contact between the infill and the columns developed further. Moreover, some local damage due to crushing of masonry was observed, partly caused by the concentration of forces in the central part of the panel close to the steel plates used for the load transfer, but no actual local failure was identified. Reaching the maximum displacement level (75 *mm*), the force-displacement curve of the infill started to degrade notably and the arching action mechanism appeared to be diminishing, both in the horizontal and in the vertical direction. Significant residual deformations showing a bulged shape of the infill and a noticeable out-of-plane slip of the panel with respect to the columns remained at the end of the last loading cycle. The damage was spread throughout the infill, both due to the formation of new cracks and due to previous in-plane damage. The damaged specimen TA2 during the test at the maximum level of imposed out-of-plane displacement (75 *mm*) and the corresponding characteristic crack pattern are shown in Fig. 7a and b, respectively.

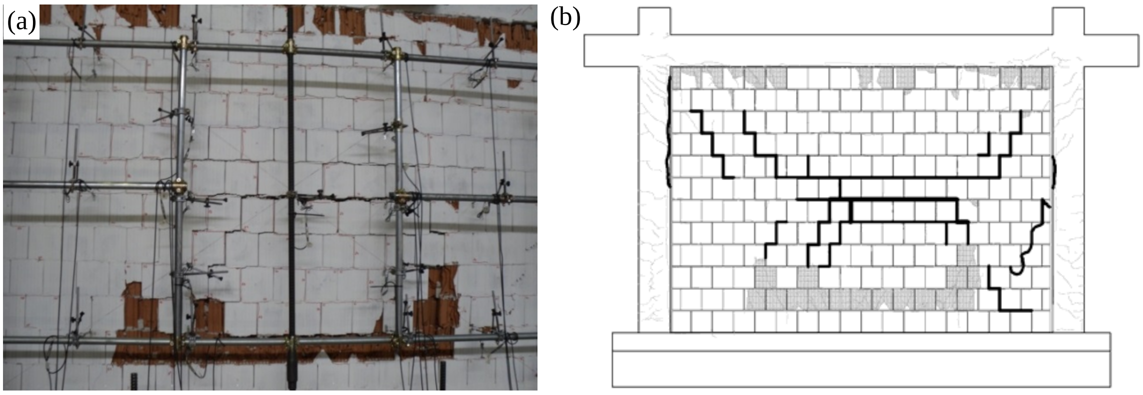


Figure 7. Specimen TA2 (previous in-plane drift: 2.5 %): (a) Damage at 75 *mm* target displacement; (b) Crack pattern (in black – out-of-plane damage; in grey – previous in-plane damage)

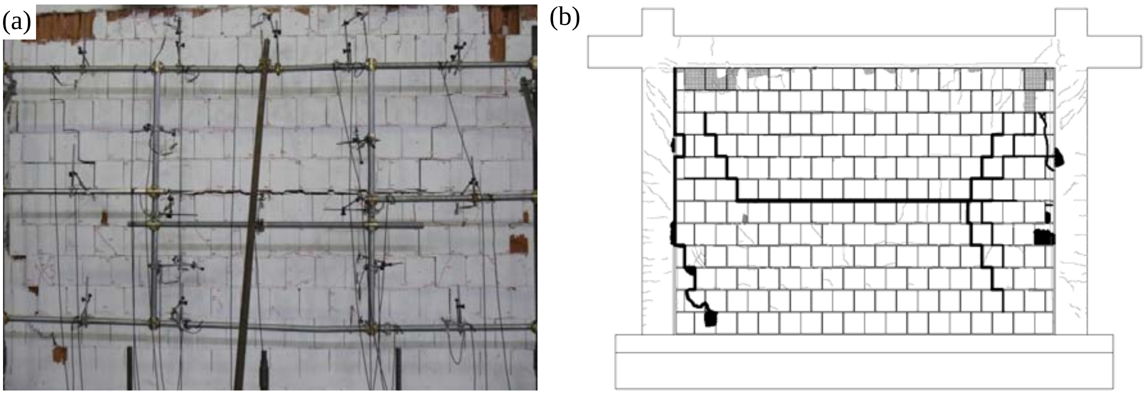


Figure 8. Specimen TA1 (previous in-plane drift: 1.5 %): (a) Damage at 75 *mm* target displacement; (b) Crack pattern (in black – out-of-plane damage; in grey – previous in-plane damage)

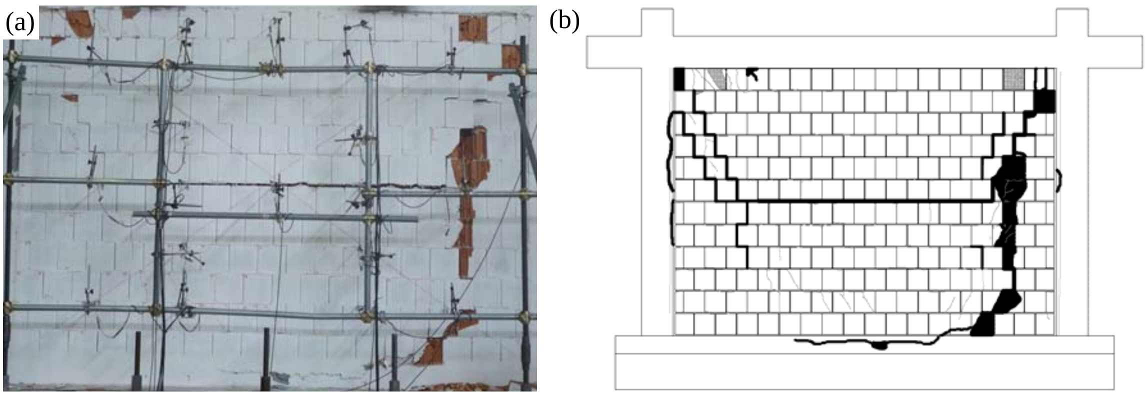


Figure 9. Specimen TA3 (previous in-plane drift: 1.0 %): (a) Damage at 75 *mm* target displacement; (b) Crack pattern (in black – out-of-plane damage; in grey – previous in-plane damage)

A comparable response was observed during the out-of-plane tests of the fully infilled frame specimens TA1 and TA3, which were subjected to lower levels of previous in-plane drift, *i.e.*, 1.5 % and 1.0 %, resulting in correspondingly less extensive damage, as well as higher out-of-plane resistance. Accordingly, in the case of specimen TA1 (Fig. 8a and b), the creation of a predominant horizontal crack at the central joint of the infill was identified accompanied with the development of a diagonal stepwise crack pattern towards the corners of the infill. Nevertheless, on the bottom left side of the panel the stepwise cracking was less pronounced and the failure of a series of blocks in the region along the left RC column and in the left bottom corner was observed instead. On specimen TA3 (Fig. 9a and b), in addition to the pronounced central horizontal crack and the characteristic diagonal stepwise crack pattern towards the corners of the infill, which was particularly pronounced in the upper half of the panel, extensive damage occurred in the region where the upper right stepwise crack joins the central horizontal crack. The failure of several masonry blocks was observed and a significant slip of the masonry blocks along the diagonal crack remained after the test. A comparison of the deflected shape of the infill for the fully infilled configurations corresponding to the first cycle of the 50 *mm* and the 75 *mm* target displacement is shown in Fig. 10a, b, c and Fig. 10d, e, f, respectively. The displacement profile of the panel has been approximated based on the displacements recorded using the installed potentiometers (see Fig. 5b), assuming a linear interpolation between the available points of measurement.

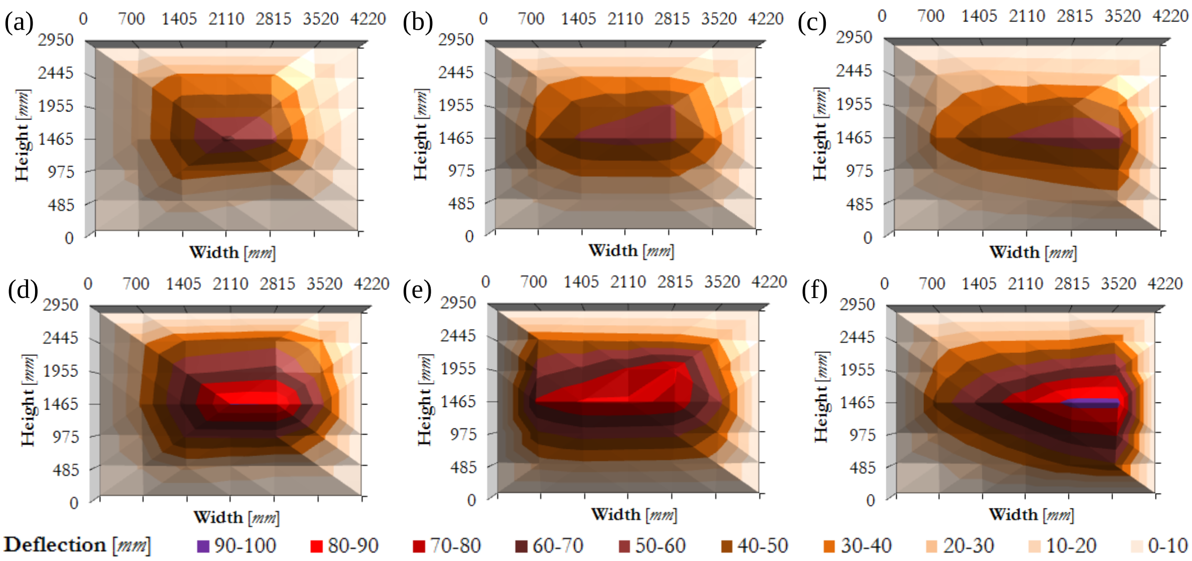


Figure 10. Deflection of fully infilled specimens at 50 *mm* target displacement: (a) TA2, (b) TA1, (c) TA3 and at 75 *mm* target displacement: (d) TA2, (e) TA1, (f) TA3

Summarising the response of the tested fully infilled configurations, a typical infill failure mechanism for the given strong masonry typology has been identified, characterised by the opening of a predominant horizontal crack at mid-height of the panel and the creation of a stepwise crack pattern, starting from the central crack and developing diagonally towards the corners of the infill. Such response underlines the formation of a double-bending resistance mechanism, based on out-of-plane arching action in both, the horizontal and the vertical direction. In addition, the response may be accompanied by the local failure of masonry blocks, such as in the region where the horizontal and the stepwise cracks join together. Clearly, the progression of local masonry damage is considerably influenced by the previous in-plane damage distribution.

The cyclic force-displacement response and the corresponding envelope obtained for specimen TA5, representing a vertical masonry stripe under single-bending conditions, is shown in Fig. 11a. Corresponding to a number of selected characteristic points on the force-displacement envelope, the deflection of the specimen along the height, presented in Fig. 11b, has been evaluated as the average of the displacements measured by means of the potentiometers installed during the test (see Fig. 5c). The corresponding progressive propagation of damage during the test is illustrated in Fig. 12a for a cross section view of the specimen, while the damaged specimen during the test at the maximum level of imposed out-of-plane displacement (75 *mm*) is shown in Fig. 12b.

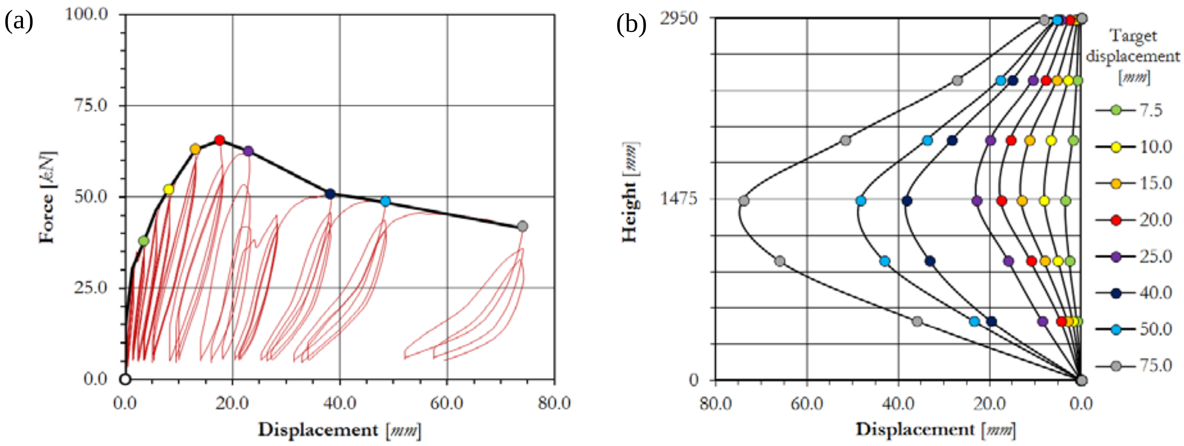


Figure 11. Specimen TA5: (a) Force-displacement response; (b) Deflection along the height

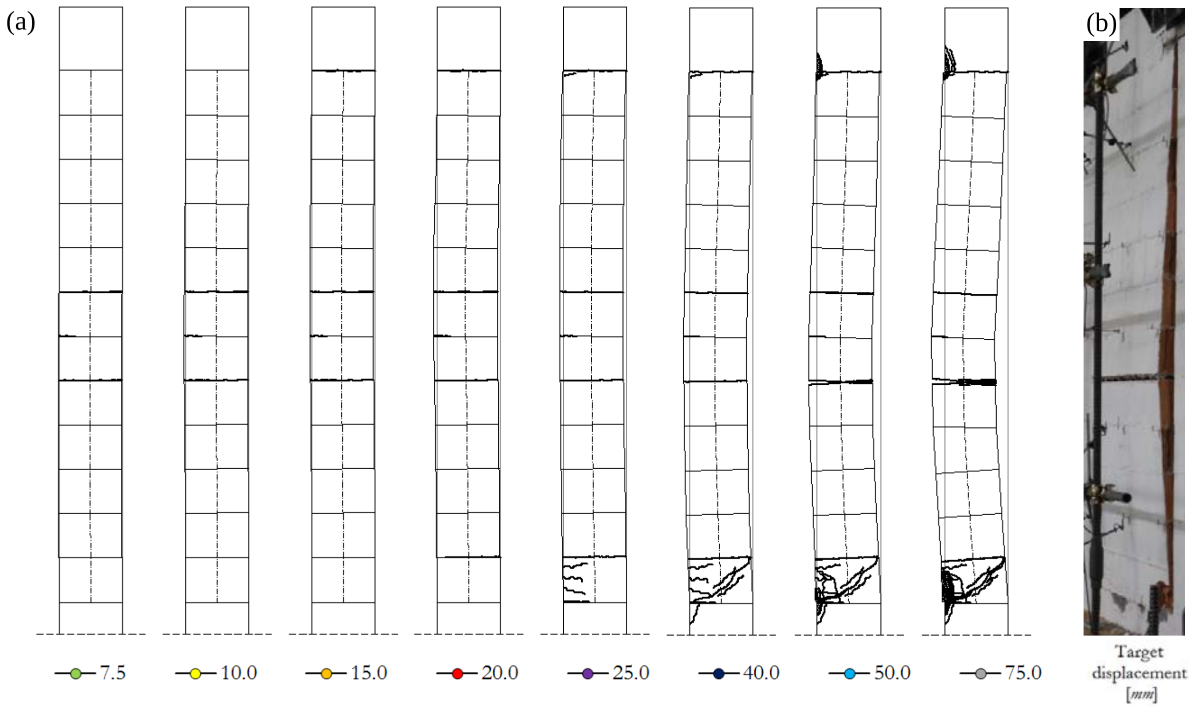


Figure 12. Specimen TA5: (a) Progression of damage; (b) Damage at 75 *mm* target displacement

During the first levels of loading, up to a target displacement of 10 *mm*, the development of a number of light horizontal cracks in the masonry bed joints could be observed, firstly one course below, then one course above the centre of the panel, and subsequently, at the central joint. Increasing the demand to 20 *mm*, cracks started to form on the plaster at the interface between the infill and the RC beam. On the back side of the specimen a crack in the mortar joint above the first course of blocks was observed and the creation of a vertical arching mechanism could be clearly distinguished. At the following target displacement (25 *mm*) the characteristic horizontal cracks in the mortar bed joints became more pronounced. Additionally, the formation of cracks at the interface between the infill and the foundation of the frame was observed, as well as the development of slight damage of the blocks in the bottom course. Reaching an imposed displacement of 30 *mm*, the detachment of concrete pieces at the bottom of the specimen was noted, underlining the flow of forces and the concentration of stresses caused by the arching action. Consequently, noticeable damage of the blocks in the first course due to local compression started to develop, causing the detachment of some outer masonry shells. Subsequently, achieving a displacement demand of 40 *mm*, an inclined sliding surface appeared to form through the masonry blocks of the bottom course, reaching from the joint above the first course at the back side of the panel towards the interface between the infill and the foundation at the front side of the specimen. The corresponding displacements due to sliding at the bottom course became evident during the following levels of increased loading, in particular at a target displacement of 50 *mm*. Furthermore, the horizontal crack above the fifth course resulted to be the most pronounced and started to open evidently. Hence, the arching action mechanism was apparently achieved through the equilibrium of two rigid bodies, with an upper support at the interface between the infill and the beam, a bottom support at the crack of the first course and the intermediate hinge of the arch at the crack in the mortar joint above the fifth course. Reaching the final loading level, corresponding to 75 *mm*, the outer shells of several blocks in the first course fell off, pointing to the occurrence of compression failure, in accordance with the observed displacement due to sliding and the concrete damage in the region of support.

CONCLUSIONS

The present paper focused on some aspects of an experimental study carried out with the aim to improve the understanding of the cyclic response of rigid masonry infills, commonly adopted for building enclosure systems in seismic regions, with particular interest in the combined action of in-plane and out-of-plane horizontal loads. Within the scope of this work, a strong masonry infill typology constructed using tongue and groove clay masonry blocks has been considered. Following a brief description of the experimental campaign, major results of the material characterisation have been summarised, the new test set-up developed for the needs of this study has been described and the testing protocol has been introduced. For the case of fully infilled frame configurations, previously damaged in-plane, tested under double-bending conditions, results obtained from the accomplished out-of-plane tests have been summarised and the related propagation of damage has been discussed. The obtained values of out-of-plane strength, equal to 168.5 *kN*, 102.7 *kN* and 163.9 *kN* for specimens TA1, TA2 and TA3, respectively, correspond to equivalent accelerations of 4.4*g*, 2.7*g* and 4.3*g*, indicating that for such strong masonry infill typologies, adherent to the r.c. frame, the out-of-plane stability does not present a critical issue. Moreover, for the given infill typology, the formation of a resistance mechanism based on two-directional arching action has been found and a typical out-of-plane failure mechanism has been identified, characterised by the opening of a predominant horizontal crack at mid-height of the panel and the creation of a stepwise crack pattern, starting from the central crack and developing diagonally towards the corners of the infill. Furthermore, the out-of-plane response of a previously undamaged masonry stripe tested under vertical single-bending conditions has been evaluated.

Based on the obtained results, the out-of-plane stiffness and strength can be related to previous in-plane damage. Accordingly, the out-of-plane strength may be expressed in function of previous in-plane drift. Hence, a simplified model describing the out-of-plane strength reduction, such as illustrated in Fig. 13, may be proposed. Even though the resistance for an undamaged panel, based on conservative assumptions, may be evaluated extrapolating the results obtained for the specimen tested under single-bending conditions, for the introduction of a strength reduction model such approach may not necessarily be safe-sided. Therefore, the obtained experimental results may be used for further considerations towards the development of analytical solutions with the aim to relate the out-of-plane response under single-bending and double-bending conditions. Nevertheless, given the rather small extent of in-plane damage for the considered infill typology at low levels of in-plane drift (*i.e.*, at 1.0 %), a relatively low corresponding out-of-plane strength degradation is expected.

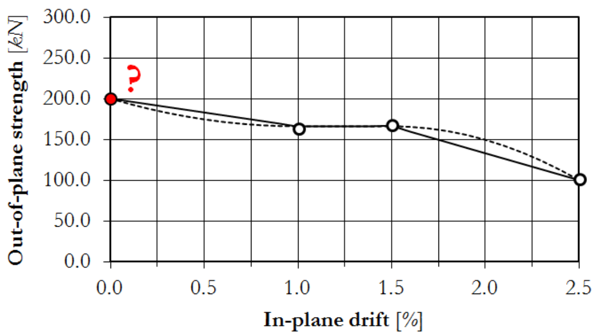


Figure 13. Out-of-plane strength reduction in function of in-plane drift

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