

ENHANCING EARTHQUAKE PERFORMANCE OF MASONRY INFILLED REINFORCED CONCRETE FRAMES BY WALL TIE ANCHORS

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Abstract: Reinforced concrete (RC) frames, with or without unreinforced masonry (URM) infill walls, are commonly treated in design as moment resisting frames, with different detailing possibilities. If the design is governed by seismic or wind actions, the crucial part in performance of the structure will be the frame-wall interaction as well as their connection. The connection may be formed by itself i.e. by mortar joints, however it's subject to early failure already at inter-story drifts of $d_r=0.05\%$, and with their increase e.g. $d_r=0.5 - 1\%$, walls or parts of walls may fall out. Particularly in the out-of-plane (OoP) direction, mortar joints are hardly able to absorb the accelerations and thus the resulting forces. This leads to an early failure of the wall, and it can no longer provide support for the frame structure. Such a connection could involve various metal connectors. This paper gives an overview of the design and the test methods employed with respect to the effectiveness of specially designed wall tie anchors in enhancing earthquake performance of URM infilled RC frames. The in-plane (IP) and the out-of-plane (OoP) tests were performed on 1/2.5 scaled URM infilled RC frames designed in compliance with EN 1992-1-1 and EN 1998-1 as moment resisting frames with medium level of seismic detailing (DCM). The brick and block URM infill wall types, built in compliance with EN 1996-1-1 and EN 1998-1, were considered. There were four frames in total, of which, two used for drift driven OoP tests (deflection oriented) were repaired and used again for inertial (push-out) OoP tests. As compared to their non-anchored counterparts, the tests revealed more favourable wall damage evolution of URM infill walls, followed by the composite frame-wall interaction up to inter-story drift of $d_r>2\%$, both IP and OoP, thus enhancing its earthquake performance.

1. Introduction

Building survey in Durrës, Albania after $M_w=6.4$ 2019 heavily damaging earthquake ($I_{EMS}=VIII$), conducted by the „American Concrete Institute (ACI)“ Technical Committee 133 „Disaster Reconnaissance“ task group (Chungwook *et al.*, 2020), found that the unreinforced masonry (URM) infill walls, integrated with the reinforced concrete (RC) frames, built in compliance with contemporary building code requirements e.g. (KTP-N.2-89, 1989; EN 1998-1, 2004), suffered very heavy damage or destruction i.e. Grade 4 or 5, respectively, in compliance with EMS-98 (Grünthal *et al.*, 1998), while, on the other hand, RC frames suffered slight or moderate damage i.e. Grade 1 or 2, respectively, as shown in Figure 1 (Abrahamczyk *et al.*, 2022a, 2022b).



Figure 1. Damage to URM infilled RC frame buildings after $M_w=6.4$ ($I_{EMS}=VIII$) 2019 Durrës, Albania earthquake: a) view of the damaged building; b) very heavy damage or destruction of URM infill walls; c) slight or moderate damage of RC frames (Grünthal et al., 1998; Chungwook et al., 2020; Abrahamczyk et al., 2022a, 2022b)

The URM infill walls sustained damage in the form of corner crushing and diagonal cracking, bed joint sliding and out-of-plane “walking-out” failure caused by the in-plane (IP) action, beam-to-infill interface separation and diagonal cracking failure caused by the out-of-plane (OoP) action i.e. Grade 4 or 5, respectively, in compliance with (FEMA 306, 1998; Grünthal *et al.*, 1998). Such observations were also evident earlier by shake table tests (Penava and Sigmund, 2017; Guljaš *et al.*, 2018) performed on a 1/2.5 scale three-storey RC frame building with masonry infill walls (see Figure 2). The RC frames of the test building were designed and constructed as medium ductility (DCM) moment-resisting frames in compliance with (EN 1992-1-1, 2004; EN 1998-1, 2004). Masonry infill walls were built from clay blocks laid in M5 general purpose cement-lime mortar (in the first test series) or clay bricks with addition of RC confining elements along vertical opening edges (in the second test series), in compliance with the regulations for structural masonry (EN 1998-1, 2004; EN 1996-1-1, 2005). The tests in both series were conducted by applying the $M_w=7.0$ ($I_{EMS}=X$) 1979 Herzeg Novi, Montenegro very destructive earthquake record by increasing its peak ground acceleration (PGA) value from 0.05 up to 1.2 g (1.4 g in the second series) by 0.1 g. In contrast to the first, the retrofitted building in the second test series experienced less variable and substantial to heavy damage i.e. Grade 3 (in the form of diagonal cracking) to masonry infill walls without destruction. The retrofitting prompted the participation of the infill walls during the entire duration of the earthquake in both, the IP and the OoP direction. During the test, a special type of OoP wall failure was observed as a result of transverse movement of the frame on clay block masonry infill walls of Series 1 tests (Penava and Sigmund, 2017).

In addition, a series of quasi-static tests was performed on a 1/2.5 scaled single-bay, single-storey RC frames with URM (clay block or brick laid in M5 general purpose cement-lime mortar) infill walls, with and without openings, and with and without RC confining elements along vertical opening edges (as a form of retrofitting), in IP (Penava, 2012; Sigmund and Penava, 2014; Grubišić, 2016) and OoP direction (Penava and Sigmund, 2017; Anić *et al.*, 2020, 2021; Pradhan *et al.*, 2021; Anić, 2022). The objective was to assess the influence of opening type, size and position on shear resistance and earthquake performance characteristics (limit states).

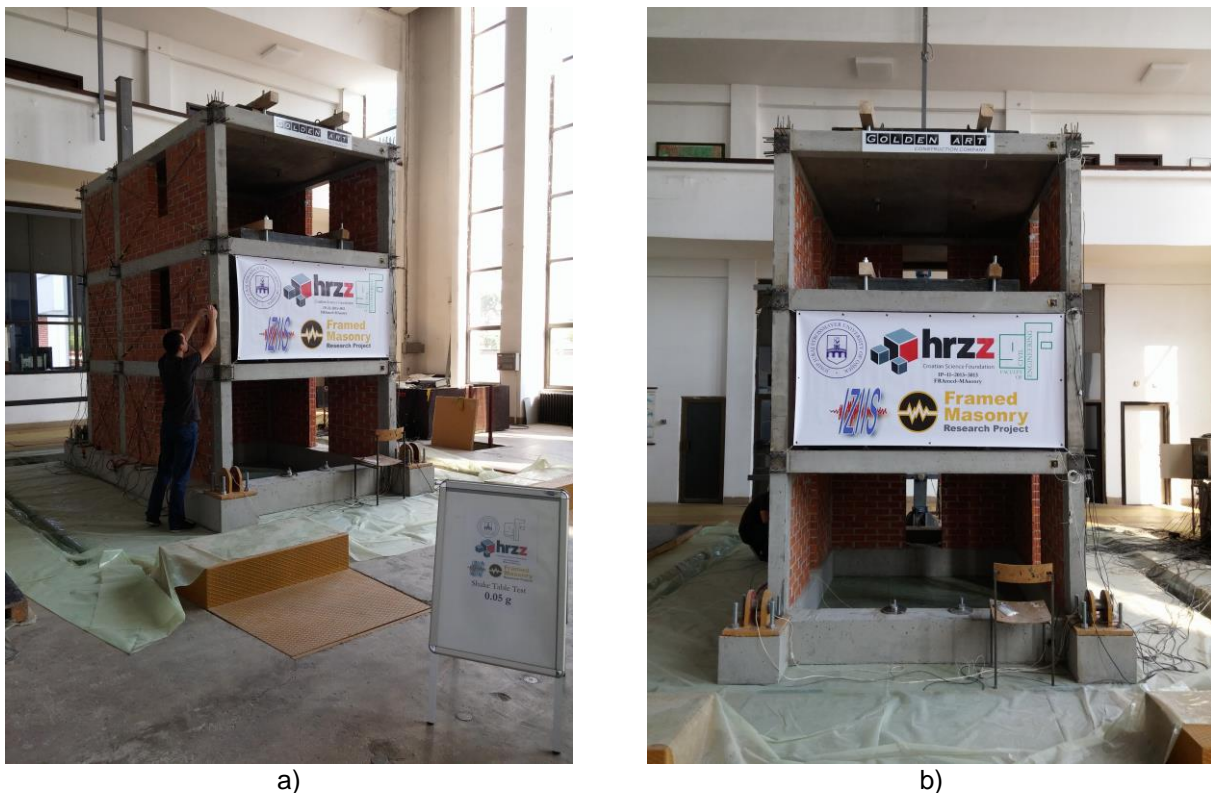


Figure 2. Building on the shaking table before testing: a) Series 1, with clay block masonry and no vertical confining elements, and b) Series 2, with clay brick masonry and vertical confining elements (Sigmund, 2014; Guljaš *et al.*, 2018)

It was observed that the RC frames with masonry infill walls, constructed in compliance with (EN 1992-1-1, 2004; EN 1998-1, 2004; EN 1996-1-1, 2005), could exceed the drift ratio of 1 % (0.5 % in the case of door openings) up to 1.25 % and contributing to the shear resistance of the RC frame in IP direction before destruction. On the other hand, it was observed that the masonry infill wall doesn't contribute to the shear resistance of the RC frame in the OoP direction under the drift-driven tests, however it is affected by its movement (e.g. beam-to-infill interface separation).

In order to correct the by tests and damage survey observed deficiencies of the IP and in particularly the OoP earthquake performance of RC frames with URM infill walls, the effect of specially designed wall tie anchors built-in in RC frame columns and URM infill wall bed joints was assessed by tests that matched the design, construction and setup of tests performed by (Penava, 2012; Sigmund and Penava, 2014) for IP and (Anić *et al.*, 2020, 2021; Anić, 2022) for OoP direction, respectively. A total of 12 shear tests were carried out on RC frames with clay block or clay brick masonry infill walls, of which 4 in the IP direction and 8 in the OoP direction, of which 4 were drift-driven (OoP loading of the frame) and 4 were push-out (OoP loading of the wall) tests, respectively. After the frame was tested, it was repaired and tested again. In the case of OoP tests, the drift-driven tests were performed first, and afterwards the push-out tests on previously damaged walls. In addition, the OoP push-out tests were performed on non-damaged masonry infill walls without anchors for the purpose of comparison. This paper presents the results of tests on previously non-damaged frames i.e. 8 tests in total.

As compared to their non-anchored counterparts, the tests revealed more favourable damage progression on URM infill walls (in particularly in the case of clay brick masonry), followed by the composite frame-wall interaction up to interstorey drift of $d_r > 2\%$, both IP and OoP direction, respectively, thus enhancing its earthquake performance.

2. Construction of test structures and test methods

2.1. Construction of model structures

A total of four 1/2.5 scaled single-bay, single-storey RC frames were designed and constructed as medium ductility (DCM) moment-resisting frames in compliance with (EN 1992-1-1, 2004; EN 1998-1, 2004) with concrete C30/37 and B500B reinforcement class, respectively. Masonry infill walls were built from clay blocks (length \times width \times height = 25 \times 12 \times 10 cm) or bricks (length \times width \times height = 25 \times 12 \times 6 cm) laid in M5 general purpose cement-lime mortar, in compliance with the regulations for structural masonry (EN 1998-1, 2004; EN 1996-1-1, 2005). The prototype details were adopted from (Zovkić, Sigmund and Guljaš, 2013). The frame elements were reinforced with ribbed reinforcing bars (longitudinal reinforcement $\varnothing 10$ mm for columns and $\varnothing 10$ mm and $\varnothing 6$ mm for beams). Stirrups in columns were $\varnothing 6$ mm and placed at a spacing of 7.5 and 15 cm, and in beams $\varnothing 6$ mm placed at a spacing of 10 and 20 cm. Reinforcement details are shown in Figure 3.

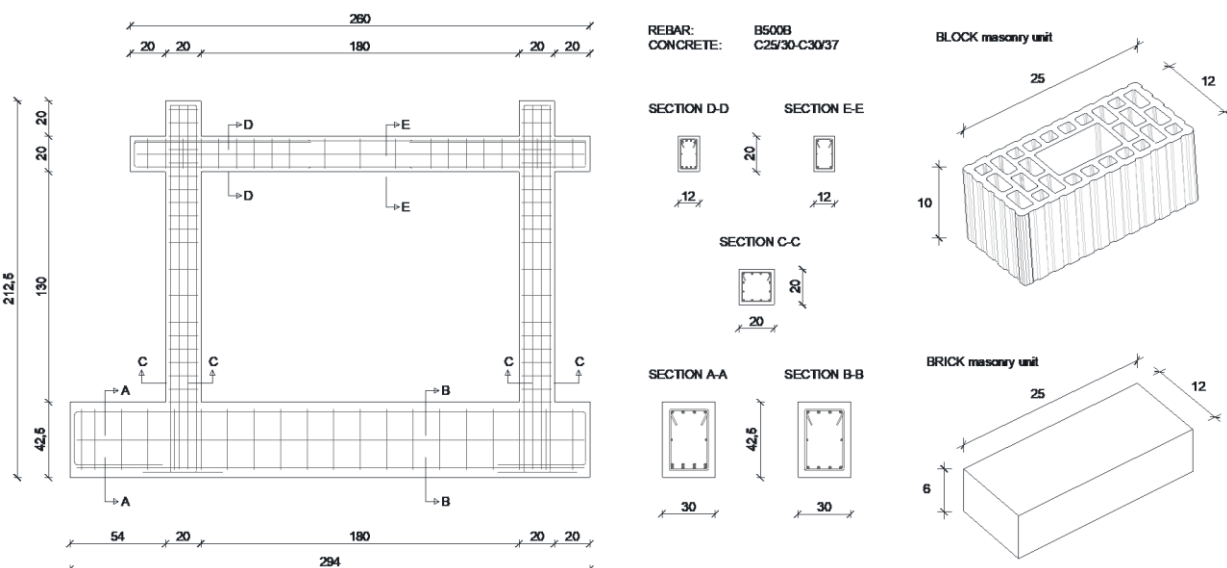


Figure 3. Reinforcement details of test RC frames (measures in cm) and clay block masonry unit used

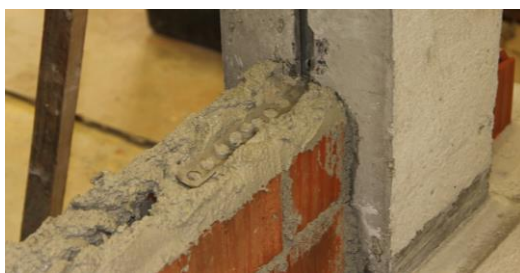
The mechanical properties of built-in materials were determined in compliance with (EN 12390-3:2009, 2009) for concrete, (EN 10080:2012, 2012) for reinforcement, and (EN 1052-1:2004, 1998; EN 772-3:1998, 1998; EN 1052-2:1999, 1999; EN 1015-11:1999/A1:2006, 2006; EN 772-1:2011, 2011) for masonry mortar, units and walls, as shown in Table 1.

Table 1. Mean values of mechanical properties of built-in materials

Property	Value		Units
Concrete:			
Compressive strength	54.5		MPa
Secant modulus of elasticity of concrete	39100		MPa
Reinforcing steel:			
	∅ 6 mm	∅ 10 mm	
Yield / ultimate tensile strength	594 / 699	564 / 589	MPa
Modulus of elasticity	207000	188000	MPa
Strain at yield / maximum force / ultimate	5.0 / 28.5 / 77.9	5.0 / 24.8 / 60.8	%
Masonry units, mortar & masonry wallets:			
	Clay block	Clay brick	
Masonry unit	Perpendicular and		MPa
compressive strength:	Parallel to bedjoints		MPa
Masonry mortar compressive strength:			MPa
Masonry wallet:			
Compressive strength			MPa
Initial shear strength			MPa
Out-of-plane bending tests (clay block) and diagonal tension / shear (clay brick):	Parallel to bedjoints		MPa
	Perpendicular to bedjoints		MPa

Note: Compressive strength of clay block masonry units with 50% voids, and compressive and shear strength of masonry wallets are based on gross area

The anchorage system was assembled by installing the steel rails in the formwork on the column's inner faces prior to concrete pouring. Wall tie anchors were positioned in every second, in case of clay block, and every third mortar bedjoint, in case of clay brick masonry infill walls (see Figure 4).



a)



b)

Figure 4. Positioning of wall tie anchors: a) clay block, and b) clay brick masonry

In summary, four RC frames were built, of which two were infilled with clay block, while the other two with clay brick masonry. The tests were performed in RC frame's out-of-plane (OoP) and in-plane (IP) direction for each particular masonry infill wall case (type).

2.2. Out-of-Plane (OoP) test methods

The out-of-plane (OoP) tests were carried out by first testing the URM infilled (clay block and brick masonry) RC frame in bending, where the load was applied at the beam-column joint node, and then, after the frame was returned to its initial vertical position, a shear push-out wall test was performed. During the latter, frame movement were prevented (see Figures 5 and 6).

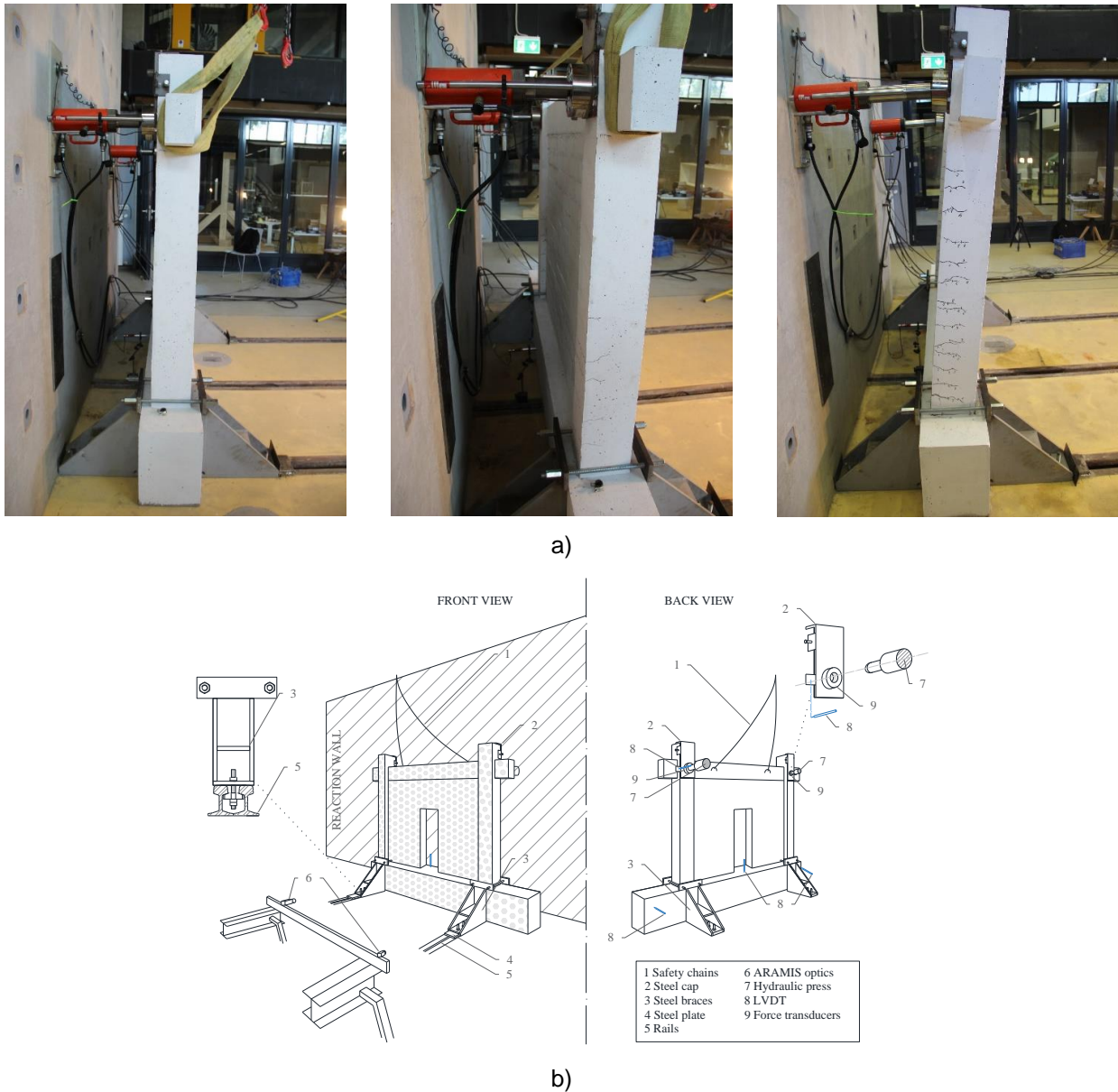


Figure 5. Out-of-Plane (OoP) bending tests on URM infilled RC frame: : a) photograph of the test, and b) tests scheme

The out-of-plane (OoP) frame bending tests (see Figure 5) were performed as cyclic in one direction only (Anić *et al.*, 2021; Anić, 2022), with force control and repeated step. After each cycle the force was increased by 5 kN up to the point when frame yielded, followed by a pushover approach with observing the behaviour of the structure with a step of every 5 mm of displacement, up to the damage grade 4 or 5 (Grünthal *et al.*, 1998), or up to reaching the measuring capacity of the equipment (up to about $d_{r,OoP}=10\%$). The out-of-plane (OoP) shear push-out wall tests (see Figure 6) were performed by a pushover method with force control and the increment of 5 kN up to the point when wall yielded, followed by a pushover approach with observing the behaviour of the structure with a step of every 1 (or 2 in latter stage) mm of displacement, up to the damage grade 4 or 5 (Grünthal *et al.*, 1998) of the wall. In both cases the tests were carried out without axial load in columns.

The equipment used in all tests were: hydraulic presses with capacity of 500 kN (Yale), LVDT's of type DCTH3000 (RDP group) with a stroke of ± 75 mm, force transducers type TC 4 (AEP company), SIRIUS-HD-16xSTGS data acquisition box (DAQ), and the optical measuring system ARAMIS (GOM). The test setup for both tests methods is given in Figures 5 and 6.

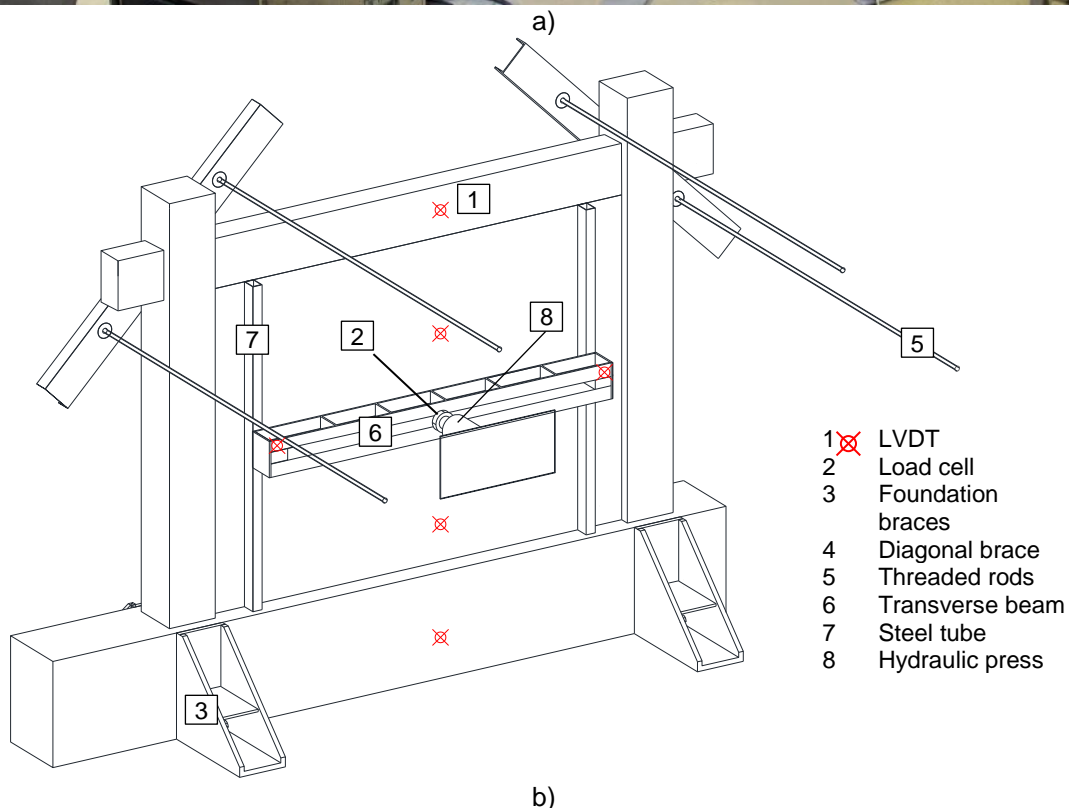
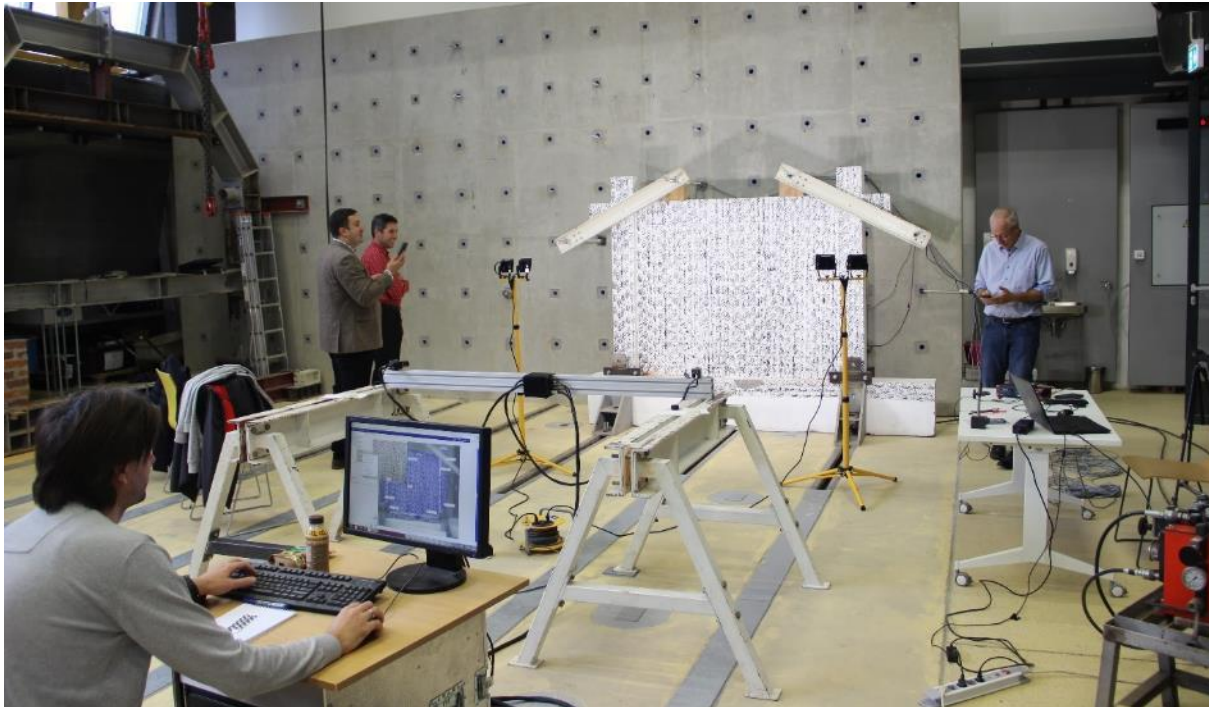
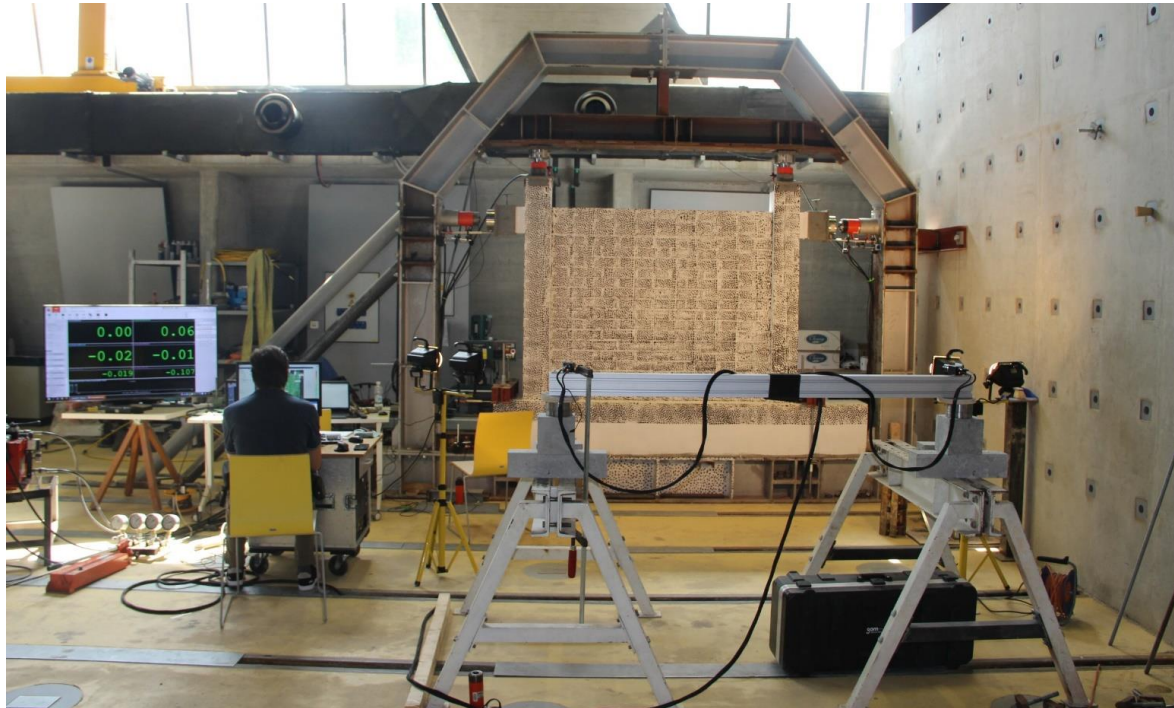


Figure 6. Out-of-Plane (OoP) push-out shear tests on URM infill wall: : a) photograph of the test, and b) tests scheme

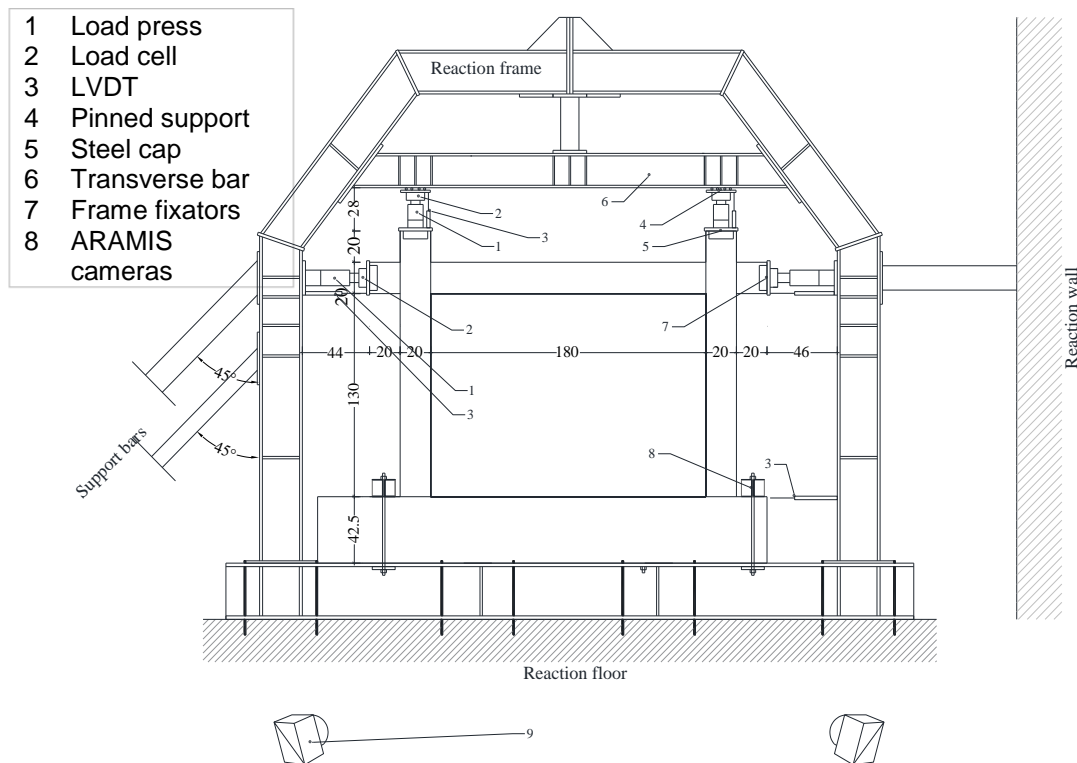
2.3. In-Plane (IP) test method

In-plane (IP) tests on URM infilled (clay block and brick) RC frame were performed in a similar manner to out-of-plane (OoP) bending tests, except that the columns of the frame were loaded with a constant axial force in the amount of 365 kN on each column (kept at value $\pm 10\%$ during the tests), representing the structure above (Penava, 2012; Zovkić, Sigmund and Guljaš, 2013; Sigmund and Penava, 2014; Grubišić, 2016). The structure was cyclically loaded (load application from both beam ends) with force control with repeated step and the increment of 10 kN, up to the point when structure yielded, followed by a pushover approach and with

observing the behaviour of the structure with a step of every 0.5 mm of displacement, up to the damage grade 4 or 5 (Grünthal *et al.*, 1998) of structure components. In Figure 7, shown are the appearance of the tests (Figure 7a) and the test setup (Figure 7b).



a)



b)

Figure 7. In-Plane (IP) tests on URM infilled RC frame: a) photograph of the test, and b) tests scheme

3. Results and comparison with reference tests

The results of out-of-plane (OoP) frame bending tests, out-of-plane (OoP) wall shear push-out tests (OoP), and in-plane (IP) tests are given in Figures 8, 9 and 10, respectively, in the form of force-displacement curves with displacement, d (mm) and drift, d_r (%) ($d_r = d/(h_i+d_b/2)$; $h_i = 1300$ mm, infill wall height; $d_b = 100$ mm, RC frame beam depth) on horizontal axis, and shear resistance V_R (kN) and shear resistance to maximum shear resistance ratio $V_R / V_{R,max}$ (-) on vertical axes. In addition, the ARAMIS images of the structures observed at the final stage of tests i.e. at the damage grade 4 or 5 (Grünthal *et al.*, 1998) of structure components, are shown in Figures 11, 12 and 13. The results are compared with the tests performed on identical structures but without wall tie anchors given in (Penava, 2012; Sigmund, 2014; Sigmund and Penava, 2014; Grubišić, 2016; Anić *et al.*, 2021; Anić, 2022).

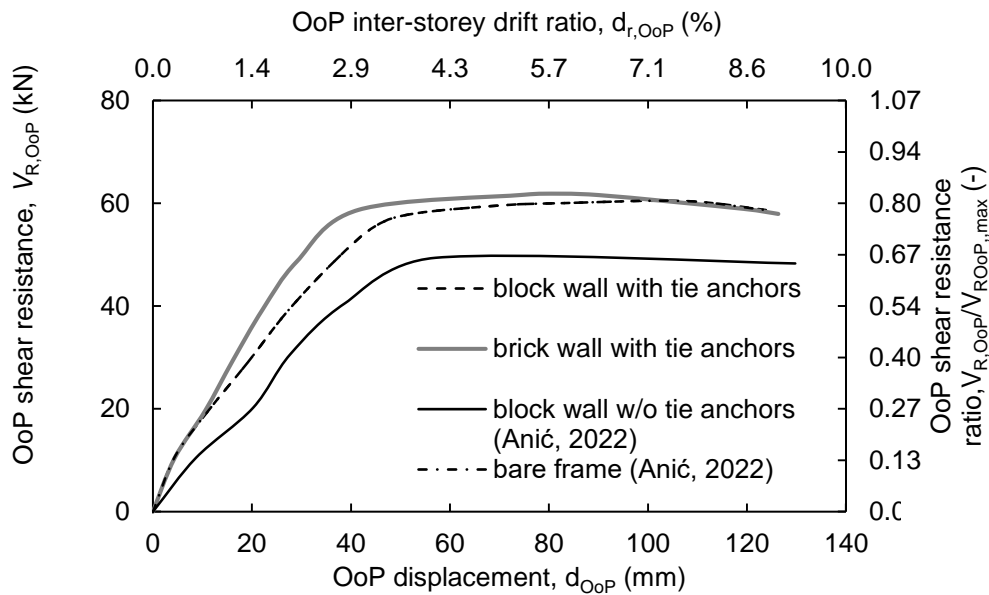


Figure 8. Force-displacement curves resulting from of out-of-plane (OoP) frame bending tests

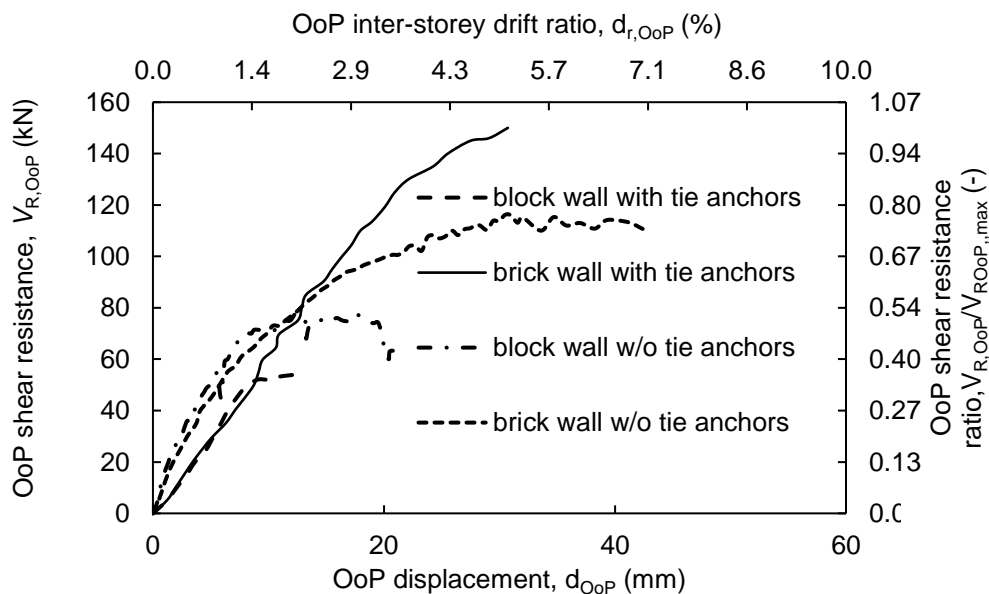


Figure 9. Force-displacement curves resulting from of out-of-plane (OoP) wall shear push-out tests

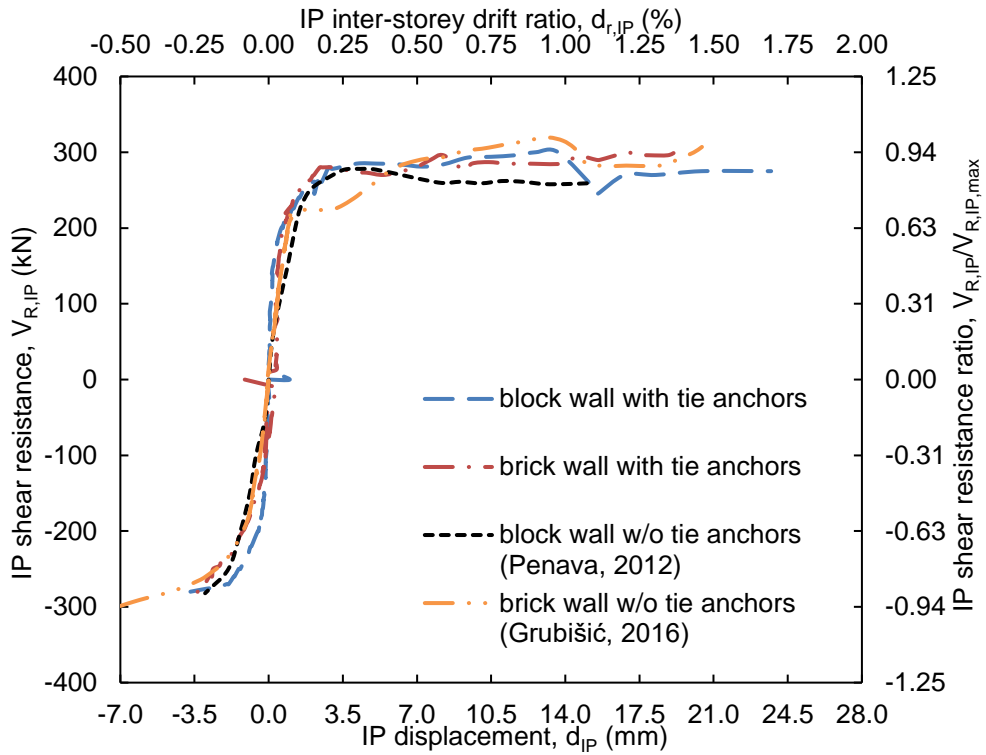
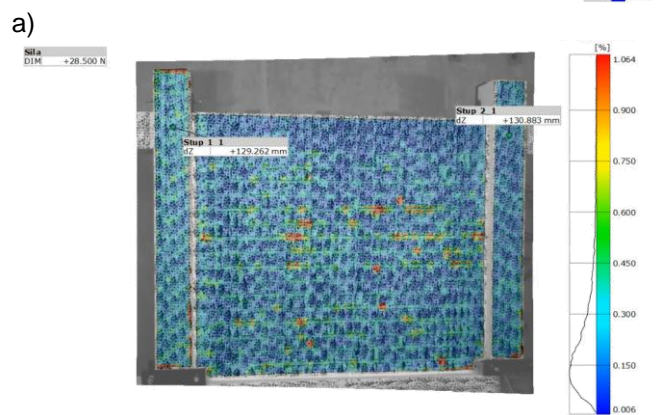
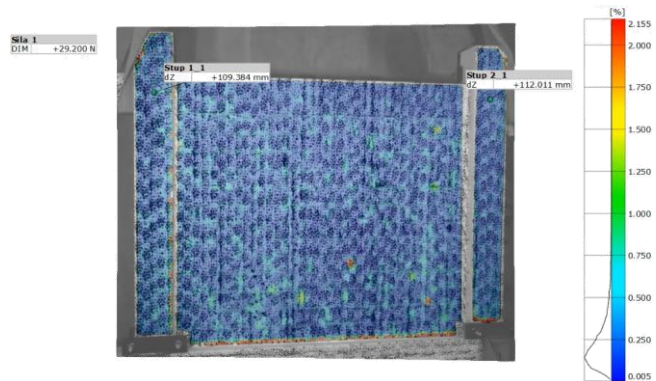


Figure 10. Force-displacement envelope curves resulting from of in-plane (IP) tests



b)

Figure 11. Damage state at final stage of OoP bending tests on test RC frame with masonry infill walls presented photograph (left) by Von Mises strains recorded by ARAMIS (right): a) clay block, and b) clay brick masonry infill wall with tie anchors

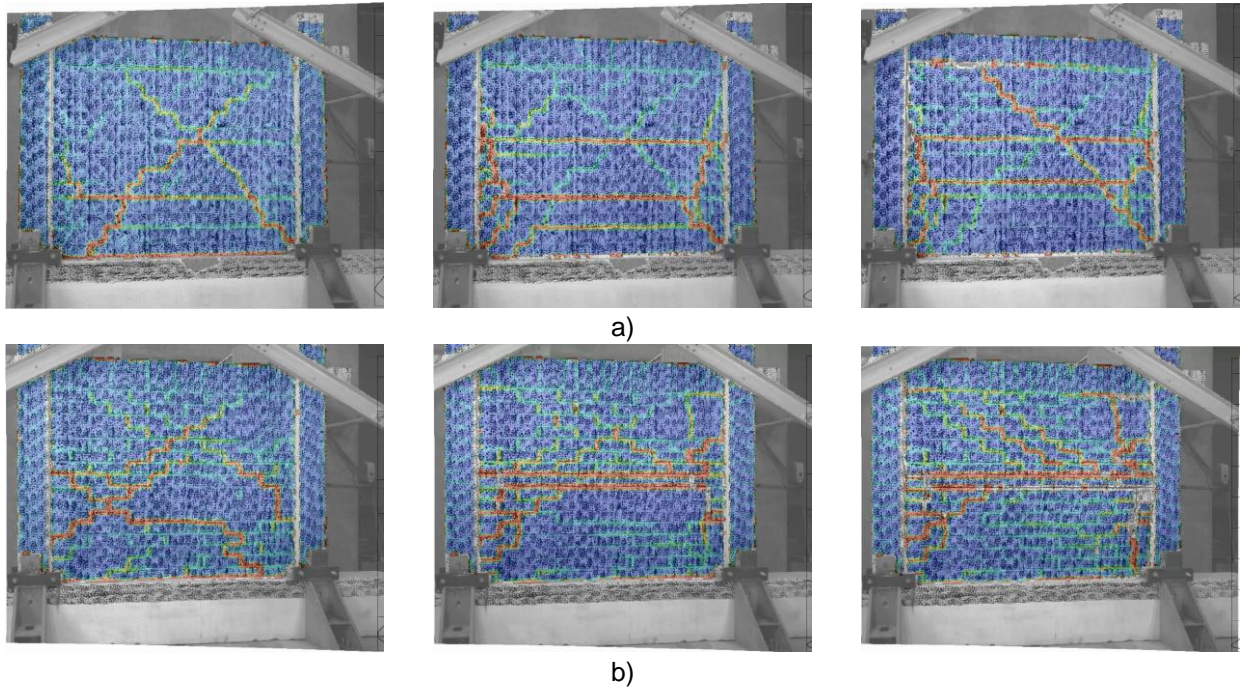


Figure 12. Damage progression on masonry infill walls during OoP shear push-out tests presented by Von Mises strains recorded by ARAMIS: a) clay block, and b) clay brick masonry infill wall with tie anchors

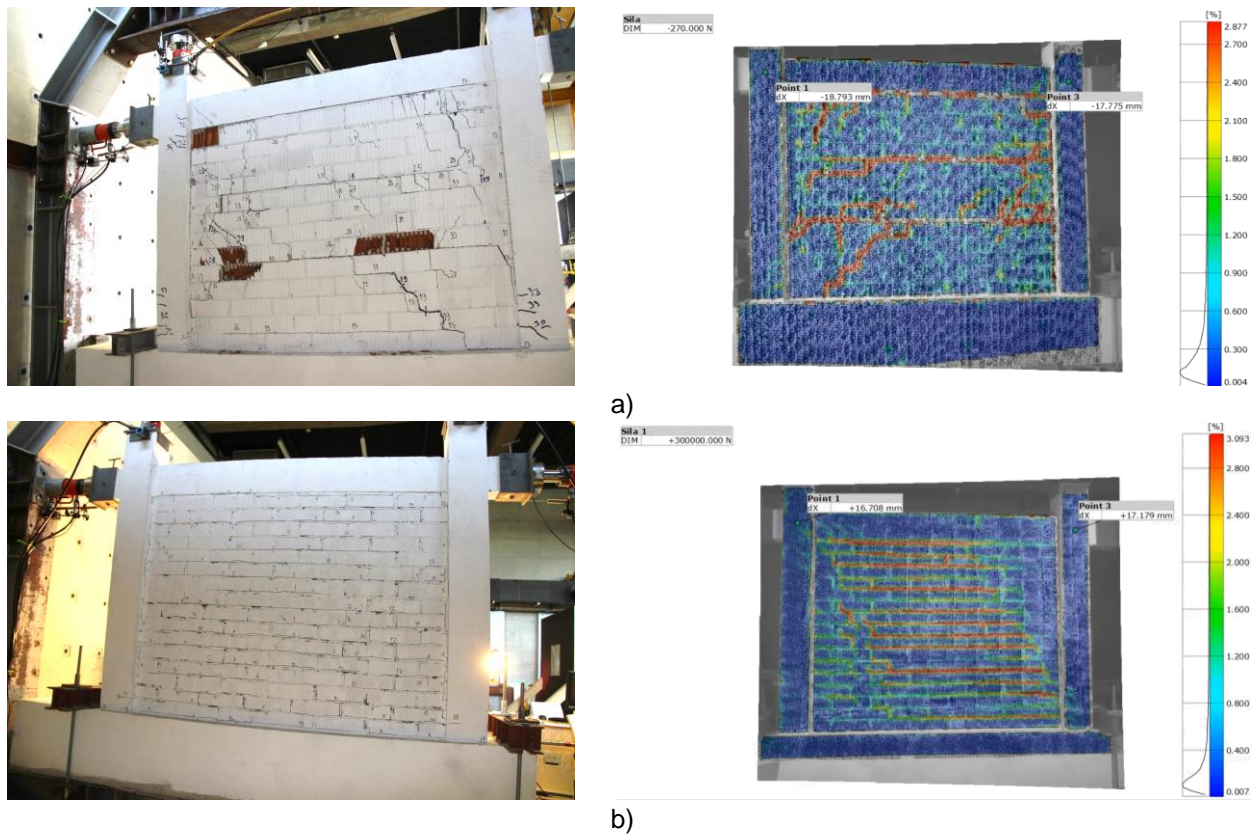


Figure 13. Damage state at final stage of IP tests on test RC frame with masonry infill walls presented photograph (left) by Von Mises strains recorded by ARAMIS (right): a) clay block, and b) clay brick masonry infill wall with tie anchors

4. Discussion of results

In general, with regard to masonry infill wall type i.e. clay blocks or bricks, the test structures with clay brick exhibited more favourable shear in-plane (IP) and out-of-plane (OoP) behaviour in terms of maximum drift capacity, as supported by the evidence from cyclic, pushover and shake-table tests i.e. (Guljaš *et al.*, 2018). The presence of wall tie anchors, in case of both wall types, enabled the increase in drift capacity of the tests structures, and also enabled to walls the withstanding (or to reaching) the critical damage grades i.e. 4 or 5 (Grünthal *et al.*, 1998) at latter stages and a more favourable crack distribution including the prevention of the loss by falling-out portions of the wall. In addition, the out-of-plane (OoP) bending tests in cases without wall tie anchors were sufficient to affect the walls in that measure that they are no longer usable, which wasn't the case with wall tie anchor presence i.e. the out-of-plane (OoP) shear push-out tests were performed. The wall tie anchor failure wasn't observed in any of the tests.

The RC frame wasn't significantly affected by the wall tie anchor presence in terms of shear resistance or damage to the frame i.e. its behaviour was matching to that observed in earlier tests without wall tie anchors, namely (Penava, 2012; Zovkić, Sigmund and Guljaš, 2013; Sigmund and Penava, 2014; Grubišić, 2016; Guljaš *et al.*, 2018; Anić *et al.*, 2020; Anić, 2022).

In Figure 8 shown are the force-displacement envelopes resulting from of out-of-plane (OoP) frame bending tests up to the $d_r=10\%$. The RC frames with walls with tie anchors, compared to the tests on RC frames without URM infill wall and tests on RC frames with URM infill wall without tie anchors, reveal merely slight discrepancies in their force-displacement relation, which can be related to test uncertainties e.g. construction material properties. The URM infill wall in all cases didn't affected the RC frame shear resistance capacity, as also reported in (Anić *et al.*, 2021; Anić, 2022). The URM infill wall suffered substantial to heavy damage i.e. grade 3 (Grünthal *et al.*, 1998) (see Figure 11) in case of walls with tie anchors, and very heavy damage i.e. grade 4 (Anić *et al.*, 2021; Anić, 2022) in case of walls without them, including the separation between the wall and the frame around the entire wall perimeter.

In Figure 9 shown are the force-displacement envelopes resulting from of out-of-plane (OoP) frame push-out shear tests in cases with wall tie anchors up to the $d_r=1.1\%$ for clay blocks, and $d_r=2.5\%$ (maximum shear resistance), or $d_r=4.3\%$ (maximum drift) i.e. up to reaching destruction i.e. grade 5 of the walls. The tests on cases without wall tie anchors haven't been tested due to the loss of connection between the wall and the frame around the entire the wall perimeter i.e. it was considered that their remaining shear capacity is negligible. The clay brick walls with tie anchors had the maximum carrying capacity about 2.5 higher than the same of clay blocks. In Figure 13 shown is the damage progression walls. In both cases the damage is represented with corner-to-corner cracking, accompanied with crushing and loss of mortar along top, mid-height, bottom and side mortar beds (FEMA 306, 1998), however without noticeable out-of-plane (OoP) dislodgment of masonry around the perimeter of the wall due to presence of wall ties.

In Figures 10 and 13 shown are the force-displacement envelope curves resulting from of in-plane (IP) tests, with and without wall tie anchors, for clay block and clay brick masonry. While the maximum shear resistance at yielding was almost the same in all cases i.e. about $V_{R,y} = 270$ kN, the maximum drift capacity differed in favour of structures with wall tie anchors i.e. approximately $1.5\% < d_{r,max} < 2\%$ for both types of masonry infill compared to $d_{r,max}=1.3\%$ of clay block, or $d_{r,max}=1.5\%$ of clay brick masonry without tie anchors, respectively. The presence of wall tie anchors enabled more favourable crack distribution and propagation, and loss prevention.

5. Conclusions

The URM infill walls of RC frame buildings, as revealed from damage surveys after e.g. $M_w=6.4$ 2019 Durrës, Albania earthquake, didn't met the basic requirements for structural masonry as required by building codes, and therefore sustained very have damage or destruction, during an event that didn't significantly damaged the surrounding RC frame. The mostly observed was the out-of-plane failure of URM infill walls made from clay block masonry, which was the cause of injuries and death to residents.

The laboratory tests were carried out in order to assess the shear (earthquake) performance of RC frames with URM (clay block and brick) infill walls with wall tie anchors, separately in in-plane and out-of-plane direction (frame bending and shear push-out tests), and compared with previous studies on cases without them.

The presence of wall tie anchors, intended primarily to prevent the out-of-plane collapse of walls or portion of walls, enhanced their performance in terms of drift capacity and damage progression, both in-plane and out-of-plane, and could be implemented as a measure of retrofitting in combination with clay brick masonry in order to achieve the most favourable outcome.

In future work, the details of placement of wall tie anchors (tension ties) and design rules, which require careful attention with regard to their spacing and size, will be studied.

6. References

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