Equivalent-frame models idealisation of laterally-loaded URM façades with irregular opening distributions

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ABSTRACT
The macro-element modelling strategy, typically implemented in equivalent-frame models (EFM), can be probably be deemed as one of the most widely-employed analysis procedures for the global assessment of unreinforced masonry (URM) structures, providing an acceptable compromise between accuracy and computational expense. Regardless, the definition of the effective height of vertical components, especially when considering the presence of irregular openings distribution, still represents an open challenge. Indeed, from a numerical viewpoint, the latter aspect might affect significantly the predicted in-plane response, unavoidably influencing gravity load distribution, cracks propagation and associated failure mechanisms. In this work, the influence of various commonly-employed EFM discretisation procedures on the numerical modelling of the global quasi-static lateral behaviour of full-scale URM façades is investigated through a comprehensive parametric study, accounting for several geometrical combinations (e.g. horizontal and vertical misalignments, different opening sizes, number of openings per story) characterised by various degrees of irregularity. The variability of the results obtained seems to indicate that this aspect should be carefully considered when performing quasi-static analysis on laterally-loaded URM systems with irregular opening distributions.

1 INTRODUCTION

The equivalent-frame modelling strategy (EFM) is widely-employed by both practitioners and researchers for simulating the in-plane governed response of unreinforced masonry (URM) structures. Indeed, with respect to more advanced discrete (e.g. Malomo et al. 2018, 2019a) and continuum-based numerical methods, its employment (which proved to led to adequate results, see e.g. Penna et al. 2014 and Kallioras et al. 2018) usually entails a relatively low computational expense. However, the selection of an appropriate discretisation scheme when considering URM structures characterised by an irregular distribution of openings might be extremely challenging. Indeed, an uncritical definition of the equivalent-frame configuration and corresponding effective height of piers, may lead to epistemic modelling errors, as noted by e.g. Berti et al. (2017). Lately, several numerical investigations of the seismic behaviour of URM buildings with structural irregularities have shown that, when using simplified macro-modelling strategies, a significant dispersion of results is typically observed (Parisi and Augenti 2012, Quagliarini et al. 2017, Malomo et al. 2019b). Regardless, the majority of the currently available building codes do not provide specific details regarding how to account for the abovementioned aspects, which is presently not treated as a source of uncertainty (Bracchi et al., 2015). In this work, after having selected some recurring typologies of irregularity, a comprehensive parametric study is conducted with a view to assess the influence of different EFM discretisation procedures on numerical accuracy. To this end, three typically-employed EFM idealisation schemes (i.e. based on minimum and average effective height, as well as on the maximum expected inclination of cracks) were herein considered for the simulation of the in-plane cyclic response of several full-scale URM façades with various degrees of geometrical irregularity. First, the models were preliminary calibrated through comparison with experimental tests on both reduced-scale isolated piers and a full-scale URM façade, carried out at the Joint Research Centre (Ispra, Italy) and at the laboratory of the University of Pavia (Italy) by Anthoine et al. (1994) and Magenes et al. (1995) respectively. Then, the influence of various EFM discretisation techniques on numerical analysis is investigated considering a series of two-storey laterally-loaded URM façades with different opening layouts.

2 MACRO-ELEMENT APPROACH AND EFFECTIVE HEIGHT

In this work, amongst other EFM presently available in literature, the macro-element initially proposed by Penna et al. (2014), recently enhanced by Bracchi et al. in 2018 and currently implemented in the research version of the software TREMURI (Lagomarsino et al., 2013a), was considered. In practise, as schematically depicted in Figure 1, a macro-element consists of a central body (which reproduce damage due to shear mechanisms) and two external zero-thickness spring interfaces accounting for axial-flexural failure modes.

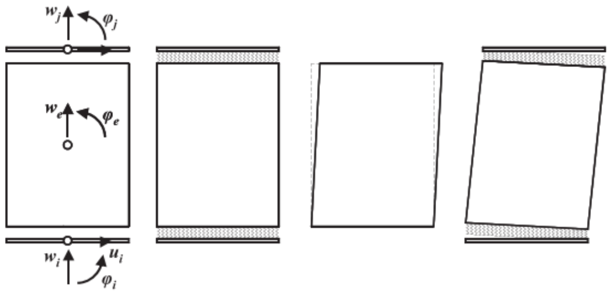


Figure 1. Macro-element (Penna et al., 2014)

The compression model herein adopted is the one lately proposed by Bracchi et al. (2018), which is characterised by the introduction of a limited compressive strength, no tension and unloading stiffness equal to the elastic one, increasing energy dissipation and damage accumulation due to masonry crushing phenomena. For what concerns the pier shear damage model, the one proposed by Gambarotta and Lagomarsino (1997) and further developed by Bracchi et al. (2018) was selected. For spandrel elements, instead, best results were obtained using the macro-element originally proposed by Penna et al. (2014). When considering complex URM systems (see Figure 2), the EFM-based macro-element idealisation comprised the identification of both spandrel, wall, and rigid node elements, whose effective height/length may vary according to the selected discretisation criterion. As depicted in Figure 3, three main typically-employed EFM subdivision methods were considered in this work, based on either geometrical or simplified analysis outcomes and hereinafter referred as to AVG (average effective height), MIN (minimum effective height) and LIM (30° limited effective height) respectively.

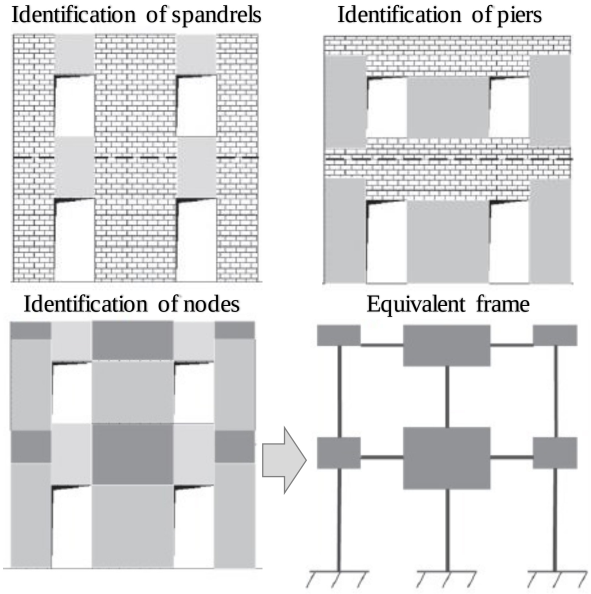


Figure 2. EFM idealisation (Lagomarsino et al., 2013b)

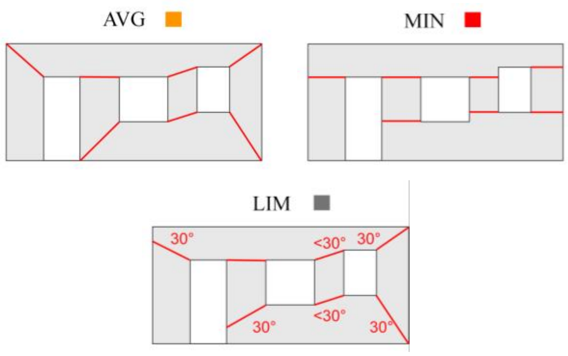


Figure 3. EFM discretisation methods (Malomo et al., 2019b)

In more details, the MIN criterion considers the minimum height of masonry wall between two adjacent openings. According to the AVG methodology, instead, the effective height is defined by the line connecting the corner of adjacent openings. Finally, the LIM criterion limits the line defined using the AVG criterion to a maximum inclination of 30°.

3 PRELIMINARY CALIBRATION WITH TEST RESULTS

The material properties of piers were calibrated through the comparison with experimental results of two masonry panels tested at the Joint Research Centre (Ispra, Italy) by Anthoine et al. (1994) according to the test layout depicted in Figure 4. Then, the adequacy of the proposed EFM was further assessed at the building scale (thus enabling a careful calibration of the mechanical properties of spandrel elements as well) by reproducing the in-plane cyclic response of the URM façades tested at the laboratory of the University of Pavia (Italy) by Magenes et al. (1995).

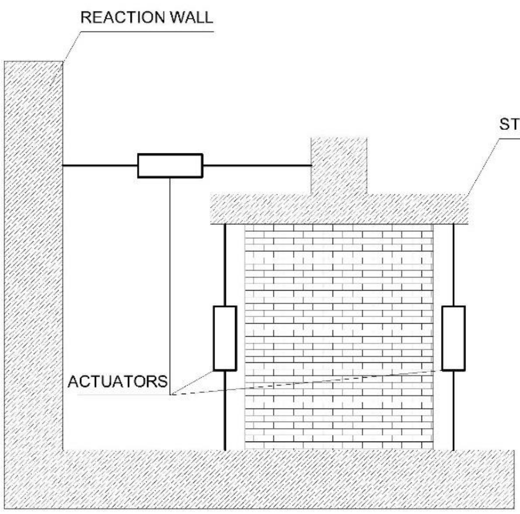


Figure 4. Testing set-up (adapted by Antoine et al., 1994)

3.1 *Reduced-scale tests on laterally-loaded isolated components*

Two clay walls, made of the same masonry type of the full-scale building prototype tested in Pavia by Anthoine et al. (1994) and subjected to in-plane shear-compression loading cycles, were considered in this modelling exercise. They were characterised by different aspect ratios (1 m x 1.35 m x 0.25 m, low wall, 1 m x 2 m x 0.25 m, high wall) and by the same applied vertical force of 150 kN (corresponding to 0.6 MPa). As it can be gathered from Figure 5, the experimentally-observed response of the high wall was mainly characterised by flexural-rocking mechanisms. On the other hand, the lower wall exhibited a diagonal-shear dominated failure mode with diagonal cracks, which led to a rather evident strength and stiffness degradation, especially in the last testing phases (see Figure 6). As shown above, the macro-element model herein proposed was actually able to capture the experimental behaviour in both the cases, in terms of initial stiffness, strength capacity and progressive deterioration of lateral resistance. This notwithstanding, minor differences concerning the modelling of the energy dissipation were found, especially in the case of the high wall.

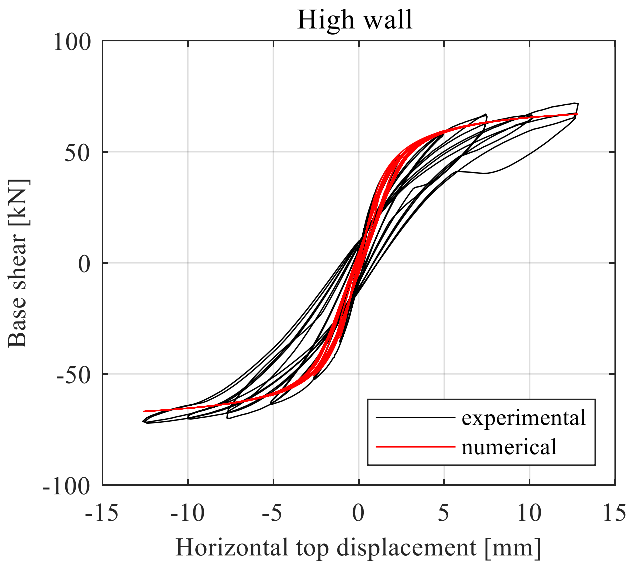


Figure 5. Comparison between numerical and experimental hysteretic response of the high wall

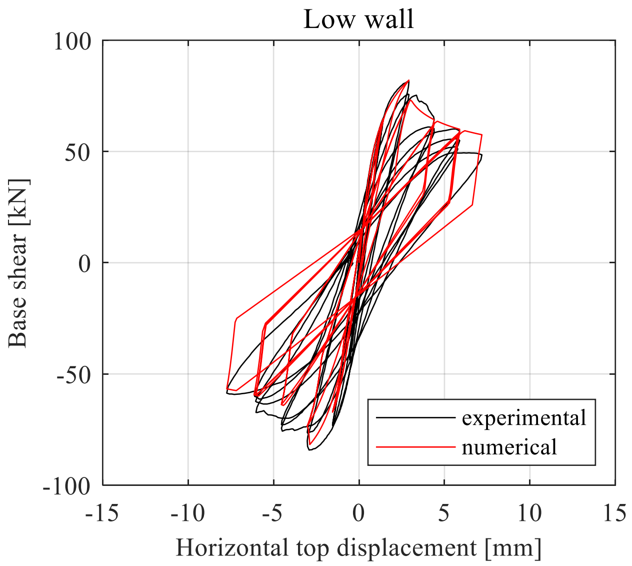


Figure 6. Comparison between numerical and experimental hysteretic response of the low wall

3.2 *Full-scale test on a URM façade*

The URM façade prototype tested at the University of Pavia by Magenes et al. (1995) consisted in the assembly of four double-wythe solid brick walls, 250 mm thick, measuring approximately 6 x 4.4 x 6.4 m (see Figure 7). It was characterised by the presence of flexible diaphragms made of a series of isolated steel beams, through which vertical and horizontal loads were applied. The total vertical applied load correspond approximately to 10 kN/m^2 at both first and second floor. The specimen was tested under a quasi-static applied cyclic displacement. For each idealisation considered, the material properties of piers have been here further adjusted with a view to enhance the agreement with the experimental outcomes (see Figure 8).

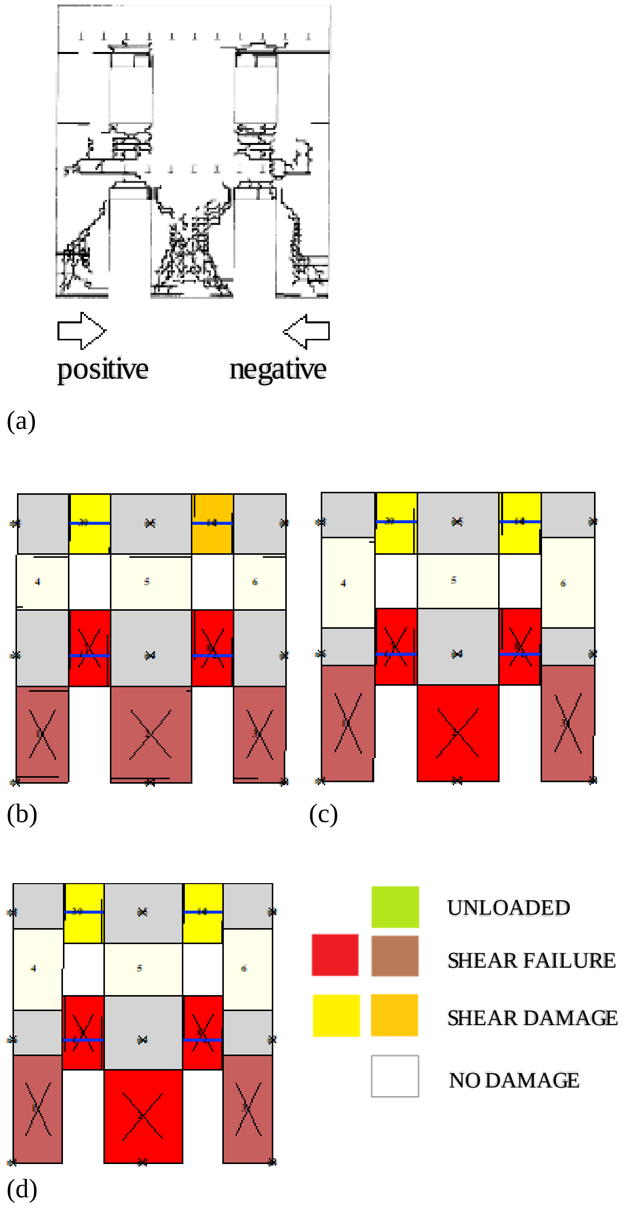


Figure 7. Comparison between experimental (a) and numerical damage pattern obtained using MIN (b), AVG (c) and LIM (d) criteria

Best results were obtained using different sets of properties for pier and spandrel elements, reported in Table 1 and Table 2 respectively (where E and G stand for Young's and shear moduli, p is density, f_m is masonry compressive strength and c is cohesion). As shown in Figure 8, where experimental results and numerical counterparts for each EFM mesh configuration are compared, an acceptable agreement was found. Indeed, both peak and residual shear capacities, as well as the final failure mode, were adequately captured, albeit minor differences were observed in the case of energy dissipation. It is worth noting that in this case (where the tested specimen featured a regular opening layout) very similar results were obtained using the calibrated EFM models with different idealisation schemes.

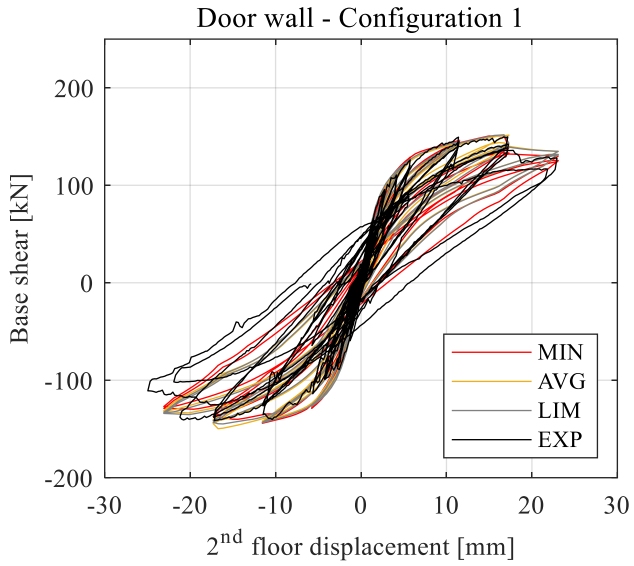


Figure 8. Comparison between experimental and numerical results for each discretisation scheme

Table 1 Calibrated material properties of piers for MIN, AVG and LIM idealisation schemes

MIN				
E [MPa]	G [MPa]	ρ [kg/m^3]	f_m [MPa]	c [MPa]
1570	600	1800	6.2	0.23
μ	f_{bt} [MPa]	tan θ	Gct	β
0.57	0.8	1	1.9	0.3
AVG				
E [MPa]	G [MPa]	ρ [kg/m^3]	f_m [MPa]	c [MPa]
2000	1000	1800	6.2	0.23
μ	f_{bt} [MPa]	tan θ	Gct	β
0.57	0.83	1	4	0.25
LIM				
E [MPa]	G [MPa]	ρ [kg/m^3]	f_m [MPa]	c [MPa]
2000	1000	1800	6.2	0.23
μ	f_{bt} [MPa]	tan θ	Gct	β
0.57	0.83	1	3.3	0.25

Table 2 Calibrated material properties of spandrels (Penna et al., 2014)

SPANDRELS			
E [MPa]	G [MPa]	ρ [kg/m^3]	f_m [MPa]
3000	500	1800	3
fv0 [MPa]	μ	Gct	β
0.14	0.15	2	0

4 PARAMETRIC STUDY

After the validation of the numerical models through comparison with experimental outcomes proposed above, a parametric study, which included the analysis of several different URM façades characterised by various opening layouts (see Figure 9), was undertaken.

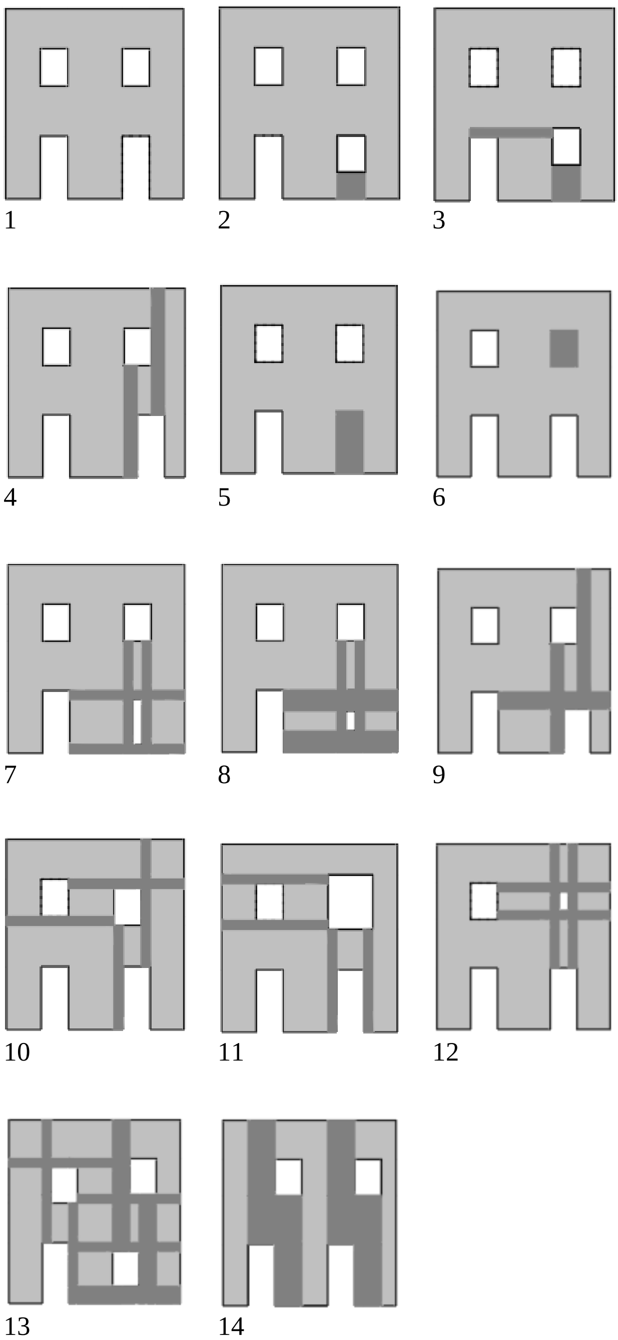


Figure 9. Considered openings layouts

For the sake of consistency, numerical tests were conducted considering the same assumptions adopted during the actual test carried out by Magenes et al. in 1995. In Figure 10, some of the most relevant results in terms of hysteretic response are depicted.

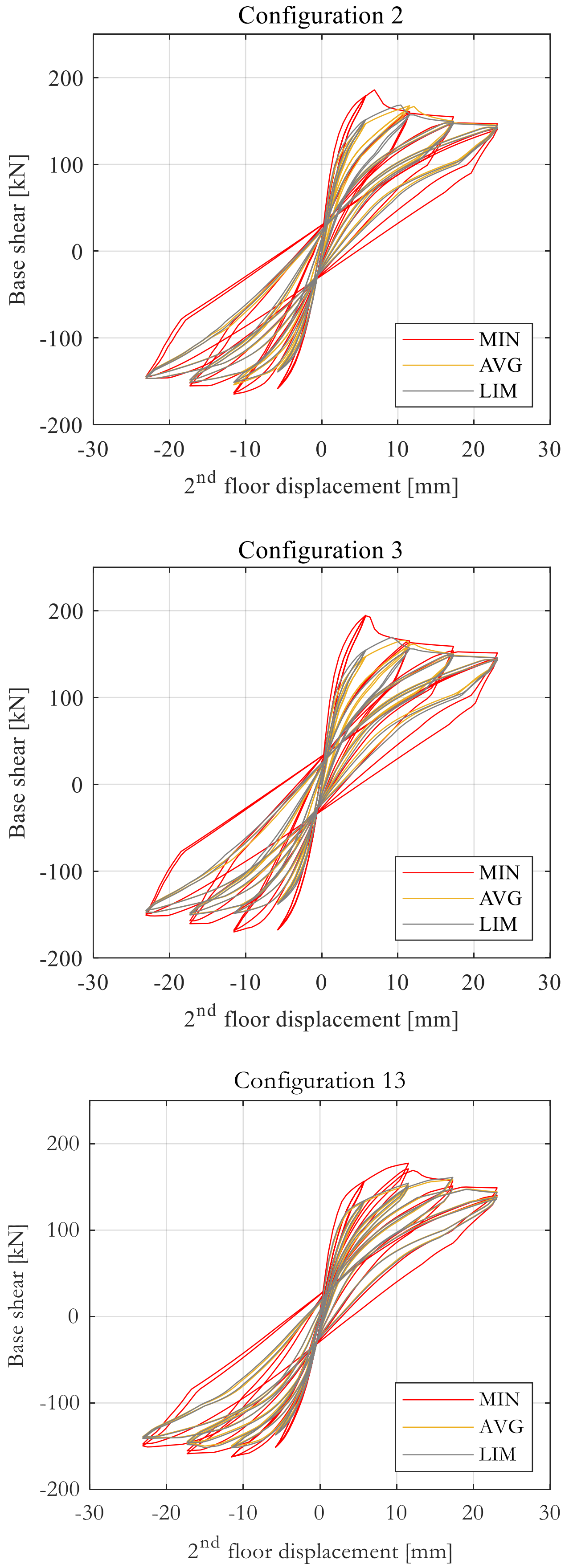


Figure 10. Comparison between the hysteretic response predicted using MIN, AVG and LIM discretisation schemes

Looking at the general picture, it was observed that in all the configurations considered the global in-plane response was governed by the behaviour of the piers at ground floor. For this reason, in the case of configuration 2,3,7,8 and 13, a higher difference between the three methods was found, given that the definition of the effective height of ground floor piers mainly depends on the ground floor openings layout. Moreover, it was noted that when considering the latter configurations higher initial stiffness and maximum base shear were obtained using the MIN criterion, while the employment of the other discretisation criteria yielded equivalent outcomes in terms of initial lateral stiffness (computed at 70% of maximum base shear) and lower maximum strength capacity. Regarding the configuration with irregularity only at the first level (i.e. 6,10,11,12 and 14) the considered effective height criteria seem to be equivalent in terms of initial lateral stiffness and predicted maximum shear base, where the first is higher only when using the LIM criterion on configuration 12 and 14. Indeed, as discussed above, for these façades, the capacity is mainly governed by openings irregularity at ground floor. The aforementioned observations are summarised graphically in Figure 11, where normalised (with respect to the experimental value) initial stiffness and maximum base shear obtained, along both positive and negative loading directions, using AVG, MIN and LIM approaches are compared to each other.

For what concerns configurations 5, only minor differences in terms of both failure mode and hysteretic response was found, as shown in Figure 12 and 13. This might related to the fact that in this case the global behaviour was governed by the rocking modes of the ground floor piers. As expected, a rocking-governed response, characterized by relatively low energy dissipation, was obtained in the case of configuration 5 and configuration 8, as shown in Figure 13.

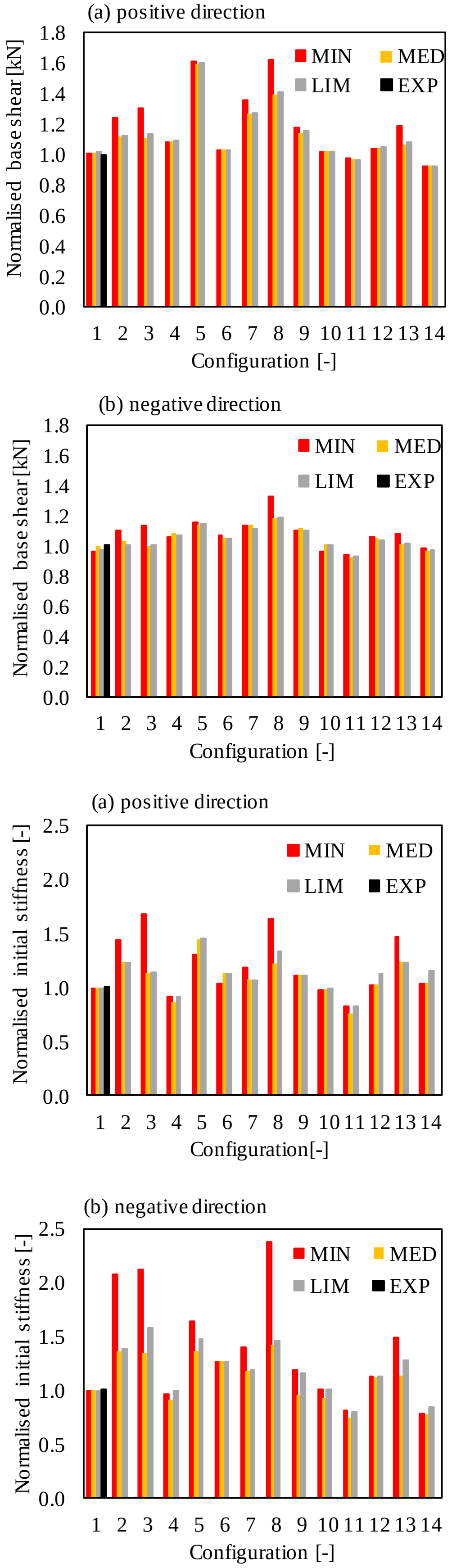
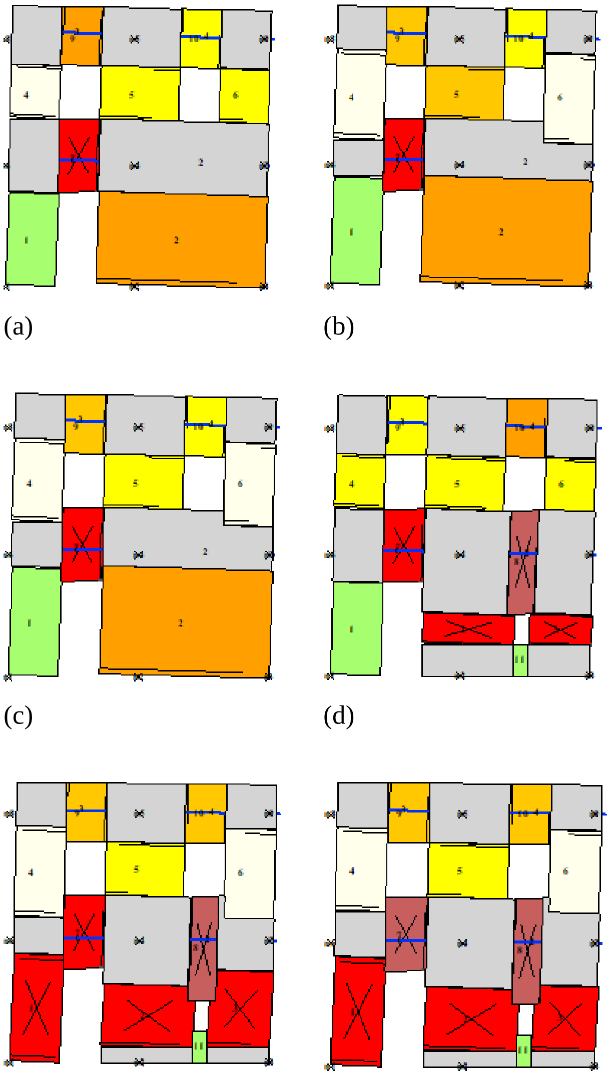


Figure 11. Comparisons in terms of normalised lateral initial stiffness (a,b) and maximum base shear (c,d) between MIN, AVG and LIM discretisation schemes



(a) (b) (c) (d) (e) (f)

Figure 12. Damage patterns of configuration 5 (a) MIN, (b) AVG, (c) LIM- and configuration 8 (d) MIN, (e) AVG, (f) LIM

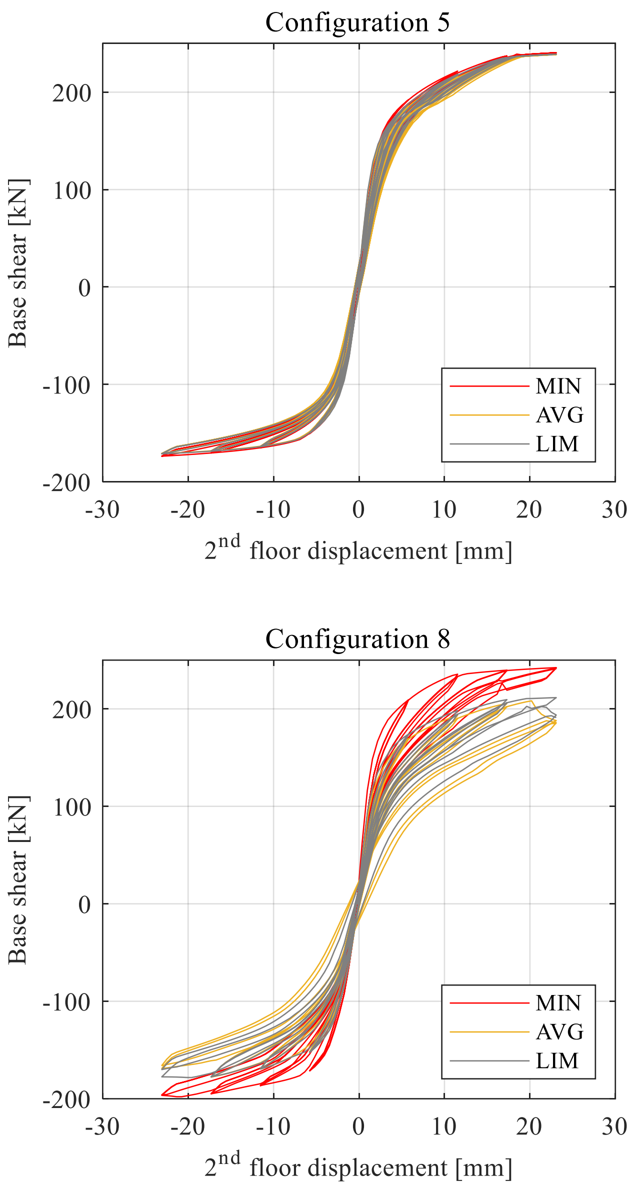


Figure 13. Comparison between the hysteretic response predicted using MIN, AVG and LIM discretisation schemes in the case of configuration 5 and 8

5 CONCLUSIONS

Structural irregularity can significantly affect the seismic response of URM buildings, influencing load distribution, cracks propagation and failure mechanisms. The equivalent frame (EF) model is one of the most widespread analysis approach for the structural assessment of unreinforced masonry (URM) assemblies, representing a reasonable compromise between accuracy and computational burden. The definition of an appropriate equivalent-frame idealisation, however, can be challenging when irregular openings distributions are considered.

In this work, the effectiveness of three different commonly-employed EF discretisation methods (i.e. AVG, average effective height, MIN, minimum effective height and LIM, 30° limited effective height) is scrutinised and discussed. To this end, an EF-based macro-element model was calibrated through comparison with results from experimental tests on both reduced and full-scale URM components, namely laterally-loaded piers and façades. Then, given the adequate results obtained, a parametric study, which included the analysis of several different geometrical configurations characterised by various types of both horizontal and vertical misalignments, was undertaken with a view to investigate the influence of the selection of the discretisation scheme on numerical accuracy.

In general, non-negligible differences were observed, especially in the case of shear-dominated responses, between the numerical results obtained according to each considered discretisation approach. In more details, the use of AVG and LIM criteria seemed to provide lower predictions of maximum base shear, while the MIN approach (whose use usually yields larger rigid node areas with respect to the latter) provided higher initial lateral stiffness and energy dissipation.

On the other hand, very similar results were obtained using AVG, LIM idealisations, with only minor differences in terms of initial lateral stiffness.

However, given that the effectiveness of the discretisation scheme is also clearly a function of several other factors, including e.g. loading direction and masonry texture, a clear trend was not identified in this endeavour. Regardless, an attempt was made to provide a number of calibrated geometries which might be readily applicable to more general and complex cases. Future developments might thus include, a broader selection of irregular opening layouts, as well as an accurate case-by-case calibration process based on both advanced micro-modelling outcomes and additional experimental results.

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