OUT-OF-PLANE SEISMIC RESPONSE OF UNREINFORCED MASONRY WALLS: CONCEPTUAL DISCUSSION, RESEARCH NEEDS AND MODELLING ISSUES

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ABSTRACT

Modeling unreinforced masonry walls, subjected to seismic loads applied normal to their plane, has received much attention in the past, from both engineers and researchers. Yet, there is a general lack of conformance with regard to what aspects of seismic response a computational model should reflect. This paper makes an attempt to discuss the most common issues.

Boundary conditions are certainly an important aspect, as the response can involve two-way bending or just one-way bending and, in the second case, along vertical or horizontal directions. In this respect, flexural restraint of wall intersections can be significant in addition to

size and placement of openings. Moreover, in-plane damage can modify the boundary conditions and the overall out-of-plane performance. Proper modeling of actions is also relevant, as they can be a result of distortions imposed upon wall elements and/or inertial forces along the span of a wall. Axial forces can markedly affect the out-of-plane response of the wall, particularly vertical compressive forces, which can enhance out-of-plane strength. The outcome of static verifications can be more conservative than that of dynamic analyses, but the latter are much more complex to carry out. These topics are discussed with reference to previous research, observations in the field and in the laboratory, as well as numerical analyses on three-dimensional models, resorting to a combined finite-discrete element strategy.

KEYWORDS

Unreinforced masonry; Out-of-plane mechanisms; Boundary conditions; Finite-Discrete Elements.

RUNNING HEAD

Conceptual issues on the out-of-plane seismic response of unreinforced masonry walls

1   INTRODUCTION

Modeling strength and behavior of unreinforced masonry walls resisting seismic loads applied normal to their plane has received much attention across the globe from both engineering practitioners and researchers. Yet, there is a general lack of conformance with regard to what aspects of seismic response a computational model should reflect. This is a result of having different objectives for such analyses, but also is attributable to the lack of consensus guidelines for users to follow. Whereas much research has been published, little of it has been consolidated into a set of modeling recommendations. This paper makes an attempt to address the most common issues, graphically described through three-dimensional numerical models (refer to the appendix for further details). The issues presented in this paper are by no means a consensus of the modeling community, but rather a list of concerns that one may wish to consider – many of which have been addressed by participants in the blind prediction exercise addressed later in this special issue.

2   WHAT BOUNDARY CONDITIONS SHOULD BE CONSIDERED?

Numerical representation of the out-of-plane response for a particular wall panel requires proper modeling of the perimeter boundary condition (Mendes et al., 2015). In an idealized unreinforced masonry building system, an exterior masonry wall panel should be adequately connected to a floor or roof diaphragm on its top and bottom, and orthogonal walls on its vertical edges (Fig. 1a). These edge restraints usually resist translation, but also may resist rotation. Such rotational restraint is often neglected (Fig. 1b), because of uncertainties of modeling such action for floor-to-wall connections and/or torsional action of corners where orthogonal walls intersect. Despite this, these rotational restraints can be significant at least until cracking occurs (Paquette and Bruneau, 2003).

Also, in many older buildings, adequate floor-to-wall connections may not be present, which means that out-of-plane walls may not be supported against out-of-plane movement (Fig. 2). On the contrary, if floor-to-wall connections are provided and diaphragms are somewhat rigid

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relative to walls, then one-way (vertical) bending may be present, which will greatly enhance out-of-plane strength (Fig. 1b). Moreover, stiff frames can guarantee arching action, e.g. in the case of infill panels. In such case, wall panels with low flexural tensile strengths can resist appreciable out-of-plane loading as wall segments attempt to rotate through their thickness (Wilhelm et al. 2007), and internal struts develop until a snap-through phenomenon occurs (Abrams et al., 1996).

In the modeling of modern masonry buildings, usually only loading from a single direction is considered. For example, response of in-plane walls is modeled without considering effects of simultaneous transverse forces (Lourenço, 2002), or the converse. Therefore, three-dimensional effects, such as interaction of orthogonal walls and behavior of intersecting walls, are often neglected or, at least they are approximated using rather simplified approaches. These approaches reduce a rather complicated problem down to one that may be handled computationally, which is usually an acceptable approach for conservative safety assessment. However, the user should be aware of the model idealizations and should exercise careful judgment when assessing true three-dimensional system behavior. For example, three-dimensional damage patterns may include damage to corners or wall intersections (this has been commonly observed as a result of strong ground shaking, Fig. 3a). This damage will obviously alter the stiffness of the edge boundary condition for an out-of-plane wall spanning horizontally.

A second example is flexural cracking of flanged walls at their base. This has been observed in laboratory tests of 3D building systems loaded in one horizontal direction (Fig. 3b). A flexural crack occurs at the base of a wall acting as a flange to an in-plane shear wall. This form of cracking affects the boundary condition for this wall spanning vertically as an out-of-plane wall. These three-dimensional interactions can seem endless for an unreinforced masonry multi-story building, and are nearly impossible to model precisely. Again, the user must interpret results of a model not incorporating these sophistications, and respect the model as only an ideal reference to the actual behavior.

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3 SHOULD WALLS SPAN HORIZONTALLY AS WELL AS VERTICALLY?

Many idealizations of out-of-plane response have been based on the behavior of simplified unidirectional strips spanning in either the vertical or horizontal direction, as done in Sorrentino et al. (2008), and Willis et al. (2004), respectively. Often, out-of-plane walls are idealized as strips spanning in the vertical direction for three reasons: (a) the height-to-length aspect ratio of a wall panel is substantially less than one (Fig. 4); (b) vertical wall segments are prone to instability effects whereas horizontal ones are not; and (c) vertical strips may be subjected to axial compressive stress due to gravity loads (for bearing walls), which may or may not be beneficial to flexural or rocking strengths.

Though such unidirectional idealizations are accepted practice, the user should be aware that they are inexact and conservative. Such modeling is warranted for safety assessment but may not reflect the actual behavior of an out-of-plane wall that may likely span in both vertical and horizontal directions (Griffith et al., 2007), particularly if the height-to-length wall aspect ratio approaches or exceeds unity (Fig. 1a). In such case, two-dimensional action can be modeled with a failure-line mechanism, which is similar to a yield-line mechanism for a reinforced concrete two-way slab, e.g. EN 1996-1-1:2005 (CEN, 2005). If wall reinforcement is not present, there are no ductile elements to yield and result in a yield-line mechanism. However, due to vertical axial compression, flexural strength can be developed after cracking and thus failure lines can result. In addition, given the interlocking of masonry units in the horizontal direction, a rather ductile response is usually obtained, and two-dimensional action is adequate. In case of weak masonry bond in the horizontal direction or damage due to dynamic actions under strong shaking, the response might be analogous to a yield-line mechanism for a concrete slab reinforced in only one direction, because the axial compressive stress is usually applied only in the vertical direction. Then, a bi-directional idealization will result in increased out-of-plane strength since the transverse strength is distributed in two directions.

Finally, since a wall panel may also resist cyclic in-plane forces as a shear wall, diagonal X cracks may develop, which influence the formation of fracture lines due to transverse bend-

ing. In a test program of masonry infill panels, such reduction of out-of-plane strength due to in-plane damage was found to be approximately 50% (Abrams et al., 1996).

4 WHAT ACTIONS SHOULD BE CONSIDERED?

Out-of-plane walls are affected by two distinct actions during shaking of a building: (a) imposition of displacements from floor or roof diaphragms at the top and bottom of a wall panel, if applicable; and (b) resistance of inertial forces transverse to the wall plane as the wall panel spans in either one or two directions, as discussed previously (Fig. 5).

If an out-of-plane wall is well anchored to the floor or roof diaphragm, and hinging occurs due to flexural tension normal to the bed joint at the top and bottom of the wall, then the wall will be subjected to rigid-body rotations due to the second action. In such case, a vertical strip of wall will adapt to large imposed diaphragm deflections without incurring further stress.

Horizontal cracking at the top and bottom of a wall panel will influence the boundary condition for the second action. In which case, out-of-plane wall failure may be a result of large inertial loadings, coupled with light vertical axial compression and the flexible boundary condition due to cracking.

5 SHOULD AXIAL STRESS BE CONSIDERED?

Common intuition might say that vertical axial compressive force is a deterrent action since it may lead to crushing of the masonry. After all, bearing wall structures are designed on the basis of the masonry resisting vertical compressive stress. However, axial compressive stress can actually be a benefit for laterally loaded buildings since it lowers the net flexural tensile stress of a masonry wall, and enhances rocking and dynamic stability. In case of historic masonry buildings, vertical axial force is often intuitively assumed as beneficial, particularly to resist the lateral thrust of arches and vaults.

Many papers on experimental studies using reduced-scale models excited on shaking tables neglect the influence of vertical axial compression. Since gravity stress due to self-weight reduces with the length scale factor (volume times density over area), experiments that do not compensate by adding weights will unrealistically model the flexural, rocking or shear strength of unreinforced masonry walls or piers (Abrams and Paulson, 1991; Tomaževič and Velechovsky, 1992). Effects of vertical compressive stress on building seismic capacity should be more carefully modeled in such research studies, if not experimentally, at least with additional parametric studies, and should be more widely acknowledged for seismic assessments of actual buildings.

Of course, excessive vertical compressive stress can lead to force-controlled actions such as toe crushing. But, a nominal amount of vertical compressive stress is usually better than no or little stress, with the exception of historic masonry buildings featuring extremely low compressive strength and reasonable wall heights. This raises interesting questions regarding the relative lateral force resisting roles of walls that are bearing walls, and those that are not, particularly in the case of slender walls (in thick walls, the effect of the weight of the floors / roofs are usually negligible for the wall response). Since floor or roof joists usually span in a single direction, walls parallel with the joists do not benefit from axial compression (Fig. 6a), and thus can be more vulnerable to flexural tension cracking, and can have lower flexural, rocking and shear strengths, compared to walls supporting the horizontal structure (Fig. 6b). The former walls will limit strength of the entire building system. Prestressing of the non-bearing walls can significantly enhance lateral force capacity of such a system (e.g., Ismail and Ingham, 2012).

A special case where a lack of vertical stress can be significant is when an out-of-plane thin wall acts with orthogonal return walls that do not resist vertical stress. In such case thin return walls that are weak in flexure act with out-of-plane walls as an assemblage. Flexural cracks at the base of return walls may develop early, causing rocking of the return walls, which will weaken the strength of the out-of-plane wall (Restrepo Vélez et al., 2014).

6   HOW SHOULD CORNERS BE MODELED?

Damage at the corners of unreinforced masonry buildings is a common observation following major earthquakes across the globe (e.g., Moon et al., 2014; Penna et al., 2014; Fig. 7). Yet little research attention has been given to this topic, perhaps because of its complexity. Corner damage is attributable to a combination of factors: (a) biaxial action of intersecting in-plane walls causing increased vertical stress, shear and crushing, (b) overlapping flange effects for orthogonal in-plane walls causing increased flexural tensile stresses, and (c) torsion of the corner region due to rotational restraint of a flexible floor or roof diaphragm. These mechanisms can be nonlinear since they involve crushing, shearing or cracking of the masonry. Their interactions create excessive complexities for most modeling procedures and thus significant challenges for seismic assessments.

Corner damage will influence strength and behavior of an out-of-plane wall since the stiffness of the edge boundary condition is decreased, or even worse, the edge condition collapses.

7   WILL OPENINGS INFLUENCE OUT-OF-PLANE BEHAVIOR?

Most research studies regarding out-of-plane seismic strength and behavior are concerned with fundamentals, and thus address mechanisms for solid wall panels. However, most buildings have windows and doors, and thus shear walls are perforated. Moreover, usually there are relieving arches, lintels or stronger frames around the openings, which might significantly affect the response. When the shear walls resist lateral forces transverse to their plane, the size, placement and boundary of the openings can affect out-of-plane strength and behavior. Particularly, the failure mechanism can be radically affected (Fig. 8), together with the dynamic response. Typically, diagonal cracks stem from the corners of the openings, which interact with other flexural and shear cracks (Fig. 9). Considerable stress redistribution occurs around such openings resulting in a flow of stress around the opening. This will certainly affect out-of-plane behavior, meaning that the size and placement of openings in an out-of-plane wall must be ideally modeled in some way (Griffith and Vaculik, 2007).

8 SHOULD EFFECTS OF IN-PLANE DAMAGE BE CONSIDERED?

As mentioned above, in-plane damage may significantly affect strength and behavior of an out-of-plane wall. In-plane damage tends to increase towards the lowest part of the building, while out-of-plane damage tends to increase towards the upper part of the building. In low rise buildings, such as historical masonry buildings, the combinations of effects seems to be much relevant, as well as in the case of relatively flexible buildings with non-load bearing walls. Diagonal stair-stepped cracks developed in an unreinforced masonry shear wall due to in-plane forces will weaken the wall with regard to out-of-plane forces (Fig. 10). The reciprocal condition also applies: out-of-plane damage will reduce in-plane stiffness and strength. Research has been done on these effects for unreinforced masonry loadbearing walls (e.g., Agnihotri et al., 2013; Najafgholipour et al. 2013; Dolatshahi et al., 2014) and masonry infill panels (e.g., Abrams et al., 1996; Paulo Pereira et al., 2011; Manfredi and Masi, 2014). Studies have found that a significant decrease in strength and stiffness can occur as a result of the prior loading in the orthogonal direction. Thus, modeling of out-of-plane seismic strength and behavior should include effects of prior or simultaneous in-plane actions. This of course broadens the analysis from that for planar elements to that for three-dimensional building systems. Whereas a user may wish to use simpler computational models, acknowledgement of such interactions should be taken into account when assessing results of such analyses.

9 SHOULD STATIC OR DYNAMIC ANALYSIS BE USED?

Design of conventional masonry buildings has traditionally been based on a linear static analysis of the building system (Abrams, 2001), even if there is an important trend to the use of state-of-the-art nonlinear analysis tools (Marques and Lourenço, 2011). Though seismic actions are indeed dynamic as are resisting modes, and significant nonlinearities may occur with cracking, simplified linear static methods are acceptable for estimating force or displacement demands on individual walls. Limiting axial, flexural and shear stress demands per allowable values is common for seismic design of unreinforced masonry buildings.

Strength design procedures based on elastic force demands are also mainstream. Recently developed linear static methods where forces are used as surrogate displacement demands and capacities have also received attention (ASCE 41, 2013) for seismic assessment and rehabilitation. Still, in case of historic buildings and monuments, linear approaches are often inadequate and macro-block approaches seem more reasonable (CMIT, 2009) or more advanced simulations.

A dynamic and/or nonlinear analysis can reveal structural characteristics not possible with a simpler model. These models are particularly suited to assessment and rehabilitation of existing buildings rather than serve as a basis for proportioning strength in new construction. Such analyses may preclude the need for retrofit, or conversely identify ductility demands that exceed capacities and thus avoid failure of individual elements. For out-of-plane walls, dynamic simulations may include modeling of wall segments rocking about their bases (e.g., Sorrentino et al., 2006; Shawa et al., 2012; Costa et al., 2015). Such kinematic modeling can indicate when out-of-plane instability will occur and at what lateral displacements. Because earthquake motions are kinematic in nature, such displacement-based analyses will capture reversals of wall segment rocking until displacement demands exceed capacities when wall collapse occurs. These analyses will give a much different assessment than with linear static models since post-cracking dynamic response is included.

Since nonlinear dynamic modeling is at the state of the art, analytical methods are usually limited to those that are programmed by individual users rather than commercially available software (or at least that can be used successfully by most engineer practitioners). Explicit definitions of ground acceleration histories are necessary as are definition of load-deflection hysteresis relations. More research needs to be done on estimating strain-rate effects, particularly with respect to cracking of masonry. In general stiffness and strength usually increase with strain rate whereas ductility may reduce (Paulson and Abrams, 1990; Abrams, 1996; Rafsanjani et al., 2014). Also, several discussions have taken place regarding modeling of dynamic impact effects, in particular as wall segments rock about each other as cracks

open and close (Sorrentino et al., 2011; Costa et al., 2013). Other papers of this special issue address dynamic modeling in more detail.

10 CONCLUDING REMARKS

As discussed in this paper, modeling aspects of out-of-plane seismic response for unreinforced masonry walls are far from trivial. Capturing all aspects of behavior may easily escape the most proficient of modelers. Considerable variance can occur in assessments done by different modelers due to the complexities of nonlinear dynamic response of these truly three-dimensional structures (Mendes et al., 2015). Because of this, a user must acknowledge that his or her own model is likely to not represent actual response precisely despite the complexity of the model or the analysis tool.

Despite the modeling challenges, structural earthquake engineers should not forget their primary objective – that being to safely assess the capacity of a given building structure with respect to collapse and thus protect the lives of its occupants and the people outside the building. With regard to this objective, some conservatism is much better than the converse. However, excessive conservatism must be circumvented when economies of retrofit solutions may not be practical or the impact on the cultural heritage may be too severe.

APPENDIX. BRIEF DESCRIPTION OF SIMULATION MODELS

In the main text the relevance of a number of modeling issues, such as the connection between façade and transverse walls, the orientation of the roof and its connection to the façade, the size and position of the openings, and the height-to-length ratio of the walls, has been underlined by means of three-dimensional comparative models.

The models are implemented through LS-DYNA, a code capable of simulating dynamic problems (Hallquist, 2006; LSTC, 2013). The approach is the same as in AlShawa et al. (2015), where a combined finite-discrete element framework is assumed. The strategy falls within the so-called meso-modelling of masonry, in which expanded units (e.g., unit + half

mortar joints thickness) are considered, cracks are allowed to appear in joints between con-

tiguous units, and frictional interaction along the predefined interfaces may take place. Each

expanded unit, also called block, is discretised by means of eight-node solid finite elements,

with a minimum length of 100 mm. Assuming constant stress, a single integration point is

sufficient, and hour-glassing modes are controlled through a Flanagan-Belytschko stiffness-

type stabilisation (Hallquist, 2006).

The connections between blocks initially in contact react to both compressive and tensile

forces, and a standard penalty method governs the contact behaviour through a linear

spring. The spring force depends on bulk modulii, face areas and volumes of the two adja-

cent finite elements. Tensile coupling is present before interface cracking, after which it is

removed. In the models presented herein the spring fails when the following inequality is sat-

isfied:

$$\frac{\sigma_n}{\text{NFLS}} \geq 1 \tag{1}$$

where σ_n is the normal stress on the contact surface, and NFLS is the normal (tensile) failure

limit stress. This criterion has been used by AlShawa et al. (2015) to simulate shaking table

tests, but alternative criteria are available in LS-DYNA. Initiation of sliding can be controlled

by a shear failure limit stress, SFLS, which is independent of normal stress and does not in-

fluence and is not influenced by the failure of the spring. Once shear capacity has been ex-

ceeded, sliding is controlled by static and dynamic friction coefficients. If shear strength is

neglected, friction alone controls initiation of sliding.

Most of the models in the main text have a square plan layout, 3.5 m ✕ 3.5 m, and are ap-

proximately 2.5 m tall (e.g., Fig. 1). The walls have a single, 235 mm thick, leaf. All materials

are linear elastic and, in the case of the masonry, Young's modulus, E = 5170 MPa, and

density, ρ = 1890 kg/m^3, have been set equal to the mean values in Candeias et al. (2015).

The model roof spans in a single direction, so that only two of the four panels are bearing

walls. The roof Young's modulus is approximately twice that of the masonry and its unit

weight is equal to 2.0 kN/m^2. For the interfaces of the façade the following parameters are

assumed: friction coefficients = 0.8, NFLS = 0.1 MPa, and SFLS = NFLS. Higher strengths are assumed for internal walls, in order to force damage on the façade.

Simulation models were subjected to gravity, slowly increasing to avoid unrealistic vibrations, and, after a time lapse, to the ground motion of the last test on the brick specimen in Candeias et al. (2015).An incremental dynamic analyses is performed, scaling the acceleration amplitude through a scale factor, S_f, until the model fails. An explicit time discretisation is implemented, as customary in the presence of contact interfaces. Noting that the results can be sensitive to the geometry, loads, mechanical parameters and ground motions, the objective of these simulations is intended to support qualitative statements expressed herein.

REFERENCES

Abrams, D. 1996. Effects of scale and loading rate with tests of concrete and masonry structures. Earthq. Spectra, 12(1):13-28. DOI: 10.1193/1.1585866.

Abrams, D. P. 2001. Performance-based engineering concepts for unreinforced masonry building structures. Prog. Struct. Engng Mater., 3(1):48–56. DOI: 10.1002/pse.70.

Abrams, D. P., Angel, R., and Uzarski, J. 1996. Out-of-plane strength of unreinforced masonry infill panels. Earthq. Spectra, 12(4):825-844. DOI: 10.1193/1.1585912.

Abrams, D. P., and Paulson, T. J. 1991. Modeling earthquake response of concrete masonry building structures. ACI Struct. J., 88(4):475-485. DOI: 10.14359/3093.

Agnihotri, P., Singhal, V., and Rai, D. C. 2013. Effect of in-plane damage on out-of-plane strength of unreinforced masonry walls. Eng. Struct., 57:1-11. DOI: 10.1016/j.engstruct.2013.09.004.

ASCE/SEI 41 2013. *Seismic rehabilitation of existing buildings*. American Society of Civil Engineers, Reston, VA.

AlShawa, O., Sorrentino, L., and Liberatore, L. 2015. Simulation of unreinforced masonry out-of-plane response through combined finite-discrete elements. Int. J. Archit. Herit., this issue.

Candeias, P. X, Campos Costa, A., Mendes, N., Costa, A. A., and Lourenço, P. B. 2015. Experimental assessment of the out of plane performance of masonry buildings through shake table tests. Int. J. Archit. Herit., this issue.

CEN 2005. EN 1996-1-1:2005 Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures. European Committee for Standardization, Brussels.

CMIT (Circolare del Ministro delle Infrastrutture e dei Trasporti) 2 febbraio 2009, n. 617. Circolare contenente le Istruzioni per l'applicazione delle "Nuove norme tecniche per le costruzioni" di cui al DM 14 gennaio 2008. Gazzetta Ufficiale della Repubblica Italiana n. 47 del 26 febbraio 2009, Supplemento Ordinario n. 27.

Costa, A.A., Arêde, A., Penna, A., and Costa, A. 2013. Free rocking response of a regular stone masonry wall with equivalent block approach: Experimental and analytical evaluation. Earthqua. Eng. Struct. Dyn., 42(15):2297-2319. DOI: 10.1002/eqe.2327.

Costa, A. A., Penna, A., Arêde, A., and Costa, A. 2015. Simulation of masonry out-of-plane failure modes by multibody dynamics. Earthqua. Eng. Struct. Dyn., accepted for publication.

Dolatshahi, K. M., Aref, A. J., and Yekrangnia, M. 2014. Bidirectional behavior of unreinforced masonry walls. Earthqua. Eng. Struct. Dyn., 43(15): 2377-2397. DOI: 10.1002/eqe.2455.

Griffith, M. C., Vaculik, J., Lam, N. T. K., Wilson, J., Lumantarna, E. 2007. Cyclic testing of unreinforced masonry walls in two-way bending. Earthqua. Eng. Struct. Dyn., 36(6):801–821, DOI: 10.1002/eqe.654.

Griffith, M. C., and Vaculik, J. 2007. Out-of-plane flexural strength of unreinforced clay brick masonry walls. The Masonry Soc. J., 25(1):53-68.

Hallquist, J. O. 2006. LS-DYNA theory manual. Livermore Software Technology Corporation. Livermore, CA, USA.

Ismail, N., Ingham, J. M. 2012. Cyclic out-of-plane behavior of slender clay brick masonry walls seismically strengthened using posttensioning. J. Struct. Eng., 138(10):1255-1266. DOI: 10.1061/(ASCE)ST.1943-541X.0000565.

Lourenço, P. B. 2002. Computations on historic masonry structures. Prog. Struct. Engng. Mater. 4(3):301–319. DOI: 10.1002/pse.120.

Lourenço, P. B., Avila, L., Vasconcelos, G., Alves, J. P., Mendes, N., Costa, A. C. 2013. Experimental investigation on the seismic performance of masonry buildings using shaking table testing. Bull. Earthquake Engin., 11(4):1157-1190. DOI: 10.1007/s10518-012-9410-7.

LSTC 2013. LS-DYNA keyword user's manual. Livermore Software Technology Corporation, Livermore, CA, USA.

Marques, R., and Lourenço, P. B. 2011. Possibilities and comparison of structural component models for the seismic assessment of masonry buildings. Computers and Structures, 89(21-22):2079-2091. DOI: 10.1016/j.compstruc.2011.05.021.

Manfredi, V., and Masi, A. 2014. Combining in-plane and out-of-plane behaviour of masonry infills in the seismic analysis of RC buildings. Earthqua. Struc., 6(5):515-537. DOI: 10.12989/eas.2014.6.5.515.

Mendes, N., Costa, A. A., Lourenço, P. B., Bento, R., Beyer, K., de Felice, G., Gams, M., Griffith, M., Ingham, J., Lagomarsino, S., Lemos, J. V., Liberatore, D., Modena, C., Oliveira, D. V., Penna, A., and Sorrentino, L. 2015. Methods and approaches for blind test predictions of out-of-plane behavior of masonry walls: An experimental comparative study. Int. J. Archit. Herit., this issue.

Moon, L., Dizhur, D., Senaldi, I., Derakhshan, H., Griffith, M., Magenes, G., and Ingham, J. 2014. The demise of the URM building stock in Christchurch during the 2010-2011 Canterbury earthquake sequence. *Earthq Spectra*, 30(1):253-276. DOI: 10.1193/022113EQS044M.

Najafgholipour, M. A., Maheri, M. R., and Lourenço, P. B. 2013. Capacity interaction in brick masonry under simultaneous in-plane and out-of-plane loads. Constr. Build. Mater., 38:619-626. DOI: 10.1016/j.conbuildmat.2012.08.032.

Paquette, J., and Bruneau, M. 2003. Pseudo-dynamic testing of unreinforced masonry building with flexible diaphragm. J. Struct. Eng., 129(6):708-716. DOI: 10.1061/(ASCE)0733-9445(2003)129:6(708).

Paulo Pereira, M. F., Neto Pereira, M. F., Dias Ferreira, J. E., and Lourenço, P. B. 2011. Behavior of masonry infill panels in RC frames subjected to in plane and out of plane loads. In *Proceedings of the 7th International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures (AMCM)*, Kraków, Poland, June 13-15, 20 pp.

Paulson, T. J., and Abrams, D. P. 1990. Correlation between Static and Dynamic Response of Model Masonry Structures. Earthq. Spectra, 6(3):573-592. DOI: 10.1193/1.1585587.

Penna, A., Morandi, P., Rota, M., Manzini, C. F., da Porto, F., and Magenes, G. 2014. Performance of masonry buildings during the Emilia 2012 earthquake. B. Earthq. Eng., 12(5): 2255-2573. DOI: 10.1007/s10518-013-9496-6.

Priestley, M. J. N. 1985. Seismic behaviour of unreinforced masonry walls. B. N. Z. Natl. Soc. Earthq. Eng., 18(2):191-205.

Rafsanjani, S. H., Lourenço, P.B., and Peixinho, N. 2014. Dynamic interface model for masonry walls subjected to high strain rate out-of-plane loads. Int. J. Impact Eng., 76:28-37. DOI: 10.1016/j.ijimpeng.2014.09.002.

Restrepo Vélez, L. F., Magenes, G., and Griffith, M. C. 2014. Dry stone masonry walls in bending — Part I: Static tests. Int. J. Archit. Herit., 8(1):1-28. DOI: 10.1080/15583058.2012.663059.

Shawa, O. A., de Felice, G., Mauro, A., and Sorrentino, L. 2012. Out-of-plane seismic behaviour of rocking masonry walls. Earthquake Eng. Struc., 41(5):949-968. DOI: 10.1002/eqe.1168.

Sorrentino, L., Masiani, R., and Decanini, L. D. 2006. Overturning of rocking rigid bodies under transient ground motions. Struct. Eng. Mech., 22(3):293-310. DOI: 10.12989/sem.2006.22.3.293.

Sorrentino, L., Masiani, R., and Griffith M. C. 2008. The vertical spanning strip wall as a coupled rocking rigid body assembly. Struct. Eng. Mech., 29(4):433-453. DOI: 10.12989/sem.2008.29.4.433.

Sorrentino, L., Al Shawa, O., and Decanini, L. D. 2011. The relevance of energy damping in unreinforced masonry rocking mechanisms. Experimental and analytic investigations. Bull. Earthquake Eng., 9(5):1617-1642. DOI: 10.1007/s10518-011-9291-1.

Sorrentino, L., Liberatore, L., Liberatore, D., and Masiani, R. 2014. The behaviour of vernacular buildings in the 2012 Emilia earthquakes. B. Earthq. Eng., 12(5):2367-2382. DOI: 10.1007/s10518-013-9455-2.

Sorrentino, L., D'Ayala, D., de Felice, G., Griffith, M., Lagomarsino, S., and Magenes, G. 2015. Review of out-of-plane seismic assessment techniques applied to existing masonry buildings. Int. J. Archit. Herit., this issue.

Tomaževič, M., and Velechovsky, T. 1992. Some aspects of testing small-scale masonry building models on simple earthquake simulators. Earthqua. Eng. Struct. Dyn., 21(11):945-963.

Wilhelm, M., Mojsilović, N., and Dazio, A. 2007. Out-of-plane shaking table tests on unreinforced masonry walls. In *Proceedings of the 10th North American Masonry Conference, St. Louis, Missouri, USA, June 3-5, 2007*, 671-682.

Willis, C. R., Griffith, M. C., and Lawrence, S. J. 2004. Horizontal bending of unreinforced clay brick masonry walls. Masonry Int., 17(3):109 – 121.

Yi, T., Moon, F. L., Leon, R. T., and Kahn, L. F. 2006. Lateral load tests on a two-story unreinforced masonry building. J. of Structural Eng., 132(5):643-652. DOI: 10.1061/(ASCE)0733-9445(2006)132:5(643).
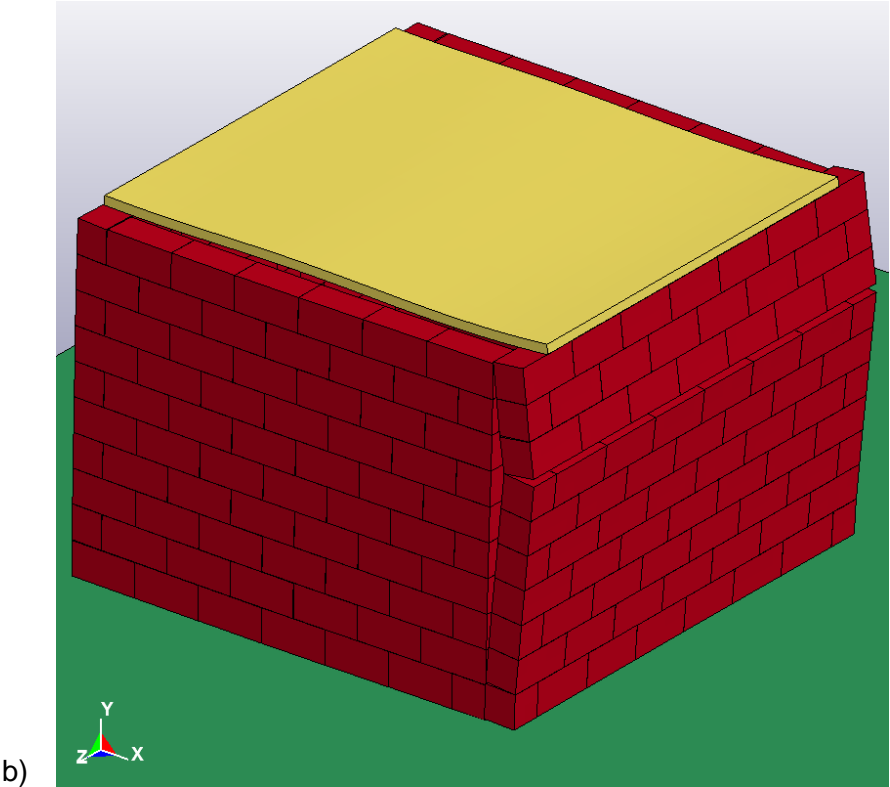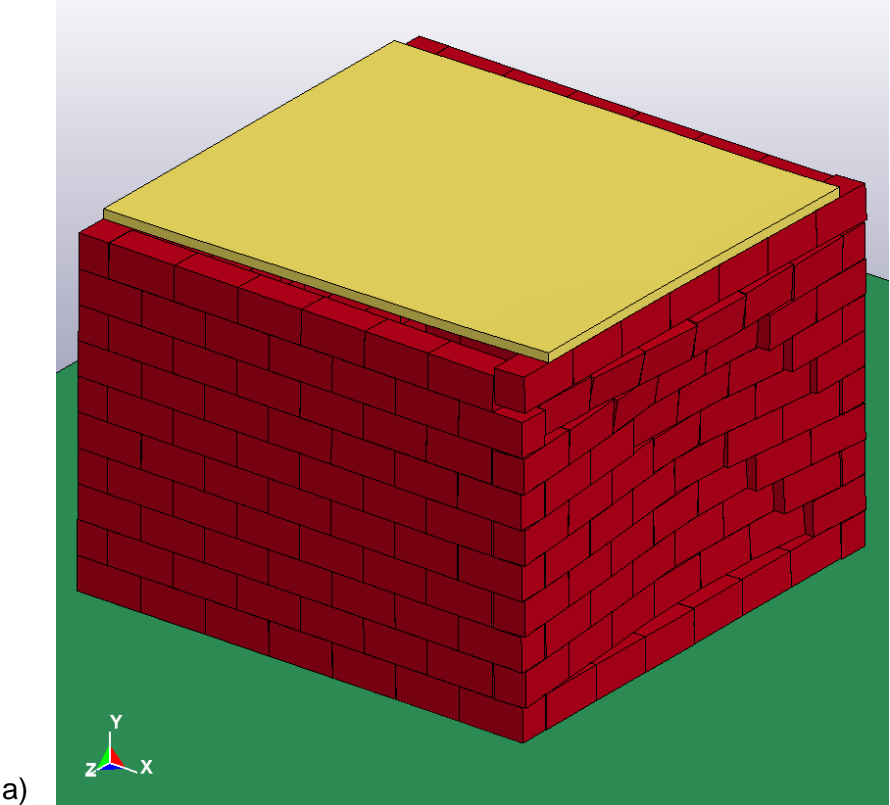
FIGURES

a)

b)

Fig. 1. Effects of different boundary conditions on out-of-plane failure mechanism of a façade connected to the roof: a) façade connected to transverse walls, $S_f = 1.8$ (refer to Appendix); b) façade not connected to transverse walls, $S_f = 1.0$. Ground motion along X.
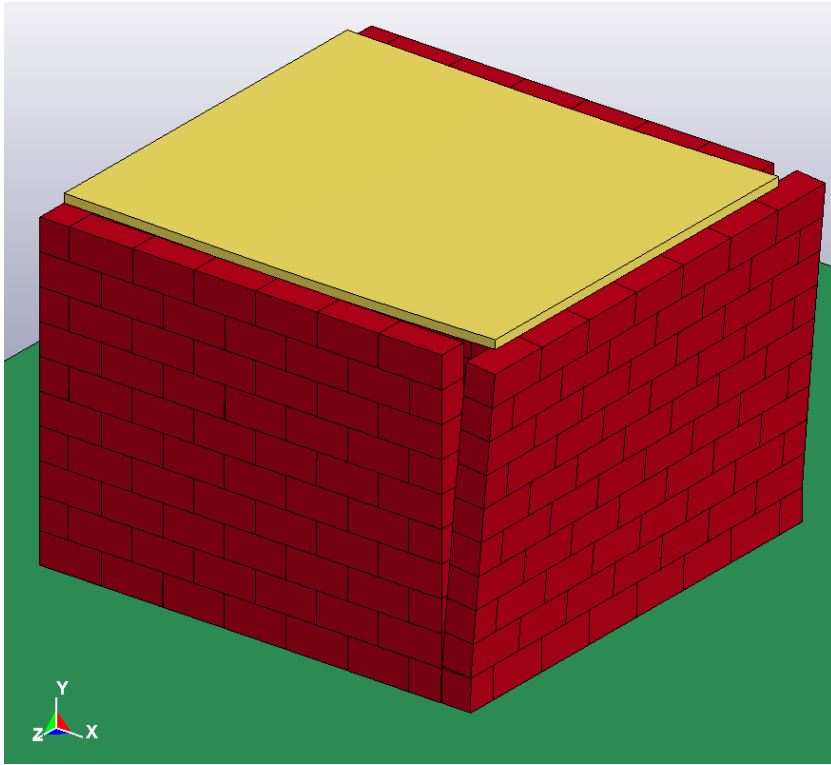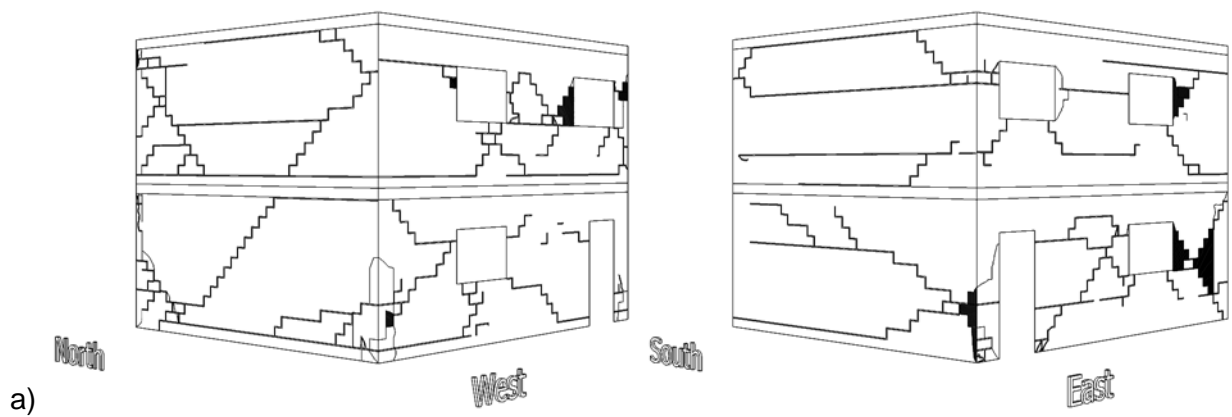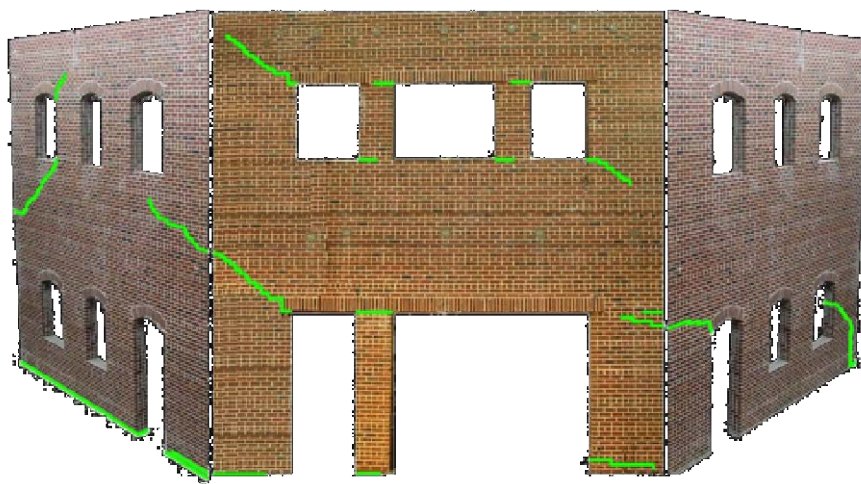
Fig. 2. Effects of different boundary conditions on out-of-plane failure mechanism of a façade not connected to transverse walls and supporting a (but not connected to) roof, S_f =0.4. Fig. 1b shows the result for a façade connected to roof, S_f = 1.0.

a)

Load Direction ⟶

b)

Fig. 3. a) Damage patterns involving corners in an unreinforced concrete-block building, tested on a shaking table (Lourenço et al., 2013); b) Cracking at base of left-hand flanged wall can alter the boundary condition for out-of-plane modeling of that wall (adapted from Yi et. al., 2006).
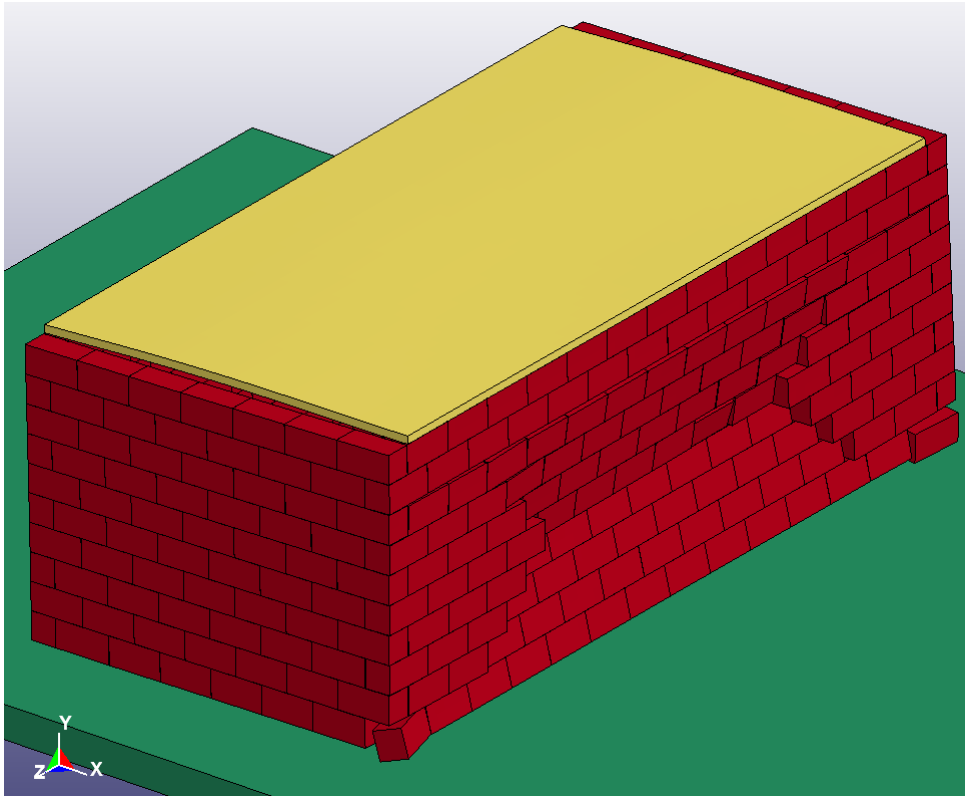
Fig. 4. Façade connected to the roof and the transverse walls. Effect of height to length (h/l) ratio: failure mechanism for h/l =0.36, S_f = 1.2. Fig. 1a shows the result for h/l = 0.72, S_f = 1.8.
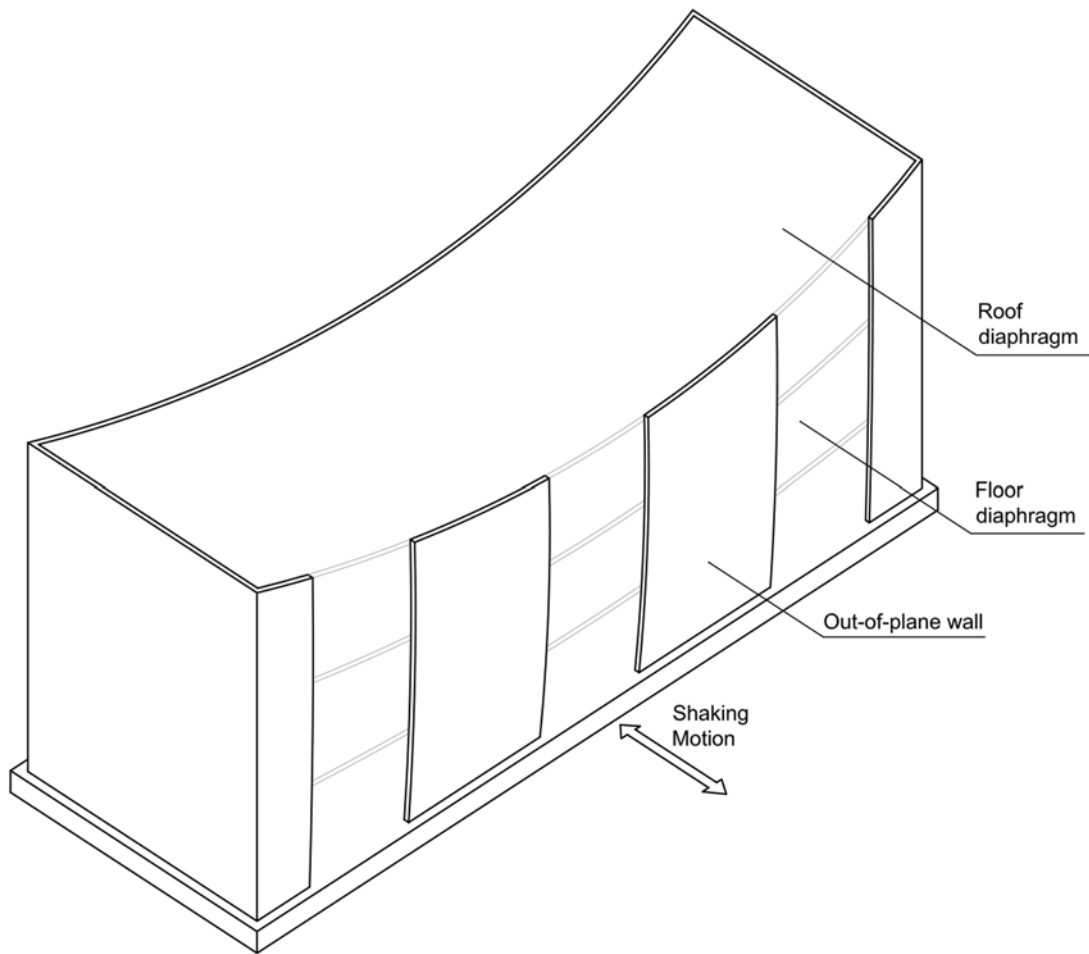
Fig. 5. Floor and inertial actions on out-of-plane walls (adapted from Priestley, 1985).
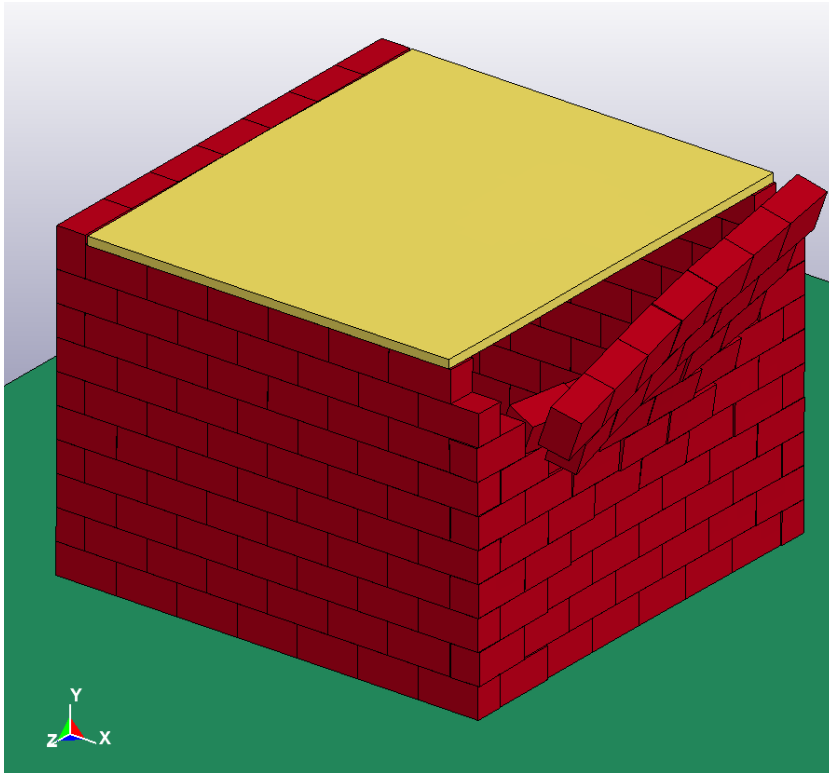
a)
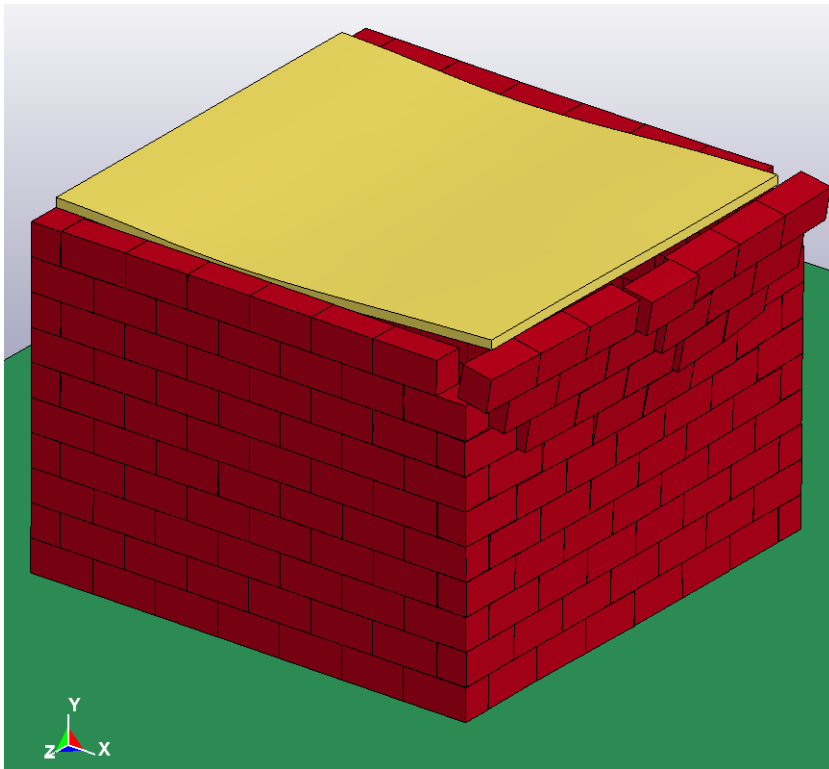
b)

Fig. 6. Effects of axial load on out-of-plane failure mechanism: a) floor resting on transverse walls, S_f = 1.6; b) floor resting on (but not connected to) façade, S_f = 1.7. Ground motion along X.

Fig. 7. Damage at corners: a) Unreinforced masonry building in Los Angeles 1994 Northridge Earthquake (photo by D.P. Abrams); b) Rural building after the Emilia 2012 earthquakes (Sorrentino et al., 2014).
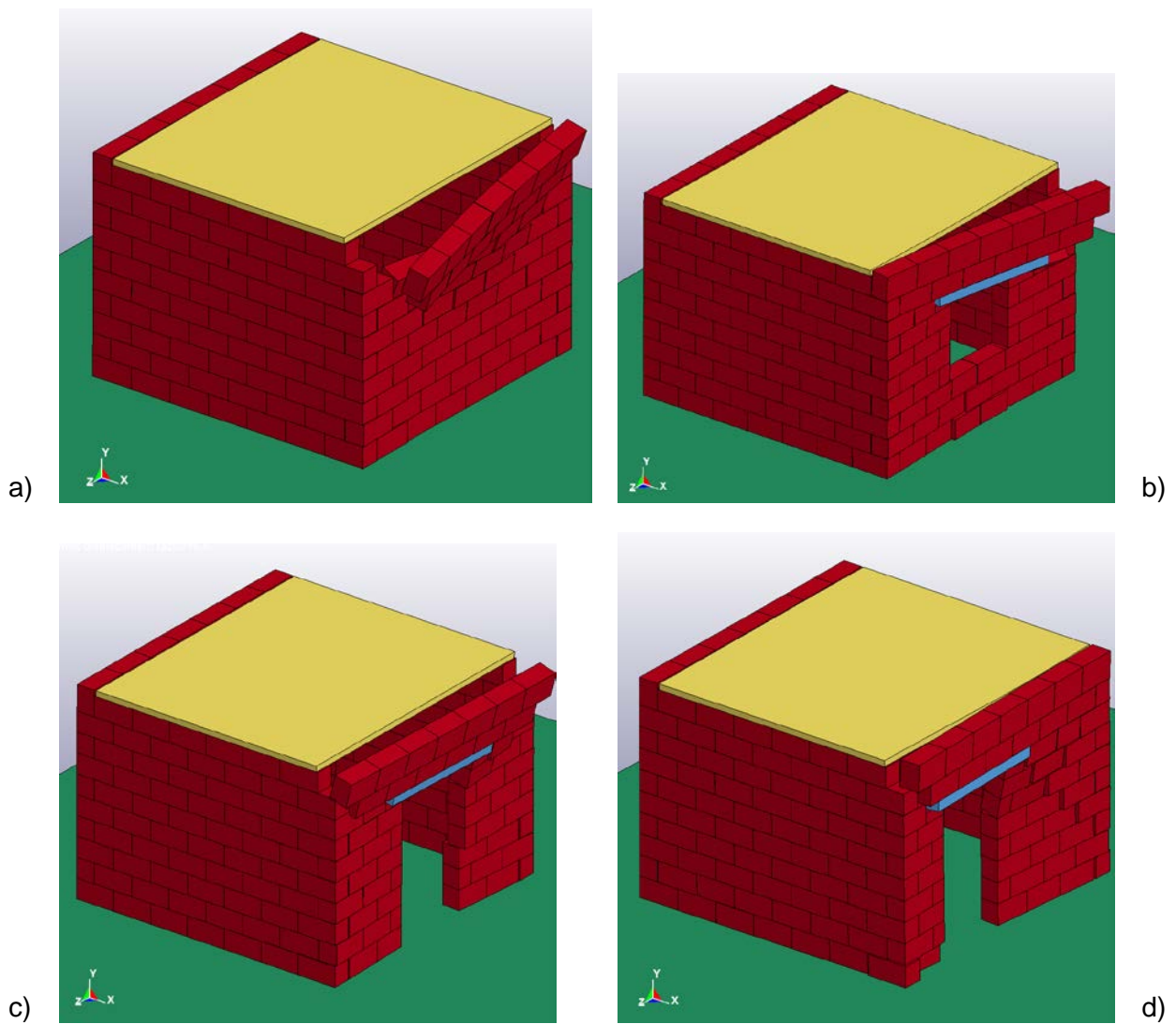
Fig. 8. Effects of openings on out-of-plane failure mechanism: a) without openings, S_f =1.6 (repeated, Fig. 6a); b) with central window, S_f = 1.6; c) with central door, S_f = 1.6; d) with eccentric door, S_f = 1.6. Ground motion along X.

Fig. 9. Damage around an opening in a clay brick masonry building after the Emilia 2012 earthquakes (photo by L. Sorrentino).
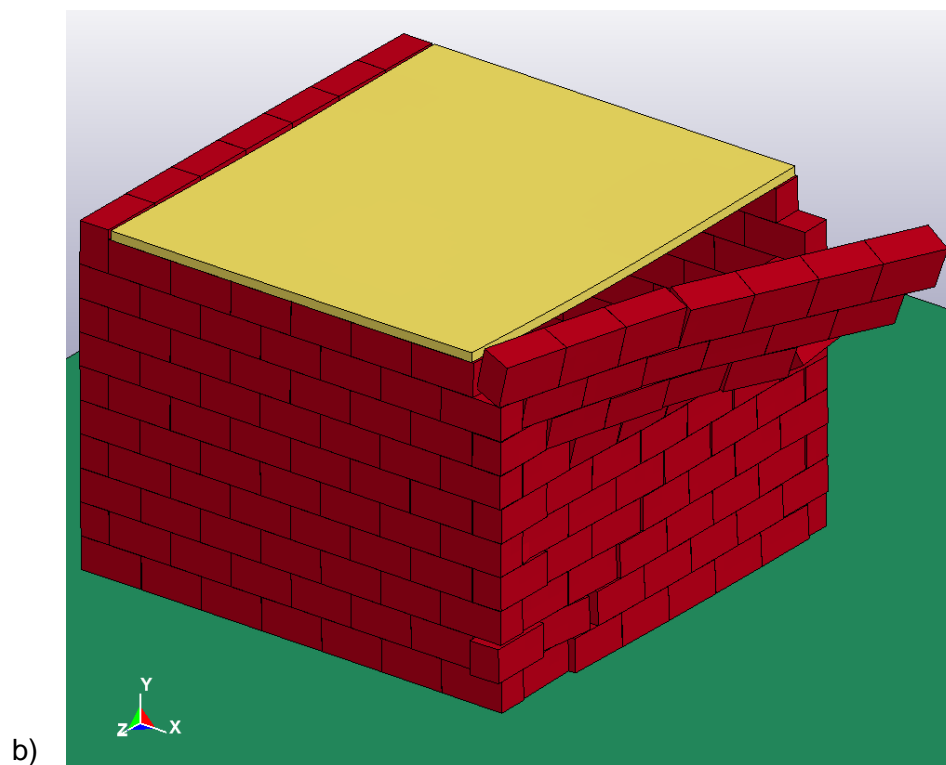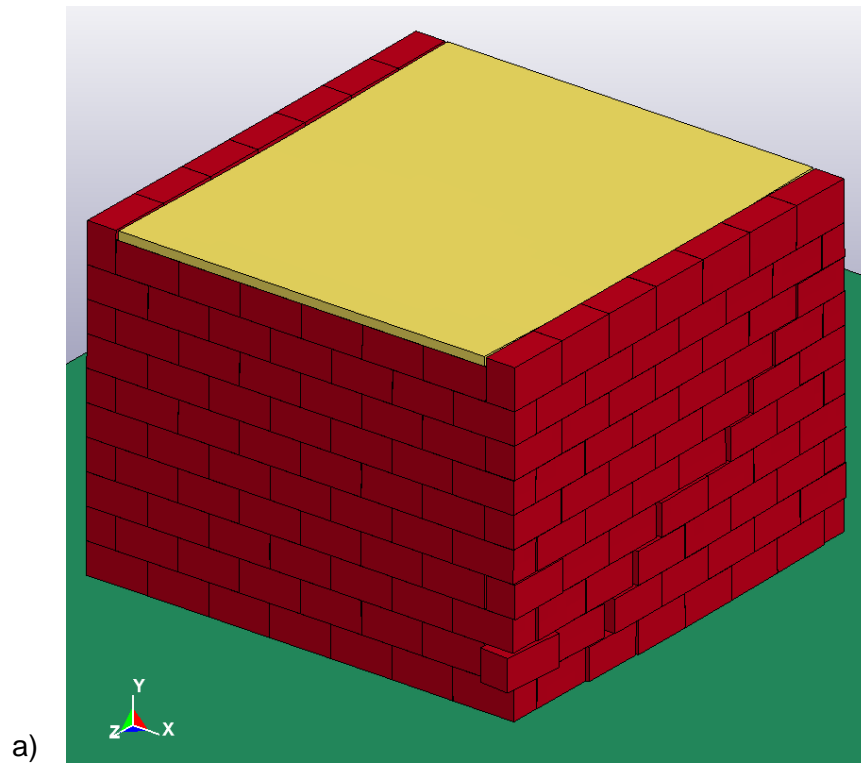
a)

b)

Fig. 10. Effects of previous in-plane damage on out-of-plane response: a) step 1: Ground motion along Z; b) step 2: Ground motion along X, S_f = 1.2 (compare with Fig. 6a).