Seismic vulnerability assessment of masonry building aggregates

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SUMMARY:
A method to assess the vulnerability of unreinforced masonry building aggregates is presented. This simplified methodology relies on the discretization of the walls into macro-elements, which model roughly the in-plane non-linear behavior (rocking and shear cracking) of each masonry panel, through plastic hinges. Each wall is divided into deformable piers and spandrels, connected through rigid links. The macro-element is coded into the open source finite element software OpenSees. The great possibilities of this program enabled us to study methodically the vulnerability of a few characteristic building aggregates. The consequences of several types of heterogeneities in the cluster have notably been investigated. The influence of the connections between adjacent buildings is also studied, the possibility of pounding being especially considered.

Keywords: building aggregates, masonry, vulnerability assessment, macro-element, frame-equivalent model.

1. INTRODUCTION

Masonry is widely used for construction in most of the world. A wide variety of buildings can be classified under this terminology: for instance, monuments made of dimension stone, common houses made of bricks or recent buildings made of concrete blocks can all be described as masonry structures. Most of these buildings are considered to be quite vulnerable to earthquakes. The Haiti 2010 earthquake illustrates well that fact: indeed, the high death toll of that event is strongly related to the vulnerability of the unreinforced masonry buildings, the most common structures in that country.

Masonry structures are often gathered in clusters, notably in historical city centers, where old historical buildings are often mixed with more recent and stronger structures. The interactions between these adjacent buildings must be carefully considered when studying their vulnerability, the dynamic response of a building being often strongly affected by the presence of adjacent structures.
The 1999 L'Aquila Earthquake was a good illustration of the vulnerability of old city centers: the old masonry buildings of this Italian town where seriously damaged by this earthquake.

In this study, we analyze the group behavior of these aggregates through the modeling of the masonry buildings with macro-elements. First, our methodology for simulating the dynamic behavior of masonry structures is presented. Then the dynamic behavior of various clusters is considered. The presence of heterogeneities in size or in mechanical properties in the cluster is notably investigated. Finally, the influence of the connections between buildings in the aggregate is also analyzed.

2. GENERALITIES ABOUT MASONRY BUILDINGS

2.1. Complexity of modeling masonry structures

The masonry walls are heterogeneous structures that cannot be directly modeled with the tools developed for the reinforced-concrete structures. In fact, these structures should be considered as made of a complex composite material, which shows a strongly anisotropic behavior.

Moreover, these structures can show complex macroscopic non-linear responses, varying a lot from a situation to another depending on geometrical and mechanical parameters. These responses are difficult to model in methods such as the finite element method, especially because of the cracks, which generate discontinuities in the deformation field.

D'Ayala and Speranza (2002) have classified the main global failure mechanisms that common masonry buildings may suffer. These mechanisms are depicted in Figure 1: depending notably on the load, the connection between the buildings and the characteristics of the structures, the main facade of a building can be damaged in many different ways. Thus, the extension of cracks in the masonry can free the rotation or the sliding of parts of the walls from the structure, which could lead to a wide set of failure mechanisms.

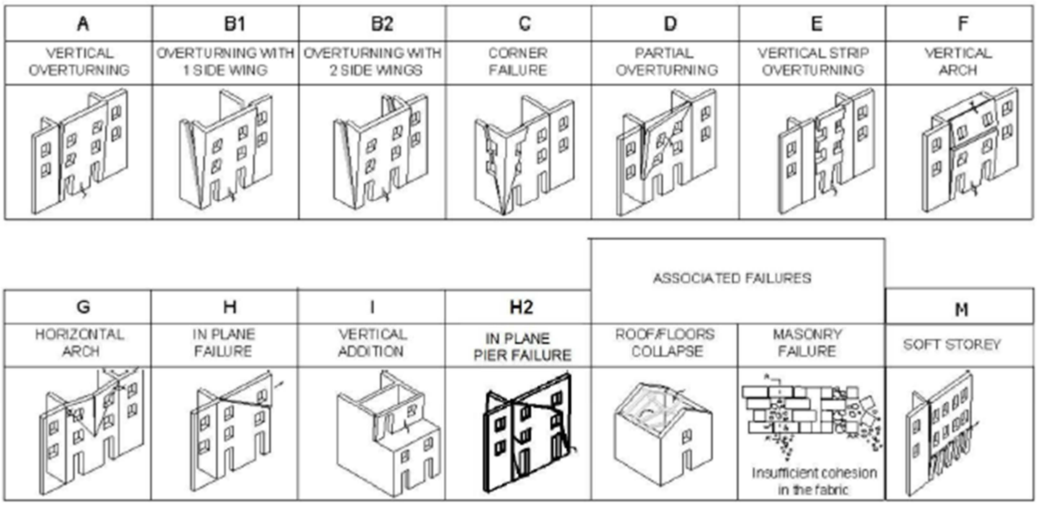

Figure 1. Failure mechanisms for masonry buildings, D'Ayala and Speranza (2003)

However, when these global failure mechanisms, related to the propagation of cracks on the whole façade, are prevented, some local failures may still appear, mostly in piers and spandrels. A good illustration could be seen in Figure 2.

Figure 2. Diagonal cracks (shear failures, surrounded by the red line) on the spandrels of a masonry building in l'Aquila. The global failure mechanisms of the façade have been prevented through the iron ties, and only local failures are observed (source: Calderoni et al, 2009).

2.2. Assessing the vulnerability of masonry structures

This chapter is not an exhaustive review of all the different approaches which have been developed to assess the vulnerability of masonry buildings, but it simply shows the different possibilities that have been considered by the authors before setting up the methodology of the study.

2.2.1. Limit state analysis

This type of analysis does not rely on numerical simulations to predict the static behavior, via pushover analyses, or the dynamic behavior, via time-history analyses, of the assessed structure. It is based on analytical formulas settled down by equilibrium considerations. Its application for the assessment of masonry buildings have been especially investigated and developed by D'Ayala and Speranza (2002). It considers a wide set of feasible failures (see Figure 1) with all the possible values for the crack angle. For each configuration, the maximum horizontal load for which the potentially moving block is still in equilibrium is computed. Then, the failure mechanism predicted by this method is determined by an optimization procedure.

This method is very interesting because it takes into consideration several failure mechanisms that are usually not considered by other methodologies (for example the out of plane failures). Nevertheless, it has some important drawbacks: for instance, the dynamic interaction between adjacent buildings and the spatial heterogeneity of the load within the buildings is difficult to take into account. Consequently, we preferred to use a different method for this study.

2.2.2. Discrete element method

The discrete element method has been extensively used for the study of granular mediums. The studied medium is discretized into elementary parts which can show discrete behavior. This methodology brings also very interesting results for modeling masonry structures, which are discretized into bricks and mortar (see Lemos 2007 for example). Although these models are computationally intensive and also require a lot of preparation time, they can be extremely valuable because they can predict accurately the collapse of masonry structures, and even the successive steps of the failure. Nevertheless, the method has not been used in this study, because of its complexity and because it seems not really adapted for modeling big models of several buildings.

2.2.3. Macro-elements and Equivalent frame models

Discretizing the walls of masonry structures into many elements with the finite element method is quite inefficient because of the complex damage patterns: then an option to realistically model these macro-scaled failures could be through the use of non-linear macro-elements. This idea has been already investigated and developed by many researchers, see for example the methods used in Tremuri (developed by Lagomarsino et al, from 1997), in SAM (developed by Magenes et al, from 1998) or in MAS3D (developed by Braga et al, from 1990).

In most of these methods, only a few local failure mechanisms are considered, the assumption being that the global failure mechanisms are prevented by a suitable design. A good example is the macro-element developed in Tremuri, which only considers the rocking effects, which are concentrated in the extremities of the panel, and the shear effects, which are located at the center of the element (see Figure 3).

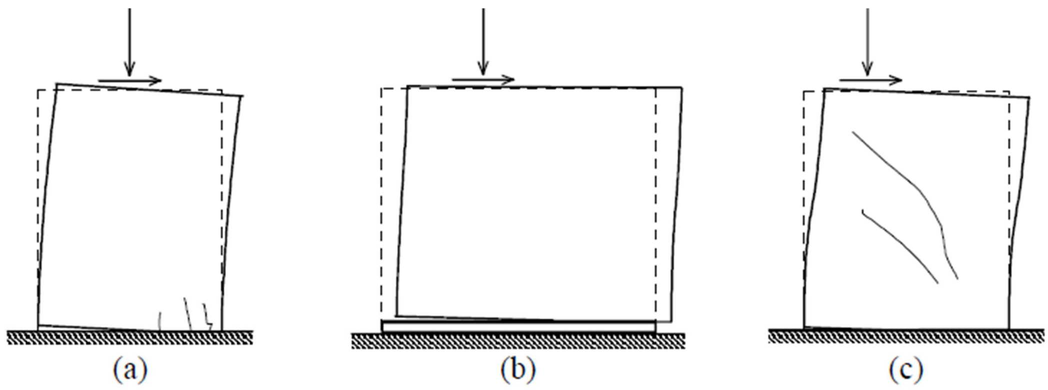

Figure 3. Masonry in-plane failure modes considered in the macro-element of the frame-equivalent models of Tremuri: flexural-rocking (a), shear-sliding (b) and diagonal-cracking shear (c) (source: Tremuri Manual)

A few approximations are usually made in these kinds of models: the deformation suffered by the walls are assumed to be only concentrated in piers and spandrels, whereas other part of the wall are considered rigid: A frame equivalent representation of walls can then be considered, the piers being the columns and the spandrels the beams (see Figure 5). Another important approximation is that the global structure is assumed to behave as a box (i.e. rigid floor acting as diaphragms), the out-of-plane behavior of masonry walls being neglected.

Despite these simplifications, this method is still useful, because it can bring a rough overview of the evolution of the deterioration of the elements of the structure during an earthquake, and is not only focused on the ultimate state (possibility to run static and dynamic analyses). Another advantage of that method is that the study of mixed reinforced concrete-masonry structures is quite easy, because these other elements are easily modeled with the finite element method. Finally, because of the small number of element necessary to model a building and the relatively small computation time, this approach is particularly suitable for the study of masonry aggregates. That is why we decided to use it in this study.

3. METHODOLOGY DEVELOPPED

3.1. Description of the macro-element

The masonry walls are modeled with non-linear beams-columns: a very simple elasto-plastic element has been coded in the open source software OpenSees. The non-linear behavior is triggered by conditions over the bending moments at both sides of the element, and by conditions over the shear force. When the moment at one side of the beam reaches its ultimate value, a hinge is formed at that end. Moreover, we made the assumption that the condition over the shear force triggers hinges at both ends. The damage softening effect is considered when unloading: the tangent stiffness is then decreased to the secant stiffness value (see Figure 4).

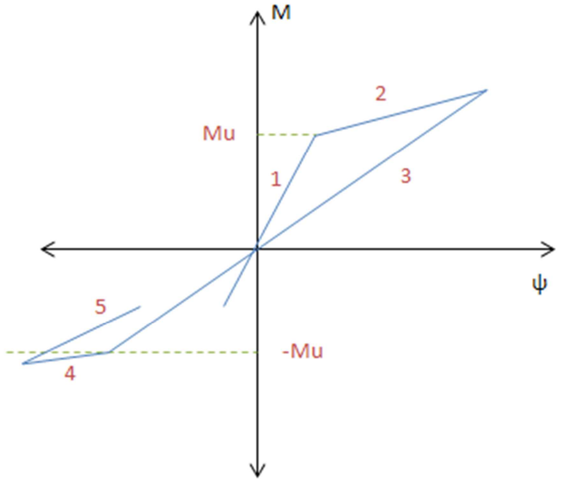

Figure 4. Moment curvature relationship of the macro-element considered in this study. The same curve applies also for the shear behavior (shear force - drift curve).

The ultimate moment (Eqn. 3.1) is computed with the formulas of Calvi and Magenes (1997), which were derivated from equilibrium consideration of a masonry panel at its limit state.

$$\boldsymbol{M_u = \frac{Nl}{2}\left(1 - \frac{N}{0.85 f_m l t}\right)} \tag{3.1}$$

The ultimate shear stress is based on the Mohr-Coulomb criteria. The same formula (Eqn. 3.2) as used in Tremuri macro-element is used (see Tremuri Manual).

$$\boldsymbol{V_u = l_{compressed} t f_{v0} + \mu N} \tag{3.2}$$

$$\boldsymbol{l_{compressed} = 3\left(\frac{l}{2} - \frac{|M|}{N}\right)} \tag{3.3}$$

Where:

- l is the width of the pier,
- t is the thickness,
- N is the axial compressive action,
- M is the moment at the lower extremity,
- f_m is the average resistance in compression of the masonry,
- f_{v0} is the shear resistance of the masonry without compression,
- μ is the friction coefficient (here μ=0.4).

3.2. Modeling a whole masonry building

A typical 3-bay masonry building has been considered in this study, with one door at the front and windows at the rear. Because the macro-element was coded in OpenSees, many already implemented tools where available for the study. For instance, the floor has been modeled with shell elements. Also the very flexible interface of OpenSees enabled us to test several cluster configurations without important modifications. In fact the command file authorizes to create the geometry and the connectivity through high-level scripting tools, for example via “for loops”: we could often easily swap from one configuration to another by simply modifying a variable.

Figure 5 illustrates the typical building considered in the study. Offset nodes are used to connect the piers and spandrels. Table 3.1 shows the proprieties chosen for the masonry panels.

The thickness of the walls has been considered constant over the height of the building, but the masses of the floors have been gradually decreased with height, because it seemed more realistic to us. In fact, the considered second floor weight is 20% lower that the weight of the first floor and the third floor (when it exists) 30% lower than the weight of the first floor.

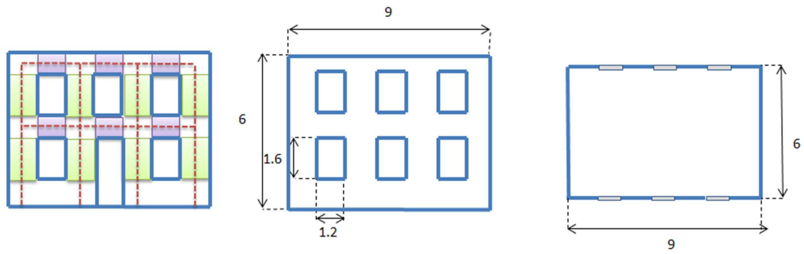

Figure 5. From left to right: front, rear and plan view of the typical masonry buildings considered in this study. The red dashed lines in the left drawing represent the frame modeling of the façade, discretized into piers (green elements) and spandrels (purple elements). These elements are connected through rigid links.

Table 3.1. Main properties of the masonry walls.

Property	Symbol	Value	Unit
Young's modulus	E	1.4e9	N/m²
Post yield ratio (E yield= p*E)	p	0.5	
Compressive strength	f_m	3e6	N/m²
Shear strength	f_{v0}	5e4	N/m²
Thickness of the wall	t	0.4	m
Friction coefficient	μ	0.4	

4. RESULTS

4.1. Regular pattern of identical buildings

The building presented in part 3.2 has been used as an elementary unit for creating various aggregates of identical buildings. The buildings were connected through rigid link, constraining both translation and rotations. The aggregate were solicited by an earthquake of PGA of about 0.2g, in the horizontal direction parallel to the main façade: the time-history solicitation has been scaled up to that value because with that level of excitation, the single building shows heavy but still realistic damage.

Our simulations showed that the aggregates with more buildings are stronger, probably because they are stiffer: fewer elements are damaged when the number of buildings is increased. Obviously, the rigidity of the aggregate does not increase linearly with the number of building added. For instance, in this specific case, the fundamental period increases from 10.7 Hz to 12.4Hz when the first building is added, but then increases more slightly to 12.9 and 13.1 Hz when aggregates of 3 and 4 buildings are formed. Consequently, we could expect that for example the vulnerability of a cluster of six buildings will not be much lower than the vulnerability of a cluster of five buildings.

Globally, with the geometric configuration and the mechanical properties considered, the weakest elements seem to be the spandrels, which always fail due to shear mechanism.

The consequence of the dynamic load on the single building was that all its spandrels were heavily damaged and the piers of the ground floor, especially the 2 central piers, underwent important rocking failure. On the contrary, when aggregates of several buildings were excited, the only damaged structures were the left-most and right-most ones, which underwent slighter damage on their central spandrels.

4.2. Buildings of different heights

We have studied the effect of the height difference between two adjacent buildings in a cluster. In fact, because of the discontinuity in the façade height, the top floor of a higher building suffers increased deformation and then damage because, contrary to the other floors, it is not strengthened by the adjacent buildings. The photo of Figure 6, taken in L'Aquila after the 1999 earthquake illustrates this fact: the highest building seems intact except for the left pier and the spandrel of the highest floor which are heavily damaged.

To investigate this phenomenon, 2 aggregates of 3 buildings each have been excited by an acceleration of PGA 0.2g. Contrary to the first aggregate, the central building of the second aggregate was one floor higher than the other buildings. Except from that difference, the buildings presented the same geometry and opening layout as in the previous parts.

The results of the simulation were as expected: All the piers of the last story were all heavily damaged in the central building of the second aggregate. Moreover, our model showed that even the 2 sides buildings were impacted by the height difference: The 2 central piers of the ground floor of each side building were slightly damaged in the second case, although it did not happened with the first aggregate. Moreover, the spandrels were more damaged in the second case.

Figure 6. In plane damage of third story due to different heights of adjacent buildings after the 1999 earthquake in L'Aquila (source: Calderoni et al, 2009).

4.3. Presence of a stronger building in the aggregate

One of our assumptions was that a strengthened building adjacent to weaker buildings could have negative effects on the behavior of buildings close to it in the aggregate. To investigate this idea, we tested two new configurations similarly laid out: 3 buildings in a row, with modified properties for the center building. In both configurations, the strength parameters of the masonry (compressive and shear strength f_m and f_{v0}) were increased so that any non-linear behavior is prevented. Moreover, in the second configuration the Young's modulus of the masonry was also increased (E multiplied by 5).

With the stiffened centered building, we noticed that the side buildings can withstand higher level of excitation, probably because the whole cluster is rigidified by the center building. In the other case, we observed that the center building is as expected not damaged, because of its increased strength, but we did not notice any modification of the damage layout in the side buildings.
It is possible that our models are too simple to focus on these kinds of problem or that the effects are not very important in that geometric configuration: further investigation would be necessary to clear the doubts.

4.4. Weak connections: pounding effect

The walls between two adjacent buildings could be well connected or not. In this second case, pounding effects between adjacent walls may happen which could damage them, and even damage the other adjacent walls (for instance the façade). To model this behavior, uniaxial non-tensile connections have been used between each adjacent wall.

The same mechanical properties (Young's modulus and compressive strength) as the one used in the macro-element have been considered for those connections. The consequences of the pounding failures (crushing of pounded bricks) were not investigated in this study: the idea was just to check if the connections reach or not the compressive strength of the masonry.

As in the precedent parts, a cluster of 3 adjacent buildings has been considered (see Figure 7). In order to trigger the pounding effect, the central building has been strengthened (Young's modulus multiplied by 1.7), so that all the buildings don't move in phase.

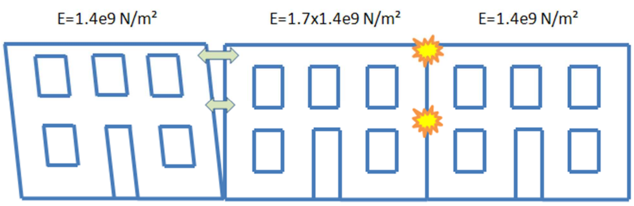

Figure 7. Cluster of 3 adjacent buildings considered to investigate the effect of weak connections.

The effects of the weak connections have been investigated by the authors very partially, because these non-tensile connections brought a lot of unexpected convergence issues. Nevertheless, we were able to run several simulations and some comment could be made: unexpectedly, the damage monitored with the weak connections was a little bit slighter than the damage observed with the rigid links. Moreover, under the acceleration load (this time PGA 0.09g), the maximum stresses in the connection were about 100 times smaller than the compressive strength of the weaker building: in that configuration and with this solicitation, a compressive failure of the pounded wall is very unlikely, because other in-plane failures will probably happen first.

5. CONCLUSION

A very simple non-linear modified beam-column macro-element has been developed and coded into OpenSees for modeling the piers and spandrels of a masonry façade. Despite this very simple approach, we were able to study some interesting aspects of the global behavior of aggregates of masonry buildings. We saw that when buildings are grouped into clusters, their vulnerability is often lower because they are strengthened by adjacent buildings. However, the effect of these clusters is not always favorable, especially when the building aggregate presents heterogeneities. We noticed for instance that height difference between adjacent buildings could have significant consequences on the vulnerability of the structures. We also noticed that our methodology does not highlight negative effects of a stronger building in an aggregate, but this conclusion must be carefully considered because of the simplicity of the model. Finally, a method to take into account weak connections has been presented, but the idea should be more developed to get steadier conclusions.

To conclude, this methodology is suitable for studying aggregates. Nevertheless, the macro-element still need to be improved in order to get more reliable results, for example by trying to consider out of plane failure mechanisms, and should be more carefully calibrated, for instance by comparison with discrete element method models.

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