ANALYSIS OF OUT-OF-PLANE DAMAGE BEHAVIOUR OF UNREINFORCED MASONRY WALLS

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SUMMARY

A thorough assessment of the lateral capacity of masonry load bearing walls subjected to seismic action is essential to define the probability of existing masonry structure to survive earthquakes, and hence to guide the design of strengthening strategies and interventions. A comprehensive experimental program on analysis of seismic dynamic behaviour of masonry structures, which includes both in-plane and out-of-plane pseudo-static titling tests on scaled stack masonry panels, as well as dynamic shaking-table tests on scaled masonry buildings, have been carried out. Models were built with different geometrical and structural characteristics to study the corresponding influence. This paper presents the series of pseudo-static tests on unreinforced masonry panels subjected to out-of-plane horizontal forces. Tests results are also compared with the analytical predictions from the program FaMIVE. Clear conclusions have been obtained on the out-of-plane damage behaviour of unreinforced masonry structures, which will not only improve the study of seismic behaviour of masonry structures on the basis of limit analysis, but also be useful to further theoretical study of masonry based on multi body dynamics.

INTRODUCTION

Masonry is one of the most common construction materials, both in history and at present with its inherent advantages, e.g. aesthetics, architectural appearance, effective heat and sound insulation, fire resistance, and economical construction. However, there are also several weaknesses. The lack of ductility in the structure and hence its inability to dissipate energy through inelastic deformations during earthquakes is one of the main reasons for high levels of observed damage in earthquake reconnaissance. A thorough assessment of the lateral capacity of masonry load bearing walls subjected to seismic action is essential to define the probability of existing masonry structure surviving from earthquakes, and hence to guide the design of strengthening strategies and interventions. For new load bearing masonry guidance is provided in the Eurocode 8, advice on strengthening and repair of masonry structure is only informative at this stage.

Recently, the research on properties and behaviour of unreinforced masonry buildings under earthquakes has gained attention and covered a wide range of relative research areas. As the main component subjected to horizontal forces, such as earthquakes and winds in masonry structures, masonry walls are considered as the basic structural element for which capacity needs to be defined. Analytical study has been carried out to develop simplified models based on limit state analysis for non conforming materials (D'Ayala and Speranza 2003). Assumptions are made on the connection between walls and other structural elements and

collapse load factors are derived for various mechanism configurations. The evidence for this approach is usually drawn from damage observation on site, but very modest experimental work has been carried out to date to underpin this theory (Griffith, Lam et al. 2004; Lourenco and Ramos 2004; Restrepo-Vélez and Magenes 2004; Lourenço, Oliveira et al. 2005).

Experimental work available in literature also states that stress state and stiffness degradation of masonry walls during the process of damage vary with material layout, and it is difficult to obtain reliable mathematical models (Calvi, Kingsley et al. 1996). Meanwhile, inconsistency between the scaled model and full-scale model makes results based on stress and strength difficult to compare and generalize. Many parameters influence the actual composition of mortar and the development of its bond strength, including not only material characteristics but also workmanship and aging conditions. Therefore, in terms of experimental research on masonry structures, generalized and reliable conclusions from laboratory activity can only be obtained on aspect of damage mechanisms rather than on accurate mechanical description of the damage process and state of stress.

On the other hand, laboratory tests conducted on brick masonry walls subjected to monotonic lateral loading have shown that failure takes place along regular pattern of lines whose arrangement depends on how the structures are supported and the height-to-width ratio (Hendry 1973; Anderson 1976; West, Hodgkinson et al. 1977). These observations have inspired approximation methods based on the fracture line theory (Sinha 1978). The structural performance of masonry can be understood provided the following factors are known (Binda, Saisi et al. 2000): (i) its geometry; (ii) the characteristics of its texture (single- or multiple-leaf walls, connection between the leaves); (iii) the physical, chemical and mechanical characteristics of the components (brick, stone, mortar); (iv) the characteristics of masonry as a composite material. As in typical masonry with lime mortar, shear and bond strength of the mortar are much smaller than its vertical compression strength and also substantially smaller than the shear strength of bricks or stone blocks, the seismic damage in the form of cracks usually propagates within the mortar beds or at their interface with the units. Some researchers have claimed that the presence of the mortar may only affect the failure strength, and has no effect on seismic damage mechanisms of masonry structures (Adams 1996).

With reference to the pseudo-static tests on dry masonry panels, only limited work has been carried out to date (Marzahn 1997; Lourenco and Ramos 2004; Restrepo-Vélez and Magenes 2004) to study their ultimate capacity and failure mechanisms as well as to validate seismic vulnerability assessment procedures. General conclusions are rather difficult to be drawn from such limited experimental activity.

Therefore, the experimental study presented here focuses on dry masonry blocks with frictional behaviour. Tests on dry masonry panels allows for quick build-up of specimens and good repeatability of tests for more reliable results. This makes it feasible to set up significant parametric analysis in a normal project time frame as well as to use the material repeatedly in different tests, which is more economical.

The whole experimental program contains both pseudo-static tilting tests and dynamic shaking-table tests. In the first part, both in-plane and out-of-plane collapse are studied on masonry panels with different configurations. Experimental results are compared in terms of collapse load factor and assigned collapse mechanism with the numerical procedure for the seismic vulnerability assessment of masonry buildings FaMIVE (D'Ayala and Speranza 2003). In the second part, 3-dimensional dry masonry models are constructed on the 6-DOF shaking table with different aspect ratios. This paper presents the experimental results and the

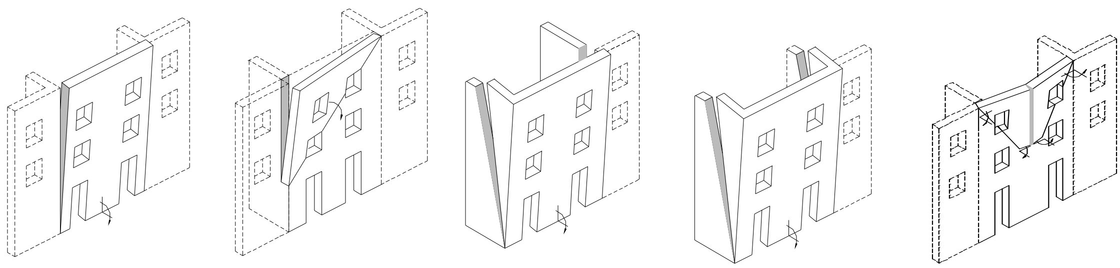
corresponding numerical analysis of the out-of-plane pseudo-static tests. Studies on other parts of this experimental program have been discussed on related references (Shi and D'Ayala 2006).

In the pseudo-static experiments, clear damage characteristics of masonry walls under increasing horizontal forces, including damage mechanisms and the corresponding collapse load factors have been collected. The influence of the structural and geometrical parameters, such as geometric dimensions and connection conditions has been systematically analyzed. Since these conclusions directly relate to the inherent structural characteristics rather than mechanical properties of the materials, they are of more general applicability to a wider range of masonry structures.

THEORETICAL BACKGROUND

The mechanical model adopted is based on the assumption of dry block masonry with essentially frictional behaviour, where cohesion may or may not be included. The out-of-plane panels under different types of connections at the two corners are analyzed. If the structure has not undergone strengthening, it is assumed that the only means of restraint exerted by other elements onto a particular wall is governed by the friction of contact surface between orthogonal walls and depends on the overlapping of bricks at the corner.

According to the parametric numerical analysis conducted in (D'Ayala and Speranza 2003), the out-of-plane failure may occur by several types of possible damage mechanisms depending on the complexity in structural configurations of masonry walls, being highly influenced by the type and strength of connection at corners. The classification of the out-of-plane damage mechanisms is shown in Figure 1.



Mechanism A Mechanism D Mechanism B1 Mechanism B2 Mechanism G

Figure 1 Out-of-plane damage mechanisms

Mechanism A assumes that no connection with side walls at the edges of the façade is available or that such connections are not sufficient to supply constraints. Mechanism D in which a portion of the facade collapses along a diagonal line assumes that the façade has effective connection at one edge only while the other is free. Mechanism B1 is also possible when this single connection gets strong enough to involve part of the side wall into the façade collapse. The damage develops to Mechanism B2 involving both side walls in the collapse when both edges of the facade have sufficiently strong connections with the side walls. Finally, Mechanism G, associated with horizontal arching action can occur when the façade span is rather long, with the failure being characterized by a central trapezoidal portion.

The collapse load factor for each mechanism is defined using a limit-state approach as the ratio between the lateral acceleration and the gravitational acceleration at incipient collapse,

i.e. $\lambda = a / g$. It is a function of the shape of the façade and depends on the restraining action due to friction. Superimposed loads and specifically the ratio of loading of orthogonal walls also influence the behaviour, while restraining action can also be exerted by the floor structures resting on the overturning panel.

EXPERIMENTAL SETUP

The definitions of geometric dimensions of bricks and panels in the tests are shown in Figure 2. The first kind of bricks used is 3/4 of a standard brick, with dimension 152*75*50mm. The second set uses smaller 1/2-scale bricks with dimension 105*50*35mm, which allows simulating walls with larger numbers of bricks and gaining clearer data about crack patterns. The average value of the friction coefficient measured is 0.56 for the large brick and 0.66 for the small one.

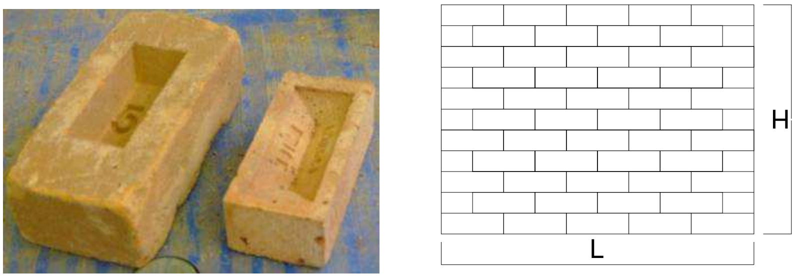


Figure 2 Bricks and geometric definition of panels

A timber table that can be tilted gradually by an electrically controlled crane is set up, as shown in Figure 3, on which dry masonry panels are built and tilted to collapse. The stiffness of the timber table is large enough so that its own out-of-plane deformation caused by the weight of the masonry panel on it can be ignored. Increasing lateral force is applied on the panel by tilting the table in a quasi-static motion until collapse occurs. As the lateral distributed force from tilting on the masonry panels is part of the gravity force and is only balanced by the friction developed between courses, the corresponding collapse load factor will equal the tangent value of the titling angle of the table. The corresponding tilting angle is measured by a digital inclinometer.

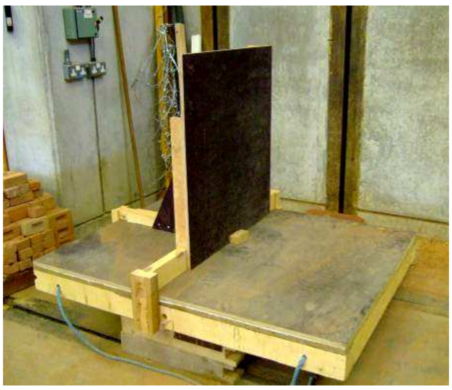


Figure 3 Experimental instrumentation

Different corner configurations are used to simulate different damage mechanisms. The staggering definitions of bad, good and strong connections for panels using large bricks correspond to overlapping of the side and façade bricks of 10mm, 50mm and 75mm respectively with the staggering ratios as 0.2, 1 and 1.5. For panels using small bricks, the

corresponding staggering are 10mm, 35mm and 50mm and the staggering ratios are 0.3, 1 and 1.5 respectively. By keeping one corner as a bad connection, façade panels are built with the other corner as bad connection, good connection and strong connection. Panels with strong connections in both corners were also tested.

EXPERIMENTAL RESULTS ANALYSIS

Variation of incipient collapse behaviour with structural configurations at corners can be seen in Figure 4, with the correspondingly ultimate collapse damage in Figure 5. Keeping one corner as bad connection, panels collapse as mechanism A, D and B1 when the other corner is laid out as bad, good and strong connection respectively. When both corners have strong connections, mechanisms B2 or G occur.

For symmetrical corner connections, without proper constraint at both corners in Figure 4(a), the façade panel collapses as Mechanism A, along a horizontal hinge line, followed by the separate in-plane collapse of side panels. A large portion of the facade panel collapses as in Figure 5(a). On the contrary, when both corners have strong connections, the top 3 courses entirely collapse taking a portion of the side panels corresponding courses with them, while only the central part of the lower courses of the façade fail, leading to Mechanism B2 in Figure 4(d). The facade panel collapse in an arch shape accompanied by the sliding of a portion of the side panels, ultimately as Figure 5(d). It is observed that the number of layers that completely collapse in Mechanism B2 keeps unchanged in spite of the variation in length and height of the facade. With increasing value of L/H, the arching behaviour is more pronounced and for values of L/H greater than 1.5 Mechanism G (Figure 4(e)) will occur in preference, taking place on the façade without involving the side panels, with clearer and larger collapsed arch in Figure 5(e).

(a) Mechanism A (b) Mechanism D (c) Mechanism B1 (d) Mechanism B2 (e) Mechanism G
Figure 4 Collapse behaviour of different out-of-plane damage mechanisms

(a) Mechanism A (b) Mechanism D (c) Mechanism B1 (d) Mechanism B2 (e) Mechanism G
Figure 5 Ultimate damage of different out-of-plane damage mechanisms

Under the condition of non symmetrical corner connections, the badly connected side fails in a manner similar to Mechanism A while the better connected side collapses with a small part of the side panel over a lower number of courses. As shown in Figure 4 and 5(b, c), this

results in a stepping oblique crack line developing across the façade panel. In case of a good connection, a complete diagonal crack line forms along the façade panel to the weak side, as outlined in Mechanism D; in case of a strong connection, a larger portion of the side panel participates in the collapse and the number of courses failing on the two sides is closer and smaller than the previous case, leading to an almost horizontal hinge line in the facade. This is Mechanism B1 in Figure 4(c).

The behaviour discussed above shows that damage mechanisms are mainly influenced by corner connections. Furthermore better connections also offer stronger constraint and therefore smaller collapsed portions. For example, for façade panels with the same geometrical dimensions in Figure 4 and 5(a-d), Mechanism A occurs with 11 collapsed courses, while for Mechanism B2 only 3 courses at corners collapse. On the other hand, as the damaged arch in the middle of the facade is formed by the stepping lines from two corners, the collapsed layers in the middle also relate to the geometrical form of the facade. Additionally, it is noticed that Mechanism B1 causes a larger collapsed portion in bad connected corner than that in Mechanism D. This originates from the stronger constraint from its strongly connected corner which also influences the sliding of side panels.

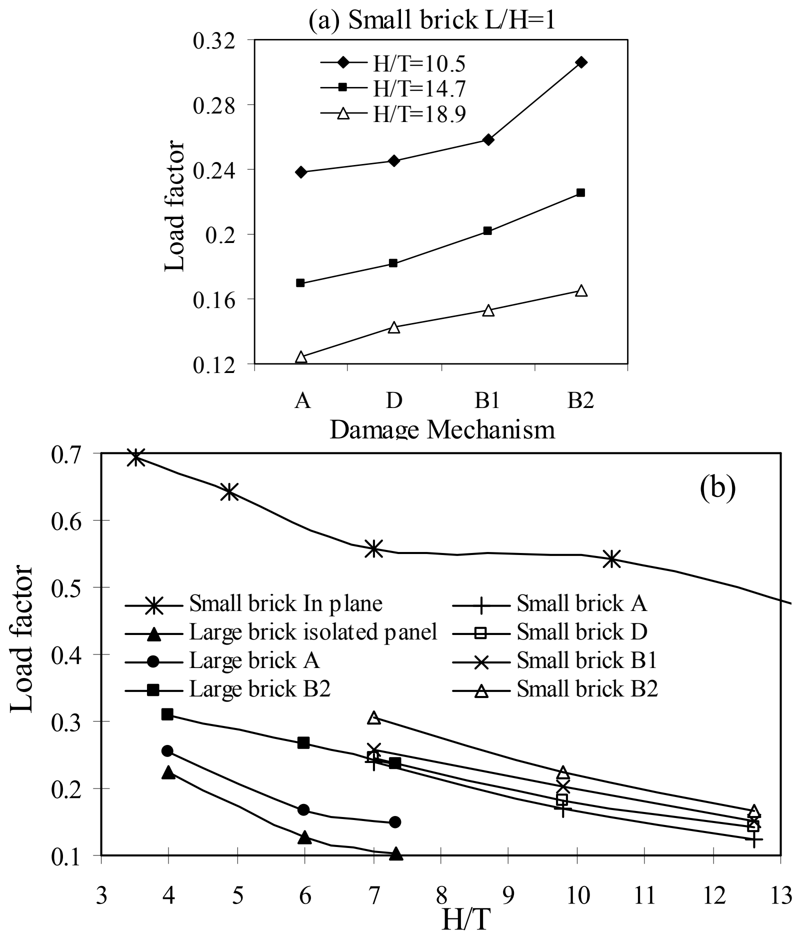


Figure 6 Variation of load factor with damage mechanism and slenderness

The variation of load factors in Figure 6(a, b) confirms that corner connection is a critical factor for out-of-plane seismic behaviour of masonry walls with increased capacity directly proportional to better connection. At the same time the collapse load factor is also inversely proportional to the slenderness of the wall.

Panels in Figure 6(a) are all constructed with small bricks with a constant L/H=1, that is, they have the same geometrical shape and only varies with scale and slenderness. Clearly, better corner connections can offer large load factors. It also can be observed that curves in Figure 6(a) are substantially parallel. This outlines that the proportional increase in load factor is to a certain extent independent of the slenderness of the wall and relates to the friction coefficient of the brick used. This is more apparent in Figure 6b where series of tests carried out with two different types of bricks with different friction coefficient are compared.

It can be noted that panels with large bricks characterised by a smaller coefficient of friction have smaller collapse load factors that panels with smaller brick for the same type of connections at corners. It also can be observed from Figure 4 and Figure 5 that the length of side panels has little effect on load factors because except for a few bricks close to corners, the major portion of the side panels does not participate in collapse. The value of in-plane load factors of panels with small bricks and same slenderness is also drawn for comparison. The in-plane collapse clearly shows much larger load factors clearly demonstrating the higher vulnerability for out-of-plane collapse for masonry facades, as also noted in post earthquake reconnaissance missions throughout the world.

By comparing the variation of load factors among different damage mechanisms in Figure 6(b), it can be found that all the curves representing the out-of-plane load factors under certain damage mechanism for panels with small bricks are parallel to one another. And they are also parallel to all the curves for panels with large bricks even though the friction coefficients and geometrical shapes of these two groups of panels are different. However, as the large brick is a 1/2-scale brick and the small is a 3/4-scale one, the ratio of L: H: T of them is both 6:3:2. Additionally, the corresponding staggering ratios that represent different degrees of corner constraints for panels with these two kinds of bricks also coincide with each other. Thus, this common layout can be thought to be derived from the similar inherent properties of these two kinds of bricks, as well as the similar way that the panels are built. This further confirms the generality of experimental results carried out in dry joint, so as to eliminate the issue of scale and associated state of stress(Shi and D'Ayala 2006).

VALIDATION OF SEISMIC VULNERABILITY ASSESSMENT PROCEDURE

Using the programme FaMIVE (D'Ayala and Speranza 2003; D'Ayala 2005), load factors and the corresponding damage mechanisms of masonry walls can be obtained by inputting their structural parameters. The ultimate load factor is chosen as the minimum value associated to the feasible damage mechanisms. Comparison between theoretical and experimental load factors can be seen in Figure 8 for all the panels with both kinds of bricks.

For facades with side panels, the procedure only defines corner connections as either absent or present, while it has been seen with the experimental results that different levels of overlapping ratio of bricks at corners will lead to different behaviour in terms of both mechanism and load factor, although this last presents little variation.

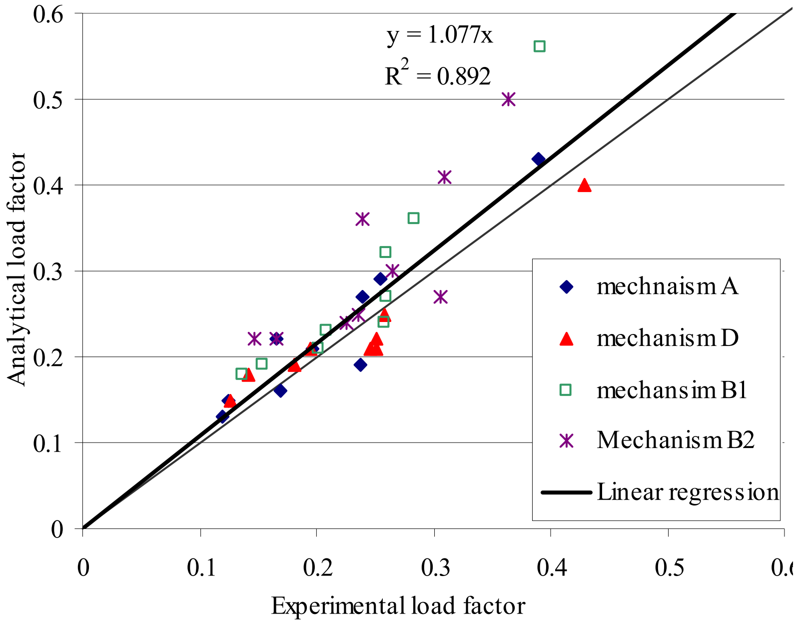


Figure 8 Comparison of experimental and numerical results of all panels

Thorough comparison between theoretical data and experimental data is presented in Figure 8 for panels using both large bricks and small bricks. It can be noted that the agreement is fairly good except for high values of the collapse load factor corresponding to stocky wall with small slenderness ratio, independently of the type of mechanism simulated. Walls with this shape are very unlikely to fail in out-of-plane mode in reality. The slight overestimate for mechanism A is to do with the imperfection of the bricks surfaces. Due to it a modest curvature results for each course both in and out of the plane of the panel. This feature, clearly, not only reduces the contact surface between bricks, but, over a large number of courses, results in a misalignment both from the horizontal and the perfect vertical. These manufacturing defects, inherent in bricks, cause in the slenderer panels a combined in-plane and out-of-plane failure, for a smaller angle of tilt. For the mechanism D the underestimate of the collapse load factor is due to the fact that in the FaMIVE procedure this is calculated disregarding the modest friction restraint developing on the bad connection side, which clearly has a small but positive effect in reality.

The largest relative error between the theoretical load factors and the experimental load factors is below 30%, while the average relative error of all tests results is 12%; as can be seen in figure 8 a best fit line as a regression factor R^2= 0.90 and a tangent coefficient of 1.07, highlighting the very good agreement between the two sets of data.

CONCLUSION

From the discussion of the experimental results from the systematic pseudo-static out-of-plane tilting tests, the basic out-of-plane damage behaviour of masonry walls has been outlined to help to understand and improve the theoretical work developed before. Conclusions on the variation of out-of-plane load factors with the variations of masonry panel's characteristics are also drawn.

1. Out-of-plane damage mechanism of masonry wall is determined by corners configurations. Mechanism A, B1, D and B2 occur gradually as the two corners get better connections. For walls with strong connections at both corners, Mechanism G is more likely to occur than

Mechanism B2 with the increase of L/H. Besides, better constraints from better corners connections causes smaller collapsed portions. The exclusive larger collapsed portion in the worse connected side of Mechanism B1 states relatively high vulnerability with highly unsymmetrical corner connections.

2. Corner connection is also the most crucial factor for out-of-plane load factor. Better connections offer larger load factors. Meanwhile, the geometric form of facade, as well as its scale, slenderness and number of bricks contained can influence the load factor to some extent.

3. The variation of out-of-plane load factor with the slenderness of masonry facade relates to the inherent properties of bricks being used, such as their shapes and friction coefficient.

4. Comparison between experimental and theoretical results indicates the validity of out-of-plane seismic vulnerability assessment procedure developed in FaMIVE.

REFERENCE

Adams, D., "Effects of scale and loading rate with tests of concrete and masonry structures", *Earthquake Spectra*, Vol. 12, No. 1, 1996, pp. 13-27.

Anderson, C., "Lateral loading tests on concrete block walls", *The Structural Engineer*, Vol. 54, No. 7, 1976, pp. 239-246.

Binda, L., Saisi, A., et al., "Investigation procedures for the diagnosis of historic masonries", *Construction and Building Materials*, Vol. 14, No. 4, 2000, pp. 199–233.

Calvi, G., Kingsley, G., et al., "Testing of masonry structures for seismic assessment", *EARTHQUAKE SPECTRA*, Vol. 12, No. 1, 1996, pp. 145-162.

D'Ayala, D., "Force and displacement based vulnerability assessment for traditional buildings", *Bulletin Of Earthquake Engineering*, Vol. 3, No. 3, 2005, pp. 235-266.

D'Ayala, D. and Speranza, E., "Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings", *Earthquake Spectra*, Vol. **19**, No. 3, 2003, pp. 479-509.

Griffith, M., Lam, N., et al., "Experimental Investigation of Unreinforced Brick Masonry Walls in Flexure", *Journal of Structural Engineering*, Vol. 130, No. 3, 2004, pp. 423-432.

Hendry, A., "The lateral strength of unreinforced brickwork", *The Structural Engineer* Vol. 51, No. 2, 1973, pp. 43-50.

Lourenço, P., Oliveira, D., et al., "Dry Joint Stone Masonry Walls Subjected to In-Plane Combined Loading", *Journal of Structural Engineering*, Vol. 131, No. 11, 2005, pp. 1665-1673.

Lourenco, P. and Ramos, L., "Characterization of Cyclic Behavior of Dry Masonry Joints", *Journal of Structural Engineering*, Vol. 130, No. 5, 2004, pp. 779–786.

Marzahn, G., "Dry-stacked masonry in comparison with mortar jointed masonry", *LACER*, Vol. No. 2, 1997, pp. 353-365.

Restrepo-Vélez, L. F. and Magenes, G., "Experimental testing in support of a mechanics-based procedure for the seismci risk evaluation of unreinforced masonry buildings". *Proceedings of the International Seminar SAHC - Structural Analysis of Historical Constructions*, Balkema, Rotterdam, 2004

Shi, Y. and D'Ayala, D., "Analysis of In-plane Damage of Unreinforced Masonry Walls". *the 7th International Masonry Conference*, London, UK, British Masonry Society, 2006

Sinha, B., "A simplified ultimate load analysis of laterally loaded model orthotropic brickwork panels of low tensile strength", *Structural Engineer* Vol. 56, No. 4, 1978, pp. 81-84.

West, H., Hodgkinson, H., et al., "The resistance of brickwork to lateral loading", *The Structural Engineer*, Vol. 55, No. 10, 1977, pp. 411-421.