Multi-Leaf Masonry Walls with Full, Damaged and Consolidated Infill: Experimental and Numerical Analyses

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\textbf{Abstract.} Multi-leaf masonry walls constitute the construction typology most widely adopted in historic buildings. This aspect, together with the intrinsic structural complexity, heterogeneity and irregularity, directs the present research towards a topic not yet sufficiently investigated by the research community of architects and civil engineers. In this paper, the case of multi-leaf masonry wall has been investigated, and with the aim of reproducing historical buildings structural elements, three different typologies of multi-leaf masonry walls have been considered: (i) full infill, (ii) damaged infill, (iii) consolidated infill. A comparative analysis has been performed and results of experimental tests have been compared with numerical ones obtained by means of Finite Element (FE) models.

\textbf{Introduction}

The structural characterization of the historical masonry buildings is still a difficult challenge for the intrinsic properties and the manufacturing imperfections of the masonry walls. These aspects are emphasized in the case of multi-leaf masonry walls. In detail, the local and global behavior of the multi-leaf masonry walls are affected by the mechanical characteristics of the materials, the structural interaction between the leaves, the geometric configuration, the size effect, the thickness of mortar and the manufacturing technology [1].

About this topic the research of Vintzileou [2] proposes simple formulae to assess the compressive strength of three-leaf masonry after grouting. Different configurations of strengthened three-leaf stone masonry walls have been analyzed by Da Porto et al. [3] and Valluzzi et al. [4], considering injections, repointing and ties connecting. Other researches about this topic have been carried out by Egermann and Neuwald-Burg [5], Drei and Fontana [6] and Pina-Hernandez with other authors [7]. This paper shows the results of compressive tests under displacement control that have been carried out on 9 masonry multi-leaf specimens. Such specimens have been built in order to reproduce the three different typologies considered. For the masonry specimens construction, standard clay bricks were used, while the mortar used for layers, joints and infills, was specially produced in order to simulate a historic mortar with very low compressive and shear strength.

Tests on masonry specimens were performed in order to check both the mechanical characteristics and to evaluate the structural improvement obtained by the consolidating injections into the infill. Specimens, as well as measuring devices, were prepared in accordance to EN 1052-1. The comparison of the experimental results obtained with the different typologies allows to evaluate the effectiveness of structural improvement. Tests have been performed at the LabSCo (Laboratorio di Scienza delle Costruzioni, Laboratory of Strength of Materials), University IUAV of Venice, Italy. Moreover, a series of preliminary tests have been carried out in order to evaluate the mechanical properties of material components. Compression tests have been performed on bricks and prismatic samples of mortar have been tested in order to determine their flexural, tensile and compressive
strength; moreover, samples made of three bricks connected with two mortar interfaces have been tested to provide initial shear strength of masonry.

In order to evaluate the role played by the infill, the masonry panels tested in laboratory have been reproduced by means of FE models. One of the targets of FE analyses is the evaluation of their reliability to describe the behavior of multi-leaf panels. The mechanical properties adopted in the numerical model are taken from the experimental results on materials component. In particular, a full 3D standard homogenization procedure [8, 9] is adopted to derive equivalent continua parameters to be used for modeling external masonry leaves.

A comparison between experimental and numerical results is proposed. FE models are adopted to perform both linear static and non-linear static analysis: the comparison between results obtained by numerical analysis and the experimental measurements detected allows to calibrate the model.

**Mechanical characterization of constituent materials**

Different types of mortar have been used during specimens construction. A special type of mortar has been created in collaboration with Tassullo Materiali S.p.A., in order to simulate a historic hydraulic lime mortar, namely type CP/5. This mortar has been used in the construction of masonry specimens both for joints and for the infill. Other two typologies of mortar (TD 13 C and TD 13 SRG) with higher structural performance have been used for the top and bottom layers of masonry specimens.

For the laboratory tests on mortars, all specimens were prepared in accordance to the EN 1015-11. The average values of the mechanical characteristics obtained by flexural and compressive tests are reported. In detail, the average values of the flexural strength \( f_{tm} \) are for CP/5=0.33MPa, TD13C=1.859MPa, TD13SRG=2.571MPa; while for the average compressive strength \( f_{cm} \) the values are for CP/5=1.162MPa, TD13C=9.024MPa, TD13SRG=6.539MPa.

The compressive tests on brick samples have been carried out on standard bricks, Danesi DM 116, UNI 12.6.25. The tests were performed on 3 specimens determining a mean value of elastic modulus equal to 4100MPa.

For the determination of initial shear strength nine specimens were prepared in accordance to EN 1052-3. The tests were performed without pre-compression. The average value of the shear strength is equal to 0.187MPa.

**Masonry specimens**

For the compressive tests, 9 masonry multi-leaf specimens were built considering 3 different typologies of infill: i) full; ii) damaged; iii) consolidated. For the construction of masonry specimens, standard clay bricks (Danesi DM 116, UNI 12.6.25) were used, while the mortar used for layers, joints and infills, was specially produced in order to simulate a historic mortar with very low shear strength (Tassullo 14303 CP/5). Masonry specimens have dimensions (1.44x1.42x0.38)m\(^3\) and they are constituted by 22 brick layers. Geometric description of specimens is reported in Fig. 1. On the bottom and on the top of each wall, 2 masonry layers are assembled in order to ensure the infill integrity. Moreover, for those layers, cement mortar reinforced by steel textile net has been used to allow an easy specimens movement in lab. In order to guarantee equally uniform distribution of the loads, during compressive tests, bottom and top of the specimens have been refinished by cement mortar.

For the 1st typology, the infill has been done with bricks potsherds and mortar CP/5. The same infill has been adopted also for the other typologies for 2/3 of the whole mass. In case of damaged infill typology, only bricks potsherds constitute the central part, while for the consolidated typology, the same part has been strengthened by a consolidating mixture.
Compressive tests on multi-leaf masonry specimens

Laboratory tests have been performed to evaluate compressive strength and non-linear behavior of multi-leaf masonry specimens. This typology is considered to be the most widely used in historic buildings. As shown in Fig. 1, different typologies of infill were considered. The idea is to evaluate the influence of the infill on the behavior of the whole specimens. Tests on masonry specimens were performed in order to check both the maximum compressive strength, and for the evaluation of structural improvement obtained by consolidating injections. Specimens, as well as measuring devices were prepared in accordance to the EN 1052-1. For each masonry typology, sets of 3 samples sized (1400x1400x370)mm$^3$ have been built.

The comparison of the results obtained by testing the different masonry typologies allows to evaluate the effectiveness of structural improvement of the consolidated case. Results of the compressive tests are reported in Table 1, that shows the maximum load $F_{i,max}$ for every typology, the coefficient of variation (COV) between the $F_{i,max}$ and the mean value and the characteristic strength $f_{ci}$. Load-displacement test results are reported in Fig. 2, while Fig. 3 provides an image of one of the specimens at the beginning (a) and at the end (b) of the test.
Table 1. Compressive test results

| Type of infill | Specimens | Dimensions [mm] | Max Load $F_{i,max}$ [kN] | Average of $F_{i,max}$ [kN] | COV [%] | $f_{ki}$ [MPa] |
|---------------|-----------|-----------------|-----------------------------|-----------------------------|---------|---------------|
| Full (B1)     | B1-20151105 | 1400x1400x370  | 2305.66                     | 1963.4                      | 14.8    | 4.451         |
|               | B1-20151112 |                 | 2010.19                     | 1963.4                      | 2.3     | 3.881         |
|               | B1-20151119 |                 | 1574.48                     | 1963.4                      | 19.8    | 3.040         |
| Damaged (B2)  | B2-20151126 |                 | 1958.58                     | 1804.3                      | 7.9     | 3.782         |
|               | B2-20151130 |                 | 1887.93                     | 1804.3                      | 4.4     | 3.645         |
|               | B2-20151210 |                 | 1566.44                     | 1804.3                      | 13.2    | 3.025         |
| Consolidated (B3) | B3-20160120 |                 | 1713.78                     | 1836.3                      | 6.7     | 3.309         |
|               | B3-20160127 |                 | 1913.32                     | 1836.3                      | 4.0     | 3.694         |
|               | B3-20160211 |                 | 1881.86                     | 1836.3                      | 2.4     | 3.633         |

Fig. 2. Compressive tests: Load – Vertical Displacement graph

Fig. 3. Specimen at beginning (a) and at the end (b) of the test
The compressive tests performed on different typologies of multi-leaf specimens (Fig. 2) outlined some common aspects. For instance, after the first machinery adjustment phase (0-2mm displacement), all the specimens showed an elastic phase that ends with initial cracking. This damage, occurred between 400kN and 700kN, defined the beginning of the non-linear behavior of the samples. Within this phase, fracture usually occurred around 1400kN, whereas the maximum load capability varied from 1566.44kN (Specimen B2-20151210) to 2305.66kN (Specimen B1-20151105). The values of characteristic compressive strength, $f_{ki}$, obtained for different typologies, are similar to each other and do not highlight a better performance of the consolidated specimens. No relevant differences has been measured both in in-plane and out-of-plane dilatancy of specimens. However, consolidated infill show a lower dispersion in results with respect to damaged infill. Then, compressive tests only are probably not exhaustive to evaluate the influence of the consolidating interventions. Fig. 4 shows the crack patterns of some masonry specimens.

**Numerical models**

In order to evaluate the role played by the infill, FE models of the masonry panels tested in laboratory have been studied. The target is to evaluate their reliability to describe the behavior of multi-leaf masonry panels. A comparison between experimental and numerical results is proposed, in order to calibrate the model. Models are used to perform linear static and non-linear static (pushover) analyses. Both 2D and 3D models are considered. Attention is paid to the mechanical properties that have to be adopted for the masonry and for the infill. Homogenization procedure is adopted for the definition of mechanical properties of masonry external panels. Parametric analysis is performed by varying the material properties in order to obtain results in good agreement with the experimental ones.

Masonry is an heterogeneous and anisotropic material, usually formed by an ordered set of interconnected blocks, joined together by means of dry or mortar joints. Mechanical properties of masonry material are strongly dependent by the ones of its individual constituents: blocks and mortar joints. Moreover, a strong influence is due the blocks arrangement. Therefore, the main mechanical characteristics of masonry, that are (i) low and uncertain resistance to tensile stress, (ii) quite good compressive strength, (iii) non-linear behavior already for low loads, can considerably change in base of specific characteristics, such as quality of components, dimension of units, thickness of joints, arrangement of units. In our case of study a further parameter plays a relevant role: the presence of the internal infill made of incoherent material. This typology of masonry has a wide diffusion in the historical architectural heritage and there are several difficulties regarding the evaluation of its structural behavior. The difficulty in modeling masonry are related to its composite nature, to the size of heterogeneity, to geometric complexities and to the presence of the infill. The literature regarding models and analyses of masonry structures is wide. Many different approaches may be found, among which the most common strategies adopted are the use of discrete or continuous models [10, 11, 12, 13].
In this work, continuous models are proposed. A multi-scale periodic homogenization procedure is adopted [8] to define an equivalent continuum able to reproduce at the macro-scale the characteristics of masonry emerging at the micro-scale. At micro-scale, a representative element of volume (REV) is identified. The REV provides all the mechanical and geometrical characteristic of masonry needed to completely describe the whole panel, that is generated by its repetition. Cinematic periodic boundary conditions are applied on the REV: the solution of the field problem at the micro-scale provides the macroscopic mechanical properties to be adopted at the macro-scale. Here a full 3D procedure of homogenization [9] has been adopted. Equivalent orthotropic continuum is adopted for the external masonry walls, while the infill has been modeled as an isotropic continuum with mechanical properties reduced with respect to masonry walls. The infill has been modelled as an isotropic continuum material because it has been built with mortar and brick potsherds. In the case of damaged infill, the central area of infill has been considered as a void. Geometrical description of REV and boundary conditions applied are reported in Fig. 5. Mechanical properties adopted in FEM models for external masonry walls are reported in Table 2. For upper and lower brick layers, an increase of 50% of mechanical properties has been assumed, in order to take into account the presence of cement mortar reinforced by steel textile.

![Fig. 5. Representative Element of Volume (REV) and periodic boundary conditions applied](image)

### Table 3. Mechanical properties of the FE model

|                         | Young’s Moduli [MPa] | Shear Moduli [MPa] | Poisson’s Coefficients | Cohesion [MPa] | Friction (°) |
|-------------------------|----------------------|--------------------|------------------------|----------------|--------------|
| **External masonry walls** |                      |                    |                        |                |              |
| E11 = 3450              | G12 = 765           | ν12 = 0.220        |                        | c = 0.33–0.66–1.16 |              |
| E22 = 3063              | G23 = 782           | ν23 = 0.248        |                        | Friction (°)               |              |
| E33 = 3560              | G31 = 933           | ν31 = 0.210        |                        |                | φ = 30°      |

| **Infill**              |                      |                    |                        |                |              |
| E = 2700                | ν = 0.30             | c = 0.33           |                        |                | φ = 50°      |

**Comparison between experimental and numerical analyses**

2D models, made by quadrilateral plate elements, represent a transversal section of the wall, while 3D models, made by bricks elements, represent the whole specimen, including the transversal external walls. In both models the steel plate used in lab to distribute the load has been modelled too, and all nodes at base are fixed. In linear static analysis different load steps are applied on top in order to compare the displacements on top with the one measured in lab. In particular, the displacement obtained for 500kN load level, when the panel is still in the elastic phase, is very close to the one measured in lab, equal to about 0.4 mm. This comparison has been used for a first evaluation of the reliability of the mechanical properties adopted for the models. Both results of 2D and 3D models are in good agreement with the tests.
In non-linear static analysis an increasing displacement on top has been applied, in order to reproduce the tests. A Mohr-Coulomb failure criterion has been adopted: different values of friction and cohesion have been used for masonry and infill. Cohesion has been estimated on the base of the tests carried on mortar: the value detected in lab, equal to 0.33MPa, has been adopted for the infill, for which a high value of friction, equal to 50°, has been used, in order to simulate the typical behavior of incoherent filling. For masonry external walls a standard value of friction, equal to 30°, has been kept constant while cohesion has been varied. A parametric non-linear analysis have been carried out with 3 different values of cohesion: 0.33, 0.66 and 1.16MPa. The sum of reactions at the base has been calculated for different load levels: the value of 1700kN, very close to the load of 1800kN reached during the test, has been obtained adopting cohesion equal to 1MPa, both in 2D and in 3D models. This value of cohesion is higher than the ones usually provided by literature, probably due to the fact that specimens are subjected during tests to a very high value of compression.

Here are reported only some of the results obtained. An example of the results provided by models in the case of full infill are shown in Fig. 6. In particular, the deformed shape of the 3D model and a graph of the parametric pushover analysis reporting the reaction at base in a central node of the base.

![Deformed shape of 3D model and reaction at base in a single node](image)

**Fig. 6.** Deformed shape of 3D model (a) and reaction at base in a single node for different values of cohesion (b). Sum of reaction at base are reported in graph

**Conclusions**

Experimental and numerical results are in good agreement. The mechanical properties adopted, obtained by homogenization procedure based on the mechanical properties of materials constituent, provide comparable results both in linear and non-linear analyses. The displacements measured, both by 3D and 2D models, in linear static analysis during the elastic phase are very close to the one obtained by experimental tests. Non-linear analysis provide results comparable to the one of the tests.

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References

[1] L. Binda, G. Baronio, D. Penazzi, M. Palma, C. Tiraboschi, Caratterizzazione di murature in pietra in zona sismica: DATA-BASE sulle sezione murarie e indagini sui materiali, in 9° Convegno Nazionale «L'ingegneria sismica in Italia», Torino (CD-Rom), 1999.

[2] E. Vintzileou, Three-Leaf Masonry in Compression, Before and After Grouting: A Review of Literature. International Journal of Architectural Heritage: Conservation, Analysis, and Restoration, 5(4-5) (2001) 13-538.

[3] F. Da Porto, M.R. Valluzzi, C. Modena, Investigations for the knowledge of multi-leaf stone masonry walls, in Proceedings of the First International Congress on Construction History, Madrid, 20th-24th January 2003.

[4] M.R. Valluzzi, F. Da Porto, C. Modena, Behavior and modeling of strengthened three-leaf stone masonry walls, Materials and Structures, 37(3) (2004) 184-192.

[5] R. Egermann, C. Newald-Burg, Assessment of the load bearing capacity of historic multiple leaf masonry walls, in: Proc. 10th IBMaC, Calgary, Canada (1994).

[6] A. Drei, A. Fontana, Influence of geometrical and material properties on multiple-leaf walls behaviour, in: Proc. 7th Int. Conf. STREMAH, Bologna, Italy (2001).

[7] J. Pina-Henriques, P.B. Lourenço, L. Binda, A. Anzani, Testing and modelling of multi-leaf masonry walls under shear and compression, in Proceedings of IV International Seminar on Structure Analysis of Historic Constructions, Padova, (2004) 299-310.

[8] A. Cecchi, K. Sab, A multi-parameter homogenization study for modeling elastic masonry, European Journal of Mechanics, A/Solids, 21(2) (2002) 249-268.

[9] E. Reccia, G. Milani, A. Cecchi, A. Tralli, Full 3D homogenization approach to investigate the behavior of masonry arch bridges: The venice trans-lagoon railway bridge, Construction and Building Materials, 66 (2014) 567-586.

[10] P.B. Lourenço, G. Milani, A. Tralli, A. Zucchini, Analysis of masonry structures: Review of and recent trends in homogenization techniques, Canadian Journal of Civil Engineering, 34(11) (2007) 1443-1457.

[11] A. Bacigalupo, L. Gambarotta, Second-order computational homogenization of heterogeneous materials with periodic microstructure. ZAMM Zeitschrift Fur Angewandte Mathematik Und Mechanik, 90(10-11) (2010) 796-811.

[12] D. Baraldi, A. Cecchi, A. Tralli, Continuous and discrete models for masonry like material: A critical comparative study, European Journal of Mechanics, A/Solids, 50 (2015) 39-58.

[13] J.V. Lemos, Discrete Element Modeling of Masonry Structures, International Journal of Architectural Heritage, 1 (2007) 190-213.