Influence of geometrical and material properties on multiple-leaf walls behaviour

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Abstract

In recent years research on the mechanical behaviour of masonry walls also considered the assessment of the carrying capacity of multiple-leaf walls. This building technology, very common in old masonry constructions, gives a non-homogeneous type of structural element, also at large scale. The behaviour of a multiple-leaf wall depends largely on the building and on the material characteristics of the "strong" external leaves, on those of the inner "weak" core, and on the interaction among these different walls. The influence of some geometric parameters, in addition to the variability of the material properties, on the response of multiple-leaf walls to horizontal loads is investigated in this study. As multiple-leaf walls have in reality large differences, the behaviour was modelled by means of simple finite element analysis, taking into account only some representative geometric features and material properties. The analysis was carried out referring both to linear and non-linear behaviour of the materials, in order to obtain a more realistic modelling of stress and strain distributions with large values of the applied forces. The aim of the modelling is to catch, by simple means, the influence of the main components of multiple-leaf walls on the behaviour of this structural element.

1 Introduction

The building technique of multiple-leaf masonry is quite common in some regions of Italy for monumental structures and also for civil constructions, particularly in small villages, up to the 19th century. This building technology
was used for vertical structural elements in houses, public buildings, churches, and also for piers in road and railway bridges, before the diffusion of reinforced concrete.

The problem of the assessment of the bearing capacity of this type of structural element was studied by several authors [1], [2], [4], [5], [6]. In this paper the attention is focused on the influence which some geometric and mechanical properties can have on the response of multiple-leaf walls, particularly to horizontal forces simulating a seismic load, as large part of the Italian territory is prone to seismic hazard.

Generally the building codes on masonry do not consider explicitly the multiple-leaf elements, which are usually very thick, and have large masses. Nevertheless the norms on usual brick/block masonry [7] can be applied to multiple-leaf walls considering only the thickness of the strong wall leaves. A typical example of multiple-leaf wall is the traditional "muratura a sacco" (sack wall), a "sandwich" wall made by two external strong leaves, generally stone masonry with a thickness larger than 25 cm, and a rubble and mortar filling with quite poor mechanical properties. It can be considered a masonry wall whose thickness is larger than 50 cm, as required by the Italian code [4], under the condition that the stress transfer at the interfaces of the vertical layers is effective.

In a previous paper some preliminary results were presented, on the response of multiple-leaf walls to horizontal forces [6]. As multiple-leaf walls are built up using very different materials and with quite different dimensions, a study on the influence of the geometry and of the mechanical properties seemed important. Due to the large variability of the mechanical and geometric parameters, it is not possible to obtain punctual indications; therefore only a simple numerical modelling was performed, in order to obtain general and qualitative results on the influence of the parameters.

The safety of masonry buildings with low height, in seismic zones can be assessed taking into account a static horizontal force [8]. As a consequence, the analysis was performed modelling multiple-leaf panels loaded by static vertical and horizontal force.

For usual masonry structures, and also for multiple-leaf buildings, the first natural period $T_0$ can be evaluated approximately from the height $H$ and the width $B$ (in the considered direction) of the building, $T_0 \text{(sec.)} = 0.06 \frac{H}{B} (2 + \frac{H}{B})^{1/2}$, $H$ and $B$ are meters [8].

For old masonry buildings, generally it is $T_0 < 0.8$ sec. In these conditions the seismic force can be represented by two systems of horizontal force, acting on two orthogonal directions on the building sides.

In a previous paper the block texture of the external leaves was found without significative influence on the response to a horizontal force [6]. The study performed, taking into account the previous results, was focused on the influence of the global wall thickness and the thickness of the different layers. Moreover the local influence of the indentation between the leaves, and the influence of a significative change of the mechanical properties of the materials was considered.
An example of a typical multiple-leaf structure is reported in fig. 1, showing a common old (historic) house in the village of Sellano, damaged by the recent Umbria-Marche earthquake of September 1997.

Figure 1: multiple-leaf stone masonry house damaged by Umbria earthquake

2 Characteristics of the model

The structural element taken into account is a multiple-leaf wall panel about 4 m in width and 3.6 m high. The reference thickness of the panel is set to 1 m. These panel geometric features can be found frequently in monumental structures and also in common old houses, particularly in central and southern Italy.

It is known the very low (negligible) contribution of the weak core in this type of structures, as an example in big piers, to the bearing capacity of vertical loads. The inner leaf-wall was modelled with large indentation to the external sheets according to real conditions, as it can be seen in the photograph reported. Generally this kind of wall was built using blocks of regular dimensions in the external surfaces, but along the depth of the wall the stones could have quite different length.

Good mechanical characteristics are assumed for the stone blocks. In real case studies the block connection is generally made up with bad quality mortar, from the beginning or due to subsequent degrading. Therefore in the models performed the Young modulus for mortar was assumed 1/10 that of the stone, for the inner material it was set to 1/7 with respect to the stone.

The intermediate leaf is generally made up by a mortar matrix with pebbles, irregular stone blocks of different quality and dimensions, bricks and rubble. The
global expected mechanical behaviour is not much better than that of the poor mortar. The non-homogeneity of this part was roughly modelled allowing an intermediate 4 cm vertical mortar joint between the core and the stone walls. The other joints were set to 2 cm.

![Figure 2: model of multiple-leaf wall](image)

The real behaviour of the built structural element is surely affected by the low resistance in traction of the constituents, particularly for the weaker component, that is the mortar layers.

The modelling performed takes into account roughly of the possible local opening of cracks and the residual resistance due to friction, considering the connection stone mortar always effective and assuming a non-linear elastic-plastic behaviour. The aim was not to model the behaviour of multiple-leaf masonry in a situation close to collapse, but to simulate a load situation with low diffusion of cracks in mortar.

The assumed elastic characteristics of the materials refer anyway to values experimentally determined in previous researches [1], [2].

As an example, the strain-stress relation adopted for stone is represented in fig. 3. The Poisson ratio has been set 0.1 for stone and 0.2 for mortar. The curve of the inner material is a little better than that of the mortar. For the mortar, as it is suggested in [2], it is assumed a tri-linear relation in compression, the strength is about 5% that of the stone. The mortar tensile resistance has been set to about 20% of the compressive strength.

The numerical models have been developed using the commercial code STRAND61, suitable to a research aimed to a general frame of the problem.
In addition to the dead load, the models have been subjected to a distributed vertical load simulating another wall over the model assumed. In order to model real loading conditions an eccentricity was assumed, 1/10 of the length of the wall.

![Stress-strain relation for stone](image)

**Figure 3: stress-strain relation for stone**

An incremental transversal triangular loading was then applied, statically equivalent to a possible out of plane seismic load. The models performed in correspondence of the last loading steps (particularly for slender elements) are obviously not really representative of the actual behaviour, but they were developed in order to obtain a more defined qualitative indication of the shear stress distribution.

### 3 Numerical analysis and results

The attention was focused on the shear stress along the thickness, at about 90 cm height from the base of the wall. In the presented graphs, the curves are obtained by smoothing the values of nodal stresses, for the nodes between the horizontal mortar joint and the stone layer below, giving a plausible indication of the real shear stress distribution. Some different geometric features were considered, obtained by changing the thickness of the vertical layers. Figure 4 represents the shear stress distribution for two quite slender multiple-leaf walls, with a global depth of 45 cm and 60 cm. These dimensions are not common in reality, particularly the smallest one, but the results are useful for
comparison with the other models. The horizontal loads applied are respectively about 10% and 15% respectively of the total vertical load.

The graphs show a shear stress concentration in the unloaded leaf-wall, at the indentation with the filling material, about 2.5 times the average value of shear stresses in the other external masonry wall.

In what regards the contribution of the internal layer, if the horizontal section is taken at a different indentation between the layers (fig. 5), where the inner core has the smaller thickness, the shear distribution is more uniform, also in the weak core. Figure 6 represents the shear distribution at the two indentation levels for the 60 cm thickness wall.

This behaviour appears quite general, as it can be seen in fig. 7, which represents the same parameters for the reference 100 cm thick wall. The graph indicates an almost constant shear stress distribution along the joint, also in the weak core, but a large stress concentration at the connection of the weak leaf to the strong one. This stress concentration depends on the feature of the indentation.

The applied load is about 15% of the total vertical load, corresponding to an initial small traction in the section considered. The figure shows also the stress distribution in the section considering only linear material behaviour; the curve obtained is almost the same for material non-linearity. At this loading level, the non-linear behaviour of the materials seems not influent. As a general indication,
for these structures the global safety seems conditioned mainly by the non-resisting in traction behaviour and by the presence of significative stress concentrations that could determine a local damaging process.

![Vertical leaves indentation](image)

**Figure 5:** vertical leaves indentation

![Shear stress distribution](image)

**Figure 6:** shear stress distribution at different indentation (slender wall)

The influence of the thickness of the different leaves can be seen in fig. 8, which represents three different possible geometric features of an 80 cm thick multiple-
leaf wall. The three curves correspond respectively to elements obtained from the reference 100 cm thick wall by a decrease only of the strong external wall (curve with larger stress concentration), only of the weak inner core (lower stress concentration), or an equal decrease of stones and filling. The load considered was the same, about 15% of the total vertical load.

Figure 7: shear stress distribution at different indentation (thick wall)

Figure 8: shear stress distribution for different wall/filling dimensions
Indications about the influence of the material properties, particularly in what regards the characteristics of the filling material, are given by the graph in figure 9, showing a comparison between two different kind of wall. One curve is the same of figure 6, obtained for the reference structural element, a multiple-leaf wall made by three materials: stone, joint mortar and inner weak core. The other one is the same wall with stones instead of the filling core: a thick stone masonry wall, made only by stone and joint mortar. In this case there is a significative lowering of the peak stresses. In sections with a different indentation a larger stress concentration is possible (the graph is not reported), but the assumption of an average stress value seems compatible with the obtained results. Nevertheless for material properties (Young modulus) of the inner core between the initial value and the value of the stone, shear stress concentrations are still present. This indication should be taken into account in case of injection strengthening; the improvement of the bearing capacity with respect to vertical loads should be referred to transversal loads (especially seismic loads) with some caution.

Figure 9: shear stress distribution in similar multiple-leaf and stone masonry walls
4 Conclusions

The results obtained indicate for the modelled multiple-leaf walls with transversal loading, that quite large shear stress concentrations are possible in correspondence of the joints of the external walls to the inner leaf. The global safety of these structures seems conditioned, apart from the non-resisting in traction behaviour, particularly by the presence of these significative stress concentrations, which are influenced by the dimensions of the leaf components. If they exceed the local resistance of the element, they could determine a damaging process also in presence, on the average, of good mechanical properties of the materials, triggering the collapse of the element.

The analysis carried out, due to the simple modelling adopted, gives only qualitative indications on the global behaviour of this type of structure. Refined models, e.g. applying now available distinct element codes, do not seem particularly useful because of the large variability of the parameters to be taken into account. The results indicate, as next step of the research, the opportunity of experimental testing to get information about the collapse mechanism and about suitable reinforcing techniques.

References


