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PARAMETRIC ANALYSIS OF OLD MULTI-LEAF MASONRY WALLS

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Abstract

A parametric study of multi-leaf masonry walls subjected to static loading conditions is presented. Linear and nonlinear analysis is performed on multi-leaf walls with varying dimensions using the finite element method. The multi-leaf walls are subjected to shear and compressive static loads assuming perfect bonding between different leaves. The response of the wall to static loads depends on the physical properties of the wall itself as well as the type of loading applied. The modulus of elasticity affects considerably the response of the structure. The length of the inner leaf does not play an important role on the response of the structure to static loads.

Keywords: *Parametric analysis; three-leaf wall; multi-leaf wall; historic masonries; restoration of historic walls*

Introduction

Multi-leaf stone and brick masonry structures can be found in many historical areas. They usually consist of three leaves. The two outer leaves are made of stone or brick and the inner one consists of a weaker rubble material. Many structural problems are encountered in these structures including a weak internal leaf, deterioration of mortar and lack of connection between the leaves. These problems can lead to the development of high stresses and separation of the leaves. Several monuments, consisting of multi-leaf walls, have experienced excessive damage and failure caused by high compressive and shear loads [1]. The vulnerability of these structures increases in areas with high seismic activity.

Restoration and preservation of multi-leaf walls, which are usually part of historic structures, can be accomplished properly if the properties and the existing internal defects or damage can be identified. Defects or damage can be identified using non destructive or slightly destructive techniques such as radar, sonic tests, boroscopy etc. [2]. Restoration techniques include grout injection of the walls where mortar is missing, mortar re-pointing of the external layers of the joints and establishment of proper connection between the leaves [3]. The restorations techniques that used often alter the properties of the wall increasing the stiffness of the inner layer and the wall itself modifying its response to different loading conditions.

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Several researchers have examined the behavior of specific multi-leaf structures that have experienced earthquake damage [4-12]. Analytical and numerical models have been developed simulating the behavior of multi-leaf walls subjected to different loading conditions [13, 14]. Further investigation is needed to predict the behaviour of multi-leaf walls to future loads and to identify the influence their properties play on their response under different loading conditions.

A simple approach that can be used to identify the response of a multi-leaf wall to static loads includes the modeling of an isolated wall with varying leaf-properties excited by different loading conditions. This paper utilizes this approach and presents a parametric study based on different properties of an isolated multi-leaf wall excited by compressive and shear load. In addition, a parametric study of a three-leaf masonry sample subjected to diagonal compressive test is presented. The finite element method is used to model the wall and masonry sample assuming linear and nonlinear behavior of the materials. The properties of the leaves vary as the structure is subjected to an increasing compressive and shear load.

Three-leaf wall

Model

The dimensions of the finite element model, for comparison reasons, match the dimensions of specimens tested experimentally by other researchers [5, 6]. The model consists of a three-leaf wall of 5.10m length, 7.90m height and 3.10m width. The inner and the outer leaves are 1.7m long (Fig. 1). 10125 solid 3-D 20-node elements are used to describe this wall. The ANSYS software is used for modeling and analysis of the wall. The lower base of the model is completely constrained in all tests performed. The mortar joints are neglected and each leaf is considered homogeneous. The two outer leaves have the same properties which differ from the properties of the inner leaf. Perfect bonding is assumed between the leaves. The density and Poisson ratio of the inner leaf are 1800kg/m^3 and 0.15 respectively while the corresponding properties of the outer leaves are 2100kg/m^3 and 0.10 respectively. Linear elastic behavior of the materials is assumed. The influence of the properties of the leaves on the response of the multi-leaf wall under static loading conditions is investigated varying the ratio of the modulus of elasticity of the leaves and the dimensions of the inner leaf.

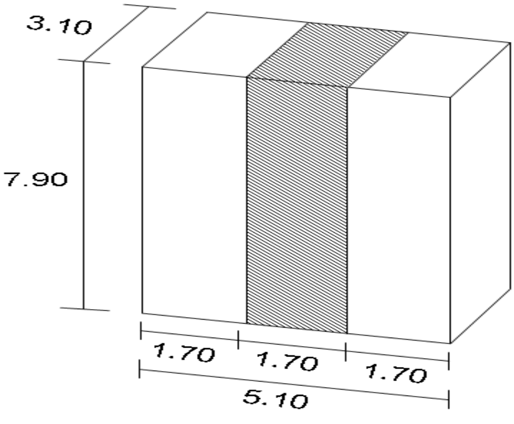

Fig. 1. Model of the multi-leaf wall.

Structural analysis

The properties of the wall considered in this investigation include the modulus of elasticity of the inner and outer leaves and the thickness of the inner wall. The types of loading considered include vertical compressive pressure and uniformly applied shear load on the top of the wall. Self-weight of the structure is included in all numerical tests performed on the walls.

Compressive Loading Conditions

Compressive load is exerted at the top on the complete transversal section of the multi-leaf wall. The intensity of the load varies from 0.5MPa to 18MPa. The validity of the numerical model is evaluated considering the same properties of the leaves as Binda et al. [5]. The modulus of elasticity of the outer leaves (E_1) is 2940MPa and of the inner one (E_2) is 1770MPa. The model reproduces the observations within 20% before yielding of the wall occurs (Fig. 2). The model cannot reproduce the observed behavior beyond the yield point because it assumes elastic behavior of the materials.

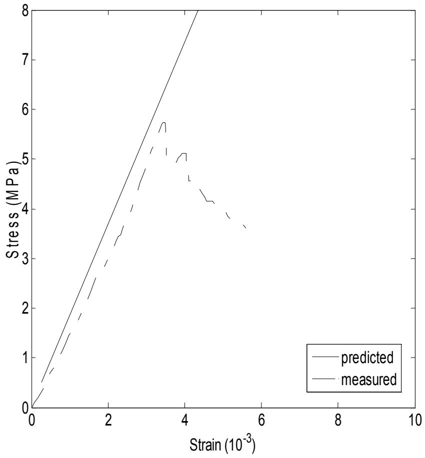

Fig. 2. Stress-strain diagram from compression of complete transversal section.
Finite element model results compared with experimental ones presented by Binda et al. (2006) [5].

The influence of the modulus of elasticity of the inner leaf on the response

Initially, the modulus of elasticity of the outer leaves is considered constant (E_1 = 3000MPa) while varying the modulus of elasticity of the inner leaf (E_2). Ratios E_2/E_1 from 0.2 to 1 are assumed. The compressive stresses and strains are calculated. Fig. 3a presents typical contour plots of the vertical compressive stresses developing in the wall for $E_2/E_1 = 0.2$ and a compressive load of intensity 10MPa. The inner leaf experiences greater stresses than the outer ones. The stresses of the inner leaf are higher at the top where the load is applied and decrease with increasing distance from the top. High compressive stresses occur at the top of the wall at the interface of the inner and outer leaves where the inner leaf pushes the outer ones by deforming and expanding. High compressive stresses occur also at the bottom of the wall at the four corners. As the modulus of elasticity of the inner leaf increases ($E_2/E_1 = 1.0$) the stresses become more uniform (Fig. 3b).

In order to quantify the role of the modulus of elasticity of the inner leaf on the response of the multi-leaf wall a stress-strain diagram is obtained for an element located at the top of the wall in the middle of the inner leaf and an element at the top of the wall, in the middle of one of the outer leaves (the same response occurs for both outer leaves). The asterisk assigned to the modulus of elasticity in the Figures, indicates the modulus of elasticity of the leaf that remains constant while the other changes. The response is affected considerably by the modulus of elasticity of the inner leaf (Fig. 4). Higher values of modulus of elasticity of the inner leaf increase the stiffness of the wall while reducing the strains. The lower strains occur for the highest value of the modulus of elasticity ratio ($E_2/E_1 = 1.0$). The straight lines of the response are close to each other at the lower compressive loads but they spread apart as the load increases reaching approximately 77% higher strains for $E_2/E_1 = 0.2$ relative to the strains developed for $E_2/E_1 = 1.0$.

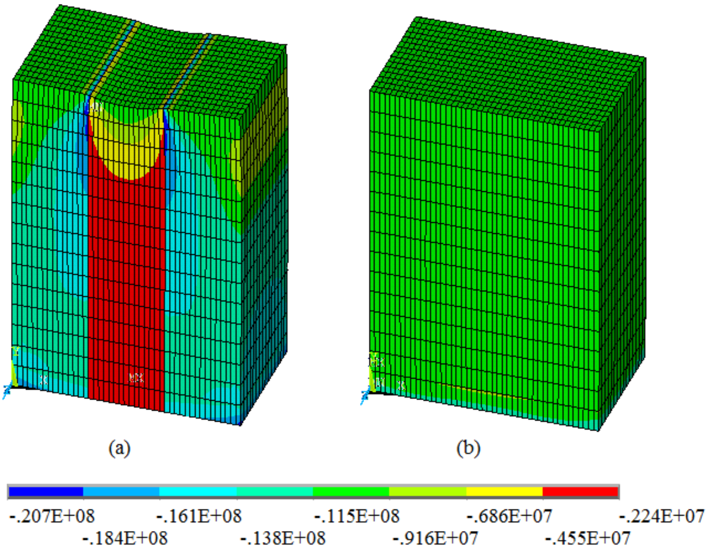

Fig. 3. Vertical compressive stresses: a) $E_2/E_1 = 0.2$, load = 10 MPa; b) $E_2/E_1 = 1.0$, load = 10 MPa.

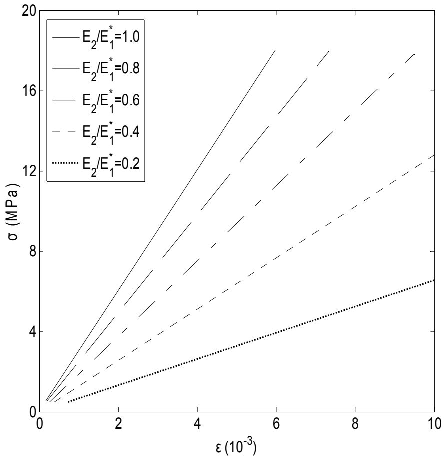

Fig. 4. Stress-strain diagram (E^*_1 = 3000 MPa) for an element located at the middle-top of the inner leaf upon applied compression.

Stress-strain diagrams are also obtained for an element at the top of the wall in the middle of one of the outer leaves. The straight lines of the response almost coincide for different values of modulus of elasticity ratios showing that the variation of the modulus of elasticity of the inner leaf does not affect the response of the outer ones. The same observations are obtained for elements closer to the interface of the leaves.

The influence of the modulus of elasticity of the outer leaves on the response

The same loads as earlier are applied to the multi-leaf wall varying the modulus of elasticity of the outer leaves while keeping constant the modulus of elasticity of the inner one (E_2 = 3000MPa). Figure 5 presents the stress-strain diagram for an element located at the middle-top of the inner leaf (the same as for Fig. 4) for three ratios of modulus of elasticity E_2/E_1: 0.2, 0.6, and 1.0.

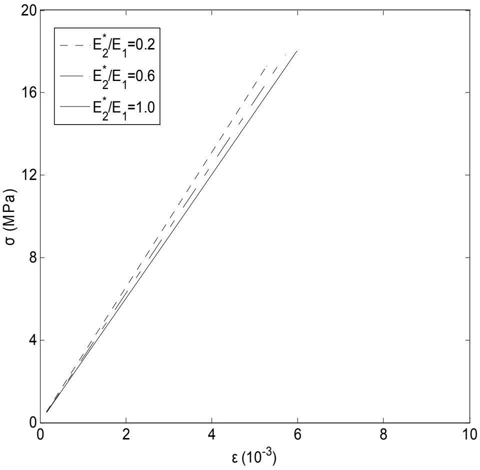

Fig. 5. Stress-strain diagram (E^*_2 = 3000 MPa) for an element located at the middle-top of the inner leaf of the wall.

The straight lines of the response are close to each other and almost coincide at the lower compressive loads. The wall becomes stiffer as the modulus of elasticity of the outer leaves increases and the lower response, producing smaller strains, occurs for the smaller modulus of elasticity ratio. Approximately 12% lower strains occur for E_2/E_1 = 0.2 relative to the strains developed for E_2/E_1 = 1.0. The response of the inner leaf to compression is not affected considerably by the modulus of elasticity of the outer leaves.

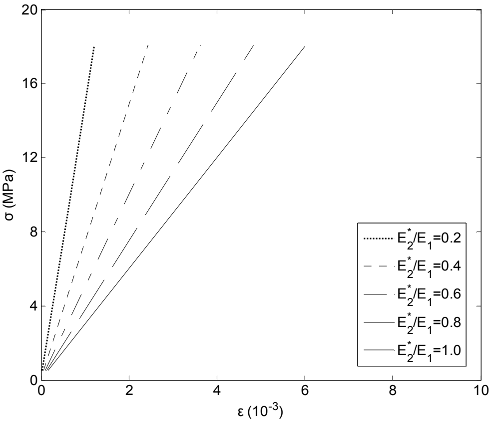

Fig. 6. Stress-strain diagram (E^*_2 = 3000 MPa) for an element located at the middle-top of one of the outer leaves of the wall.

The stress-strain diagram for an element located at the middle-top of one of the outer leaves is presented in Figure 6. The response is affected considerably by the ratio of modulus of elasticity. Lower strains develop for higher modulus of elasticity of the outer leaves (approximately 80% lower strains for $E_2/E_1 = 0.2$ relative to the strains developed for $E_2/E_1 = 1.0$).

Shear Loading Conditions

The three-leaf wall is also examined for shear loading conditions. A uniform horizontal load is applied on the top surface varying from 10-140kN/m^2.

The influence of the modulus of elasticity of the inner leaf on the response

Initially, the modulus of elasticity of the outer leaves is considered constant (E_1 = 3000MPa) and the modulus of elasticity of the inner one (E_2) is varied in order to achieve ratios E_2/E_1 from: 0.2 to 1. Figure 7 presents the stress-strain diagram for an element located at the top of the wall in the middle of the inner leaf. The straight lines of the response are affected by the modulus of elasticity of the inner leaf. For low modulus of elasticity ratios the straight lines of the response are spread apart while for high ratios (E_2/E_1 greater than 0.6) they are close to each other. This indicates that the response of the wall is affected less when the modulus of elasticity of the inner leaf is high reaching the values of the modulus of elasticity of the outer leaves. Approximately 47% lower strains occur for $E_2/E_1=1.0$ relative to the strains developed for $E_2/E_1 = 0.2$. The same almost response appears for inner and outer leaves.

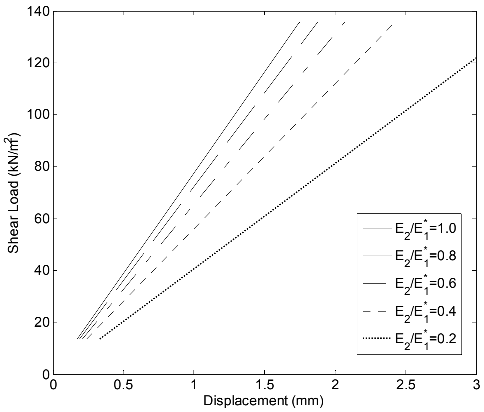

Fig. 7. Shear load-displacement diagram (E_1 = 3000 MPa) for an element located at the middle-top of the inner leaf of the wall.

The influence of the modulus of elasticity of the outer leaves on the response

The same loads are applied to the multi-leaf wall varying the modulus of elasticity of the outer leaves while keeping constant the modulus of elasticity of the inner one (E_2 = 3000MPa). Figure 8 shows the load-displacement diagram for a point at the middle-top of the inner leaf. The modulus of elasticity affects considerably the behavior of the wall in shear loading. The smallest response occurs for the lowest value of the ratio of modulus of elasticity ($E_2/E_1 = 0.2$). Approximately 60% lower strains occur for $E_2/E_1 = 0.2$ relative to the strains developed for $E_2/E_1 = 1.0$. The response is the same for the outer leaves. Elements at lower heights show smaller response with smaller strains developing due to loading for all ratios of modulus of elasticity and the straight lines of the response are closer to each other.

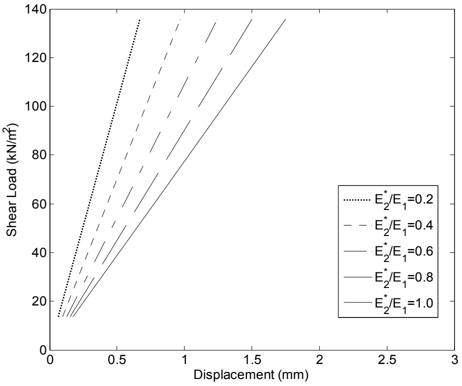

Fig. 8. Shear load-displacement diagram (E_2 = 3000 MPa)
for an element located at the middle-top of the inner leaf of the wall.

Variation of length of inner leaf

The influence of the thickness of the inner leaf to the response of the multi-leaf wall when it is subjected to increasing compressive or shear loads is examined. Three walls are considered having the same height (7.90m) and length (5.10m) but different length of the inner layer (1.0m, 1.70m and 2.2m). The modulus of elasticity of the outer leaf is 3050MPa and of the inner leaf 1830MPa (E_2/E_1 = 0.6). Figures 9 and 10 show the response of the wall for an element at the top of the wall in the middle of the inner leaf to compressive and shear loads respectively. The length of the inner leaf does not affect the response of the wall when compressive loads are applied and has a small effect when the shear loads applied. The thinner inner layer produces lower strains.

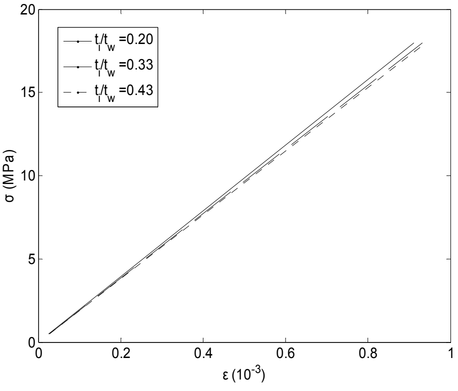

Fig. 9. Stress-strain diagram (E_2/E_1 = 0.6) for an element located at the middle-top of the inner leaf of the wall (t_i = length of inner leaf, t_w = length of wall).

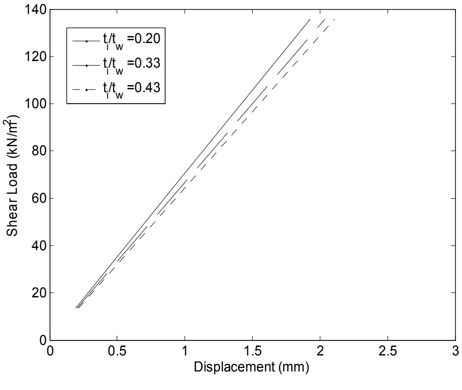

Fig. 10. Shear load-displacement diagram (E_2/E_1 = 0.6) for an element located at the middle-top of the inner leaf of the wall (t_i = length of inner leaf, t_w = length of wall).

Masonry sample

The response of a masonry sample to diagonal compression is examined using the finite element method. This test is often used to different types of masonry because of its capability to provide representative values of the shear mechanical parameters. The data obtained through these numerical tests are essential to understand the mechanical behaviour of the masonry system [15].

Model

The sample model consists of three-leaves of 900mm length, 900mm height and 500mm width. In addition, two metal brackets are considered at the upper and lower corners, simulating the engine mounting. The inner leaf has a length of 200mm and the outer leaves are 150mm long (Fig. 11a). Nonlinear behavior of the materials is considered. The finite element model consists of 2300 solid 3-D 8 node elements. The lower base of the model is completely constrained and the metal brackets can be displaced only vertically. A total vertical compression load equal to 70490kN is applied on the upper edge and a compression pressure equal to 0.1MPa is applied on the two opposite sides of the sample (Fig. 11b). Gravity loads are not considered. The MSC/MARC software is used for the modeling and the analysis. Each leaf is considered homogeneous and perfectly bonded with the adjacent leaves.

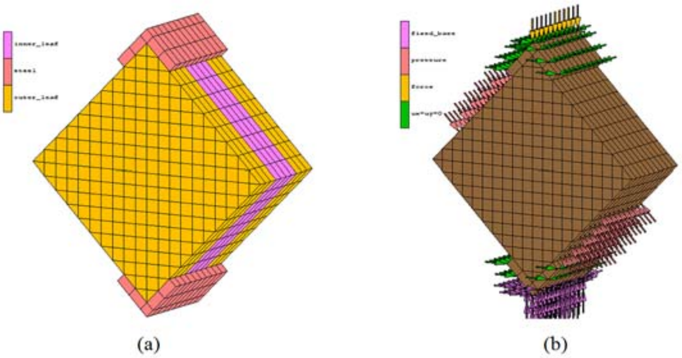

Fig. 11. Finite element model of masonry sample: a) Materials, b) Boundary conditions.

The linear Mohr-Coulomb material model is used to describe elastic-plastic behaviour based on a yield surface that exhibits hydrostatic stress dependence. Such behaviour is observed in a wide class of soil and rock-like materials. The two outer leaves have the same properties which differ from the properties of the inner leaf. In order to study how the modulus of elasticity of the leaves influences the static behavior of the sample, two cases are examined. In the first case the modulus of elasticity of the outer leaves is E_1 = 700MPa while the modulus of elasticity of the inner leaf varies from 20% to 100% of E_1, representing the reduction of the inner leaf material strength. In the second case the modulus of elasticity of the inner leaves is E_2 = 700MPa while the modulus of elasticity of the outer leave varies from 20% to 100% of E_2, representing the reduction of the outer leaves material strength. The Poisson ratio of all the leaves is 0.25 and the initial yield stress (for the plasticity) is assumed 70KPa.

Structural analysis

The influence of the properties of the inner leaf in the response of the three-leaf masonry sample under static loading conditions is investigated varying the ratio of the modulus of elasticity of the leaves. In order to compare these results, the same yield stress is considered for the different materials. Figure 12 presents the variation of the vertical displacement of the sample. The response is affected by the modulus of elasticity of the inner leaf. High values of modulus of elasticity of the inner leaf increase the stiffness of the wall and reduce the vertical displacements. The results are in agreement with those presented earlier when the masonry wall analysis was considered (Fig. 4).

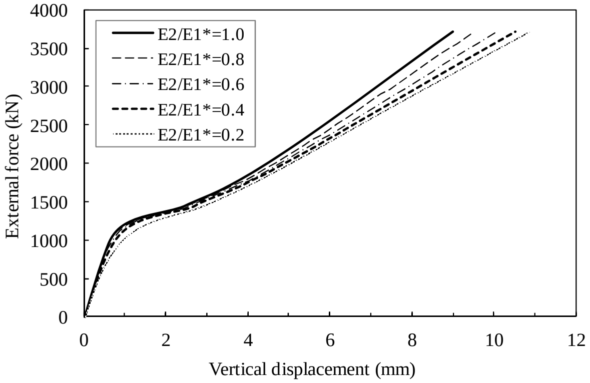

Fig. 12. Compression load-vertical displacement diagram.

Parametric study reducing the modulus of elasticity of the inner leaf

In order to examine the influence of the elasticity of the inner leaf to the deformation of the sample, the horizontal, the vertical and the out of plane extensions are evaluated applying compressive loads on the sample (Fig. 13-15). The reduction of modulus of elasticity of the inner leaf affects more the out of plane strains of the sample (Fig. 15). In particular, as the modulus of elasticity of the inner leaf decreases the out of plane deformation increases. This results to failure of the outer layer when there is a reduction of the strength of the inner layer. The reduction of the modulus of elasticity of the inner leaf affects the vertical deformation but not to the same degree (Fig. 14). Almost no effect is observed to the horizontal in plane deformations (Fig. 16).

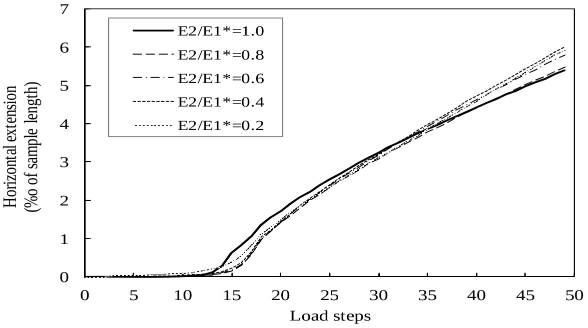

Fig. 13. Horizontal extension- load steps diagram.

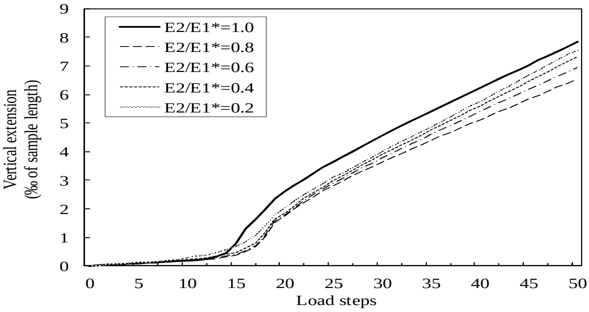

Fig. 14. Vertical extension – load steps diagram.

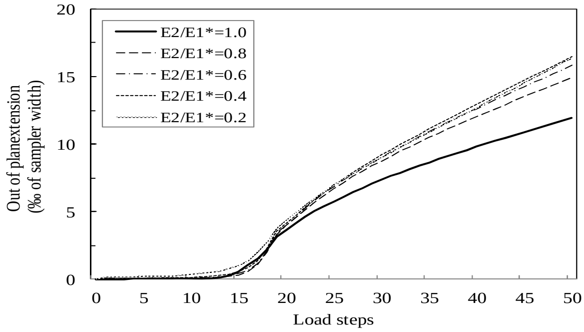

Fig. 15. Out of plane extension – load steps diagram.

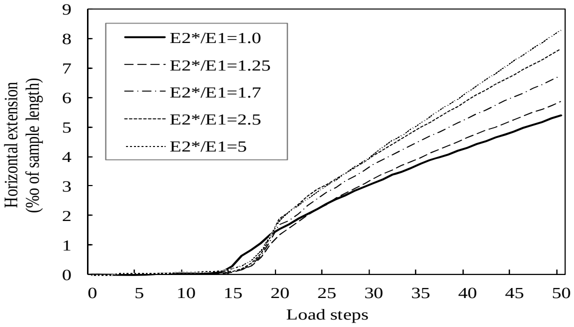

Fig. 16. Horizontal extension- load steps diagram.

Parametric study increasing the modulus of elasticity of the inner leaf

The case where the outer leaves material strength is reduced due to stone or mortar failures is examined. This corresponds to the case where the inner layer is reinforced (for example applying grout injection) leading to a strength higher than that of the outer leaf material. The influence of the elasticity of the inner leaf to the horizontal, vertical and out of plane extension of the sample is presented in figures 16-18. The increase of modulus of the elasticity of the inner leaf leads to significant decrease of the out of plane deformations of the sample (Fig. 18). Therefore, a strong inner layer leads to a reduction of the out of plane deformation, while increasing the in-plane (especially the horizontal) one (Figs. 16 and 17).

Experimental research has shown that strengthening of three-leaf stone walls by grout injection while invoking a greater contribution of the inner leaf to the response of the walls, due to the improvement of the mechanical properties of the inner leaf and the bond of the leaves, failures occur from cracking and detachment of stones or parts of the external leaves [16].

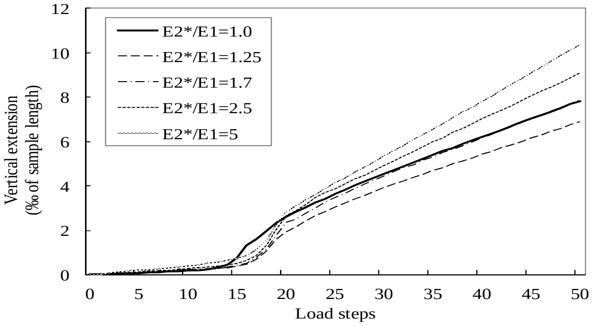

Fig. 17. Vertical extension – load steps diagram.

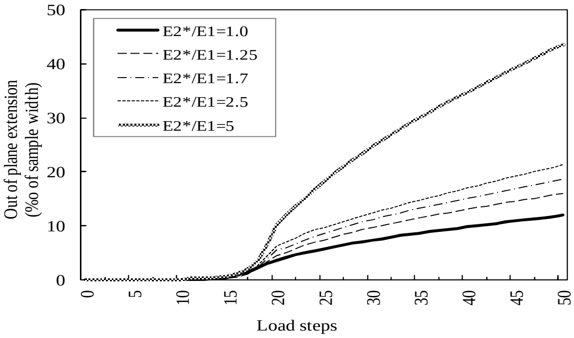

Fig. 18. Out of plane extension – load steps diagram.

Conclusions

Unattended multi–leaf masonry walls are vulnerable to future loading conditions due to the weak internal leaf, lack of connection between the leaves and deterioration of mortar. The most common restoration techniques used alter the stiffness of the wall and as a consequence its response to different loading conditions.

This paper presented a parametric study of multi-leaf walls and masonry samples using the finite element method in order to identify the significance of the properties and the extent their variations influence the response of the wall to different static loading conditions. The response of the wall depends considerably on the loading conditions and the physical properties of the wall. In particular, for compressive loading conditions the modulus of elasticity of the inner or outer leaf affects mainly the response of the corresponding leaf. Variations of the modulus of elasticity of the inner or outer leaf affect the response of the whole structure when shear loading conditions are applied. An increase of the strength of the outer leaves does not affect the response of the inner one when the leaves are in compression but reduces considerably the response of the wall when the leaves are in shear. The variations of the length of the inner leaf do not affect significantly the response of the wall under either compressive or shear loading conditions.

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