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Modal Analysis for Study of Minor Historical Architecture

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***Abstract*—**Cultural heritage conservation is a challenge for contemporary society. In recent decades, significant resources have been allocated for the conservation and restoration of architectural heritage. Historical buildings were restored, protected and reinforced with the intent to limit the risks of degradation or loss, due to phenomena of structural damage and to external factors such as differential settlements, earthquake effects, etc. The wide diffusion of historic masonry constructions in Italy, Europe and the Mediterranean area requires reliable tools for the evaluation of their structural safety. In this paper is presented a free modal analysis performed on a minor historical architecture located in the village of Bagno Grande, near the city of L'Aquila in Italy. The location is characterized by a complex urban context, seriously damaged by the earthquake of 2009. The aim of this work is to check the structural behavior of a masonry building characterized by several boundary conditions imposed by adjacent buildings and infrastructural facilities.

***Keywords*—**FEM, masonry, minor historical architecture, modal analysis.

I. INTRODUCTION

THIS research focuses attention on a minor architecture, partially damaged during the notorious earthquake that struck the city of L'Aquila (Italy) on April, 6th, 2009.

The earthquake seriously damaged many structures of the city and of the surrounding areas. In some cases, damages were so critical and extensive, causing buildings to collapse.

The area of L'Aquila is classified as highly seismic by Italian Seismic Code [1]. The event of 2009 was particularly important since the Peak Ground Acceleration (PGA) registered was greater than the PGA considered by the design rules.

The village of Bagno Grande, located on the South-East side of L'Aquila, rises at an altitude between 600 m and 800 m above sea level. The shape development of the village (Fig. 1), as same as building typologies evolution, followed the orographic configuration of the area and economic conditions, passing from rural buildings to contemporary urban types. The village developed its shape along the main street, whereas the church and the main square did not represent the focus of the village. This configuration is typical for the villages of L'Aquila urban area, since the city itself was conceived mainly as a market area.

Fig. 1 Aerial view of Bagno Grande

Most of the buildings of Bagno Grande, as well as those of the villages surrounding L'Aquila, can be classified as minor architecture since they were built only for residential purposes, adopting poor materials and basic construction techniques (Fig. 2). Moreover, the whole village is conceived as an aggregate of small buildings, often sharing structural walls.

The structural analysis of a single building, in such complex urban context, becomes very difficult since, adjacent buildings cannot be investigated and their mass involves the global behavior of the building.

Many historic buildings classified as minor architecture have been studied in last decades, since they represent an important part of the architectural heritage in the Mediterranean area. Codices and design rules have been developed in order to define valid methodologies to study the vulnerability assessment of masonry building typologies in seismic areas [2]-[4].

Here the attention has been paid to a single building and its structural behavior was evaluated, simulating adjacent buildings and infrastructural facilities with different boundary conditions. For this reason, an FE model has been developed

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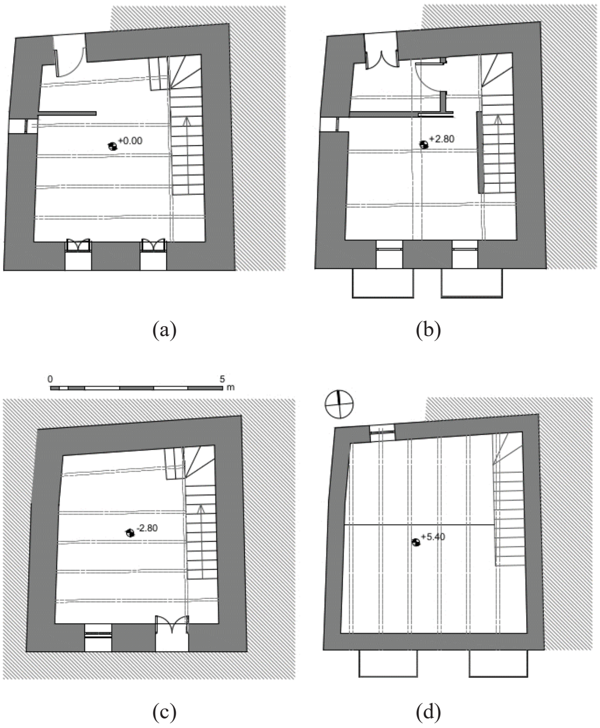
and natural frequencies have been analyzed. The results obtained imposing different boundary conditions have been successively analyzed and compared.

II. STUDY CASE DESCRIPTION

The building studied in this research is a masonry construction composed of a residential and a storage part. According to local use, the building includes two residential levels (Figs. 2 (a) and (b)), a partially undergrounded floor (Fig. 2 (c)) originally used for agricultural purposes and an attic area (Fig. 2 (d)), whereas the roof has a mono slope shape, which spans from the northern side to the southern façade.



(a) (b)

(c) (d)

Fig. 2 Plans: (a) Ground level, (b) 1st level, (c) basement, (d) attic area

The external dimensions of the plan are nearly equal (6.43 m x 6.42 m), whereas floors have an average height of 2.8 m each. Following traditional use, the external walls are made of rubble masonry (average thickness 0.65 m), constituted by local sandstone and lime mortar. As a characteristic of long term building processes, many buildings present the attic level that has been added successively, using industry produced clay blocks and air lime mortar (Fig. 3).

Another emblem of building transformation is represented by the roofs built with steel beams and masonry vaults (Fig. 4). This technique was particularly diffused during the 2nd half of the XIX Century and many examples are still available in the L'Aquila area. For this study case, steel girder ware set up with a wheelbase of 0.85m and fixed into the masonry walls. Each couple of steel beams is connected by masonry vaults, constituted by a single course of clay bricks. Over the vaults, a thin layer of mortar and various building material was set down to ensure the horizontality and provide the finishing level for flooring.

Fig. 3 Typical residential building

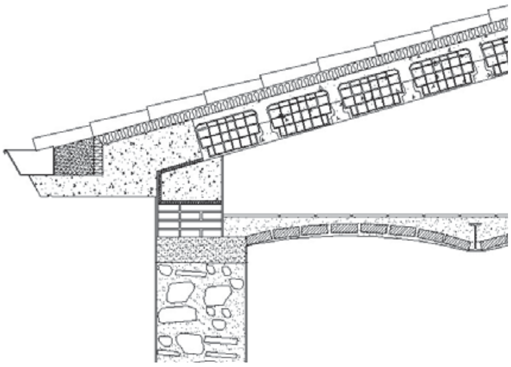
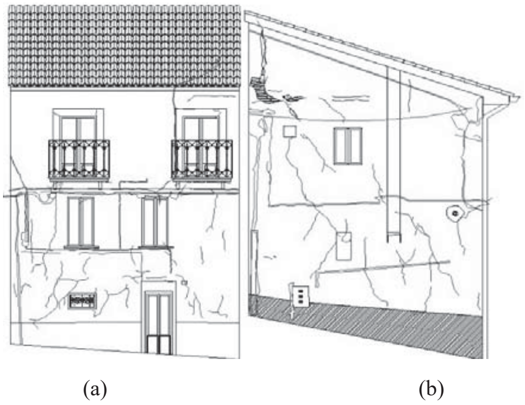


Fig. 4 Attic level section, particular

Observing the crack pattern carried on after the earthquake, it is possible to observe that the main cracks developed in the lower part of the building (Fig. 5 (a)), whereas a vertical crack (Fig. 5 (b)) emanates from the beginning of a façade rocking mechanism, probably induced by the roof's thrust and weak angular connection [5].

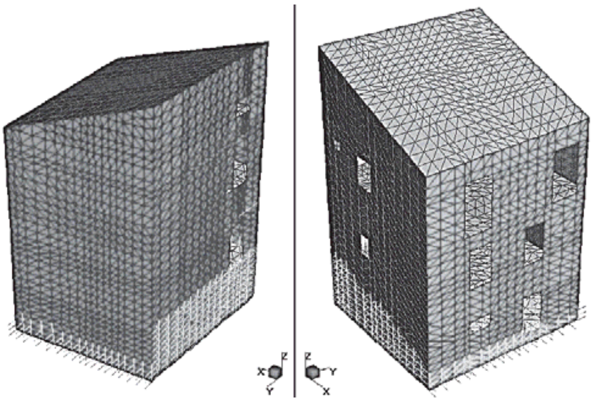


(a) (b)

Fig. 5 Crack pattern after the earthquake: (a) damages on the lower part of the building, (b) façade rocking mechanism

III. F.E. MODEL

This model aims to evaluate the natural frequencies and modal shapes of the building study case, imposing several boundary conditions, both on the basement floor and on the walls. Since the building was conceived as a portion of an urban aggregate, the aim of this research is to evaluate the sensitivity to the surrounding buildings, or portions, on the analyzed one.



(a) (b)

Fig. 6 Model 1: (a) North – East sides, (b) South – West sides

Starting from these structural considerations, attention has been paid on the influence of boundary conditions to the seismic behavior of the building. In particular is proposed a Finite Element model with two different boundary conditions: i) Model 1 (Fig. 6), with vertical and two horizontal translations avoided; ii) Model 2 (Fig. 8), as Model 1 enhanced with the eastern façade bonded and northern façade partially bonded.

The model was done with 6,470 three node plate elements, with four different properties. Each property reproduces different geometrical thickness, whereas the structural characteristics, for this preliminary research, are considered common for all the materials. Since the aim of this research is to evaluate the global behavior of the building, for simplicity, the complex floor structures have been represented with plate elements. Table I shows the structural properties adopted.

TABLE I
MODEL PROPERTIES

Materials	Thickness (m)	Element	E (Mpa)	ν	γ (Kg/m^3)
1	0.65	stone masonry	1000	0.2	1800
2	0.35	clay masonry	1000	0.2	1800
3	0.20	floors	1000	0.2	1800
4	0.20	roof	1000	0.2	1800

IV. MODAL ANALYSIS

As the successive step of the research, a free modal analysis was performed on Model 1 and Model 2. In particular, the modal analysis was carried on determining the first 10 vibrating modes and the corresponding frequencies. Moreover, for each vibrating mode, the percentages of participant mass (PFs - Participation Factors) have been evaluated in X and Y horizontal directions (Fig. 7). These values allow to define the main vibration modes and to evaluate the oscillating direction of the model. For simplicity, the mass participation in Z axis (Fig. 7) has been ignored, since the structural behavior in the vertical direction is less significant than the others in the plan.

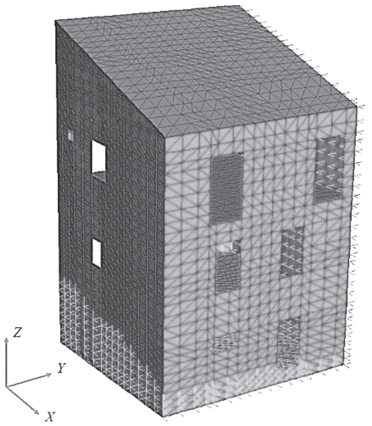


Fig. 7 Modal analysis axes reference

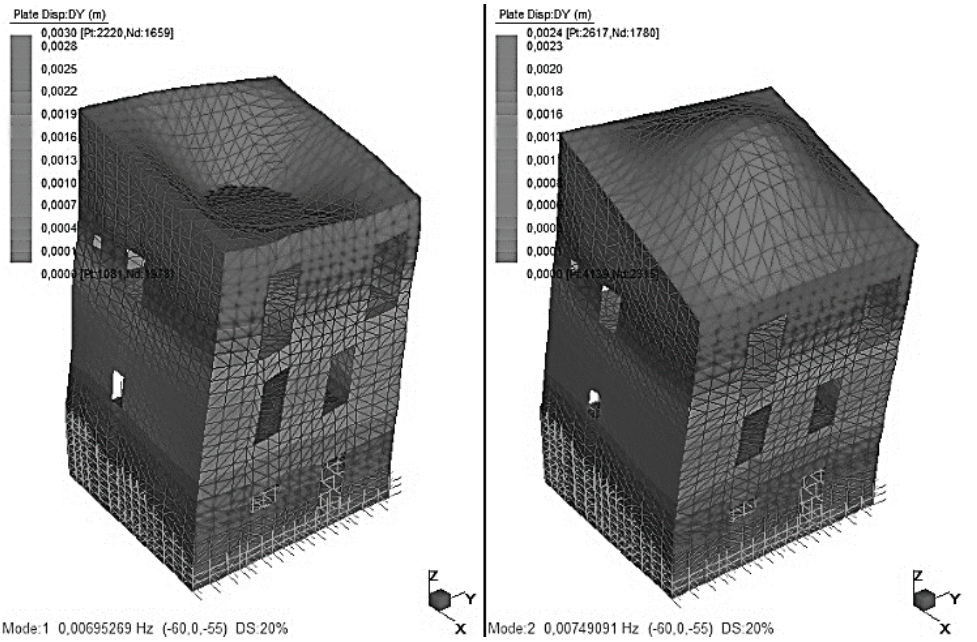
A. Model 1

The purpose of developing Model 1 is to evaluate the structural behavior of the building, in the case that the eastern and northern façades are completely free (Fig. 8). This condition aims to simulate the global behavior of the structure free from the urban aggregate.

TABLE II
MODEL 1 - MODAL ANALYSIS

Mode	Frequency (Hz)	PF-X (%)	PF-Y (%)
1	0.0069	24.454	41.498
2	0.0074	28.496	25.883
3	0.0083	12.908	1.185
4	0.0089	0.114	0.003
5	0.0090	0.265	0.008
6	0.0091	0.003	0.002
7	0.0121	0.074	0.002
8	0.0160	0.048	0.397
9	0.0166	0.508	0.249
10	0.0172	0.034	0.120
Total participant mass		66.904	69.346

In Table II are collected the results of modal analysis. It is possible to observe that modes 1 and 2 have nearly the same frequency (0.7 Hz), whereas the participant mass factors are major in the Y direction. Both modes have bending trends following a sinusoidal deformation with one half-wave. Since most of the openings concentrate in the X direction, Mode 1 involves major participant mass in the Y direction (41.5%), whereas Mode 2 mobilizes nearly the same mass percentage in both directions.



(a) (b)

Fig. 8 Modal analysis: (a) Mode 1, (b) Mode 2

Successive modes involve less than 1% of the total mass, hence they should be related to local modes and are not significant for the global behavior, even if Mode 3 follows the same modal shape of Mode 1 (Fig. 9).

In Fig. 9 is proposed an evaluation of the maximum displacement of the structure due the natural frequencies. From the graph, we can observe that for main modes, the maximum displacement is lower than 3 mm.

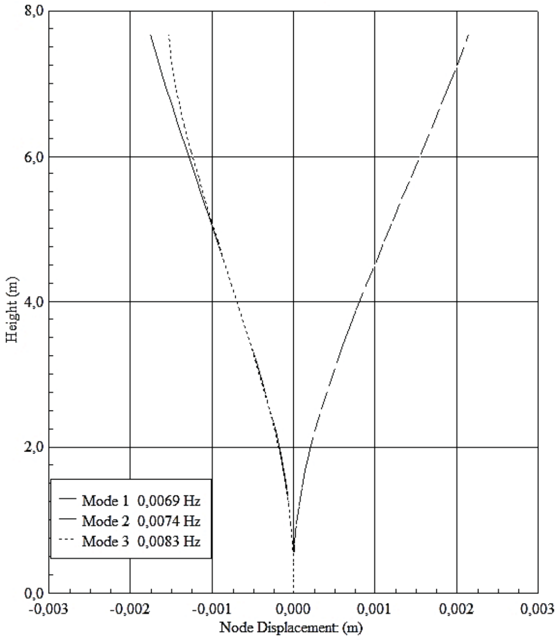
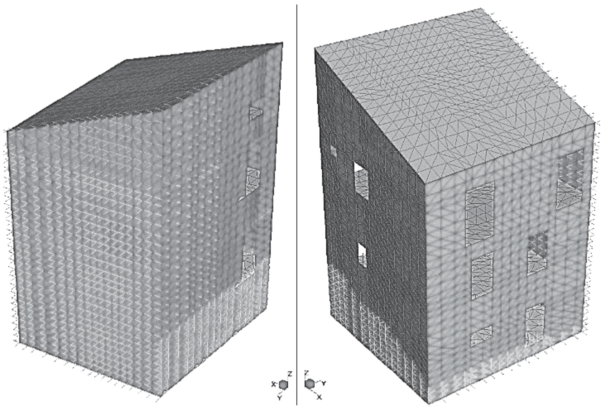


Fig. 9 Displacement evaluation on Model 1

B. Model 2

A second modal analysis has been performed on the model with bounded base, partially bonded northern side, in X direction, and completely bonded eastern side, in Y direction (Fig. 10). The results are reported in Table III.



(a) (b)

Fig. 10 Model 2: (a) North – East sides, (b) South – West sides

The results show that due to the strong boundary conditions imposed, the model presents only local modes, but no global modes. In particular, among the first 4 Modes, none involve the structure for more than 1% of the total mass in any direction. Modes 5 and 6 mobilize major mass percentages in X direction, as well as Modes 8 and 9. Considering that the eastern façade is completely bounded, no one mode involves participant mass greater than 1%. Focusing attention on the first three modes, an evaluation of maximum displacement in X direction has been carried out (Fig. 11).

TABLE III
MODEL 2 - MODAL ANALYSIS

Mode	Frequency (Hz)	PF-X (%)	PF-Y (%)
1	0.0082	0.641	0.002
2	0.0090	0.046	0.001
3	0.0090	0.003	0.001
4	0.0091	0.005	0.004
5	0.0162	5.405	0.189
6	0.0169	3.631	0.109
7	0.0172	22.669	0.480
8	0.0174	10.905	0.344
9	0.0175	0.723	0.052
10	0.0176	0.088	0.087
Total participant mass		44.117	1.269

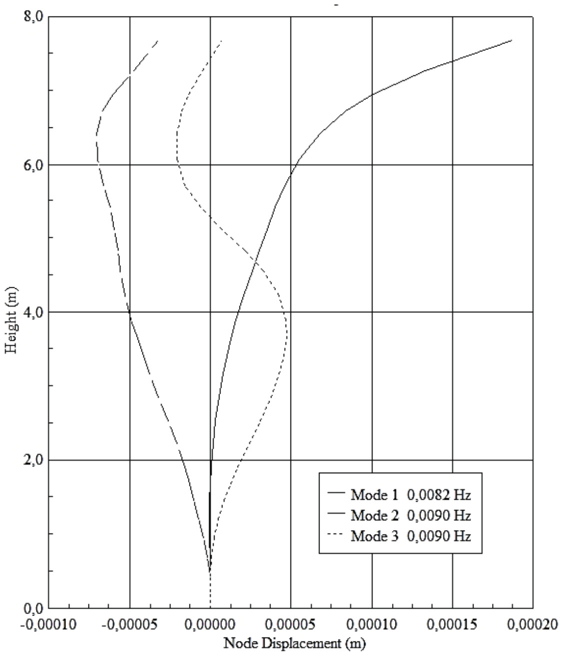


Fig. 11 Displacement evaluation on Model 2

The analysis showed that, for Mode 1, the maximum displacement is lower than 0.2 mm, whereas the modal shape, like in the previous case, is sinusoidal with one-half wave. On the contrary, Modes 2 and 3 registered displacements lower than 0.1 mm, following different modal shapes. In particular, Mode 2 follows a sinusoidal deformation with one half-wave, whereas Mode 3 follows a sinusoidal deformation.

V. CONCLUSION

The research performed on a minor architecture, located in Bagno Grande, aimed to check the structural behavior of an historic masonry building in a complex urban context. In particular, attention has been paid on the boundary conditions that can be set up in a numerical model, in order to evaluate properly the natural frequencies and the modal shapes of the construction.

TABLE IV
DISPLACEMENT COMPARISON

Mode	Model 1 |mm|	Model 2 |mm|
1	2.0	0.2
2	1.8	0.05
3	1.6	0.07

Table IV focus the attention has been focused on the evaluation of the maximum displacement in X direction for the first three modes.

The analysis outlined the significant influence of boundary conditions on the global behavior of the structure. The displacement obtained with Model 2 is strongly reduced if compared to those obtained by Model 1. Moreover, the strongly bounded model outlined only local modes, since the participant mass factors were very low, especially for the first modes.

In conclusion, for a preliminary evaluation of natural frequencies and modal shapes, Model 2 suggests that the structural behavior is focused only in local mechanisms, which probably led to the damage induced by the earthquake.

A further prospective for the analysis of minor architecture in a complex urban context should be the application of some methodologies aimed at the definition of material characteristics through non-destructive, slightly destructive and laboratory tests [6].

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