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On the static and dynamic behavior of a prehistoric structure typical of Apulia in Italy

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Abstract

This paper examines the structural behavior to vertical and horizontal loads (static equivalent by horizontal forces) of a structure typical of Apulia, in Italy. The structure is in masonry and is called "*trullo*". It is very famous and is found only in Apulia. This structure, in fact, known as one of the "wonders of the world", was built in the prehistoric age and therefore it has not been realized by mean of a structural design, but only thanks to the experience of "master" builders.
By mean of a linear static analysis and having previously calculated the horizontal load, it has been possible to demonstrate the good resistance of this structure to earthquakes.
The results will give more information of the behavior of *Trulli* and if they need any retrofitting to dynamic loads.
Knowing the characteristics of this structure that make it resistant to the most severe actions, it will be possible to use them for future buildings. A structure of the past will become then a starting point for constructions of the future.
Finally, this research should give directions to the definition of sustainable methodologies that could be able to classify and control old structures and perhaps prevent their collapse, giving information on which interventions of consolidation are to be adopted.

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1. Introduction

A *Trullo* is a type of construction typical of the central and southern parts of Apulia region. A large part of the historical center of Alberobello town (near Bari) consists of *trulli*. Itria Valley, which stands these buildings, is protected by UNESCO since December 1996.

The early *trullo* was a kind of simple stone cottage with a nearly circular cross section. The *trulli* are built utilizing a simple technique, which ensures a minimum manufacturing of the material and, at the same time, avoids the installation of temporary structures necessary to sustain the vault during its construction [1].

A *trullo* is characterized by four principal elements: the wall, the trilithic entrance, the arch and the vault cap. All these elements are made of limestone with no binder type (Fig. 1; Fig. 2). Though their structures are very simple, they have been shown to have sufficient flexibility and durability to withstand several major earthquakes over the years. These dry-stone walls also have the advantage of having a low environmental impact and being economically efficient [2]. Dry masonry mechanics received little attention from research community, when compared with resources invested in traditional (mortar joint) masonry. Nevertheless, a large number of historical stone houses use dry masonry joints, while, in constructions originally built with weak lime mortar, mortar deterioration leads to a behavior similar to dry masonry [3].

From a resistance point of view, a *trullo* is composed of two major structural components: the basement and the vault.

The basement is made in a masonry sack consisting of two facing walls, spaced apart by a layer of disintegrated materials [4]; the thickness, of considerable size, has the function of restraining the horizontal loads, which are generated by the presence of the dome, although the latter has a structure that makes these loads minimal [5]. The basement, in addition, was not made orthogonal to the ground but the stones were arranged in such a way as to create a small inclination (about 10 °) relative to the vertical axis to give a higher stability to the wall structure.

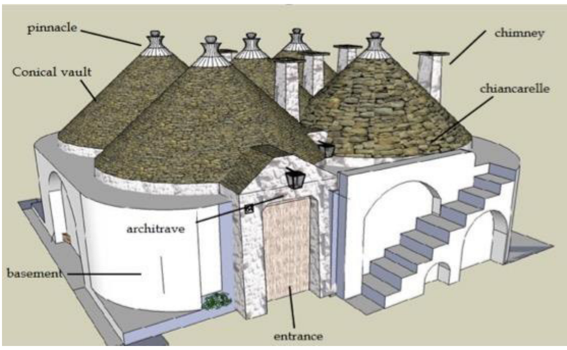

Fig. 1. Constructive elements of a *Trullo.*

After the basement, the vertical walls are built up to the design height; then, it proceeds to the construction of the vaults (the cones).

The vault of a *trullo* is realized with a method of construction, which provides for the implementation of a series of overlapped concentric rings of increasingly smaller diameter, up to a minimum opening, which is closed by a last stone. In this way and without any rib the vault of the *trullo* is realized, a simple stone structure that stands by gravity and by side contrasts, without the aid of any binder.

The cone is then covered with "*chiancarelle*" (slim layers of limestone), which are arranged with a slope towards the outside in order to facilitate the drainage of water.

The cover ends with the pinnacle, placed to complete the work, according to the fantasies of the "*trullaro*" builder.

The structural complexity of *trulli* means that they cannot be analyzed with the classical methods of investigation, and visual controls on-site are not sufficient. A preliminary safety assessment, in fact, requires a more detailed analysis that takes into account the geometry of the structure.

Unlike masonry domes circles, the pseudo-conical roofs of *trulli* have been the subject of very few studies; thus, there is no documents that explains their static and dynamic behavior.

Fig. 2. Typical construction of a *Trullo*.

The main problem in the study of these prehistoric structures was only addressed exclusively in a project called Apuliabase [6], which consists in the implementation of an assessment database in which *trulli* are classified according to their static strength, seismic stability, and their quality-damage status. The classification of the case studies relies on the computation of an overall Vulnerability Index (V.I.) that is calculated as a combination of three indexes, static index of stability (St.I.), seismic index of stability (Se.I.) and durability index (D.I.).

Differently from Apuliabase project the present study proposes and shows a methodology for assessing the stability of *trulli* from a 3D point of view with the use of a calculus software and the use of manual calculus.

2. Description of the Trullo case-study

The *trullo* analyzed in this work is sited in the countryside of Itria Valley, on the road that connects Ostuni to Martina Franca. It is part of a complex of *trulli* and is placed centrally. From a geometric point of view it has a structural height (excluding the pinnacle) of about 6.00 m, a base diameter of 4.70 m, which is reduced in correspondence of the base of the cone to a diameter of 4.00 m with an inclination of about 10 ° from the vertical axis.

The masonry of the basement and the cone is made of two facing walls in limestone, typical of Apulia region, separated by a lot of disjointed material and straw. The thickness of these layers is decreasing from the outside inwards, in particular the external face and the sack have a thickness of about 40 cm, while the internal face of about 30 cm.

As well known, from a structural point of view the masonry can be defined as a material with compression strength much greater than the tensile one.

In the masonry without binder like in a *trullo*, the transmission of forces occurs between the points of contact among the stones [7] (Fig. 3).

Since the masonry is subjected to forces in its plane, it behaves like a plate spreading forces inside and diverting them in correspondence of the openings to find paths where the material provides to the wall enough resistance (Fig. 3).

In the specific case of a sack masonry like in a *trullo*, the forces do not spread throughout the entire thickness of the wall but deviate where the material offers greater resistance. This can lead to instability effects and the masonry is deflected in the direction of lower stiffness (Fig. 3).

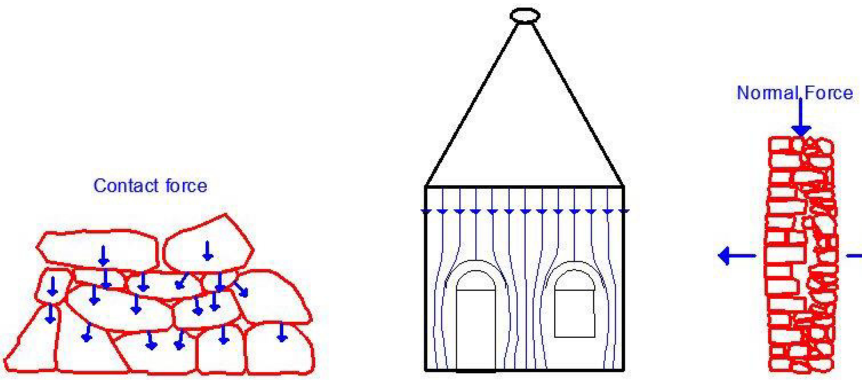

Fig. 3. Transmission of the forces; deviation of the stresses; inflection phenomenon of a sack masonry.

The mechanical and geometrical characteristics of the "*trullo*" here considered are described in detail in the following sect. 3; also the on-site and laboratory tests that have been performed to obtain these values are described.

3. Experimental Tests

A series of on-site tests have been carried out on the *trullo* considered as a case-study in the present paper:

- High-frequency radar measurements (2 GHz): non-destructive and non-invasive investigation methodology, which allows to acquire information easily interpreted within the medium investigated in a short time; these analyzes calibrated to the endoscopies were able to evaluate the interface surfaces between the masonry wall layers (Fig. 4a).
- Endoscopic Analysis: investigation methodology that provides for the execution of an endoscopic measurement by means of a sonde equipped with a camera inside a hole aimed at the direct evaluation of the stratigraphy and geometry of the masonry wall (Fig. 4b).

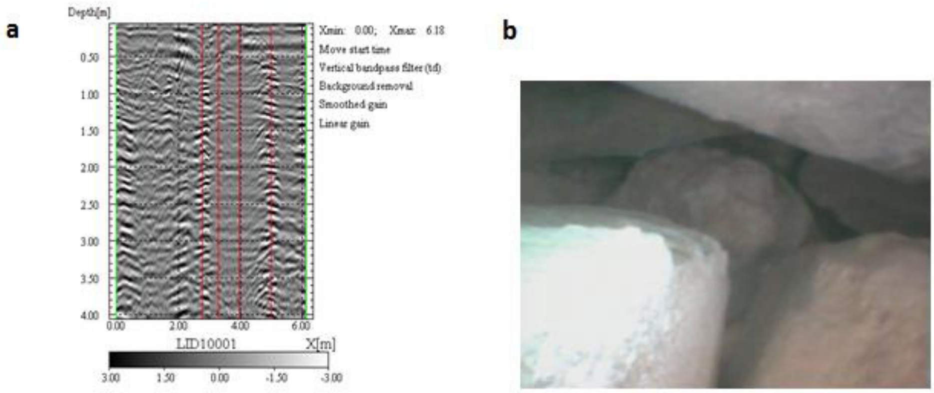

Fig. 4. (a) Radar Measurement; (b) Endoscopic Analysis.

Figure 5 shows the results endoscopic investigation of the cone.

80 cm		
35	10	35
"CHIANCARELLA"	FILLING MATERIAL	CANDLE

Fig. 5. Results endoscopic investigation.

- Laser scanner measurement: equipment that allows the acquisition of the 3D Cartesian coordinates of the indirectly collimated point, by measuring the azimuth and zenith angles and the distance of the points, able to acquire a cloud of points in the space [8] (Fig. 6).

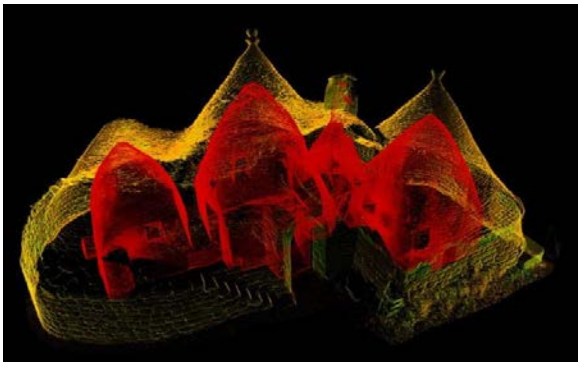

Fig. 6. Laser scanner relief.

Laboratory tests have been also performed:

- Mineralogical and petrographic analyses of mortars taken on-site and performed by means of electron microscopy observation on thin sections (Fig. 7): this analysis is helpful to check the quality and nature of the binder.

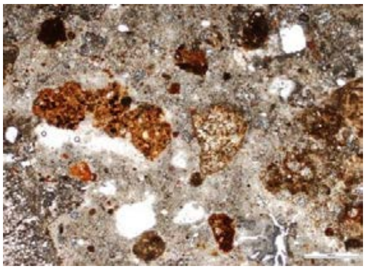

Fig. 7. Mineralogical and petrographic analyses of mortars.

The analysis found the presence of iron clusters, lithic, lime and quartz lumps, useful to the dating of the *Trullo*.

- Evaluation of the compressive strength of a block taken from the masonry (Fig. 8): the natural and artificial stone materials reach the compression failure due to the transversal expansions. This kind of failure is related to the deformation mode.

Fig. 8. Evaluation of compression strength of an ashlar.

A single ashlar (brick or stone) can be considered as a rigid element between two less rigid elements, i.e. the mortar joints. The strength of the masonry is intermediate between the stone and the mortar.

The use of such instrumentation made it possible to characterize the masonry and the mortar and to get a reliable and real-measurement of the structure. In particular, it was possible to have a complete view of the stratigraphy of the masonry and the mechanical properties of the mortar and the ashlar taken on-site.

Some studies proposed the possibility to utilize for masonry values more reasonably than those proposed by the codes in absence of on-site tests [9].

Table 1 shows the mechanical characteristics of the external wall (obtained on-site) and of the core (obtained in the literature).

Table 1. Mechanical characteristics of the external wall and the core.

	External wall face	Core
Specific weight	22000 N/m^3	19000 N/m^3
Young's modulus	15 N/m^2	3 N/m^2
Poisson's modulus	0.3	0.2
Shear modulus	5.77 N/m^2	1.25 N/m^2

4. Numerical study

With the use of diagnostic investigations it was possible to evaluate the mechanical characteristics of the constituent materials and the geometry of the *trullo* under exam. These parameters have been introduced in the calculus model for the structural control of the structure to vertical and horizontal loads. The control followed five main steps:

- Geometrical modeling;
- Linear static analysis;
- Calculus of the forces;
- Analytical tests of the forces;
- Analytical check of the strength to vertical loads.

The global structure appears to be complicate to handle, since it is a group of *trulli*, therefore, as previously described and in order to simplify the modeling operations, only the central *trullo* has been examined.

The geometrical modeling has been performed considering the masonry composed by an internal wall, the core and the external wall (Fig. 9a). The mechanical and geometrical characteristics of these three elements are of course different, and therefore they show a different behavior to vertical and horizontal actions. Like for the basement, the two walls have the same mechanical properties; instead the thickness changes: it is smaller for the internal wall than the external one. The core, however, has very low compressive strengths because it is composed of a heterogeneous material.

The *trullo* has been numerically modeled and analyzed with ANSYS software [10]: the geometrical modeling has been realized and then a mesh of 25 cm side has been created. In particular, the mesh has been thickened at the ground-basement constraint and around the entrance. Figure 9b shows the mesh of the finite element model utilized for the *trullo*.

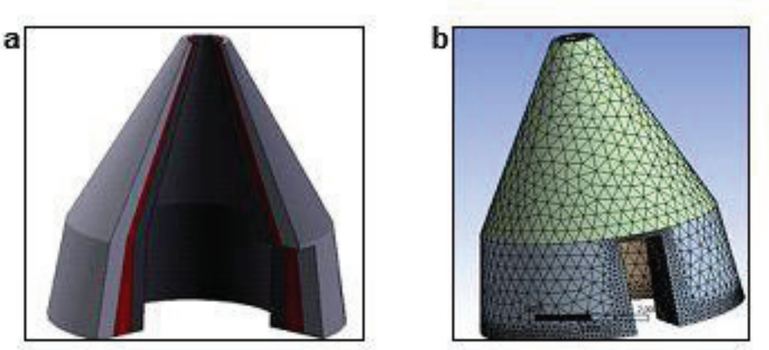

Fig. 9.(a) Geometrical modeling; (b) Mesh of the model: it is thicker at the basement.

The structure has been considered fixed at the base. In fact, the foundation is deepened up to the rock layer. Therefore, it could be considered an extension of the basement, making the structure practically joined with the ground.

In order to apply the linear static analysis, it was first verified that the Code prescriptions are respected [11] (sect. 7.3.3.2, NTC 2008); then the strength to be used was evaluated from the following formulas (1)(2):

$$F_i = F_h \cdot \frac{z_i \cdot W_i}{\sum_j z_j \cdot W_j} \quad (1)$$

$$F_h = S_d\left(T_1\right) \cdot W \cdot \frac{\lambda}{g} = 0.166g \cdot \frac{630.74KN}{g} = 104.70KN \quad (2)$$

This horizontal force has been applied to the geometrical model to evaluate stresses and deformations. In particular, the loads that have been applied are:

- Weight of the structure;
- Horizontal force (in X direction) due to the earthquake;
- Variable load from the Code (DM 2008) [11];
- Hydrostatic action in the core of the cone.

After applying the loads, the forces that have provided some very useful results for the interpretation of the structural behavior of the *trullo* can be evaluated.

In Figure 10a it is possible to notice that there are not very high values of stress on the external surface of the structure, while the highest values are obtained on the internal surface and in correspondence of the lower part of the basement. Moreover, the behavior in correspondence of the zone of connection between the cone and the base is not linear; in fact there are areas where the stresses are higher and areas where they are lower. In particular, the areas that undergo high stresses are those in correspondence of the stone lintel of the entrance opening. For this reason, the presence of a crack in correspondence of that area is not rare; in fact, it is one of the main causes of collapse (Fig. 10b).

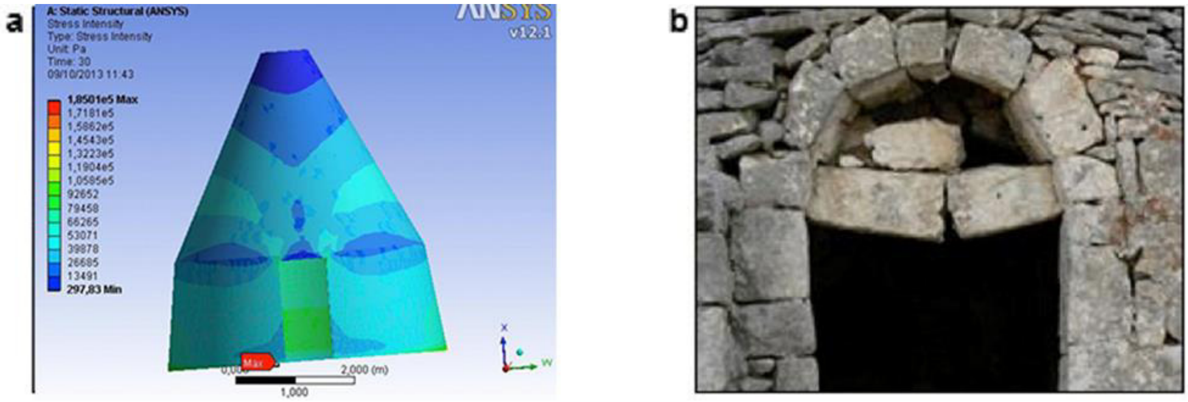

Fig. 10. (a) Plot of the tensile stresse; (b) Crack in a lintel.

As regards to the stress intensity trend (Fig. 11a) it is possible to notice that the most loaded areas are those provided in the numerical analysis, namely the basement and the lower part of the cone. In particular, the stresses are very high in correspondence of the lower part of the basement and decrease upward. In fact, the weight force, which is very high, decreases upward. This result is often confirmed also for other *trulli*. In fact, taking as an example another *trullo* of Itria Valley, which presents the same mechanical characteristics of the examined one, it is possible to notice a crack that appears just at the lintel (Fig. 11b), where the stresses are higher.

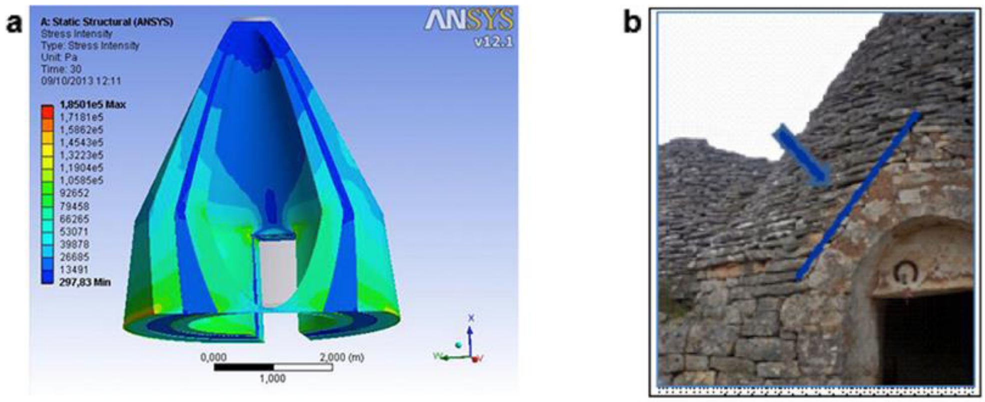

Fig. 11. (a) Distribution of the stresses; (b) Crack in correspondence of the lintel.

It was decided to evaluate, even intuitively, the surface where a mechanism of collapse of the trullo could appear. The criterion utilized has been to consider the surface of higher stresses (Fig. 12). In fact, there have been actual cases with a similar kinematic mechanism [12].

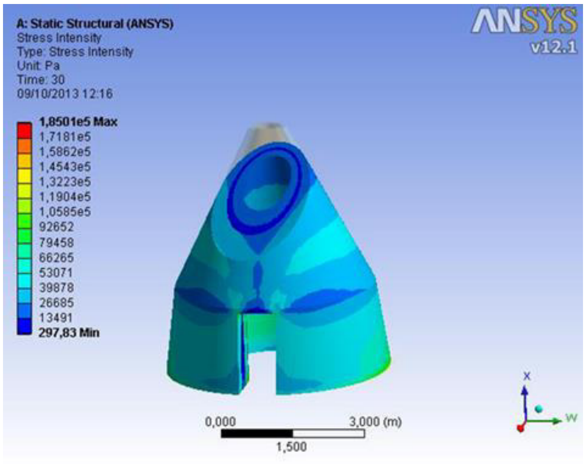

Fig. 12. Surface of a probable collapse mechanism.

For example Figure 13a shows a *trullo* with almost similar constructive characteristics of the *trullo* case-study, which suffered a mechanism similar to the one previously described.

It is interesting to note the trend of deformations (Fig. 13b). Minor deformations will appear at the lower part of the basement, but this was expected because of the presence of a fixed base as a link to the ground. It means that this area is more rigid. Figure 13c shows the deformed configuration where the deformation mode of the blocks' layers due to the weight force is evidenced.

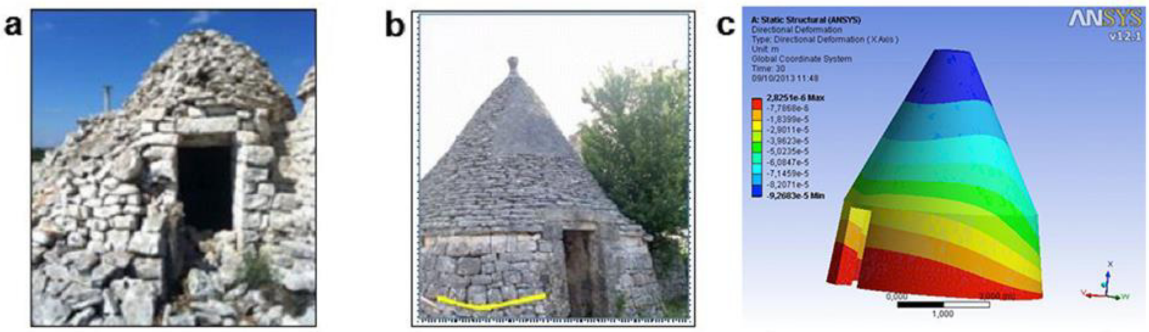

Fig. 13. (a) Example of a kinematism; (b) Deformation behavior; (c) Deformation configuration.

Figure 14 shows the direction of the stresses; it is interesting to observe that there are tense areas and compressed areas.

To make an analytical evaluation of the mechanical behavior of *trulli* it is necessary to calculate the actual loads acting on the cone. To do this it is necessary to assume some conditions, in particular the presence of water pressure into the core such as during rainy periods, when it is saturated by water because *chiancarelle* are not able to block the passage of fluid.

In the model we are referring to stresses, not to forces. Therefore to compare the results obtained with the static analysis, the stresses that are generated between the cone and the base of the *trullo* had been first evaluated (3):

$$\sigma_n = \frac{P}{l \cdot t} = \frac{352890N}{14.77m \cdot 1.1m} = 24.91N/m^2 \tag{3}$$

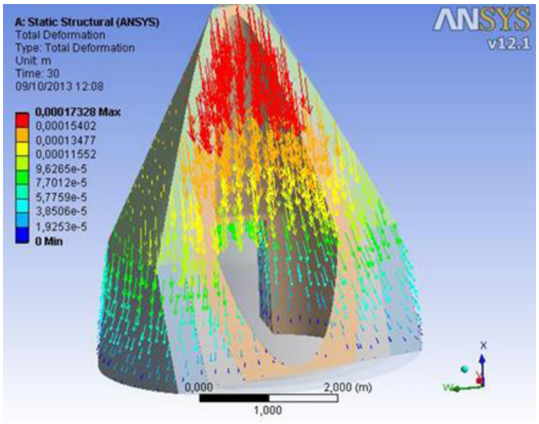

Fig. 14. Direction of the deformations.

The results obtained with an analytical calculus are similar to those obtained by the calculus software.

For buildings made in masonry composed by solid or semisolid artificial resistant elements or natural resistant elements, falling in seismic zone category 2, 3, and 4, if they can be called "simple" manufactured, a simplified seismic analysis can be conducted.

Following the directions of the Code (sect. 7.8.1.9.) the structure can be considered simple [11]. Therefore, substituting (4):

$$\sigma = \frac{N}{A} = \frac{367086\,N}{12.44\,m^2} = 29508.52\,N/m^2 \le \frac{0.25 \cdot f_k}{\gamma_m} = \frac{0.25 \cdot 4950000\,N/m^2}{3.6} = 343750\,N/m^2 \qquad (4)$$

the structural control is largely satisfied and the structure can resist well to vertical actions.

Through linear static analysis, a horizontal equivalent action was inserted to describe the earthquake of the site, from which one it can detect that the deformations of the structure are greatest at the pinnacle but of minor entities (tenth of a millimeter). This assertion leads to the conclusion that the structure optimally resists to horizontal actions.

5. Conclusions

In this paper the we analyzed the structural behavior of a *Trullo* of Itria Valley subjected to static and dynamic loads, the latter assigned as equivalent static horizontal loads. Complex and sophisticated calculation models have been used to hypothesize the behavior of the materials constituting the masonry. From the final model the stresses, widely validated by a numerical analysis, and the displacements of the structure result to be decidedly small compared to the size of the *trullo*. Indeed, the structure well resists the static stress, which means that it has a very high resistance. It is just thank to this resistance that the *trulli* are preserved up to the present days and we can still admire these peculiar and original houses.

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