Deformation measurement as a calibration tool for structural modelling of built heritage

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Abstract. In spite of the important advances in structural modelling tools, the numerical analysis of masonry historical constructions is still a challenging activity, due to the significant difficulties in reliably describing their complex geometry, history, materials and damage evolution. A deep geometrical analysis, in combination with advanced numerical models, can represent a powerful tool for the analysis of masonry structures, able to take into account the outcome of a series of events suffered in time. Moreover, the precise measurement of deformation can give fundamental indication for masonry building structural interpretation, representing a crucial calibration tool for setting up a reliable structural model. In this paper two different case studies are presented, which represent as many possible ways to “use” the more and more precise survey methods for ancient structures in order to reliably interpret their structural models.

1. Introduction

The present geometry of historical masonry buildings is the outcome of a series of events suffered in time: construction phases, soil settlements, earthquakes, material deformations. These events alter not only the visible geometry of structures, but also the invisible internal stresses of the materials composing them, whose investigation is the main purpose of structural analyses. Therefore, it results clear that basing numerical models of complex masonry buildings only on their present geometrical survey - even extremely precise and complete - can lead to disregard the role of history in modifying their structural behavior; in many cases this misunderstanding causes negative results, as an overestimation of the real final safety levels.

Nevertheless, complicated and really detailed numerical models are commonly built just starting from the surveyed geometry in order to simulate the behavior of complex and deformed historic structures, simply ignoring the geometrical transformations occurred in the meantime [1].

In order to create more reliable models, able to interpret the real behavior of ancient monuments, a different approach can be adopted, based on the precise information we can have on the present geometry, making the most of the more and more evolving survey technologies and software. In this process, a fundamental role is played by the critical interpretation of the “distance” between the present and the original geometry: this becomes a crucial calibration tool for numerical model analysis. Through the analysis of two different case studies, the present paper aims to show two possible ways of carrying out this calibration, underlining the importance that a critical approach in interpreting the geometrical data as important evidences of damages and deformations is mandatory for a correct numerical analysis.
2. Calibrating structural models by deformation measurement: two possible approaches

It’s a matter of fact that the numerical models used so far, frequently built starting directly from the present geometry, are not able to reliably simulate the complex behavior of ancient masonry buildings, whose resistant structure is substantially unknown. Due to the lack of resistance to tensile stress, in fact, there isn't an adequate diffusion of stress states and the resistance properties themselves change with the changing of the forces acting on masonry structures. Furthermore, it’s really difficult to assign realistic values to the mechanical parameters of masonry, which are the results of craft and inconsistent procedures and which have been strongly and variously modified in time by damage and degradation phenomena [2]. Moreover, the large variability of masonry textures, depending on time of construction and on building elements (dome, pillars, walls), would require numerous tests spread on each zone characterized by different features, with an unsustainable impact on conservation.

In this paper, two are the possible paths proposed in order to take advantage of the precise survey of deformation in calibrating numerical models without disregarding the effects of history. The first case study sees the correction of the results of even refined and accurate numerical analyses by examining the evidences of the real behavior of a building, starting from its deformation measurements; the second approach considers the stress produced on the structures by the movements occurred in time.

In both cases, the key point has been the translation of the complex relation between present and original geometry of ancient buildings into a crucial calibration tool for more realistic numerical model analyses, able to give results not so divorced from the reality.

2.1. Structural parameters from deformation survey, passing through metrology: the case of a 17th century dome.

It’s well known that one of the main uncertainties in the numerical analysis of ancient buildings is which mechanical parameters have to be assigned to the materials in order to interpret at best their real behaviour. The issue is even more challenging in case of monuments, where the mechanical tests on materials have to be limited in order to preserve them. Hence, due to the lack of mechanical information - as the real stiffness of the various components, the internal masonry texture and, accordingly, their tensile and compressive strengths - it’s necessary to operate parametrically by assigning a possible range of variation to the mechanical properties.

In this operation, an interesting method could be the “geometrical” one: indeed, as already stressed, the current shape of the building can be considered as the result of all the changes, damages and degradation phenomena (alterations in the soil, geometric variations, deformations and material degradation) occurred on it during times and the “distance” from its original geometry directly depends on the capacity, of the same building, to resist to all these actions: in a word, by its stiffness, and, in particular, by its modulus of elasticity (E). Therefore, the comparison between surveyed and original geometries, can help in defining the mechanical properties of the materials in reacting to all these changes through deformation. Hence, the best way to achieve the real building behavior and its possible deficiencies is to identify the original shape (by means of a metrological analysis), and studying the relationship between failures, consolidations and results.

An interesting application of this procedure has been the structural analysis of the 17th century church of Santa Maria del Quartiere in Parma, whose main structural element is represented by a masonry pavilion dome (9 meters in diameter), which stands up at the center of a hexagonal plan which recalls the “tempio essagono” prescribed by Sebastiano Serlio [3].

2.1.1. The metrology and the measured “distance” from the original geometry

In this case, a careful study on the geometry of the structure has represented the fundamental step for the understanding of its static behaviour and for the setting up of a reliable structural model. It’s well known that digital survey techniques, and most notably terrestrial laser scanning, offer robust and realistic methods for adequately surveying heritage assets, and can provide very accurate base models for further investigations. Therefore, firstly, a precise architectural survey of the church has been carried out, in order to acquire the dimensional data necessary to describe the whole monument, by different
integrated methodologies. Outside, stereoscopic metric frames have been acquired through the materialization of support points and relative monographs for the photogrammetric survey of the main fronts of the church, while the continuous survey of the inside of the monument has been achieved by terrestrial laser scanner technology (Leica HDS 3000 with “flight time” technology, and a fixed net of 2 cm), with 5 different measurement stations - positioned along the main axes of the church - enabled to capture almost all the details of the structure. The overlapping of the five data sets ensured a complete 3D description of the dome and the underlying structures (software Cyclone 5.6). Moreover, the information on the curvature of the six wedges of the dome has been achieved by tracing lines along the intrados, using the point cloud model with only some horizontal cut planes plotted (Fig. 1a), in order to understand better the deformation of the dome, referred to the hypothesized mechanism of dome thrust combined to a conceivable differential settlement towards the North direction.

Indeed, as stated before, the current configuration is the result of the deformations occurred to the monument during centuries and it’s a matter of fact that the top of the dome has lowered sensibly since the time of construction. In order to identify, in absence of ancient project drawings, the original shape of the un-deformed dome, the geometrical investigation prosecuted by metrology. Translating the quantitative results of the survey into the original measurement units (“Braccio parmigiano”/arm equal to 54.52 cm) has unravelled a rigorous scheme and a significant progression 18-6-6 in plan distribution which can be referred to a precise 17th century symbolism and which is also maintained vertically. However, it’s very interesting to note that the current shape of the dome, even considering the change in level of the internal flooring (testified by a deep historical analysis), doesn’t fit in this original re-constructed (and perfect) scheme (Fig. 1b). In fact, the height of the dome was found to be 20 cm less than expected when compared to the original drawing and this discrepancy could further support the research of a structural parameter (E) which could reliably interpret the response of the monument to the actions and damages occurred on it in time, justifying this measured “distance” from its original shape.

2.1.2. The parametrical analysis, returning to metrology
Thanks to a fusion between historical analysis, precision geometrical survey and experimental investigations (like some dynamic tests carried out on the monument) the structural analysis of the dome has been then performed following a parametric procedure, in order to assign the more realistic mechanical values to the materials composing the monument, just starting from deformation evidences and working by difference between the original geometry and the current one.
Therefore, a simplified model has been built assuming the original geometry of the structure (as resulted by metrology) and taking advantage of the radial symmetry of the dome. However, even when the original geometry is not so different from the surveyed one, a strong critical reduction and simplification of the numerous (sometimes redundant) data obtainable by laser scanner survey is needed, in order to build a more serviceable numerical model of the ancient building. In the process of mechanical identification of the structure, a first virtual Finite Element Model of the dome alone has been built up with the commercial code ABAQUS, using solid tetrahedral iso-parametric finite elements in order to discretize a regular single shell solid on a symmetric hexagonal base, which grows in height following the original circular profiles of the six webs, with a variable thickness (from 30 cm at the abutment, to 20 cm at the top).

Then, different analyses have been performed, attributing to this simplified model the mechanical characteristics of an elastic, homogeneous, isotropic solid, assuming a linear behavior of masonry and operating parametrically by assigning different values for the modulus of elasticity (E) [4].

![Image of FEM results on the un-cracked model of the dome and the modal analysis of the church](image)

**Figure 2.** On the left, visualization of the FEM results on the un-cracked model of the dome, Smax principal stresses (2a); On the right, the modal analysis of the church (2b).

The damage and the crack pattern were analysed and used to calibrate the numerical model to fit the present shape of the dome. Starting from two different literature values for the elastic modulus (E) of the different parts of the structure, these were varied in order to reproduce reliable tensile stresses which could justify the presence of the cracks at the corners and in the middle of the webs (Fig.2a). Thereafter, the hypothesized mechanical parameters used for the numerical modeling have been further corroborated by a very simplified modal analysis model (Fig.2b) which has been related to the dynamic tests carried out on the monument.

Then, discrete cracks, matching with the crack pattern survey, have been inserted into the model, obtaining a final geometrical configuration coherent with the surveyed one. It is noteworthy to observe that the hypothesis on materials, boundary conditions and structural and non-structural masses of the building are so variable that very different results can be obtained by changing parameters and this procedure is only a first attempt to check the previous results. Anyhow, through a deep analysis of measurement variance, it has been possible to establish a connection between the actual configuration and the static movements in the monument, developed during the centuries, and to control and reduce, more reliably, the unavoidable uncertainties regarding the numerical modeling of a historic building.

### 2.2. The deformation data as information on the changing boundary conditions: the case study of a Romanesque parish church

Ancient masonry structures carry on their own shape the signs caused by historical movements, changes and damages. When numerical analyses are developed on this type of buildings, these “footsteps of history” [1] cannot be disregarded, or the results obtained even by the most up to date tools can turn out to be completely wrong. For this purpose, the first step represented by the direct contact with the
building, its precise geometrical survey, the interpretation of deformations and damages for the comprehension of these “footsteps” is fundamental.

In particular, the deformation measures can become an important input for the numerical model, in terms of changing boundary conditions, applied progressively to the un-deformed structure.

The case study of a thousand-years-old church, which only recently has shown severe damages, is here presented in order to point out the importance of this process and the influence that the deformation (in this case constituted by soil settlements) have both on the real building and on its virtual model.

2.2.1. Following the changes in deformations to understand the uneven evolution of cracks: the importance of historical monitoring

The parish church of San Pietro is located in Costa di Tizzano (Northern Italy), on the top of a hill, dominating the surrounding landscape. It dates back to the end of the 10th or beginning of the 11th century and, although it was modified in time, it is entirely built in local stone masonry (Fig. 3).

![Figure 3. The parish church of San Pietro with its clocher-porche: outside historical view (left) and an inner damaged pillar recently subjected to a provisional intervention (right).](image)

It is a typical Romanesque church – with three naves separated by rough stone masonry columns and covered by a timber roof – but its most peculiar feature is represented by the bell tower, which stands over the entrance, in the middle of the façade. This element, called clocher-porche, is quite widespread in France and in some parts of North-West Italy, but is very rare in this area. Usually the clocher-porches are either protruding outside of the church, with their own large sustaining walls and minor openings, or built over the first bay of the central nave, enlarging the first two pillars or adding specific supports. On the contrary, in the San Pietro church, the relevant weight of the clocher-porche is divided between the façade wall and the first two columns of the nave, which, however, have the same dimensions as the others, carrying instead a much larger load. This load is at the base of the present crack pattern, which has been increasing rather rapidly since the end of the summer of 2016, leading to the decision of inserting provisional steel hoopings around the columns and struts under the two longitudinal arches, carrying the clocher-porche. The two columns, in facts, showed vertical cracks all around their perimeter, rapidly increasing in number, length and width, clearly indicating that the compression stresses had reached the masonry strength and that a brittle, sudden collapse could be close to come. Once the safety conditions were re-established, the question about the origin of the damage arose: how could the columns be able to stand their load for one thousand years and then suddenly show such a severe crack pattern? Any standard calculation or numerical model would supply indications about the stress state which are time-independent, therefore they would not be able to explain the real present conditions of the church. The maximum compression was calculated manually in 1.35 MPa: a rather high value, indeed, but that was carried by the masonry for centuries with no signs of major damage until recent years. Two possible explanations could be hypothesized: the development of a creep
phenomenon, decreasing the materials strength in time, or a change in the boundary conditions, increasing the actions on the columns.

The fact that the heavy worsening of the conditions followed a very dry summer, seems to validate the idea that the origin of the phenomenon should be searched for in the soil settlements, although the effects could have been possibly worsened by creep. Considering the second hypothesis, it should be also taken into account that about 20 m North of the church, a steep slope begins, characterised by a progressive detachment of materials, that is getting closer and closer to the church in the last decades. Indeed, in other parts of the church, cracks related to a differential soil settlement can be seen and, in the past, several interventions (the last ended in 2013) were made in order to reinforce the walls foundations with underpinning. Nevertheless, the information about the soil composition are limited and no investigations were made up to now about the slope stability. Under these circumstances, a possible contribution to explain the present situation can be obtained inserting survey data about the deformations of the structure inside the numerical model, thus taking into consideration not only the theoretical static compression on the columns, but also the increase in stress caused by the soil settlements and by the consequent deformations of the structure.

As already described in [8], the procedure in order to take into account the structural effects of deformations in the numerical model starts with a precision geometrical survey, which must be able to identify the changes in the geometry from an original, un-deformed condition. In the San Pietro church, the survey revealed a settlement of 3 cm between the capitals of the two cracked columns and the ones on the inner façade, which were clearly at the same level at the time of construction. Moreover, the difference between the levels measured on the flooring is of only 1 cm, as this was changed in 1992. This approach, defined “historical monitoring”, allows to reconstruct the evolution of the deformation during centuries, supplying an even more refined information for the structural analysis and for the comprehension of the present stability conditions.

2.2.2. The settlement measures as changing boundary conditions in the model

Starting from these geometrical data, the most probable original shape of the arch was reconstructed with a parametric approach (Grasshopper software), based on the proportional analysis, on the comparison with other parts of the structure built in the same period and on considerations about the building features. In particular, the following assumptions have been made: original supports originally vertical and at the same level and round arches, originally undeformed.

An approach based on the Discrete Element Analysis of rigid blocks was chosen, with the aim of following the large deformations of the structures ([7,8]). The blocks interact with one another with unilateral, no-tension constraints, elastic in compression and sliding under a Coulomb friction model ([9,10]). In particular, two-dimensional plane elements in the UDEC environment were considered sufficient to describe the behaviour of the partial longitudinal section of the church. The real masonry texture of the stone arches was adopted as a base for the subdivision in discrete blocks (Fig. 4).

As far as the materials properties are concerned, only friction and density are relevant in this approach, as the blocks are considered rigid and the deformation is concentrated in the interfaces. For the stone masonry, the density was considered 2.1 kN/m$^3$ with a friction angle of 25$^\circ$. The loads were then applied to this virtual original structure and the soil settlements were added, with the aim of understanding what these actions have induced in terms of stress state in the materials.

At first, the structure was analysed only under its own self load. The results in terms of stresses of this first analysis, carried out on the undeformed shape, show a good agreement with the first approximate calculations made, with a mean compression of 1.24 MPa, which do not explain the present crack pattern. Then, a first differential settlement of 2 cm was applied between the two springers of the arch, as an imposed vertical movement of the right support, corresponding to the façade. The results show a significant increase in the stresses inside the pillar (Fig.4), reaching 3.36 MPa, which is within the range of the expected mean strength of the material, as suggested by the Italian technical code for the roughly split stone masonry. At last, an increase in the differential settlement of further 1 cm was applied, reaching 3.8 MPa, which corresponds to the upper limit of the aforementioned range of strength.
This is perfectly consistent with the damage observed and also explains why the pillars have cracked only recently, rather than showing problems all along their history. The numerical analysis under these modified boundary conditions also show a crack pattern in the wall over-standing the arch which is coherent with the present conditions and a deformation of the arch which is the means of the increased stress state in the columns (Fig.4).

![Figure 4. The UDEC numerical model of a part of the longitudinal section: (a) in the original geometry, (b) with 2 cm differential settlement, (c) with the final, 3 cm settlement. On the left, the stresses, on the right the crack pattern.](image)

These results support the hypothesis that the damage is caused by the soil settlement and also explain the reasons for the sudden, recent onset of the damage. As a consequence, a deepening of the available knowledge in the geotechnical field has been proposed, together with a monitoring of the built structure, in order to reach a better understanding of the present evolution speed and to identify the most suitable solutions to hinder the soil movements and strengthen the church, thus limiting the interventions to the ones which are really needed for the preservation of the monument, unlike what has been done until now.

3. Conclusions
Masonry structures have been built for centuries with a design focused on the geometry and on the proportions of buildings, rather than on the strength of the materials. This strict relation between form and stability has been shading with the introduction of new materials, like steel and reinforced concrete, which allowed to build shapes more independent from the structural scheme. The development of new tools for the prevision of the behaviour of these new materials has progressively led the structural experts to disregard the aspects related to the geometry in favour of the materials properties. But when ancient masonry buildings are concerned, analysing their structures without taking into consideration their geometry and their changes in time risks to lead to dangerous conclusions.

The present paper focused on the important role that the deformations play in the definition of the present state of internal stresses and underlined, as a consequence, the necessity of adopting the deformation data as calibration tools for structural analysis, in order to represent at best not only what we see now, but also the historical path that lead to the present conditions. In particular, through the analysis of two case studies, two different, complementary approaches are presented: the use of the precise deformation survey data in order to calibrate the mechanical parameters of the masonry, limiting the need of destructive tests, and the adoption of the information on the displacement, possibly reconstructed in its evolution in time thanks to the historical monitoring method, as an input for the numerical analysis, in terms of changing boundary conditions.

The aim is reducing the distance, sometimes too large, between the real building and its virtual numerical model, recovering through the survey analysis the role of experience and of empiricism [10], which lead the actions of the ancient builders of our precious cultural architectural heritage.

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