Creep behavior of cultural masonry heritage by means of "structure from motion method"

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RESUME Masonry structures demonstrated to be vulnerable against both seismic actions and long-term effect in past decades. In particular, the creeps effect is very deleterious since it may produce the collapse of the structure in a fragile way and without any visible alerts. Dramatic, but explanatory, is the case of the San Marco bell tower in Venezia; which suddenly collapsed even if cracks were not manifest. This particular failure is strongly related to the global deformation of the structure. For this reason, the monitoring of the safety-state is strongly linked to the geometric survey. The "structure from motion" method (SFM) is based on the photo's elaboration of the building for computer graphic processing. The outcome is the accurate geometry survey, as largely demonstrated in the literature. The present study reports on an SFM application referring to an ancient masonry church. The innovative contribution consists of the indoor and outdoor surveying than aligned and matched. The main result was the solid model of the building; which was then compared with an available survey in order to monitoring the creep-state. The proposal can be considered a pilot-case for the "building watch" programming aimed to the cultural heritage preservation.

Mots-clefs Survey, Monitoring, Drone, Seismic, Heritage, Masonry

I. INTRODUCTION

Cultural heritage represents a large part of world's buildings. Historical masonry structures are vulnerable to natural hazards, such as earthquakes. These cause damage to cultural heritage, heavy economic losses, and difficult reconstruction processes. Besides, long-term effects are a critical issue for this kind of constructions. In fact, lack of maintenance exposes materials to external agents such as temperature change and humidity. Simultaneously, a state of prolonged compression could provide a diffuse micro-crack pattern associated with the creep effects and material decay. Visual observation is not enough for a proper evaluation of this type of phenomenon, that makes a prediction of the collapse not easily achievable. In fact, a large number of buildings have collapsed without apparent cause as for San Marco bell tower in Venice, Italy (1902) (Binda et al, 2008), the civic tower in Pavia (Binda et al 1992), Italy (1989) or the Palau Bridge, Republic of Palau (1996) (Burgoyne, Scantlebury 2006). In addition, in the case of the curved floor like vaults and domes, the long-term effect may produce the over pushing against the supporting walls up to the out-of-plane failure.

The present research worked in order to achieve tools able to predict creep effects.

An analytical way is represented by rheological models, that estimate long-terms effects by means of springs and dashpots (Choi et al, 2007). Using these models and specific formulations (e.g. in Ignoul et al. 2006), it is possible to achieve quite accurate results. Unfortunately, a huge number of parameters is required for making this type of model which are difficult to assess and time-consuming.

On the other hand, recent studies report on a structural health monitoring by means of electrical sensors aimed to cracks opening monitoring. In fact, in Rossi P. and Rossi C., 2015, electrical extensometers and long base extensometers are used in order to evaluate local displacement in time with appreciable results, while inclinometers and temperature sensors complete data set.

The herein study represents a proposal for creep effect evaluation, that aims to prevent the potential structural collapse by means of periodical geometry monitoring. Buildings could be surveyed using *structure from motion* (SFM) algorithm built-in *Agisoft Metashape* (or similar) software that allows constructing a 3-D model based on high-definition photos. In this paper, the 3D survey of an historical masonry church was modelled through an outdoor and indoor acquisition. The proposal represents a displacement control strategy by comparing different time surveys.

II. CREEP IN MASONRY

Masonry strain is strictly connected to time flow. Creep behavior could be identified in three different step, dependent on the link between strain and creep ratio as reported in Figure 1. In the first stage, the increasing strain corresponding to decreasing creep rate could be observed. Alternatively, the second one is represented by stability or a strain increasing at constant creep rate. A third stage could manifest if the material is subjected to very high a compressive stress, causing a fragile breaking. Tertiary creep represents the principal collapse cause in ancient buildings. Internal damages reduce material performance facilitating the achievement of the third stage.

In order to prevent the structural collapse, authors have estimated creep evolution laws by Lenczner (1988) who defined the creep coefficient for single-leaf masonry walls related to compressive strength, and here reported in equation (1).

$$\phi_{\infty} = 4.46 - 0.33\sqrt{f_B} \quad (1)$$

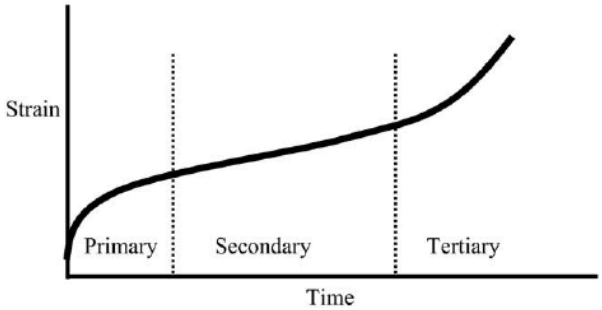


Figure 1-Basic creep curve

More recent studies have improved the mentioned law accuracy using a large number of coefficients that required more computational time for structural evaluation.

For these reasons, practitioners prefer monitoring technologies to recognize local displacements through electrical devices as reported in P. Rossi & C. Rossi, 2015 in which two venetian cathedrals were monitored using strain gauges inclinometers, temperature sensors and piezometers. Data processing provided a signal frequency analysis and a deformation trend evaluation that correlated displacement to temperature changes through linear regression analysis.

In this case, despite a lower complexity of use than analytical methods, a high number of sensors is required. Besides, device durably is strictly connected to the environmental condition as for humidity and weather, making this method more useful but expensive. Digital Photogrammetry represents a cheaper alternative that aims to estimate displacements through periodical survey and points cloud elaboration comparison.

III. Solid model creation

In the 1855m The St. Mary at the Gate's Church in Lecce (Figure 2), was built. It is characterized by a central plane and a massive dome. Several subsequent restorations occurred over the time that modified the understructure.

Figure 2. aerial view of the building.

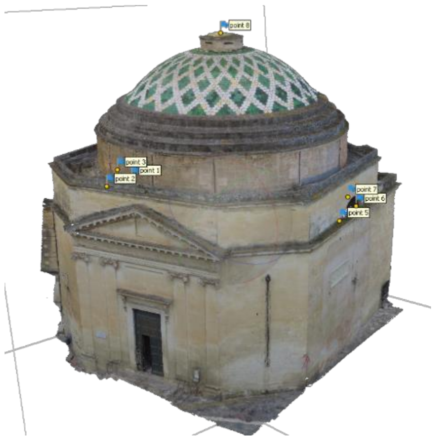
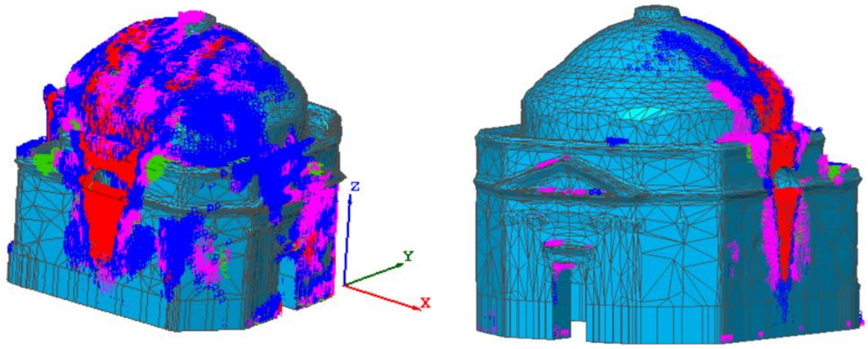


Figure 3. Matching points

Some high-definition photos were taken using an Unnamed Aerial vehicle (also known as drone), then processed by means of a photogrammetry software (i.e. Agisoft Metashape) in a SFM-based method. Thanks to two flight session, the internal and external surfaces were acquired. Then, of the pictures were aligned by means some matching points in windows surfaces, as reported in Figure 3, obtaining a solid model.

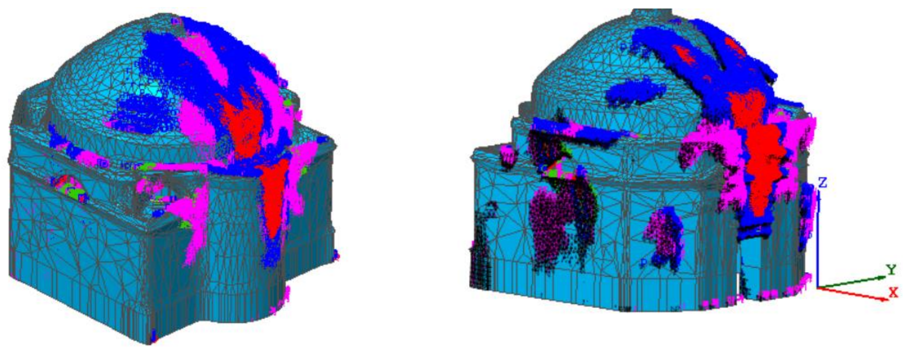
In order to make the SFM-object useful for FE codes, it was necessary to manipulate the data by means of *Grasshopper* 3D plug-in for *Rhino*. This visual programming environment offers a number of suitable tools able to handle solids and export them in various computer formats. MidasFEA™ code was used for the analysis, allowing to discretize the geometry by means of 273497 tetrahedral elements with a characteristic length equal to 300 mm.

Modal and pushover analyses were both performed according to the European Code 8. Pushover analysis (carried out in two normal directions) identifies criticalities over the opening (i.e. windows and principal door) as reported in Figure 4 and Figure 5 due to an unloaded zone under the trust-line.



(a) *(b)*

Figure 4. Crack patterns: -Y (a) and +Y (b)



(a) *(b)*

Figure 5. Crack patterns: -X (a) and +X (b)

IV. Conclusions

The proposed tool provided a new method to represent a complex geometries structure accurately. Cultural heritage is commonly affected by the impossibility of investigating materials and thicknesses. At the same time, the traditional measure tool does not allow to evaluate time depending displacements such as creep effects. In this scenario, the herein reported procedure could be a proposal for monitoring purposes and make the survey fast, safe, and accurate. In detail, other drone-base surveys are planned to be performed over the years in order to detect potential differences in the global geometry which are alert of a creep behavior when external forces are not acting.

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