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Overview of structural health monitoring systems for the foundations of historic buildings

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***Abstract* – Structural monitoring represents one of the most important scientific and research sectors in the field of civil engineering. Using a Structural Health Monitoring (SHM) system, it is possible to reduce management costs, to operate in areas difficult to access and acquire data also during dangerous events such as landslides and earthquakes. Last researches have made available SHMs that operates in a non-invasive way, allowing the continuous monitoring without the need to suspend the use of the structure (for example in the case of an historical building , it is not necessary to install the measurement instruments for the periodic inspection suspending their normal activities and then creating loss of money, and it is not necessary to sample the structure itself). This paper presents an overview on the last researches on SHM systems in the field of civil engineering focused on the monitoring the foundations structures of the historical buildings, in order to stimulate the research in the field by highlighting the benefits obtained with their use**.

I. INTRODUCTION

The term Structural Health Monitoring (SHM) identifies the monitoring of the state of conservation of buildings over time. The SHM is necessary in many fields of civil engineering, in fact it is used to identify the presence of structural variations due both to changes in the behavior of the materials and to geometric changes in an advanced state of aging [1]-[3]. Through SHM it is possible to obtain many information concerning the health of the constructions. These systems are used to monitor different types of structures such as dams, tunnels, pillars, walls and foundations [4]. This article aims to highlight and show a preliminary overwiev on SHM applied to the foundation structures of historic masonry buildings[5]-[7].

The monitoring of this particular parts of the structures is based on several static and dynamic parameters, which values allow us to detect the possible presence of any anomaly or hazard from the foundations to the elevated structures. In particular, the proposed overview highlight on one side how SHMs could provide the collection of time series of data[6]-[8] allowing the use of dynamic models able to characterize the operational status of the buildings on the other sides the difficulties to provide effective and low cost SHM for foundations due to the heterogeneous quantities to be monitored, the high number of sensor to be used and the fact that such sensors must be installed according to a pattern that varies with the size and geometry of the structure. This paper would be a starting point to stimulate the research in the field and to furnish a critical overview on the existent solutions especially the ones based on the IoT paradigm [8]-[13]. The paper is organized as it follows. In section II the classification of masonry structures is given in order to show how the different structures distribute the weight and the strengths on the foundations. In section III the possible foundation failures are described.

II. CLASSIFICATION OF MASONRY STRUCTURES

Masonry buildings are classified according to five basic construction parameters: homogeneity of raw material, period of construction, restoration work, continuity of the piers and regular floors that are repeated in the development in height.

In addition, a further typological classification was proposed by Pagano [14] on the basis of the vertical loads that act on the structure and consequently are transmitted to the ground by the foundations. The classes of buildings identified in chronological order are three:

- first class buildings
- second class buildings
- third class buildings

The first-class buildings are those structures built entirely of masonry and where all vertical and horizontal structural elements are made with the same raw material [15]-[16]. They are characterized by a low tensile strength and the loads are transmitted only by a compression stress which is often not centered but eccentric. The horizontal elements are often made by barrel or cross vaulted systems lightened with the use of hollow elements. An important example are the structures made with fictile tubules bricks which lighten the construction and decrease the thrust against the piers [17]-[21].

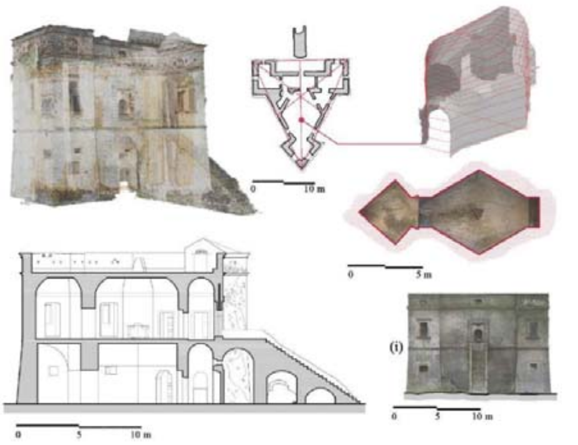

Fig. 1. Example of first class buildings

The second class buildings are regular structures, with a square or rectangular plan characterized by a wooden floor. The peculiarity of these structures is in the horizontal closures that are not embedded with the masonry but only supported [22]-[24]. This structural condition is simplified by the "smooth" constraint hypothesis which guarantees free horizontal sliding between the parts. in this hypothesis the piers and beams are independent structural systems and only the vertical reactions are transmitted to each other and to the foundations [25]-[26].

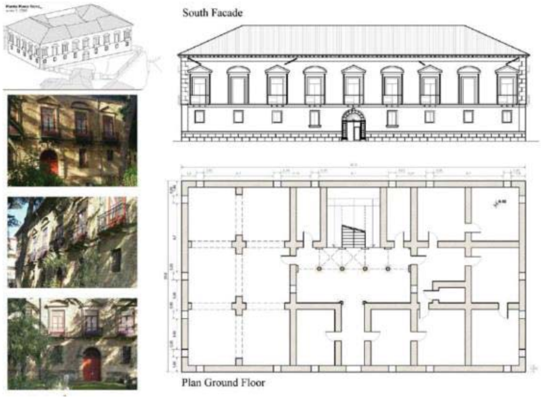

Fig. 2. Example of first class buildings [27]

The third class buildings are structures made up of load-bearing masonry walls and horizontal monolithic closures. This class includes buildings with reinforced concrete floors which has the function of connecting the entire structure ensuring a congruence of displacement and rotation of the parts [28]-[29]. The loads in this case are transmitted to the foundations in a distributed way without creating concentrated loads and local instabilities.

III. INSTABILITY OF FOUNDATIONS

The term "foundation structural failure", in the field of civil engineering, means the vertical displacement of the foundation plane induced by the deformation of the ground [30]-[31]. The evaluation of foundation subsidence for ancient masonry structures requires geotechnical tests in order to obtain information on the site on which the building was built, the type of foundation, the construction material of the same, the depth and their degradation [32]. Typically, some subsidence of the foundation soil already occurs during the construction phase of the building due to the compaction and the relative reduction in volume of the ground.

In the historical and cultural heritage, the foundations of masonry constructions are simple enlargements of the masonry within the ground and are of a continuous type [33]. However, there are also discontinuous structures composed of pillars and reverse arches. The foundations of masonry buildings always have a greater thickness than the wall above, and are built by enlarging the section going down into the depth. In existing buildings, the most frequent cases of continuous foundation typology are [34]:

Typology obtained by widening the excavation in depth and filling it with infill wall rubble masonry (Figure 3)

Type of masonry with wall surface of different thickness (Figure 4)

Masonry with vertical wall surface with recesses (Figure 5)

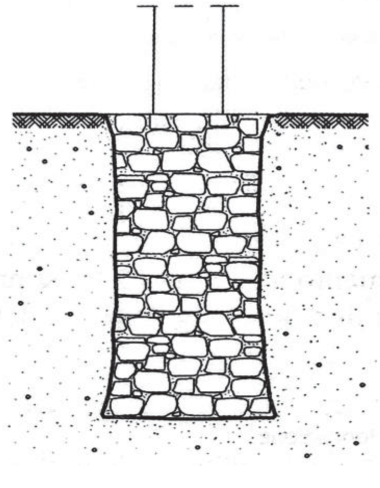

Fig. 3. Infill wall foundation [35]

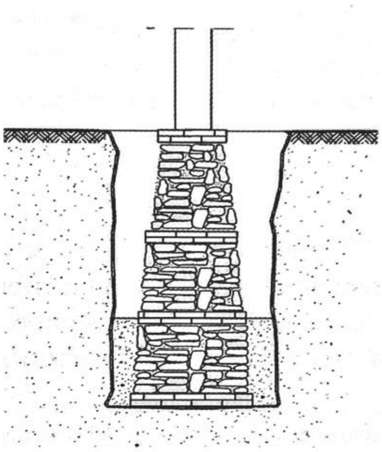

Fig. 4. Wall surface of different thickness foundation [35]

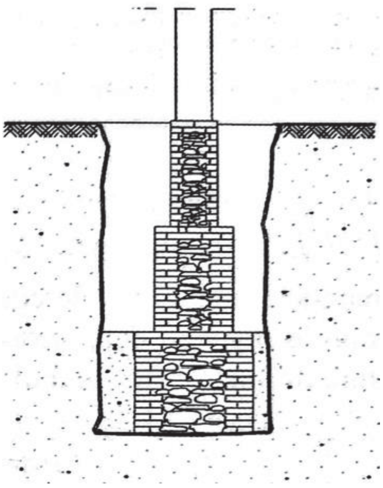

Fig. 5. Wall surface with recesses foundation [35]

Continuous foundations can be subject to two types of structural failure: uniform and non-uniform. The uniform structural failure occurs in foundations with high stiffness due to a massive development in plan in comparison with the overlying parts. It does not cause a variation in the stress state of the building in elevation, making high settlements tolerable. This type of subsidence is characterized by a constant lowering of every single point of the structure as shown in figure 5 and it is dangerous because it could cause breakage of gas pipes and damage to nearby buildings.

Uneven foundation structural failure often causes the building to tilt or distort angularly (Figure 6). The causes that induce it can be:

- heterogeneous soil,
- foundation loads distributed unevenly,
- evenly distributed loads on foundation with poor stiffness,
- drains,
- foundation plan at different depths,
- construction on non-compacted ground.

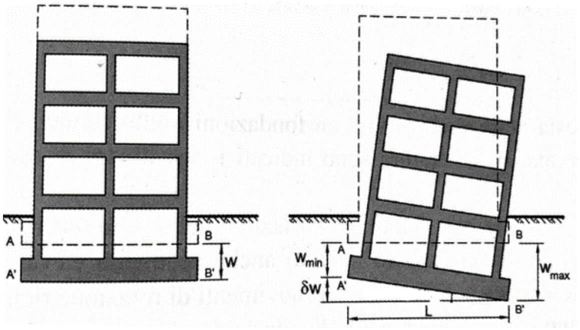

Fig. 6. Different types of foundation structural failure

The typical cracks that are formed are inverted V and occur in the center of the wall subject to failure when the ratio between length and height is greater than three.

In the case of vertical failure of a section of foundation, the traction cracks caused by stresses have an inclination of 45° as shown by the behavior of the masonry described with the circle of Mohr [36]. If the translation of a part of the foundation is horizontal, the tensile stresses form vertical cracks with constant development.

The last case that can happen is the rotation of a part of the foundation which induces the formation of vertical cracks characterized by a V-shaped growing width.

IV. SHM SYSTEMS FOR FOUNDATIONS

The use of the SHM can be successfully adopted for monitoring the behavior of neutral pressures in the soils that interact with the foundation structures. To this aim in [37] it is proposed a SHM based on the use of optical fiber that can detect areas where there is greater flow. In the literature there are two types of SHM for structural monitoring [37]-[38]:

- data-driven
- model –based.

The model-based techniques require a validated mathematical model of the structures under monitoring typically developed with the finite element method FEM. Starting from the mathematical model, the identification of the damage takes place solving a problem called "inverse" in which the variation of the system behavior is evaluated. It turns out instead a "direct" problem when damage is noted, and the perturbed parameters are determined [39]-[41].

Usually the solution to an "inverse" problem occurs when the number of parameters to be estimated is greater than the data of a layout. The number of available data cannot be increased as wish, mainly because they could be not easy to obtain or very expensive [42]-[44]. It turns out therefore that a condensation or a reduction of the parameters to be estimated is necessary [45].

The data-driven methods are based on a statistical model and do not require any mathematical model of the systems under monitoring [46]. Such methods are based on the experimental data acquired to study the dynamics answer system. Statistical methods are typically applied to manage the uncertainty associated to the acquired measurements [46]. Data-driven also includes pattern-recognition techniques that from the experimental measurements achieved by several heterogeneous sensors quantify the state of structure damage. There are two kind of pattern recognition techniques based, respectively, on: supervised-learning, when the behavior of both the intact and the damaged structure are known, and unsupervised-learning, in case the behavior of the intact structure only is known [47]-[48]. The use of unsupervised methods is usually limited to first point of the identification process regarding the detection of damage, but have the advantage of requiring only knowledge of the parameters of the intact structure.

For the purpose of damage management, an SHM system implements a process based on the following functions:

- detection;
- location;
- characterization and assessment of severity;
- damage reporting and assessment of the structure's residual useful life.

A SHM system for foundation has, typically, a distributed architecture. It can be used to monitor one or more structures composing the funtation. In general, it can only use devices placed on the ground (terrestrial SHM system) and/or sensors housed as payloads on Earth Observation satellites or on aircraft (use of helicopters or drones) [49].

The macro functions of a SHM systems are: data acquisition; processing of acquired data to identify the existence of damage with its location and severity; indications of maintenance and any limitation of use. Success of the location of SHM in the foundations depends to the adopted design criteria to detect the point to be monitored and to the used methods to analyze the acquired data to support of the maintenance decisions [50].

V. SHM FOR SOIL AND FOUNDATIONS

In recent years, the study and monitoring of the foundations of masonry constructions has been of great interest. In order to ensure this an accurate monitoring of the land on which the buildings are built is necessary.

The study of the liquid and gas phase that fill the fractures of the soil, and the intrinsic properties of the solid, guarantee the identification of the geophysical properties of the damaged rock. The electrical properties of deteriorated rocks are obteined by electrolytic conduction occurring through fluid-filled fractures as well as ionic conduction in the electrical double-layer forming at fracture-fluid interfaces [51].

The sensors used for this type of monitoring are different. The most employed are: Strain Gauges and Piezoelectric Sensors that are used in order to measure displacement, rotations, strain and curvature, Fiber Bragg Grating Sensors (FBG); and Acoustic Emission (AE).

The methods used for on-site investigations are commonly geophysical and provide information about fluid properties, borehole conditions, lithology and discrete fracture locations [52]. This type of sensors allows the collection and recording of a suite of logs to decrease system costs. The software for processing and visualizing the data is based on the comparison of multiple registers collected as suites and provides valuable information on the statistics on the orientation of the fractures around the foundation and geological structure of the soil.

The use of AEs, however, provides more accurate information on the depth and orientation of the discrete fractures that intersect the structures under monitoring [53]-[55]. The only drawback of this method is that for very deep foundations on which it is not possible to carry out an inspection excavation, the acquisition of emissions is indirect and increases the possibility of error.

VI. CONCLUSIONS

In this paper an overview of the Structural Health Monitoring Systems for foundations is provided. The aim is to stimulate the scientific research in the field due to the usefulness of such kind of monitoring systems and their peculiarity.

VII. ACKNOWLEDGMENT

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