2019 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Florence, Italy, December 4-6, 2019

SHM systems applied to the built heritage inventory at the territorial scale. A preliminary study based on CARTIS approach

Renato S. Olivito[1], Saverio Porzio[1], Carmelo Scuro[2], Domenico L. Carnì[3], Francesco Lamonaca[4]

[1] *Department of Civil Engineering, University of Calabria, Via P. Bucci Cubo 39B, 87036 Rende (CS) Italy, (reanto.olivito, saverio.porzio)@unical.it*
[2] *Department of Physics, University of Calabria, Via P. Bucci Cubo 31B, 87036 Rende (CS) Italy, carmelo.scuro@unical.it*
[3] *Department of Informatics, Modelling, Electronics and Systems Science, University of Calabria, Via P. Bucci Cubo 41C, Rende (CS), Italy, dlcarni@dimes.unical.it*
[4] *Department of Engineering, University of Sannio, Corso Garibaldi 107, 82100 Benevento (BN), Italy, flamonaca@unisannio.it*

Abstract **– Past seismic events have shown that the existing built heritage is strongly vulnerable to dynamic stresses induced by earthquakes. This issue concerns not only reinforced-concrete buildings but also masonry ones, which are concentrated in the historical centers that characterize the Italian peninsula. The inadequacy of existing structures to withstand the seismic actions is due to significant constructive variables, such as the materials used and the construction details, neglected in building practices.**

This work deals with the analysis of the built heritage through the inventory with the CARTIS (Caratterizzazione TIpologica Strutturale) form developed by the ReLUIS (Rete Laboratori Universitari Ingegneria Sismica) together with the DPC (Dipartimento Protezione Civile). Through the knowledge of the building framework, it is possible to apply Structural Health Monitoring (SHM) systems on the Town Compartments (TC) which present the highest vulnerabilities. Starting from the building inventory by detecting the TC through the CARTIS-based data, a priority criticalities scale can be drawn. The next stage consists of the implementation of proper SHM in order to provide import information about the structural integrity of buildings. The proposed methodology is illustrated in this paper referring to the suggested SHM system.

I. INTRODUCTION

In the management of historical buildings, seismic prevention is one of the main goals of researchers. However, a proper assessment of the built heritage requires the definition of the buildings features to examine, with particular attention to (i) the construction type (i.e., reinforced concrete or masonry), (ii) the intended use (i.e., residential or specialized) and (iii) the state of conservation (i.e., good or neglected).

With a focus on non-specialist buildings, having the survey-measure is the first step in building inventory. The narrowing of investigation framework is necessary to optimize the effectiveness of the analysis. This paper represents a preliminary study aimed to define a methodology able to coupling the recent trends in building inventory with those of structural monitoring. In the last decades, there have been several attempts in the formulation of refined collecting models. At the regional scale, the CENSUS data were the first sources for the buildings vulnerability classification. The data sources provided by interview-based survey or building-by-building allowed deep investigation, in the face of the greater difficulty of access to information [1]. From the collaboration between RELUIS and DPC is born CARTIS, a knowledge territory tool based on the building typology concept with specific structural features. This approach is strongly adaptable to the diversity of buildings throughout the Italian territory in which each city is the result of a historical evolution leading it to the current situation.

The use of more or less expeditious approaches allows the identification of TCs in which the most critical issues in terms of structural safety are concentrated. Real-time damage identification systems might help prevent seismic risk. The goal is acting only on the most vulnerable buildings with minimal intervention in order to optimize both technical and economic resources. This objective can be followed by using SHM systems combined with the Internet of Things (IoT) paradigm. In this work, a preliminary study aimed to define an integrated methodology for inventory, monitoring, transmission, and data management is proposed.

II. BUILDING INVENTORY WITH CARTIS APPROACH

The first step of CARTIS methodology concerns the definition of homogeneous territorial zones, namely the TCs, which collect buildings with the same age and construction technique. The data collection takes place by filling forms subdivided into different levels: a 1st level single form for the city (Fig. 1); 2nd level forms, one for each TC detected in the local territory; 3rd level forms, one for each building type within each TC.

Fig. 1. Example of CARTIS form.

The survey campaign is carried out by qualified technicians (professionals and researchers) both building-by-building and through interviewing local experts operating in the sector and having an in depth knowledge of the territory.

In the 3rd level surveying, the classification of the building typologies of each compartment takes place by identifying the macro classes of buildings, first of all between reinforced concrete and masonry (respectively, CAR and MUR inside the forms). Other discriminating factors, which contribute to defining the typologies, are the slab-types, the number of floors, the percentage of openings, and so on. However, it is worth noting that masonry typologies can be multiple. In reinforced concrete buildings, proper building details correspond to the date of construction (e.g., class of strength of concrete, diameter/spacing of strips, percentages of rebars in beams and pillars). For masonry buildings, a more significant variability might be found for the same kind of material, owing to the texture and cross-section, presence of courses and diatons, type of corner connections, thin-bed joints, and so on. Moreover, these buildings are usually irregular in geometry both in plan and in elevation. It is easy to understand how the role of the data collector is of fundamental importance and related to its ability to access information.

Although the collected data may appear to be aggregated, they can already be used to define vulnerability models at different scales. Another great possibility of CARTIS is the web application, available at the address "https: //cartis.plinivs.it", in which all the data manually collected through the forms are introduced and accessible to the scientific community. The data entry procedure is guided within the web application, reducing the possibility of human error that can affect the collection. Furthermore, the data can be queried through specific "query" commands. Thus, the same information might be subjectively evaluated in order to define and calibrate new refined models of seismic vulnerability.

III. SEISMIC VULNERABILITY

Several approaches are used today to estimate the seismic vulnerability of buildings [2]. However, the strategy employed must establish a priori (i) which are the discriminants that contribute to defining the seismic behavior of a typological class, (ii) the damage scale, and finally (iii) how much these classified buildings are vulnerable to a certain level of seismic intensity. Therefore, the researchers tried to standardize the vulnerability concept in order to make comparable investigations [3].

In this framework, the Damage Probability Matrix (DPM) is one of the main tools used. They relate the probability that a given damage level k occurs for a seismic event of a certain intensity

$$I : p_{k|I} = P\left[D = k \mid I\right] \tag{1}$$

taking into account a specified building class. For each I values, the distribution of damage d presents a mean value of:

$$d(I) = \frac{1}{5}\sum_{k=0}^{5}\left(p_{k|I} \cdot k\right) \quad (2)$$

where the term *1/5* is related to the five damage degrees D_k expected by this kind of approach. Depending of the adopted model, particular curves called vulnerability curves (Fig. 2) which plot the damage distribution *d* vs. intensity *I* can be drawn.

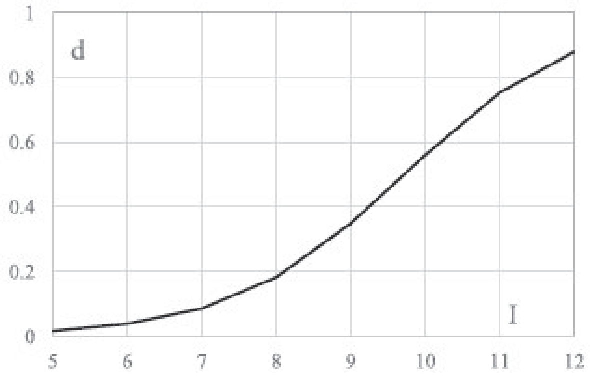

Fig. 2. Example of vulnerability curve.

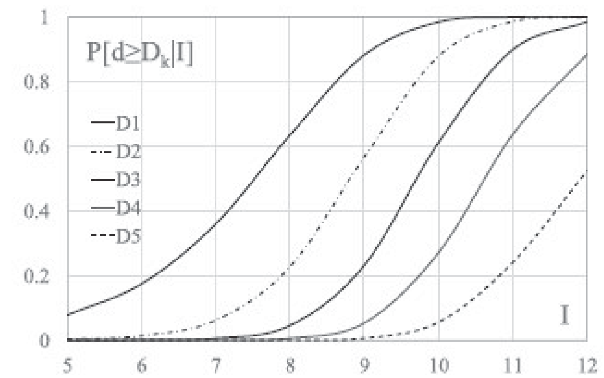

Fig. 3. Example of fragility curve.

When several damage grades D_k are taken into account, the curves become fragility curves (Fig 3) commonly developed on the basis of a lognormal distribution of *d* values [4].

It seems clear that vulnerability studies conducted through such approaches lead to having a complete picture of the most critical building classes. Generally, higher mean damage is achieved by the more vulnerable building classes instead of less vulnerable classes. The attention should be focused on these buildings, implementing systems for monitoring structural safety in real-time.

However, past earthquakes revealed the possibility that a given building class might work better in case of weaker seismic events instead of stronger ones. So, it might be hard to compare different building classes in terms of vulnerability.

IV. MONITORING SYSTEM FOR HISTORICAL BUILDINGS

The possibility of classifying a historic city center through the application of CARTIS, ensures the identification of the building compartments that could be most damaged if subject to seismic action. In view of this, it is of interest to monitor these compartments through the application of preventive SHM systems.

In the latter, the modification of structural behavior associated with local variations in structural rigidity, typically produced by seismic events or dynamic loads, is obtained by monitoring dynamic actions and evaluating dynamic parameters [5]

The possibility of obtaining reliable dynamic parameter estimates from in-service response data is one reason making vibration-based SHM systems very attractive. These results will be obtained through automated operational modal analysis (OMA) techniques by the use of a small number of sensors [6].

The prediction of degradation of the physical and chemical properties of the masonry, that is the major raw material employed in the buildings of the historic centers, is influenced by sensitivity of the sensor of the SHM.

In the near future, the new technologies will try to solve the above-mentioned problem by implementing set for the simulation of intelligent data processing associating at the SHMs the IoT paradigm [7-8]. The events, which cause to an important damage of the engineering structures, presently, are studied through the transformation of models that simulate their behavior. This is due to the fact that the processes described are often dynamic and they change over time. If the dynamics of source events is higher than that world, their description became hard [9, 10].

V. PRELIMINARY STUDY

In order to define a preliminary study, the CARTIS methodology is implemented on a case study. The objective is to set up a SHM system to be applied to the most vulnerable building classes, detected with CARTIS. The methodology is valid only for residential buildings, which are the most widespread in the territory and have same properties during the time. Specialized buildings, such as noble palaces, religious buildings, historic buildings, require specific insights developed with other methodologies [11-14]. This work aims to evaluate the exposure to the seismic risk of an urban center in the Calabria Region, in the south of Italy, namely Mendicino. In particular, the examined area is the “old town”, which is notoriously the most vulnerable TC of the city. After the buildings inventory by detecting the TC through the CARTIS-based data, a study based on the pushover approach [15] applied to the most common building typologies (BTs) of the TC is carried out. The seismic safety indexes of the configurations detected are calculated by varying the geometric and structural parameters [16].

The VEM calculation software is used to this aim. A qualitative reading of the urban fabric is carried out in this way, providing a ranking of the most suitable strengthening for each BT configuration.
Regarding the monitoring system, a possible preliminary SHM to monitor in real time the building sectors is proposed in this paper. The SHM system proposed is composed by a cyber and physical part. In this framework, the quality of analytical or numerical models, the choice of using an algorithm and its parameters, the accuracy of sensor measurements, are all sources of errors and uncertainty [17].

A. CARTIS methodology on a case study

The case study analyzed is the municipality of Mendicino, which is very close to the provincial capital of Cosenza. Although the investigate territory is vast (35.7 km^2), the built-up area counts the "old town" and "expansion area" TCs (Fig. 4). Further subdivisions into smaller TCs are possible. However, this work aims to identify a prevalent BT within the "old town" (Fig. 5) in order to carry out studies on the seismic vulnerability of these buildings and possible reinforcement interventions. Thus, the focus is on the 2nd and 3rd levels of CARTIS forms. The “old town” TC is the only one until the year 1954. The masonry BTs are the main ones in this TC, distinguishing them in three types according to the formal and constructive properties. However, there are examples of reinforced concrete buildings not taken into account during the survey campaign performed with the aid of the 2nd level forms. From a typological point of view, the terraced house is the recurring building kind formed by the primary unit called "tower-house", as shown in the example diagram of Fig. 6. For the definition of the structural behavior of BT, three existing buildings placed in three different points of the “old town” TC have been taken into account: square plan, rectangular plan and irregular plan. Without going into too many details, the properties of the tower-house commons for all typologies are as follows:

- an average story height of 2.50 m;
- 2 to 3-story structures with elevations built in the mid-twentieth century (in most cases);
- a ground floor, mostly semi-underground, with a lower height than the intermediate levels. Furthermore, it changes the intended use from a workshop or shelter for animals to a residential area;
- a top floor with a further reduction of hm.
- wide openings compared to the size of the masonry panels.

Other parameters, as well as to the shape of the plan, are:

- the thickness of the masonry, of 0.60 m throughout the height;
- the masonry type, from the weaker rubble masonry to the stronger masonry blocks;
- the different ground floor height, ranging between 2.30, 2.50 and 2.80 m;
- the type of slab, wooden slab (lightweight) or steel I-beam with hollow flat blocks (stiffer).

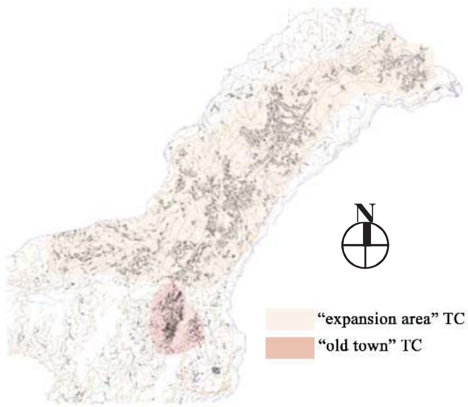

Fig. 4. TCs of the municipality of Mendicino.

Fig. 5. “Old town” TC.

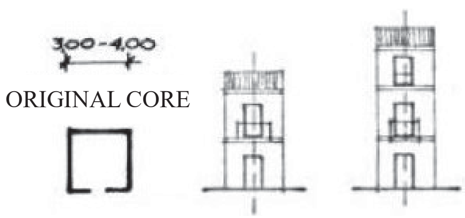

Fig. 6. Typological evolution of the tower-house in Mendicino.

According to the pushover approach provided by the Italian Structural Codes [18, 19], the seismic safety of a building is defined by:

$$i_s = \frac{u_{\max}}{d_{\max}} \quad (3)$$

This index represents the ratio between capacity displacements detected in the control point (u_{max}, usually located onto the centroid of the attic floor) and seismic demand (d_{max}). The work aims to identify the safety indexes by varying the percentage of openings (from 9 to 20%), and the mechanical parameters of the structure. Moreover, i_s<1 is the non-reliability condition.

B. Physical part

A possible solution of the SHM physical part will be composed by a wired Sensor network characterized by two types of piezoelectric accelerometer sensors (Integrated Electronic Piezoelectric—IEPE): KS48C-MMF with voltage sensitivity of 1 V/g and measurement range of ± 6 g; KB12VD-MMF with voltage sensitivity if 10 V/g and measurement range of ± 0.6 g. The data recorded with the sensors are acquired by gateway to be sent towards a remote control and service room, where they will be analyzed and compared to the results obtained by the FEM model.

C. Cyber part

The Natural Computing is used today to automate the monitoring processes in order to reduce errors due to human decisions. The possible sources of errors are identify trough a sensitivity analysis of the parameters employed in the dynamic models. The nature-inspired algorithms are used in order to ensure a converge solutions of the problems in a local framework, with particular attention to the suitable of the solutions in constraints problems as the Optimal Sensor Placement (OSP) and the model-based Damage Identification (DI). In particular, when the DI-strategies is used, it is possible to evaluate damage parameters from changes in the elastic-mechanical properties of the structural system by solving inverse problem of the system analyzed [20].
Vibration-based methods allow initial identification of damage through measurements of dynamic properties. They concern the changes in mass, damping and rigidity of the system, which can be determined through the analysis of natural frequencies by the use of accelerometers [21-23].

VI. CONCLUSIONS

The pushover analyses carried out for several configurations of 2 to 3-story BTs show some important results. First of all, the safety index which always reaches values more significant than one in the case of 2-story buildings, while the reliability condition is rarely not satisfied with the 3-story buildings. An index reduction is also noted from buildings with a regular plan to those with an irregular one. The performance decay is due to weaker mechanical properties of the calculation model, such as the type of masonry and the flexural strength of the floors, as can be expected. The growing of the story-height, as well as the percentage of openings in the main façade, led to adverse effects on seismic safety. However, the index tends to similar values regardless of the structural properties of the model.
In particular, the vulnerability elements are so ordered: the number of floors > the story-height > the stiffness of slabs > the percentage of openings (with a focus of vertical misalignment of them) > the plan shape. Thus, the SHM system proposed might be applied to the buildings that present the elements above defined through the vulnerability ranking (Fig. 7).

	Number of floors
	Average story-height
	Slabs stiffness
	% openings
	Plan shape
	Masonry properties

Fig. 7. Ranking of vulnerability structural elements.

REFERENCES

[1] M. Polese, M. Gaetani d'Aragona, A. Prota, "Simplified approach for building inventory and seismic damage assessment at the territorial scale: An application for a town in southern Italy", Soil Dynamics and Earthquake Engineering 121 (2019) 405–420.

[2] G.M. Calvi, R. Pinho, G. Magenes, J.J. Bommer, L.F. Restrepo-Vélez, H. Crowley, "Development of seismic vulnerability assessment methodologies over the past 30 years", ISET Journal of Earthquake Technology 43(3) (2006) 75-104.

[3] S. Cattari, S. Lagomarsino, D. Ottonelli, "Fragility curves for masonry buildings from empirical and analytical models," Proc. of 2nd European Conference on Earthquake Engineering and Seismology, 2014, pp. 25-29.

[4] G. Zuccaro, F. Dato, F. Cacace, D. De Gregorio, S. Sessa, "Sesmic collapse mechanisms analyses and masonry strucutures typologies: a possible correlation", International Journal of Earthquake Enginnering 4 (2017) 121-149.

[5] Olivito, R. S., Scuro, C., Porzio, S., Codispoti, R., & Demarco, F. (2019, July). "Seismic vulnerability of ancient masonry buildings: the case study of low-rise towers". In AIP Conference Proceedings (Vol. 2116, No. 1, p. 420007). AIP Publishing.

[6] Ubertini, F., Comanducci, G., & Cavalagli, N. (2016). "Vibration-based structural health monitoring of a historic bell-tower using output-only measurements and multivariate statistical analysis". Structural Health Monitoring, 15(4), 438-457.

[7] Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). "Internet of Things (IoT): A vision,

architectural elements, and future directions. Future generation computer systems", 29(7), 1645-1660.
[8] Lamonaca, F., Sciammarella, P. F., Scuro, C., Carni, D. L., & Olivito, R. S. (2018, April). "Internet of things for structural health monitoring". In 2018 Workshop on Metrology for Industry 4.0 and IoT (pp. 95-100). IEEE.
[9] Weiser, M., 1994, March. "Ubiquitous computing". In ACM Conference on Computer Science, p. 418.
[10] Marzat, J., Piet-Lahanier, H., Damongeot, F., Walter, E., 2012. "Model-based fault diagnosis for aerospace systems: a survey", Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, SAGE Publications, 226(10), 1329-1360.
[11] Olivito R.S. & Porzio S., "A new multi-control-point pushover methodology for the seismic assessment of historic masonry buildings", Journal of Building Engineering 26 (2019).
[12] Olivito R., Porzio S., Funari M.F., Scuro C., & Demarco F. " A numerical-geometrical methodology to represent out of-plane mechanisms of unreinforced masonry structures by using pushover analysis", COMPDYN 2019 VII Conference of Computational Methods in Structural Dynamic and Earthquake Engineering, 24-26 June 2019, Crete, Greece.
[13] Olivito, R. S., Porzio, S., & Tedesco, A. (2019). "An Interdisciplinary Approach for the Seismic Vulnerability Assessment of Historic Masonry Buildings: The Case Study of the Ex Jesuits College in Amantea (Italy)". In Structural Analysis of Historical Constructions (pp. 1247-1256). Springer, Cham.
[14] Olivito, R. S., Porzio, S., Scuro, C., & Codispoti, R. (2018, November). "Evaluations on the seismic vulnerability of masonry churches: A case study in Amantea (Cosenza–Italy)". In AIP Conference Proceedings (Vol. 2040, No. 1, p. 090009).
[15] Clementi F, Mezzapelle PA, Cocchi G, Lenci S. Global analyses of historical masonry buildings: Equivalent frame vs. 3D solid models. AIP Conference Proceedings; 2017.
[16] Olivito, R. S., Codispoti, R., Scuro, C., & Porzio, S. (2018). "A seismic analysis for ancient Trentacapilli palace with different schematization methods of masonry walls". In Proceedings of the International Masonry Society Conferences, 0(222279).
[17] F. Lamonaca, R.S. Olivito, S.Porzio, D.L. Carnì, C.Scuro. "Structural Health Monitoring System for Masonry Historical Construction". In Proceedings of International Conference on Metrology for Archaeology and Cultural Heritage METROARCHEO 2018, Cassino, Italy - October 22-24, 2018.
[18] CS. LL. PP. Aggiornamento delle norme tecniche per le costruzioni. Gazzetta Ufficiale della Repubblica Italiana, 2018, 42.
[19] CS. LL. PP. Circolare 2 febbraio 2009, n. 617, Istruzioni per l'applicazione delle «Nuove norme tecniche per le costruzioni». 2009.
[20] A. Barontini, M. G. Masciotta, L. F. Ramos, P. Amado-Mendes and P. B. Lourenço. (2017). An overview on nature-inspired optimization algorithms for Structural Health Monitoring of historical buildings. Procedia Engineering, 199, 3320-3325.
[21] Serov, A. (2017). Cognitive Sensor Technology for Structural Health Monitoring. Procedia Structural Integrity, 5, 1160-1167.
[22] Scuro, C., Sciammarella, P. F., Lamonaca, F., Olivito, R. S., & Carni, D. L. (2018). IoT for structural health monitoring. IEEE Instrumentation & Measurement Magazine, 21(6), 4-14.
[23] Lamonaca, F., Scuro, C., Grimaldi, D., Olivito, R. S., Sciammarella, P. F., & Carnì, D. L. (2019). A layered IoT-based architecture for a distributed structural health monitoring system System. ACTA IMEKO, 8(2), 45-52.