Engineering Structures 161 (2018) 108–117

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Short communication

Long-term monitoring of a damaged historic structure using a wireless sensor network

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A R T I C L E I N F O

Keywords:
Long-term monitoring
Structural health monitoring
Wireless sensor network
Heritage construction
Environmental effects

A B S T R A C T

Recent advances on sensing and data communication systems have allowed the optimization of the structural health monitoring systems, as well their employment for long-distance remote monitoring of civil structures. Moreover, structural health monitoring techniques can be particularly interesting for heritage constructions assessment, because they allow a real-time analysis of the structural properties, and the collected data can be used as support of safety maintenance. This work describes the strategies employed for structural health monitoring of a damaged historic structure from the XVI century, namely the Foz Côa Church (in Portugal), beside the results of 1-year monitoring of the displacements observed on the structural elements of the church. Additionally, the influence of the temperature and relative humidity were studied. Removing the environmental influences from the observed displacements in the structural elements allowed to conclude that these are not motived by the damage progression, instead they are related with influence of environmental parameters.

1. Introduction

Recent advances on the field of sensorial systems and wireless communications, as well their implementation on cost reduction, have contributed significantly to dissemination and employment of Structural Health Monitoring (SHM) in support of the structural characterization and safety assessment [1,2]. In fact, sensing systems with embedded microprocessors and wireless communication represent a deep change on a way that structures are assessed, monitored and controlled [3], taking into account that these techniques allow the remote access in real time to the parameters monitored. In the last two decades, a considerable high number of cases of SHM employment on different civil structures typologies (i.e. bridges, towers and buildings) is described in the literature [4,5], overcoming several technical issues, while a few cases of SHM of Heritage Constructions (HC) have been reported [6].

In fact, historical structures constitute an interesting challenge for development of SHM due to variability and complexity of their structural components, which demand for advances in the monitoring strategies, as well in the data processing approaches. Additionally, for an assertive and reliable assessment of the HC, the data offered by SHM, that generally is focused in specifics components of the constructions, need to be discussed with information on the current state and global behavior of the structure under service operation. Moreover, it is important to highlight that all strategies employed for characterization and assessment should be conducted with respect to historic value of the construction and without inducing new damage emergence, as stated by [7]. Recent developments on the SHM field, related with HC, reported in the literature will be summarized and discussed following.

In [8], the Torre Aquila, a medieval tower with valuable artworks, was instrumented with accelerometers, relative displacements, via temperature and relative humidity sensors. The sensors were connected to the data acquisition system that sends the collected Basically, the SHM was focused on providing information on the vibration and displacements of the tower, as well of the environmental effects on the measurements. The work also demonstrates how the collected information can be used to predict anomalous situations of the behavior of the tower under service.

According to [9], the walls' inclination of a historic wooden church undergoing rehabilitation was monitored through a simplified wireless sensor network, and even with the low sensitivity of the sensorial modes, they were able to identify long-term trends in the tilt of the church walls. In [10], a sensorial system composed by 19 fiber optical displacement sensors and 5 temperature sensors was employed for monitoring of the damages on Santa Casa de Misericordia de Aveiro, and the collected data was used for updating a finite element model for to assess the damage state of the church.

Following, the long-term dynamic monitoring of the Basilica S.

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https://doi.org/10.1016/j.engstruct.2018.02.013
Received 5 April 2017; Received in revised form 1 February 2018; Accepted 1 February 2018

Maria di Collemaggio was reported by [11], where the authors describe the strategies of sensor network design and data processing, focused on seismic assessment. The SHM was focused on the management of the structural safety for situations where the structure can be subjected to natural disasters, such as earthquakes. The dynamic characterization of the church was carried-out, and the data was used in computational simulations. Furthermore, the data acquisition systems were composed by accelerometers connected wirelessly to a signal processing station. The results allowed the clear detection of the interaction between the masonry structures with an existing protective installation, and the modal information identified from different excitation sources (i.e. release tests, seismic events, etc.) was used for updating a finite element model on the church. Further reading on this case study can be found in [12] and [13].

Even that dynamic monitoring of HC constitutes a relevant topic for safety assessment [14,15], studies establishing a link between the environmental effect with structural behavior are also particularly interesting because they can provide useful information to understand cyclic displacements behavior in stony masonry elements and its damage mechanisms. According to [16], in heterogeneous materials, as stone masonries with low tensile strength capacity, the actuation of small tensions can easily make emerge cracks, mostly first appearing on the connection zones. Even thermal effects can produce sufficient tension to produce a crack, due to the different thermic behavior of the stone and the mortar. Moreover, in historic structures, several thermal cycles over the time can develop plastic deformation on the structural components, cracks and its progression.

The present work contributes for the SHM implementation through the strategy description, and monitoring of the Foz Côa Church (Portugal). Moreover, this work reports the monitoring period between March 13th 2015 to March 29th 2016 and discuss the relative displacements and tilt records in some structural elements of the church, as well analyses the environmental influence on the displacements collected by the wireless sensor network.

2. The Vila Nova de Foz Côa Church

The Foz Côa Church (Fig. 1) is a stone masonry building from XVI century, located at Vila Nova de Foz Côa, 390 km North from Lisbon, Portugal. The Church presents a *Manuelino* architectural style, with regular geometry, composed by three naves which are separated by columns and arches. It's dimensions are 37.00 m of length and 16.00 m of width, with a maximum height at the main façade of 13.30 m.

Fig. 2. Photograph of column 2, evidencing its inclination.

The main façade is characterized by an exposed granitic stone masonry (Fig. 1a) where the arch on the main door is decorated with *Manuelino* marks and there are three bells on the top. At the interior side of the church, two plans of columns and arch represent the division between the main nave with the left and right naves. Fig. 1c shows the interior view of the Church.

The church presents some damages, essentially cracks and deformation along the structural elements. The walls and columns on the right side are significantly deformed, especially the columns, as can be observed in the details in Fig. 2, whereas some vertical cracks on the main façade can be observed, as demonstrated in Fig. 3. Fundamentally, the main deformations and cracks are related with two seismic occurrences, namely the earthquakes of 1755 and 1969, being the first one related with the deformation of the structural elements inside of the church, specifically on columns and arches, while the last seismic occurrence has been pointed as the responsible by the emergence of cracks in the main façade (Fig. 3).

Over the years, several inspections and interventions were carried out in order to minimize the damage progression, such as the one

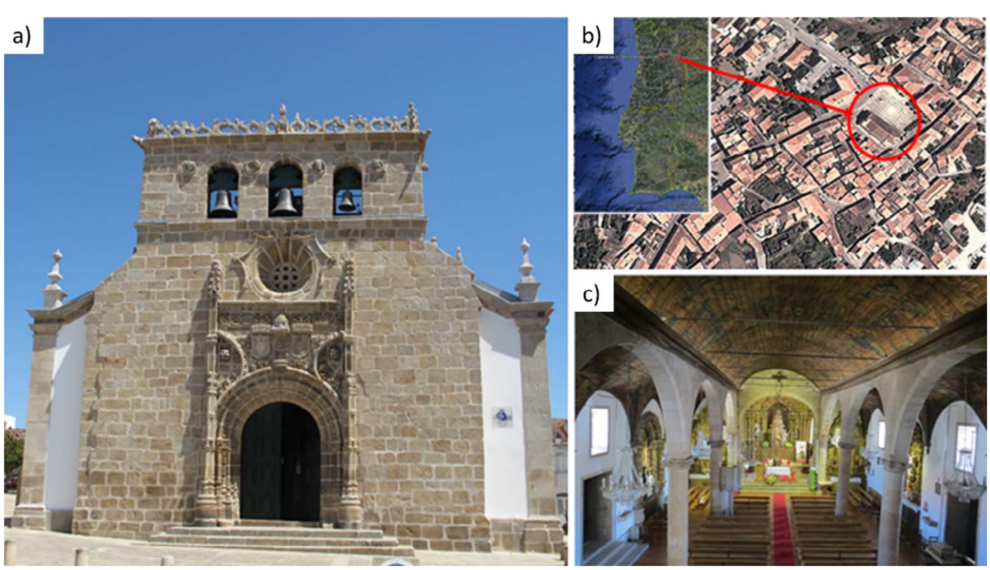

Fig. 1. Foz Côa Church: (a) main façade, (b) geographic location, and (c) interior view of the Foz Côa Church.