Construction and Building Materials 116 (2016) 169–187

Contents lists available at ScienceDirect

Construction and Building Materials

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

A multidisciplinary approach to assess the health state of heritage structures: The case study of the Church of Monastery of Jerónimos in Lisbon

Maria-Giovanna Masciotta [a,*], João C.A. Roque [b], Luís F. Ramos [a], Paulo B. Lourenço [a]

[a] ISISE, University of Minho, Department of Civil Engineering, Campus de Azurém, Guimarães, Portugal
[b] Polytechnic Institute of Bragança, Department of Applied Mechanics, Bragança, Portugal

HIGHLIGHTS

- A wide experimental/numerical campaign is carried out on a famous historic church.
- The structural behaviour is evaluated through a multidisciplinary approach.
- Different diagnosis and analysis tools are used for assessing the system health.
- Potential collapse mechanisms are identified.
- The environmental variability of static and dynamic behaviour is analysed.

ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form 22 April 2016
Accepted 28 April 2016

Keywords:
Historical masonry structures
Multidisciplinary approach
Structural health monitoring
Environmental effects
Safety assessment

ABSTRACT

The preservation and risk mitigation of built cultural heritage require the use of reliable tools which enable to give a better insight into the complex behaviour of these structures, by providing a correct diagnosis of their health conditions, and to identify potential vulnerabilities in order to prevent the risk of damage and to design in advance adequate retrofit solutions. The present paper describes an extensive experimental/numerical investigation campaign carried out on the Church of Monastery of Jerónimos in Lisbon in accordance with an iterative multidisciplinary approach and with the purpose of assessing the health state of one of the most prominent Portuguese monument, in light of future prevention actions. Special stress is given to the diagnostic procedure which includes and details in situ and laboratory testing, dynamic identification, continuous structural health monitoring and analysis of environmental effects on the static and dynamic behaviour of the church. The structural performance of the temple under conditions of gravity loading is analysed as well and potential collapse mechanisms are identified. The results are compared with the actual response of the temple allowing to evaluate its safety level.

1. Introduction

Architectural heritage is an irreplaceable expression of the intellectual richness and cultural diversity of modern societies. The protection and enhancement of heritage structures do imply acknowledgement and respect of different cultural roots and belief systems. In a changing world, built cultural landmarks provide identity to people, regions and towns and act as live documents of outstanding technical achievements from which study and utilization the mankind can still learn and improve. In addition to their historical interest, monuments do yield aesthetic, environmental and economic benefits, contributing to the global wealth and the touristic attractiveness of a country. For these reasons, the conservation and maintenance of architectural heritage is not only a cultural requirement [1].

In this context, the structural analysis and the safety assessment of historical constructions are issues of great importance, but they conceal several challenges and difficulties due to the geometrical complexity of ancient structures, the variability of

* Corresponding author at: ISISE, University of Minho, Department of Civil Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal.

E-mail addresses: mg.masciotta@gmail.com (M.-G. Masciotta), jroque@ipb.pt (J.C.A. Roque), lramos@civil.uminho.pt (L.F. Ramos), pbl@civil.uminho.pt (P.B. Lourenço).

http://dx.doi.org/10.1016/j.conbuildmat.2016.04.146
0950-0618/

materials and building techniques adopted, the poor knowledge on past events which might have affected the current condition of the constructions and the lack of design codes. Thus, the restoration projects related to architectural heritage are not straightforward and they require a multidisciplinary approach able to foster a fully comprehension of the structural behaviour before proceeding with specific conservation measures. In the last decades, recommendations have been proposed [3] to ensure systematic methods of analysis and adequate tools of intervention in order to guarantee safety and durability of heritage structures without compromising their historical value.

In the process of preserving ancient buildings, engineers should act according to a step-by-step methodology organised in stages similar to those used in medicine [2]: condition survey (anamnesis), identification of the causes triggering damage and decay (diagnosis), choice of the remedial measures (therapy) and control of the efficiency of the interventions (control). Within this methodology, the first two stages are crucial for the subsequent decision-making with regard to the need of specific treatment measures, whereas the last stage is fundamental in terms of monitoring and evaluation of the effectiveness of the intervention. Any heritage structure is the result of different building phases, constructional techniques and changes which have followed over time up to the present state. Therefore, condition survey, direct observation of structural and non-structural damage, historical investigation, non-destructive tests, health monitoring and structural analysis procedures are all indispensable tasks within this iterative process for safety evaluation of heritage structures. A more exhaustive discussion on these issues can be found, e.g. [4].

In this paper, an outstanding example of Portuguese architectural heritage, i.e. the Church of Monastery of Jerónimos in Lisbon, is selected as a case study in order to provide the reader with a full-scale application in which different diagnosis and analysis tools are combined together to achieve a thorough assessment of the structural performance of the monument in accordance with the aforementioned multidisciplinary approach. This case study may also serve as an example on how to address similar issues in analogous heritage structures. The information acquired at each stage represent a step forward within this gradual and continuous process of knowledge accumulation. Firstly, the paper details the investigations carried out for the experimental characterization of the church, including ultrasonic and radar inspections for the definition of the internal constitution of the structural elements, laboratory tests on sampled materials for the estimation of the mechanical features and output-only modal analysis techniques for the identification of the dynamic parameters of the structure. Then, two main aspects are treated: the safety assessment of the church under conditions of gravity loading and the characterization of the structural behaviour over time from both static and dynamic points of view. Special regard is given to the environmental variability of the system, as subtle changes caused by damage in masonry structures may be often masked by changes due to varying ambient conditions [5–6]. Indeed, in the last decades, the analysis of the environmental effects on the system's behaviour has been regularly introduced in the common practice of structural health monitoring [5–11].

Although the structural behaviour of this monument has been already explored [7,12], new and fundamental aspects are addressed in the present work. The final scope of the paper is to give completeness to the diagnostic investigation of the Church of Jerónimos, merging the findings hereafter presented with the ones obtained in previous studies, in order to attain a deep comprehension of the global behaviour of this outstanding historical landmark for future design of adequate remedial measures.

2. Description of the case study and historical background

Built in three successive phases during the XVI century, the Church of 'Santa Maria de Belém' is within one of the most notable examples of Late Gothic Manueline style of Portuguese architecture, namely the monastic complex of Jerónimos in Lisbon. The majestic monastery (Fig. 1a), four times smaller than the original planned construction, stretches over an area of $300 \times 50\ m^2$ and develops around two courts. The larger court is bordered by a two-storey arcade which hosts the Ethnographic Museum of Archaeology and the Maritime Museum, whereas the smaller court or Cloister (Fig. 1c) is bordered by the Sacristy, the Chapter Room, the Refectory and the Church (Fig. 1b), object of the present work.

Oriented towards the liturgical East, the plan of the temple is characterized by a cruciform shape with a single nave crossed by a transept with two lateral chapels and a chancel (Fig. 2). A single bell tower of 50 m height rises in the corner between south and west façades. The church was built with limestone ("calcário de lioz") quarried locally and has considerable dimensions, viz. a length of 70 m, a width of 23 m (40 m in the transept) and an average height of 24 m. Either limb is covered with a slightly curved barrel vault provided with stone ribs that branch according to a spider's web pattern (Fig. 2b and c). Exceptional examples of space unit of the latest Gothic, the barrel vaults spring directly from one external wall to the other. Two rows of octagonal columns with a free height of 16 m and a radius ranging from 1.04 m (nave columns) to 1.88 m (nave-transept columns) divide almost imperceptibly the longitudinal limb and the clear fusion of the naves. The columns are connected to the vault above by means of large fan capitals and do act as supports reducing the free span of the nave (Fig. 2c). On top of the vaults, brick masonry wallets built during the 1930 s provide support for the roofing tiles. The thickness of the walls varies from side to side ranging from 1.90 m of the south wall to 2.5–2.65 m of the east walls (chancel side), whereas the north wall has an average thickness of around 3.5 m due to the presence of an internal staircase which provides access to choir, cloister and bell tower. It is noticed that the south wall is pierced by large openings and its stability is ensured by three trapezoidal buttresses, which are indeed not aligned with the columns of the church. This proves that the south wall existed before the conception of the vault.

The seismic performance of the compound was successfully tested during the great earthquake of 1755. In that occasion, no severe damage was registered in the monastery. On the contrary, the subsequent shake of 1756 caused the collapse of one of the column supporting the vaults of the church (with subsequent ruin of the nave) and also the partial collapse of the vault of the higher choir [12]. In addition to these events, during the XIX century, changes were made in the structure of the two towers and in the roof. The effect of these changes in the seismic performance of the structure remained an open issue [12]. Hence, several studies and numerical simulations have been performed in the last decades to investigate the structural behaviour of this temple [12–14].

3. In situ investigations in the church

3.1. Non-destructive tests (NDTs)

In order to assess the safety of the Church of Monastery of Jerónimos, several preliminary in situ investigations have been carried out aimed at gaining a thorough insight into the internal constitution and integrity of the structural elements, determining their actual geometry and identifying possible local defects and vulnerabilities. In detail, the NDTs experimental campaign focused on the