TOWARDS A METHODOLOGY FOR SEISMIC ASSESSMENT OF MONUMENTS: THE CASE STUDY OF SANTA MARIA OF BELÉM CHURCH

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ABSTRACT

This paper presents an integrated methodology for the seismic behaviour characterization of ancient masonry structures of significant cultural heritage importance, towards the mitigation of the seismic risk. The proposed methodology is here applied to an outstanding case study composed by the Santa Maria of Belém Church, in Lisbon, Portugal. This Church was built during the 16th century and is included in the Monastery of Jerónimos compound, which is one of the most emblematic Portuguese monuments.

The methodology includes the following main steps: local seismic action characterization including site effects; simple numerical modelling for a preliminary knowledge of the structural behaviour; experimental mechanical characterization of materials and structural elements; establishment and installation of static and dynamic monitoring systems aiming at a better understanding of the static and dynamic behaviour; development of advanced numerical models including the necessary calibration against relevant experimental data; non-linear dynamic analysis of the structure for different earthquake levels. According to the non-linear dynamic analyses performed in the time domain, the results obtained so far show that the monument will be under great stress against a far-field earthquake as strong as M = 7.4 (475 yrp), able to cause damage but neither local or global collapse are to be expected.

1. INTRODUCTION

Ancient masonry structures are particularly vulnerable to dynamic actions, especially to seismic ones. Due to the ageing process, as well as to environmental factors, many cultural heritage buildings, as structures planned and constructed in the past, are vulnerable to earthquakes, which may unpredictably induce a collapse of a portion of the building or drive the whole structure to a rapid failure. However, anti-seismic design requires the definition of the local seismic action (a rather challenging issue) and knowledge about the characteristics of existing buildings.

The peculiarities of ancient masonry constructions require an approach similar to those used in medicine, including stages as [4]: (a) anamnese, (b) diagnosis; (c) recommendations for conservation or design reinforcement; (d) intervention; (e) evaluation of the effects of the intervention (e.g. monitoring of the structure). Based on these ideas, the proposed methodology prescribes a set of experimental and numerical procedures for the seismic behaviour characterization as a support for conservation recommendations or for possible strengthening measures towards the mitigation of the seismic risk. The methodology should be understood as a dynamic and interactive process. Due to the modern context of minimum repair and observational methods, NDT techniques including monitoring procedures are particularly attractive.

Considering that each historical building is unique, it is really important that each structure should be studied accordingly. In this sense, the proposed methodology is here applied to an outstanding case study composed by the Santa Maria of Belém Church, a part of the Monastery of Jerónimos compound, which is one of the most emblematic Portuguese monuments.

The paper is organized as follows. In section 2 the approach proposed for the seismic assessment of monuments is described. Afterwards, in section 3 the methodology is applied to the case study. Finally, in section 4 the first results and conclusions are discussed.

2. SEISMIC ASSESSMENT OF MONUMENTS

The seismic safety assessment of historical constructions is a quite complex task. In particular, little is known about materials and variability of its mechanical properties, existing damage, constitution of the inner core of walls, columns and vaults, among other relevant difficulties. Usually, this task cannot be carried out without combining historical data with an experimental and analytical investigation.

A proper methodology should be initiated with a preliminary investigation, interpretation of historical documentation, understanding of the historical context and appraisal of the general structural characteristics of the construction (anamnese). Then, a second step might deal with a preliminary diagnosis using simplified methods whose application is based on geometric data manipulation of structural masonry walls and columns to produce scalar indexes for in-plane or out-of-plan safety. A detailed description can be found in [8] and [11].

Afterwards, a more rigorous assessment of the current safety conditions is necessary. Nowadays, an advanced safety assessment of existing structures is, in general, based on numerical analyses. However, no reliable modelling is possible without proper insight into the relevant characteristics of the structure. For that purpose and given the complexity of these constructions, an integrated program of tests is proposed, involving the following tasks: (a) detailed visual inspection (aiming at locating critical zones with damage or other irregularities); (b) soil foundations survey (aiming at a geological and geotechnical characterization); (c) definition of a set of experimental, in-situ and laboratory works.

All these tasks are essential for the definition of further actions and for the implementation of monitoring programs. In what concerns to site inspection and evaluation techniques, today's technology makes available a vast range of equipments and techniques, mostly non-destructive or low invasive, which enable the gathering of data required to feed and validate numerical models, e.g. see [1] and [6]. Additional laboratory tests can also be carry out on material samples for mechanical, chemical and physical characterization.

Within the framework of this methodology, both dynamic identification and monitoring are fundamental NDT techniques to be used. In the case of historical constructions, these aspects are highlighted due to the importance of the structure. The dynamic identification provides the modal parameters of the structure and long term monitoring systems, with continuum data record and seasonal analysis, are important complementary tools for any experimental or numerical research as they allow satisfying the following purposes: (a) better understanding of the complex structural behaviour of the construction; (b) identification of any possible progressive phenomenon; (c) detection of damage at an earlier stage; (d) calibration of boundary constrains and global stiffness of numerical models under development; (e) assessment of environmental influences in the structural behaviour; (f) effectiveness assessment of possible strengthening/repair works.

Another important and challenging issue for advanced safety assessment of monuments is the local seismic action characterization. This characterization should be done in accordance with regional seismic hazard and local geotechnical conditions. Besides the attenuation conditions of the seismic signal from distant source sites, the local ground motion amplifications are of great importance, e.g. see [5] for further details.

The next step is deeply related with the numerical modelling and structural analysis of the construction. In many ancient constructions, the borderline between architectural details and structural elements is not always clear. The geometrical complexity of structures increases the difficulty in defining a finite element model appropriate for structural analysis. Therefore, any numerical model to be adopted should not be excessively complex, especially when non-linear dynamic analyses in time domain are to be used.

The validation/calibration process should ensure that a reliable simulation of the present condition of the structure is achieved. Therefore, this process involves an interactive development in which the behaviour of the structural elements is

checked step by step against experimental results. However, a preliminary elastic static analysis prior to any non-linear dynamic analysis is of great interest to identify the main structural vulnerabilities and to define strategies for subsequent analysis. In general, to avoid conclusions of doubtful reliability, a structural observation over a large period of time, with proper monitoring systems, seems to be necessary to validate preliminary analyses of results (qualitative, quantitative and experimental).

The structural intervention, if really necessary, should be done observing the cultural and historic significance of the construction, without inducing significant changes to the structure (minimal intervention) and with adequate materials and techniques. The post-intervention assessment of the effects produced is of crucial importance. At times, the difficulty of evaluating the real safety level and the possible benefits of interventions may suggest "an observational method", i.e., with iterative and step-by-step approaches, starting from a minimum level of intervention, with the possible subsequent adoption of a series of supplementary or corrective measures, see [4] for further details. After the intervention, a monitoring plan is also required, most of the times using the same monitoring systems installed previously.

3. APPLICATION TO A CASE STUDY

The Monastery of Jerónimos, dating from the 16th century, is, most probably, the crown asset of the Portuguese architectural heritage. One of the courts is composed by the Church and the cloister of the monastery. The Church has considerable dimensions, namely 70 m long and 23 m width, see Figure.

The main nave is divided by two rows of slender columns, with a free height of about 16.0 m. The transverse sections of the octagonal columns in the nave have a radius of 1.04 m with top fan capitals that reduce the effective free spans of the slightly curved vault, see Figure. For additional information see reference [3].
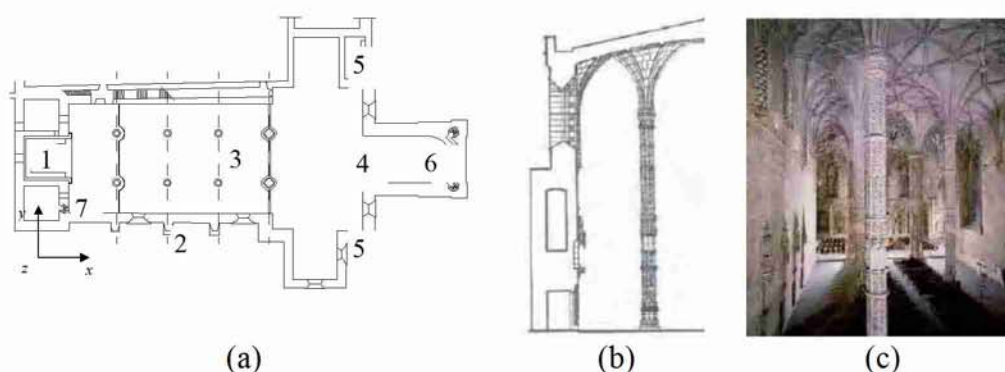

(a)   (b)   (c)

Figure1. Santa Maria of Belém Church: (a) plan (1-axial doorway, 2-lateral doorway, 3-nave, 4-transept, 5-side chapels, 6-chancel; 7-South bell-tower); (b) half of transversal cross-section; (c) view of the three naves.

The construction resisted quite well to the 1755 Lisbon earthquake. In the following year (December, 1756), a new earthquake caused the collapse of one column of the nave and a partial ruin of the high choir [9]. Later on, in 1887-1888 the bell-tower was modified and elevated. In 1947-1949 the Church covering was restored and brick masonry walls were built at the extrados of the vault nave to provide support for tiles. In 1963, minor consolidation works were performed including the vault bed joints refill. Since 1949, several historical documents have referred stone fragment falls from the vaults of the Church. These successive happenings illustrate clearly the need for a reliable seismic assessment of the monument. The analysis of previous existing works allows concluding that the geometrical survey of the main nave demonstrates a vertical non-alignment for all the columns and the external walls. Also, the radar investigation and ultrasonic tests carried out show that the columns of the nave seem to be made of a single block or two blocks [3] and a variable thickness mortar layer seems to exist on the extrados of the vault. On the other hand, a concrete-like material with stones and clay mortar fills the fan capitals [10]. Finally, an existing geotechnical report shows that the bed rock is located a few meters below the surface and that direct foundations were found in the monastery.

Using available geometric data, a set of simplified in-plane and out-of-plane indexes were computed. The results, summarized in Table , stress the high slenderness of the columns (γ_4) and the apparent vulnerability of the Church in the transversal direction ($\gamma_{3,y}$). For detailed information about these indexes the reader is referred to [8].

Table 1. Simplified indexes based on geometric data.

In-plan area ratio (γ_1)		Area to weight ratio (γ_2)		Base shear ratio (γ_3)		Slenderness ratio of columns (γ_4)	Thickness to height ratio of columns (γ_5)	Thickness to height ratio of perimeter walls (γ_6)
X	Y	X	Y	X	Y			
0.17	0.12	1.2	0.8	1.4	0.95	70	0.06	0.08

A campaign of experimental tests was performed aiming at: (a) mechanical characterization of the materials; (b) dynamic modal identification; (c) long term monitoring through the installation of both static and dynamic monitoring systems. As it was neither allowed to collect samples nor to use flat-jacks, the mechanical characterization of the masonry was performed in laboratory by carrying out uniaxial compressive tests on prismatic limestone prisms, as similar as possible to those observed in the monument. An average compressive strength of 10 MPa and a Young's modulus within the range of 20 - 50 GPa were found.

Both static and dynamic monitoring systems were installed in the main nave of the Church. The static monitoring system (see Figure a) is composed by six temperature sensors (TS1 to TS6), two uniaxial tiltmeters (C1 and C2) and one data logger (D) for the data acquisition and data record. The dynamic monitoring system

is composed by two triaxial accelerometers connected to two strong motion recorders. Both recorders are interconnected, which allows a common trigger and time programmed records. Figure b shows the sensors layout position.
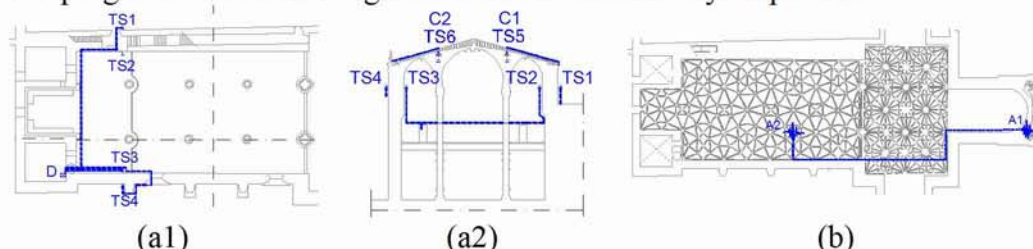

(a1) (a2) (b)

Figure 2. Monitoring systems: (a) static monitoring system, (a1) nave plan and (a2) nave cross-section; (b) dynamic monitoring system.

The main nave (vault and columns) of the Church was dynamically identified by resorting to two experimental techniques (EFDD and SSI). Thirty points on the extrados of the vault were selected to measure the acceleration response. Table summarizes the four estimated resonant frequencies, damping coefficients and Modal Assurance Criteria (MAC) for both techniques. The modal identification of the nave columns allow to identify typical first mode shape configurations with a 7.0 Hz resonant frequency.

Table 2. Measured resonant frequencies and damping coefficients for the vault.

Mode	Frequency [Hz]		Damping [%]		MAC
	EFDD	SSI	EFDD	SSI	
1	3.69	3.68	2.34	1.26	0.99
2	5.12	5.04	1.11	2.68	0.92
3	6.29	6.30	1.00	0.82	0.67
4	7.23	7.29	0.77	1.44	0.67

Supported by specific stochastic seismic hazard studies conducted for mainland Portugal, see reference [12], three hazard scenarios with return periods of 475 years (M=7.4), 975 years (M=7.8) and 5000 years (M=8.2) were used. In the absence of available seismic earthquake records, three acceleration time-histories were artificially generated for each seismic scenario using specific generation numerical models, as described in reference [2], resulting PGA values within the range of 0.09g-0.12g, 0.14g-0.17g and 0.21g-0.23g, respectively, for return periods of 475, 975 and 5000 years. Based on an existing geological-geotechnical report, it seems reliable to assume that Jerónimos Monastery is founded on the bed rock. Therefore, no site effects were considered within this study.

For the numerical analysis, a global model of the Church and adjacent structures was developed. Despite the high complexity of the structure, a simplified 3D model composed of beam elements was adopted. A total strain crack model with an ideal plastic material behaviour was adopted with $f_c = 10$ N/mm^2 (compressive strength) and $f_t = 0.01$ N/mm^2 (tensile strength). All the analyses were performed using DIANA 9.1 software [12]. The calibration of

the global model was performed in two phases. First, a preliminary comparison against an existing detailed numerical analysis of the vault under its self-weight was performed [7]. A second calibration was based on experimental existing results obtained from the dynamic identification and laboratory tests, presented above. In this way, the Young modulus was assumed to be equal to 30 GPa for the columns and 12 GPa for the other structural elements. The foundation boundaries were kept fixed. Figure illustrates the first and fourth computed mode shapes.
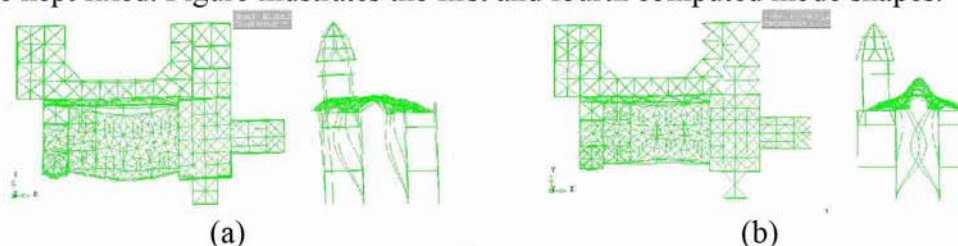

(a)   (b)

Figure3. Numerical mode shapes: (a) 1st mode at 3.8 Hz; (b) 4th mode at 5.34 Hz.

A preliminary linear static analysis under vertical and horizontal loads confirmed that the transversal direction (y) of the nave, see also Figure 1(a), controls the behaviour of the structure. Therefore, it was decided to perform non-linear static analyses for both vertical and transversal directions under an increasing gravity load factor until the development of collapse mechanisms. The results from this analysis show the need for a carefully numerical analysis against earthquakes.

Following the methodology presented above, non-linear dynamic analyses were performed for the transversal direction using the HHT time integration method with a time step of 0.01 s. A damping coefficient of 2% was adopted for the computation of the Rayleigh matrix. Up to the moment, only results from the first hazard scenario (475 yrp) are available. The numerical results obtained so far show that: (a) maxima drift is below 0.3%; (b) the average shear base ratio in the y direction is equal to 0.10; (c) important compressive stresses in the vault are observed; (d) the South belfry tower collapse is nearly to happen by overturning; (e) the remaining global stiffness of the structure is about 60% of the original one. According to these results, the Church will be under an important stress state against earthquakes as strong as M = 7.4 (475 yrp) that will cause cracking but neither local nor global collapse is expected. The remaining two and more severe seismic hazard scenarios are currently being analysed and, therefore, no results are available so far. These analyses are of major importance in order to assess the seismic safety of the monument.

4. CLOSING REMARKS

The methodology presented in this paper aims at the seismic risk mitigation of historical structures and it can be used towards the development of management policies for the cultural heritage. The main results, both experimental and numerical, achieved by the application of such methodology to an emblematic Portuguese case study have been presented and discussed.

For the numerical analysis, a 3D model considering both non-linear material and geometric behaviour was developed and calibrated against experimental results. The numerical results concerning the step-by-step seismic analysis for 475 yrp scenarios show that the monument is submitted to a significant stress state that causes cracking, but neither local nor global collapse is reached. However, the collapse of the South bell-tower by overturning is nearly to happen. Two more severe seismic scenarios are currently under analysis.

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