Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 3392–3397

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Ambient vibration testing and dynamic identification of a historical building. Basilica of the Fourteen Holy Helpers (Germany).

V. Compan[a], P. Pachón[b] and M. Cámara[c]*

[a]Dep. of Building Structures and Geotechnical Engineering, University of Seville, 41012, Spain.
[b]Dep. of Building Structures and Geotechnical Engineering, University of Seville, 41012, Spain.
[c]Dep. of Building Structures and Geotechnical Engineering, University of Seville, 41012, Spain.

Abstract

The preservation of the architectural heritage is a fundamental aspect in the cultural development of modern cities. This heritage has to be preserved and different technical analysis are usually necessary to ensure its proper preservation. Due to this fact, before performing these analyses, non-destructive techniques are usually an indispensable tool to provide information about the current structural behavior of the building. The use of ambient vibration tests is widespread as a technique to identify dynamic properties of historical constructions from a global point of view, but not to identify these dynamic properties of specific elements with a local character. In this paper, these techniques are used to characterize dynamically concrete parts of a historical building. These dynamic structural parameters identified by using the operational modal analysis method allows the adjustment of numerical models in order to obtain a more accurate estimation of the actual behavior of the structure. In this way, updated FE models can be used to assess the structural behavior of the historical building.In the present paper, the use of ambient vibration tests on the masonry roof of the Basilica of the Fourteen Holy Helpers is presented. This is a church located near the town of Bad Staffelstein near Bamberg, in Bavaria, southern Germany. The late Baroque-Rococo basilica, designed by Balthasar Neumann, was constructed between 1743 and 1772. It is dedicated to the Fourteen Holy Helpers, a group of saints venerated together in the Catholic Church, especially in Germany at the time of the Black Death.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Historic construction; Masonry structures; Ambient Vibration Tests; Operational Modal Analysis

* Corresponding author. Tel.: +34 652 795 037.
E-mail address: ppachon@us.es

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.572

1. Introduction

The historical construction, purpose of this study, is the Basilica of the Fourteen Holy Helpers [1]; a Baroque-Rococo church located in Bavaria, southern Germany (Figure 1). It was designed by Balthasar Neumann [2, 3], and constructed between 1743 and 1772. This chapel is a very singular construction, mainly due to the configuration of its vaults, with a complex spatial geometry, which includes warped intersections between them, and due to the high level of technology required from a construction point of view. In this sense, it is one of the few examples that can be found in Europe with this level of complexity [1].

Fig. 1. Basilica of the Fourteen Holy Helpers.

One of the main difficulties that need to be addressed in structural analysis of historical buildings is the level of uncertainty associated with many factors affecting the behaviour of the structure. Aspects like the mechanical properties of the structural materials, the building construction process, the connections between structural parts or the cracking condition of the building may cause important changes between the results obtained from a numerical analysis and those experimentally observed [4]. In this sense, non-destructive techniques appear as useful tools to provide information about the structural behaviour of the building [5, 6]. In particular, dynamic properties provided by ambient vibration techniques have proved to be quite well-suited to validate and update numerical models [7].

Operational Modal Analysis (OMA) has consolidated as one of the most adequate methods to estimate the modal parameters of a structure, due to the facts that: (i) it is a non-destructive and non-invasive technique and (ii) it can be performed under service conditions. For these reasons, OMA is currently recognised as a quite convenient technique to dynamically characterise historical buildings, since the use of the stronger external excitation (impact hammers or shakers) required to perform the traditional Experimental Modal Analysis (EMA) is not needed. The interested reader is referred to reference [8] for a more involved discussion on the practical and technical differences between OMA and EMA when applied for testing of masonry vaults. Subsequently, modal properties provided by the application of OMA allows the adjustment of numerical models in order to obtain an accurate estimation of the actual behaviour of the structure. In this sense, updated FE models can be used to carry out a structural analysis under existing conditions or further predict the effects of different structural situations that the structure could undergo. In the last decades, many cases of application of ambient vibration tests to update numerical models can be found in historical buildings [9, 10, 11, 12]. However, the applications of OMA to assess structural behaviour of specific complex parts of a building, such as domes or vaults, are much more limited [13, 14]. The main purpose of this study is to characterize dynamically the vaults of the chapel in order to gain further knowledge over such complex structure and, in later studies, update a finite element model with the objective of estimating and analysing its current safety level. A brief description of the chapel, the methodology followed to dynamically characterise the building and the results obtained will be presented in this document. The paper is organised as follows: Section 2 summarizes the main characteristics of the chapel. Section 3 presents the dynamic characterisation of the vaults of the chapel by using the Operational Modal Analysis method. It further describes the initial finite element model developed to estimate the modal parameters of the system. Finally, Section 4 draws the main conclusions of this study.

2. Basilica of the Fourteen Holy Helpers

2.1. Historical Aspects

It is often repeated that the Basilica of the Fourteen Holy Helpers has been the greatest creation of Balthasar Neumann, "one of the most ingenious pieces of architecture ever built". All the fundamental concepts of baroque ecclesiastical architecture are reflected in the basilica [3]. Situated on the banks of the Main, in front of the monastery of Banz (P.93), it presents an imposing and austere facade with two great bell towers (Figure 1), basing its design on the Benedictine monastery of Banz.

2.2. Architectural Configuration

The initial project of the Basilica consists of three large domes with oval base of longitudinal main axis, connected by others, also of oval plant, oriented along a transverse axis. To the transverse domes are added, in one case, two lateral chapels of oval plant and, in the other, two great spherical domes to form the cruise. The result of this design does not correspond to the final construction. The proposal proposed by Neumann was completely disrupted when the execution reached the level of the cornice, place of start of the domes. The final result modifies all the curvatures of all the domes, giving rise to a much lower recess, where the original Neumann space intentions are no longer appreciated. The death of Neumann in 1753 can justify the change in the original design, since the differences correspond to the elements that were executed from that moment. There are two main reasons why the chapel vaults are unique in their complexity. A first feature, from a geometrical point of view, is that five in-plan oval vaults with warped intersections among them make the ceiling. Each one of these intersections was geometrically determined by the intersection between two cylinders with orthogonal axis and different diameters. These cylindrical shape was essential in the construction process, because intersections were defined first as edges of the vaults boundaries, and then the surface of the vaults was built according to the intersections. A second feature is that the construction technique used was quite refined. Vaults surfaces are made of only one layer of brick masonry (30 cm thick), with neither ribs nor any sort of local reinforcement at warped intersections (Figure 2).

Fig. 2. Basilica of the Fourteen Holy Helpers. Chapel of the Würzburg Residence. Vaults extrados.

3. Ambient vibration tests and Operational Modal Analysis method

The dynamic characterization of the Basilica of the Fourteen Holy Helpers has been performed by means of ambient vibration tests. These tests were carried out between 25 and 29 of July 2016, with the aim of identifying the natural frequencies, mode shapes and damping ratios of the vaults.

3.1. Initial Finite Element Model

The application of the Operational Modal Analysis usually requires the creation of an initial model (Figure 3.a) in order to estimate the natural frequencies and mode shapes and thus determine adequate positions of the accelerometers. This initial FE model was built using Abaqus/CAE 6.13 Software [15]. The model consists mainly of two components, namely walls and vaults, modelled using solid elements. Material properties were initially estimated from bibliography [1, 16]. For brick masonry of the vaults, the adopted properties were: density, 1980 kg/m^3; Young's Modulus, 1100 MPa; Poisson's ratio, 0.2. Similarly, the following values were considered for the stone masonry: density, 2100 kg/m^3; Young's Modulus, 2200 MPa; Poisson's ratio, 0.2. Furthermore, the weight of the roof over the vaults was taken into account in the FE model. Based on the largest modal displacements obtained from this initial model, the appropriate positions for the reference accelerometers were selected.

3.2. Ambient Vibration Tests

Following the results obtained from the initial FE model, Figure 3.b shows a schematic representation of the sensors arrangement. The set-up consists of a total of 276 measuring points, which is a rather dense mesh. All of the measuring points were set in the three principal directions, in order to capture the global vibration modes in the longitudinal, lateral and vertical direction of the vaults. Since only three uniaxial and three triaxial accelerometers were available for the testing process and the three uniaxial (placed at points 86-250, Figure 3.b) were kept fixed for reference, a series of ninety-one set-ups were necessary to cover all measuring points. In each one of these set-ups, accelerations were recorded with a sampling rate of 100 Hz and a sampling time of 12 min.

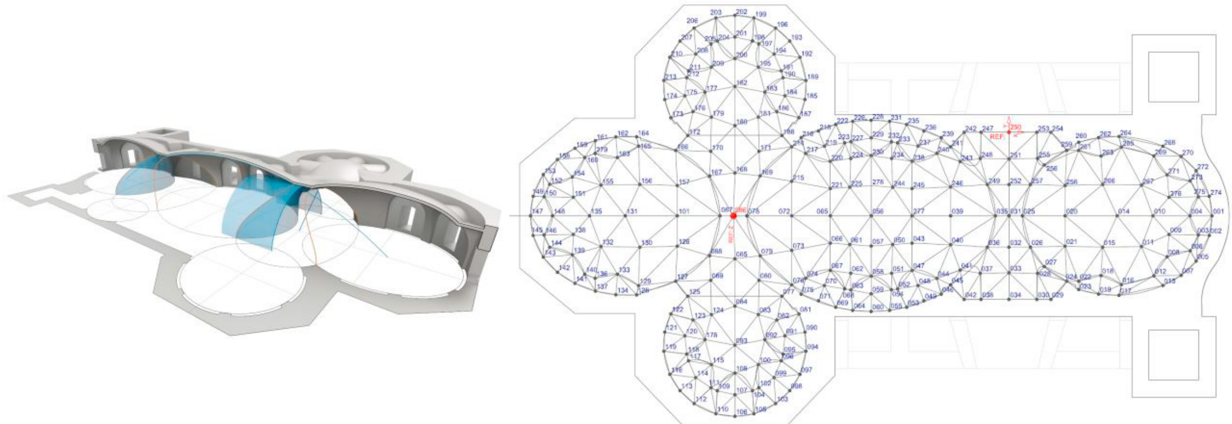

Fig. 3. a. Initial FE model. b. Accelerometer locations and directions Ref. accelerometers in red.

Excitations during ambient vibration tests were associated with environmental loads. The equipment used for these tests was composed by force balance accelerometers with a bandwidth ranging from 0.01 to 200 Hz, a dynamic range of 140 dB, a sensitivity of 10 V/g and 0.35 kg of weight (model ES-U2). These accelerometers were connected via eight 40m long cables to a twelve-channel data acquisition system with a 24-bit ADC, provided with anti-alias filters (model GRANITE). The equipment is manufactured by the company KINEMETRICS.

3.3. Operational Modal Analysis

The above recorded measured were processed by two operational modal analysis methods, one in frequency domain, Enhanced Frequency Decompostion (EFDD) and one in the time domain, Subspace Stochastic Identification (SSI). Both methods [17, 18] are implemented in the Artemis software.

The modal frequencies, damping ratios and mode shapes were determined by applying both methods –EFDD and SSI- and were later correlated using the Modal Assurance Criterion (MAC) [19] between both sets of results, in order to assess the accuracy of the obtained mode shapes:

Table 1. Reults OMA: natural frequencies (f), damping ratios (ξ) and standard deviation (Std).

	SSI				EFDD				MAC
	f (Hz)	Std. f	ξ (%)	Std. ξ	f (Hz)	Std. f	ξ (%)	Std. ξ	
Mode 1	1.47	0.01	1.25	0.40	1.49 (1,3%)	0.01	0.99 (26%)	0.28	0.82
Mode 2	1.56	0.05	1.84	0.68	1.57 (0,6%)	0.27	1.72 (7%)	1.24	0.81
Mode 3	2.22	0.06	2.16	0.66	2.19 (1,3%)	0.20	2.79 (29%)	0.91	0.88
Mode 4	2.35	0.03	1.65	0.48	2.36 (0,4%)	0.02	2.85 (72%)	0.28	0.80
Mode 5	2.79	0.04	2.24	0.95	2.79 (0,0%)	0.03	2.11 (7%)	0.66	0.95
Mode 6	3.39	0.10	2.84	0.55	3.28 (3,3%)	0.09	2.41 (18%)	1.42	0.89
Mode 7	3.81	0.12	3.15	2.35	3.69 (3,2%)	0.26	4.11 (30%)	2.46	0.87
Mode 8	4.60	0.08	4.44	1.95	4.52 (1,7%)	0.38	3.41 (30%)	1.76	0.76

The percentage within parenthesis indicates the relative difference between SSI and EFDD results (SSI results as reference).

As Table 1 shows, the ambient vibration tests allowed to accurately identify the first eight vibration modes in a frequency range up to 6 Hz. The frequencies were identified with relative differences lower than 3.5%, taking the results of the SSI method as reference. The results for the damping ratio show as higher variability (up to 72%), with average modal damping ratios of the building being 2.44% and 2.54% for SSI and EFDD techniques, respectively. This result is not surprising and higher excitation seems to be required in order to obtain reliable measures of damping, which is not needed for static structural analyses, as done later in this paper. With respect to mode shapes, MAC values were always higher than 0.75, which indicate a good correlation between both methods. The first two modes are caused by the towers, the third and the fourth ones show transversal and longitudinal translation modes respectively, while the other modes correspond to bending modes of the vaults (Figure 4).

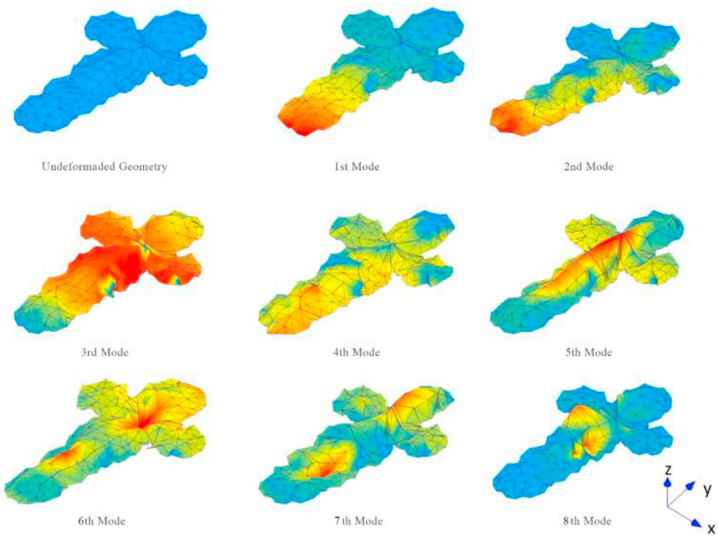

Fig. 4. Mode shapes associated with the experimental results (EFDD).

4. Conclusions

In the present paper, the use of ambient vibration tests on the masonry roof of the Basilica of the Fourteen Holy Helpers has been presented. This chapel presents singularities and a level of geometrical complexity that make it unique. The vaults are made of a thin brick masonry (only one 30cm thick layer) and have been generated by intersecting a series of oval in plant vaults. Their geometrical complexity is mainly due to the warped intersections among the main vaults and the secondary ones, generated as the result of intersecting two cylinders with different diameters. In this sense, the Operational Modal Analysis method appears as a suitable tool to experimentally determine the modal properties of this kind of structures from ambient vibration tests, in order to later calibrate the FE model. The first eight vibration modes of the Basilica of the Fourteen Holy Helpers have been estimated by the application of the operational modal analysis methodology to the measurements made during an ambient vibration test. These eight vibration modes with their associated natural frequencies and vibration modes have been successfully identified, with MAC values ranging between 0.76 and 0.95 for the EFDD and SSI results (see Table 1).

Acknowledgements

Special thanks to the Institute of Building Design and Construction of the University of Stuttgart and particularly to Professor Matthias Rottner. This work has been financially supported by Research Project P12-TEP-2068, funded by the Government of Andalusia, Spain.

References

[1] Compán V. Comportamiento estructural de las geometrías arquitectónicas del barroco centroeuropeo. PhD Thesis, University of Seville; 2010.
[2] Compán V., Cámara M. & González F. The Geometric Principles of Warped Rib Vaults in Central European Baroque Architecture from Guarini to the Dientzenhofer Family and Balthasar Neumann. Nexus Network Journal 2015; 17:183-206.
[3] Hansmann, W. Balthasar Neumann. Dumont 2003; 3-8321-7167-3.
[4] Atamturktur S. & Laman J. Finite Element Model Correlation and Calibration of Historic Masonry Monuments. Structural Design of Tall and Special Building 2012; 21(2): 96-113.
[5] Diaferio M., Foti D. & Giannoccaro N, Identification of the modal properties of a building of the Greek heritage. Key Engineering Materials 2015; 628: 150-159. doi:10.4028/www.scientific.net/KEM.628.150.
[6] Lacanna G., Ripepe M., Marchetti E., Coli M. & Garzonio C. Dynamic response of the Baptistery of San Giovanni in Florence, Italy,based on ambient vibration test. Journal of Cultural Heritage 2016.
[7] Friswell M. & Mottershead J. Finite Element Model Updating in Structural Dynamics. Kluwer Academic Publishers; 1995.
[8] Atamturktur S., Fanning P. & Boothby T. Traditional and Operational Modal Testing of Masonry Vaults. ICE. Engineering and Computational Mechanics 2010; 163: 213-223, ISSN: 1755-0777, E-ISSN: 1755-0785.
[9] Gentile C. & Saisi A. Ambient vibration testing of historic masonry towers for structural identification and damage assessment Construction and Building Materials 2007; 21: 1311-1321.
[10] Gentile C., Saisi A. & Cabboi A. Structural Identification of a Masonry Tower Based on Operational Modal Analysis Int. J. of Architectural Heritage 2015; 9: 98-110.
[11] Aras F., Krstevska L., Altay G. & Tashkov L. Experimental and numerical modal analyses of a historical masonry palace. Construction and Building Materials 2011; 25: 81-91.
[12] Ramos L.F., Aguilar R., Lourenço P.B. & Moreira S. Dynamic Structural Health Monitoring of Saint Torcato Church. Mechanical Systems and Signal Processing. 2013; 35: 1-15.
[13] Calık I., Bayraktar A., Turker T. & Karadeniz H. Structural Dynamic Identification of a Damaged and Restored Masonry Vault Using Ambient Vibrations. Measurement 2015; 55: 462-472.
[14] Atamturktur, S., Luke B., François H. & Sezer A. 2011. "Vibration Characteristics of Vaulted Masonry Monuments Undergoing Differential Support Settlement." Engineering Structures 33 (9). Elsevier Ltd: 2472–84. doi:10.1016/j.engstruct.2011.04.020.
[15] Users manuals. Dassault Systemes, SIMULIA, ABAQUS v.6.13-3; 2015.
[16] Augenti N., Parisi F. & Acconcia E. MADA: online experimental database for mechanical modelling of existing masonry assemblages. In Proc. 15th World Conference on Earthquake Engineering, Lisbon (Portugal); 24-28 September 2012.
[17] Brincker, R., Ventura, C. & Anderser, P. Damping estimation by frequency domain decomposition, in: 19th International Seminar on Modal Analysis, IMAC, Kissimmee, USA. 2001.
[18] Overschee, P. & De Moor B. Subspace identification for linear systems: theory, implementation, applications. London: Kluwer Academic Publishers. 1996.
[19] Allemang R. J. & Brown D. L. A Correlation Coefficient for Modal Vector Analysis. Proceedings, International Modal Analysis Conference 1983: 110-116.