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Operational modal analysis and FE model updating of the Metropolitan Cathedral of Santiago, Chile

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ABSTRACT

Heritage buildings in Latin American countries possess high architectural value. Studying these constructions under extreme loads, particularly earthquakes, requires representative models for simulating expected response. At present, the non-invasive Operational Modal Analysis (OMA) tests offer interesting possibilities for obtaining modal parameters to update and validate a structural model for this type of structure. In this context, this article focuses on the calibration and adjustment process for a finite element model of the Metropolitan Cathedral of Santiago Chile, based on experimentally identified modal and mechanical material properties. Accordingly, an in situ experimental campaign, aimed at obtaining the response of the structure due to ambient vibrations is presented and discussed. Six high-sensitivity synchronous triaxial accelerometers were employed in this campaign. Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI), system identification methods, were applied. Mechanical tests were performed on the Cathedral's stone blocks. The experimental data and derived modal properties were used to generate and update a finite element model. Several considerations were made in the model updating process: the most relevant was the homogeneous treatment of the stone masonry with their mortar interface, and the boundary elements restraining effect caused by adjacent structures. A preliminary model updating process was applied to define the boundary conditions and initial material properties. This optimization was based on minimizing an error function given by the difference between the experimental and analytical frequencies. A second step was then applied, in which models with different material properties were evaluated within a physically possible range. The final model selection was based on the distance between the experimental and analytical frequencies, and the mode shapes. The updated model allows an assessment to be made of the structure behavior in its current condition and models to be prepared for a wide range of possible future research scenarios.

1. Introduction

Studying the structural performance of heritage masonry constructions has become a priority in cities around the world where architectural heritage needs to be preserved. However, this assessment remains a complex task. A major difficulty is knowing the mechanical properties of component materials, the current structural damage, and the degree of interaction between various internal and external elements and systems. Because of these and other difficulties, some general recommendations for structural analysis of historic constructions have been proposed using a multidisciplinary approach [25].

Powerful computational tools are currently available for assessing the structural behavior of historic masonry construction. A summary of the different available strategies can be found in Roca et al. [44]. Analytical models of these structures can be from detailed models, like micro-modeling [30] or simplified models that consider the masonry as a continuous isotropic material [39]. In the latter modeling type, the yield surface for compression is given by the Hill criterion and the yield surface for traction by the Rankine criterion [17]. This approach is more manageable, because it has adequate computational effort, fewer parameters and a mathematically simpler representation [44].

A methodological approach to assessing a historic building should incorporate non-destructive or minimally destructive

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Nomenclature

a_i, b_i, c_i	Quadratic function constants for ith frequency
d	Distance between experimental and numerical model
E	Young's module
$E_{30\text{-}60\%}$	Young's module, experimentally determined in the monotonic compression test, in the range 30% to 60% of the maximum strength
E_{bm}	Young's modulus of brick masonry
E_{rm}	Young's modulus of reinforced brick masonry
E_{sm}	Young's modulus of stone masonry
fc	Compressive strength
fex_i	ith frequency obtained from experimental model
f_i	ith frequency obtained from numerical model
Im(*)	Imaginary part of the complex mode
J	Minimizing function in the model update process
Re(*)	Real part of the complex mode
w_i	ith weighting factor for each ith frequency
w_f	Weighting factor for frequency term
$w_{i,MAC}$	ith weighting factor based on the MAC between experimental modal shape and numerical one
w_φ	Weighting factor for modal shape term
x_j	jth calibration parameter for the model updating process
ε_i	Error between experimental and numerical frequency
ϕex_C	Experimental complex mode
ϕex_R	Equivalent real mode to the experimental complex mode
ϕex_i	ith experimental modal shape
ϕi	ith numerical modal shape
$(\ )^T$	Transposed matrix
$(\ )^{-1}$	Inverse matrix
CTE10	Quadratic tetrahedral element of 10 nodes
DD	Damage in dome
DLW	Damage in central longitudinal wall
DTA	Damage in transverse arch
EFDD	Enhanced Frequency Domain Decomposition
FDD	Frequency Domain Decomposition
FMAC	Frequency scaled MAC
GPS	Global Positioning System
MAC	Modal Assurance Criterion
OMA	Operational Modal Analysis
SA	Setup located on base of arches
SSI	Stochastic Subspace Identification
ST	Setup located on top of walls
SW	Setup located on base of windows
UTC	Coordinated Universal Time

experimental techniques. One example is the well-known vibration analysis technique, used to estimate the structure's natural frequencies and modal shapes. The modal parameters thus obtained can then be used to calibrate numerical models by adjusting their mechanical properties [5]. Among the non-invasive methods the Operational Modal Analysis (OMA) is the most commonly used [4,15,42]. By measuring the response to ambient vibrations and assuming that the input is white noise, the modal properties can be defined based on the system identification process. There are some complications involved in using OMA methodology, including: signal noise from the very long cables [18], the difficulty of detecting modal shapes for very close modes, definition of adequate system order (in case of parametric identification method), and detection of spurious modes generated by signal noise [33].

Several studies have used OMA methodology with the aim of studying the components of historical constructions, mainly towers, vaults, domes and arches [9,21]. By contrast, defining the modal properties in a historic structure's more rigid zones, like perimeter walls and resistant transverse and longitudinal axes, is a less studied subject. One of the main difficulties relates to the complexity of identifying high-frequency close modes, which are common in structures with uniform stiffness and mass distribution. Additionally, the low- response level to ambient excitation and the typical device resolution and precision make their identification a confusing and difficult process [12,13].

One additional difficulty in identifying structural systems in this type of structures is that their structural elements do not have purely flexural or torsional modes, but a mixture of the two, unlike what occurs in conventional structures [10]. Therefore, the measuring devices need to be distributed in the structure, to capture all these special movements. Another common difficulty relates to the highly nonlinear response, which is due to the friction interaction between units at low deformation levels; this introduces anomalies, which can be confused with structure modes, i.e. they generate spurious vibration modes that can cause interpretation problems in the identification process [12].

In similar previously developed cases, preliminary analytical models were developed, from which an optimal location for the response measuring devices was defined [32] based on the modes to be identified. Although this analysis is a good initial guide for defining the location of measuring points, the final location will depend on the structure's accessibility and operational conditions for measuring its response to environmental vibration.

Within the identification process, there is a list of previous research in which a frequency domain method (FDD) is contrasted with a time domain method (SSI), as making a comparison is important for highly uncertain problems, in order to generate consistent results [18,31,43]. However, there is other research into heritage structure, in which the FDD method alone is enough to identify the structure's mechanical properties [3,20,29]. One of the final aims of some similar studies [1,21,42] is to determine the structures' modal properties using the OMA methodology and subsequently update the model with multivariable optimization techniques [14]. These techniques minimize error function, where the calibration parameters (model variables that can vary within a range) comply with user-given constraints. This error function is given by the difference of the natural frequencies and the structure's modal shapes, between the experimental and analytical model [8].

Chile is widely recognized as one of the most seismic countries in the world. This is due to its location in the subduction zone between the Nazca plate and the South American plate. There are additional seismic considerations for Santiago, the capital city, since there exist two more seismic sources: an intraplate seismogenic source for medium depth earthquakes, and a crustal seismogenic source for superficial earthquakes [28]. An iconic architectural heritage structure of Santiago Chile, is the Metropolitan Cathedral. This historical structure more than 250 years old was chosen as a case study for this research.

The Metropolitan Cathedral of Santiago, Chile, has been affected by environmental factors throughout its history, but mainly by earthquakes occurring on the site [24]. A preliminary research project took place to identify and update the models for the Cathedral [48]. In this research, a mathematical optimization technique was used by minimizing an error function [14] in the model updating process, using only the modal frequency.