# Application of Operational Modal Analysis Method in the Monastery of San Jerónimo (Seville, Spain)

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The use of Operational Modal Analysis is establishing as an acceptable tool for the update of numerical models. Through its application, mechanical properties of structural elements, as stiffness or mass, can be obtained with great accuracy. The analysis of the current structural state of the Monastery of San Jerónimo, an important piece of heritage located in Seville (Spain), is presented in this paper. The monastery dates from the XV century. The cloister has been analysed by OMA in order to update a FE model, to subsequently carry out the structural assessment of the Monastery.

*Keywords:* *Operational Modal Analysis, Cultural heritage, Monastery of San Jeronimo.*

## NOTATION

*OMA* Operational Modal Analysis;
*FE* Finite Elements;

## 1 INTRODUCTION

The Monastery of San Jerónimo is a piece of heritage that is located in Seville (Spain). The construction of the monastery was initiated in 1414. In 1964, the monastery was declared heritage. Since then it has been subjected to some restorations. Recently, an intervention has been carried out in order to convert the monastery into a civic centre. The intervention consisted of the construction of a new building attached to two wings of the cloister. The structural assessment of the current state of the monastery is being done by means of updating of FE models using OMA. For this reason, some Finite Element models and some dynamic in-situ tests have been done. As a result, a numerical model with similar dynamic behaviour than the observed in-situ has been achieved. This model has been used to evaluate the structural behaviour of the complex. A historical analysis of the monastery, the followed methodology and the obtained results are the goal of this paper.

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## 2 HISTORICAL ASPECTS

The Monastery of San Jerónimo began to be constructed in the XV century. By the time, Seville experienced a huge economic and military activity. In the beginning, the Monastery was composed of five main buildings: the church, the main cloister, the east cloister, the tower and the printing press (Figure 1).

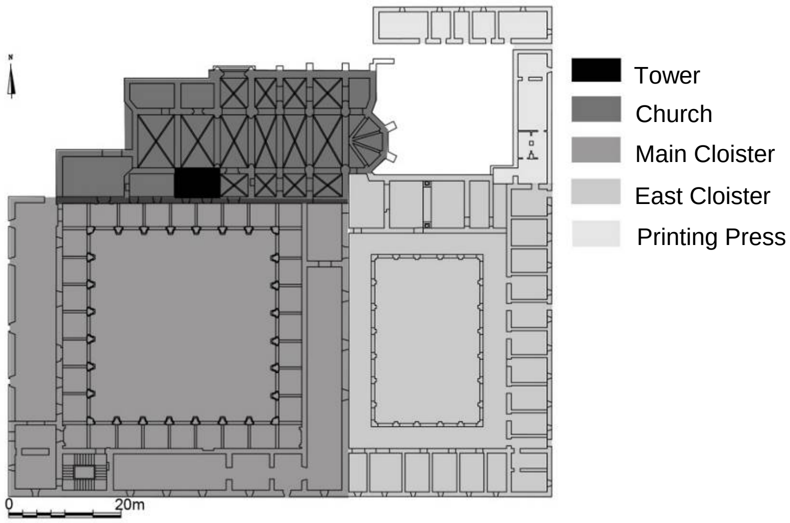


**Figure 1.** Initial configuration of the Monastery of San Jerónimo (Seville).

The construction of the church was finished in the first third of the XVI century. It was a Gothic style church, constituted by a nave, two wings of chapels, an apse and a sacristy. At the same time, the construcction of the east cloister was initiated [1].

Also in the first third of the sixteenth century, next to the east cloister, the construction of the main cloister was initiated. The works were completed in the first half of the seventeenth century. It is a Renaissance-style building. The patio is composed by calcarenite pillars and semicircular arches. The galleries are bounded by brick walls and covered by ribbed stone vaults. In the upper floor gallery, there are segmental arches (Figure 2).

**Figure 2.** Views of the main cloister.

The tower and the printing press were the last buildings which were built. Their constructions were started in the late sixteenth century. The printing press is an independent construction composed of two long buildings connected with the east cloister and the church.

In the mid-seventeenth century, the complex had been finished. Until the early nineteenth century, it was used as a monastery. During the seventeenth century, it had become inhabited by over 150 monks. In 1809, the regular clergy was extinguished, what initiated the decay of the monastery [2]. In 1823, the building was again used by monks, but finally, in 1835, the monks left the monastery due to the destruction of the church. The buildings began to be used as a glass factory in 1850. This fact caused several changes in the architectural configuration of the tower and the church. The process of degradation of the architectural complex got its highest point when it was used as a fattening farm. This lasted until well into the twentieth century.

In 1964, the building complex was declared heritage [3]. After this fact, some consolidation works were carried out in 1966. In spite of that, the remains of the monastery were again damaged caused by the earthquake of 1969.

In 1984, the monastery became property of the City of Seville, and since then, several operations of restoration and functional recovery have been performed.

Nowadays, the church and the east cloister are virtually disappeared. Only two chapels and the wall annexed to the the main cloister are preserved [1]. Moreover, the ground floor of the Renaissance cloister is preserved, while on the upper level, only the vertical structure and some covers of the north gallery are conserved (Figure 3). The tower also remains standing, but with internal new elements (Figure 4).

**Figure 3.** View of the upper gallery.

**Figure 4.** View of the tower

The rehabilitation project of the Monastery of San Jerónimo to adapt it to civic center is currently being performed. The project basically consists of the reconstruction of the south and east wings, and the use of such as a civic center for the neighborhood in which the monastery has been included.

The main premise of the project is to respect the existing historic remains of the monastery in such a way that the contemporary part were recogniseable from the historical construccion. An architectural neutral language is used in the new buildings [2]. From a structural point of view, a mixed system of load-bearing walls and pillars that support large beams is used to build the new building. (Figure 5).

**Figure 5.** View of the new construction. Upper floor.

## 3 OPERATIONAL MODAL ANALYSIS

The analysis of the current structural state of the Monastery of San Jerónimo is being done by ambient vibration tests. The Operational Modal Analysis procedure was followed. The process consisted on obtaining the modal parameters of the main cloister, to later update the parameters (density, young's modulus and poisson coefficient) which define the numerical model. In this way, the difficulties in determining the mechanical properties and the stiffness of the elements of the structural assembly are minimised.

The equipment for the experimental campaign is composed by a 12-channel adquisition system (GRANITE) and 8 uniaxial force balance accelerometers (EPISENSOR). The equipment is manufactured by the company KINEMETRICS (Figure 6). Six campaings of Operational Modal

Analisys were carried out, four in the cloister (wings 1, 2, 3 and 4, figure 7) and two in the new building (wings 3B and 4B, figure 7). Furthermore, a general campaing of OMA was conducted in order to compare and validate the experimental results of the other singular campaings.

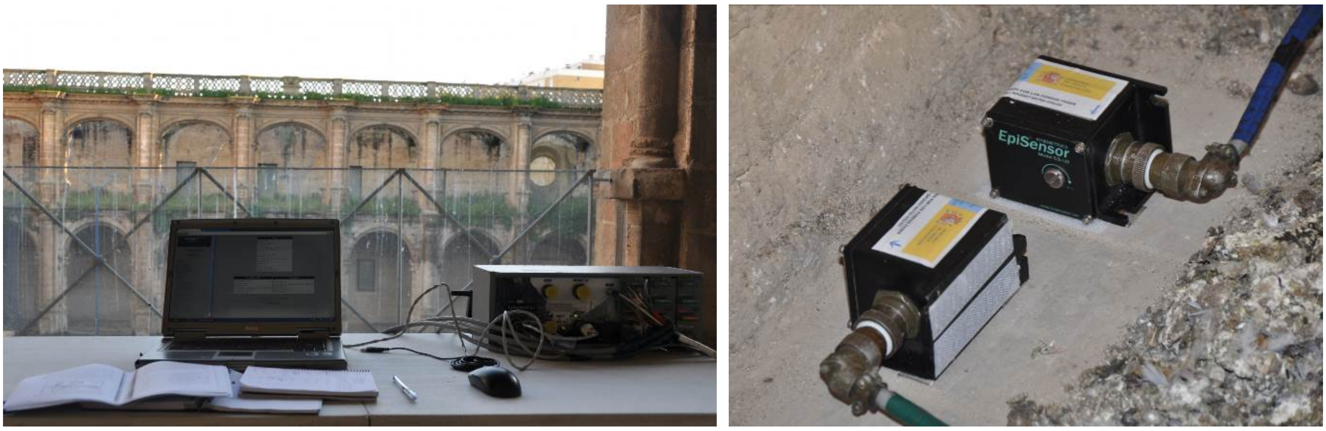


**Figure 6.** Measurement equipment.

The application of the Operational Modal Analysis requires the generation of a model to check the position of the accelerometers [4, 5]. This model was called preliminary model and was carried out using the Finite Element Method Programme Abaqus. This model is mainly composed by two parts: historical and new building. The new part was modeled with surfaces, so first order reduced integration elements (3-node elements) were used. On the other hand, first order reduced integration tethaedral elements (4-node elements) were used for the historical part. The material properties of density, Young's Modulus and Poisson Coefficient were obtained from bibliography [6, 7, 8] (table 1). The main conclusion obtained from this model was the position of the reference accelerometers for each campaing of OMA (Figure 7).

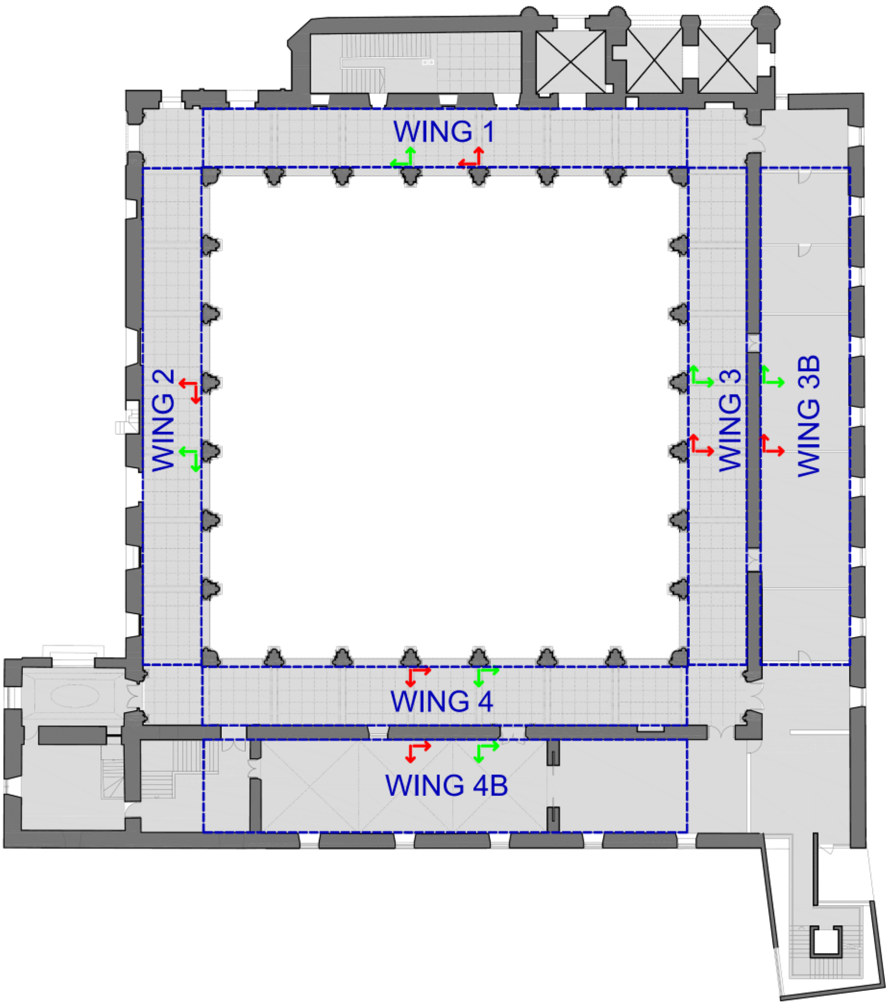

**Figure 7.** Position of the reference accelerometers in plan. (Green: +6.8 m. (1st floor). Red: +12.2 m. (2nd floor))

**Table 1.** Mechanical properties of materials in the preliminary Finite Element Model

| | Preliminary FE Model | | | | |
|---|---|---|---|---|---|
| | **Masonry** | **Filling Vaults** | **Filling Walls** | **R. Concrete** | **Steel** |
| **Density (Kg/m$^3$)** | 1800 | 500 | 1500 | 2500 | 7850 |
| **Young's modulus (MPa)** | 1000 | 500 | 500 | 21000 | 210000 |
| **Poisson Coefficient** | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 |

The parameters set for the dynamic tests were 100 Hz of frequency sampling and 15 minutes of time duration for each set-up. These assumptions assure that frequencies from 1 to 50 Hz would be measured. Eight accelerometers were used in each campaing, placing four of them as references (Figure 7). The other four ones were moved along the columns and the walls in two differents levels (6,8 m. and 12,2 m). In total, the resulting number of set-ups was fifteen in each ccamping . The dates obtained in-situ were processed with the software ARTEMIS using two different identification methods, one of them in the frequency domain (EFDD) and the other in the time domain (SSI). In this way, the mode shapes and the modal frequencies were obtained and later validated using the Modal Assurance Criterion (MAC) (Figure 8).

| WING | Nº MODE | SSI (F) | EFDD (F) | MAC | MODE SHAPE |
|---|---|---|---|---|---|
| 1 | 1 | 2,01 | 2,01 | 0,99 | Bending Mode |
| | 2 | 3 | 3,04 | 0,97 | Traslation Mode |
| | 3 | 3,72 | 3,73 | 0,99 | Bending Mode |
| | 4 | 4,94 | 4,89 | 0,97 | Tralation Mode |
| | 5 | 10,15 | 10,08 | 0,96 | Vert. Bending Mode |
| 2 | 1 | 2,32 | 2,33 | 0,99 | Bending Mode |
| | 2 | 3,34 | 3,35 | 0,88 | Bending Mode |
| | 3 | 3,51 | 3,57 | 0,78 | Traslation Mode |
| | 4 | 4,28 | 4,29 | 0,9 | Bending Mode |
| | 5 | 4,75 | 4,71 | 0,89 | Bending-Tral. Mode |
| 3 | "0" | 2,04 | 2,03 | 0,7 | Traslation Mode |
| | 1 | 3,13 | 3,13 | 0,99 | Bending Mode |
| | 3 | 4,13 | 4,26 | 0,95 | Bending Mode |
| | 4 | 6,25 | 6,35 | 0,8 | Local Bending Mode |
| | 5 | 7,22 | 7,17 | 0,92 | Vert. Bending Mode |
| 3B | 1 | 3,07 | 3,08 | 0,99 | Bending Mode |
| | 2 | 4,34 | 4,34 | 0,98 | Bending Mode |
| | 3 | 7,08 | 7,12 | 0,85 | Vert. Bending Mode |
| 4 | 1 | 3,06 | 3,3 | 0,91 | Bending Mode |
| | 2 | 3,67 | 3,68 | 0,99 | Bending Mode |
| | 3 | 4,4 | 4,33 | 0,96 | Local Bending Mode |
| | 4 | 4,74 | 4,88 | 0,86 | Local Bending Mode |
| | 5 | 6,31 | 6,34 | 0,9 | Local Bending Mode |
| 4B | 1 | 3 | 3,06 | 0,98 | Bending Mode |
| | 2 | 3,6 | 3,55 | 0,88 | Bending Mode |
| | 3 | 4,28 | 4,68 | 0,99 | Bending Mode |

**Figure 8.** Experimental results.

Once analysed the preliminary Finite Element model with modal analysis and compared the obtained results in terms of dynamic parameters (natural frequencies and mode shapes) with the values measured in situ (table 3), the mechanical properties of the materials were set as the values in Table 2.

**Table 2.** Mechanical properties of materials in the updated Finite Element Model

| | **Updated FE Model** | | | | |
|---|---|---|---|---|---|
| | **Masonry** | **Filling Vaults** | **Filling Walls** | **R. Concrete** | **Steel** |
| **Density (Kg/m$^3$)** | 1900 | 500 | 1500 | 2500 | 7850 |
| **Young's modulus (MPa)** | 900 | 500 | 500 | 23000 | 210000 |
| **Poisson Coefficient** | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 |

Once the numerical model had been updated in the way described before, and after the comparison between the experimental and the numerical model (figure 9), a Finite Element model with a similar dynamic behaviour than the observed in-situ was addressed (Figures 10 and 11). The new results results confirmed the efficacy of the calculation.

| | | BEFORE UPDATING PROCESS | | | AFTER UPDATING PROCESS | | |
|---|---|---|---|---|---|---|---|
| WING | MODE | Pre. F.E.M. | EXP. M.* | % DIF. | Up. F.E.M. | EXP. M.* | % DIF. |
| **1** | 1 | 1,83 | 2,01 | 8,96 | 1,93 | 2,01 | **3,98** |
| | 2 | 3,5 | 3 | 16,67 | 3,13 | 3 | **4,33** |
| | 3 | 3,64 | 3,72 | 2,15 | 3,69 | 3,72 | **0,81** |
| | 4 | 5,33 | 4,94 | 7,89 | 4,74 | 4,94 | **4,05** |
| **2** | 1 | 2,38 | 2,32 | 2,59 | 2,27 | 2,32 | **2,16** |
| | 2 | 3,48 | 3,34 | 4,19 | 3,33 | 3,34 | **0,30** |
| | 3 | 3,78 | 3,51 | 7,69 | 3,69 | 3,51 | **5,13** |
| | 4 | 4,89 | 4,28 | 14,25 | 4,6 | 4,28 | **7,48** |
| | 5 | 5,57 | 4,75 | 17,26 | 4,74 | 4,75 | **0,21** |
| **3** | "0" | 1,83 | 2,04 | 10,29 | 1,93 | 2,04 | **5,39** |
| | 1 | 3,5 | 3,13 | 11,82 | 3,13 | 3,13 | **0,00** |
| | 2 | 4,89 | 4,36 | 12,16 | 4,6 | 4,36 | **5,50** |
| | 3 | 7,7 | 6,25 | 23,20 | 6,39 | 6,25 | **2,24** |
| | 4 | 8,88 | 7,22 | 22,99 | 6,81 | 7,22 | **5,68** |
| **3B** | 1 | 3,5 | 3,07 | 14,01 | 3,13 | 3,07 | **1,95** |
| | 2 | 7,89 | 4,34 | 81,80 | 4,6 | 4,34 | **5,99** |
| | 3 | 8,88 | 7,08 | 25,42 | 6,81 | 7,08 | **3,81** |
| **4** | 1 | 3,5 | 3,06 | 14,38 | 3,13 | 3,06 | **2,29** |
| | 2 | 3,64 | 3,67 | 0,82 | 3,69 | 3,67 | **0,54** |
| | 3 | 5,57 | 4,4 | 26,59 | 4,74 | 4,4 | **7,73** |
| | 4 | 5,8 | 4,74 | 22,36 | 5,1 | 4,74 | **7,59** |
| | 5 | 7,7 | 6,31 | 22,03 | 6,39 | 6,31 | **1,27** |
| **4B** | 1 | 3,5 | 3 | 16,67 | 3,13 | 3 | **4,33** |
| | 2 | 3,78 | 3,6 | 5,00 | 3,69 | 3,6 | **2,50** |
| | 3 | 5,57 | 4,68 | 19,02 | 4,74 | 4,68 | **1,28** |

* Experimental data obtained from SSI.

**Figure 9.** Comparison of frequencies (Hz) obtained for the modes analytically and experimentally.

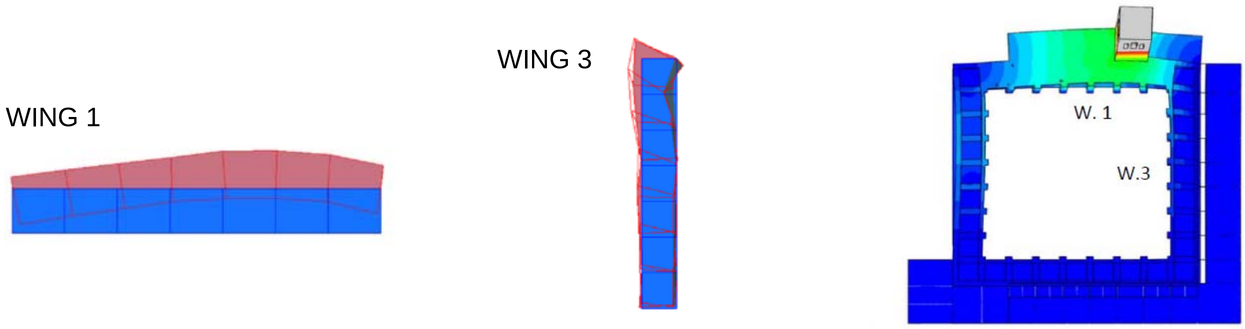


**Figure 10.** Mode shape number 1 (wings nº 1 and nº 3) obtained by ARTEMIS using the EFDD method (left and centre) and by numerical model (right).

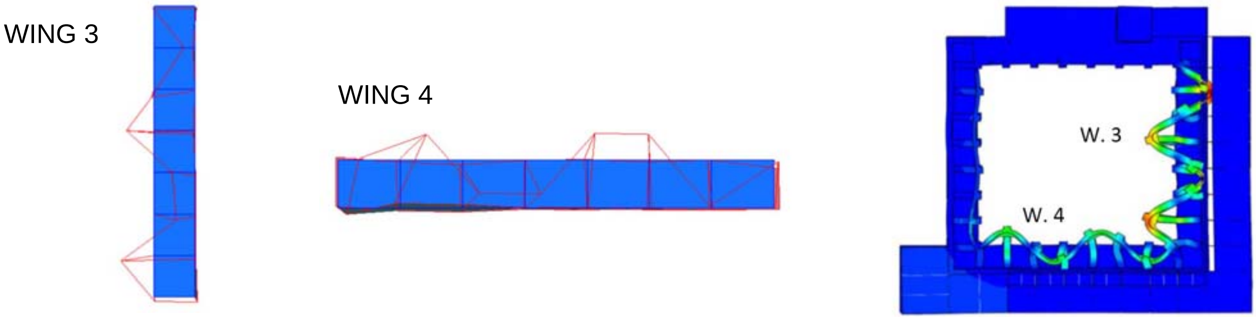


**Figure 11.** Mode shape number 3 (wing nº 3) and number 5 (wing nº 4) obtained by ARTEMIS using the EFDD method (left and centre) and by numerical model (right).

## 4 CONCLUSIONS

The Operational Modal Analysis has been applied in order to assess the current structural state of the Monastery of San Jerónimo (Seville). For this purpose, a 3D numerical model has been made. The mechanical properties has been set from bibliography and adjusted by comparing the dynamic behaviour of the numerical model and the data collected in-situ.

As a result, a numerical model with similar dynamic behaviour than the observed in-situ has been achieved. For all collected data the percentages of difference between natural frecuencies associated to vibration modes were all lower than 0,10 % (figure 9). After the updating process showed in this paper, the model is ready to be used in later phases of the works in order to evaluate the structural behaviour of the Monastery.

## ACKNOWLEDGEMENTS

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