A MASONRY BELL-TOWER ASSESSMENT
BY MODAL TESTING

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Abstract

The bell-tower of Santa Justa y Rufina is located in the historical city of Orihuela (Alicante-Spain). Its construction dates from the XV century, having suffered several remodellings later. The monumental group was declared National Monument by the Spanish government in 1971. For the study of the structural behaviour of the tower it becomes necessary to know its dynamic response due to two important aspects: a) the construction is located in a high seismic risk area, and b) the tower is endowed with six bells that rotate on their axis according to the Spanish characteristic system at a speed between 20 cycles/min and 40 cycles/min. With the purpose of studying its dynamic response a monitoring program has been carried out using accelerometers with the aim of determining the bending and torsional natural frequencies of the tower as well as approaching the value of the structural damping ratio of the construction. Once the experimental results were analyzed, a numerical model of the tower was carried out. This model has been calibrated using the experimental results to assess the seismic vulnerability of the structure to earthquakes that currently the Spanish Standard states for this area, as well as to evaluate the effect of the swinging of the bells after the future restoration planned.

1 Introduction

This paper presents an initial work made on the belltower of Santa Justa y Rufina church in Orihuela (Alicante-Spain). This structure is a gothic belfry made in XV century that possesses five bells. Some restoration works are planed on these bells and it’s necessary to know de dynamic characteristics of the tower to discard future problems originated by a possible dynamic interaction between the natural frequencies of the tower and the horizontal forces introduced by the bells on the tower.

1.1 Geometric description.

The belltower has three main bodies typical from the gothic belltowers built in XV century: base, bell room and crown –Fig. 1 and 2-. The main body possesses a square section with 8.8 m long; inside there is a stairway that gives access to the body of bells. All the structure is made in masonry, arranging brick masonry with ashlers, maintaining a constant thickness of 1.5 m along the whole first body of the tower. The total height is 25.5 m. The bell room reaches the height of 35.5 m with 1.0 m wall thickness. Seven windows are inside this body (in each wall) to accommodate the bells with 5.5 m² approximately each window.
The tower has a rigid joint with the lateral walls of the main body of the church. This joint can be observed in the west, south and east sides of the tower. The joint in the west wall of the nave reaches the height of 18 m, although the joint of the east wall reaches 9 m high. (Figure 3)

Figure 1 West façade

Figure 2 East façade

Figure 3. General diagram of the tower. (a) Architectural plan. (b) Simplified model. (c) Model to simulate with FEM.
2 Dynamic test

Several dynamic tests have been performed on the belltower to know the mechanical parameters, vibration modes (bending and torsion) and structural damping. All of them are based on the registration of ambient vibrations at different heights and directions. Only bending and torsional vibrations are registered due to the high longitudinal stiffness.

The works of Bachmann (1997) and Casolo (1998) fix the main torsional and bending frequencies between 0.9 and 2 Hz for slender towers, similar results are obtained by Gentille (2007). The work made by Ivorra (2006) in a similar belltower allows evaluating frequencies and the experimental procedure.

From equation (1) proposed in NCSE-02 (2002), belltower frequencies can be estimated:

\[
\omega_1 = \sqrt{\frac{L}{0.06H}}; \quad \omega_2 = 3\omega_1; \quad \omega_3 = 5\omega_1
\]

where: \(L\) is the plan dimension along the vibration direction and \(H\) is the height.

So, it is expected to register a first frequency round 1.7 Hz or higher, since the stiffness is higher due to the contact with the church.

In order to make the dynamic experimental measurements, four piezoelectric seismic accelerometers have been placed at the height of the bell room as shown in Fig. 4. The working range of these accelerometers varies between 0.5 and 2000 Hz, with a conversion factor equal to 1000 mV/g. According to the arrangement commented, belltower vibrations in the E-W and N-S directions could be determined. The dynamic data obtained from the ambient vibration have been registered by a Kyowa PCD-320 equipment with a sample rate of 200 Hz. Temporal acceleration movements have been analysed with DAS-100a Kyowa software to obtain frequency results.

![Figure 4: West view. Accelerometers arrangement in the belltower.](image-url)
Power spectra responses in E-W and N-S directions have been obtained from ambient vibrations, and the modal parameters can be concluded from them as shown in Table 1:

Table 1: Belltower natural frequencies.

<table>
<thead>
<tr>
<th>Accelerometer Direction</th>
<th>Frequency (Hz)</th>
<th>Mode classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3 N-S</td>
<td>2.30</td>
<td>Bending</td>
</tr>
<tr>
<td>1-4 E-W</td>
<td>2.40</td>
<td>Bending</td>
</tr>
<tr>
<td>1-4-3 (2)</td>
<td>5.50</td>
<td>Torsion</td>
</tr>
</tbody>
</table>

The structural damping ratio is obtained from the results in Ivorra (2006), since the structures involved have very similar characteristics and similar period of construction. The average damping ratio used in the present work for the masonry belltower is 0.0159.

3 BELL FORCES

On the windows of the belfry five bells are located. These bells swing according to the Spanish system: A counterweight provides a high level of balance (see figure 5) and the bells, directly anchored on the tower windows, rotate continuously in the same direction.

The characteristics of these bells have been determined according to the works of Heyman & Therefall (1976), Ivorra & Llop (2002) and Ivorra et al. (2005); they are presented in the table 2.

Table 2: Characteristics of the bells of the tower

<table>
<thead>
<tr>
<th>Bell</th>
<th>Unbalanced1 (m)</th>
<th>Bronze weight (N)</th>
<th>Total weight (N)</th>
<th>Swing velocity (Hz)</th>
<th>Adim. Horizontal force2</th>
<th>Adim. Vertical force2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maria Antonia</td>
<td>0.08</td>
<td>1310</td>
<td>2096</td>
<td>0.67</td>
<td>0.65</td>
<td>1.81</td>
</tr>
<tr>
<td>San Jose</td>
<td>0.07</td>
<td>2350</td>
<td>3760</td>
<td>0.57</td>
<td>0.54</td>
<td>1.41</td>
</tr>
<tr>
<td>Ntra. Sra. de Guadalupe</td>
<td>0.07</td>
<td>4360</td>
<td>6976</td>
<td>0.58</td>
<td>0.58</td>
<td>1.71</td>
</tr>
<tr>
<td>Ntra. Sra. del Rosario</td>
<td>0.09</td>
<td>7500</td>
<td>12000</td>
<td>0.42</td>
<td>0.7</td>
<td>2.18</td>
</tr>
<tr>
<td>Stas Justa y Rufina</td>
<td>0.08</td>
<td>12720</td>
<td>20352</td>
<td>0.30</td>
<td>0.64</td>
<td>1.92</td>
</tr>
</tbody>
</table>

1 Distance between centre of rotation and centre of gravity.
2 Maximum horizontal/vertical force divided by total weight.
4 3D-FEM Model

As a first approximation, a simplified 5 degrees of freedom numerical model has been used to know the belltower response to bell forces. A more refined numerical model has been done using the commercial software SAP2000™. 8-node-hexaedral finite elements have been used to mesh the model, and three degrees of freedom per node. An iterative process has been performed to fit, through a modal analysis, the fundamental frequencies of the initial model and those registered from the real model. The results of this stage are shown in Fig. 5 and Table 3.

The main assumptions for the numerical model are:

1. Average material density 18 kN/m³ constant, as stated in the Spanish standard NBE AE –88 applied to masonry structures with solid brick. In the beam models it is supposed to be uniformly distributed.
2. The Poisson’s ratio of the masonry was held constant and equal to 0.15.
3. Linear and elastic mechanical behaviour during the calibration stage and modal analysis.
4. The tower is supposed to be clamped at the ground level.
5. Displacements are restrained in the W-E direction on the East wall up to a height of 18.2 m and on the West wall up to a height of 10.3 because of the contact with the lateral wall of the nave. Equally, displacements in the N-S direction are restrained in the South wall for the same reason. These constraints can be observed in Figure 6.

Fig. 5 shows the model, where 4312 solid elements, 6932 nodes and 19.847 degrees of freedom are used.

![North and west façades](image1)

![East and south façades](image2)

(a) (b) (c)

Figure 6. 3D FEM of the tower, connections with chapel and church.

Figure 7. 3D FEM of the tower, (a) First mode (N-S). (b) Second mode (W-E) (c) Third mode. Torsion
Table 3: 3D model. Modal participating mass ratios

<table>
<thead>
<tr>
<th>Mode classification</th>
<th>Natural Freq. (Hz)</th>
<th>Direction</th>
<th>Rotation-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N-S %</td>
<td>E-W %</td>
</tr>
<tr>
<td>Bending (N-S)</td>
<td>2.17</td>
<td>30.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Bending (E-W)</td>
<td>2.27</td>
<td>5.5</td>
<td>28.6</td>
</tr>
<tr>
<td>Torsion</td>
<td>5.31</td>
<td>1.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Bending (N-S)</td>
<td>6.70</td>
<td>7.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Axial</td>
<td>6.95</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Once the numerical model has been calibrated using the experimental results, the horizontal forces caused by the swinging bells are introduced in the model. From this analysis it has been obtained that the dynamic amplification factor is lower than 1 for all the bells, so no dynamic interaction is found between belltower and bells.

5 Conclusion

A theoretical and experimental dynamic investigation of a historic masonry bell-tower is described in the paper. The following conclusions can be drawn from the study:

1. A simplified and low-cost method is described to evaluate the dynamic effect generated by the swing of bells on the bell tower.
2. With this non-destructive and low-cost method five vibration modes were clearly identified within the frequency range 0–10 Hz.
3. This gothic belltower has its first natural frequency higher than others presented in the scientific literature. This can be a singular aspect for this type of tower, because the ratio between wall thickness and slenderness can suggest a more rigid belltower than other architectural styles.
4. On this belfry, the swinging of bells, swinging in the Spanish system, causes no special or singular structural problems.

6 References


