Analysis of the dynamic actions when bells are swinging on the bell-tower of Bonrepos i Mirambell Church (Valencia, Spain)

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ABSTRACT: Dynamic actions caused by bell ringing are a characteristic aspect in bell towers. There are differences between the English, Central Europe and Spanish systems of bell ringing as in the Spanish system bells are swung full circle through 360º in a continual manner; in addition Spanish bells are well balanced, thus presenting bell ringing characteristics different from those of the other bell systems. This paper presents the effects of bell ringing on the bell tower of Nuestra Sra. del Pilar Church, located in the Valencian village of Bon Repos i Mirambell. The main features of this bell tower are its building materials (brick) and its slenderness.

1 DESCRIPTION OF THE BELL TOWER

1.1 Historical background

The first stone for the building of the bell tower of Nuestra Sra del Pilar Church, located in the Valencian village of Bon Repos i Mirambell, was placed on the 2nd of April 1775 and it was finished on the 8th of October 1774. The architect was Joan Baptiste Mingues, a member of a family of architects who designed the most important bell towers of the Valencian region in the 18th century. The artistic style of the bell tower follows the same pattern as most bell towers built in the time, known as Valencian Baroque.

The bell tower has been restored in different occasions along history, the most important being after the Independence War, as the French had burnt the church and its structure got seriously damaged. In 1874, according to the report by the "mestre d'obres" held at the Archivo del Reino in Valencia, the tower was totally repaired. The most recent repair works happened in 1982, when the plaster of the facade was removed and plastered again, water leaks and damp were removed from roofing and cornices using damp-proof materials, and the damaged ornamental elements were replaced.

1.2 Description of the bell tower geometry

Following the trends of the Valencian Baroque style the bell tower can be divided into three main bodies. The first body or basement is the cane that supports the bell tower; it consists of a square area of 4.68 m per side and a wall 1.45 m thick. Inside we may find the main stairway, which gives access to the upper body, and the main access to the church choirs. This first body has three small openings located at different heights in the direction of the main facade of the church. The openings are 1.2 m high and have a variable section of 30 cm on the outer side and 60 cm on the inner side.

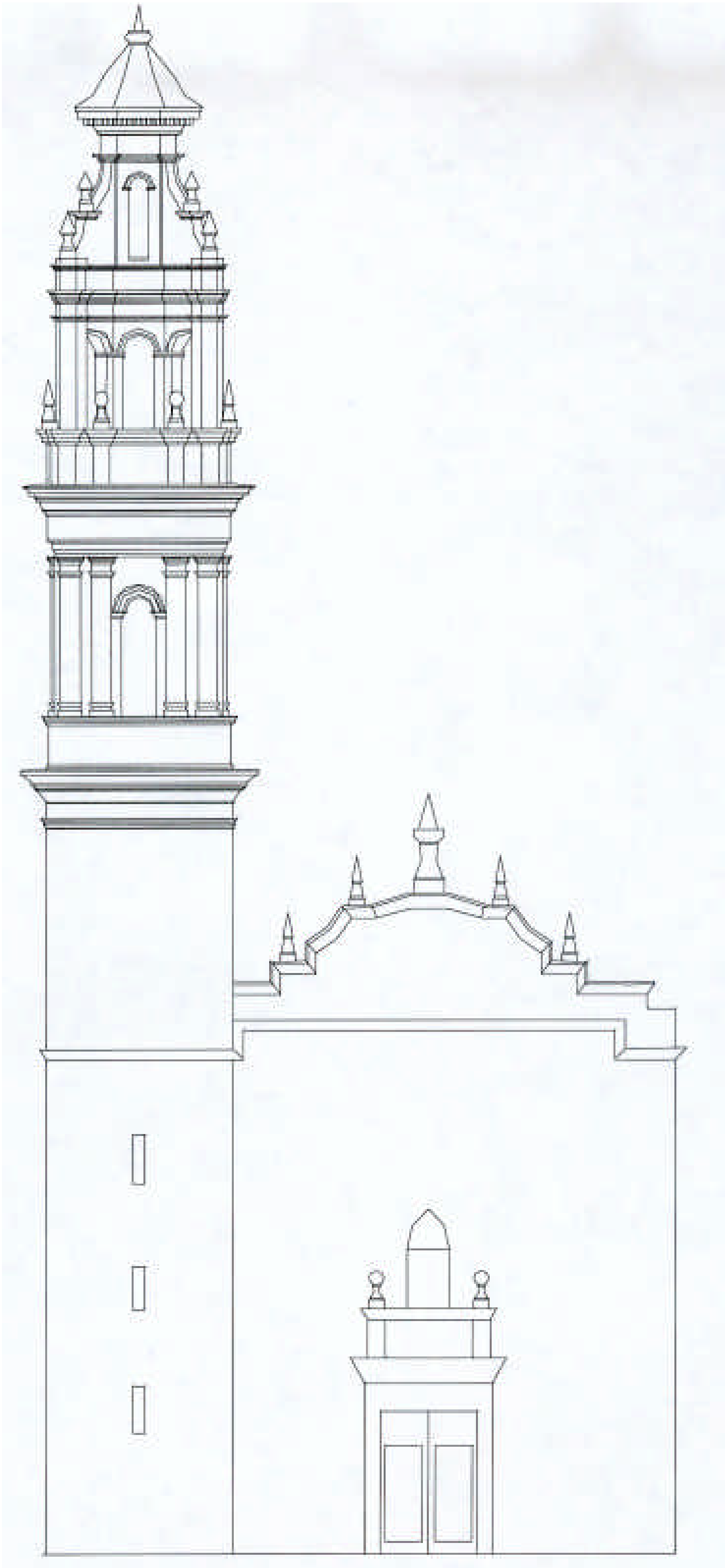

Figure 1: Main facade of the Ntra Sra. del Pilar Church

There is another opening at a height of 16.6 m that housed a clock in ancient times; this opening consists of a square section 1.4 m per side. The second body is the belfry where the bells are housed; it ends at a height of 26.6 m. It contains four similar openings in each of the sides of the tower that house the four bells of the belfry.

Table 1: Bells housed in the belfry

Location	Name	Weight N
S Facade (main facade)	Virgen. del Pilar	6310
N Facade	Jesús	500
W Facade	San Juan Bautista	3170
E Facade	San Vicente Ferrer	1540

The third body constitutes the top of the tower; it is part of an ornamental structure with a height of 37.19m. It presents two well defined changes in section: up to 31.59m it is orthogonal and ends again with a square section. Access to this body is done by means of an outside ladder fixed to the inner walls of the second body.

The main material used in the building is brick, a typical material in the Valencian buildings of that period. The material used at the base of the tower up to a height of 1.5m is local sandstone. The mechanical properties of the materials of the bell tower were analysed using non-destructive measurement tests.

2 DYNAMIC ANALYSIS OF THE TOWER STRUCTURE

2.1 Forces introduced by bell ringing

One of the main external actions in bell towers is the excitation forces caused by bell ringing. From the three main bell ringing systems (English, Central Europe and Spanish) found in Europe, the Spanish system presents the lowest dynamic forces imparted onto the bell tower structure. This is due to the fact that the Spanish bell system is better balanced. In the English and Central European systems the bells are swung around the bell axis with swing angles ranging between 60-180º in the Central European system, and 360º in the English system; whereas in the Spanish system the bells are swung full circle around their axis in a continual manner. In the first two bell ringing systems bell yokes are no more than the bell support, while in the Spanish system bell yokes are very heavy acting as counterweights, thus allowing unbalance values of only 2-11 cm.

Different approaches have been developed for the analysis of the vertical and horizontal forces caused by bell ringing. From different tests performed on the bells of the tower, the most important characteristics of each of the bells were obtained: unbalance, turning speed, inertia and weight. A mathematical model was used to calculate the maximum values of the horizontal and vertical forces acting on the bell supports. The results are shown in table 2.

Table 2: Features of the tower bells

Name	h Unbalance m	Swing velocity rad/s	Max. Horizontal force. N	Max. Vertical force. N	Weight N
Virgen. del Pilar	0.016	2.82	114	6432	6310
San Juan Bautista	0.020	3.35	98	3300	3170
San Vicente Ferrer	0.015	4.19	46	1590	1540
Jesús	0.032	4.92	47	552	500

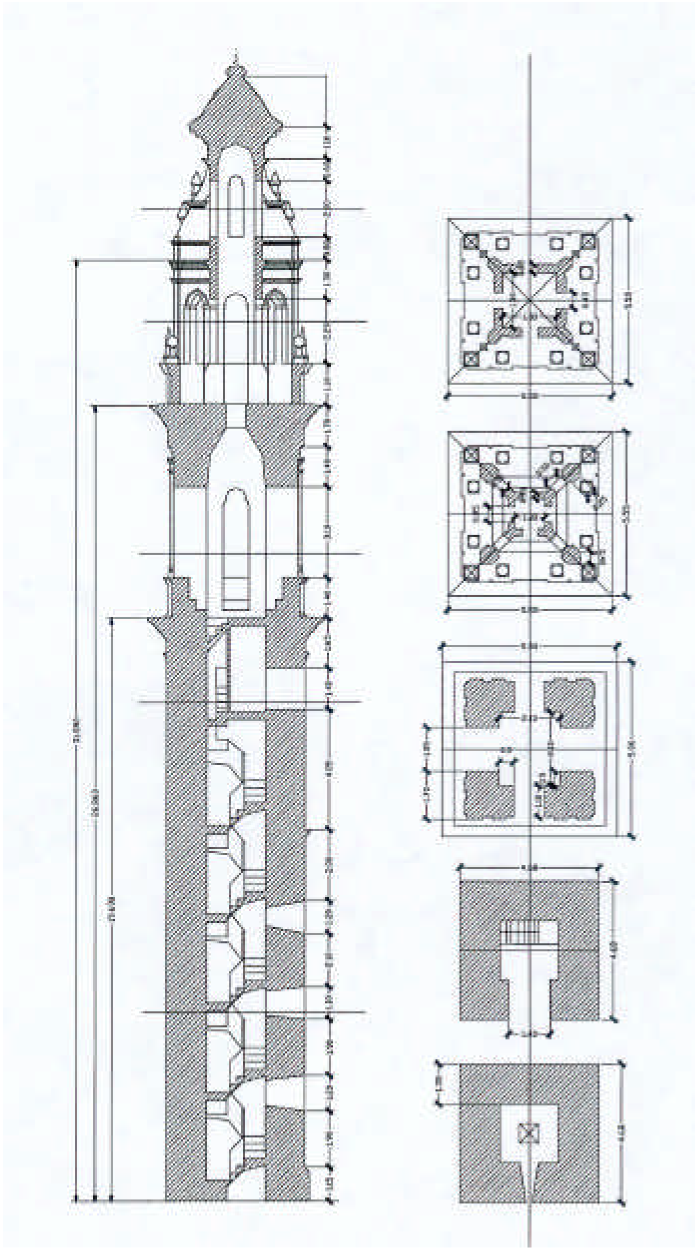

Figure 2: Section of the bell tower from the main facade

In the case of the Spanish system, the actions caused by bell ringing can be calculated using a simplified approach in which bell ringing action is considered to behave as a simple pendulum concentrating all the mass on the gravity centre of the pendulum; thus the expressions for the horizontal and vertical forces will be

Horizontal Forces $$F_H(t) = F_H \cdot \text{sen}(w_0 \cdot t + p) \quad (1)$$

Vertical Forces: $$F_V(t) = 1 - F_V \cdot \cos(w_0 \cdot t) \quad (2)$$

where F_v = Maximum horizontal force, F_h= Maximum horizontal force, ω_0 Constant angle velocity (rad/s)

2.2 Numerical modelling of the dynamic analysis of the tower

The numerical modelling is based on the detailed analysis of the geometrical data of the tower structure. The characterisation of the tower materials has been obtained from the dynamic characteristics of the tower and subsequent data fitting.

The excitation forces required for the dynamic analysis were obtained from the tolling of the main bell: Virgen del Pilar, turning at a velocity of 25 rev/min (2.62 rad/s). The result of such dynamic action, for a period of 2.3 s, can be seen in Fig. 3.

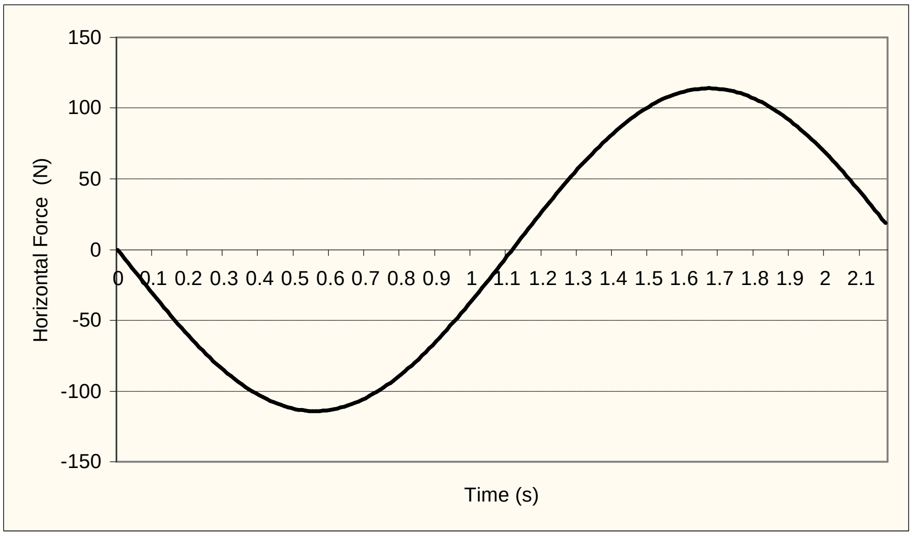

Figure 3: Horizontal forces introduced by Virgen del Pilar bell onto the bell tower.

Through monitoring with low resolution accelerometers - 0.025-800 Hz - the response spectrum shown in Fig 4. was obtained. From this diagram it can be deduced that the first natural frequency of the tower structure sets up at 0.725 Hz in the N/S direction, i.e., the direction in which the main bell turns round. In addition, from the monitoring data the viscous damping value of the tower has come out to be 0.01456.

From these results the dynamic amplification coefficient value has a value of one for Virgen del Pilar bell, as the relationship between the first natural frequency and the excitation frequency of the tower is 1.61. The maximum value of the horizontal forces produced by the ringing of the bell is only 114 N, and therefore shear deformations present very low values.

Once these values are obtained, together with the specific weight of the material (14120 N/m^2), and using an iterative computational process the average elasticity modulus value of the material was obtained for the complete tower; the first natural frequency values of the model were matched with the first natural frequency values determined experimentally. Table 3 shows a simplified version of the process of matching experimental and measured values.

Table 3: Results of the value fitting process

Initial values			Result of the fitting process
Specific weight N/m^2	First natural frequency (Hz)	Viscous damping	Average elasticity modulus N/m^2
14120	0.725	0.01456	$1.10 \cdot 10^9$

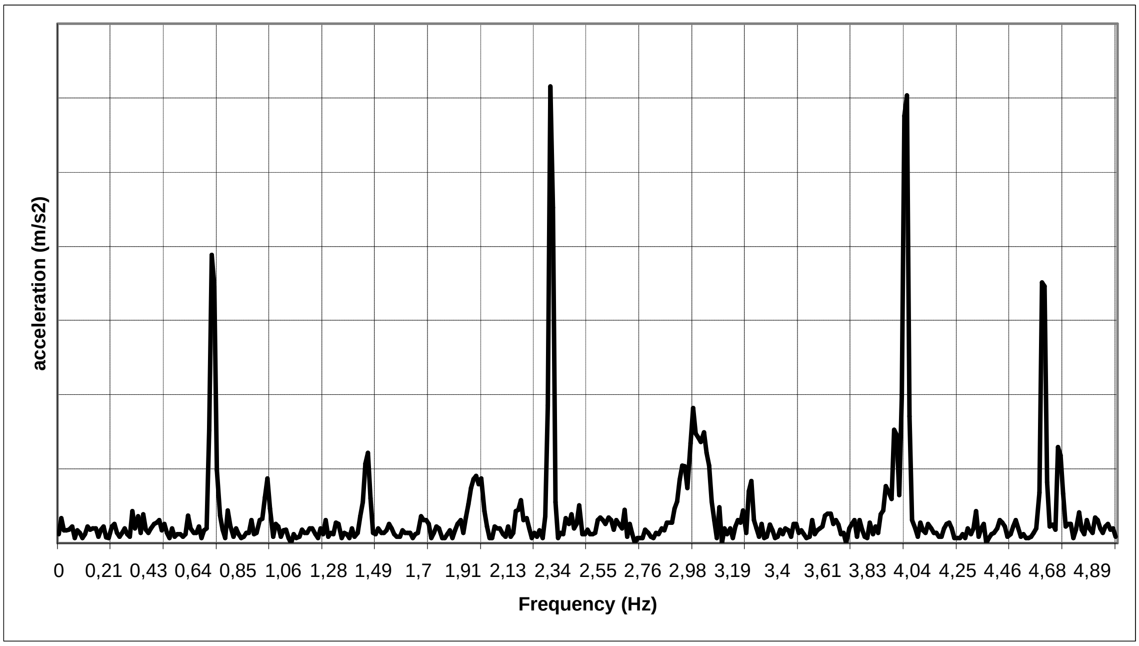

Figure 3: Spectrum of the tower response under dynamic excitation.

The numerical model uses the finite element approach with 8 nodes, thus maintaining the geometry of the bell tower. The only actions acting on the tower structure that were taken into account were the weight of the material and the excitation forces produced by the tolling of Virgen del Pilar bell. Because in this kind of building structures stresses are transmitted through compression, the effect of the structure weight is very important, with a value of $1.4{\cdot}10^7$ N as opposed to the value of 114 N produced by the horizontal forces when ringing the bell.

Fig. 4 shows the finite element modelling, with details of the bell chamber and the tower top.

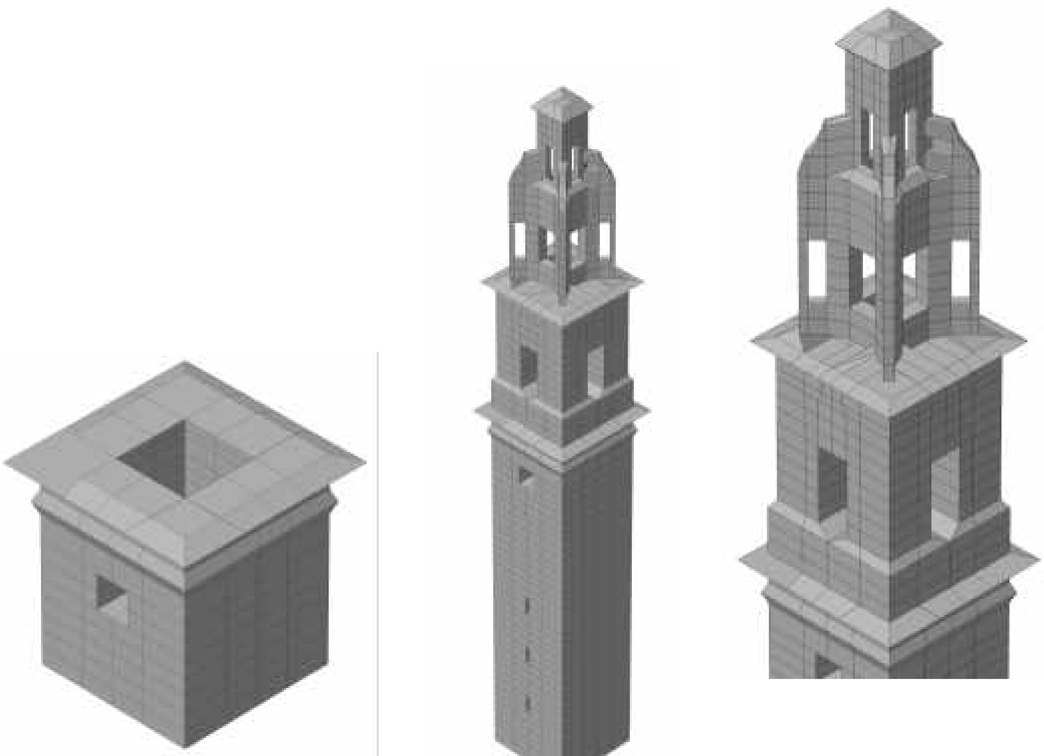

Figure 4: Tower modelling with the finite element approach.

3 CONCLUSIONS

The bells of the Spanish bell ringing system are well balanced and turn round full circles of 360º in a continual manner; this is the reason why their analysis differs from the models used in the English or Central Europe bell ringing systems. From non-destructive measurement tests and the subsequent fitting of the test results for the dynamic analysis of the data the determination of the average elasticity modulus of the tower structure was obtained. Once the numerical model is completed, the effect of the other bells on the tower structure can be calculated, with different bell turning velocities and different bell sizes. The results of this analysis can be used as the guidelines for the future restoration of bells.

The effect of bell ringing on this tower is negligible in comparison with the weight of the tower structure because its bells are well balanced, small (low weight) and their turning velocity values are relatively lower than those of the tower frequencies. The results obtained in this study may be of importance as guidelines for the restoration of tower bells. There are many bell towers in the Valencian region where metal yokes are being replaced by wooden yokes -usually more unbalanced- with the purpose of recovering old bell shapes and sounds; similarly, continuous oscillation motors are being replaced by new stepping motors. From this analysis the limit values of bell swing velocities can be deduced for this bell tower in order to avoid the effects of the dynamic amplification coefficient.

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