The role of model calibration in seismic FE analysis: the case study of an old reinforced concrete structure by using ambient noise modal analysis

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SUMMARY

In order to perform a reliable non-linear dynamic seismic analysis of a building, the first step is to build the linear numerical model of the structure and validate it by means of the modal analysis against *in-situ* measurements. The seismic analysis of the Perret Tower offers the opportunity to show the potentialities and the difficulties that can be faced in this preliminary though fundamental phase of the analysis. Without to enter in the details of the FE modeling, the attention is focused on the usual practice of "calibration" of the numerical models by means of *in-situ* modal analysis measurements and on the importance to understand which components of the structure have structural relevance.

Keywords: Modal Analysis, Model calibration, Ambient vibration, Non-linear behavior

1. PRESENTATION OF THE BUILDING

Figure 1. Perret tower

The Perret tower (Fig. 1) is the first tall (83 m) reinforced concrete structure built in Europe. It has been designed by the French architect Auguste Perret for the International "Houille Blanche et Tourisme" exhibition of 1925 in Grenoble, France. Its main purpose was to be a panoramic observation point and it has been opened to the public until 1960 when the bad conditions of the lift system lead to its closure. In 1998 the tower has been classified by the French authority as historical heritage building.

The structure of the tower is constituted by an octagonal skeleton mainly composed by 8 reinforced concrete columns linked together by three series of RC shear walls (Fig. 4) acting as stiffener elements. The sides of the octagon separating the 8 columns are constituted by concrete screen walls (Fig.2). Due to the weakness of the links with the columns, their degradation status and their "design" weakness (purely decorative) these elements have been identified as weak parts having no role in the structural behavior (do not participate to the structural stiffness) from the point of view of the seismic response.


Figure 2. Screen walls: left, interior view; right, exterior view

Internally to the tower (Fig. 3): helicoidal stairs allow people to rise up to the top of the building; two steel columns constitutes the frame of the old lift system; annular slabs are present at the level of the shear walls. The tower is lying on a shallow foundation supported by 72 deep inclusions.


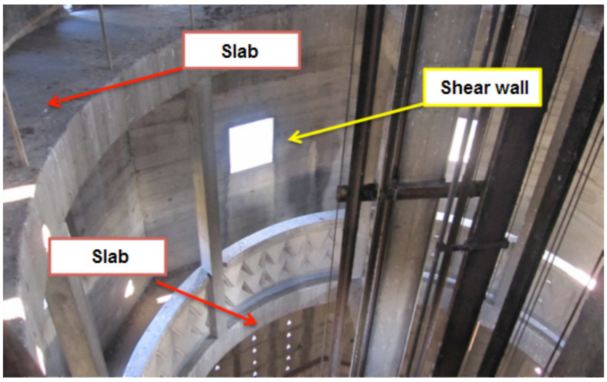

Figure 3. Detail of the interior: left, helicoidal stairs and lift system frame; right, slabs

2. AMBIENT NOISE DATA

An *in-situ* modal analysis campaign has been performed on the Perret Tower in 2011 by the French company Miage Sarl: the tower has been monitored by means of nine accelerometric stations. Four of these have been placed at the base of the tower, four at the level of the visitor platform (60m) and another one at the top of the tower (83m). Such instrumentation allowed to perform the modal analysis of the tower by means of the ambient noise technique [Trifunac, 1972; Hans *et* al. 2005; Michel *et* al. 2010]. By means of this procedure it is possible to identify the dynamic response of the building subjected to ambient noises (ex. traffic induced vibrations) or weak earthquakes, in other words, without the needs for artificial-induced loading (e.g. vibrodine). The results of the *in-situ* analyses on the Perret tower are summed up, in terms of natural frequencies, in Table 1 (note the different values for the two directions EW and NS).

Table 1. *In-situ* modal analysis, natural frequencies

Modes	EW –Direction Frequency (Hz)	NS – Direction Frequency (Hz)
First bending	0.81	0.75
Second bending	2.88	2.56
Third bending	4.88	4.69

3. NUMERICAL MODELING

In the following, a (very) brief description of the FE modeling is given: the details about the non-linear modeling are completely omitted.

The tower's skeleton (columns and beams) has been modeled by means of multifiber beam elements [Guedes *et* al., 1994; Spacone *et* al., 1996]. The same has been done for the stairs. Being the main structure modeled by means of 1D elements, it has been chosen to also represent the shear walls by a bar-truss sub-model (Fig. 4) implemented following the approach of [Kotronis *et* al., 2003]. A similar bar-truss modeling has been employed to model the screen walls. The slabs have been modeled by means of shell elements. Due to the strongly degraded status of the links with the tower, the lift steel frame has no been modeled (do not participate to the dynamic behavior of the tower).

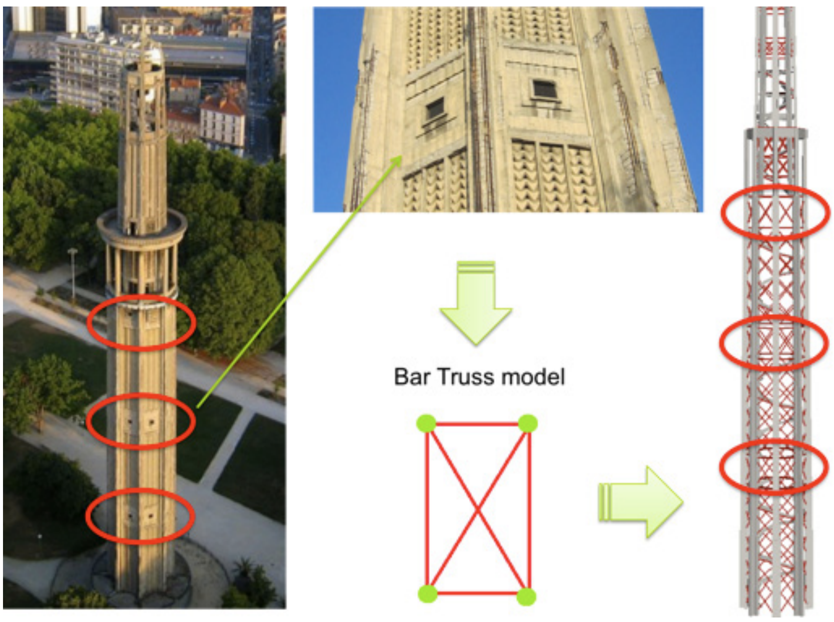

Figure 4. Implementation of the shear walls (and the screen walls) into the whole FE model of the tower

The mass of the building has been arranged in the numerical model by means of concentrated masses: these have been distributed on 23 sections along the height of the tower. Regarding the boundary conditions, the model is clamped at the base and SSI has no been considered.

The mechanical characteristics of the concrete (Tab. 2) have been extracted by means of experimental test performed on the tower in 2004. Data about the mechanical properties of the rebars' steel were no available at the time of the study, then the steel properties have been fixed on conservative values.

Table 2. Materials elastic characteristics

Property	Concrete	Steel
Poisson ratio	0.17	0.3
Young Modulus [GPa]	30	190

4. EVALUATING THE FE MODEL BY MODAL ANALYSIS

4.1 Identification of the most accurate numerical model

The columns, the beams and the shear walls have been identified as the main components of the structure. In order to understand the effect of the “secondary” components (slabs, stairs and screen walls) of the tower on its dynamic properties, an analysis component by component of the numerical FE model has been performed by means of the finite element code Cast3M [Millard, 1993]: starting from the complete model of the tower (the one taking into account for all the components), the “secondary” parts have been one-by-one removed and the modal analysis has been performed. The results of these analyses have been compared to the *in-situ* modal analysis results (Tab. 1) and to the results of the complete numerical model (Tab. 3).

Table 3. Numerical modal analysis, complete model, natural frequencies

Modes	EW –Direction Frequency (Hz)	NS – Direction Frequency (Hz)
First bending	0.754	0.75
Second bending	2.67	2.64
Third bending	4.87	4.71

The conclusions of this procedure are:

1- The slabs only participate to the global stiffness marginally (Tab. 4 vs Tab. 3). Their structural role is essentially limited to link together the columns, action, this last, that is already carried on with larger contribution by the shear walls and the stairs.

Table 4. Numerical modal analysis, model without slabs, natural frequencies

Modes	EW –Direction Frequency (Hz)	NS – Direction Frequency (Hz)
First bending	0.748	0.743
Second bending	2.64	2.60
Third bending	4.77	4.61

2- The helicoidal stairs are the origin of the loss of axial-symmetry of the model (Tab. 5 vs Tab. 3). Their introduction in the numerical model allowed to reproduce the difference for the frequencies provided in two orthogonal directions.

Table 5. Numerical modal analysis, model without stairs, natural frequencies

Modes	EW –Direction Frequency (Hz)	NS – Direction Frequency (Hz)
First bending	0.74	0.74
Second bending	2.49	2.49
Third bending	4.32	4.32

3- Even if structurally very weak, against all expectations, the screen walls play a role in terms of stiffness under low load level: the structural model arrangement without screen walls does not match with the *in-situ* modal analysis results (Table 6 vs. Table 1). The model that gives (very) accurate results in terms of natural frequencies (compared to the experimental data coming from ambient noise technique) is the one taking into account the screen walls (Table 3 vs. Table 1).

Table 6. Numerical modal analysis, model without screen walls, natural frequencies

Modes	EW –Direction Frequency (Hz)	NS – Direction Frequency (Hz)
First bending	0.65	0.648
Second bending	2.01	1.98
Third bending	3.43	3.33

Note that the numerical modeling presented take into account for the actual geometry and material properties of the tower: only the screen walls stiffness, particularly difficult to evaluate "in blind", has been tuned to match exactly the numerical modal analysis results with those coming from the *in-situ* modal analysis: it is important to keep in mind that tuning only one parameter allowed to obtain the 3 first natural frequencies (Tab. 3) and natural modes (Fig. 5).

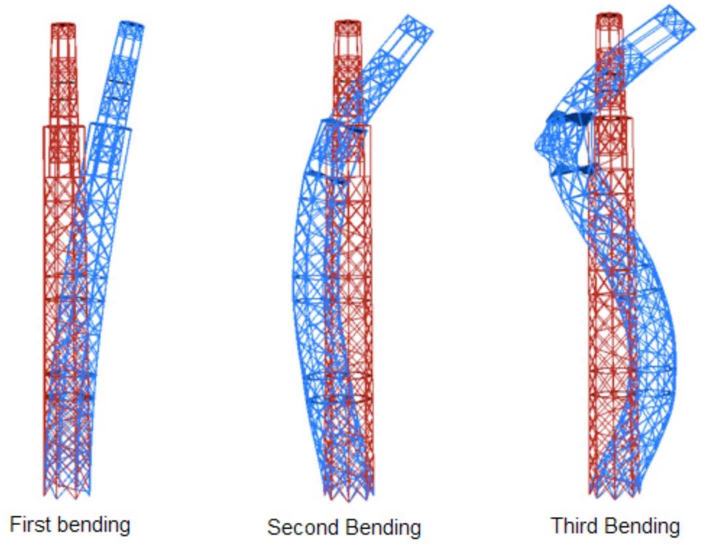

Figure 5. Numerical modal analysis, modal shapes

4.2 Evaluation of the robustness of the model

After the calibration of the model, a sensibility analysis with respect to the structural components stiffness has been performed in order to evaluate the effect of the modeling uncertainties on the modal frequencies.
For each structural element a variation of stiffness is performed and the consequences in terms of maximum error in percent on the fundamental frequency of the structure is reported (Tab 7).

Table 7. Maximum error (%) on the fundamental natural frequency with respect to the reference model

Stiffness variation	Slabs	Shear walls	Screen walls	Stairs
+ 20 %	0.26	0.85	2.87	0.71
- 20 %	0.22	0.85	3.56	0.84
+ 50 %	0.48	1.6	6.4	1.54
- 50 %	0.56	3.27	9.6	2.29

The results provided by this simple sensibility analysis show clearly the effects of the different components: a large variation of the elastic parameter of the shear walls, the slabs or the stairs does not affect significantly the fundamental frequencies of the tower. Indeed, the maximum difference is reached by varying the stiffness of the screen walls: but varying this one of -50% lead to a difference in terms of frequency of only 9.60%. This result highlights that although the slabs, shear walls and stairs have, due to their design (concrete thickness and reinforcement ratio), a clear structural effect for high load level, they have a lower importance on the early elastic response with respect to the screen walls.
Furthermore, these results also show that the numerical model employed to simulate the tower is very robust, which gives legitimacy to this numerical modeling.

5. CONCLUSIONS

Only by using the modal analysis it has been possible to understand the role of the different structural parts of the tower on its linear dynamic behavior: particularly, it has been shown that it is possible to better understand the contribution to the global stiffness given by the "secondary" structural components (i.e. the ones for which there are doubts about the role). In the case of the Perret tower, it has been verified that: 1- the annular slabs have an effect almost negligible on the linear dynamic response; 2- the helicoidal stairs cause the loss of symmetry of the tower's response; 3- the decorative screen walls, despite their structural weakness, give a not negligible contribution to the global stiffness of the tower.
The understanding of the structure has been driven by the comparison of numerical vs. *in-situ* modal analysis data: such a comparison it is revealed as an indispensable tool in order to validate the numerical model.
The results of the modal analysis of the Perret tower clearly show that the numerical simulation can reach very high accuracy (max error less than 0.07 %) with respect to the identification of the natural frequencies of the structure.
The numerical modal analysis of the tower shown that only to take into account the screen walls allows to match the in-situ analysis results, with a difference at least equal to 15% with respect to the modal frequencies of the model without screen walls. Although, the severe conditions of degradation of these decorative elements authorize to hypothesize, for them, a low-strength and fragile behavior under true seismic loading (i.e. in case of earthquake these elements collapse quickly without to bring a significative amount of stiffness to the structure). These two observations suggest, generally speaking, that the dynamic properties coming from *in-situ* modal analysis should be treated with caution having, potentially, the tendency to overestimates the natural frequencies. The behavior of the structure under weak (i.e. ambient vibrations) or strong (i.e. earthquake) excitation could be very different if some of the components has very early stiffness deterioration or non-linear behavior under low imposed load, as it is the case for the screen walls of the Perret tower. In such cases, if a linear technique (i.e. spectral analysis) is used to estimate the seismic behavior of the building, the true natural frequencies should be then noteworthy decreased: this could change significantly the seismic response of the structure and the determination of its performance point.

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