From ambient mechanical noise to the structural functioning of regular buildings

S. Hans, C. Boutin, A. Rallu, Q.C. Bui
Université de Lyon, DGCB,CNRS, ENTPE

C. Chesnais
IFSTTAR, Université Paris-Est, Paris

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SUMMARY:
The seismic assessment of existing buildings is difficult because of the diversity of structures and the lack of available information. These latter can be in part obtained with in situ monitoring of the ambient mechanical noise. Nevertheless the difficulty is transferred to the determination of the structural mechanisms from these experimental results. A theoretical frame based on the homogenization theory was built to describe the possible dynamic behaviours for periodic buildings. This study showed these behaviours could be modelled by continuous generalized beams, whose parameters are calculated in elastostatics on a unique level. Two models seem to dominate the classical behaviour: the Timoshenko beam and the Sandwich beam. This is illustrated on three real buildings in France and in Guadeloupe (Caribbean Island). As a conclusion, if in situ information are important to understand the behaviour of a real building, a frame of analysis is necessary to exploit them.

Keywords: continuous modelling, mechanical noise, in situ monitoring, Timoshenko, Sandwich

1. INTRODUCTION

The seismic assessment of existent building is a difficult question because of the great diversity of the typologies, of the important number of buildings and of the lack of available information about them. In situ dynamic measurements under mechanical noise could make up in part for this lack. However the difficulty turns into the use of these information, in particular to determine the real structural functioning of the studied building. This step is necessary to integrate the in situ measurement in procedures of seismic vulnerability diagnosis.

In the first part, the lessons of a measurement campaign in Guadeloupe are detailed. The use of this information requiring a robust framework for analysis, we present in the second part a possible theoretical framework to describe different dynamic behaviors for buildings. An illustration of the use of this framework is then presented in the third part. Finally, a way of use to the diagnosis is proposed through a methodology to estimate limit thresholds based on both the established models and on criteria of rupture in deformation of constitutive materials.

2. LESSONS OF THE CAMPAIGN OF GUADELOUPE

The purpose of this paragraph is to provide the elements to prove the robustness and the interest of the ambient noise measures. These elements are in addition to those that can be found in (Hans, 2002) (Boutin et al., 2005) (Dunand, 2005) (Michel, 2007). The following presentation is based mainly on the campaign of in situ measurements performed in 2007 in Guadeloupe (Caribbean Island) in the framework of the ANR project ARVISE.

2.1. Details of the in situ campaign

The tested buildings are representative of the period of construction of the 1960s through the 1980s and are all located in Pointe-a-Pitre, except one localized in Basse-Terre. The special feature of the buildings studied in Pointe-a-Pitre is to be based on a layer of soil of poor mechanical quality with a thickness ranging from a few meters to a couple of meters (towers of the Gabarres) due to the fact that the recent extension of Pointe-a-Pitre was realized on mangrove swamps. We have been able to find on the spot of the compaction from a few tens of centimeters up to 1 meter, which is materialized by additions of staircase to gain access to the building or by the emergence of the heads of piles (Buildings Henri IV, Amede Fangarol street). Our team (of the ENTPE) has operated in parallel to that of the ISTERRE during this campaign, each team implementing its own systems of measures, the objective being to validate the results by comparison on the same buildings. The principle of the measures is the same in both cases and is to record the response of buildings under the mechanical noise ambient (of human origin - traffic, industry etc… - or natural – distant earthquake, sea waves, etc…) with velocimeters placed at different points in the structure or on the ground in its immediate surroundings. Our own device was made up of 5 sensors TROMINO® without cables synchronizable by GPS, the measures obtained being of this fact synchronized. The processing of the data is based on the Fourier transform and is operated in function of the studied system: the characteristics of the system structure/foundation/soil can be obtained by ratio of (spectra structures/spectra ground), the characteristics of the structure only are obtained by the ratio (spectrum floor-spectre base) /spectre base. The analysis is carried out also either in the natural axes of the building, either, by using the technical FDD (Frequency Domain Decomposition (Brinker et al., 2001)) in the natural axes of modes of vibration.

2.2. Direct Observations: effect of soil and similar structures

A first remarkable observation has quickly emerged from the spectra of the towers of Pointe-a-Pitre: their forms were clearly atypical (Fig. 1 and fig. 2) with a fundamental frequency quasi-identical (in frequency and amplitude) in the two directions of buildings and with higher modes very attenuated; finally, the strong contribution of the vertical component is observed at the same frequency as the fundamental. Usually, the spectra of buildings, as their modal frequencies, are very different from one axe to another, the contribution of higher modes are more important and the vertical component very low as can be seen on Figure 1 for the building 'Grain d'Or'. The internal structures (walls) could not explain a fundamental frequency also isotropic (cf. Fig. 3 on the floor plan), so a reasonable explanation for this atypical behavior is a forcing by the soil, of very poor mechanical quality, interacting with the system of foundation on piles. This conclusion is strengthened by the measures on the building of Basse-Terre, founded on rock and presenting a conventional spectrum. In situ measurement thus provides evidence of the phenomena and quantified the effect on the dynamic behavior, evidence hardly justifiable so clearly with other methods. A second observation was also made by comparing the spectra of buildings of similar design that are the three towers of the 'Gabarre', the towers 'Frebault' and the towers 'Faidherbe', based on a system of piles. Without surprise, all the spectra show a shape very near (Fig 1 & 2), which showed that the measures are well connected to the mechanical structural system and little sensitive to non-structural additions.

2.3. Findings after analysis of the results

The analysis of the measures allows to access, with more or less sophisticated methods, to the modal characteristics of the system soil-structure or of the system structure only. For the tower of the Gabarre presented in figure 3, the method FDD has been used to isolate the first vibration modes for these two systems. There is of course a gap between the frequencies, those of the soil-structure system, mechanically more flexible, being lower than those of the system structure only. It quantifies not only the values of the frequencies, which constitutes direct information, but also the impact of the ground effect. It also gives access to modal shapes, which, in this case, are of different orientations of the 'natural' axes of the buildings and moreover these orientations vary in function of the order of the mode. This result, obtained by FDD, was verified by rebuilding the spectra in the identified directions (for the fundamental, cf. figure 3). Finally, always on this building, the existence of a mechanical joint (materialized in red on the map of figure 3) also raised the issue of its impact on the structural behavior of the building: if he was not playing, the set was monolithic, if it is playing, a degree of decoupling could appear on both sides. The measurement has been taken in one hand and in the other

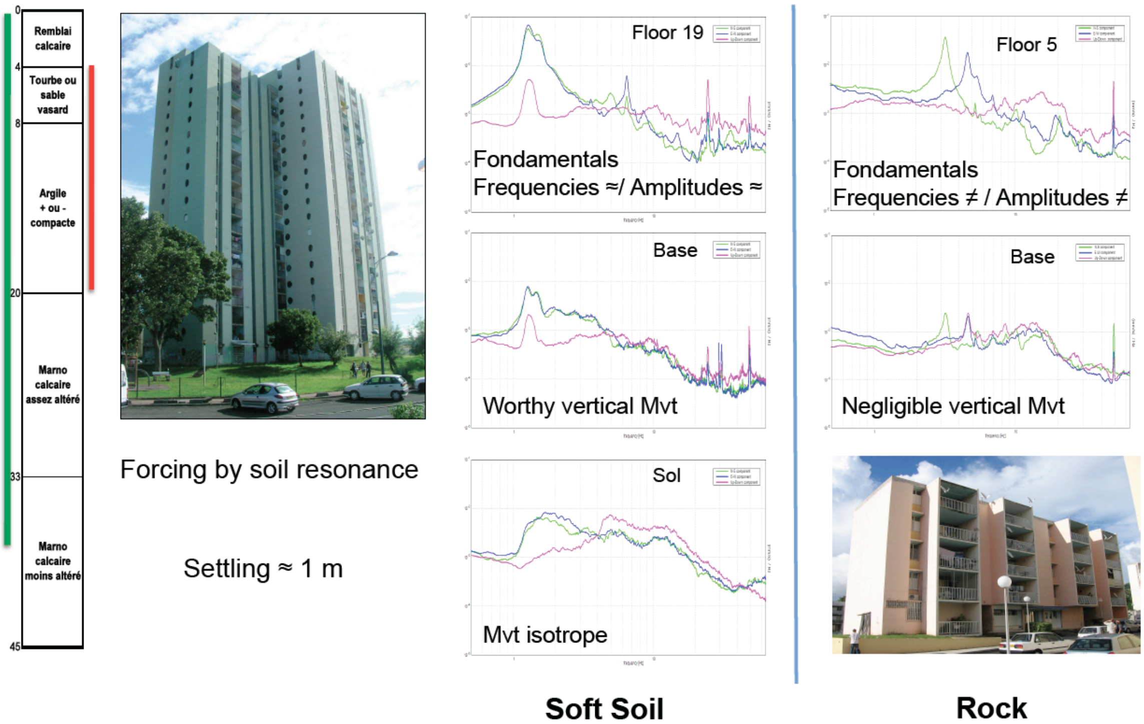

Figure 1. To the left, one of the three towers of the 'Gabarre', with, on the soil profile to the left of the photo, the depth of the piles (green) and the soil layer of poor properties (red) and to the right, the spectra to the ground, on the ground floor and at the head of building. To the right, building 'Grain d'Or' based on rock in Basse-Terre and spectra to the base and in the higher level.

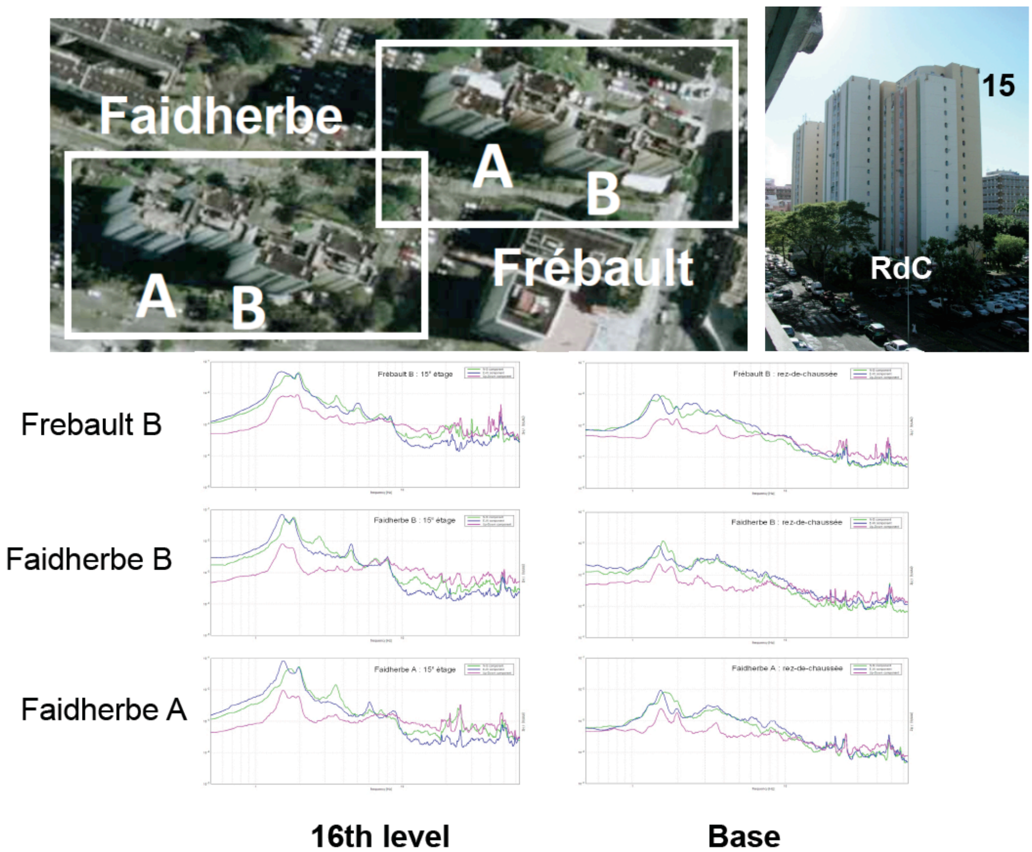

Figure 2. Comparison of the spectra on the 16th floor and on the base of three buildings of similar design.

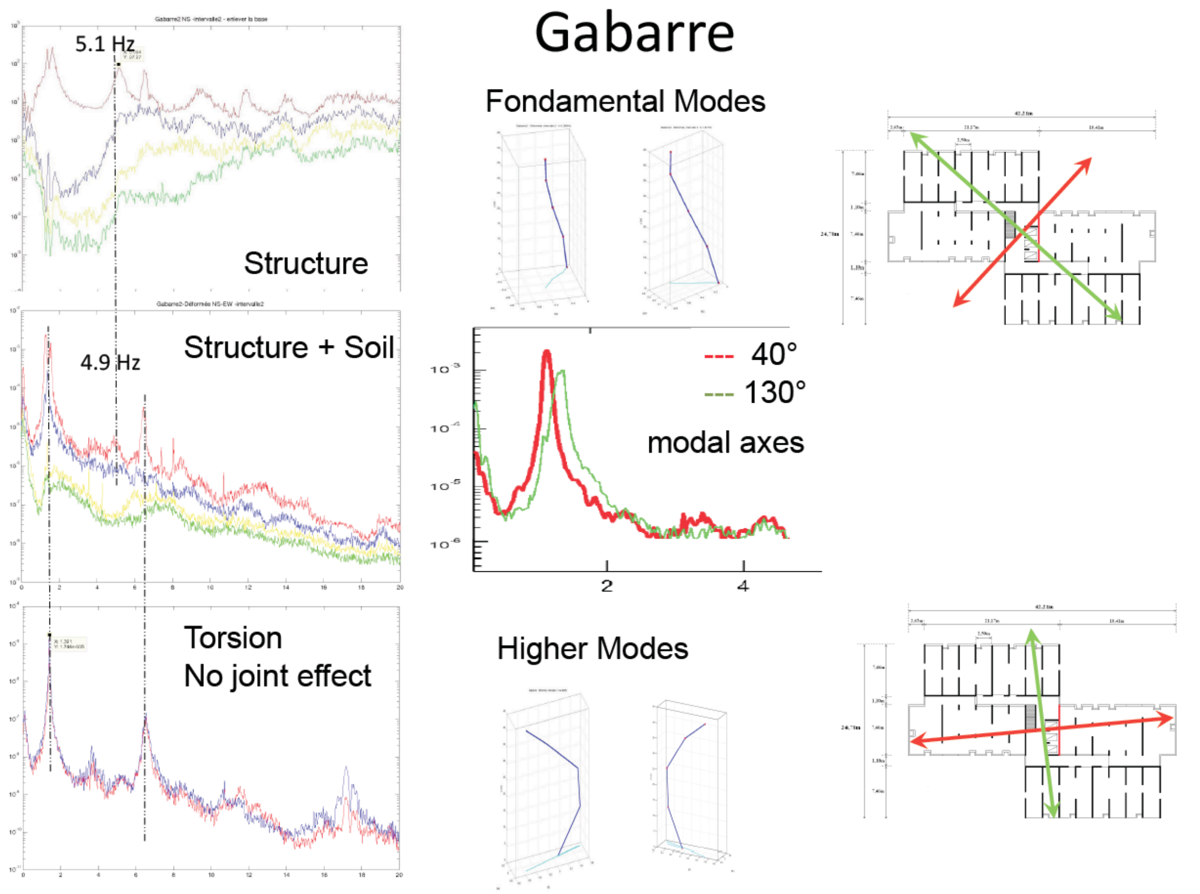

Figure 3. Modal extraction on one of the towers 'Gabarre'. To the left, spectra from analysis of the FDD for the structure only, the system soil-structure and the torsional mode. In the center and to the right, the first two modes and their directivity.

hand of this joint has shown that the motion of the floor was monolithic, which argues in favor of a blocked joint.

2.4. Conclusion on in situ monitoring

The measurement is used to collect direct information, which, combined with elements of context (plans, nature of the soil and foundations, surroundings…) allow to understand or to guid the assumptions on the dynamic behavior of structures tested. It also allows, by quantifying the modal values of the parameters, to provide a basis for analysis. On the other hand, only, it does not allow to go much further on the internal structural functioning of buildings, and it is necessary to define a broader framework of analysis in order to better use these information.

3. MODELS OF DYNAMIC FUNCTIONING OF BUILDINGS

3.1. Theoretical Description

The results presented below are the result of a theoretical study whose details can be found details in (Boutin et al. , 2003) and (Hans et al. , 2008). The idea that has motivated this study is based on the observation that, for a long time, the models of continuous beam are used to describe the dynamic behavior of buildings. This approach is appealing, because these models condense in a few key parameters the phenomena that control the global dynamic. However, there were no procedures indicating which model assign to a given building. Based on the method of homogenization of periodic discrete circles formalized by D. Caillerie (Toellenaere, 1994 & 98) (Verna, 1991), we established for a family of idealized periodic buildings all the models of behavior possible. These calculations have been carried out in a fully analytical manner and have led to generalized equations of beams whose parameters are directly evaluated from the geometry and the mechanical characteristics of the elements of a floor. In summary, three mechanisms controlling the overall dynamics have been identified: a mechanism of shear (K) and two mechanisms of bending - global (EI) and internal (EIμ). In theory, the most general formulation of the behavior is represented by the Generic Beam of degree 6. The predominance of one (or two) mechanism(s) on the other(s) led to two models of beams more simple, the Timoshenko beam (shear and Global Bending) and the Sandwich beam (Shear and Internal Bending). The behavior of these two beams is very different, as in the Timoshenko beam, the two mechanisms are working in series, while in the Sandwich beam, they are in parallel. This leads to the deformation of internal elements very dissimilar, therefore to the mechanisms of damage depending on the model of behavior. Other results from these models can find a direct interest in relation to the measurement: the value of the fundamental period in relation to the number of levels and the distribution of higher frequencies. In a pure shear model, the fundamental period is proportional to the number of floor and the distribution of frequencies follows that of the odd numbers (1, 3, 5…) while in the models of bending, the fundamental is proportional to the square of the number of floors and the distribution is similar to the square of odd numbers (1, $(3/ 1.2)^2$, $(5/ 1.2)^2$ …). Using the theory, the knowledge of these data may allow a direct estimation of the appropriate model of behavior.

3.2. Application to buildings

If these results have been established for 'simple' structures, their validity has been tested with success on real buildings (Chesnais, 2010). These theoretical results can therefore be used as a general framework of analysis of the dynamic operation of buildings, provided they are periodic in elevation and that they have at least 5 floors, so to respect the basic assumptions of the theory of homogenization. For more generality, a representation of the distribution of the different models according to two dimensionless parameters C and γ and of a scale parameter ε was constructed (Figure 5). These parameters C and γ evaluate the contrast of stiffness between the different mechanisms and this evaluation is realized with the scale parameter ε.

$$C = \frac{EI}{KL^2} \qquad \gamma = \frac{EI_\mu}{EI} \qquad \varepsilon = \frac{\pi}{2N}$$

where L = 2H/π is proportional to the height of the building. The knowledge of these parameters allows you to position the behavior in this representation. In practice, the estimation of these parameters is possible from a elastostatic calculation on one level of a building, and can be done, depending on the complexity of the geometry, either 'by hand', either under calculation EF. The additional benefit is that it is theoretically possible to go back to the local deformations of the elements after determines the global response of the structure using the continuous model.

4. STRUCTURAL FUNCTIONING OF BUILDINGS

Is used here the generalized models of beam as a framework of analysis to determine the structural functioning of building. This approach is shown on three examples.

4.1. Timoshenko beam functioning

The first example of a building is derived from a previous measurement campaign, conducted in Vaulx-en-Velin in 2000. This building is a 16 levels rooming housing with floors and shear walls in reinforced concrete casted in place. Two approaches have been tested. The direct approach consists to calculating 'by hand' from the plan, which allows to estimate the parameters of stiffnesses of the different mechanisms (Shear K, global bending EI and inner bending EIμ). It is during this phase that we include or not some elements, such as prefabricated panels. A comparison of the results of the model and in situ measurements allows to validate or not the assumptions. Another approach, so-called indirect, is based on the distribution of modal frequencies. The approach on given plan for a module of concrete taken arbitrarily to 20 GPa gives the frequencies sequence of (2.58-7.91-14.1) in the longitudinal direction, close to the frequencies measured (2.15-7.24-13.97). The indirect approach is even better, because it gives, for a module of concrete estimated to 21 GPa, exactly the measured frequencies in the two directions of the buildings, as well as the modal calculated shapes are very close to the measured shapes. This means that the model of Timshenko seems very well to correspond to this building, and that the structural functioning chosen for the calculation is not exactly the actual functioning.

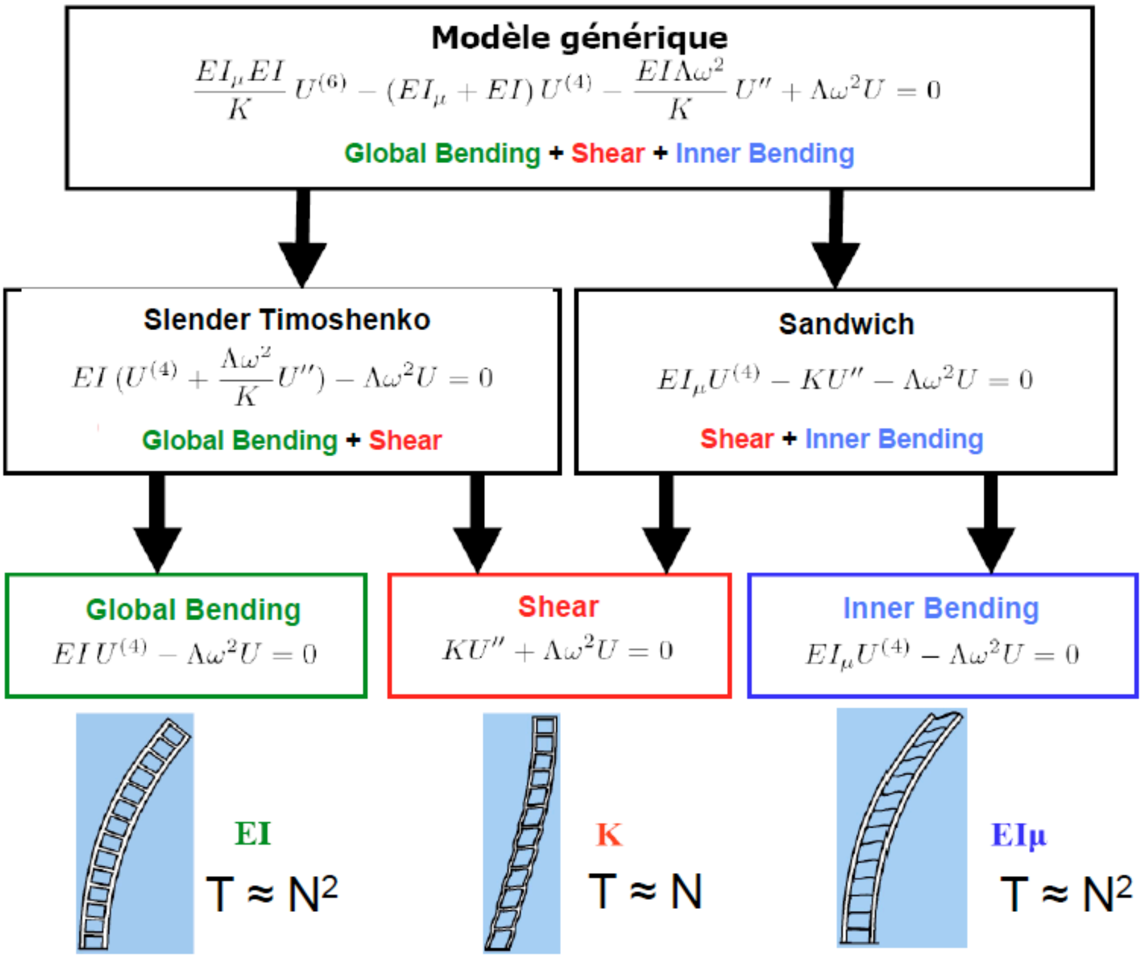

Figure 4. The models of generalized beams

4.2. Sandwich beam functioning

The following two examples are respectively one of the towers ‘Frebault’ and one of the towers ‘Gabarre’. They have both a very similar design, but not exactly identical. On the first tower, an estimate of the structural parameters has been carried out 'by hand' to the transverse direction. The obtained model is that of a Sandwich beam and the structural functioning deduced (Fig 6) is that of three beams running in bending and connected by the floors in shear. The frequency estimate provides, after registration of the fundamental frequency, a reasonable value of 22 GPa for the elastic modulus. The second building (tower Gabarre) has a more complex functioning, as evidenced by the in situ measurements and the orientation of the first vibration modes identified (Fig. 3 & 7). In this case, the functioning the more relevant is still the beam Sandwich, but the absence of elements of bracing in the central part of the building compared to that of the tower 'Frebault' allows greater flexibility of floor. The first modes are then disrupted and tend to align along the axes of flexibility of the floor. For the higher modes, this effect is lessened, and they have the initial axes of flexibility of the building.

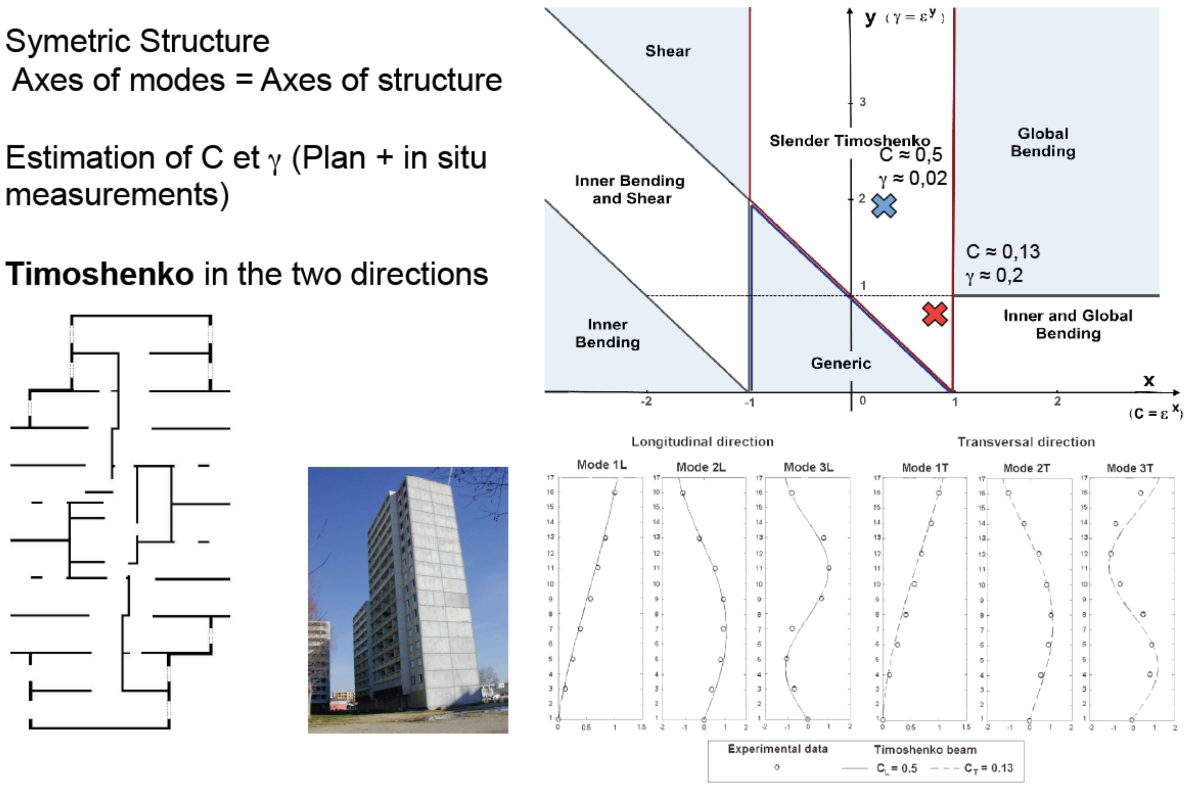

Figure 5. Example of modeling with Timoshenko beam: the building in Vaulx-en-Velin. At the top right, position on the plan (C, γ) of the estimated models. At the bottom, comparison of measured and theoretical modal shapes.

5. PRACTICAL USE FOR A DIAGNOSTIC LEVEL MORE PUSHED: CONCEPT OF THRESHOLDS OF OPERATION

All previous analyzes are carried out in the range of elastic behavior. A way to use this information for the diagnosis is to estimate an 'elastic' threshold corresponding to the achievement of a level of strain in the elements leading to a beginning of damage. Using the correct model, identified by the previously described procedure and which allows to describe the global behavior with the opportunity to determine the local strains, it is possible to estimate the level of acceleration (within the meaning of the standard) that corresponds to the achievement of a criterion of deformation (Boutin, 2005). The question is then the choice of this criterion. The more natural is the limit in extension of the concrete (10^{-4}). For concrete structures weakly reinforced, this criterion may be sufficient. For structures better reinforced, this criterion gives a first level of cracking, but it will be too restrictive. We can consider to use the limits the compression of the concrete or of plasticification of the steel (10^{-3}), on the condition taking into account the nature of the elements in the presence (wall or column). We get through this an estimate of thresholds (in acceleration) beyond which the functioning can change drastically. In any event, a comparison of these thresholds with the regulatory acceleration quantified, with the use of a minimum of assumptions and a timing by in situ measurement, a certain level of security can be used to establish a sieve between different structures.

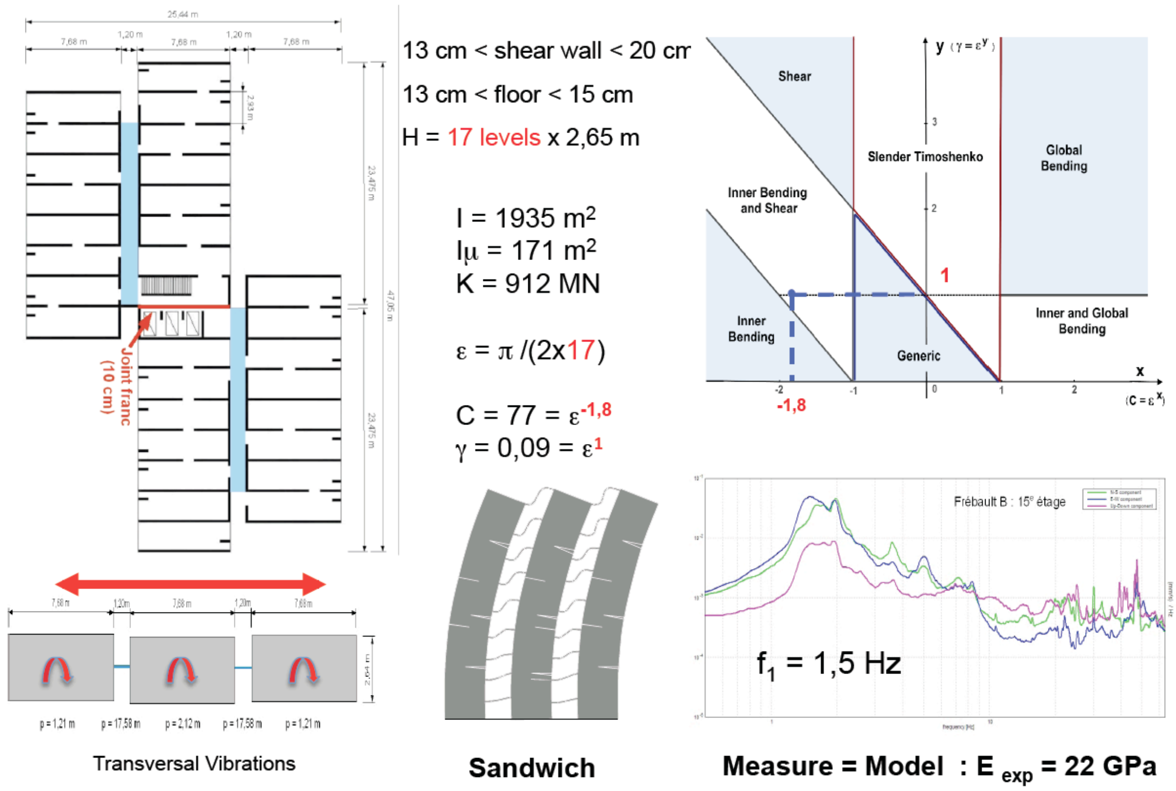

Figure 6. Tour Frébault. Estimation of transversal dynamic functioning.

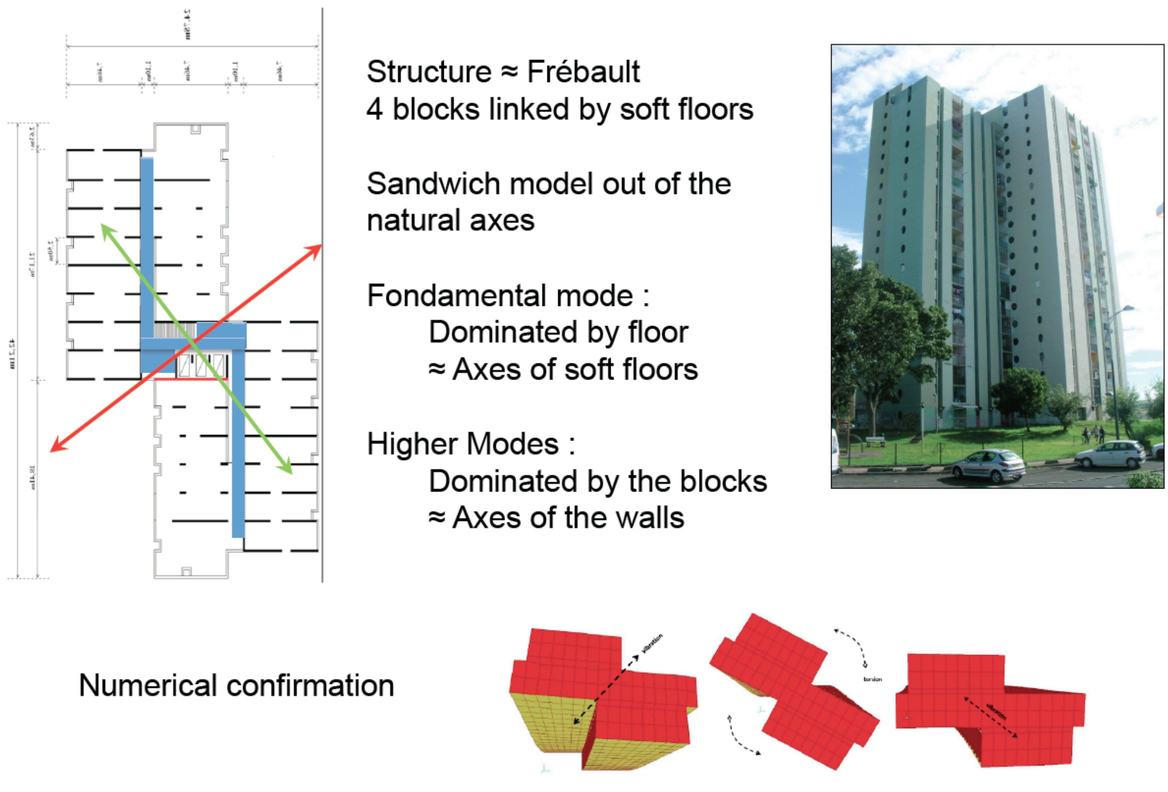

Figure 7. Gabarre. Estimation of dynamic functioning.

6. CONCLUSION

This article showed the interest of the measures of mechanical noise to the seismic assessement. It has been shown that these measures, very robust, reflect well on the real dynamic operation and allow you to highlight the complex mechanisms that it is not possible to prove otherwise to convincing way. However, these measures require an operating framework if it wants to access the internal structural operation of the building. The framework presented, applicable to buildings in periodic elevation, allows, once the proper model valid by the measures, to greatly simplify the analysis by replacing the dynamic study of a building by the dynamic calculation on a beam. The last step, the estimation of a level of vulnerability, is still a way to develop, and the concept of thresholds presented may constitute a track to deepen.

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