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THE USE OF FINITE ELEMENTS FOR DYNAMIC SIMULATION OF THE VIBRATORY BEHAVIOR OF FLAGSTONES

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Abstract. *One of the big problems of modern society is the effect of the noise on sleep. Noise increases the duration of the superficial sleep periods while the necessary periods for resting are drastically reduced. Waking up normally occurs due to noise peaks, between 8 and 19 dB (A), above background level. In modern buildings where the flats have thin flagstones and great free surfaces, someone walking during the night can become a tragedy for rest of the neighbor in the lower flat. The zero flagstone concept in civil construction result in thin floors with poor acoustic properties which is in disagreement whit the acoustical requirement of at least 50 CTSA for floor between superposed units. The level of transmitted impulsive noise between flats is strongly dependent on the flagstone configurations such as distance between beams and type and thickness of the regularization, for example. In function of the different possibilities of building plants it would be interesting for the architect and the civil engineer to predict the transmitted impulsive noise levels between superposed flats to define the best acoustic project. In this way a study of the applicability, and viability, of the use of finite element method for the solution of vibroacoustics problem of impacts in residential flagstone is interesting. The main problem of this approach is the properties of the element used to model flagstone and structural beams which is highly nonlinear because the stiffness of concrete in traction is zero. The usual dimensions of the flagstone make dynamic simulations of the transient responses due to impulsive forces not practical. To resolve this problem, this study uses linear shells and beams to model the flagstone transient dynamic response. Given flagstone geometry, first, through a static deflection analysis, the parameter values of the linear elements is adjusted so that the analysis results are in agreement with the nonlinear results. A series of simulations with a small flagstone was done to study the influence of the impulsive parameter (intensity and duration of the impact) precision. Finally, the simulations are compared with experimental measurements of a residential flat for validation purposes.*

Keywords: *Flagstones, dynamic simulation, and finite elements*

1. Introduction:

The urbanization model in big cities has become vertical due to various reasons. Nowadays, we work and live in multi-storey buildings because of security, transport difficulty or centralization of economy in specific regions. Hence generating areas of high population density. Changing from an isolated construction to a building in which an occupied unit is separated from other neighboring units only by walls, ceiling and thin floor with poor acoustic implies in a series of considerations to permit living together without conflicts. Some of these considerations are in regard to behavior involving respect to the neighbor's rights. Others, however, are the responsibility of the architects and the engineers.

One engineering problem is in consequence of floor isolation of impact noise, where the normalized indices of acoustic performance of the floors should be obeyed, otherwise the footstep noise of the person above will be transmitted with little attenuation.

The history of civil construction shows a view of great technological advances in building construction by different races and cultures in various regions. However in the search for cheaper materials and design optimization, these innovations lead to constant reduction of acoustic isolation of the building elements. On the other hand, civil construction nowadays has a range of new equipment, which offers comfort, and practicity to the everyday life of the XXI century man. However, some undesired consequences are also incorporated. One of the results is an increase in noise pollution, sometimes not considered by many people, but which causes effects harmful to health. Also along the years, while the buildings became less isolated acoustically the level of background noise has increased exponentially (Duarte, 2003).

In a globally competitive world, the civil construction companies naturally try to reduce their costs to become more and more competitive, which result in a continuous new technology search. In this technological advance, many times, the acoustical comfort of the future residents is not taken in account. For example the use of new materials mechanically stiffner and modern construction techniques, it is possible to reduce the thickness of the floors and walls, reducing the weight and allowing the increase of usable area of the building, consequently buildings are built, that:

a) Do not protect adequately the resident from normal external noise.
b) Do not permit its use as expected without exceeding the noise limits and hence prejudice the neighbor's silence and health.

According to Presets, 2003, the principal cases verified related to problems of inadequate isolation in buildings are:

a) Buildings without the intermediate layer, that is, the tiles are applied directly on the 8-cm thick concrete flagstone.
a) Buildings with pre-molded flagstone.
b) Buildings with thin walls of insufficient isolation.
c) Buildings with ventilation shafts between bathrooms that allow one to hear the neighbors` shower.

Sometimes resident blames the neighbor above without knowing that the noise came through the building structure from floors even higher up. Complaints common in buildings, such as noise from walking and from children jumping, are noise from impacts that make the flagstone vibrate and in following are transmitted by the walls responsible for generation of up 50% of the noise from impacts (Nunes et al, 2004). The other 50% of vibration energy of a reinforced concrete flagstone are transferred to beams and columns. These supports, once connected to the walls of the floor below, will cause the walls to vibrate and became secondary sources of noise.

The use of absorbent materials applied to the flagstone and walls, like sheets of glass fiber or mineral wool, can reduce the noise in 40%, which not always satisfies people more sensitive to this type of problem (Baring, 2000).

Of all environment noise, the impact ones is the must difficult to be reduced because impacts on whatever rigid surface produces vibrations, which generates noise audible to the human ear as of 20Hz (low frequency), which is very difficult to be treated.

Due to importance of impact noise in buildings, this paper presents a study about the viability of applying the finite element method to solve vibroacoustic problems by prediction of vibration behavior resulting from impacts loads on flagstone in residential buildings.

2. Methodology:

The proposed methodology consists of predicting, still in the design phase, the vibration velocity pattern of a flagstone due to impact forces, using finite element technique. For modeling of flagstone and structural beams, element of the concrete type was used. This type of element is highly nonlinear once the rigidity of concrete in tension is not considered. These nonlinerities together with the usual size of the flagstones make the dynamic simulation of transient vibrations responsible for transmission of noise due to impact in large flagstones not practical. To overcome this problem, this paper studies the possibility of using Shell type elements to simulate transient vibrations in flagstone in residences.

After the viability study of the proposed methodology with a sample flagstone of 1 m^2, a real building was chosen and its flagstone was modeled using finite elements and the transient vibration response was simulated. During the construction of the building, the vibration levels of a standard flagstone was measured to be used in studies of the vibration transmission pathsin the structure of the building and to validate the prediction of the vibration behavior by finite element technique, when the simulated average velocities of vibration were compared with the experimental ones.

The experimental flagstone structure used in this work is shownd in Fig.1. The flagstone studied has 10 cm tickness with both positive and negative reinforceements placed 0.005m from the surfaces of the flagstone. However the spacing between the trams vary in the structure. The distances shown in Fig.1 are used for illustration purpose only.

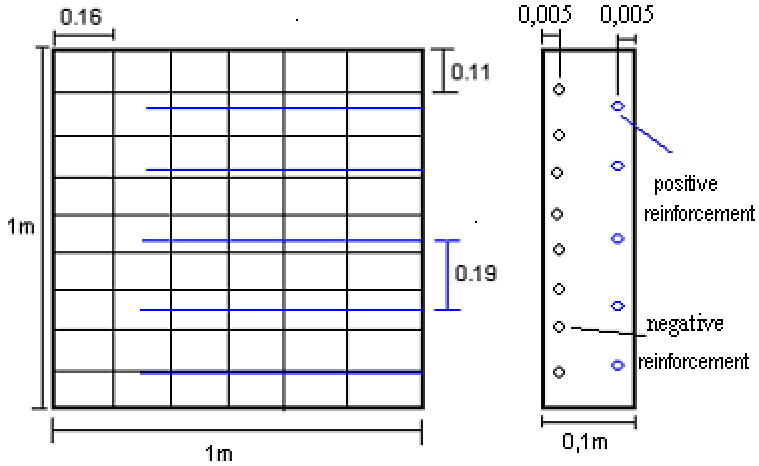

Figure 1 - Reinforced concrete flagstone

The experimental procedure consisted of applying controlled impacts during various phases of the construction of the apartment and measuring the vibration levels in flagstones, beams, columns and walls to quantify the different paths of transmission of vibrations in the building. The average sound pressure levels in the apartment were also measured to estimate the irradiation efficiencies (Beranek, 1992).

In the numerical simulations with ANSYS software the 'Solid65' and 'Shell93' models were used. The 'Solid65' is a reinforced concrete model, which uses 'Link8' elements for the steel trams. This element model resists only tension loads and is highly nonlinear, which makes its use, for a parameter analysis involving transient response of large flagstone, not practical. On the other hand, the element 'Shell93' is linear , which permits the use of reduced models (condensed or modal analysis). Once the amplitudes studied are small (of order of 10^{-3} m), it is believed that the use of this element ('Shell') in simulations produces results of engineering precision (+/- 3 dB in acoustic).

The methodology used for simulation is constituted of 6 steps:

- Static analysis of the flagstone to ajust the elasticity modulus of the shell model, which results in the same deformation that is obtained with the nonlinear model for a given static load at the excitation point.
- Estimation of the proportional damping factors to be used in finite element analysis (alfa and beta coefficients).
- Estimation of the force applied during the experimental procedure.
- Transient analysis using the finite element model.
- Experimental procedure and preparation of the data set (filtering, integration, rms. circuit and etc).
- Comparison of the results.

First, the flagstone of the chosen flat was modeled and the Modulus of Elasticity of the equivalent 'Shell93' elements is ajusted so that the "Shell93" solutions was ajusted with the static deflection of the simulations with the nonlinear 'Solid65' element model. For analysis, the flagstone was divided in sub-areas depending on the number of beams and the steel meshing used in the concrete. The sub-area division is shownd in Fig.2. In following, a transverse load of 500 N is applied at the center of each area and the deflections calculated for 'Shell93'and 'Solid95' respectively. The equivalent Young's Modulus for 'Shell93' is obtained using Eq.1.

$$E_{shell\_eq} = E_{concrete} * \frac{\Delta_{concrete}}{\Delta shell} \tag{1}$$

Where, $E_{shell\ eq}$ is the equivalent Modulus of elasticity to be used for 'Shell93'.

$E_{concrete}$ is the Modulus of elasticity of concrete (E=2600 Kg/m^3).

Δ_{shell} is the deflection obtained at the center of each sub-area using 'Shell93'with properties (density and Poisson's ratio) same as concrete.

$\Delta_{concrete}$ is the deflection obtained of the center of each sub-area using 'Solid65'with properties of a 10 cm thick slab of concrete.

The apartment's flagstone was divided in 23 areas and then 23 equivalent Young's Modulus was obtained. Figure 2 shows the 23 areas with the dimensions.

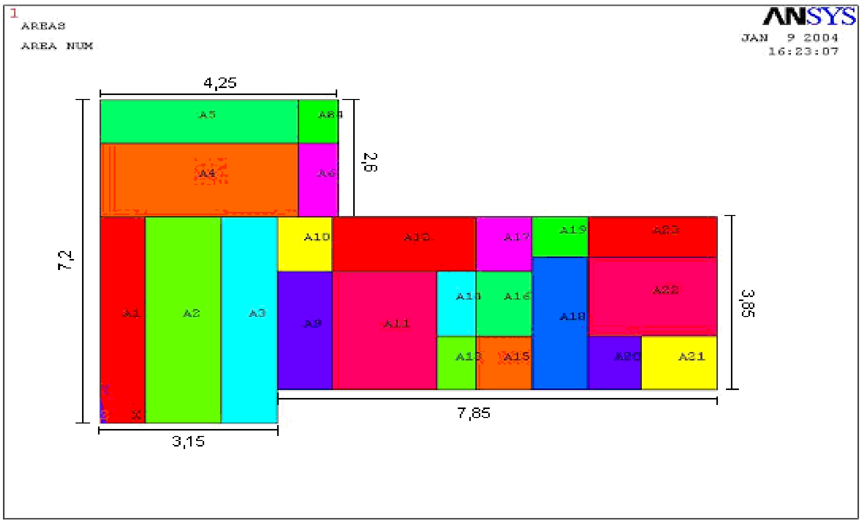

Figure 2 - Equivalent areas ('Shell93')

In the next step the proportional damping coefficients factors (alfa (α) and beta (β)) to be used in the model were estimated. The results of a modal analysis testing of a reduced model (1 m^2) were used. After the modal testing, two extracted modal damping factor (natural frequencies of 19 Hz and 1000Hz, respectively) was chosen to get the proportional damping factors according to Eq. 2.

$$\begin{Bmatrix} \alpha \\ \beta \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{2 \cdot \omega_{19}} & \dfrac{\omega_{19}}{2} \\ \dfrac{1}{2 \cdot \omega_{1000}} & \dfrac{\omega_{19}}{2} \end{bmatrix} \cdot \begin{Bmatrix} \delta_{19} \\ \delta_{1000} \end{Bmatrix} \tag{2}$$

Where, ω_i is the i-th modal's natural frequency.
δ_i is the i-th modal damping coefficient.

The third step consists of estimation of the real force applied to the flagstone to be used in transient simulations. A test bench made up of a steel bar supported on 3 load cells as shown in Fig.3 was used. The same conditions used in applying loads in the flagstone were repeated at the test bench. 10 tests to measure the forces was done, where each test results in 5 impact load data. The sample rate of 4096 Hz was used in the acquisition system. The average force at each load cell was calculated in the frequency domain. After the averaging procedure, an inverse Fast Fourier Transform (FFT) algorithm was applied to get a time domain force vector with 4096 points to be used in simulations of the vibration behavior of the studied flagstone.

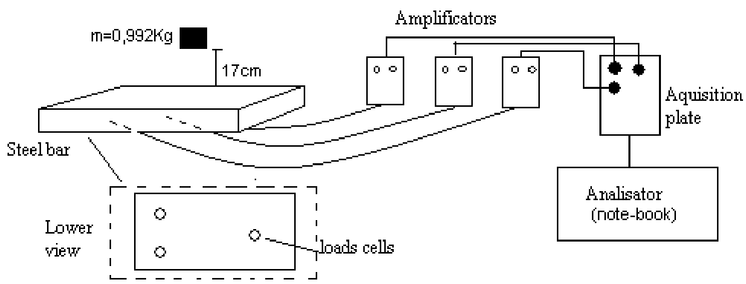

Figure 3 - Experimental workbench utilized for determination of the impact force.

The last step consists of modeling the equivalent flagstone using 'Shell93'elements. The element has 6 degrees of freedom in each node: translation (in x, y and z) and rotation (in axis x, y and z).

Due to the size of the structure (large number of nodes and elements), it is necessary to make a reduced transient analysis (Guyan's condensation). A Newmark's family algorithm (α=0.25 and δ=0.505) was used for integration procedure to obtain the transient responses.

The transient force was applied at the node corresponding to the experimental force (x=1,89 m and y=5,29m). The analysis was made in 5 steps and each step is subdivided in intervals of dt=1/4096s. The sub-step size is related to the data acquisition frequency so that the total integration time is equal 1 second.

The numerical solution using first order finite differences yield the displacement and the velocity values at 85 random nodes. The mean square values of the velocities in 1/3 octave bands are used to predict the sound power level generated by vibration of the surfaces. The velocity values were obtained from the filtered signal using a 6-th order Butterworth digital filter.

The 1/3 octave frequency bands ranged from 63 Hz to 2KHz. After filtering, the signal is squared and its mean square value is obtained by a routine with time constant of 125 ms for the study of impact noise. The theoretical mean square vibration velocity values were compared with the experimental values.

3. Results and Analyses:

The material properties corresponding to each element type that was used in simulation steps are shown in Tab.1, when the equivalent Elasticity Modulus was obtained from Eq. 1 according to previously shownd in the methodology section.

Table 1 - Materials Propriety used

Elements	E(MPa)	ρ(Kg/m^3)	ν
Solid65	$2.5x10^{10}$	2600	0.17
Link8	$2.1x10^{9}$	7800	0.29
Shell93	$2.5x10^{10}$	2600	0.17
Shell_equivalent	E(MPa) obtained from Eq.(1)	2600	0.17

The good agreement found between the deformed shapes curves, due to a static load, resulting of the use of the two finite elements models show that the change of ‘Solid65’ model by ‘Shell93’ modal is possible in small amplitude transient vibration analysis. For example, Figs. 4 and 5 show the displacement curves obtained for area 1. Observe that although the two models result in different values for the displacement curves, the shape of the two graphs are similar.

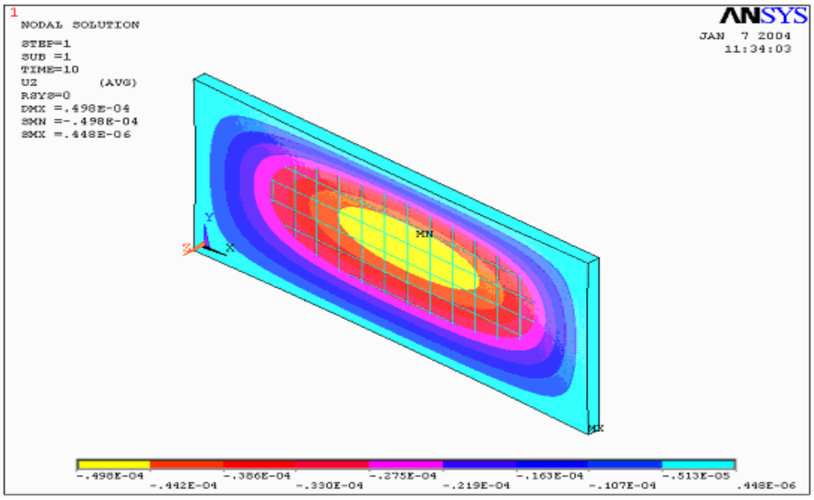

Figure 4 - Area 1 modeled as element 'Solid65'

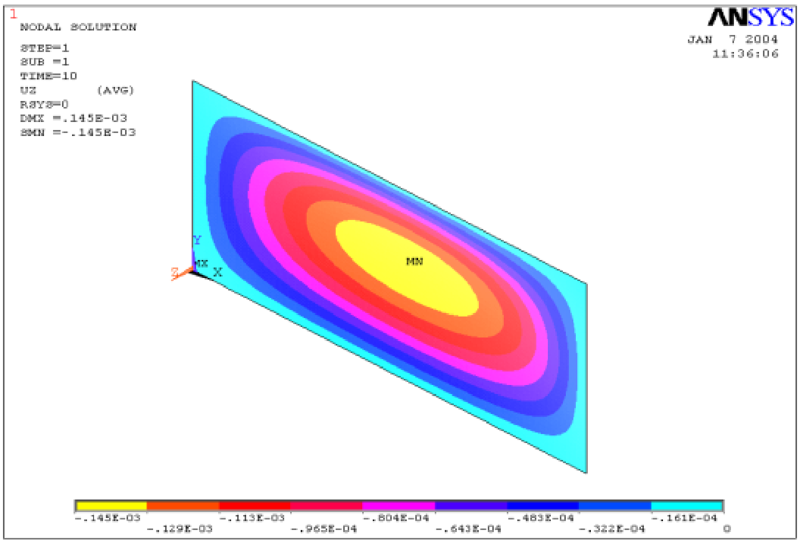

Figure 5 - Area 1 modeled as element 'Shell93'

Figure 6 shows the displacement curves for area 1 modeled using element 'Shell93' with equivalent Young's Modulus. Comparing Fig.4 and Fig.6, the displacement values of the two models are close.

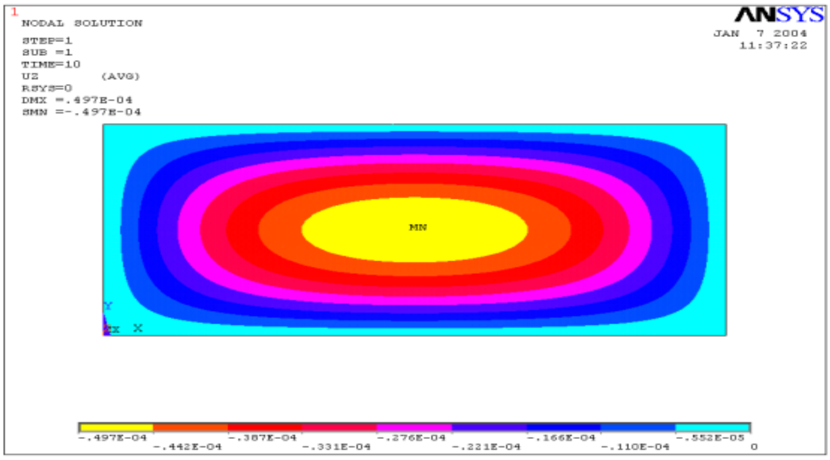

Figure 6 - Area 1 modeled with 'Shell93' and equivalent Modulus of Elasticity given by Eq.1

Table 2 shows the equivalent Modulus of Elasticity for the 'Shell' sub-areas as given by Eq.1. A variation of 30% in the values due to different trames and area sizes can be seen.

Tabela 1 - Equivalent Modulus of Elasticity obtained from Eq(1)

Areas	E(MPa)	Areas	E(Mpa)
1	7.279×10^{10}	12	6.8919×10^{10}
2	8.0212×10^{10}	13	6.597×10^{10}
3	6.5965×10^{10}	14	5.7721×10^{10}
4	1.1252×10^{10}	15	8.6163×10^{10}
5	6.4694×10^{10}	16	4.5394×10^{10}
6	7.6149×10^{10}	17	4.5394×10^{10}
7	7.9202×10^{10}	18	6.0465×10^{10}
8	5.7843×10^{10}	19	7.2781×10^{10}
9	7.4036×10^{10}	20	5.9796×10^{10}
10	6.0465×10^{10}	21	6.2984×10^{10}
11	6.8966×10^{10}	22	6.5789×10^{10}
		23	1.1618×10^{10}

The proportional damping factor adjusted values are shown in Tab. 3.

Table 3 - Damping factors values

α	β
12,8299	4,0184

The force applied in experimental measurements was obtained as described previously. The signal obtained was simplified to a minimum of load steps for numerical solution of the problem. Figure 7 shows the force model used in numerical simulations.

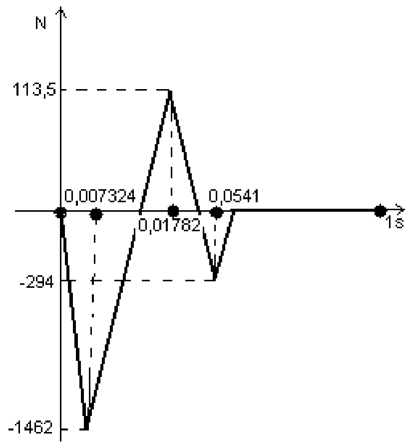

Figure 7 - Experimental transient force

Elements of size of 0.05m, 5 time steps (shownd in Fig 7) and duration of 1 second was used for transient simulating, with sub-steps of 1./4096 s. The boundary conditions are considered as simple supported nodes in the beam regions which is used in structural engineering design. Figure 8 shows the model used in analysis.

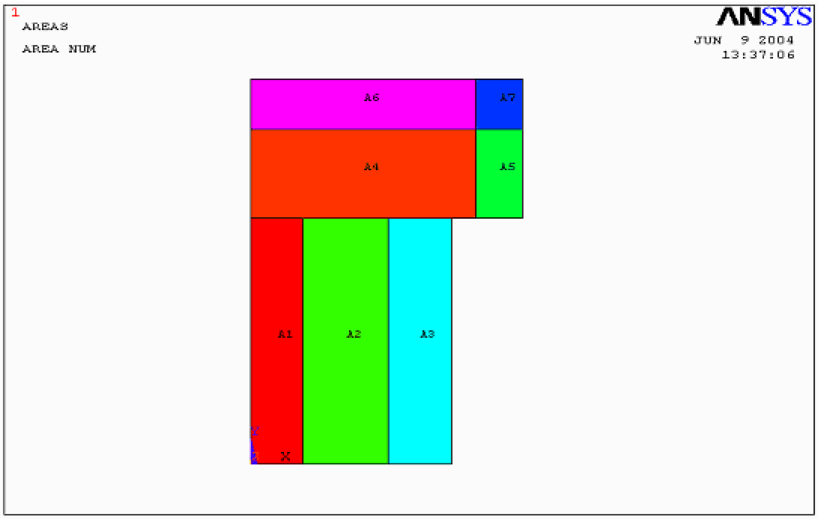

Figure 8 - Area modeled for transient analysis

The displacement curves in time for 85 random points (nodes) were obtained. For example, Fig. 9 shows the displacement shape for node 22041 at time equal 1 second. The deflection of this node vs. time is shown in Fig.10, where it is possible to observe that a time interval of 1s is sufficient for transient analysis.

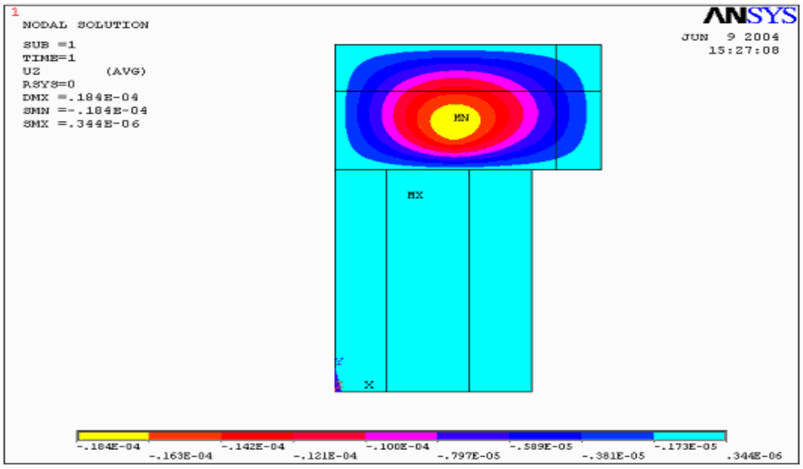

Figure 9 - Displacement obtained in the structure at t=1s.

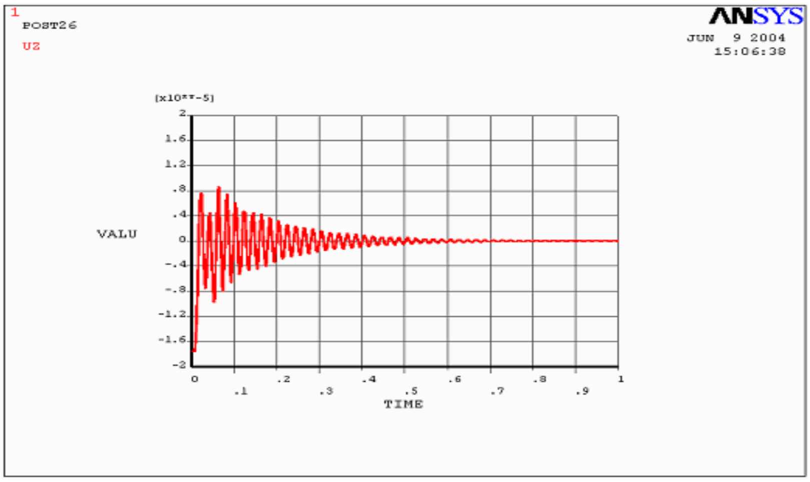

Figure 10 - Displacement against time at node 22041

Starting from the results of the numerical solution, the velocities at the 85 points are calculated. The velocity is obtained differentiating the deflection (first order finite difference). The average of the 85 points was compared with the results obtained experimentally in 1/3 octave bands.

Figure 11 shows both numerical and experimental results from 63 Hz to 2000 Hz in band of 1/3 octave.

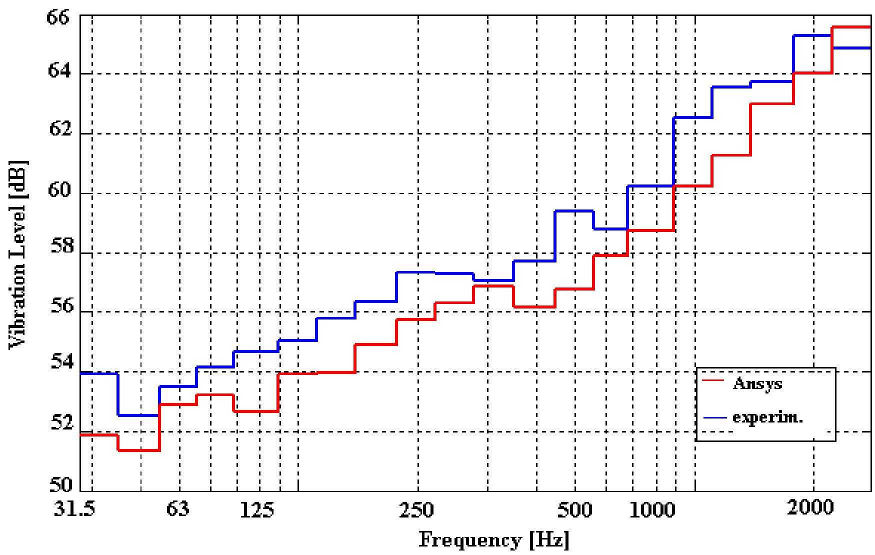

Figure 1 - RMS Velocity in dB

Figure 11 shows good agreement between theoretical and experimental results with an average error of 3 dB, which is expected due to the precision of the field measurements.

4. Conclusions:

The technological advances in the last decade in the area of digital electronics made available quicker computers with more memory, which made possible the use of numerical methods for solution of complex vibro-acoustic problems.

However, even with this technology it is necessary to find new methods in order to reduce cost and time of computation. This paper shows that the possibility to do vibroacoustic studies of reinforced concrete flagstone modeling using linear elements (Shells). In this way, the designer can predict the vibro-acoustic behavior of a building at the design stage and can act to reduce the noise effects.

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7. Responsability notice: