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A 3D FINITE ELEMENT MODEL FOR THE DETERMINATION OF VIBRATION REDUCTION INDEX FOR JOINTS WITH FLOATING FLOORS

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Abstract. *This paper is in the context of building acoustics and the aim is to obtain a more accurate approach of the acoustic insulation prediction on constructive solutions, quantifying the contribution of the structure borne sound. It is necessary to point out that the standard UNE-EN 12354, in his parts 1, 2 and 3 [1, 2, 3], provides some tools for its estimation. However, these tools are not accurate enough and a better quantification of sound flanking transmission is needed. On the other hand, the procedure for laboratory flanking transmission determination is presented in [4]. A similar procedure is used for in situ measurements, but the comparison between experimental and theoretical results is not satisfactory at all [5, 6]. Numerical methods can facilitate the implementation of acoustic projects and provide better results at a low economic cost. In this work we present 3D Finite Element Model for the determination of vibration reduction index on joints with floating soils. This work can be considered a continuation of [7], where a 2D model was presented.*

1 INTRODUCTION AND PURPOSE

The present paper is situated in a Project in the building's acoustics research context. Its general objective is to contribute to the improvement of the predictions to air-borne sound insulation and impact sound insulation of the more used constructive solutions. It consists of endowing numerical methods and/or experimental data that facilitate the realization of the acoustic projects and provide more accurate results.

It is necessary to point out that the standard UNE-EN-12354, in their parts 1, 2 and 3 [1,2,3] provides some tools for estimation. However, these tools are not sufficiently accurate as it would be desirable concerning to the transmission of sound by flanks. On the other hand, the procedure for laboratory flanking transmission determination is presented in [4]. A similar procedure is used for in situ measurements, but the comparison between experimental and theoretical results is not satisfactory at all [5, 6]The Project consists of improving these tools, following the methodology that is explained later, starting from the following work lines:

1. Measurements with scale models (but of size near to the real one).
2. In-situ measurements to air-borne sound insulation and impact sound insulation.
3. Numerical simulations with the finite element method.

A first evaluation of the numerical simulations will be achieved by the equations indicated in the mentioned normative. The results of the measurements with scale models will provide us a second approach, and the last approach will be given by the in-situ measurements.

The results expected in this project are the following:

1.A more accurate approach to the problem of the prediction in the acoustic insulation of constructive solutions, quantifying the contributions of the transmitted sound in the structure regarding to the air-borne sound insulation and impact sound insulation.

2. Location of weak points in acoustic insulation solutions ("in situ").

3. To have computer tools for simulating the global behaviour of the partitions "in situ".

In order to achieve this goal, we are working in both the vibrational characterization of structures like those in Figure 1:

Figure 1. Experimental models under study

as in the implementation of numerical models that respond to the experimental measurements.

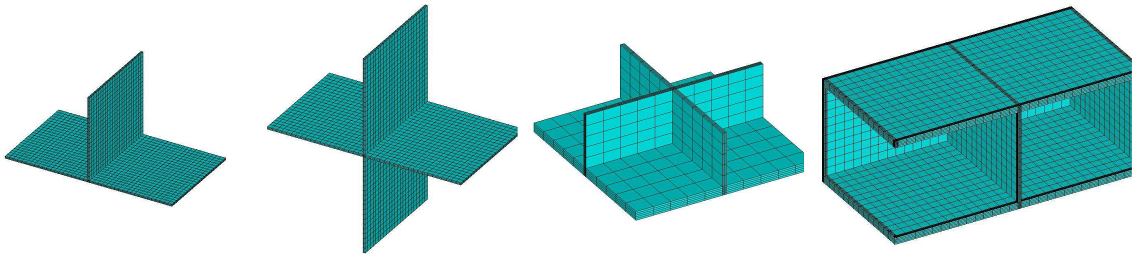


Figure 2. Numerical models under study.a)T joint b) Cross-joint c)Cross with slab d) Coupling rooms

In this work we present 3D Finite Element Models for the determination of vibration reduction index in models a) and b) on joints with and without floating soils and a methodology to adjust the numerical results to the standard is proposed.

2 BACKGROUND THEORY

According to [1, 2, 3] flanks transmissions can be determined by the vibrational reduction index. This standard provides empirical formulas recognized for some constructive solutions and a limited set of designs with rigid or elastic elements inserted. Solutions for “heavy” elements with an elastic interlayer and a given material Young’s Modulus/thickness relationship are offered.

The Kij vibrational reduction index is a quantity related to the vibrational power transmission through a junction between structural elements, normalized in order to make it a scale invariant. It can be determined experimentally through laboratory tests according to ISO 10848-1 [4]. The volumes and corresponding dimensions of the test compounds should not be exactly the same. It is recommended a difference in the volumes and / or linear dimensions of at least 10%.

The vibrational reduction index is determined experimentally by normalizing the averaged velocity levels difference of speed in all over the joint, $\overline{D}_{v,ij}$, with the length of the junction and the equivalent absorption length, if relevant, from both elements according to equation (1):

$$K_{ij} = \frac{D_{v,ij} + D_{v,ji}}{2} + 10\log\frac{l_{ij}}{\sqrt{a_i \cdot a_j}} \tag{1}$$

$D_{v,ij}$ is the velocity levels difference between elements i and j when i element is excited, in dB, $D_{v,ji}$ is the velocity levels difference between elements j and i when j element is excited, in dB, l_{ij} is the length of the junction between elements i and j, in m, a_i is the equivalent absorption length of element i, in m, a_j is the equivalent absorption length of element j, in m. The equivalent absorption length can be calculated using equation:

$$a = \frac{2.2 \cdot \pi^2 \cdot S}{c_0 \cdot T_s}\sqrt{\frac{f_{ref}}{f}} \tag{2}$$

being T_s the structural reverberation time of element i or j, in s , S the area of element i or j in m^2, f is the band central frequency, in Hz, f_{ref} is the reference frequency, 1000 Hz and c_0 is the speed of sound in air, in m/s.

In [1], Kij given equations are obtained through empirical data, for common types of joints, depending on the surface densities of the elements connected to the union, denoted by m1 and m2. These expressions can be used only for the case of unions in which the elements on both sides of the junction in the same plane have the same mass, thus, the mass ratio is reduced to two. Figures 3 and 4 show rigid joint.

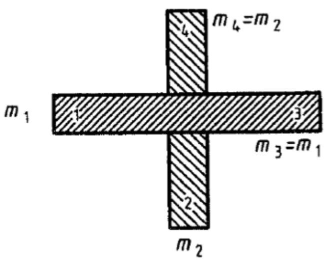


Figura 3. Rigid cross joint

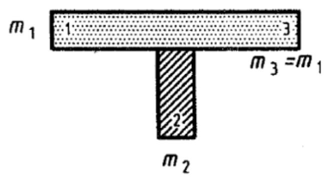


Figura 4. Rigid T joint

In the case of a T rigid connection, the following relations for the vibrational reduction index are defined:

$$K_{13} = 5{,}7 + 14{,}1\,\mathrm{M} + 5{,}7 \cdot \mathrm{M}^2 \quad \text{dB;} \qquad 0 \text{ dB/octave} \tag{3}$$

$$K_{12} = 5{,}7 + 5{,}7 \cdot \mathrm{M}^2 \;\; (= \mathrm{K}_{23}) \quad \text{dB;} \qquad 0 \text{ dB/octave} \tag{4}$$

These expressions are given in terms of the magnitude M, defined as $M = \lg \frac{m'_{\perp i}}{m'_i}$, where m'_i is the mass per unit area of element i in the transmission path ij, and $m'_{\perp i}$ mass per unit area of the other element, perpendicular to i , that forms the union. The calculation of these masses only takes into account the base material connected to the adjacent construction elements and masses of the coatings, such as floating floors, suspended ceilings and extrados must be excluded. The magnitudes given in (3) and (4) are no frequency dependent. The standard states that, in general, the transfer is less dependent on frequency in the range of 125 to 2 kHz, so it is considered 0 dB / octave

The vibrational reduction in the joints can be significantly improved with flexible intermediate layers. For flexible intermediate layers, the improvement on the the rigid, Δ_1, is characterized by a frequency f_1 that depends on the elastic modulus E_1 and the thickness of the flexible element brought t_1, see Figure 5. Regarding the above equations, there is a correction factor Δ_1, which represents the outcome depending on the frequency of Kij and that it is valid for a certain relationship between Young's modulus and thickness of the interlayer. Recognized formulas are:

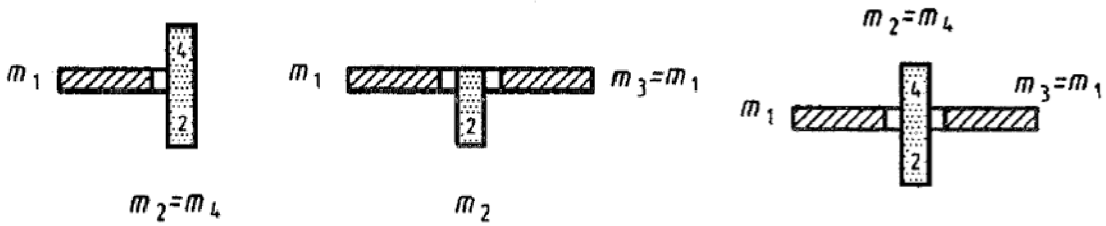


Figura 5. Joints with flexible interlayers

$$K_{13} = \mathbf{5{,}7} + 14{,}1\,M + 5{,}7 \cdot M^2 + 2 \cdot \Delta_1 \quad dB; \tag{5}$$

$$K_{24} = 3{,}7 + 14{,}1\mathrm{M} + 5{,}7 \cdot \mathrm{M}^2 \quad \mathrm{dB}; \qquad -4\,\mathrm{dB} \le \mathrm{K}_{24} \le 0\,\mathrm{dB}; \tag{6}$$

$$K_{12} = \mathbf{5{,}7} + \ 5{,}7 \cdot M^2 + \Delta_1 \ \ (= K_{23}) \ \ dB; \tag{7}$$

$$\begin{aligned} &\Delta_1 = 10 \cdot lg\left(f \,/\, f_1\right) \quad dB \quad para\ f > f_1\,, \\ &f_1 = 125\,Hz \ \ si\,(E_1 \,/\, t_1) \approx 100\,MN/m^3 \end{aligned} \tag{8}$$

For flexible intermediate layers, the improvement of the interlayer on the rigid joint, Δ_1, is characterized by a frequency f_1 that depends on shear modulus G, the thickness t_1 of the flexible element interposed, and the density ρ_1 and ρ_2 of connected elements. This frequency varies according to the following expression:

$$f_1 = \left(\frac{G}{t_1 \sqrt{\rho_1 \rho_2}} \right)^{1.5} \tag{9}$$

The estimation given in (9) is a global value for some typical joints, characterized by $E_1 / t_1 \approx 100\ MN/m^3$, where E_1 is the elastic modulus ($G_1 \approx 0.3 E_1$) and t_1 is the thickness of the interlayer. The parameters determining the dynamic stiffness of an elastic band are her nature and thickness according to the following relationship: $s' = E_1 / t_1$. For the same material elastic modulus remains constant, therefore, when thickness increases dynamic stiffness decreases and the damping effect increases.

Pedersen defined crossover frequency f_1, see eq. (10), above which the improvement of the elastic layer increases with frequency. At low frequencies, regarding interlayer rigidity, no improvement can be appreciated due to the interlayer existence.

$$f_1 = 2.5 \cdot 10^{-6} \left(\frac{\sqrt{\rho_1 \rho_2}}{G} d \, \frac{t_1}{w} \right)^{-3/2} \tag{10}$$

where ρ_1 and ρ_2 are the volumetric densities of the elements that compose the union, G is the shear modulus, t_1 is the thickness of elastic layer, l is the common length of the elements that compose the union and w is the common length of the elastic element in the union.

For frequencies f < f_1, vibrational reduction can be calculated as if there were no interlayer. Above f_1 frequency, vibrational reduction increases $10\log(f / f_1)$ with an interlayer in the union, and $20\log(f/f_1)$ when the transmission path crosses two interlayers [8-10].

On the other hand, the vibrational reduction index can also be obtained experimentally following the procedure on ISO 10848-1:2006 [4]. As specified in this standard, it is possible to obtain the value of Kij using equations (1) and (2), from measuring velocity levels difference through into both directions and measuring the structural reverberation time of both elements. To obtain the velocity levels difference, standard marks a set of geometric constraints. Some of the conditions specified in the standard are:

• 3 excitation positions and 9 of transducer (3 * excitation) must be made on each element.
• The positions should be distributed randomly but not symmetrically.
• The position of the transducer and excitation points must meet the following minimum distances:

  • 0.5 m between the excitation points and the limits of the element to be tested.
  • 1 m between the excitation points and the associated transducer positions.
  • 0.5 m between each transducer position.

In addition, the corresponding standard for the determination of the velocity levels difference requires coupling conditions between the elements forming the union, if these conditions are not met, the data obtained from in situ measurements are not representative of the energy distribution between these elements, not being valid to obtain the reduction vibrational index. This coupling condition is assessed in the following inequality:

$$D_{v,ij} \geq 3 - \lg\left(\frac{m_i f_{cj}}{m_j f_{ci}}\right) dB \tag{11}$$

Where m_i, m_j are the masses per unit area of the elements, in kilograms per square meter, and f_{ci}, f_{cj} are the critical frequencies of the elements, in Hertz.

3 DEVELOPMENT

3.1 Numerical model description

A numerical experiment has been carried out, following the testing methodology specified in standard 10848 [5], regarding the placement of excitation sources and measurement transducers and regarding the models size. Materials simulated have a density of 2400 kg/m^3, a Young's modulus of 32 • 10^9 Pa and a Poisson coefficient of 0.22. The simulated thicknesses are 10, 20 and 30 cm and the internal loss factor 0.01. Regarding the elastic sheet, we have chosen a layer that meets the condition imposed by the formula (8b) and a loss factor of 0.2.

A constant force of 1N is applied in the considered frequency range at positions marked with arrows and the velocities at points marked by stars are obtained through finite element simulation, as can be seen in figures. There has been left 1 m between applied forces points, and 0.5 m between measurement points, trying to emulate the standard.

From simulations, velocities at different positions i, j are obtained. From this data, we obtain the average according to the standard and the average velocity levels difference is calculated.

To obtain the structural reverberation time, the following expression given by [2] is employed:

$$T_s = \frac{2,2}{f\eta_{TOY}} \tag{12}$$

Where the total loss factor can be obtained using the relationship:

$$\eta_{TOT} = \eta_{\text{int}} + \frac{m}{485\sqrt{f}} \tag{13}$$

And m is the mass per unit area. The formula is valid, according to [1], if m < 800 kg/m^2.

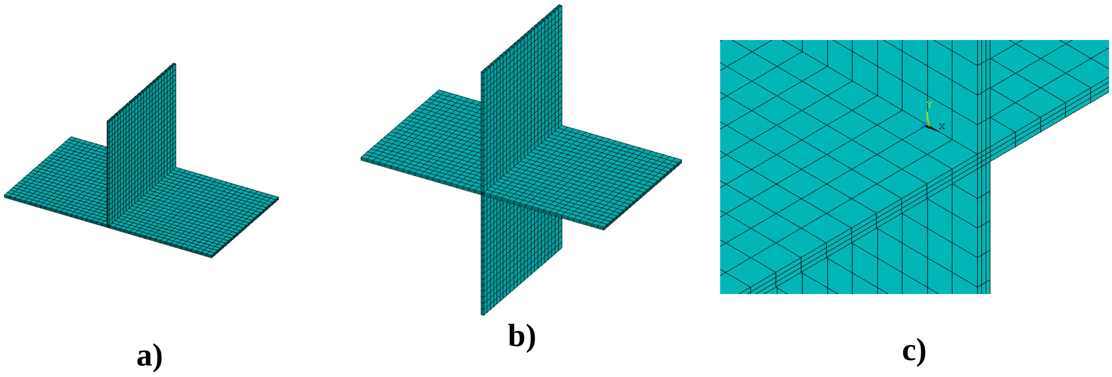
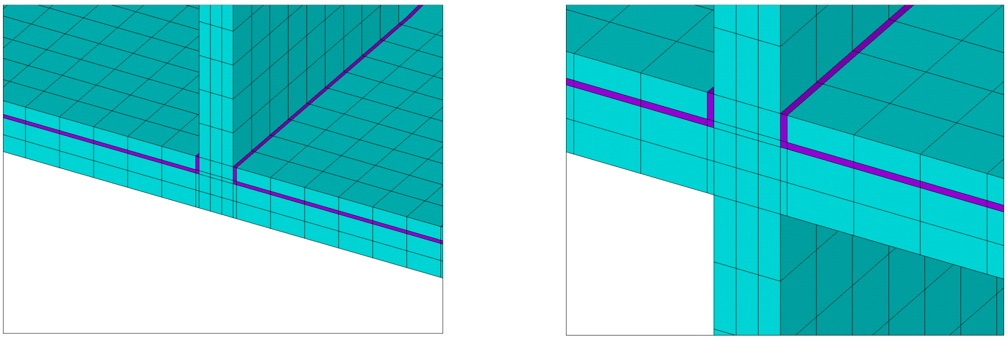


Figure 3. Models implemented. a) T joint. b) Cross-joint. c) Model details.

The Ansys finite element model has 5727 elements (with high order 3-D 20-node solid elements that exhibits quadratic displacement behavior. Three degrees of freedom per node: translations in the nodal x, y, z directions). The materials are modeled with linear behavior and a constant loss factor. The size of the elements is fulfilled if less than a tenth of the wavelength. Regarding the boundary conditions, there have been coerced three degrees of freedom of all nodes located at both ends of the model. To account for the complexity of the model suffice to say that for cross-joint has 29,808 nodes and 3 x 29808 = 89424 degrees of freedom. The elements used are type *Brick* knotted at the corners and centers of each edge.

In addition to the previous results and in order to compare them with the case where a flexible interlayer is assembled, two new models were implemented, one for each of the joints under study. Some details of the mesh employed for these models are shown in Figure 2.



a) b)

Figure 2. Models with flexible interlayer. a) T joint. b) Cross-joint.

As shown in the figure above, the flexible interlayer is not located as specified in [1] (Annex E), since there are no estimated equations for these kinds of joints where the interlayer does not cover the entire joint and it extends to the whole floor surface (pressure reduction index equations in Annex C [2] are obviously not directly applicable when evaluating K_{ij}).

3.2 Data results

Having simulated the models described above, the data results were exported from ANSYS and a tool for its smart visualization was developed in MATLAB. The main purpose was to be able to choose a frequency which velocities spatial distribution was desired to study, in order to visualize modal patterns on structures. An example is shown in Figure 3.

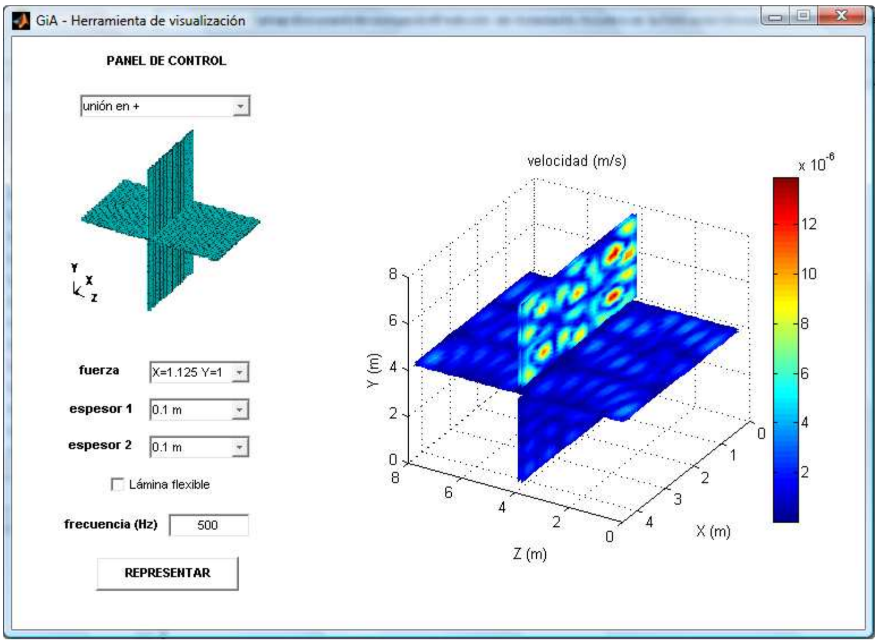
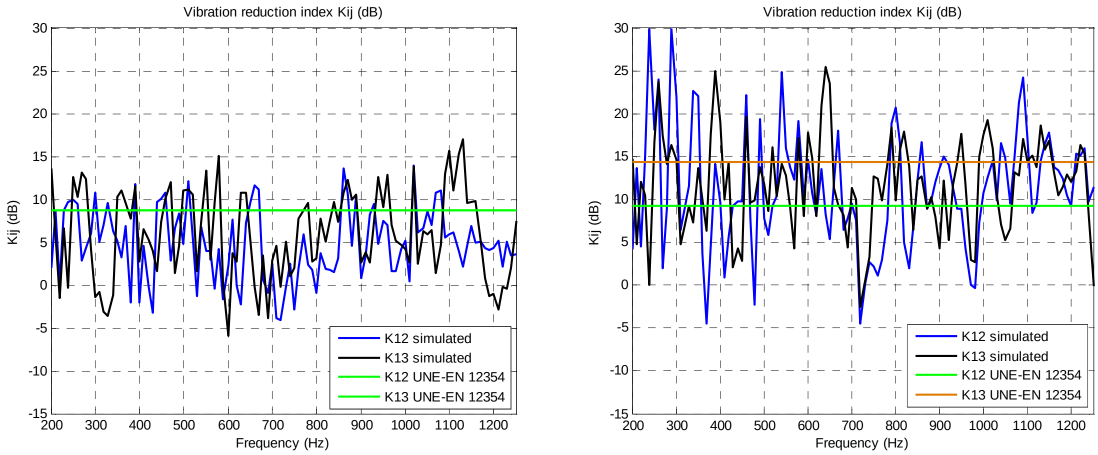


Figure 3. Data results MATLAB visualization tool

Since simulations were developed for several thickness combinations, it allowed us to compare the mass and geometry effect on structural vibration. Furthermore, as part of our interest to compare the results with UNE-EN 12354 estimations and to accomplish the measurement conditions specified in [4], simulations were carried out for several excitation points.

3.3 Numerical K_{ij} for rigid cross-joints

The first results to show are those obtained for rigid cross-joints. Having calculated velocity level differences as an average of several source and sensor points and meeting the relevant restrictions, we obtain the vibration reduction index for flanks of transmission and compare them with those of the standard.

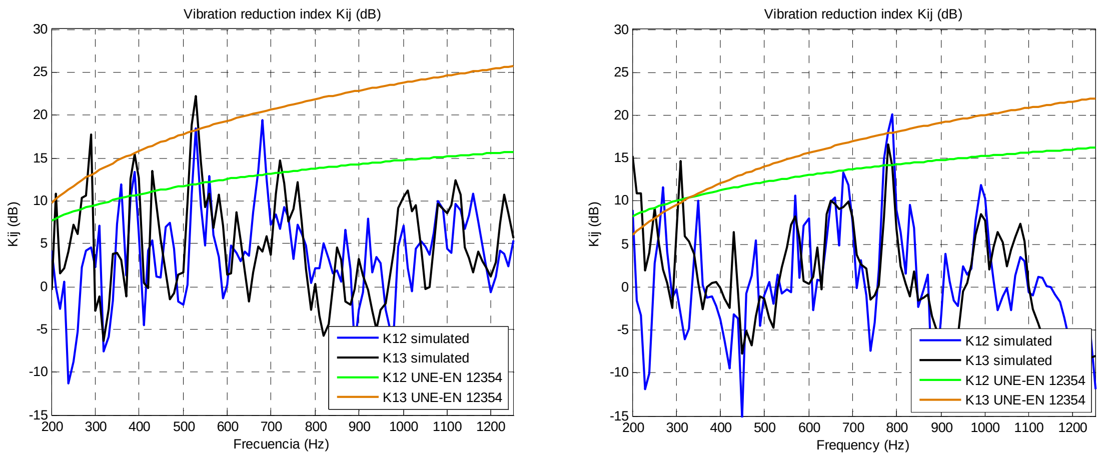


a) **b)**

Figure 4. Vibration reduction index K_{ij} for rigid cross-joints.
a) Same thickness (M=0). b) Different thickness (M≠0).

3.4 Numerical Kij for cross-joints with flexible interlayer

The results obtained when evaluating these models are shown in Figure 5.



a) **b)**

Figure 5. Vibration reduction index K_{ij} for rigid cross-joints with flexible interlayer.
a) Same thickness (M=0). b) Different thickness (M≠0).

There should be highlighted the fact that, like in the case of rigid junctions, some of the vibration reduction index values obtained are lower than the $K_{ij,\,min}$ specified in [1] (eq. (11)) ,and, therefore, should be neglected.

4 DISCUSSION

Firstly, we will focus exclusively on rigid unions. In order to make the simulation results and the empirical equations of UNE-EN 12354 converge, an adjustment of the first of them is proposed. Assuming that the elements i and j that take part in the junctions evaluated have an equivalent absorption length l_{ij} = 4.5 m and the same surface S = 16 m^2, we define a “coupling factor“ τ that relates i and j elements total loss factors $\tau = \eta_i/\eta_j$. The resulting K_{ij} expression:

$$K_{ij} = Dv_{ij} - 5\log\left(10.47\tau\eta_j^{\,2}f\right) \qquad (14)$$

where appropriate substitutions have been made (c_0 = 340 m/s, f_{ref} = 1000 Hz). Evaluating previous equation for different values of τ in a rigid cross-joint transmission flank where we assume a value of η_j=0.01, it can be appreciated the inverse relation between this parameter τ and the resulting K_{ij} (to make results more understandable, a linear fit and a full band frequency average have been applied).

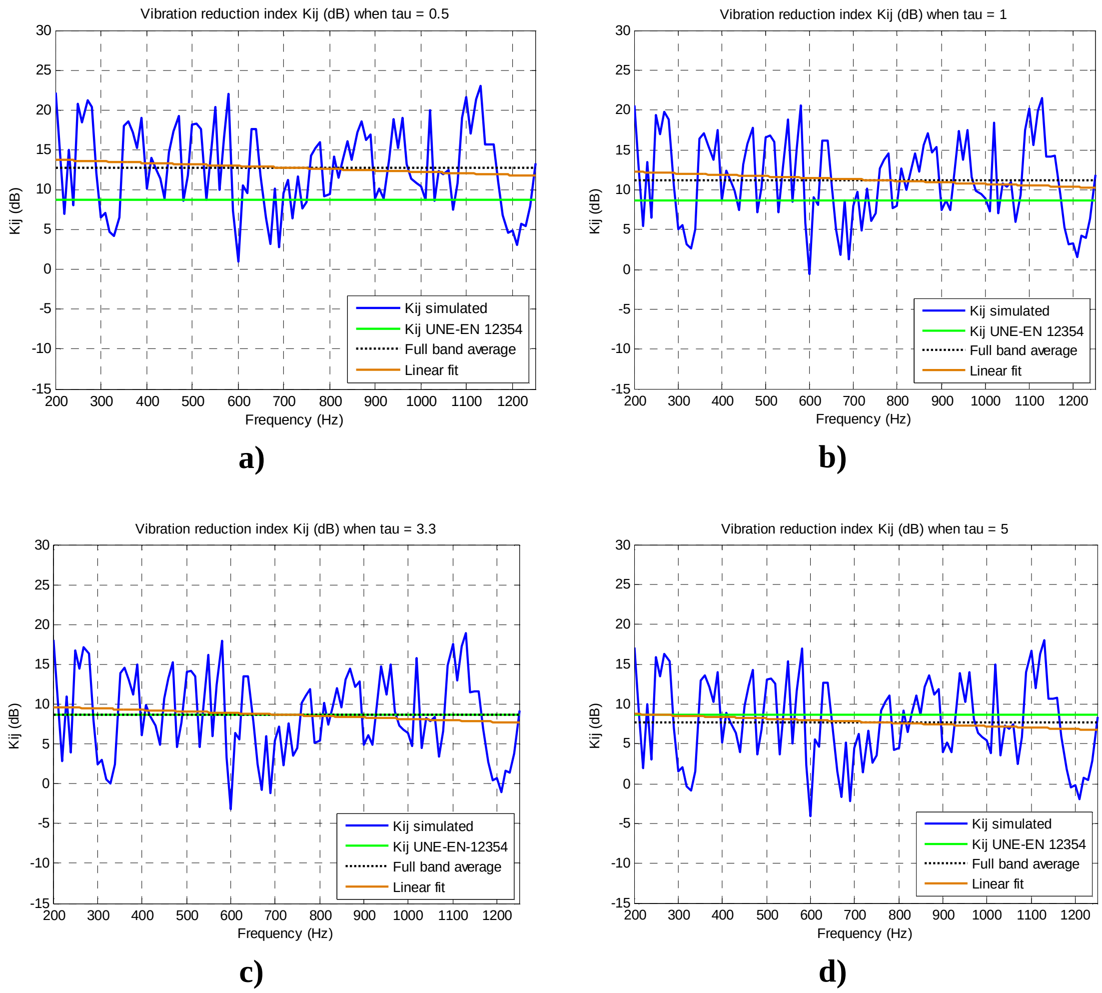


Figure 6. Vibration reduction index K_{ij} for rigid cross-joints with different τ values.

a) τ = 0.5 b) τ = 1 c) τ = 3.3 (optimum value) d) τ = 5

being the τ= 3.3 adjustment the nearest approach. However, unlike the models with flexible interlayer, no frequency dependence is considered for rigid junctions, that is why a more accurate analysis is needed. To carry it out, an additional frequency dependent term T is added to equation (14).

$$K_{ij} = Dv_{ij} - 5\log(10.47\tau\eta_j^2 f) - T \qquad (15)$$

this logarithmic* term T can be expressed as a frequency dependent variable *k* that multiplies frequency (the term T can also be expressed linearly as T = af + b, but it has been expressed logarithmically for inclusion in Kij formal expression). By introducing this term in previous equation, we obtain the final expression:

$$K_{ij} = Dv_{ij} - 5\log(10.47k\tau\eta_j^2 f^2) \qquad (16)$$

Therefore, replacing the previous τ and η_j values that better fit and giving values to *k* so as to obtain the linear fit of Figure 6c, the convergence between standard and simulations is achieved for *k* curve as in Figure 7.

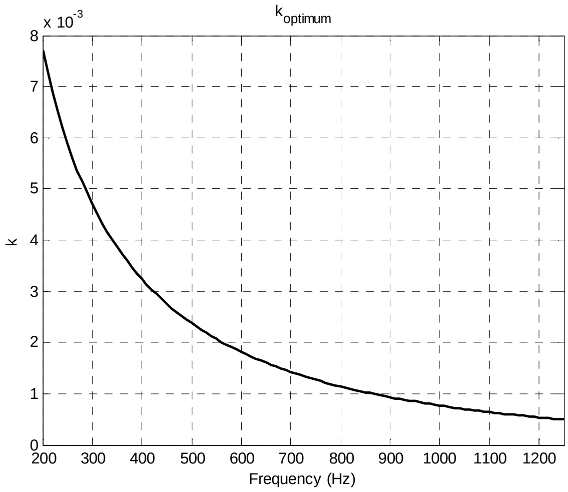


Figure 7. k curve that better converges with the standard K_{ij}

An exponential adjustment could be carried out in order to achieve similar results for joints with floating floors.

5 CONCLUSIONS

We have presented a 3D Finite Element Model for the determination of vibration reduction index in models. Results are showed for T and Cross joints, with and without floating soils. In addition, a methodology to adjust the numerical results to the standard is proposed.

ACKNOWLEDGEMENTS

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