# CHAPTER 1
# PREDICTION METHODS FOR SOUND AND VIBRATION PERFORMANCES, INCLUDING LOW FREQUENCIES

**COST Action FP0702**

Net-Acoustics for Timber based Lightweight Buildings and Elements

**Working Group 1**: Prediction methods for sound and vibration performances

# CONTENTS

**This chapter presents the final proposals for prediction of the relevant building performances, resulting from discussions during WG1 meetings; the proposals are presented separately for acoustics and vibration. The two documents produced can be seen as technical proposals which can be used as work documents in standardization committees**

# 1 - FINAL PROPOSAL FOR PREDICTION OF ACOUSTIC PERFORMANCE IN LIGHTWEIGHT BUILDINGS

## 1.1 - Introduction

Lightweight building systems can have various appearances, combing heavy and light weight elements, lightweight homogeneous or lightweight composed elements and coupling between elements in various ways. Some important common aspects, different from the generally more heavy building elements normally considered are the clearer need to distinguish between forced and resonant transmission, the damping within the elements and the additional transmission paths between composed, layered elements. Based on the research work over the last years as regularly presented within this COST action and the discussion within this COST action, the global contours of an approach to predict sound transmission for lightweight buildings systems are emerging. This approach is based on refining and adjusting the model in EN 12354 in order to fit the specifics of lightweight building systems indicating also how to collect the necessary input data through measurements and calculations. While other methods can also be used for predicting acoustic performance of complete systems or elements, like FEM, SEA or reverse SEA measurements, it is felt that the EN 12354 approach can provide a practical method on an engineering level also for light weight building systems.

This memo will summarized the possible approach for the most important items in preparation for proposals to CEN/TC126/WG2 to amend EN 12354 accordingly

## 1.2 - EN 12354 bases

The bases for EN 12354-1 is the paper by Gerretsen (1979) applying power transmission and reciprocity:

$$\tau_{ij} = \tau_i d_{ij} \frac{\sigma_j}{\sigma_i} \frac{S_j}{S_s}$$

$$\tau_{ij} = \sqrt{\tau_i \tau_j} \sqrt{d_{ij} d_{ji}} \frac{\sqrt{S_i S_j}}{S_s} \qquad (1a)$$

where

$\tau_{ij}$ is the flanking transmission factor for path from element i to element j;

$\tau_i$, $\tau_j$ is the transmission factor for resp. element i and element j;

$d_{ij}$ is the average vibration ratio between excited element i and element j;

$S_s$, $S_i$, $S_j$ are the areas of the separating element, element i and element j, in m$^2$;

$\sigma_i$, $\sigma_j$ is the radiation factor for resp. element i and element j;

This is applicable to the whole frequency range provided that the transmission coefficients are for free transmission only with the main assumption that the radiation efficiency is not varying with wall dimensions; this was confirmed Bosmans & Nightingale in their comparison with SEA modeling. In all cases the additional presumption is that the forced waves in the sending side do not create a significant contribution to the free waves at the receiving side. To be more accurate equation (1) with these assumptions should have been written as, where the additional subscript *r* and *s* refer to resonant vibrations and structural excitation respectively:

$$\tau_{ij} = \tau_{r,i} d_{s,ij} \frac{\sigma_{r,j}}{\sigma_{r,i}} \frac{S_j}{S_s}$$
$$\tau_{ij} = \sqrt{\tau_{r,i}\tau_{r,j}} \sqrt{d_{s,ij} d_{s,ji}} \frac{\sqrt{S_i S_j}}{S_s} \tag{1b}$$

A comparable but different approach would have been to base the derivation on airborne excitation (though than a direct link to impact sound could be more questionable), indicated with an additional subscript *a*:

$$\tau_{ij} = \tau_{a,i} d_{a,ij} \frac{\sigma_{r,j}}{\sigma_{a,i}} \frac{S_j}{S_s}$$
$$\tau_{ij} = \sqrt{\tau_{a,i}\tau_{a,j}} \sqrt{d_{a,ij} d_{a,ji}} \frac{\sqrt{S_i S_j}}{S_s} \sqrt{\frac{\sigma_{r,i}\sigma_{r,j}}{\sigma_{a,i}\sigma_{a,j}}} \tag{1c}$$

As deduced in section 1.3., as a first approximation, the last term here is precisely the term to transfer the total transmission coefficient for airborne excitation into the one for free transmission (resonant transmission only), if we assume (reasonable with indirect excitation) that $\sigma_r = \sigma_s$.

Or if we use the second relation to transfer the transmission coefficient, we get a term which precisely transfers also the velocity ratio for airborne excitation in the one for structural excitation.

So the two approaches are identical, but for the difference and/or equality between vibration level difference with airborne and with structural excitation. The most practical to chose would basically be (1b): it is currently used in EN 12354, junction transmission is measured easier and is identical for airborne and impact sound transmission. So far only more or less homogeneous single elements have been considered, not only heavy, but also lightweight ones. This approach is now to be extended with the possibilities and additional aspects for double and triple constructions. In that case special attention is required for which element is to be considered in the predictions, the double element as a whole or just the inner leaf, single or multilayered. In principle both is possible in combination with the appropriate $K_{ij}$, which will be quite different. The choice will depend largely on the type of input data available. Considering the double element as a whole opens the possibility to apply measured data for the sound reduction index, but the $K_{ij}$ measurements have to be adjusted to this choice (see ISO 10848). Considering primarily the inner leaf makes the $K_{ij}$ measurements more straight forward, but the sound reduction index often is not directly available.

## 1.3 - Sound reduction index *R* for resonant transmission

One important item for lightweight elements, certainly homogeneous elements is the need to consider only resonant transmission in flanking path and hence the need to know $R$ of the element for resonant transmission only. This means at the same time that for the corresponding transmission over the junction, $K_{ij}$ shall also be for resonant transmission only and thus determined by mechanical excitation. Although somewhat different approaches seem also possible, this seems to be the most practical and appropriate approach.

The sound reduction index $R$ as input can be based on pure calculation or, more common, laboratory measurements in accordance with ISO 10140.

*Calculated input data*

In case of calculated values for the sound reduction index these shall only refer to resonant transmission. For homogeneous elements this is already mentioned and presented in EN 12354-1, annex B, though the given equation needs some minor adjustment (i.e Davy [1]); see N20. For more complex elements other models from literature could be used, for layered elements possibly based on SEA. Care should be taken that with commercially available models it might not be possible to delete the forced transmission.

However, recent research has indicated that reliable predictions for the resonant transmission are hardly possible at the time [10], either due to insufficient estimates of the radiation efficiencies and/or the actual damping in the lightweight elements. Therefore this approach is not recommended for (very) lightweight elements.

*Measured input data*

Completely based on measured data, $R_{lab}$, we need not only the sound reduction index but also the measured radiation efficiencies with airborne and structural excitation. The correction is than given by [2]

$$R^*_{lab} = R_{lab} + 10\lg\left[1 + \frac{\sigma_f}{\sigma_r}\frac{\sigma_a - \sigma_r}{\sigma_f - \sigma_a}\right] \approx R_{lab} + 10\lg\frac{\sigma_a}{\sigma_s}\frac{1-\sigma_s}{1-\sigma_a} \approx R_{lab} + 10\lg\frac{\sigma_a}{\sigma_s} \qquad (2)$$

where $\sigma_f$ and $\sigma_r$ are radiation efficiencies for forced and resonant transmission (theory) and $\sigma_a$ and $\sigma_s$ are the radiation efficiencies with resp. airborne and structural excitation (measurement). The assumption in the estimations is that $\sigma_r = \sigma_s$ and $\sigma_f \approx 1$. It is recommended to apply only the most right estimation of the correction term in predictions.

As stated before, calculation of the correction term is as yet insufficiently reliable, so it should be based on measurements. Most recent measurements [2], [5], [9], [10], [11] have indicated that in case of double elements the correction is small or negligible, so as global estimate the measured data can be applied without correction in that case (correction of 0 dB). For single, homogeneous or layered, elements the correction seems to be reasonably independent of the type of element and around 8 to 10 dB below the critical frequency. This opens possibilities for global estimates of the correction in case measured data is not available (see later).

*Measured sound reduction index only*

The most common case currently is that only measured data on the sound reduction index are available, to which corrections according to eq. 2 should be applied. Since calculations of the radiation efficiency ratio has proven to be unreliable, in that case only a global correction can be applied, based on the measured data currently available. As summarized above, a global estimation of the correction could be as follows: no correction for double (or triple) elements and a correction of 8 dB for single, homogeneous or layered, elements below the critical frequency only. A simple implementation of this last correction is applying the method of subtracting the contribution of forced transmission with a limit of 8 dB. Although that method in itself is not very reliable due to the normally small contribution of the resonant transmission, it provides a smooth calculation method with continuous results over the frequency range without the need to know the critical frequency exactly [3]. The only values needed for this correction are the mass *m'* of the element and the radiation efficiency $\sigma_f$ which is readily available for the fixed laboratory situation (10 m$^2$)

For $f \leq 2 f_c \approx 88000 / m'$ it follows:

$$\boldsymbol{R}^* = \boldsymbol{R}_{meas} + 10\,\mathbf{lg}\left[1 - 10^{\boldsymbol{R}_{meas}/10}\left(\frac{2\rho \boldsymbol{c}}{2\pi \boldsymbol{fm'}}\right)^2 2\sigma_f\right]^{-1} \tag{3}$$

If the term between [ ] becomes smaller than 0,16 or even negative the correction shall be limited to 8 dB.

## 1.4 - Presenting overall performance per transmission path ($D_{nf}$, $L_{nf}$)

### 1.4.1 - General

In lightweight building systems the elements normally have a larger damping and the vibration levels are thus less effected by the energy losses at the borders. Furthermore, with light elements the laboratory sound reduction index is also mainly determined by internal damping and thus independent form the situation in which it is built into. That means that measurement results in a mock-up or a field situation with reasonable dimension will give results that can easier by transferred to other situations and dimensions. In other words, the results for the overall flanking transmission, $D_{nf}$ or $L_{nf}$, in one -laboratory – situation can be transferred to other situations as already indicated in EN 12354 [4].

$$R_{ij} = D_{nf} + 10\lg\frac{S_s l_{ij,lab}}{A_0 l_{ij}};\quad L_{n,ij} = L_{nf} - 10\lg\frac{S_i l_{ij,lab}}{S_{i,lab} l_{ij}} \tag{4}$$

where $l_{ij}$ and $S_i$ refer to coupling length and excited area in the field situation and the same quantities with the additional subscript *lab* to the laboratory situation.  This can be combined with estimations for other paths, either using the same equation or combining it with predictions following EN 12354 if appropriate.

### 1.4.2 - Direct measurement

In ISO 10848 it is prescribed how $D_{nf}$ en $L_{nf}$ can be measured in dedicated lab facilities. These measurements refer only to the path Ff. Though it seems that in many lightweight building that indeed is the dominating flanking path, we have seen element combinations and junctions were other paths, like Fd or Df, have a considerable contribution. Hence, those path can not be neglected from the start. Measuring $D_{nf}$ and $L_{nf}$ for other paths is not a principle problems but mainly a practical problem: the separating element should also be representative for the junction studied and transmission by the other paths than the one studied must be reduced by linings. Such an approach have been taken by the research at NRC, Canada, for instance. So direct measurements for each relevant flanking paths following eq. (4). will provide the data needed for predictions following 1.3.1

$$D_{nf} = L_s - L_r - 10\lg\frac{A}{A_0};\quad L_{nf} = L_r + 10\lg\frac{A}{A_0} \tag{5}$$

### 1.4.3 - Hybrid approach

Besides direct measurements the overall flanking transmission could also be estimated from a combination of measured and calculated data. If the element damping is indeed not varying much between situation, as is the presumption for the application of $D_{nf}$, than it could be expressed as:

$$\begin{aligned} \boldsymbol{D_{nf}} &= \frac{\boldsymbol{R_i}}{2} + \frac{\boldsymbol{R_j}}{2} + \Delta\boldsymbol{R_i} + \Delta\boldsymbol{R_j} + \overline{\boldsymbol{D_{v,ij,n}}} + 10\,\mathbf{lg}\frac{\boldsymbol{A_o}}{\boldsymbol{l_{ij,lab}}} \\ \boldsymbol{L_{nf}} &= \boldsymbol{L_{n,ii}} + \frac{(\boldsymbol{R_i} - \boldsymbol{R_j})}{2} - \Delta\boldsymbol{L_i} - \Delta\boldsymbol{R_j} - \overline{\boldsymbol{D_{v,ij,n}}} - 10\,\mathbf{lg}\frac{\boldsymbol{S_{i,lab}}}{\boldsymbol{l_{ij,lab}}} \end{aligned} \tag{6}$$

where $l_{ij,lab}$ = 4,5 m (horizontal junction) or 2,6 m (vertical junction) and $S_{i,lab} \approx 19\ m^2$, $R$ is the sound reduction index of the indicated element, $L_n$ the normalized impact sound pressure level and $\Delta R$ the improvement of the sound reduction index by a lining for the indicated element.

The new quantity for the junction is actually the $K_{ij}$ from ISO 10848 and EN 12354 with standardization to area. The make a more clear distinction this is further denoted as $\overline{D_{v,ij,n}}$ ; see also 1.4.4.

So $D_{nf}$ can be estimated from the knowledge on elements, junctions and linings, either based on measurement or on calculations. The advantage of this approach is that it can be estimated more easily what would be the effect of changes in the elements. Furthermore, since $R$ and $K_{ij}$ or $\overline{D_{v,ij,n}}$ can vary hugely in number and it is only the combination that gives a correct ranking of systems, a correct ranking is directly provided by $D_{nf}$ and not for instance by a high value for $K_{ij}$ or $\overline{D_{v,ij,n}}$ .

In eq. (5) distinction is made between the element and linings ($\Delta R$, $\Delta L$). Some research [4] has shown that indeed also for lightweight elements these can be treated independent, though the assumption $\Delta R_{direct} = \Delta R_f$ seems no longer valid.

### 1.4.4 - Renewed definition of $K_{,ij}$

With damped elements the standardization on damping is not only not necessary – no large differences between situations – but the structural reverberation time may also not be relevant in those cases. The structural reverberation time can be dominated by local effects, while the attenuation over distance is what should be taken into account (with homogeneous elements these are directly coupled but not necessarily with composed light weight elements). Hence, the practical and appropriate definition for the junction attenuation will be the normalized direction-average velocity level difference:

$$\overline{D_{v,ij,n}} = \frac{D_{v,ij}}{2} + \frac{D_{v,ji}}{2} + 10\lg\frac{l_{ij}}{\sqrt{S_{m,i}S_{m,j}}} \tag{7}$$

were $S_{m,i}$ and $S_{m,j}$ are the measurement areas, equal or smaller than the element areas. In this way this quantity includes both the reduction effects at the actual junction as well as level reductions over the damped element. If the areas are not too small the result will be independent of the actual area. ( in the current versions of EN 12354 and ISO 10848 this quantity is also denoted as $K_{ij}$). Furthermore it must be added, that due to the inclusions of the element damping it is necessary to specify additional positions for excitation and measurement (at least also not to far from the junction line). As a global estimate the effect of the junction and the element damping could be estimated by:

$$\overline{D_{v,ij,n}} \approx K_{ij,junction} + 10\lg\sqrt{\delta_i\delta_j} \tag{8}$$

where $K_{ij,junction}$ could be estimated by taking into account the structural reverberation times for reasonable homogeneous elements and $\delta_i$ and $\delta_i$ are the average extra attenuation in dB per meter, over the geometric spreading of the elements. Eq. (7) could be used to estimate the effect of added damping to an element on $\overline{D_{v,ij,n}}$ . Determining $\delta$ from measurements could be added to the measurement standard ISO 10848.

### 1.4.5 - Undamped elements in lightweight building systems

In lightweight building systems also less light and hardly damped elements can be present, or instance a concrete layer in the floor. Though in such cases the damping for such elements could be taken into account through the actual structural reverberation time, the variation in damping is likely to be rather small – mainly internal, small amount of border loss - , so it could be dealt with simpler. That means in $\overline{D_{v,ij,n}}$ and /or $D_{nf}$ and $L_{nf}$ with such elements can be treated as all the lightweight elements. The main effect will be that the sound reduction index and/or normalized impact sound pressure level can be quite different from the one determined under laboratory situations: the damping in the lab (losses at the border) will be generally larger than in the field here. The effect can not be neglected. Besides the possibility to estimate it by detailed calculations, a global estimate that could be used would be:

$$R^*_{situ} = R^*_{lab} + 10\lg \frac{0{,}01 + 0{,}05/\sqrt{f}}{0{,}01 + (m/485)/\sqrt{f}} \qquad (9)$$

## 1.5 - Impact sound transmission and sound due to service equipment

For impact sound transmission the approach can be fully identical, especially since structural excitation for $K_{ij}$ or $\overline{D_{v,ij,n}}$ has been chosen. The use in this case of the total flanking transmission $L_{nf}$, directly measured or the hybrid approach, has already been presented. It is to be discussed if specific additional transmission path need to be considered in case of the application of floating floors [6].

For sound due to service equipment more or less the same holds, but for one aspect. Due to the fact that a piece of equipment will mostly excite the structure at one point or small area only, and not random over the element as with the tapping machine, that excitation point in relation to the junction can be important in case of well damped elements. Adjustment terms for that have been studied and proposed [3] but need further attention.

## 1.6 - References

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[3] Gerretsen, Eddy, *Some aspects to improve sound insulation prediction models for lightweight elements*, Internoise 2007, Istanbul, 2007

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[6] Metzen, H.A., e.a., *Prediction of sound insulation in timber frame buildings*, Forum Acusticum Budapest, 2005.

[7] Villot, Michel & Catherine Guigou-Carter, *presentation COST workshop Duebendorf*, 2011

[8] Mahn, J.P. and J. Pearse*, Separation of Resonant and Non-Resonant Components Part I: Sound reduction index*, Buildings Acoustics **15** (2008), 95-115.

[9] Guigou-Carter, C. and Michel Villot, *Prediction and measurements for lightweight buildings and low frequencies*, Euronoise 2012, Prague, Czech Republic, 10-13 June 2012, 185-190.

[10] Mahn, J. and J. Pearse, J.. *The calculation of the resonant sound reduction index for use in EN12354*, Euronoise 2012, Prague, Czech Republic, 10-13 June 2012, 168-173.

[11] Schoenwald, S.. *Comparison of proposed methods to include lightweight framed structures in EN12354 prediction model*, Euronoise 2012, Prague, Czech Republic, 10-13 June 2012, 174-179.

# 2 - FINAL PROPOSALS FOR PREDICTION OF RELEVANT VIBRATION QUANTITIES IN BUILDINGS

## 2.1 - Introduction

The low- frequency behaviour of floors with respect to walking induced vibrations, both on the same floor as the walker as on a neighbouring floor, is important for the comfort assessment. Yet the best descriptor for the subjective assessment of these vibrations is not yet completely clear or agreed.

For the 'own' floor the Canadian approach seems the best for the time being, so fundamental frequency $f_r$ and unit force deflection $w$ will have to be predicted. Furthermore, the damping is to be added as important factor and a response, for instance the unit impulse response $v_{rms}$ [1] or the single step response OS-RMS$_{90}$ [3]. These last two quantities are the only one that can also be applied for neighbouring floors.

For the prediction of $f_r$ and $w$ it seems that the Eurocode 5 [1] approach is adequate, some improvements have been discussed in the report by de Klerk (STSM [2], see also Delft workshop). So a proposal is made, based on this report, to improve the Eurocode somewhat. (it should be checked if Eurocode 3 for steel constructions offers additional information that could be applicable).

For the response on the own floor or neighboring floor no simplified analytical method has been found adequate, hence a proper FEM-calculation is needed to calculate a transfer function as bases for the appropriate descriptor. However, due to the complexity of lightweight floors and building junctions the modelling is not self evident. A proposal is made for a step-by-step plan to create simplified but reproducible FEM-models that reliably represent the complex lightweight floors and junctions.

The proposals in this memo should be helpful to improve and extend existing standards like the Eurocodes and will be presented to the appropriate standardisation bodies.

## 2.2 - Own floor: fundamental frequency and unit load deflection

### 2.2.1 - *fundamental frequency*

#### 2.2.1.1 - ***isotropic plate***

To predict the fundamental frequency $f_r$ the Euler-Bernoulli model as currently used in the Eurocode-5 seems adequate for solid and solid joist floors:

$$f_r = \frac{C}{2\pi l^2}\sqrt{\frac{D}{m}} \quad \text{with} \quad D = \frac{Eh^3}{12(1-\upsilon^2)} \tag{1a}$$

For joisted floors an improvement can be achieved by taking shear into account , leading to:

$$f_r = \frac{C}{2\pi l^2}\sqrt{\frac{D}{m}}\left[\frac{\pi^2}{L^2}\frac{D}{k'GA}+1\right]^{-1/2} \tag{1b}$$

where

*D* is the bending stiffness per unit width, in Nm;

*E* is Youngs modulus, in N/m$^2$;

*h* is the plate thickness, in m;

*m* is the area mass, in kg/m$^2$;

*l* is the span width, in m;

*b* is the floor width, in m;

*C* is a number depending on the dimensions and type of support of the floor and can be taken from table 1 according to Leissa or Blevin [4], [5];

*k'* is a shape factor for the joists which can be taken as $k' \approx 0{,}85$ for rectangular wooden beams;

*G* is shear stiffness, in N/m$^2$;

*A* is the effective beam cross section, in m$^2$.

Table 1: C-value for fundamental frequency ($f_r$ = $f_{11}$) for orthotropic plates with SFSF support.

| ratio | C from Leissa | C from Blevin |
|---|---|---|
| $l/b$ = 0,5 | 9,87 (= $\pi^2$) | 9,74 |
| $l/b$ = 1,0 | 9,87 | 9,63 |
| $l/b$ = 2,0 | 9,87 | 9,52 |

The results according to Leissa are thus somewhat higher than according to Blevin.

#### 2.2.1.2 - ***orthotropic plate***

Orthotropic plate means orthogonal and anisotropic, with different stiffness ($D_x > D_y$) in the two directions of the plate. For floor constructions with wooden beams the Poisson's ratio can normally be neglected, i.e. $\nu = 0$. To predict the fundamental frequency $f_r$ with that assumption Leissa proposes for simply supported floors all around (S-S-S-S):

$$f_r = \frac{\pi^2}{2\pi l^2}\sqrt{\frac{D_y}{m}\left[\left(\frac{l}{b}\right)^4 + \frac{D_x}{D_y} + 2\left(\frac{l}{b}\right)^2 \frac{D_{xy}}{D_y}\right]} \tag{2a}$$

$D_{xy}$ can often be taken as $D_y$.

For free and simply supported plates (S-F-S-F) the results is:

$$f_r = \frac{\pi^2}{2\pi l^2}\sqrt{\frac{D_x}{m}} \tag{2b}$$

The same as with the isotropic plate, but in general the use of equation (2a) is recommended.

### *2.2.2 - unit load deflection*

The unit load deflection $w$ according to the Eurocode (load of 1000 N) can be estimated as:

$$w = \frac{10^3 L^3}{48EI} \tag{3}$$

However, this formula is much too simple for plates structurally fastened to the beams. For such cases at present no simple, analytical equation is available, so the use of an adequate FEM model is necessary.

## 2.3 - FEM modeling for dynamic response, own floor and neighbor floor

### 2.3.1 - Modelling, transfer function and response descriptor

In the next paragraph 2.3.2 the floors and junction will be modelled step by step. In paragraph 2.3.3 recommendations are given to calculate the transfer mobility with the derived model and paragraph 2.3.4 gives the possibilities to use this transfer mobility to calculate appropriate responses for walking induced vibrations. Finally paragraph 2.3.5 compares calculated mobilities with measurement results.

### 2.3.2 - Step by step modelling

#### 2.3.2.1 - *__Step 1: Choosing the boundary conditions__*

The choice of boundary conditions to be deployed in the model depends on the type of junction under investigation. The way in which the floors and the walls are connected to the junction is typical for specific junctions and thereby defines the boundary conditions in the model. Figure 1 displays schematically the boundary conditions of all relevant types of lightweight junctions.

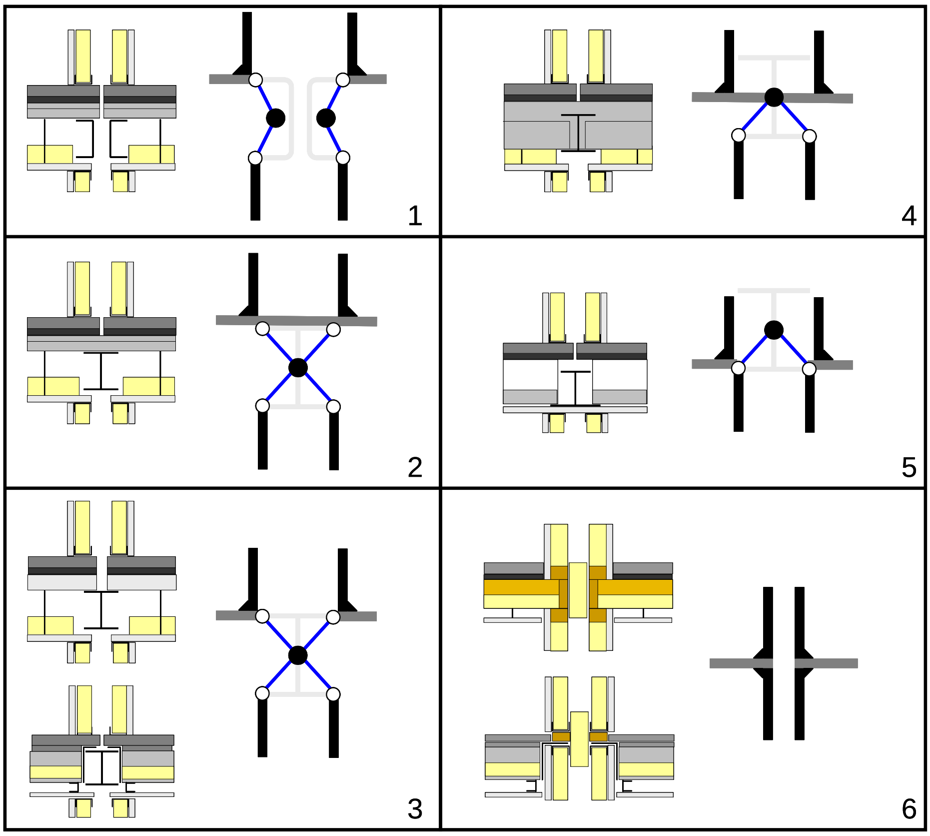


*Figure 1: The required six types of boundary conditions to model all relevant types of lightweight junctions.*

The modeller determines in which category the building system belongs and from the figure above he knows which boundary conditions are to be applied. The six types of boundary conditions are determined from a study in which all relevant lightweight building systems in the Netherlands are investigated. In the following a short description of the types is given.

***Type 1*:**

In group 1 the systems, consisting of a steel skeleton with floors supported by dilated joists, can be found. The floors are simply supported by the joist which is denoted by the white dots. Further, the floors are cinematically coupled to the joists. This is denoted by the blue lines. It basically means that the eccentricity has to be taken into account. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed.

***Type 2*:**

In group 2 the systems, consisting of a steel skeleton with a single floor passing through the dwelling separating wall supported by a single joist, can be found. The base floor passes over the junction. It is therefore simply supported on the edges of the flanges of the joist. This is denoted by the white dots. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed. The blue lines denote the node pairs that a kinematically coupled.

***Type 3*:**

In group 3 the systems, consisting of a steel skeleton with floors supported by single joists, can be found. In this group the floors are simply supported on the edges of the flanges of the joists. This is denoted by the white dots. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed. The blue lines denote the node pairs that a kinematically coupled.

***Type 4*:**

In group 4 the systems, consisting of a steel skeleton with the joist moulded into the floors, can be found. As the joists are moulded into the floors, a clamped coupling between the joists and the floors has to be assumed. This is denoted by the black dots. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed. The blue lines denote the node pairs that a cinematically coupled.

***Type 5*:**

In group 5 the systems, consisting of a steel skeleton with floors supported by the lower flange of single joists, can be found. Systems belonging to group 5 are modelled equally as the systems belonging to group 3. The only difference lies in the fact the the floors in group 5 are supported by the lower flange of the joists.

***Type 6*:**

The systems consisting of wooden skeletons or a steel frame can be found in group 6. These junctions are characterised by the horizontal decoupling between dwellings. The systems belonging to the platform method and those belonging to the balloon method are modelled equally. Due to the weight and the supporting role of the walls, it is assumed that these are clamped in between the floors.

Kinematical couplings can be realised without difficulty in the majority of commercially available FEM-packages. It is important that the modeller connects the building components properly (either hinged or clamped) and that the relative position between the components is taken into consideration. In the FEM-package DIANA, which is developed by TNO, the kinematical couplings can be realised by so-called *tyings*.

#### 2.3.2.2 - *Step 2: Modelling the floors*

As soon as the boundary conditions are determined, the floors are modelled subsequently. These, generally inhomogeneous, floors are represented by the modeller as equivalent homogeneous orthotropic plates with equal dimensions in the tangential plane. The process of homogenisation is performed according to the following steps:

- Choose a fictitious thickness $h$ for the equivalent plate in the order of 1% of the span. Alternatively the thickness $h$ can also be chosen such that the volume of the equivalent plate equals the volume of the real floor.
- Compute the bending stiffness per meter of the floor in the carrying direction, $EI_y$, and in the direction perpendicular to this, $EI_x$.
- If floor screed is applied, then its bending stiffness per meter has to be simply the bending stiffness of the base floor. It is assumed that no shear is transferred from the base floor to the floor screed.
- Compute the equivalent Young's moduli $E_y$ and $E_x$ such, that the homogeneous orthotropic plate contains a bending stiffness equal to that of the real floor (in both directions).
- The Poisson coefficients $\nu_{xy}$, $\nu_{yz}$ and $\nu_{zx}$ of the equivalent plate are set equal to zero.
- The density of the homogeneous plate, $\rho$, is computed such that the total mass equals the total mass of the floor (base floor + floor screed + (suspended) ceiling). For the suspended ceiling it is thus assumed that only its mass will be taken into account.

The computed material properties are assigned to the orthotropic plate. Subsequently the element size $D$ of the finite elements, discretising the floor, has to be chosen as

$$D = 0.2\lambda \quad \text{with} \quad \lambda = \sqrt{1.8c\frac{h}{f}} \quad \text{and} \quad c = \sqrt{\frac{E_{\min}}{\rho}}, \tag{4}$$

where *f* is the maximum frequency to be simulated with the model.

For resilient layers in the floor, as well as resilient supports of the floor, it is assumed that the resonance frequency is well above frequency domain of interest. Therefore no additional damping has to be taken into account.

#### 2.3.2.3 - ***Step 3: Modelling the walls and the joists***

The, generally inhomogeneous, lightweight walls are also represented by equivalent homogeneous orthotropic plates. The procedure of homogenisation is equal to that described in step 2 for the floors. The supporting structure (of the categories 1 to 5) is modelled as a framework of finite beam elements. The properties of the beam elements are chosen such that the bending stiffness $EI$ in both directions perpendicular to the longitudinal direction, the torsion stiffness $GI_t$ and the mass per length $\mu$ are equal to those of the real beam.

#### 2.3.2.4 - ***Step 4: Modelling the damping***

The damping ratio $\zeta$ is the last parameter defining the model. Determining the damping ratio by measurement is preferable. In case this is not possible, then the modeller is referred to the table published in the SBR guideline [3] (see Table 1). ). In this table the damping for the whole system is determined as the sum of three parts. The three parts depend either on the used material of the floor, the type of furniture or the presence of floor screed and a suspended ceiling.

The damping ratio is simulated in the model using the Rayleigh damping model. The Rayleigh damping is computed using two quantities, namely the mass-factor $\alpha$ and the stiffness-factor $\beta$. The damping ratio $\zeta$ is then determined as

$$2\zeta\omega = \alpha + \beta\omega^2 \tag{5}$$

The Rayleigh damping is thus a frequency depending quantity. Generally, two frequencies are chosen with the corresponding damping ratios. From these two pairs, the two unknown $\alpha$ and $\beta$ can be determined. Since the first eigenmode is the most dominant one when determining de OS-$RMS_{90}$ value it is important that the damping ratio at that frequency is fulfilled. Therefore the factor $\beta$ can be set equal zero and $\alpha$ can be determined such that the damping at the first eigenfrequency is fulfilled identically. Therefore the modeller initially has to perform an eigenvalue analysis of the model in order to determine the eigenfrequency of the first bending mode of the floors.

*Table 1: Table for determining the damping ratio [3].*

| Type | Damping [%] |
|---|---|
| Damping (material) $\zeta_1$ | |
| Wood | 6% |
| Concrete | 2% |
| Steel | 1% |
| Steel-concrete | 1% |
| Damping (furniture) $\zeta_2$ | |
| Traditional office for 1 to 3 people with separating walls | 2% |
| Paperless office | 0% |
| Office with open spaces | 1% |
| Library | 1% |
| Residences | 1% |
| Schools | 0% |
| Gymnasiums | 0% |
| Damping (finishing) $\zeta_3$ | |
| Suspended ceiling | 1% |
| Floating Floor screed | 1% |
| **Total Damping** $\zeta = \zeta_1 + \zeta_2 + \zeta_3$ | |

### 2.3.3 - Computation of Y

The FEM-model is completed after performing the steps 1 to 4. The last step is to determine the transfer function, the transfer mobility's *Y,* with the created model. This can be done in three different ways. Which way has to be chosen, depends on the possibilities of the used FEM-software. Other quantities can be calculated from such mobility's or directly.

*Explicit computation in the time domain*

In an explicit computation in the time domain the modeller defines a force *F(t)* directed downward at the excitation position as

$$F(t) = \begin{cases} \sin\left(\pi \dfrac{t}{0.01}\right) & t < 0.01\text{s} \\ 0 \quad 0.01\text{s} \leq t \leq 4\text{s} \end{cases} \tag{6}$$

The time step size $\Delta t$ is mostly chosen by the FEM-software such that the calculations remain stable. In case the time step size is not chosen automatically then is can be determined by the modeller as

$$\Delta t = 0.9 \frac{2}{\omega_{\max}} \tag{7}$$

where $\omega_{\max}$ denotes the maximum angular eigenfrequency of the system, which can be determined by an eigenvalue analysis. The described determination of the time step size is used with the common explicit *central difference* scheme. The maximum simulation time is set equal to 4s.

The transfer mobility, relating the velocity at the response point to the force at the excitation point, is determined by dividing the velocity spectrum by the force spectrum. For this procedure the modeller should use FFT-software (e.g. Matlab) to determine both spectra from the time traces generated by the FEM-software and determine the the relevant transfer mobilities *Y.*

*Implicit computation in the time domain*

In an implicit computation in the time domain the modeller defines a force *F(t)* directed downward at the excitation position as

$$F(t)=\begin{cases}\sin\left(\pi\dfrac{t}{0.01}\right) & t<0.01\text{s}\\ 0 \quad 0.01\text{s}\le t\le 4\text{s}\end{cases} \tag{8}$$

The time step size $\Delta t$ is chosen equal to 2 ms. This time step size satisfies the Nyquist criterium more than sufficiently in order to create spectra up to 80Hz. The maximum simulation time is set equal to 4s. Since the implicit computations are based on the inversion of large matrices, it is common that explicit computations use less computation time for these kind of analyses, even though the maximum time step size in implicit computations can be chosen much larger.

The transfer mobility, relating the velocity at the response point to the force at the excitation point, is determined by dividing the velocity spectrum by the force spectrum. For this procedure the modeller should use FFT-software (e.g. Matlab) to determine both spectra from the time traces generated by the FEM-software and determine the transfer mobilities *Y*.

*Harmonic response analysis*

In a harmonic response analysis the transfer mobility's can be determined in the FEM-software without the intervention of signal analysis procedures. Such an analysis is namely performed in the frequency domain. The transfer mobility's Y should be determined in the frequency range from 1Hz to 80 Hz. according to the SBR guideline [3]. However, in most cases it has appeared sufficient to determine the spectra in the frequency range from 1Hz to 30Hz. Further, the spectra should be determined with a resolution of at least 0,25Hz.

At the excitation point a unit force directed downwards is introduced and the velocities at the response points are exported as output from the FEM-software. With these settings the output equal the velocity spectrum at the response point due to an ideal pulse excitation with the amplitude equal one. This is equal to the transfer mobility *Y*.

### 2.3.4 - Computation of walking induced vibration levels

The determined transfer mobility *Y* can be used in the procedure described in the SBR guideline [3] or HIVOSS guideline to determine the OS-RMS$_{90}$ values or any other response like the unit impulse response $v_{rms}$.

In this guideline the quantity OS-RMS$_{90}$ is introduced which denotes the 90% upper limit of the RMS vibration levels due to one step of a walking person. In order to determine this quantity according to the guideline, the structural engineer is required to know the transfer mobility's *Y* from the excitation point to the receiving point of the structure as computed from the FEM-model. The receiving point being on the sending floor ('own' floor) or on the neighbouring floor.

Since the transfer mobilities are general quantities, also other response could be predicted by using appropriate source forces for other types of sources of structure-borne sound.

### 2.3.5 - Comparison with measurements

In the laboratory of TNO in Delft, the numerical models of several lightweight junctions have been experimentally validated. As an example the comparison of a junction consisting of two neighbouring lightweight floors of 5x5m, is described. The floors consists of 20mm chipboard and 185mm C-beams. The floors are supported by HE240A-beams. The Gyproc Metal Stud-walls are chosen as separating walls. The junction is illustrated in figure 2

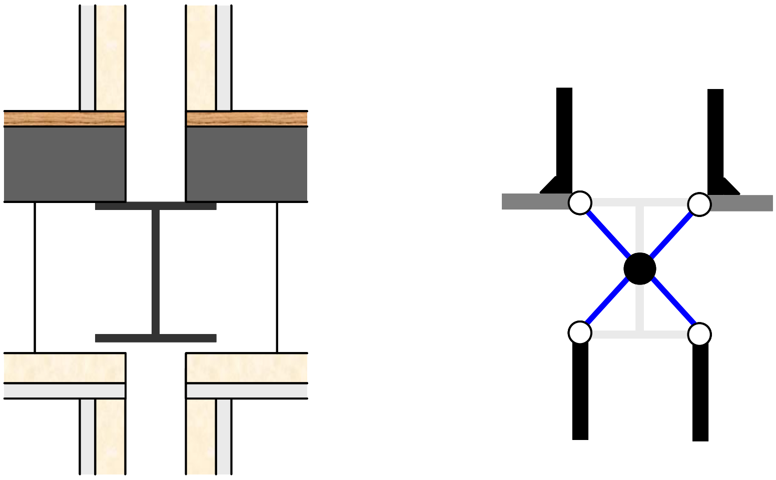

*Figure 2: Schematic illustration of the junction and its boundary conditions.*

Two variants are validated, namely one without floor screed and one with a lightweight floor screed consisting of 2x12.5mm gypsum board on mineral wool.

The measured (meting) and the predicted (DIANA harmonisch) transfer mobilities are presented in the following two figures.

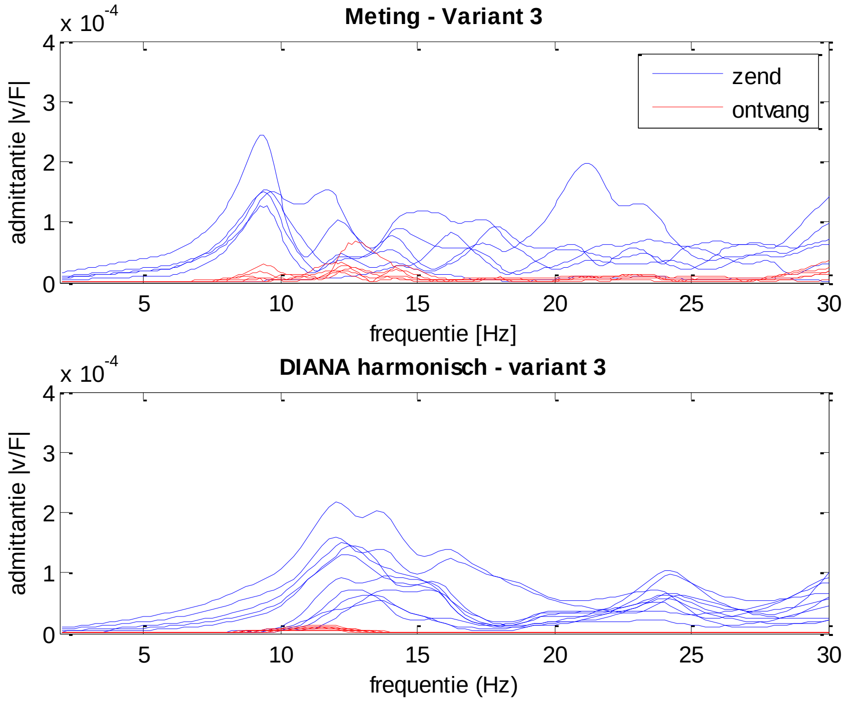


*Figure .3: Comparison between the measured and the predicted transfer mobility of the junction without floor screed (meting=measurement, DIANA harmonisch=prediction, admittantie = mobility= transfer function, zend = send, ontvang= receive, frequentie=frequency)*

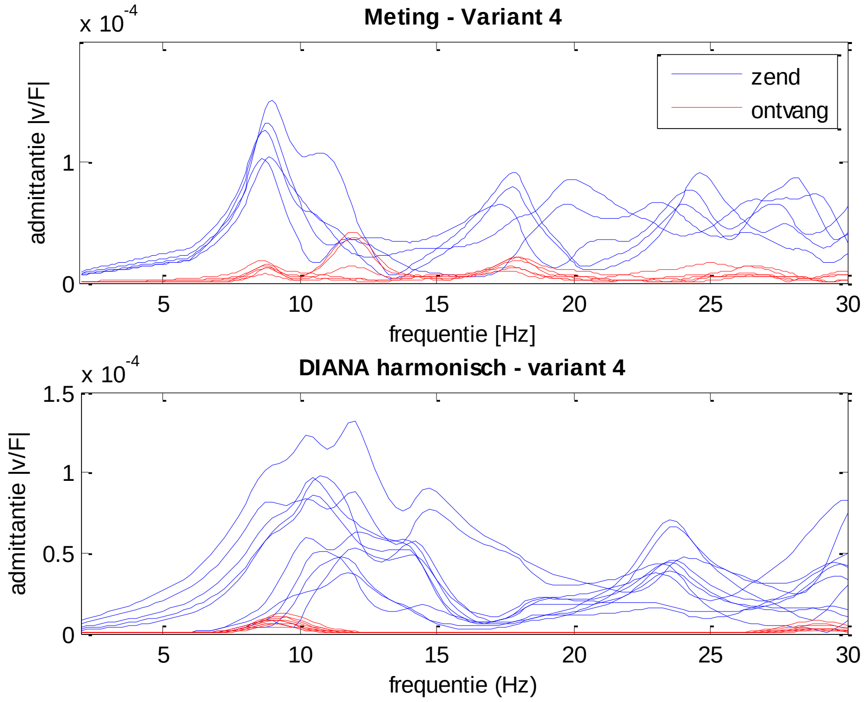


*Figure 4: Comparison between the measured and the predicted transfer mobility of the junction with floor screed. (see figure 3 for the meaning of words)*

The blue curves indicate transfer mobilities from on the excited floor and the red curves indicate transfer mobilities on the neighbouring floors.

From all the junctions that were investigated, the first eigenfrequency of the first variant deviated most. The difference between the measured and the predicted first eigenfrequency is about 2,5Hz. The predicted frequencies are always (somewhat) higher since the modeling will always assume stiffer connections between elements and at the boundaries than in reality. The overall response as in the one-step rms-value is not very sensitive to such a shift in predicted eigenfrequencies. In the predicted results the dominant harmonic of walking frequency is higher than in the measured results. In the resulting OS-$RMS_{90}$ values this leads to a difference of 1,1 (measured: 4,1; predicted: 3,0).

In the second variant the damping is clearly under predicted. This leads to a difference of 1,2 (measured: 3,7; predicted 2,5). For both variants the OS-$RMS_{90}$ on the neighbouring floor was measured to be 0,4 and predicted to be 0,2.

From all the junction that have been compared it was concluded that the simplified model can predict the OS-$RMS_{90}$ for the excited as well as the neighbouring floor within a range of factor 2.

The predicted eigenfrequencies for a single junction, following the described procedure, compare well with those found in a larger simulation of a building with several junction. In that case the responses at neighbouring floors are somewhat lower though, which could be expected from the additional energy loss to added elements. The prescribed simulation is thus on the safe side.

## 2.4 - References

[1] EuroCode-5

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[5] Leissa, A., *Vibration of plates*, NASA SO-160, Washington DC, 1969

[6] Ohlsson, S., *Springiness and human induced Floor vibrations. A design guide,* report D12:1988, Swedish Council for Building Research, Stockholm, 1988.

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