SEA based prediction for integrated vibro-acoustical design optimization of multi-storey buildings

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Summary

In order to enable the design of a multi-storey timber building with respect to the requirements or recommendations for an enhanced acoustic comfort, a collaboration of various experts is required during the design process creating their own individual building models. A simplification of the design process and the procedure of verification could be achieved if all of the experts involved work on one single CAD based Building Information Model (BIM). The required design tools (FEM and SEA for the acoustic computation) can be directly coupled to the BIM. For this purpose, it is necessary to allocate much more validated input data for timber building elements.

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1. Introduction

Timber buildings have been pioneering building constructions in terms of energy conservation and resource efficiency. The number of multi-storey residential buildings erected in timber construction has risen steadily in the last few years, also in urban areas and centres.

Compared to similar construction projects built in concrete the design of a multi-storey building in timber construction is more demanding and challenging to the architect and construction engineer. Reasons for this are more stringent requirements on fire safety regulations in these buildings as well as the absence of sufficient realized examples and design tools for the proof of performance of vibration control and sound insulation. In a current project [1] these design tools shall be further developed by using a combination of FEM and SEA for the proof of performance based on the BIM.

The contribution presents first an overview of the used computation models used. Then the SEA based method according to EN 12354 [2] and the needed input data are focused. Therefore coupling loss factors of several junctions built with massive wood elements were measured and design values for the vibration reduction index sampled. The influence of the structural reverberation time to the accuracy of the propagation was proofed and different single value methods were compared.

2. Overview of computation

A preliminary flow chart of the design process and the verification of the building properties from the first draft to the construction documentation are depicted in Figure 1. The overview shows an integrated computation of the required building properties within the planning process of the building design. The building information model is directly used for generating computational models for the different computations.

The FEM model provides the basis for the computation of the vibrations and acoustics. The vibration control needs the first eigenfrequencies of the building. The acoustic performance of the building can be described by the sound reduction of separating elements including the transmission along all flanking elements. The FEM based acoustic model is restricted to the low frequency range (0 – 250 Hz). For the computation in the mid and high frequency range, SEA based models, carried out in accordance with EN 12354, are well suited. For these prediction models, a specific BIM is needed which includes not only the geometric information but also material data and measured acoustic data for the flanking elements and the junctions. The boxes for the material data and the element properties in Figure 1 represent all the necessary input data for the computational models, which have to be sampled or measured in the experimental part of the project.

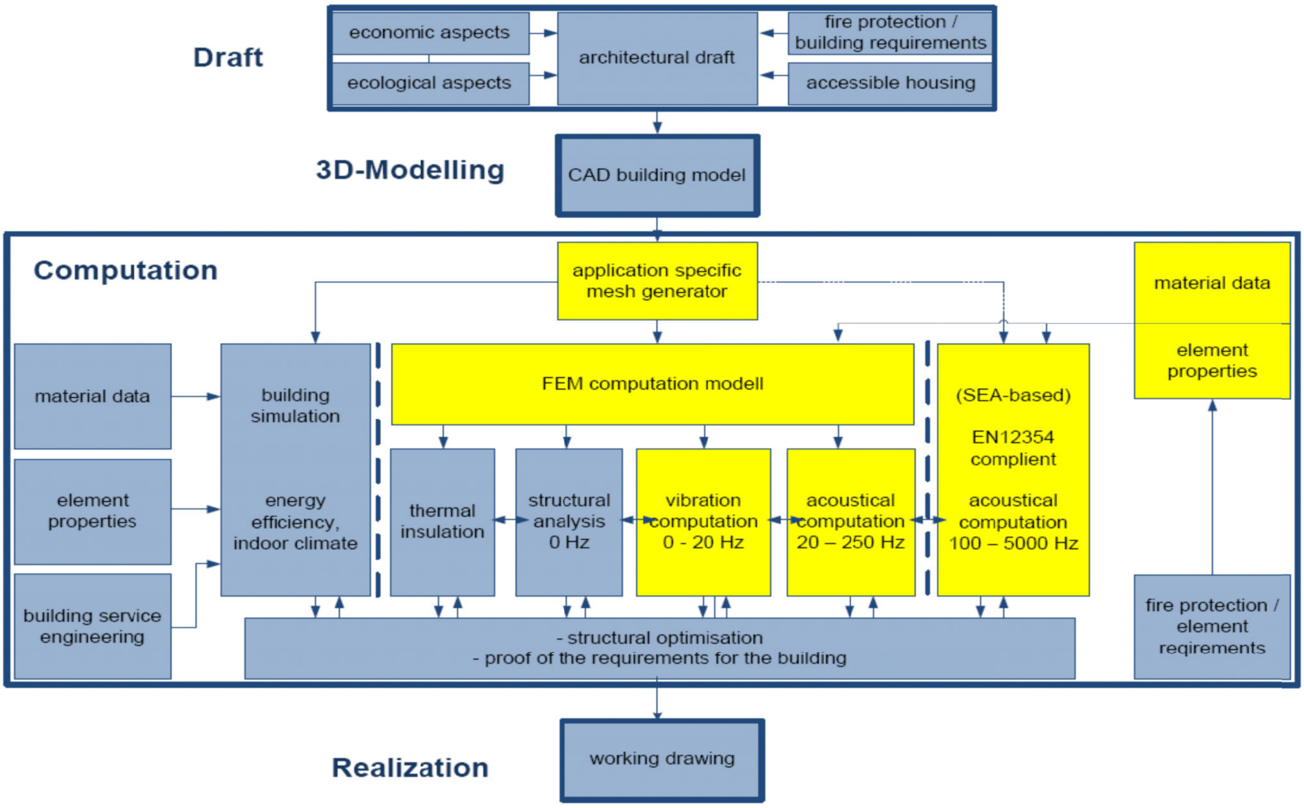

Figure 1. Flow chart of the design process

The experimental part includes the measurement of input data for the vibration optimization and the measurements for the acoustic optimization of the solid wood elements. For the vibration optimization especially the knowledge of elastic constants in the orthotropic case and the understanding of the boundary conditions are essential. The acoustic performance of a separating building element is described by the structure-borne and the airborne sound insulation. Therefore, the direct sound transmission and the sound transmission via the flanking building elements have to be taken into account.

3. Measurement results

The flanking sound reduction index R_{ij} of an element i (in the source room) and j (in the receiving room) can be described by the (direct) sound reduction index R_i, the areas S of the flanking elements and the separating element and the vibration level difference D_v:

$$R_{ij} = \frac{R_{i,situ} + R_{j,situ}}{2} + \overline{D_{v,ij,situ}} + 10\log\left(\frac{S_{Tr}}{\sqrt{S_i S_j}}\right) \qquad (1)$$

The direction averaged vibration level difference depends on the vibrations reduction index K_{ij}:

$$\overline{D_{v,ij,situ}} = K_{ij} - 10\log\frac{l_{ij}}{\sqrt{a_{i,situ}\,a_{j,situ}}} \qquad (2)$$

K_{ij} is needed as measured or computed input data. Therefore data of timber building elements were measured and validated.

The first step of sampling these input data was the investigation of several influences on the vibration reduction index. For this purpose, the dependence of the direction of transmission has been investigated in section 3.1. The influence of the mass ratios was studied in Section 3.2. A summary of the measured results is shown in Section 3.3.

3.1. Directional dependency of $D_{v,ij}$

According to ISO 10848, the vibration reduction index has to be derived from the direction-averaged velocity level difference. In order to determine this, the measurement direction has to be changed between the first and the second measurement. This leads in case of very different mass ratios of the coupled building elements to the effect that the energy flow from the heavier to the lighter component is significantly larger than the other way around (see Figure 2, left).

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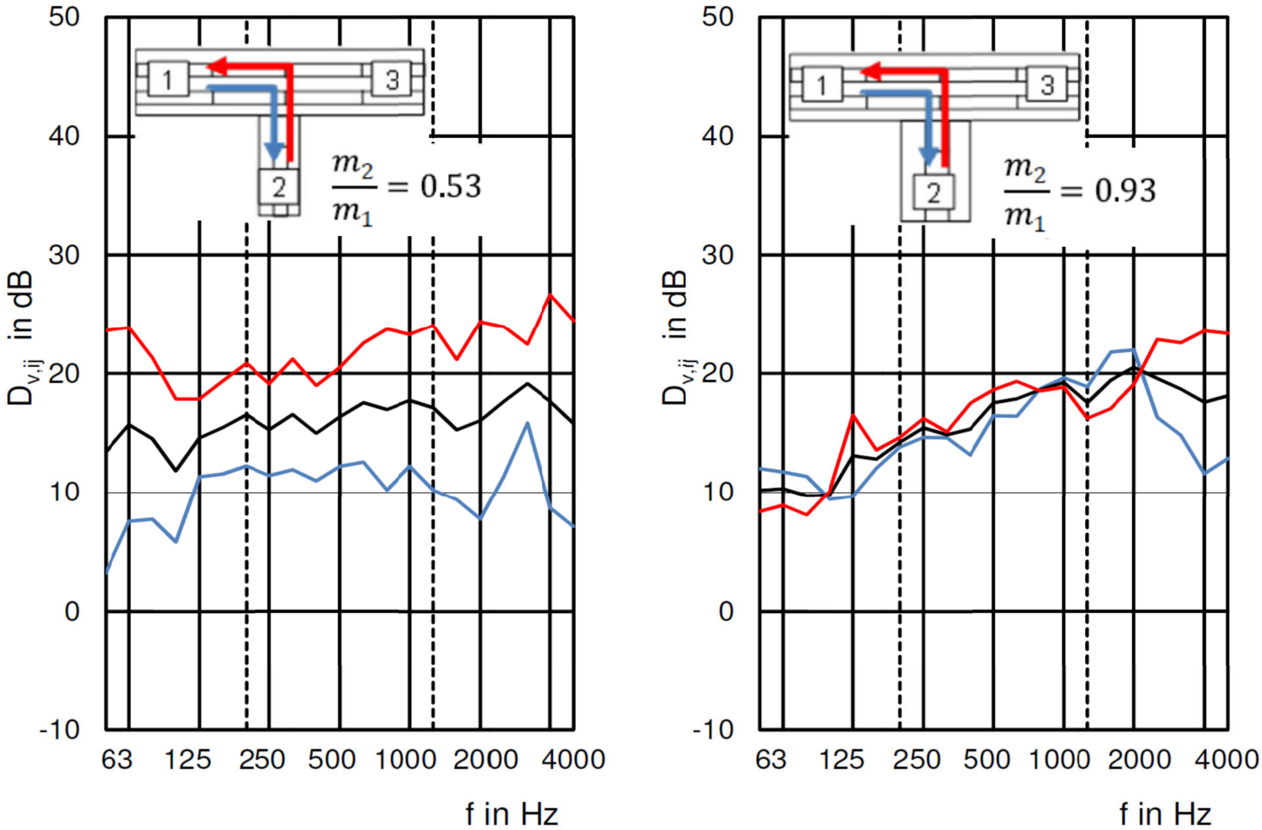


Figure 2. Directional dependence of the velocity level differences at different mass ratios between the excited and radiating element. Left: $m_2 / m_1 = 0.53$, right: $m_2 / m_1 = 0.93$

This effect can be understood within the context of SEA theory. If the velocity level difference $D_{v,12}$ is considered between element 1 and element 2 of Figure **2**, we obtain for the measurement-equation:

$$D_{v,12} = L_{v,1} - L_{v,2} = 10 \cdot \log\left(\frac{\tilde{v}_1^2}{\tilde{v}_2^2}\right) \quad (3)$$

The velocity level difference is thus formed directly from the ratio of vibration velocities in element 1 and 2. If now the energy balance for component 2 is established on the basis of the SEA theory [4], which describes the energy flow from element 1 to element 2 by the coupling loss factor η_{12}, the reflow and the energy losses in element 2 (described by $\eta_{2,int}$), it follows:

$$E_1 \omega \eta_{12} = E_2 \omega \eta_{21} + E_2 \omega \eta_{2,\mathrm{int}} \quad (4)$$

respectively with: $E = \frac{1}{2} m v^2 = m \tilde{v}^2$

$$\tilde{v}_2^2 = \frac{m_1 \tilde{v}_1^2 \, \eta_{12}}{m_2 \, (\eta_{21} + \eta_{2,\mathrm{int}})} \quad (5)$$

If the energy losses in element 2 are neglected, v_2 can be represented directly by the ratio of the masses and the coupling loss factors.

$$\tilde{v}_2^2 \approx \frac{m_1}{m_2} \frac{\eta_{12}}{\eta_{21}} \tilde{v}_1^2 \quad (6)$$

Thus a parallel shift of 3 dB per measurement direction is obtained at a mass ratio of 2: 1.
Further 6 dB results from the ratio of the coupling loss factors, if the modal density n is used as condition of symmetry as shown in [4]:

$$\eta_{12} = \frac{n_2}{n_1} \eta_{21} \quad with: \quad n = \frac{\pi S f_c}{c_0^2} \quad (7)$$

Whereby the ratio of coupling loss factors also contributes to the parallel shift with the ratio of the coincidence frequencies which are related to the element thickness respectively the element mass.

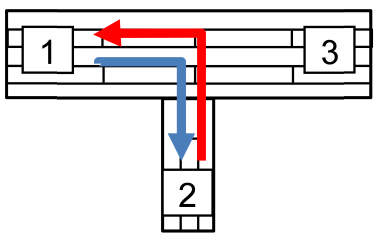


Figure 3. T-junction with a mass ratio of 1:2 as basis for the SEA consideration.

Finally the influence of the previously neglected energy losses in element 2 can be considered. In the lower frequency range these energy losses strongly depend on the support of the edge (base point of element 2) [3]. As the boundary losses are also mass dependent [2], the parallel shift is increased once more.

3.2. Influence of the mass ratio

The influence of the mass ratio (m_2/m_1) depends strongly on the design of the element junction and the transmission path. On the transmission path 1-2, the influence averages out as shown in section 3.1. Also the horizontal transmission over the junction in element 1 shows no strict influence of mass ratio as long as the flanking element is not separated at the junction (see Figure 4, left). Is the element separated, the dependence is strong (see Figure 4, right). The higher the mass of the perpendicular element the larger is K_{ij}. The perpendicular element acts here as a blocking mass on the transmission path. This could also be observed in the flanking sound reduction index R_{ij}. This varies from $R_{Ff,w}$ = 44 dB for the continuous element and $R_{Ff,w}$ = 49 dB (m_2/m_1 = 0.53) to $R_{Ff,w}$ = 57 dB (m_2/m_1 = 2.14) for the separated element.

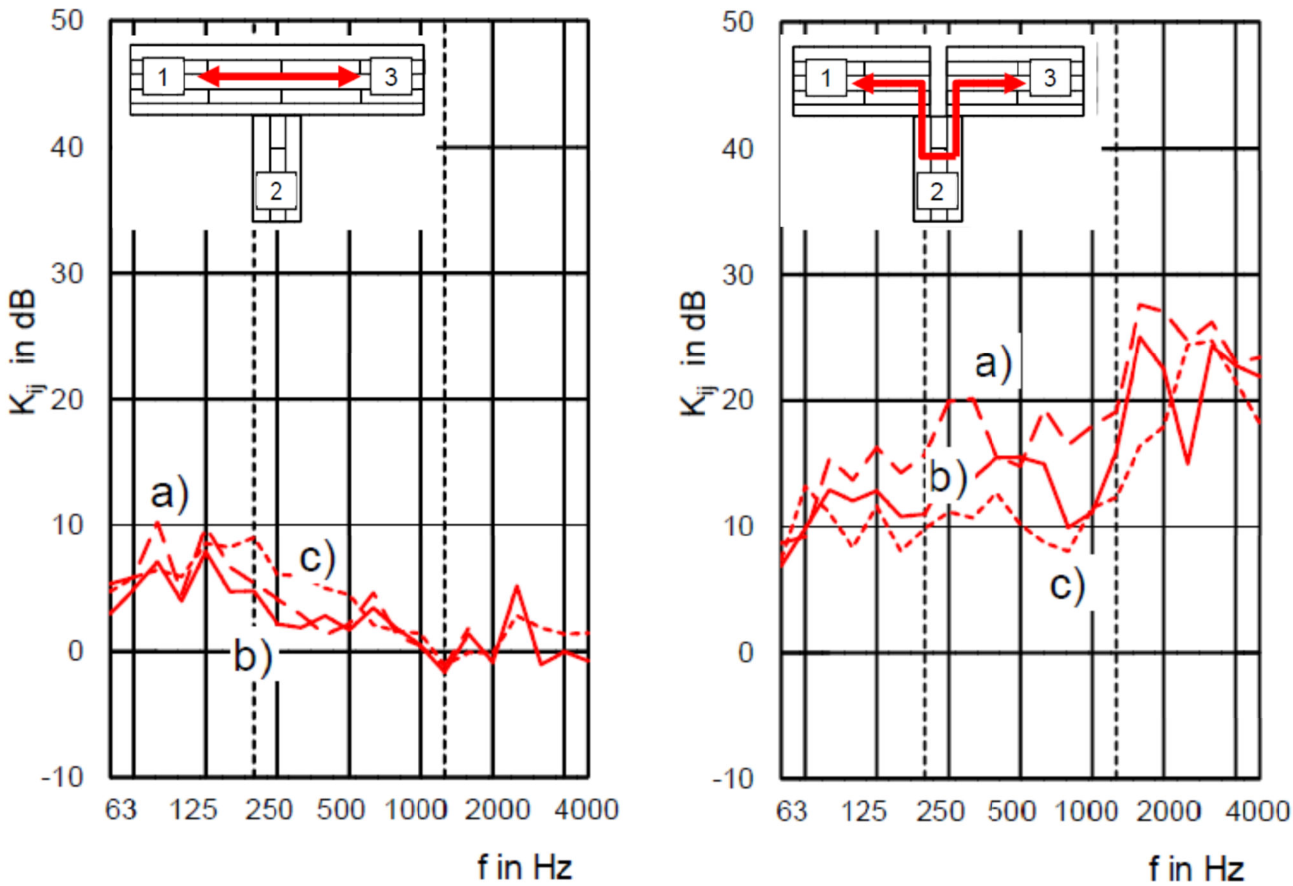


Figure 4. Influence of the mass ratio to the vibration reduction index K_{13} (K_{Ff}).

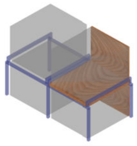
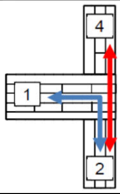
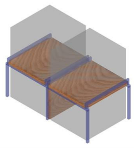
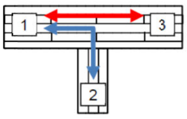
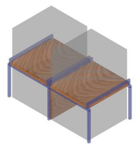
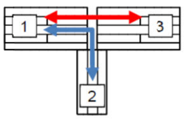
Left: Element 1and 3 (ceiling) continuously
a) m_2/m_1 = 2.14, K_{13} = 2.3 dB
b) m_2/m_1 = 0.93, K_{13} = 1.9 dB
c) m_2/m_1 = 0.53, K_{13} = 3.8 dB

right: Element 1 and 3 separated.
a) m_2/m_1 = 2.14, K_{13} = 17.7 dB
b) m_2/m_1 = 0.93, K_{13} = 13.6 dB
c) m_2/m_1 = 0.53, K_{13} = 10.6 dB

3.3. Design values for K_{ij}

One aim of the project was the investigation and collection of vibration reduction indices for the prediction of the flanking sound reduction. Input data for typical vertical and horizontal T-junctions of CLT-elements are shown in Table I. The frequency-dependence results are illustrated in Figure 5. Besides the results of the project [1] also literature data for these junction-types were collected [5] - [9]. The data are used for the computation according to EN 12354 in section 4.

Table I. Vibration reduction index K_{ij} of CLT-elements (t = 80 – 160 mm), joints screwed or mounted with brackets

Junction type	K_{ij} [1]	*Range of data* [1],[5],[6],[7],[8],[9]
 	K_{24} = 20 dB K_{12} = 13 dB K_{14} = 13 dB	K_{24} = 17 … 23 dB K_{12} = 12 … 15 dB K_{14} = 12 … 15 dB
 	K_{13} = 3 dB K_{12} = 14 dB K_{23} = 14 dB	K_{13} = 3 … 5 dB K_{12} = 14 … 15 dB K_{23} = 14 … 15 dB
 	$K_{13} = 12 + 10 \log(m_2/m_1)$ K_{12} = 14 dB K_{23} = 14 dB	

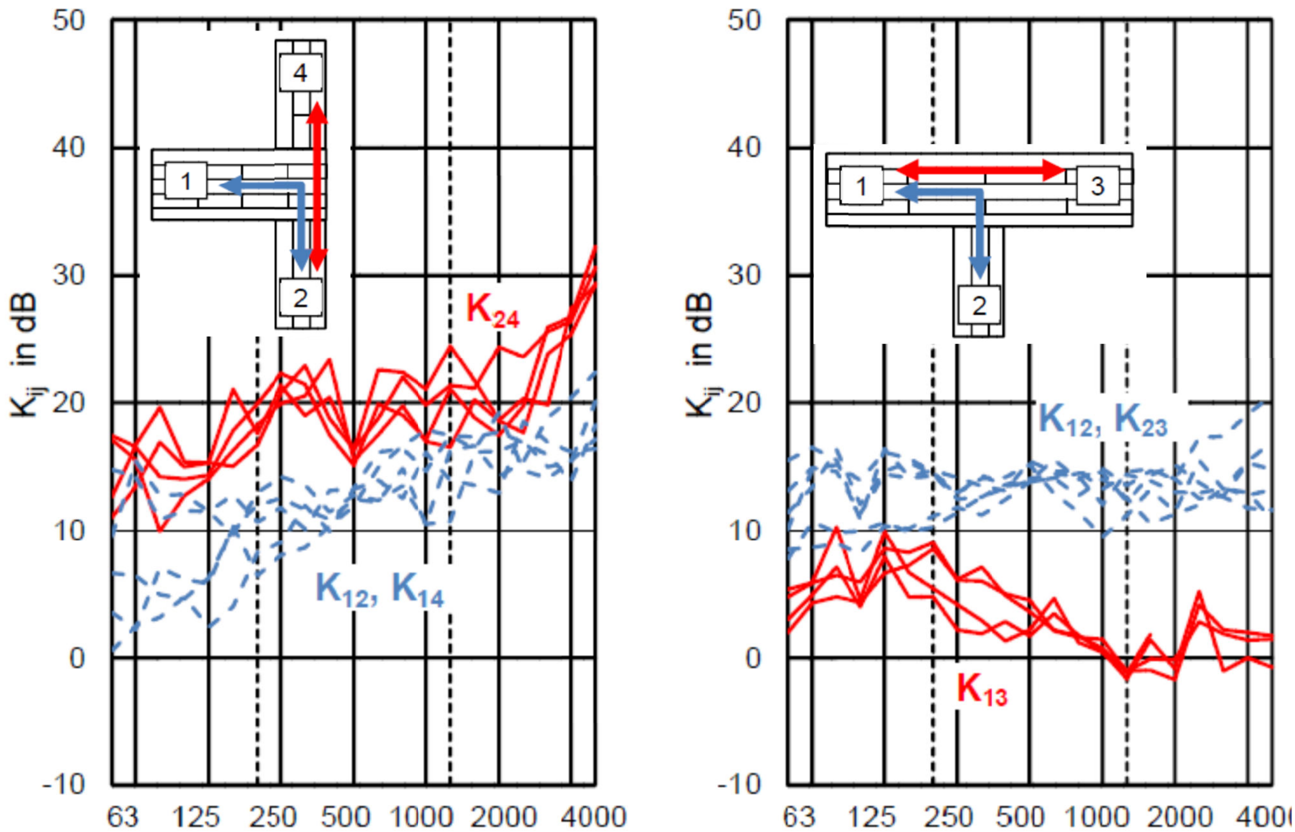


Figure 5. Measured data [1] of the vibration reduction index K_{ij} for vertical and horizontal T-junctions with different mass ratios.

4. Validation of the input data

A validation of the input data can be performed with directly measured flanking transmission. These were determined by airborne sound excitation and successive shielding of the transmission paths. The computation of the flanking sound reduction index was carried out according to (1) and (2), with data from Table I. In addition, the calculation was also done without "in-situ" correction (see (8)) to study the influence of structure-borne sound reverberation time on the result.

$$R_{ij} = \frac{R_i + R_j}{2} + K_{ij} + 10\log\left(\frac{S_{Tr}}{l_0 l_{ij}}\right) \tag{8}$$

As shown in Figure 6 the influence is significant. For this reason the correction should not be neglected.

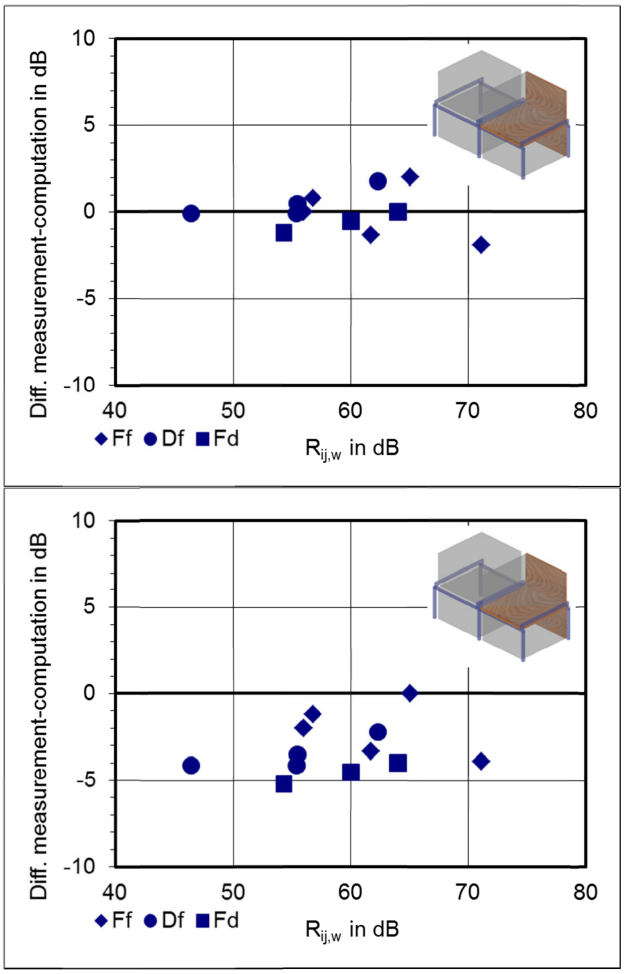


Figure 6. Difference of measurement - calculation for $R_{FF,w}$, $R_{Fd,w}$, and $R_{Df,w}$ top: calculation according to (1),(2): n = 12, mean $\bar{x}$ = 0 dB, standard deviation σ = 1.2 dB. bottom: calculation according to (8): n = 12, mean $\bar{x}$ = -3.2 dB, standard deviation σ = 1.5 dB.

However, the computation of the "in-situ" correction for rather light solid wood elements has not yet been validated. For this purpose, comparisons with measurements on building sites will be required, which are scheduled for the second part of the project.

5. Conclusions

Within the project the directional dependency of the velocity level difference and the dependence of the mass ratio were examined. It was shown that the mass ratio plays no role as long as the flanking element is not separated. The validation of the input data showed a good agreement with the measurement results of the flanking transmission if the "in-situ" correction is considered.

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