Wave Conversion in Coupled Plates of Cross Laminated Timber: A Case Study of the Effect and its Consequences

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Abstract

The sound radiation of a vibrating surface is based on the out-of-plane movement of the structure. A significant part of the total vibration energy may be carried by the in-plane movement. At junctions, where incoming bending waves are converted not only in outgoing bending waves but also in quasi-longitudinal waves, this effect may become important. An immediate contribution to the sound radiation may not occur, but an essential part of the overall energy may be carried by the converted waves. These quasi-longitudinal waves travel to other junctions, where they are converted back to bending waves and, therefore, contribute to sound radiation. To neglect these effects may lead to an error in the determination of the flanking sound reduction index based on EN ISO 10848-1. Subsequently, it also may influence predictions of sound insulation between adjacent rooms based on EN 12354-1, where values of the flanking sound reduction index are included in the calculation model. This in principle known effect has been studied in this paper by using numerical models of selected junctions made of plates of cross-laminated-timber. Furthermore the results have been compared to results of equivalent models made of concrete. The results show the relevance of this effect for common practical situations.

Introduction

The EN 12354-1 [1] is commonly used to describe the sound insulation between two adjacent rooms. Using this framework the transmitted energy is divided into different energy-flow paths that are depending on which wall is absorbing sound energy from the source room and which wall is radiating sound energy into the receiving room.

In general, the reduction of the resulting energy flow from one wall to another is depending on:

- internal losses of the individual walls
- sound radiation of the individual walls
- flanking transmission to adjacent elements
- energy partitioning and damping in the junction

The transmission characteristics of the junction is described by the flanking sound reduction index K_{ij}

$$K_{ij} = \overline{D_{v,ij}} + 10 \lg \frac{l_{ij}}{\sqrt{a_i a_j}} \quad \text{[dB]} \qquad (1)$$

which quantifies the mechanical energy reduction by the junction at the corresponding transmission path. This parameter is defined by the difference of the spatially and direction averaged velocity levels of the out-of-plane components of the diffuse vibration fields $\overline{D_{v,ij}}$

$$\overline{D_{v,ij}} = \frac{1}{2}\left(D_{v,ij} + D_{v,ji}\right) \quad \text{[dB]} \qquad (2)$$

as well as a normalization term that contains the junction length l_{ij} between the elements i and j and the absorption length a. The sound field in the source room leads to an out-of-plane movement and finally the out-of-plane components of the walls of the receiving room cause sound radiation. This is the reason why the out-of-plane part of the kinetic energy is used to describe the transmission loss across the junction. Nevertheless, also the in-plane movement carries a part of the energy that often can be neglected, in that cases, where it finally does not lead to sound radiation into the receiving room. This approach requires that the ratios of the kinetic energies in different types of waves are comparable and the associated vibration fields of the investigated walls are similar.

Former investigations show that the flanking sound reduction index in general tends to increase at rectangular junctions and to decrease at straight paths by including in-plane components depending on frequency [2]. This may be interpreted that a part of the kinetic energy is carried by the in-plane wave and a junction influences the ratio of the energy content of the different wave types. The flanking sound transmission apparently decreases because of this conversion, but the question arises what happens, if there is an inverse-conversion in a second junction (junction of 2nd order). In general junctions of 2nd order as well as paths and walls of 2nd order are neglected by the standard model [1] because less contribution of this wall to the sound radiation into the receiving room is assumed. In practice this assumption works well if primary bending waves propagate and their energy content is sufficient reduced by the previous mentioned factors and as a consequence, not too much energy arrives the wall of 2nd order to cause a sufficient out-of-plane movement. However, if an essential part of the kinetic energy is converted to the in-plane movement, the reduction is small, because at the same frequency, in-plane waves show a much higher wavelength associated with a less damping. Furthermore, this transmitted part of the energy is not captured by the flanking sound reduction index that subsequently may lead to an error in the results of predictions of sound insulation between adjacent rooms due to EN 12354-1 [1]. In the following these considerations are studied on selected models using numerical investigations including paths and junctions of 2nd order.

Basic Assumptions and Methods

The statistical energy analysis (SEA) is commonly used for investigations in wave coupling and wave conversion [2]. The usage of this method requires reverberant vibration fields, therefore suitable calculation results are obtained only above the fundamental in-plane mode in the mid- and high-frequency range, where a sufficient modal density and modal overlapping occur [2].

In this paper, the finite-element-method (FEM) has been used to focus on numerical investigations in the low- and mid-frequency range. Figure 1 shows the chosen geometry. A commonly used T-shape has been extended to an H-shape of rigidly connected plates to generate a path of 2nd order and a junction of 2nd order. The dimensions (see table 1) comply to the requirements of the standard ISO 10848-1 [3]. These dimensions result in a base area of the receiving room of about 15 m² that is comparable to a commonly used sleeping room. The surfaces of the walls are able to vibrate freely. The constraints at the side faces have been set to zero (i.e. displacements are equal to zero) to approximate rigid floors, ceilings and rear walls. Additionally, this allows a generation of in-plane waves at the junction [2].

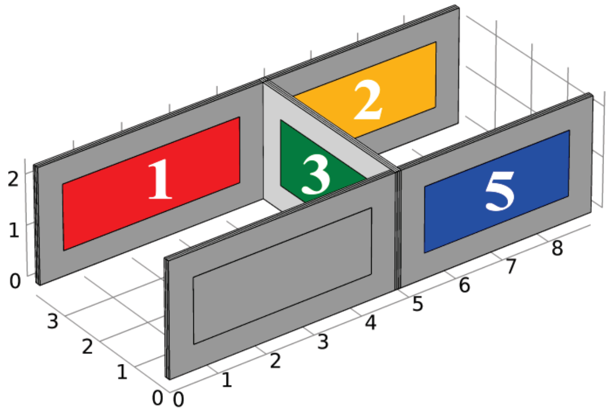

Figure 1: Geometry of the FEM model and area of spatial averaging of the velocities (CLT)

The CLT-plates have been modelled by three linear-elastic orthotropic layers. The interior layer is perpendicular to the exterior layers with respect to the fibre direction. Calibrated parameters of spruce (see table 2) have been used [5,6]. Material damping has been implemented using Rayleigh-damping [5]. To compare the obtained results to concrete, the same geometry has been combined with a linear-elastic isotropic material law using typical parameters (see table 2). Hysteretic damping has been implemented for concrete. The model has been meshed using tetrahedron elements and a quadratic shape function has been chosen. A correct sampling, especially, of the wavelength of bending-waves has been ensured during preliminary investigations.

Table 1: Dimensions and ratios of the walls

	Dimension [m]			Ratios
	Width	Depth	Heigth	ISO 10848-1
Separating	3,6 m	0,12 m	2,3 m	0,31
Flanking SR	4,7 m	0,12 m	2,3 m	0,12
Flanking RR	4,15 m	0,12 m	2,3 m	0,13

Table 2: Material data

	ρ [kg/m³]	$E_{0°}$/ $E_{90°}$ [GPa]	$\nu_{0°/90°}$ / $\nu_{90°/90°}$ [-]
CLT [5]	470	10,98 / 0,137	0,052 / 0,3
Concrete [6]	2300	25	0,33

Wall 1 has been excited using an arbitrarily distributed, random force perpendicular to the surface. This procedure induces a high level of out-of-plane vibration and a low level of in-plane vibration. The reaction of the walls has been evaluated using the spatial averaged velocities excluding the nearfield close to the boundaries.

Third-octave bands from 200 Hz to 1250 Hz have been investigated. Within this range the values of the flanking sound reduction index are used to calculate a single number based on ISO 10848-1 [3].

Results and Discussion

The sound power radiated by the walls of the receiving room have been evaluated to get an impression, whether including paths of 2nd order have an influence on the resulting sound energy transmission between the adjacent rooms or not. The radiated sound power P_i of the single walls i

$$P_i = \rho c \overline{v^2} S \sigma \quad [W] \qquad (3)$$

were calculated depending on ρ (density of air) and c (speed of sound in air) [4]. The out-of-plane velocities v have been spatial averaged using the total surface S of the walls. Same values for the radiation efficiency σ have been assumed for every wall because of the same composition and similar widths.

The sum of the radiated sound power of walls 2 and 3 has been compared to the sum of the radiated power of walls 2, 3 and, additionally, wall 5.

$$\Delta L_W = 10 \lg \left[\frac{P_2+P_3+P_5}{P_2+P_3}\right] \quad [dB] \qquad (4)$$

Figure 2 shows the increasing one-third-octave based values of the air-borne sound power by including wall 5.

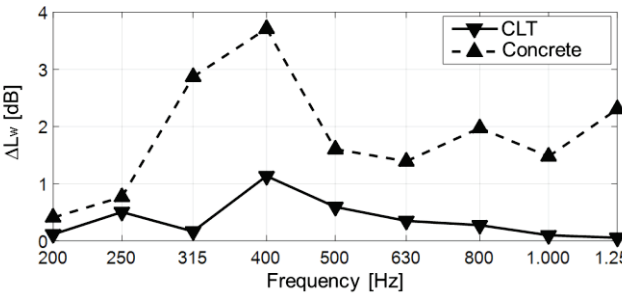

Figure 2: Contribution of sound radiation of wall 5 to the air-borne sound power of the receiving room

In general the reduction of the transmitted energy in the structure is depending on internal losses, radiation, flanking transmission to adjacent elements and the damping caused by the junction. The CLT model shows less influence of wall 5 caused by the high dissipation.

Depending on the required accuracy of the final prediction procedure, this additional power contribution may be neglected. In practice, the CLT-plates are not rigidly connected, so the resulting velocity at wall 5 as well as the sound radiation should decrease. In addition, a high radiated power caused by wall 5 seems to be evident in the concrete model. To prove, if the wave conversion exists and has an effect on the transmission, the contribution of the out-of-plane component to the total movement has been evaluated.

Figure 3 and figure 4 show the ratio of the spatial and frequency averaged squared velocities of the out-of-plane component to the sum of all components for wall 1, 2, 3 and wall 5

$$\text{ratio}=\frac{\overline{v^2{}_{oop}}}{\sum \overline{v^2{}_i}} \qquad [-] \qquad (5)$$

A high ratio represents a high proportion of out-of-plane components and a low ratio represents a high proportion of in-plane components.

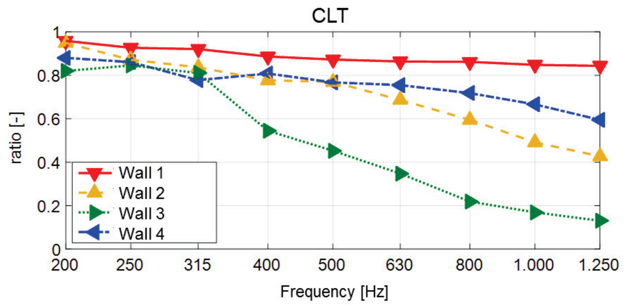

Figure 3: Ratio of out-of-plane components to the sum of out-of-plane and in-plane components (CLT)

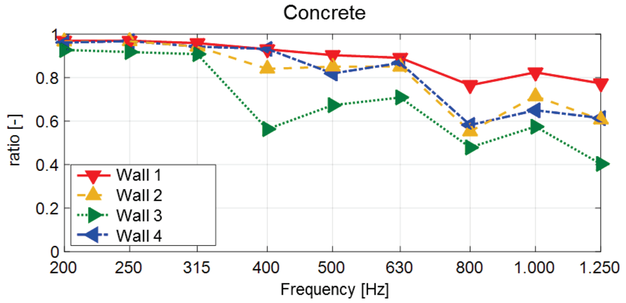

Figure 4: Ratio of out-of-plane components to the sum of out-of-plane and in-plane components (concrete)

As expected, the excited wall 1 shows a high level of out-of-plane velocities. More or less, a conversion process appears for both materials shown by the altering ratios at the different walls. The separating wall 3 partly shows significant less ratio of out-of-plane velocity compared to the flanking walls 1 and 5. Therefore, this effect may be interpreted as a wave conversion from - as an example - bending-wave in wall 1 to a quasi-longitudinal wave in wall 3 and an inverse-conversion of the quasi-longitudinal wave in wall 3 to a bending wave in wall 5.

In a next step, the out-of-plane velocity level difference

$$D_{13}=10\ \lg\left[\frac{\overline{v^2{}_1}}{\overline{v^2{}_3}}\right] \qquad [\text{dB}] \qquad (6)$$

has been compared to the real reduction of the total kinetic energy density

$$E_{kin,13}=10\ \lg\left[\frac{\overline{E_{kin,1}}}{\overline{E_{kin,3}}}\right] \qquad [\text{dB}] \qquad (7)$$

of wall 1 and wall 3 (figure 5 and figure 6). The total kinetic energy density includes all vibration directions and has been volume-averaged in the areas of the evaluation surfaces.

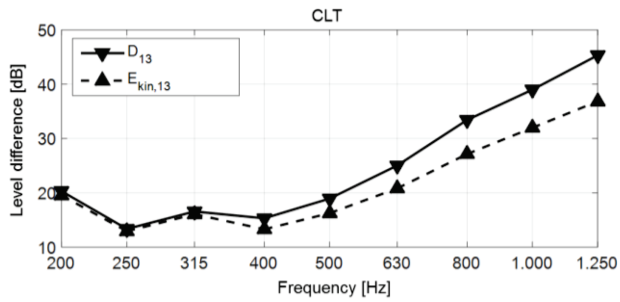

Figure 5: Velocity level difference compared to the level difference of the total kinetic energy density (CLT)

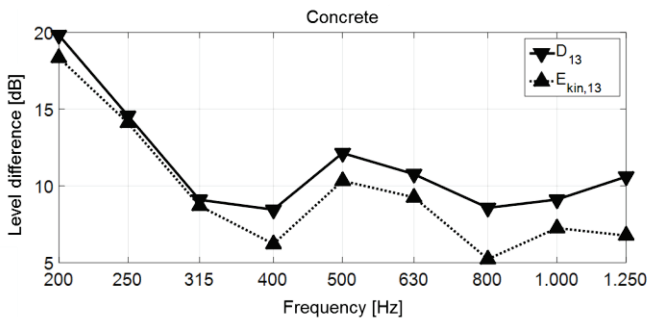

Figure 6: Velocity level difference compared to the level difference of the total kinetic energy density (concrete)

Figure 5 and figure 6 allow the conclusion that the out-of-plane velocity level difference does not capture the total transmitted kinetic energy. This underestimation of the transmission has been found by determining the deviation of the values. Then it has been compared to the difference of the logarithmic ratios of the out-of-plane components (see figure 3 and figure 4).

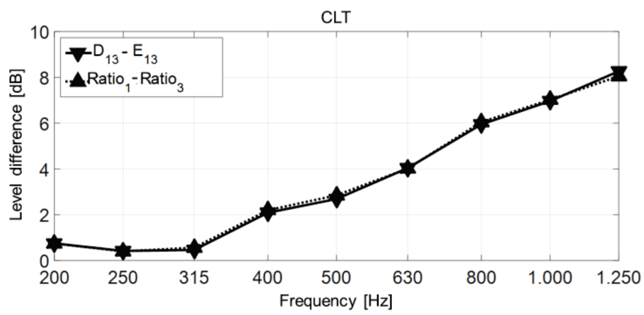

Figure 7: Correlation between deviation of velocity and energy based level differences and wave conversion (CLT)

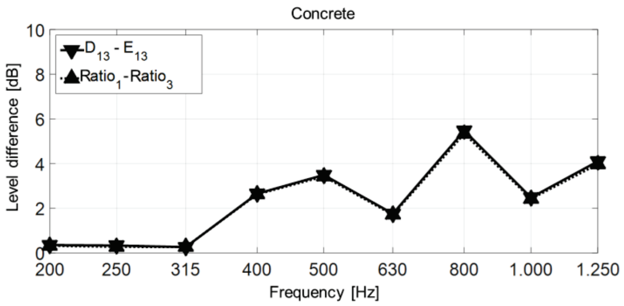

Figure 8: Correlation between deviation of velocity and energy based level differences and wave conversion (concrete)

The results are shown in figure 7 and figure 8, where a high correlation between this underestimation and the conversion of vibration components is evident for both materials. This high correlation is caused by the fact that, finally, the deviation between the out-of-plane velocity level difference and the difference of total kinetic energy density results in a similar calculation using the same velocity components.

$$D_{13} - E_{kin,13} \quad \text{[dB]} \quad (8)$$

$$= 10 \lg \left[\frac{\overline{v^2}_{1,oop}}{\overline{v^2}_{3,oop}} \bigg/ \frac{\overline{E_{kin,1}}}{\overline{E_{kin,3}}} \right]$$

$$= 10 \lg \left[\frac{\overline{v^2}_{1,oop}\ {}^1\!/_2\ \rho \left(\overline{v^2}_{3,x} + \overline{v^2}_{3,y} + \overline{v^2}_{3,z}\right)}{\overline{v^2}_{3,oop}\ {}^1\!/_2\ \rho \left(\overline{v^2}_{1,x} + \overline{v^2}_{1,y} + \overline{v^2}_{1,z}\right)} \right]$$

$$\text{Ratio}_1 - \text{Ratio}_3 \quad \text{[dB]} \quad (9)$$

$$= 10 \lg \left[\frac{\overline{v^2}_{1,oop}}{\left(\overline{v^2}_{1,x} + \overline{v^2}_{1,y} + \overline{v^2}_{1,z}\right)} \bigg/ \frac{\overline{v^2}_{3,oop}}{\left(\overline{v^2}_{3,x} + \overline{v^2}_{3,y} + \overline{v^2}_{3,z}\right)} \right]$$

$$= 10 \lg \left[\frac{\overline{v^2}_{1,oop} \left(\overline{v^2}_{3,x} + \overline{v^2}_{3,y} + \overline{v^2}_{3,z}\right)}{\overline{v^2}_{3,oop} \left(\overline{v^2}_{1,x} + \overline{v^2}_{1,y} + \overline{v^2}_{1,z}\right)} \right]$$

This fact emphasises the hypothesis that a wave conversion process in junctions leads to an underestimation of the real transmitted kinetic energy, if measurement values of common used standards [1, 3] are used. The small deviations between the values in figure 7 and figure 8 are caused by the different areas for spatial averaging: the sum of the components for the ratio calculation was averaged using the surface, whereas the kinetic energy densities were averaged using the volume.

In general, four cases of wave conversion exist during wave propagation across two independent junctions. Table 3 shows an interpretation of these cases, whether wave conversion may be a problem or not. If no conversion occurs, the out-of-plane velocity level difference is comparable to the reduction of total kinetic energy that finally leads to sound radiation (case A). Approximately this case is evident in figure 3 at third-octave bands from 200 Hz to 315 Hz. A wave conversion in one of the two junctions transforms energy into in-plane movements that finally do not lead to sound radiation (case B and C). As a consequence, this effect additionally reduces the sound transmission between two rooms. A problem occurs, if the transformed components of junction 1 are inverse transformed in a second junction (case D). This case is evident in figure 3 in the range of third-octave bands from 400 Hz to 1250 Hz. A part of the transmitted energy is not captured by the out-of-plane velocity level difference and this neglected energy, finally, can lead to sound radiation. As a consequence this effect may cause deviations between measurement and prediction of the sound transmission between two rooms based on common used standards [1, 3].

Table 3: Case Study

Case	Conversion		Problem
	Junction 1	Junction 2	
A	-	-	NO
B	+	-	NO
C	-	+	NO
D	+	+	YES

Conclusion

The transformation of out-of-plane components to in-plane components of a wave leads to an apparently increasing flanking sound reduction index. The influence of this effect is depending on the amount of the damping mechanism during wave propagation. Depending on the accuracy and the base problem, the effect may be neglected in most cases for materials showing high propagation damping like cross-laminated-timber. For materials with less amount of damping mechanism - concrete, as an example - the effect of reverse transformation becomes more important, especially, during investigations in flanking sound transmission. As a consequence, a part of the transmitted energy in the structure is not captured by the measurement values. Nevertheless, this neglected energy may lead to sound radiation in some cases.

Acknowledgements

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