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A NOTE ON METHODS FOR THE ESTIMATION OF THE AIRBORNE SOUND INSULATION OF TIMBER FRAME STRUCTURES

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ABSTRACT

Acoustic behavior of structures with wooden elements is nowadays of great interest. At the same time, the estimation of the airborne sound insulation of timber frame structures is a complex procedure which includes the prediction of several resonances and the analysis of a significant decrease of the transmission loss in the low frequency range.

Three case studies are presented in the paper. The emphasis is put on the transmission loss in 1/3 octave frequency bands of double leaf structures with gypsum panels, wood studs and a well-damped cavity. Methods of Sharp and Davy are used for the transmission loss prediction. Particular issues are discussed for an asymmetrically sheathed timber frame structure, wood studs with resilient channels and staggered studs.

The paper also presents that the weighted sound reduction index is not sufficient quantity for characterizing the airborne sound insulation of timber frame structures. Various methods are employed for the calculation of the transmission loss of a traditional structure on a silicate base. Characteristic differences between a silicate based structure and a timber frame structure are highlighted. The usage of the spectrum adaptation terms is encouraged.

The paper intends to be helpful in the field of the transmission loss estimation of double leaf structures with wood studs. Since the acoustic behavior of double leaf structures with wood studs is certainly a complex phenomenon, there is a further need for an improvement of methods for the transmission loss estimation and single number quantities for the evaluation of the sound insulation.

KEYWORDS

Sound insulation; timber frame structures; transmission loss; weighted sound reduction index; resonance frequency

INTRODUCTION

A trend of contemporary society is to increase the living standard constantly together with an effort to achieve the sustainable construction. Timber frame houses belong among structures which are considered to be environmentally friendly and at the same time energy (and therefore also financially) efficient. Nevertheless, one should not neglect the importance of the acoustic comfort when designing houses with wooden elements.

Since timber frame houses are lightweight and double leaf structures, their acoustic behavior differs significantly from the acoustic behavior of widely used heavy-weight materials as bricks or concrete. The airborne sound insulation is usually characterized by the sound reduction index (abbrev. SRI) in 1/3 octave frequency bands. The term transmission loss (abbrev. TL) is interchangeable with the term SRI in this paper.

The evaluation of the TL in 1/3 octave frequency bands is too complex for practical use and there is need for single number quantities for the assessment of the sound insulation. Vast investigation made by COST Action TU0901 [1] revealed that 16 European countries (out of 30) are applying only the weighted apparent sound reduction index R'_w for evaluating the airborne sound insulation. R'_w is calculated for center frequencies of 1/3 octave bands ranging from 100 Hz to 3150 Hz according to the standard ISO 717-1 [2].

ISO 717-1 also describes the spectrum adaptation terms C and C_{tr} both for the standard frequency spectrum (from 100 Hz to 3150 Hz) and for the extended frequency spectrum (from 50 Hz to 5000 Hz). Only one country (Sweden) is combining R'_w with the spectrum adaptation term for the low frequency range ($C_{50\text{-}3150}$). Besides the weighted apparent sound reduction index, the weighted standardized level difference $D_{nT,w}$ is employed in 10 European countries (in some of them it is together with the spectrum adaptation terms but only for the standard frequency range) [1].

COST Action TU0901 suggested to use the weighted standardized level difference $D_{nT,w}$ with the spectrum adaptation term $C_{50\text{-}3150}$ for the classification of the airborne sound insulation. There are also many studies proposing various improvements of current sound insulation evaluation scheme with respect to more accurate assessment of lightweight structures in particular, e.g. [3] and [4].

Important issue is the improvement of methods for the estimation of the airborne sound insulation in order to achieve higher prediction reliability for timber frame structures. The tricky part is especially to estimate the TL in the frequency region below 100 Hz.

FUNDAMENTAL THEORY

The paper is concerned with the TL of timber frame structures consisted of gypsum panels with wood studs and damped cavity. Besides timber frame structures, massive structures from solid wood are available on market. However, such structures can be approximated as single walls from the point of view of the TL. Very specific chapter is the field of triple leaf walls whose TL is quite challenging to estimate because of multiple resonances.

Three important frequencies have to be taken into account for double walls: the acoustic resonance f_2 expressing the first occurrence of the standing wave pattern in the gap between panels, the mechanical resonance of the structure f_0 and the limiting frequency related to the gap between panels f_l [5].

The structural mechanical resonance should be, in the best case, below the sound insulation spectrum [6]. This rule is possible to keep for the standard insulation frequency spectrum but not so easy to keep for the extended frequency spectrum. The fundamental mechanical resonance f_0 [Hz] can be calculated [7]:

$$f_0 = \frac{1}{2\,\pi}\left(\frac{1.8\,\rho_0\,c_0{}^2\,(m_1 + m_2)}{d\,m_1\,m_2}\right)^{1/2} \tag{1}$$

where ρ_0 [kg/m3] is the air density,

where c_0 [m/s] is the sound speed in the air,

where m_1 [kg/m2] and m_2 [kg/m^2] are the panel surface mass densities,

where d [m] is the gap thickness.

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The constant 1.8 in Eq. 1 is obviously empirical and it is introduced by Sharp in Ref. [8] in order to obtain better agreement with experimental results. On the contrary, Davy in Ref. [9] does not use this constant.

The fundamental acoustic resonance expresses that half of the wavelength is equal to the gap width. The standing wave pattern can be eliminated by usage of the sound absorbing material which provides an attenuation inside the gap and does not form a mechanical bridge between panels [5]. The fundamental acoustic resonance f_2 [Hz] is calculated as:

$$f_2 = \frac{c_0}{2\,d} \tag{2}$$

The limiting frequency f_l [Hz] has no special physical meaning but it formulates the border line between low frequency and high frequency behavior inside the air cavity [10]. It is also called the cross-over frequency and it is calculated as follows [5]:

$$f_l = \frac{c_0}{2\,\pi\,d} \tag{3}$$

The TL of a double leaf structure is highly dependent on the fact whether there is mechanical coupling inside the cavity (e.g. wood studs) and consequently, whether there is structure-born transmission through the cavity. The TL for frequencies $f < f_0$ and for the case of a wall with two leafs which are acoustically and mechanically isolated is calculated [11] as:

$$R = 20\,\log\left(\frac{\omega\,(m_1 + m_2)}{2\,\rho_0\,c_0}\right) - 5.5 \tag{4}$$

where R [dB] is the transmission loss of a double leaf structure,

where ω [rad/s] is the angular frequency.

Eq. 4 basically says that the TL of double leaf walls is for frequencies $f < f_0$ estimated according to the mass law with the sum of surface mass densities of partial panels. The TL can be calculated for frequencies $f_0 < f < f_l$ as [11]:

$$R = R_1 + R_2 + 20\,log(2\,k\,d) \tag{5}$$

where k [m^{-1}] is the wave number,

where R_1 and R_2 [dB] are the transmission losses of partial panels.

The gap thickness is not important parameter for high frequencies as it can be seen from following Eq. 6. The TL can be calculated for $f > f_l$ as [11]:

$$R = R_1 + R_2 + 6 \tag{6}$$

However, the achieved TL is significantly lower when panels are mechanically connected via point or line connections. The decrease of the TL of a structure with studs occurs above the bridging frequency which expresses the structure-born conduction limits of used connections. The bridging frequency can be found either graphically or with equations of the analytical geometry. It is also important to notice that a dip in the TL occurs around the critical frequency when the wavelength of the bending wave in the structure equals to the trace wavelength of the incident sound wave at the grazing angle [5].

CASE STUDIES

Case studies of three timber frame structures are presented in this chapter. Experimental data is taken from a report published by the National Research Council of Canada [12]. Davy claimed that the experimental data contained in this report is at the lower end of the measurement results from outside of Australia [9].

Sharp´s method used in case studies was published in Ref. [8], [11] and reviewed in Ref. [5]. Davy´s method was published in Ref. [13], [14], [15] and reviewed in Ref. [5]. All calculations in this paper were executed by Matlab scripts programmed by the author.

Gypsum boards are modelled with these properties:

- Young modulus: E = 2.0 * 10^9 Pa [5],
- Total loss factor: η_{TOT} = 0.1 [5],
- Length of the opening: l_x = 3.05 m [12],
- Height of the opening: l_y = 2.44 m [12].

Young modulus is used together with the surface mass density and the thickness to calculate the longitudinal speed of sound waves. The surface mass density of gypsum boards and the overall wall composition vary for different case studies. Obviously, there is uncertainty in input parameters, especially in the total loss factor.

Asymmetric timber frame wall

The first case study is an asymmetrically sheathed timber frame wall depicted in Fig. 1. The TL calculated after Sharp and Davy along with the experimental data is shown in Fig. 2.

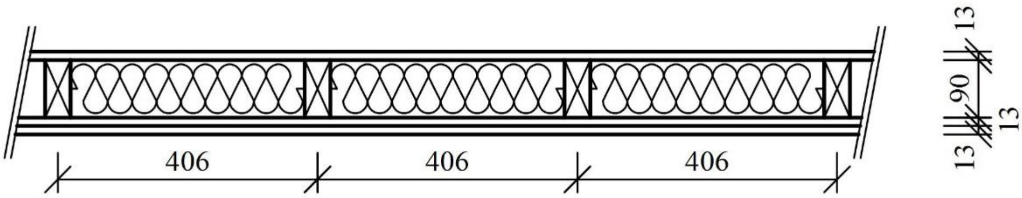

Fig. 1: Geometry of the asymmetrically sheathed timber frame wall (dimensions in mm)

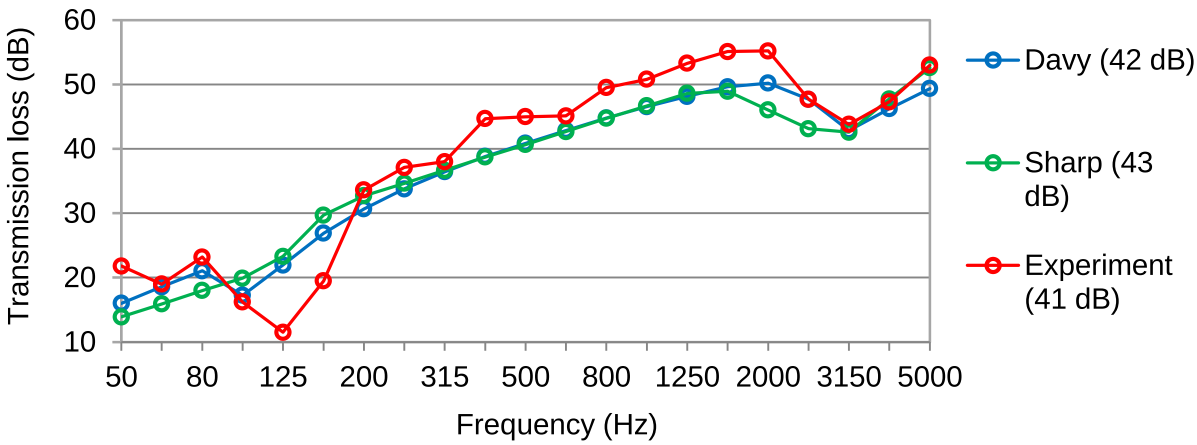

Fig. 2: The TL of the asymmetrically sheathed timber frame wall as a function of the frequency obtained with Davy's and Sharp's methods and an experiment (performed in Ref. [12]) with R_w in parenthesis

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While the dip at the critical frequency is estimated very well, the dip around 125 Hz is poorly predicted. The TL is underestimated between the bridging frequency and the critical frequency and so the methods seem to be on the safe side in the middle frequency range.

Line-line rigid connections are modeled by both methods. The surface mass density of one gypsum board is 8.3 kg/m^2. Gypsum boards are connected with screws and frictional losses can occur between the boards screwed together. Still, applied methods estimate the weighted sound reduction index with a reasonable precision.

Wood studs with resilient channels

The second case study deals with modeling of resilient channels attached to the wood studs on both sides. Geometry of the case study is shown in Fig. 3. The TL calculated with Sharp´s and Davy´s method together with the test results is shown in Fig. 4.

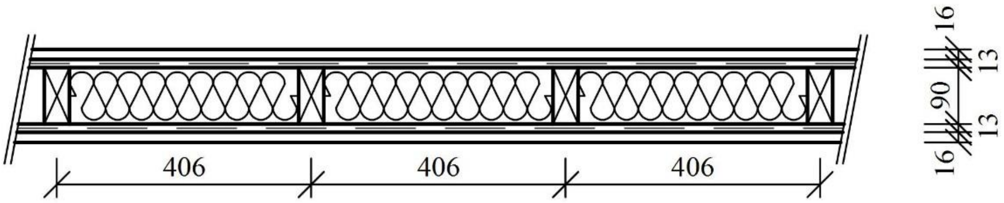

Fig. 3: Geometry of the timber frame wall with resilient channels on both sides (dimensions in mm)

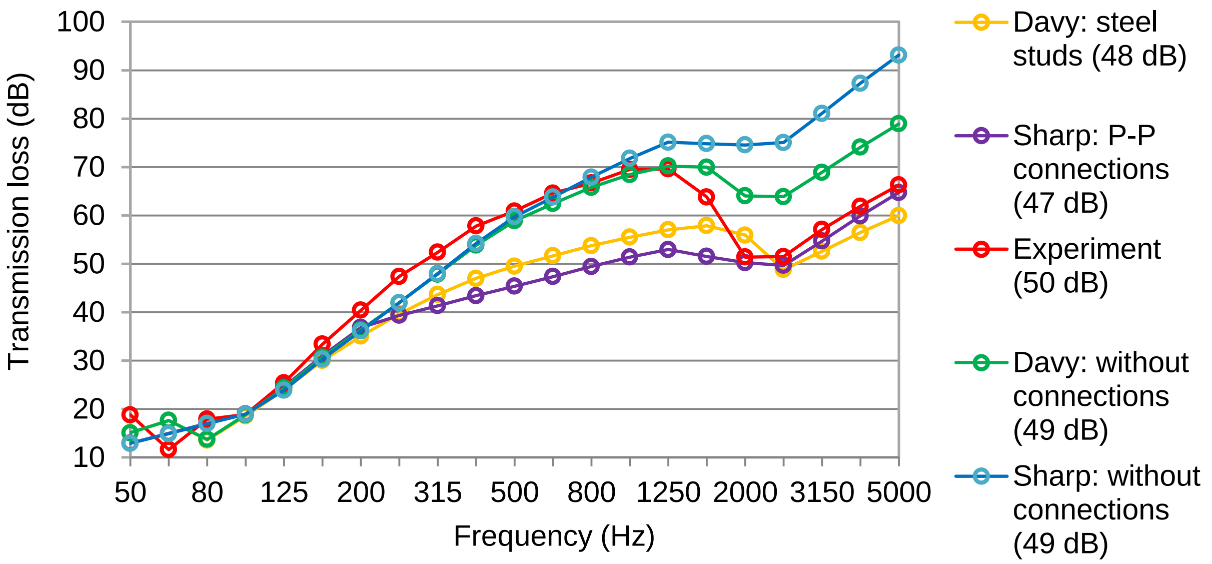

Fig. 4: The TL of the timber frame wall with resilient channels on both sides as a function of the frequency obtained with Davy's and Sharp's methods and an experiment (performed in Ref. [12]) with R_w in parenthesis

The gap width is 116 mm in total (90 mm plus two times 13 mm for resilient channels). The wall is symmetrically sheathed with one gypsum board on each side (surface mass density 11.1 kg/m^2). Spacing of resilient channels is 610 mm. Sharp´s method is calculated both with point-point connections and with acoustically and mechanically isolated panels. Davy´s method models steel studs (compliance C_M = 10^{-6} m^2 N^{-1} [13]) and a point support of the second panel (after Fahy [7]). The second calculation with Davy´s method models a wall without any structure-born sound transmission (sound is transmitted only through the damped cavity).

Fig. 4 shows that the TL is estimated fairly well in the domain of low frequencies and reasonably well in the domain of medium frequencies by Davy and Sharp (both without any connections). Still, the TL around the critical frequency is poorly estimated by the calculations with mechanically isolated panels. Apparently, resilient channels cause the structure-born transmission similar to the point-point supports above the critical frequency.

Staggered wood studs

The third case study investigates a double leaf wall with staggered wood studs. Geometry of the timber frame wall with staggered studs is shown in Fig. 5. The TL calculated with Sharp´s and Davy´s method along with the test results is shown in Fig. 6.

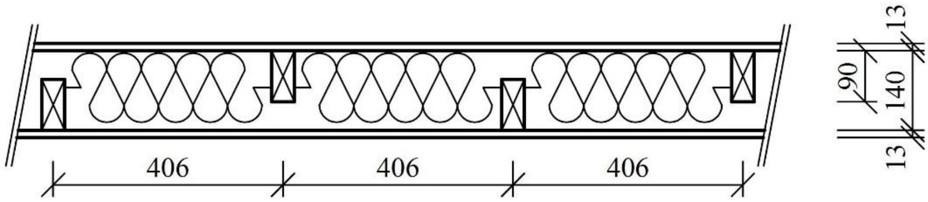

Fig. 5: Geometry of the timber frame wall with staggered studs (dimensions in mm)

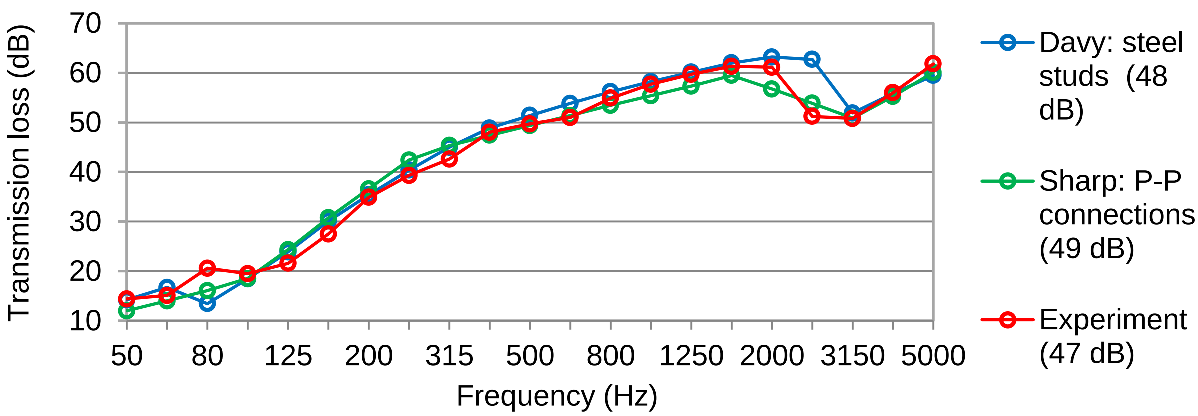

Fig. 6: The TL of the timber frame wall with staggered studs as a function of the frequency obtained with Davy's and Sharp's methods and an experiment (performed in Ref. [12]) with Rw in parenthesis

The surface mass density of a gypsum board is 10.0 kg/m^2. Davy´s method employs steel studs (compliance C_M = 10^{-6} m^2 N^{-1} [13]) and a point support of the second panel (after Fahy [7]). Spacing of connections entered in the calculation was doubled (812 mm).

Surprisingly, models with steel studs (after Davy) and P-P connections (after Sharp) estimate the TL of the timber frame wall very well. It is possible to draw a conclusion that even though staggered studs do not form a mechanical bridge between gypsum panels, they cause change in the sound propagation inside the cavity. In this case estimation methods are i slightly over predicting the weighted sound reduction index.

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SINGLE NUMBER QUANTITIES FOR THE EVALUATION OF THE SOUND INSULATION

Single number quantities are suitable for the evaluation of the sound insulation of traditionally used heavy-weight structures, e.g. concrete and masonry walls, as it is shown in this section. Experimental data for the investigated concrete wall was published in Ref. [18].

The examined wall is constituted from solid concrete blocks with these properties:

- Thickness: t = 140 mm [18],
- Surface mass density: m = 300.7 kg/m^2 [18],
- Internal loss factor: η_{INT} = 0.006 [17],
- Longitudinal speed of sound waves: c_L = 3500 m/s [17].

An application of estimation methods for single walls is also demonstrated. Watters´s method was published in Ref. [16] and reviewed in Ref. [6]. EN 12354-1 was described in the standard [17]. The total loss factor is calculated for the laboratory conditions with an equation from Ref. [17]. Since the structure was tested by the same research council, test opening dimensions are regarded to be identical to previous timber frame structures.

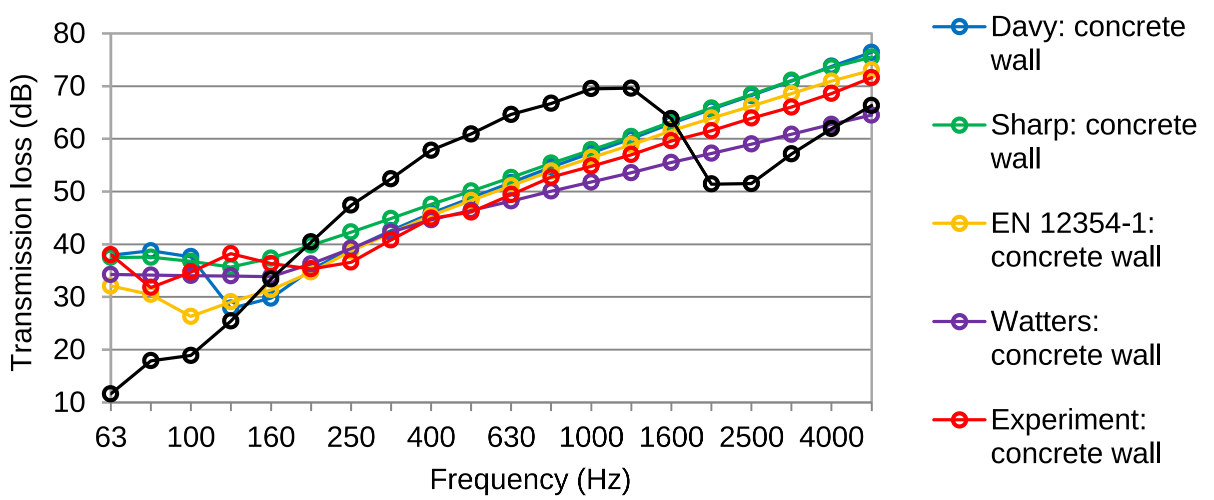

Fig. 7: The TL of the concrete wall and the timber frame wall with resilient channels as a function of the frequency obtained with different methods and experiments (performed in Ref. [12] and [18]). The black curve represents experimental outputs for the object of measurements, i.e. the timber frame wall

The TL of the timber frame structure with resilient channels (see Fig. 3) is compared to calculated and measured TL of the concrete wall. Results of the comparison are presented in Fig. 7 and single number quantities R_w, C and C_{tr} are presented in Tab. 1.

Tab. 1: Single number quantities for the evaluation of the sound insulation

Indicators	Davy: concrete wall	Sharp: concrete wall	EN 12354-1: concrete wall	Watters: concrete wall	Experiment: concrete wall	Experiment: timber frame wall
R_w	50	53	49	50	50	50
C	-2	-1	-2	-2	-1	-5
C_{tr}	-7	-5	-7	-5	-5	-12

CONCLUSIONS

The last section of this paper demonstrated that the design of the sound insulation of timber frame structures introduces different issues than the design of traditional heavy-weight structures. On the other hand, Fig. 7 showed that the precise estimation of the TL in the low frequency range is still a challenge even for a concrete block wall.

In spite of the fact that the weighted sound reduction index is the same for a concrete wall and a timber frame wall, the spectrum adaptation terms are quite different. It is also appropriate to remark that only the standard frequency range was evaluated. The spectrum adaptation terms for the extended frequency range would give even higher differences.

The estimation of the TL of a timber frame wall is a complex procedure because of many possible wall compositions (resilient channels on one or two sides, staggered or double studs, differently damped cavity etc.). Responsible acoustician should in practice collect all possible data about the designed structure and also about similar structures which were already tested.

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