EXTENDING THE CEN-CALCULATION MODEL FOR SOUND TRANSMISSION IN BUILDINGS TO HEAVY DOUBLE WALLS AS SEPARATING AND FLANKING WALLS

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ABSTRACT
The calculation model in EN 12354-1 to estimate the sound transmission between rooms is extended to heavy double separating and flanking walls in conjunction with the relevant junction types. Besides a theoretical model to estimate the sound insulation of heavy double walls the different junctions types are modelled empirically. Comparison with measured data shows good agreement with the calculated results. However, deviations are expected to be higher than for single constructions due to higher spread of workmanship.

1. INTRODUCTION

The calculation model presented in EN 12354-1 to estimate the airborne sound transmission between rooms is mainly focused on single heavy walls [1]. However, in some European countries heavy double walls are quite common. For example, heavy double walls are used as separating walls between detached or row houses where a higher sound insulation is oftenly required due to national or local building regulations. Heavy double walls are also found quite frequently in appartment housing in town centres where a construction joint is needed between individual buildings forming a double wall system.

Furthermore, in central and northern Europe heavy double walls are used as outer walls to provide higher sound or thermal insulation or to prevent direct rain impact to the inner wall leaf. In these cases, the heavy double wall is the flanking element in situations with horizontal or vertical transmission between rooms.

As these types of junctions is a frequent design characteristic in contemporary building construction it was found a major lack of the CEN-model not being applicable in these situations as the required data to describe the junction transmission is missing in the CEN-standard. To enhance the CEN-model for these situations the following aspects have to be covered:

- calculation of the direct transmission (path Dd) through a separating heavy double wall (by a theoretical model including a "generalized" sound bridge to improve the correspondence with measured results),
- modelling the transmission along the outer leaf of a flanking heavy double wall (treated empirically according to vibration measurements and comparisons between calculated and measured results),
- modelling the transmission across the different transmission paths at the relevant junctions on the basis of the definitions in EN 12354-1, by introducing a new term describing the additional loss by the cavity of the heavy double wall, and by energy addition.

2. DESIGN CHARACTERISTICS OF HEAVY DOUBLE WALLS

Heavy double walls used as separating walls between buildings mostly are of symmetrical design, constitute of two single walls (hereafter called 'wall leaves') with the same thickness h, surface mass m", longitudinal wave speed c_{L2} , critical frequency f_c and total loss factor η and separated by a cavity of a given depth. The cavity is in most practical cases filled with a sound absorbing material (such as mineral wool slabs) to suppress propagation of sound waves parallel to the walls surface and to prevent against structural connections between the two wall leaves ('sound bridges'). For heavy double walls made of masonry work the dynamic stiffness of the cavity is given by the dynamic stiffness of the enclosed air as the two wall leaves are not structurally connected via the insulation material. Assuming an isothermal compression of sound waves with a porous sound absorbing material in the cavity the dynamic stiffness s" (in MN/m³) can be expressed by means of the cavity depth d (in m):

$$s''_{cavity} = \frac{0{,}12}{d_{cavity}}$$

In heavy double walls made of concrete casted on site the two wall leaves are in direct contact with the absorber material in the cavity due to the casting process. The dynamic stiffness of the cavity is governed by the dynamic stiffness of the insulation materials. As in the standardized test procedure according to ISO 9052-1 the dynamic stiffness of the enclosed air is included in case of porous materials the test result equals the dynamic stiffness of the cavity:

$$s''_{cavity} = s''_{material}$$

Heavy double walls being used as outer walls have different design characteristics as for static reasons connections between the inner and outer wall leaf are required. These "wall ties' are usually made from stainless steel and fixed to either wall leaf by adhesive binder or mortar filled into the horizontal joints in masonry work construction. Because outer walls of this type form in horizontal and vertical situations the flanking element, the additional transmission path via the wall ties and the outer leaf has to be considered when calculating the junctions transmission.

3. DIRECT TRANSMISSION ACROSS HEAVY DOUBLE WALLS

The sound reduction index for the direct path Dd at low frequencies (i.e. below the critical frequencies f_c of either plate and below the resonance frequency f_0) is expressed according to HECKL [2] by:

$$R_{double,low} = 20\,\lg\left(\frac{2\pi f m''}{\rho c}\right) - 3\ \text{dB}$$

For higher frequencies the direct path has been modelled applying the Statistical Energy Analysis (SEA) with the following four systems: 1. source room, 2. wall leaf on sending side, 3. wall leaf on receiving side, 4. receiving room (see Fig. 1).

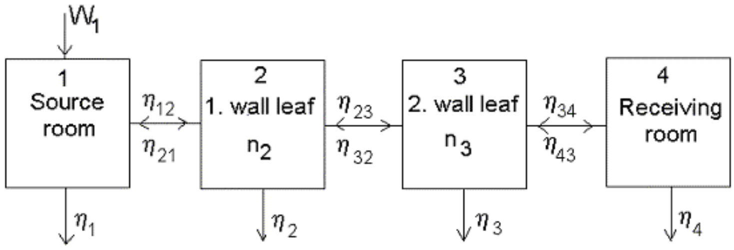


Fig. 1: SEA-systems with energy flows for modelling a double wall

The sound power W_1 generated by the sound source in the sending room is transmitted via each system with a corresponding coupling loss factor. Due to the assumed symmetry of the double wall the following modal densities n_i, loss factors η_i for dissipated energy and coupling loss factors η_{ij} among the systems correspond to each other: $n_2 = n_3$, $\eta_2 = \eta_3$, $\eta_{21} = \eta_{34}$, $\eta_{23} = \eta_{32}$.

The sound reduction index is given by:

$$R_{double,high} = 10\lg\frac{D_1}{D}\,dB$$

where

$$D_1 = \begin{vmatrix} 0 & -\eta-\eta_{21}-\eta_{23} & \eta_{23} \\ -\eta_{21}\cdot n_2 & \eta_{23} & -\eta-\eta_{23}-\eta_{21} \\ \frac{f\cdot S}{4\cdot\pi\cdot c^2} & 0 & \eta_{21} \end{vmatrix} \;;\; D = \begin{vmatrix} \eta_{21}\cdot n_2 & -\eta-\eta_{21}-\eta_{23} & \eta_{23} \\ 0 & \eta_{23} & -\eta-\eta_{23}-\eta_{21} \\ 0 & 0 & \eta_{21} \end{vmatrix}$$

with S the area of the double wall.

The cavity between the two wall leaves has not been modelled as a separate system because in most practical cases its coupling loss factor is unknown and cannot be easily derived from parameters relevant in wall design. Instead, the cavity has been modelled by its dynamic stiffness. The coupling loss factor across the cavity η_{23} (from system 2 to system 3) and the modal densities of the plates n_2 are:

$$\eta_{23} = \frac{f_c\, s''^2}{64\pi^3 f^5 m''^2} \;;\; n_2 = \frac{\sqrt{3}\,S}{2\pi h c_{L2}}$$

For high frequencies these formulas do not apply when the bending wavelength is no longer large compared with the thickness of the plate. The following formulas for corrected bending waves are used instead [3]:

$$\eta_{23} = \frac{f_g s''^2}{64\pi^3 f^4 m''^2}\cdot\frac{7{,}2\,d}{c_{L2}} \;;\; n_2 = \frac{2\cdot S\cdot f}{c_{L2}^2}$$

For the coupling loss factors from the sending room to the 1st wall leaf (η_{21}) and from the 2nd wall leaf to the receiving room (η_{34}) above the critical frequency it holds:

$$\eta_{21} = \eta_{34} = \frac{\rho\, c\, \sigma}{2\,\pi\, m''}$$

The radiation factor σ can be assumed to be $\sigma = 1$ above the critical frequency f_c, especially in the frequency region where the corrected bending wave applies. For lower frequencies, the radiation factor was calculated according to MAIDANIK [4] with the correction according to TIMMEL [5].

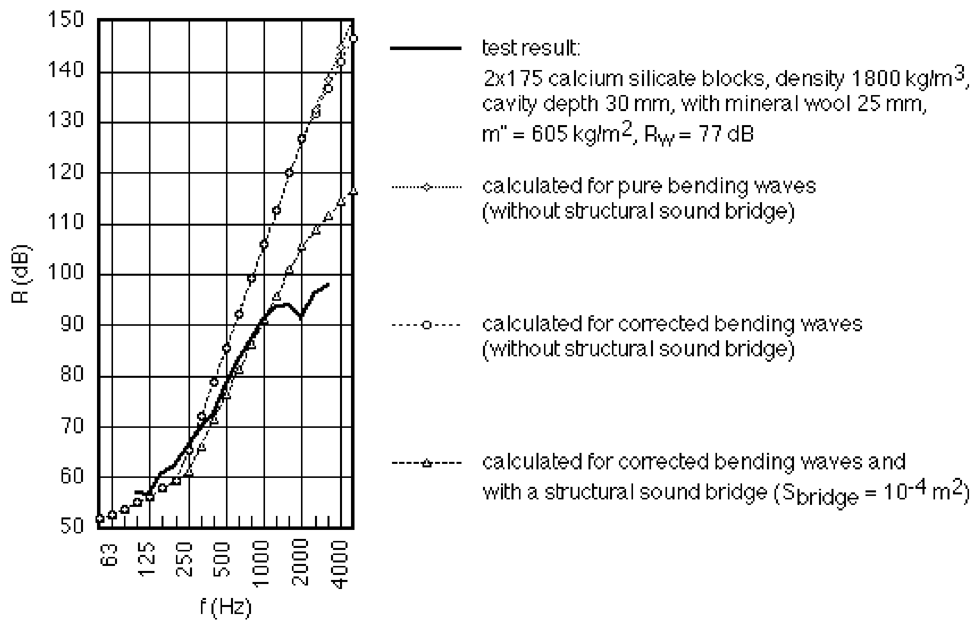


Fig. 2: Measured and calculated sound reductions indeces for a heavy double wall

When comparing calculated data with measured results it became obvious that the calculation gives too high sound reduction indeces at high frequencies. Therefore, an additional coupling loss factor $\eta_{23,\ bridge}$ for a pre-defined sound bridge between the two plates was introduced and added to the loss factor η_{23}. The area and material of this "standard sound bridge" was evaluated empirically modelling a small structural connection as oftenly found in practical building construction (S_{bridge} = 10^{-4} m², ρ_{bridge} = 1728 kg/m³, $c_{L,bridge}$ = 2600 m/s). The calculated results in comparison to the measured results for a heavy double wall are shown in Fig. 2. The correspondance between measured and calculated results is - as far as the model with an additional sound bridge is concerned - fairly good at sound reduction indeces R < 95 dB. At higher frequencies (i.e. with sound reduction indeces R > 95 dB) deviations may also be caused by measuring errors due to unsufficient sound radiation of the sound source and flanking transmission of the test facility.

4. FLANKING TRANSMISSION ACROSS SEPARATING HEAVY DOUBLE WALLS

The CEN-calculation model focuses on structural transmission across junctions between the separating element and the flanking elements when calculating flanking transmission [1]. For heavy double walls with a cavity extended over the whole wall surface no structural connections exist. The increase in sound insulation via each of the flanking paths by a separating double wall in comparison to the single wall (represented by one wall leaf of the double wall) can be formally written as:

$$\Delta R_{double} = R_{double} - R_{single} \cong \Delta L_v = 10\lg\frac{v^2_{single}}{v^2_{double,RR}}$$

The parameter ΔR_{double} represents the influence of the cavity on the sound energy transmitted via all flanking paths across a junction and the increase in sound insulation due to the double wall. ΔR_{double} is proportional to the difference of the velocity level $L_{v,single}$ on the single wall to the velocity level $L_{v,double\ RR}$ on the receiving side of the double wall:
For description of the transmission across a junction the vibration reduction index K_{ij} has been defined in EN 12354-1. However, as the parameter ΔR_{double} has been defined on the basis of velocity levels and not on an energetic basis the correction applies to the situation dependant direction-averaged junction level difference $\overline{D_{v,ij,situ}}$. For example, the transmission along the flanking path Ff at a cross-junction with a heavy double wall as separating construction is given by the sum of the level differences due the transmission along path 12 on the sending side, the parameter ΔR_{double} to account for the double wall and the transmission along path 23 on the receiving side. The transmission along paths 12 and 23 is expressed by means of the junction transmission index K_{ij} making use of the data in EN 12354-1, annex E (see Table 1). Paths Fd and Df are expressed analogously considering one junction on either side only.

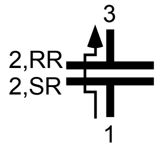
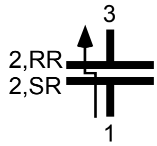
R_{ij}	Path	$\overline{D_{v,ij,situ}}$ with $M = \lg\frac{m''_{2,SR}}{0{,}5(m''_1+m''_3)} = \lg\frac{m''_{2,RR}}{0{,}5(m''_1+m''_3)}$
R_{Ff}		$\overline{D_{v,(1,2-2,3),situ}} = \overline{D_{v,12,situ}} + \Delta R_{double} + \overline{D_{v,23,situ}}$ $\overline{D_{v,12,situ}} = [5{,}7 + 5{,}7\,M^2] - 10\lg\frac{l_{ij}}{\sqrt{a_{1,situ}a_{2,situ}}}$ $\overline{D_{v,23,situ}} = [5{,}7 + 5{,}7\,M^2] - 10\lg\frac{l_{ij}}{\sqrt{a_{2,situ}a_{3,situ}}}$
R_{Fd}		$\overline{D_{v,(1,2-2),situ}} = \overline{D_{v,12,situ}} + \Delta R_{double}$

Table 1: Direction-averaged junction velocity level differences in dB for the flanking paths Ff and Fd at a cross-junction with a heavy double wall as separating element

For example, the results for 3 different types of separating double walls d (2x100, 2x200, 2x300 mm concrete, ρ=2300 kg/m², cavity depth 30 mm, with mineral wool) and for four different types of flanking walls f (50, 100, 200, 300 mm concrete, ρ=2300 kg/m²) each are shown in Fig. 3.

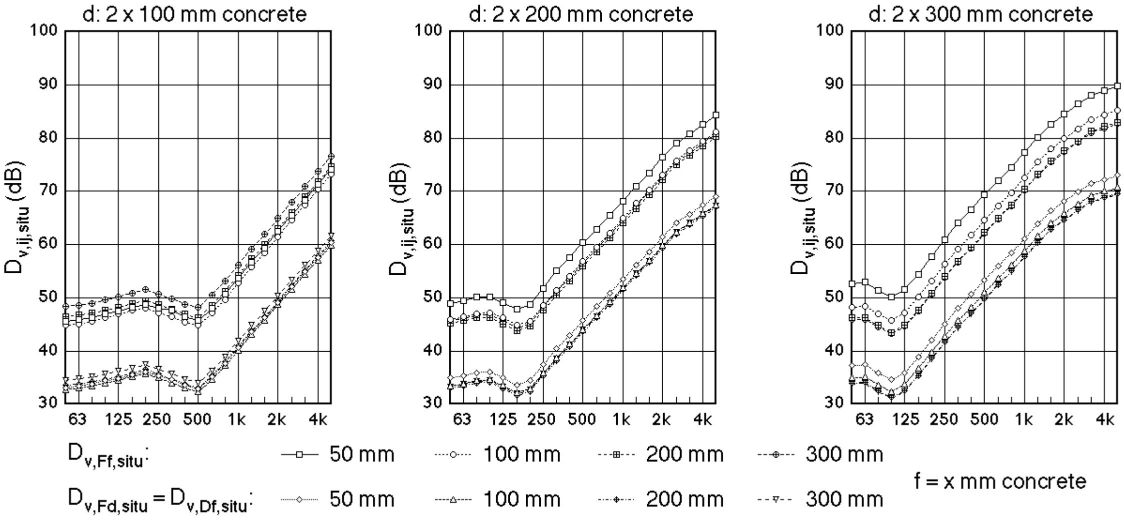


Fig. 3: Direction-averaged junction velocity level differences for flanking paths Ff, Fd and Df for 3 types of separating heavy double walls (d) and for 4 types of flanking elements (f) each.

The direction-averaged junction velocity level difference according to this approach starts from low frequencies with a more or less constant "plateau"-region and increases with frequency above the critical frequency of the single wall leaf caused by the parameter ΔR_{double}. The minimum values are observed for the transmission along flanking paths Fd and Df, while the transmission along path Ff is 10-15 dB smaller. In general, it can be concluded that the overall transmission is dominated by the path Dd as the smallest values for $\overline{D_{v,ij,situ}}$ are about 30 dB. This coincidences with measured results in field situations where the overall transmission is mainly dominated by the direct path and the contribution of all flanking paths is observed to be 1 to 5 dB on the final result, e.g. for R'_w. However, this statement assumes a perfect design and construction of the heavy double wall without major defects. At high frequencies the apparent sound reduction index R' measured in field situations is oftenly dominated by ubiquitous flanking transmission paths causing a larger difference to the calculated results.

5. FLANKING TRANSMISSION ACROSS FLANKING HEAVY DOUBLE WALLS

For a T-junction with a heavy double separating wall combined with an heavy double flanking wall the transmission along the outer leaf of the flanking wall has to be considered separately. This can be achieved by energetic addition of the sound energy transmitted via paths Ff, Fd and Df of the double wall and the energy transmitted via the outer leaf which is structurally connected by wall ties to the inner leaf:

$$D_{v,Ff,situ} = -10\lg\left(10^{-0.1\left(\overline{D_{v,(1,2-2,3),situ}}\right)} + 10^{-0.1\left(\overline{D_{v,outerleaf,situ}}\right)}\right)$$

The direction-averaged junction level difference $\overline{D_{v,(1,2-2,3),situ}}$ at the T-junction is treated analogously to the considerations as described before. The transmission along the outer leaf has been developed from vibration measurements in field situations and been validated by comparisons between calculated and measured sound insulation [6]:

$$\overline{D_{v,outerleaf,situ}} = \left[8 + 10|M| + 10\lg\frac{m''_{outer\ leaf}}{285}\right] - 10\lg\frac{l_{ij}}{\sqrt{a_{1,situ}\,a_{3,situ}}} \quad \text{with } M = \lg\left(\frac{m''_{inner\ leaf}}{m''_{outer\ leaf}}\right)$$

where m''_4 is the surface mass of the outer leaf of the flanking heavy double wall and M_3 the common logarithm of the ratio of surface masses of the inner to the outer leaf. This relation assumes that the distance between the wall ties connecting the inner to the outer leaf is in the range of 600-800 mm. In addition, when calculating the flanking sound reduction index R_{ij} the sound reduction index of the inner leaf R_i resp. R_j is corrected by:

$$R_{eff} = R + 20\lg \frac{m''_{inner\ leaf} + 0{,}5\, m''_{outer\ leaf}}{m''_{inner\ leaf}} dB$$

This correction accounts for a small improving influence by the surface mass of the outer leaf. In fact, the transmission along the outer leaf is not considered in the calculation as a separate transmission path but by adjusting the junction transmission and the input data of the inner leaf accordingly. The dependance from the surface mass of the outer leaf is illustrated in Fig. 4.

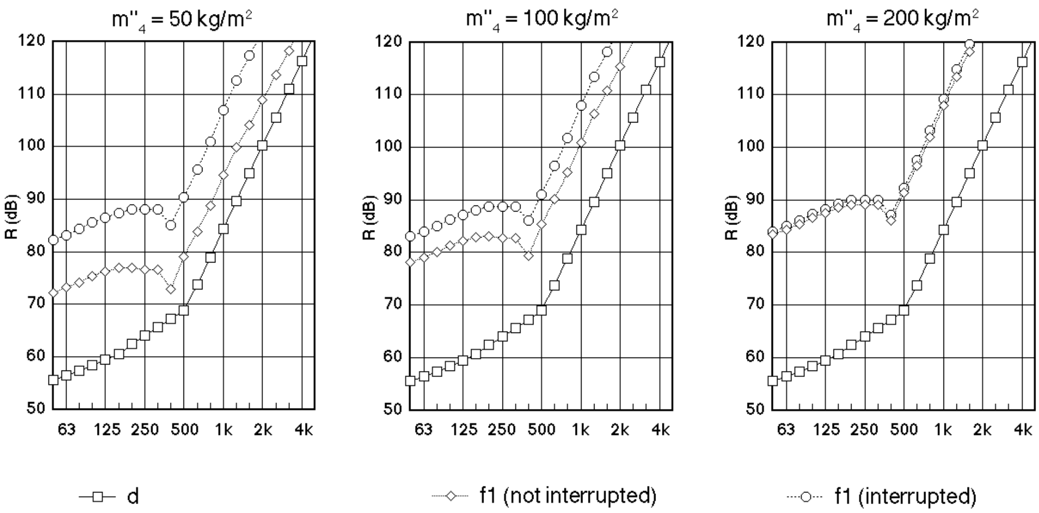


Fig. 4: Sound reduction index per element for different surface mass of the outer leaf (separating element: 2 x 100 mm concrete 2300 kg/m², flanking element: 100 mm aerated concrete 700 kg/m²), without and with interruption the outer leaf with surface mass m''_4).

For a given situation the sound reduction along flanking element f1 (includes flanking paths Ff and Df) causes a higher insulation with increasing surface mass of the outer leaf m''_4. A sufficient high surface mass of the outer leaf has the same effect on the flanking transmission as with a vertical interruption in the outer leaf (where $\overline{D_{v,outerleaf,situ}} \to \infty$ dB).

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