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Flanking Sound Transmission in Massive-Lightweight Connections

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Assessing the impact of flanking sound transmission is one of the most significant challenges in the process of designing building partitions. Acoustic parameters declared by manufacturers of lightweight systems are subject to errors of up to several decibels – and in the case of inaccurate construction on site, these differences can reach even higher values. One factor contributing to this is the phenomenon known as flanking sound transmission, which involves the transmission of acoustic energy through partitions connected to the partition directly dividing two adjacent rooms. For this reason, estimating the resultant acoustic insulation of a partition, taking flanking paths into account, is crucial at an early stage of the design process to ensure compliance with the requirements outlined in standard recommendations, and the literature. Currently, there are regulations and studies that provide guidance on calculating the estimated reduction in acoustic insulation due to flanking transmission. However, in practice, situations arise that have not yet been addressed in standards or the literature. Examples include partitions made of plasterboard, which are among the most common types of partition walls in Poland, yet are not covered by current normative procedures, as well as glass systems. This study aims to further explore this topic by analysing the impact of combining a massive partition with flanking lightweight partitions for selected structures (glass, plasterboard with single or double panelling, with full or partial sound-absorbing material infill, and without infill) and connection types.

Keywords: building acoustics, flanking sound transmission, sound insulation, statistical energy analysis.

1. Introduction

When estimating the sound transmission index of a partition, it is essential to take into consideration not only the direct partition between rooms, but also all alternative paths through which sound is transferred, known as flanking paths. These paths can significantly decrease the resultant sound insulation of a direct partition, particularly if the flanking partitions provide weaker insulation or have a lower density than the direct partition. A methodology for estimating the impact of flanking transmission for several types of partitions is described in the standard EN 12354-1 (International Organization for Standardization, 2017); however it does not cover all types of partitions encountered in practice. Although there have been numerous articles written on the matter, most of them discuss flanking transmission through timber or cross-laminated timber (CLT) partitions (Neusser, Bednar, 2022), which are not among the popular building materials in Poland, where gypsum board partitions prevail. Less frequently, other constructions are discussed, such as gypsum board partitions or double walls (Dijckmans *et al.*, 2019; Crispin *et al.*, 2017; Gerretsen, 2015; Schoenwald, 2008). This paper, however, examines a previously unstudied case: the use of lightweight gypsum board and glass partitions and their impact on the resultant sound insulation of a massive partition, using statistical energy analysis (SEA). Several cases are described – case 1 shows a basic situation of a single concrete partition between two rooms without flanking paths, case 2 includes single-cladding gypsum-board-based flanking partitions. Cases 3 to 5 focus on double-cladding partitions without filling in the cavity between plates, with a cavity partially filled with sound-absorbing material, and with a cavity fully filled with a sound-absorbing material. Case 6 focuses on glass flanking partitions. All cases show results for C-, T-, and H-shaped connections.

2. Statistical energy analysis

SEA, widely described by Craik (1996) as well as Crocker and Price (1969), is one of the methods used to calculate sound and vibration transmission through a given acoustic system. The general principle of SEA is to create a model of a system consisting of smaller subsystems and then determine the equilibrium equations describing the energy flow between them. A subsystem is a set of modes with the same properties and similar modal energy; it represents a physical object, such as a partition, a room, or a void. In SEA, the measure of sound in a room or vibration of a partition is energy. The value of power transferred from subsystem i to subsystem j (W_{ij}) depends on the sound energy in the transmitting subsystem E_i, the angular frequency ω, and the energy loss factor η_{ij}:

$$W_{ij} = E_1 \omega \eta_{ij}. \tag{1}$$

Some of the energy leaving a subsystem is lost as heat or transferred to a different partition that is not a part of a system (W_{id}, W_{jd}), and some is radiated and transmitted to other subsystems (W_{ij}, W_{ji}). The energy entering the subsystem includes the external excitation (W_1) and the transmission from other subsystems (W_{ji}, W_{ij}).

In the SEA model, it is assumed that the energy is distributed evenly in all frequency bands, so that each band must contain an appropriate number of modes. The number of modes per unit frequency is defined by the modal density $n(f)$, and the number of modes in a band is expressed as ΔN for a given subsystem. The modal density depends on the type of wave and on the geometry, material, and boundary conditions of the subsystem. The number of modes depends on the width of the frequency band.

All modes in a given subsystem and frequency band are excited equally, and their responses are independent of one another. The modal density, according to Craik (1996), Kleiner, Tichy (2014), and Schoenwald (2008), is described as follows:

a) for plates:

$$n(f) = \frac{2\pi f S}{c^2}, \tag{2}$$

where S refers to the surface area of the plate and c is the wave speed. For bending waves on thin plates, modal density is described as

$$n(f) = \frac{\pi S f_c}{c_0^2}; \tag{3}$$

b) for rooms:

$$n(f) = \frac{4\pi f^2 V}{c_0^3} + \frac{\pi f S'}{2c_0^2} + \frac{L'}{8c_0}, \tag{4}$$

where V is the volume of the room, S' is the total surface of the room, and L' is the total length of all edges in the room;

c) for cavities: for thin voids and for low frequencies below the eigenfrequency of the first cross mode, calculated using the following formula:

$$f_{m,n,o} = \frac{c_0}{2}\sqrt{\frac{m^2}{l_x^2} + \frac{n^2}{l_y^2} + \frac{o^2}{l_z^2}}, \tag{5}$$

where m, n, o are positive integers (Craik, 1996; Schoenwald, 2008), and l_x, l_y, l_z are the dimensions of the void, the system is treated as 2D and Eq. (2) should be used, whereas above this frequency, the void is treated like a room, which implies the use of Eq. (4).

The number of modes in a given frequency band is calculated using:

$$N = n(f)\Delta f, \tag{6}$$

where

$$\Delta f = 0.23 f_m \tag{7}$$

for 1/3 octave bands, and

$$\Delta f = 0.707 f_m \tag{8}$$

for 1-octave bands, where f_m is the centre frequency of a given frequency band.

2.1. Damping

A key element in calculating the energy in individual subsystems is determining the energy loss coefficients, which define the energy flow between subsystems. The loss coefficient is the fraction of energy lost by a subsystem in one cycle. Damping is described by several types of loss factors: internal loss factors $\eta_{i,d}$, coupling loss factors (CLFs) η_{ij} and total loss factors η_i, where

$$\eta_i = \sum_{j=1}^{n} \eta_{ij} + \eta_{i,d}. \tag{9}$$

2.1.1. Coupling loss factors

The CLF describes the attenuation due to coupling between subsystems. It is the fraction of energy transferred from one subsystem to another in one cycle, and is generally expressed as follows:

$$\eta_{ij} = \frac{W_{ij}}{E_i \omega}. \tag{10}$$

The formulas for connections between different types of subsystems are as follows:

a) energy transfer from a room to a partition:

$$\eta_{ij} = \frac{\rho_0 c_0^2 S_j f_{c,j} \sigma_j}{8\pi f^3 V_i \rho_{s,j}}, \tag{11}$$

b) energy transfer from a partition to a room:

$$\eta_{ij} = \frac{\rho_0 c_0 \sigma_i}{\omega \rho_{s,i}}, \tag{12}$$

c) energy transfer between partitions:

$$\eta_{ij} = \frac{l_{ij} c_{g1} \tau_{ij}}{\omega \pi S_i}, \tag{13}$$

d) energy transfer from a cavity to a partition:

$$\eta_{ij} = \frac{\rho_0 c_0 f_{c,j} \sigma_j}{4\pi f^2 \rho_{s,j}}, \tag{14}$$

e) energy transfer from a cavity to a room:

$$\eta_{ij} = \frac{\tau_{ij}}{4\pi}, \tag{15}$$

f) energy transfer between rooms:

$$\eta_{ij} = \frac{c_0 S \tau_{ij}}{8\pi f V_i}, \tag{16}$$

where $f_{c,j}$ is the critical frequency for element j, S_j is the surface area of element j, V_i is the volume of the source room, $\sigma_{i/j}$ is the resonant radiation efficiency of element i/j, $\rho_{s,i/j}$ is the surface mass of element i/j, τ_{ij} is the transmission coefficient from element i to j, $c_{g,i}$ is the corrected group velocity, and l_{ij} is the length of the connection between elements i and j.

If the CLF from subsystem i to j is known, the energy flow from subsystem j to i can also be calculated using:

$$\eta_{ji} = \frac{\eta_i \eta_{ij}}{\eta_j}. \tag{17}$$

The transmission coefficient can be calculated using Eq. (18), as stated by Craik (1996):

$$\tau_{ij} = \left(\frac{\rho_0 c_0}{\pi f \rho_j (1-\mu^{-4})}\right)^2 \left\{ \ln\left(\frac{2\pi f\sqrt{S}}{c_0}\right) + 0.16 + U(l_x, l_y) + \frac{1}{4\mu^6}\left[\left(2\mu^2-1\right)\left(\mu^2+1\right)^2 \ln\left(\mu^2-1\right) + \left(2\mu^2+1\right)\left(\mu^2-1\right)^2 \ln\left(\mu^2+1\right) - 4\mu^2 - 8\mu^6 \ln(\mu)\right]\right\}, \tag{18}$$

where $U(l_x, l_y)$ is a shape function that can be omitted if $0.1 < l_x, l_y < 10$, and μ is a square root of f_c/f, where f_c is the critical frequency.

2.1.2. Internal loss factors

The internal loss factor (ILF) represents the amount of energy lost by a subsystem and converted into heat, or transferred to another structure not included in the model, in one cycle. It is defined as follows:

$$\eta_{id} = \frac{W_{id}}{E_i \omega}. \tag{19}$$

ILFs for common material types can be found in Table 1.

Table 1. Internal loss factors of common materials.

Material	Internal loss factor $\eta_{id} \cdot 10^{-3}$
Steel	~0.1
Aluminium	~0.1
Glass	0.6–2
Concrete	4–8
Lightweight concrete	10–20
Autoclaved aerated concrete	10–20
Gypsum plate	10–15
Chipboard	10–30

2.1.3. Total loss factors

The total energy loss factor (TLF), denoted as η_i, is the sum of the energy loss due to coupling of subsystems (CLF) and the internal losses of a given subsystem. Equations for each type of subsystem are specified as follows:

a) TLF of a room:

$$\eta_i = \frac{2.2}{T_{60,i} f}, \tag{20}$$

b) TLF of a cavity:

$$\eta_i = \frac{c_0 \sum l\alpha'}{2\pi^2 f S_i}, \tag{21}$$

c) TLF of a partition:

$$\eta_i = \frac{c_g L\alpha}{2\pi^2 f S}, \tag{22}$$

whereas for massive partitions, it can be assumed that:

$$\eta_i \approx \frac{1}{\sqrt{f}} + 0.015, \tag{23}$$

and for a lightweight partitions:

$$\eta_i = \frac{c_0}{f\pi^2\sqrt{\frac{f_{\text{ref}}}{f}}}, \tag{24}$$

where $T_{60,i}$ is the reverberation time of element i, f is the frequency, c_0 is the speed of sound in air, l is the length of the cavity, α' is the average sound absorption coefficient in the void, S_i is the surface area of element i, c_g is the group velocity, and $f_{\text{ref}} = 1000\,\text{Hz}$. The group velocity, which describes the velocity at which energy is transported, is given by

$$c_g = \frac{\mathrm{d}\omega}{\mathrm{d}k}. \tag{25}$$

2.2. Transfer matrix

In order to calculate the energy in each subsystems, the first step is to form equilibrium equations, based on the assumption that the energy entering a subsystem is equal to the energy leaving it. Using these equations, a transfer matrix is formed:

$$\begin{bmatrix} -\eta_1 & \eta_{21} & \eta_{31} & \eta_{41} & \cdots \\ \eta_{12} & -\eta_2 & \eta_{32} & \eta_{42} & \cdots \\ \eta_{13} & \eta_{23} & -\eta_3 & \eta_{43} & \cdots \\ \eta_{14} & \eta_{24} & \eta_{34} & -\eta_4 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ \cdots \end{bmatrix} = \begin{bmatrix} -W_1/\omega \\ 0 \\ 0 \\ 0 \\ \cdots \end{bmatrix}. \tag{26}$$

2.3. Analysed cases

For each analysed case, the same initial conditions were assumed, as presented in Table 2.

Table 2. Initial conditions assumed for the calculations.

Parameter	Symbol	Value
Initial power [W]	W_1	0.005
Speed of sound in air [m/s]	c_0	343
Density of air [kg/m^3]	ρ_0	1.2
Air temperature [°C]	T	20

It was assumed that both the source and receiving rooms were identical in terms of their dimensions and reverberation time. The assumed parameters of the rooms are listed in Table 3.

Table 3. Parameters of the source and receiving rooms assumed for the calculations.

Parameter	Symbol	Value
Width [m]	W_R	3
Length [m]	L_R	5
Height [m]	H_R	4
Volume [m^3]	V_R	60
Reverberation time [s]	$T_{60,R}$	0.6

The main partition between the source room and receiving rooms is a massive concrete wall. Flanking partitions were assumed to be gypsum board or glass-based. Their parameters are specified in Table 4.

The description of cases analysed in the study is presented in Table 5.

The connection shapes are presented in Fig. 1.

Table 4. Parameters of the walls.

Parameter	Symbol	Value		
		Massive wall	Gypsum board panel	Glass panel
Width [m]	W	3	3	3
Thickness [m]	T	0.15	0.012	0.0066
Height [m]	H	4	4	4
Surface [m^2]	S	12	12	12
Perimeter [m]	P	14	14	14
Density [kg/m^3]	ρ	2400	720	2500
Surface mass [kg/m^2]	m'	360	8.64	16.5
Critical frequency [Hz]	f_c	110	2846	1808
Young's modulus [N/m^2]	E	3.6e+10	2.4e+9	7.2e+10
Poisson's ratio	μ	0.2	0.3	0.2
Bending stiffness [Nm]	B	3.1e+6	380	1.8e+4

The cavity between the gypsum board or glass panels is assumed to be 0.05 m deep.

Table 5. Description of analysed cases.

Case number	Description
1	Basic model with no flanking partitions – source and receiving rooms divided by a 15 cm thick concrete wall.
2	One, two or four flanking partitions, consisting of a single gypsum board cladding with no absorptive filling; three connection types ('T', 'C', 'H').
3	One, two or four flanking partitions, composing of a double gypsum board cladding with no absorptive filling; three connection types ('T', 'C', 'H').
4	One, two or four flanking partitions, consisting of a double gypsum board cladding; cavity filled with an absorptive material in 50 %; three connection types ('T', 'C', 'H').
5	One, two or four flanking partitions, consisting of a double gypsum board cladding; cavity fully filled with absorptive material; three connection types ('T', 'C', 'H').

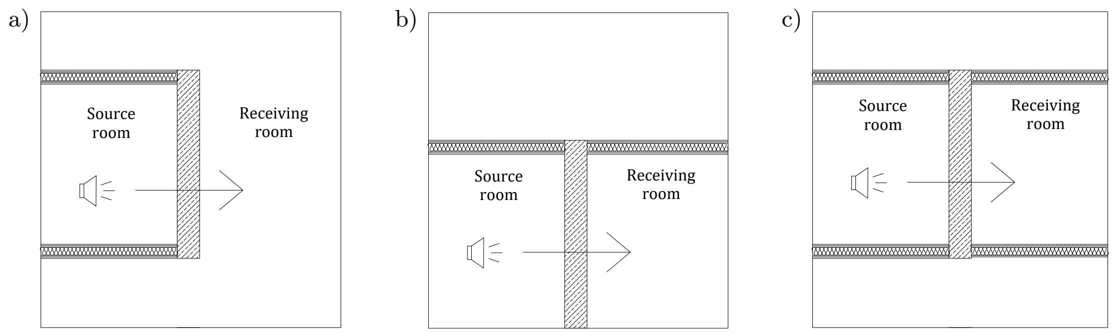

Fig. 1. Schematic layout of the analysed connections in case 2:
a) C-shaped connection, b) T-shaped connection, c) H-shaped connection.

2.3.1. Subsystems

The connections between subsystems were assumed according to Fig. 2 to Fig. 5. For cases 2 to 6, the connections are identical, as the double-cladding of gypsum board walls is considered as a single subsystem.

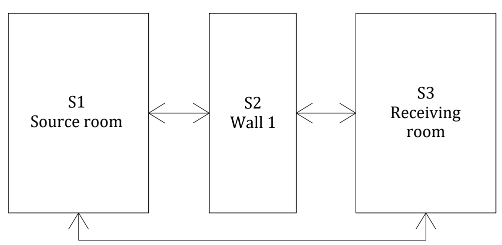

Fig. 2. Energy flow scheme between subsystems for case 1.

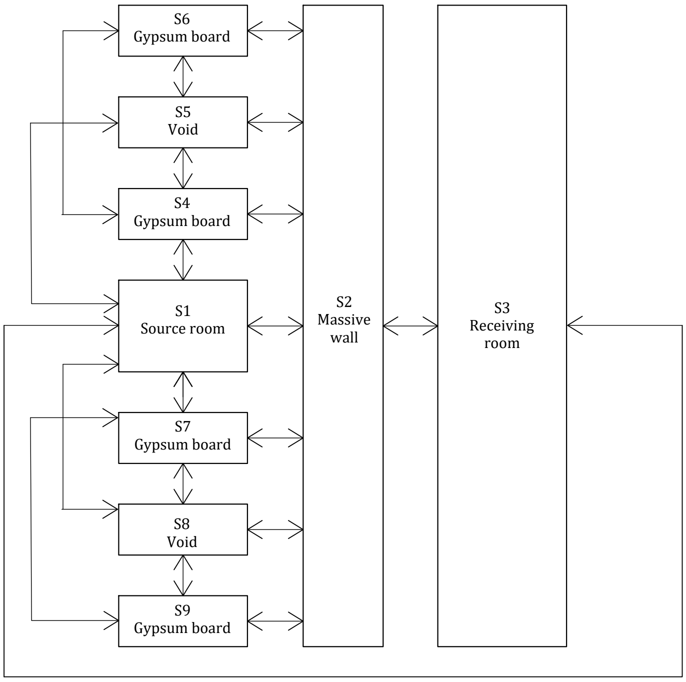

Fig. 3. Energy flow scheme between subsystems for C-shaped connections.

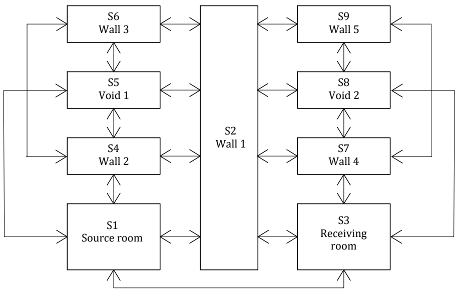

Fig. 4. Energy flow scheme between subsystems for T-shaped connections.

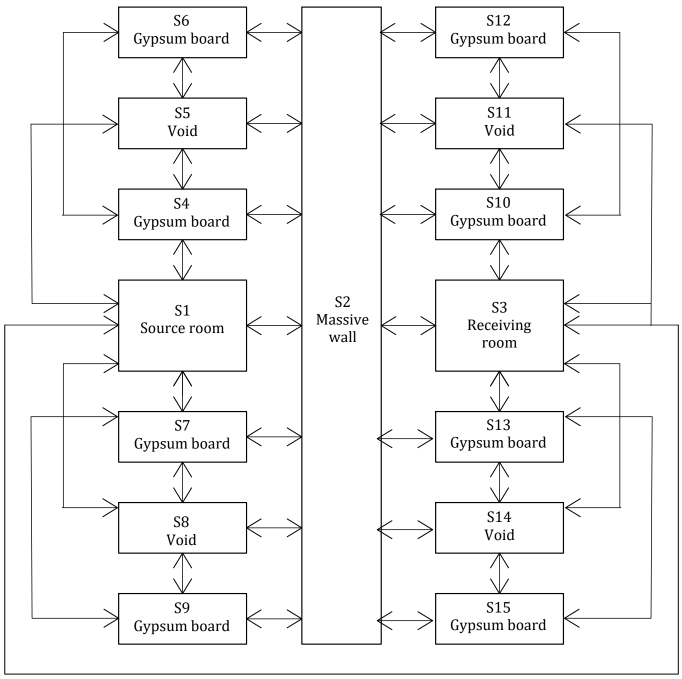

Fig. 5. Energy flow scheme between subsystems for H-shaped connections.

3. Results

For each case and each connection type, the energy in every subsystem was calculated. The results obtained for cases 2 to 6 were then compared to the basic situation (case 1) in order to show the difference between the resultant sound insulation of the massive wall with no flanking paths and the insulation obtained after adding lightweight partitions. The results are presented in Fig. 6 and Fig. 7.

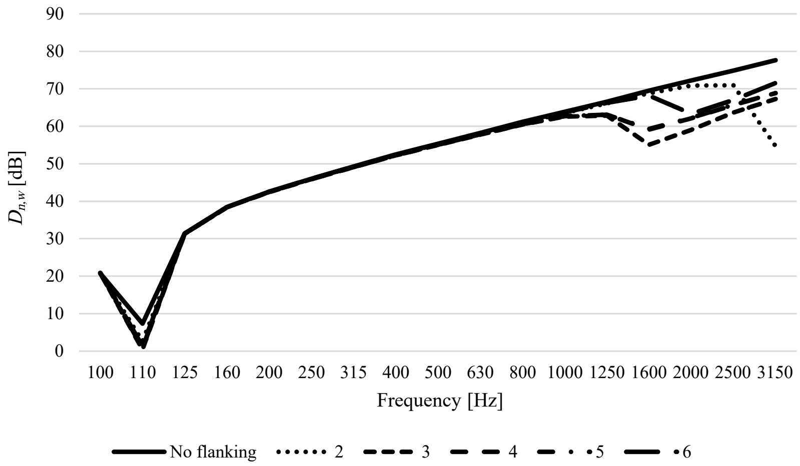

Fig. 6. Weighted sound reduction indexes for H-shaped connections (cases 1–6).

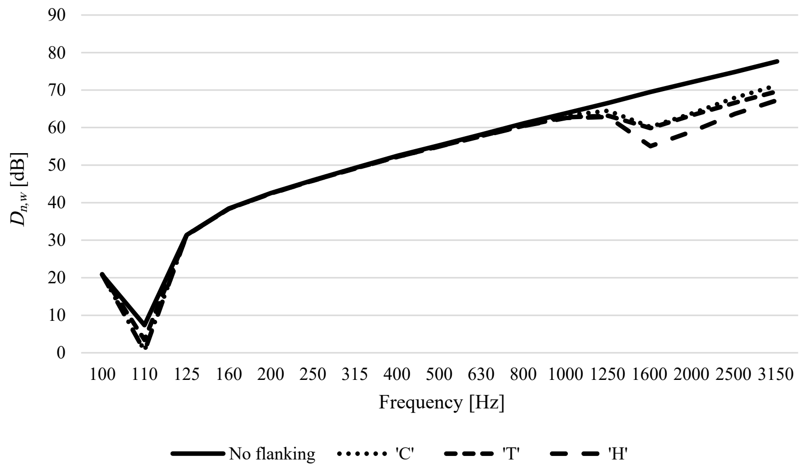

Fig. 7. Weighted sound reduction indexes for case 3 with three connection shapes.

The differences in sound insulation of H-shaped connections between the massive wall and gypsum walls with no filling, partial filling, and fully filled cavities are presented in Table 6.

The results show that the sound reduction index, compared to case 1, decreases above the critical frequency of the gypsum/glass board. In the case of single cladding, the reduction occurs above 2500 Hz, while in the case of double cladding, the reduction begins above 1250 Hz. In the case of glass flanking partitions, the decrease occurs above approximately 1850 Hz. The highest reduction of sound insulation can be observed for H-shaped connections, as these include the largest number of flanking partitions.

As for the absorptive material in the cavities, the resultant sound reduction difference between cases 3, 4, and 5 appear above the critical frequency of the gypsum board, which for the double-cladded wall is around 1400 Hz. Differences at higher frequencies are clearly noticeable and impact the overall resultant single-number sound insulation of the wall. The difference between cases 4 and 5, representing walls with partially and fully filled cavities, is also observed; however, the resultant single-number sound reduction index is $R_{A1} = 48$ dB. For case 3, the sound reduction index is $R_{A1} = 45$ dB.

Table 6. Sound insulation difference between three of the analysed cases.

Frequency [Hz]	$D_{n,e,w}$ [dB] – case 3	$D_{n,e,w}$ [dB] – case 4	$D_{n,e,w}$ [dB] – case 5
100	20.9	20.9	20.9
125	31.3	31.3	31.3
160	38.4	38.4	38.4
200	42.4	42.4	42.4
250	45.9	45.9	45.9
315	49.1	49.1	49.1
400	52.2	52.2	52.2
500	55.0	55.0	55.0
630	57.8	57.8	57.8
800	60.4	60.5	60.5
1000	62.6	62.7	62.7
1250	62.8	63.1	63.1
1600	55.1	59.1	59.3
2000	59.1	62.1	62.3
2500	63.7	65.7	65.7
3150	67.3	68.8	68.9

4. Conclusions

SEA, when applied correctly, can be an effective method for calculating the sound transmission of a partition, including contributions from flanking paths. While most recent publications focus on timber or massive constructions when discussing flanking transmission, this research analysed connections between gypsum-board-based or glass partitions and massive partitions, which are commonly used in Poland. The results for six different cases were presented, starting with a standard situation without flanking transmission. Cases 2 to 5 represent connections between a massive wall and a gypsum board wall, considering three different connection shapes (C-shaped, T-shaped, and H-shaped) and both single- and double-cladded walls. Filling the cavity with absorptive material was also taken into consideration. Case 6 represents the situation when the flanking partitions are glass systems for the same types of connections between partitions as in the case of gypsum board partitions.

The results indicate a noticeable impact of flanking paths on the resultant sound insulation of a massive wall. The reduction in sound insulation occurs above the critical frequency of the gypsum or glass board. For this reason, the damping in case 2, where the flanking walls have single cladding and therefore a higher critical frequency, is smaller than in cases 3 to 6. The shape of the connection is also significant, with H-shaped connections resulting in the greatest reduction among all analysed cases, as they include the largest number of flanking partitions.

Another factor that has an impact on sound insulation is the filling of the cavity between gypsum boards with absorptive material. The calculations imply that higher attenuation in the cavity increases the sound insulation of the massive partition, thereby the impact of flanking paths.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

Agnieszka Wójtowicz performed the analysis and contributed to data interpretation. Tadeusz Kamisiński and Jarosław Rubacha conceptualized the study and contributed to data interpretation. All authors reviewed and approved the final manuscript.

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