The relationship between the in situ flanking sound reduction index and the laboratory measured flanking normalized level difference

Mahn, Jeffrey; Müeller Trapet, Markus

Publisher's version / Version de l'éditeur:
https://doi.org/10.1177/1351010X231206240
Building Acoustics, 30, 4, pp. 409-424, 2023-11-09

The Relationship between the *In Situ* Flanking Sound Reduction Index and the Laboratory Measured Flanking Normalized Level Difference

Jeffrey Mahn and Markus Müller-Trapet

ABSTRACT

From Gerretsen's 1979 Applied Acoustics paper through four series of standards including ISO 12354 and ISO 10848, a significant amount of effort has gone into creating a standardized prediction method that uses standardized laboratory measured values to predict the apparent sound reduction index to demonstrate compliance with regulations. The terms and equations in the prediction method have evolved over time as researchers have evaluated the results of the prediction method, especially in the case of lightweight constructions for which statistical energy analysis is not well suited. To reflect the changes to other equations in the prediction method over the past forty years, this paper suggests an update to the relationship in ISO 12354-1 between the *in situ* flanking sound reduction index and the laboratory measured flanking normalized level difference. The suggested changes are of importance for Type B elements such as timber and steel framed walls and floors for which the prediction of flanking transmission according to ISO 12354 requires the measurement of the level difference in laboratory flanking facilities.

KEYWORDS

Flanking sound insulation, ISO 12354, lightweight building element

---

National Research Council Canada

Corresponding author

J. Mahn, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, Canada
Email: jeffrey.mahn@nrc-cnrc.gc.ca

Introduction

In Canada, lightweight timber and steel framed walls and floors are popular building elements for intertenancy walls in multitenancy buildings. These include steel and mass timber high-rise buildings where lightweight, non-loadbearing steel or timber framed walls are typically specified for the interior walls. It was to evaluate the transmission of structure-borne noise through these lightweight elements that the National Research Council Canada (NRC) constructed the first dedicated flanking facility in the world in 1993.[1] In the years since the testing in the facility began, the NRC has published the data measured in the flanking facilities in several research reports to support the calculation of the flanking sound reduction index in lightweight building constructions to demonstrate compliance with the acoustic requirements in the provincial, territorial or national building codes.

The National Building Code of Canada and some of the provincial Codes have adopted the Apparent Sound Transmission Class (ASTC) Rating as part of the acoustic requirements for multitenancy buildings. The ASTC rating is comparable but not equal to the apparent weighted sound reduction index and is to be calculated using the prediction method outlined in ISO 12354-1[2] and explained in ASTM metrics in the Research Report RR-331: Guide to Calculating Airborne Sound Transmission in Buildings,[3] now in its sixth edition. To perform the calculations, the measured normalized flanking level difference $D_{n,f,ij,lab}$ measured in the flanking transmission loss facilities according to the ISO 10848[4–7] series of standards needs to be converted into the *in situ* flanking sound reduction index $R_{ij,situ}$ as described in ISO 12354-1.

In a 1984 paper about the prediction method, Gerretsen[8] discusses the conversion of the sound reduction index R and the vibration reduction index K_{ij} made according to standardized laboratory measurement methods to *in situ* values to predict the flanking transmission loss in actual buildings. The relationship between the laboratory and *in situ* values for the sound reduction index and the vibration reduction index were presented in Equation 22 of the paper as:

$$R^* = R_{lab} - 10\log\frac{T_{s,situ}}{T_{s,lab}} \tag{1}$$

$$K_{ij}^* = K_{ij} - 5\log\frac{T_{s,i,situ}}{T_{s,ref}} - 5\log\frac{T_{s,j,situ}}{T_{s,ref}} \tag{2}$$

where the * indicates an *in situ* value, T_s is the structural reverberation time, $T_{s,ref} = 0.1\sqrt{f_o/f}$ and f_o = 500 Hz. Gerretsen then substituted these *in situ* values into the flanking sound reduction index defined in Equation 24 of the paper to be:

$$R_{ij} = \frac{R_i^* + R_j^*}{2} + K_{ij}^* - 10\log\frac{l_{ij}}{l_o} + 10\log\frac{S_s}{S_o} \tag{3}$$

to derive Equation B2 of the paper which shows the relationship between the flanking sound reduction index in the field situation R_{Ff} and the normalized flanking level difference:

$$R_{Ff} = D_{n,f} + 10\log\frac{S_S}{A_O}\frac{l_{lab}}{l_{Ff}} + 10\log\frac{T_{s,F,lab}}{T_{s,F}} + 10\log\frac{T_{s,f,lab}}{T_{s,f}} \tag{4}$$

where $D_{n,f}$ is defined as the product information, the term l_{Ff} is the common junction length between the flanking elements, l_o = 1 m is a reference length, S_s is the area of the separating element, S_o = 1 m^2 and A_o is the reference absorption area of 10 m^2. The term l_{lab} was not defined in the 1984 paper, but ISO 12354-1 describes l_{lab} as a laboratory value as a reference for the junction length l_{Ff}. ISO 12354-1 further states that the value of l_{lab} is usually 4.5 m for horizontal flanking elements like ceilings and usually 2.5 m for vertical flanking elements like façades. Metzen and Schumacher[9] have noted that the reference length l_{lab} is 2.25 m for walls, 4.5 m for floors and 5 m for roofs.

Equation 4 is identical in form to Equation F.4 of ISO 15712-1[10] and it is the same in form as Equation 16 of ISO 12354-1:

$$R_{ij} = D_{n,f,ij,situ} + 10 \log \frac{S_S l_{lab}}{A_o l_{ij}} \tag{5}$$

if the terms with the structural reverberation times are neglected and the $D_{n,f}$ term in Equation 4 is the *in situ* value as specified in ISO 12354-1. Equation 21 of ISO 12354-1 is similar to Equation 16 of ISO 12354-1, but it uses single number ratings instead of data in one-third octaves:

$$R_{ij,situ,w} = D_{n,f,ij,situ,w} + 10 \log \frac{S_S l_{lab}}{A_o l_{ij}} \tag{6}$$

It is suggested in this paper that the relationship between the R_{ij} and the $D_{n,f,ij}$ terms in Equations 16 and 21 of ISO 12354-1 should be reconsidered. To demonstrate the recommended changes, this paper begins by using statistical energy analysis (SEA) to derive the relationship between $D_{n,f,ij}$ and the R and $\overline{D_{v,ij}}$ terms and the element dimensions. The relationship between $R_{ij,situ}$ and $D_{n,f,ij}$ is then derived.

Derivation of the Normalized Flanking Level Difference

Consider the set of four rooms shown in plan view in Figure 1. There are several flanking paths between rooms 1 and 3, but for simplicity, only the flanking path from room 1 through walls 4 and 5 to room 3 as shown by the arrow in Figure 1 will be considered for the derivation.

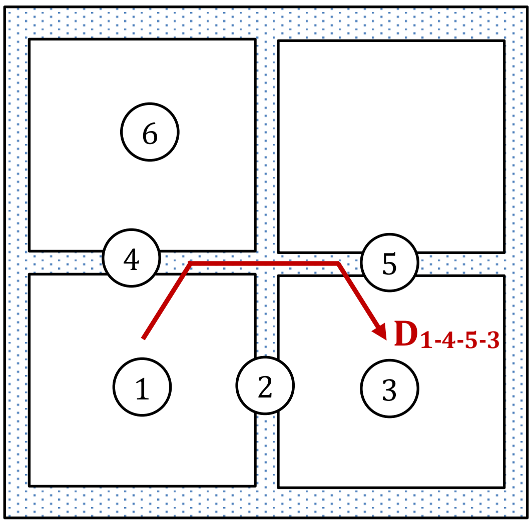

Figure 1: Plan view of the four rooms used to determine the flanking level difference $D_{1\text{-}4\text{-}5\text{-}3}$.

The SEA model of the subsystems and the power flow between the subsystems is shown in Figure 2.

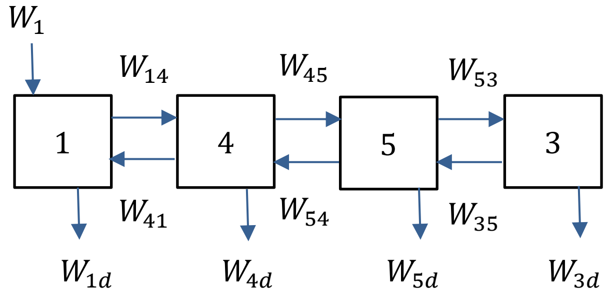

Figure 2: The SEA model of the subsystems included in the flanking path 1-4-5-3.

The term W_1 is from an external noise source which is exciting subsystem 1, W_{ij} is the power flow from subsystem i to subsystem j and W_{id} is the power that is lost from subsystem i that does not return. The power balance for the subsystems may be written as:

$$\begin{gathered} W_1 + W_{41} = W_{14} + W_{1d} \\ W_{14} + W_{54} = W_{41} + W_{45} + W_{4d} \\ W_{45} + W_{35} = W_{54} + W_{53} + W_{5d} \\ W_{53} = W_{35} + W_{3d} \end{gathered} \tag{7}$$

Rewriting in terms of energy E where $W_{ij} = E_i \omega \eta_{ij}$, $\eta_i = \sum \eta_{ij} + \eta_{id}$, η_{ij} is the coupling loss factor between elements i and j and η_i is the total loss factor yields:

$$\begin{gathered} \frac{W_1}{\omega} = -E_4\eta_{41} + E_1\eta_1 \\ E_1\eta_{14} + E_5\eta_{54} - E_4\eta_4 = 0 \\ E_4\eta_{45} + E_3\eta_{35} - E_5\eta_5 = 0 \\ E_5\eta_{53} - E_3\eta_3 = 0 \end{gathered} \tag{8}$$

If it is assumed that the energy flow for subsystem 4 only comes from subsystem 1, the energy flow for subsystem 5 only comes from subsystem 4 and the energy flow for subsystem 3 only comes from subsystem 5, the equations can be arranged such that:[11]

$$E_1\eta_{14} = E_4\eta_4 \tag{9}$$
$$E_4\eta_{45} = E_5\eta_5 \tag{10}$$
$$E_5\eta_{53} = E_3\eta_3 \tag{11}$$

Rearranging in terms of the energy ratio yields:[11]

$$10\log\frac{E_1}{E_3} = 10\log\frac{\eta_4\eta_5\eta_3}{\eta_{14}\eta_{45}\eta_{53}} \tag{12}$$

The energy in an acoustic space can be written in terms of the time and spatially averaged mean-square sound pressure $\langle p^2 \rangle$, the volume of the space V, the speed of sound in air c_o and the density of the air ρ_o such that:

$$E = \frac{\langle p^2 \rangle V}{\rho_o c_o^2} \tag{13}$$

Substituting Equation 13 into Equation 12 yields the sound pressure level difference between subsystems 1 and 3 due to the path 1-4-5-3 such that:

$$D_{1-4-5-3} = 10\log\frac{\langle p_1^2 \rangle}{\langle p_{45}^2 \rangle} = 10\log\frac{\eta_4}{\eta_{14}\eta_{53}} + 10\log\frac{\eta_5}{\eta_{45}} + 10\log\frac{\eta_3 V_3}{V_1} \tag{14}$$

where $\langle p_{45}^2 \rangle$ is the time and spatially averaged mean-square sound pressure in the receiving room (subsystem 3) due only to the structure-borne sound transmitted along the flanking path through subsystems 4 and 5. The total loss factor for a subsystem is given by:

$$\eta_i = \frac{2.2}{f T_i} \tag{15}$$

where T_i is the reverberation time of subsystem i. Substituting for η_3 yields:

$$D_{1-4-5-3} = 10\log\frac{\eta_4}{\eta_{14}\eta_{53}} + 10\log\frac{\eta_5}{\eta_{45}} + 10\log\frac{2.2 V_3}{f T_3 V_1} \tag{16}$$

It is assumed that subsystems 4 and 5 are made of the same material and have the same thickness. It is also assumed that the walls are thin enough that longitudinal and transverse waves can be ignored.[12] The radiation from a wall to a room, assuming resonant transmission only is:

$$\eta_{41} = \frac{\rho_o c_o}{2\pi f m_4}\sigma_{4,res} \tag{17}$$

where m_4 is the mass per unit area of subsystem 4 and $\sigma_{4,res}$ is the resonant radiation efficiency of subsystem 4. Using the reciprocity relation for coupled resonant systems, the coupling loss factor from a room to a wall can then be approximated as:[12]

$$\eta_{14} = \frac{\rho_o c_o^2 S_4 f_{c4}}{8\pi f^3 m_4 V_1}\sigma_{4,res} \tag{18}$$

Therefore, assuming that $\eta_{53} = \eta_{46}$ which means that the construction of wall 4 in room 6 is identical to the construction of wall 5 in room 3:

$$\frac{\eta_4}{\eta_{14}\eta_{53}} = \left(\frac{2.2}{f T_4}\right)\left(\frac{8\pi f^3 m_4 V_1}{\rho_o c_o^2 S_4 f_{c4}\sigma_{4,res}}\right)\left(\frac{2\pi f m_4}{\rho_o c_o \sigma_{4,res}}\right) \tag{19}$$

The assumption that $\eta_{53} = \eta_{46}$ has implications if this coupling loss factor is applied to Type B walls that are not symmetric in construction or if different linings are applied to Type A walls in different rooms of the building. Rearranging terms yields:

$$10\log\frac{\eta_4}{\eta_{14}\eta_{53}} = 10\log\left(\frac{\omega m_4}{2\rho_o c_o}\right)^2 - 10\log\left(\frac{c_o^2\sigma_{4,res}^2}{2\eta_4 S_4 f}\frac{\pi S_4 f_{c4}}{c_o^2}\right) + 10\log\left(\frac{V_1 f}{S_4}\frac{8\pi}{c_o}\right) \tag{20}$$

The transmission loss for resonant transmission is given by:[13]

$$R_{4,res} = 10\log\left(\frac{\omega m_4}{2\rho_o c_o}\right)^2 - 10\log\left(\frac{c_o^2\sigma_{4,res}^2}{2\eta_4 S_4 f}\frac{\pi S_4 f_{c4}}{c_o^2}\right) \tag{21}$$

And therefore:

$$10\log\frac{\eta_4}{\eta_{14}\eta_{53}} = R_{4,res} + 10\log\left(\frac{V_1 f}{S_4}\frac{8\pi}{c_o}\right) \tag{22}$$

Which is the first term in Equation 16. For the second term in Equation 16, the coupling loss factor between two walls (in this example, subsystems 4 and 5) connected along a line is given by:[12]

$$\eta_{45} = \frac{c_o l_{45}\gamma_{45}}{\pi^2\sqrt{f}\sqrt{f_{c,4}}S_4} \tag{23}$$

where γ_{45} is the structure-to-structure transmission coefficient. The total energy in a plate can be expressed as:

$$E = mS\langle v^2\rangle \tag{24}$$

where $\langle v^2\rangle$ is the time and spatially averaged mean-square velocity. Following from Equations 10, 15 and 24:

$$\frac{E_4}{E_5} = \frac{m_4 S_4\langle v_4^2\rangle}{m_5 S_5\langle v_5^2\rangle} = \frac{2.2}{fT_5}\frac{\pi^2\sqrt{f}\sqrt{f_{c,4}}S_4}{c_o l_{45}\gamma_{45}} \tag{25}$$

Rearranging yields:

$$\gamma_{45} = \frac{2.2\pi^2}{c_{B,4}}\frac{m_5}{m_4}\frac{\langle v_5^2\rangle}{\langle v_4^2\rangle}\frac{S_5}{l_{45}T_5} \tag{26}$$

where:

$$c_B = c_o\sqrt{\frac{f}{f_c}} \tag{27}$$

is the bending wave phase speed.[14] The equivalent absorption length is introduced[8] which describes all of the absorption at the plate boundaries by using a single length. The absorption length is the ratio of the power absorbed by the plate boundaries to the intensity incident on them.[15] The power absorbed is:

$$W_{abs} = \frac{2.2\omega E}{fT_s} \tag{28}$$

where E is the plate energy. Assuming the vibratory field is diffuse in the plate, the intensity incident on the boundaries is given by:

$$I_{inc} = \frac{c_g E}{\pi S} \tag{29}$$

where c_g is the group speed which is assumed to be equal to two times the bending speed which is the case where $f < f_s/4$ and f_s is the cross-over frequency where the bending wave phase speed equals the shear wave phase speed.[14] The ratio yields:

$$\frac{W_{abs}}{I_{inc}} = a_i = \frac{2.2\pi^2 S_i}{T_{s,i} c_{B,i}} \tag{30}$$

However, as Hopkins[15] notes, the definition of c_B in Equation 27 includes a single critical frequency which is not well defined for non-homogeneous plates. Therefore, f_c was later replaced by f_{ref} = 1000 Hz in ISO 12354-1 and the equivalent absorption length would be defined in the standard as:

$$a_i = \frac{2.2\pi^2 S_i}{c_o T_{s,i}} \sqrt{\frac{f_{ref}}{f}} \tag{31}$$

Rewriting Equation 26:

$$\gamma_{45} = \frac{m_5 \langle v_5^2 \rangle}{m_4 \langle v_4^2 \rangle} \frac{a_5}{l_{45}} \frac{c_{B5}}{c_{B4}} \tag{32}$$

Rewriting in terms of dB yields:

$$-10 \log \gamma_{45} = D_{v,45} + 10 \log \frac{m_4 c_{B4}}{m_5 c_{B5}} + 10 \log \frac{l_{45}}{a_5} \tag{33}$$

Where $D_{v,45}$ is the velocity level difference. Equation 33 is consistent with Equation 13 of Gerretsen's 1994 paper.[8] Earlier definitions such as in Gerretsen's 1979 paper[16] had not yet included the l_{ij} term.

Substituting Equations 15 and 33 into $10 \log \frac{\eta_5}{\eta_{45}}$ yields:

$$10 \log \frac{\eta_5}{\eta_{45}} = 10 \log \frac{2.2}{f T_{s,5}} \frac{\pi^2 \sqrt{f} \sqrt{f_{c,4}} S_4}{c_o l_{45}} - 10 \log \gamma_{45} \tag{34}$$

Substituting in Equation 27 for c_B, Equation 30 for a and Equation 33 for $-10 \log \gamma_{45}$ yields:

$$10 \log \frac{\eta_5}{\eta_{45}} = 10 \log \frac{a_5 S_4}{S_5} \frac{c_{B5}}{c_{B4}} + D_{v,45} + 10 \log \frac{m_4 c_{B4}}{m_5 c_{B5}} + 10 \log \frac{1}{a_5} \tag{35}$$

Lastly, substituting Equation 22 and Equation 35 into Equation 16 yields:

$$D_{1-4-5-3} = R_{4,res} + D_{v,45} + 10 \log \frac{m_4}{m_5} + 10 \log \frac{A_3}{S_5} \tag{36}$$

where the sound absorption area of a room is defined as:

$$A = 2.2 \frac{8\pi}{c_o} \frac{V}{T} = \frac{0.16V}{T} \tag{37}$$

Normalizing the level difference by a reference absorption area A_o:

$$D_{n,1-4-5-3} = R_{4,res} + D_{v,45} + 10\log\frac{m_4}{m_5} + 10\log\frac{A_o}{S_5} \tag{38}$$

Following from Gerretsen[17], it is assumed that reciprocity can be applied such that:

$$D_{n,1-4-5-3} = D_{n,3-5-4-1} \tag{39}$$

Therefore, substituting $D_{n,1-4-5-3}$ and $D_{n,3-5-4-1}$ into Equation 39 yields the direction-averaged level difference:

$$D_{n,f,45} = 5\log\left(\left(\frac{m_4 A_o}{\tau_{4,res} d_{45} m_5 S_5}\right)\left(\frac{m_5 A_o}{\tau_{5,res} d_{54} m_4 S_4}\right)\right) \tag{40}$$

Rewriting in more general terms:

$$D_{n,f,ij} = \frac{R_i + R_j}{2} + \overline{D_{v,ij}} + 10\log\frac{A_o}{\sqrt{S_i S_j}} \tag{41}$$

where:

$$\overline{D_{v,ij}} = \frac{D_{v,ij} + D_{v,ji}}{2} \tag{42}$$

This reciprocity relationship between the transmission coefficients γ_{ij} and γ_{ji} was shown by Kihlman[18] based on a relationship that included the wave numbers.

Equations 17 and 19 of ISO 10848-1 could potentially be used to compare Equation 41 with the flanking normalized level difference defined in ISO 10848, noted as $D_{n,f,ij,10848}$. However, Equation 19 of ISO 10848-1 is missing the contribution from the improvements due to linings ΔR_i and ΔR_j. This is corrected in Equation 20 of ISO 10848-1 which relates $D_{n,f,ij,10848}$ to the normalized direction-average vibration level difference $\overline{D_{v,ij,n}}$:

$$D_{n,f,ij,10848} = \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij,n}} + 10\log\frac{A_o}{l_{ij} l_o} \tag{43}$$

where:

$$\overline{D_{v,ij,n}} = \overline{D_{v,ij}} + 10\log\frac{l_{ij} l_o}{\sqrt{S_{mi} S_{mj}}} \tag{44}$$

and where S_m is the area over which the surface velocity is measured. If it is assumed that the surface velocity is measured over the entire area of the element, then $S_m = S$ and:

$$D_{n,f,ij,10848} = \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij}} + 10\log\frac{A_o}{\sqrt{S_i S_j}} \tag{45}$$

The difference between Equation 45 and Equation 41 is that Equation 45 includes the improvement due to linings on the elements ΔR_i and ΔR_j. The ΔR terms were not included in Gerretsen's 1979[16] or 1986[17] papers so the terms are not part of the early derivations of the modeling approach, but the terms were later added in the standard EN 12354-1:2000.[19]

The $D_{n,f,ij}$ values are typically measured according to ISO 10848 for constructions that include Type B elements rather than Type A elements which meet the assumptions required for SEA to be applied. If $D_{n,f,ij}$ is measured in the laboratory or the field for Type A elements, it is reasonable to expect that a lightweight lining such as a layer of gypsum board attached to wood or metal battens with thermal insulation in the cavities between the battens will not have an appreciable effect on the $\overline{D_{v,ij}}$ values. However, in the case of Type B elements such as wood or steel framed walls or floors, the addition of a lining can change the $\overline{D_{v,ij}}$ values. The degree of the change will depend on the properties of the lining relative to those of the Type B elements. Furthermore, if the lining is also anisotropic such as the addition of hardwood plank flooring over a plywood subfloor, then the effect of the lining on the transmission of structure-borne noise also depends on the orientation of the lining relative to the floor joists.[3] Therefore, while the $D_{n,f,ij}$ values are measured in the laboratory, any linings should be attached to the elements during the measurements and are therefore part of the measured $D_{n,f,ij}$ values for Type B elements and improvements due to linings are not included in the equations. However, it is important to include the effect of linings in the equations for R_{ij} in the case of Type A elements which will require the improvements due to linings to be included. Therefore, Equation 41 is updated to include the improvements due to linings for Type A elements:

$$D_{n,f,ij,Type\ A} = \frac{R_i+R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij}} + 10\log\frac{A_o}{\sqrt{S_iS_j}} \quad (46)$$

In the case of Type B elements where the $D_{n,f,ij,Type\ B}$ should be measured with the linings already attached, the relationship remains the same as in Equation 41:

$$D_{n,f,ij,Type\ B} = \frac{R_i+R_j}{2} + \overline{D_{v,ij}} + 10\log\frac{A_o}{\sqrt{S_iS_j}} \quad (47)$$

Alternatively, rewriting Equation 46 in terms of $\overline{D_{v,ij,n}}$ and assuming $S_m = S$ yields:

$$D_{n,f,ij,Type\ A} = \frac{R_i+R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij,n}} + 10\log\frac{A_o}{l_{ij}l_o} \quad (48)$$

for the laboratory situation which matches Equation 20 of ISO 10848-1 and Equation G4 of ISO 12354-1 with the exceptions that Equation 48 is explicitly for Type A elements in the laboratory situation due to the inclusion of the ΔR terms.

The Flanking Sound Reduction Index

Returning to the situations shown in Figure 1 and Figure 2, the flanking sound reduction index is expressed as:[20]

$$R_{1-4-5-3} = 10\log\frac{\eta_4\eta_5\eta_3}{\eta_{14}\eta_{45}\eta_{53}}\frac{V_3}{V_1} + 10\log\frac{S_S}{A_3} \quad (49)$$

where S_S is the area of the element that is common to both the source and the receiver room.[15] Rewriting this equation in terms of $D_{n,f,45}$:

$$R_{1-4-5-3} = D_{n,f,45} + 10\log\frac{S_S}{A_o} \qquad (50)$$

or in more general terms:

$$R_{ij} = D_{n,f,ij,Type\ A} + 10\log\frac{S_S}{A_o} \qquad (51)$$

Therefore:

$$R_{ij} = \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij}} + 10\log\frac{S_s}{\sqrt{S_i S_j}} \qquad (52)$$

This equation is identical to Equation 15 of ISO 12354-1 using the detailed method for Type A elements. Alternatively, Gerretsen[16] has demonstrated a different method of deriving the flanking transmission coefficient which is defined as the ratio between the radiated sound power via a flanking path and the sound power incident on the common element which results in the same equation after reciprocity is applied.

Conversion to in-situ values

As described in ISO 12354-1, the conversion to *in situ* values is based on the structural reverberation times of the elements in the laboratory and *in situ* conditions such that:

$$\overline{D_{v,ij,situ}} = K_{ij} - 10\log\frac{l_{ij,situ}}{\sqrt{a_{i,situ}a_{j,situ}}} = \overline{D_{v,ij,lab}} + 10\log\frac{\sqrt{a_{i,situ}a_{j,situ}}}{\sqrt{a_{i,lab}a_{j,lab}}} + 10\log\frac{l_{ij,lab}}{l_{ij,situ}} \qquad (53)$$

where the value a is defined in Equation 31. Equation 10 of ISO 12354-1 does not state if l_{ij} is the laboratory or the *in situ* junction length, but here it is assumed to be the *in situ* value. Equation 53 differs from the equations originally discussed by Gerretsen in 1984 where the K_{ij} term was not yet invariant and therefore, needed to be converted to an *in situ* value.

The *in situ* sound reduction index is calculated from the laboratory measured value according to:

$$R_{situ} = R_{lab} - 10\log\frac{T_{s,situ}}{T_{s,lab}} \qquad (54)$$

Substituting Equation 53 and Equation 54 into Equation 52 yields:

$$R_{ij,situ} = \frac{R_{i,lab} + R_{j,lab}}{2} - 5\log\frac{T_{s,i,situ}}{T_{s,i,lab}} - 5\log\frac{T_{s,j,situ}}{T_{s,j,lab}} + \Delta R_{i,situ} + \Delta R_{j,situ} + \overline{D_{v,ij,lab}} + 10\log\frac{\sqrt{a_{i,situ}a_{j,situ}}}{\sqrt{a_{i,lab}a_{j,lab}}} + 10\log\frac{l_{ij,lab}}{l_{ij,situ}} + 10\log\frac{S_{S,situ}}{\sqrt{S_{i,situ}S_{j,situ}}} \qquad (55)$$

where $\Delta R_{situ} \approx \Delta R_{lab}$ according to Equation 8 of ISO 12354-1. Likewise, if the R_{situ} and the $\overline{D_{v,ij,situ}}$ terms are substituted into Equation 46 for $D_{n,f,ij}$ then:

$$D_{n,f,ij,situ} = \frac{R_{i,lab}+R_{j,lab}}{2} - 5\log\frac{T_{s,i,situ}}{T_{s,i,lab}} - 5\log\frac{T_{s,j,situ}}{T_{s,j,lab}} + \Delta R_{i,situ} + \Delta R_{j,situ} + \overline{D_{v,ij,lab}} + 10\log\frac{\sqrt{a_{i,situ}a_{j,situ}}}{\sqrt{a_{i,lab}a_{j,lab}}} + 10\log\frac{l_{ij,lab}}{l_{ij,situ}} + 10\log\frac{A_o}{\sqrt{S_{i,situ}S_{j,situ}}} \quad (56)$$

Therefore, the relationship between the *in situ* terms is given by:

$$R_{ij,situ} = D_{n,f,ij,situ} + 10\log\frac{S_{S,situ}}{A_o} \quad (57)$$

Equation 57 is applicable to both Type A and Type B elements and is similar to Equation 16 of ISO 12354-1 with the exception of the l_{lab}/l_{ij} term which is no longer included and the S_S is defined as the *in situ* area whereas it is not explicitly defined as such in Equation 16 of ISO 12354-1.

According to Section 4.2.3.3 of ISO 12354-1 in the case when structure-borne noise transmission is dominant (there is no airborne flanking transmission through openings in the elements or through the ceiling plenum), then $D_{n,f,ij,situ} = D_{n,f,ij,lab}$. However, substituting in Equation 46 for $D_{n,f,ij,lab}$ into Equation 55 yields:

$$R_{ij,situ} = D_{n,f,ij,lab} + 10\log\frac{S_{S,situ}l_{ij,lab}}{A_o l_{ij,situ}} - 5\log\frac{T_{s,i,situ}}{T_{s,i,lab}} - 5\log\frac{T_{s,j,situ}}{T_{s,j,lab}} + 10\log\frac{\sqrt{S_{i,lab}S_{j,lab}}}{\sqrt{S_{i,situ}S_{j,situ}}} + 10\log\frac{\sqrt{a_{i,situ}a_{j,situ}}}{\sqrt{a_{i,lab}a_{j,lab}}} \quad (58)$$

The last term of Equation 58 can be written in terms of the areas and the structural reverberation times of the elements such that:

$$10\log\frac{\sqrt{a_{i,situ}a_{j,situ}}}{\sqrt{a_{i,lab}a_{j,lab}}} = 10\log\frac{\sqrt{\frac{S_{i,situ}}{T_{s,i,situ}}\frac{S_{j,situ}}{T_{s,j,situ}}}}{\sqrt{\frac{S_{i,lab}}{T_{s,i,lab}}\frac{S_{j,lab}}{T_{s,j,lab}}}} = 5\log\frac{T_{s,i,lab}}{T_{s,i,situ}} + 5\log\frac{T_{s,j,lab}}{T_{s,j,situ}} + 10\log\frac{\sqrt{S_{i,situ}S_{j,situ}}}{\sqrt{S_{i,lab}S_{j,lab}}} \quad (59)$$

This results in:

$$R_{ij,situ} = D_{n,f,ij,lab} + 10\log\frac{S_{S,situ}l_{ij,lab}}{A_o l_{ij,situ}} + 10\log\frac{T_{s,i,lab}}{T_{s,i,situ}} + 10\log\frac{T_{s,j,lab}}{T_{s,j,situ}} \quad (60)$$

which is similar to Equation B2 of Gerretsen's 1984 paper and Equation 16 of ISO 12354-1 with the exceptions that the $D_{n,f,ij}$ term is explicitly stated as the laboratory value, the area of the separating element is explicitly stated as the *in situ* value and the structural reverberation times are not neglected. For Type B elements, the last two terms of Equation 60 may be neglected due to both the typically high internal loss factors[8] and the small differences between the laboratory measured and in situ structural reverberation times for these elements resulting in:

$$R_{ij,situ} = D_{n,f,ij,lab} + 10\log\frac{S_{S,situ} l_{ij,lab}}{A_o l_{ij,situ}} \quad (61)$$

The consequence of the differences between Equation 57 and Equation 60 is the relationship:

$$D_{n,f,ij,situ} = D_{n,f,ij,lab} + 10\log\frac{l_{ij,lab}}{l_{ij,situ}} + 10\log\frac{T_{s,i,lab}}{T_{s,i,situ}} + 10\log\frac{T_{s,j,lab}}{T_{s,j,situ}} \quad (62)$$

for Type A and Type B elements and therefore the equality between $D_{n,f,ij,lab}$ and $D_{n,f,ij,situ}$ stated in Section 4.2.3.3 of ISO 12354-1 is not correct. For Type B elements, the last two terms of Equation 62 may be neglected.

Case Studies

Consider Example L.2.2 found in Appendix L of ISO 12354-1 for a wall / wall junction which was part of a study in the eight-room flanking facility at the NRC. The *in situ* dimensions of the common and flanking elements are presented in Table L.14 of ISO 12354-1, but the laboratory dimension $l_{ij,lab}$ is missing from the example. However, the value can be found in Research Report RR-336[21] to be $l_{ij,lab}$ = 2.5 m. Table L.15 shows the laboratory measured $D_{n,f,ij,lab}$ and the corresponding $R_{ij,situ}$ values which are described as calculated according to Equation 16 of ISO 12354-1. While Equation 16 is cited, the calculation of the $R_{ij,situ}$ values for Example L.2.2 of ISO 12354-1 actually follows Equation 61 of this paper using the laboratory measured $D_{n,f,ij,lab}$ and junction length such that:

$$R_{ij,situ} = D_{n,f,ij,lab} + 10\log\frac{S_{S,situ} l_{ij,lab}}{A_o l_{ij,situ}} = D_{n,f,ij,lab} + 10\log\left[\frac{(10.44\,m^2)(2.5\,m)}{(10\,m^2)(2.41\,m)}\right]$$
$$= D_{n,f,ij,lab} + 0.3$$

Alternatively, if the $D_{n,f,ij}$ values given for the example were measured *in situ* as part of a field study to calculate the weighted apparent sound reduction index, what value for $l_{ij,lab}$ should be used in Equation 16 of ISO 12354-1 since this situation only pertains to *in situ* values? If it is assumed that $l_{ij,lab} = l_{ij,situ}$ then Equation 16 becomes Equation 57 of this paper. The differences between the field and *in situ* values of $D_{n,f,ij}$ are small (0.2 dB) for Example L.2.2 since the laboratory and *in situ* dimensions are similar, but the differences between the field and *in situ* values of $D_{n,f,ij}$ would be larger for dissimilar laboratory and *in situ* junction lengths.

To demonstrate this, consider two rooms, one-above-the-other in a lightweight steel-framed construction as shown in Figure 3. Junctions 1, 3 and 4 are all cross-junctions between a lightweight cold-formed steel joist floors and cold-formed steel stud walls. Junction 2 is a T-junction.

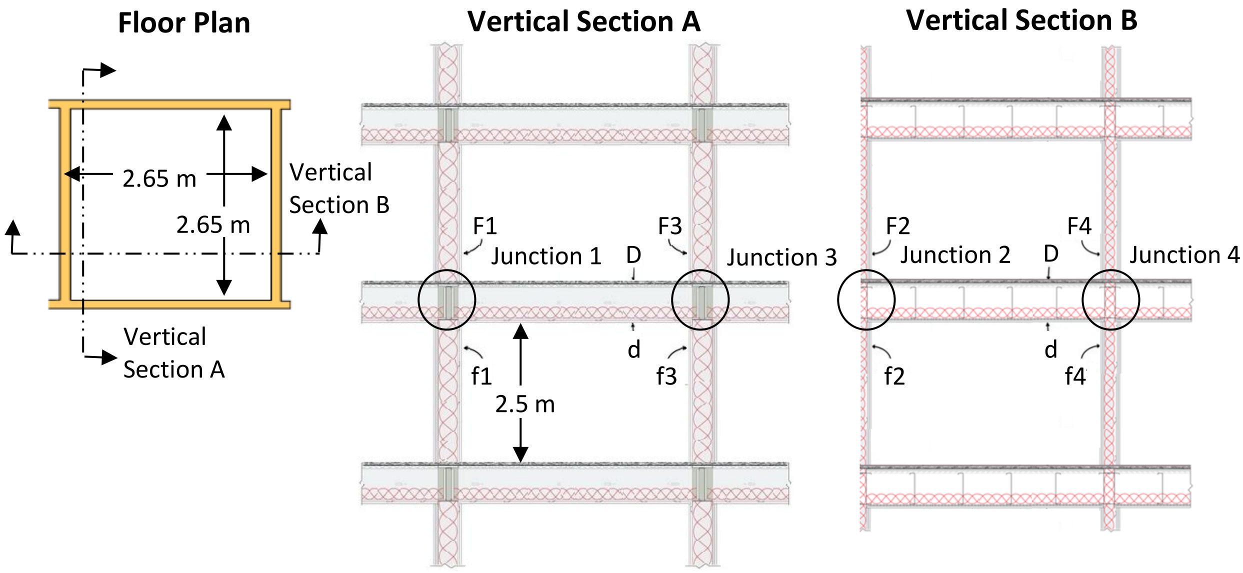

Figure 3: Junctions between the lightweight steel framed walls and floors for the example

The floor is constructed from 254 mm high joists spaced 406 mm on center with 89 mm thick sound absorbing material in the inter-stud cavity. The subfloor construction is a corrugated steel deck 0.76 mm tick with 14 mm deep corrugations. A 32 mm tick gypsum concrete floor deck was poured on the steel deck and 10 mm thick laminate was installed on a 3 mm thick foam pad over the subfloor. The ceiling is one layer of 15.8 mm thick fire-rated gypsum board supported on resilient channels spaced 305 mm on center.

Walls 1 and 3 are constructed of 152 mm cold formed steel studs spaced 406 mm on center with 152 mm thick sound absorbing material in the inter-stud cavities. There are two layers of 15.8 mm thick gypsum board supported on resilient metal channels spaced 406 mm on center.

Walls 2 and 4 are constructed of 92 mm cold formed steel studs spaced 406 mm on center with 89 mm thick sound absorbing material in the inter-stud cavities. There are two layers of 15.8 mm thick gypsum board directly attached to the studs.

The junction lengths from the laboratory and the *in situ* situation are shown in Table 1. The *in situ* dimensions are based on the Ontario Building Code[22] which allows for bedrooms to be as small as 7 m^2. It is reasonable to assume that builders will specify bedrooms of this size and that acousticians will rely on data from the NRC's four-room flanking facility to calculate the flanking sound transmission for these rooms.

Table 1: The laboratory and the *in situ* values for the junction lengths l_{ij}.

Junction	$l_{ij,lab}$ (m)	$l_{ij,situ}$ (m)
1	5.20	2.65
2	4.65	2.65
3	5.20	2.65
4	4.65	2.65

The example uses the simplified method for the calculations and the weighted values for the normalized flanking level difference and the *in situ* flanking sound reduction index are shown in Table 2.

Table 2: The weighted values for the normalized flanking level difference and the *in situ* flanking sound reduction index.

Junction	Path	$D_{n,f,ij,w,lab}$ (dB)	$R_{ij,w,situ}$ (dB)	$D_{n,f,ij,w,situ}$ (dB)
1	Ff	63.0	64.4	65.9
	Fd	67.0	68.4	69.9
	Df	70.0	71.4	72.9
2	Ff	71.0	72.4	73.9
	Fd	69.0	70.4	71.9
	Df	66.0	67.4	68.9
3	Ff	63.0	64.4	65.9
	Fd	67.0	68.4	69.9
	Df	70.0	71.4	72.9
4	Ff	71.0	72.4	73.9
	Fd	69.0	70.4	71.9
	Df	66.0	67.4	68.9

The $D_{n,f,ij,w,lab}$ values in the table represent those measured in the flanking facility. The $R_{ij,w,situ}$ values are calculated from the $D_{n,f,ij,w,lab}$ values using Equation 64 of this paper. The $D_{n,f,ij,w,situ}$ values are calculated from the $R_{ij,w,situ}$ values based on Equation 57 of this paper, but written in terms of weighted values such that:

$$R_{ij,w,situ} = D_{n,f,ij,w,situ} + 10\log\frac{S_{S,situ}}{A_o} \tag{63}$$

The difference between the laboratory and the *in situ* $D_{n,f,ij,w}$ values for this example is 2.9 dB which is not small enough to be ignored.

Conclusions

Based on the derivation of the relationship between the $R_{ij,situ}$ and $D_{n,f,ij}$, it is recommended that the Equation 16 of ISO 12354-1 for use with Type B elements using the Detailed Method should be replaced with Equation 61 of this paper. The change would in agreement with the calculations already used in Example L.2.2 of ISO 12354-1. Likewise, it is recommended that the weighted flanking sound reduction index found in Equation 21 of ISO 12354-1 for use with Type B elements using the Simplified Method should be replaced with:

$$R_{ij,situ,w} = D_{n,f,ij,lab,w} + 10\log\frac{S_{S,situ}l_{ij,lab}}{A_o l_{ij,situ}} \tag{64}$$

The comparable equations that would be presented in RR-331 for use in ASTM standards would be:

$$TL_{ij,situ} = D_{n,f,ij,lab} + 10\log\frac{S_{S,situ}l_{ij,lab}}{A_o l_{ij,situ}} \quad (65)$$

for the Detailed Method and

$$STC_{ij,situ} = D_{n,f,ij,lab,w} + 10\log\frac{S_{S,situ}l_{ij,lab}}{A_o l_{ij,situ}} \quad (66)$$

for the Simplified Method where $D_{n,f,ij,lab,w}$ is calculated following the procedures of the standard, ASTM E413.[23]

In addition, it has been shown in this paper that the relationship between the *in situ* and the laboratory values of $D_{n,f,ij}$ is based on the ratio of the laboratory and *in situ* junction lengths between elements i and j and the ratios of the laboratory measured and *in situ* reverberation times of the elements i and j. It is therefore recommended that Equation 62 of this paper which shows the relationship between $D_{n,f,ij,situ}$ and $D_{n,f,ij,lab}$ should replace the text of Section 4.2.3.3 of ISO 12354-1 which currently states that *in the case of dominant structure-borne sound transmission,* $D_{n,f,ij,situ}$ *can be taken as identical to the laboratory situation.*

Declaration of conflicting interests

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

ORCID iD

Jeffrey Mahn https://orcid.org/0009-0002-5403-5404
Markus Mueller-Trapet https://orcid.org/0000-0002-4081-7942

References

1. Mahn J. Announcing the publication of the sixth edition of RR-331: The Guide and a history of the transition to the ASTC rating. *Canadian Acoustics / Acoustique canadienne*; 52(2), 45-50. https://jcaa.caa-aca.ca/index.php/jcaa/article/view/3943 (2023).

2. *ISO 12354-1:2017 Building acoustics. Estimation of acoustic performance in buildings from the performance of elements - Part 1: Airborne sound insulation between rooms*. ISO 12354-1:2017, Geneva, Switzerland: International Organization for Standardization, 2017.

3. Mahn J., Mueller-Trapet M., Skoda, S., Cunha I., *RR-331: Guide to Calculating Airborne Sound Transmission in Buildings: 6th Edition*. RR-331, Ottawa, Canada: National Research Council Canada, https://publications-cnrc.canada.ca/eng/home/ (2023).

4. *ISO 10848-1:2017 - Acoustics - Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms - Part 1: Frame document*. ISO 10848-1:2017, Geneva, Switzerland: International Standards Organization, 2017.

5. *ISO 10848-2:2017 - Acoustics - Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms - Part 2: Application to Type B elements when the junction has a small influence*. ISO 10848-2:2017, Geneva, Switzerland: International Standards Organization, 2017.

6. *ISO 10848-3:2017 - Acoustics - Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms - Part 3: Application to Type B elements when the junction has a substantial influence*. ISO 10848-3:2017, Geneva, Switzerland: International Standards Organization, 2017.

7. *ISO 10848-4:2017 - Acoustics - Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms - Part 4: Application to junctions with at least one Type A element*. ISO 10848-4:2017, Geneva, Switzerland: International Standards Organization, 2017.

8. Gerretsen E. European developments in prediction models for building acoustics. *Acta Acustica* 1994; 2: 205–214.

9. Metzen HA, Schumacher R. Prediction of Sound Insulation in Timber Frame Buildings. In: *Proceedings - Forum Acusticum 2005*. Budapest, Hungary, 2005.

10. *ISO 15712-1:2005 -- Building acoustics -- Estimation of acoustic performance of buildings from the performance of elements -- Part 1: Airborne sound insulation between rooms*. ISO 15712-1:2005, Geneva, Switzerland: International Standards Organization, 2005.

11. Craik RJM. *Sound Transmission Through Buildings: Using Statistical Energy Analysis*. Aldershot, England ; Brookfield, Vt., USA: Gower Pub Co, 1996.

12. Craik RJM. The noise reduction of flanking paths. *Applied Acoustics* 1987; 22: 163–175.

13. Rindel JH. *Sound Insulation in Buildings*. Boca Raton: CRC Press, doi.org/10.1201/9781351228206 (2017).

14. Rindel JH. Dispersion and absorption of structure-borne sound in acoustically thick plates. *Applied Acoustics* 1994; 41: 97–111.

15. Hopkins C. *Sound Insulation*. 1st Edition. Amsterdam: Routledge, 2007.

16. Gerretsen E. Calculation of the sound transmission between dwellings by partitions and flanking structures. *Applied Acoustics* 1979; 12: 413–433.

17. Gerretsen E. Calculation of airborne and impact sound insulation between dwellings. *Applied Acoustics* 1986; 19: 245–264.

18. Kihlman T. *Transmission of Structure-Borne Sound in Buildings. A Theoretical and Experimental Investigation*. 9, Stockholm, Sweden: National Swedish Institute for Building Research, 1967.

19. *BS EN 12354-1:2000 Building acoustics. Estimation of acoustic performance in buildings from the performance of elements. Airborne sound insulation between rooms*. BS EN 12354-1:2000, London, UK: BSI, 2000.

20. Nightingale TRT, Bosmans I. Expressions for First-Order Flanking Paths in Homogeneous Isotropic and Lightly Damped Buildings. *Acta Acustica united with Acustica* 2003; 89: 110–122.

21. Hoeller C, Quirt JD, Mueller-Trapet M. *RR-336: Apparent Sound Insulation in Wood-framed Buildings*. RR-336, Ottawa, Canada: National Research Council Canada, doi.org/10.4224/23002820 (2017).

22. Ontario Building Code. O Reg 332/12, 2012.

23. *ASTM E413 - 16, Classification for Rating Sound Insulation*. ASTM E413 - 16, West Conshohocken, PA: ASTM International, 2016.