Sound Transmission of Wood Frame Split Insulated Rainscreen Cavity Wall Assemblies: an Experimental Approach

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A Thesis

in the

Building Science Graduate Program

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Applied Science in Building Engineering/Building Science

at the

British Columbia Institute of Technology

Burnaby, British Columbia, Canada

November 2017

BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY

Building Science Graduate Program

This is to certify that the thesis prepared

By: Eduardo Stehling

Entitled: Sound Transmission of Wood Frame Split Insulated Rainscreen Cavity Wall Assemblies: an Experimental Approach

And submitted in partial fulfillment of the requirement for the degree of:

Master of Applied Science in Building Engineering/Building Science

Complies with the regulations of the Institute and meets the accepted standards with respect to originality and quality.

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Abstract

Exterior building envelope walls with rainscreen cavities are now required by British Columbia building codes. The introduction of the rainscreen cavity and optional external thermal insulation can alter sound transmission loss and consequently affect indoor sound levels in single and multi-family wood-frame housing. In this study, 57 exterior wall assemblies were built and acoustically evaluated using a hybrid sound intensity technique. The variables investigated were cladding material (vinyl, fibre cement board, and stucco), exterior insulation (mineral wool and XPS), exterior insulation thickness (1 ½" and 3"), cladding attachment type (resilient and non-resilient), and rainscreen cavity width (3/8" and 1"). The sound transmission class of the tested wall assemblies ranged from 37 to 52; the outdoor-indoor transmission class rating ranged from 26 to 37. Results indicated that the selection and the combination of the material layers were fundamental to sound transmission loss performance. Cladding material and cladding attachments influenced sound transmission and resulted in a broad range of overall performance. The split insulated rainscreen cavity wall assemblies presented higher transmission loss than single insulation walls, provided that the exterior insulation had sound absorbing properties. The best performing wall assemblies generally have high mass cladding, resilient cladding attachment, and 3" mineral wool exterior insulation (in addition to the interior cavity insulation). Given the research outcomes, in denser and noisier urban areas, a building envelope professional has additional options to design an exterior rainscreen cavity wall to meet thermal performance and acoustical criteria for exterior sound levels in wood frame buildings.

Acknowledgements

To my supervisor, Dr. Maureen Connelly, my sincere gratitude for all your support and attention in every step of this journey. Having worked and learned from you was the greatest learning experience that I could have. Not only is your knowledge immense but also your kindness. Without your help, this project would not have been possible. Thank you so much!!

I am also thankful to Mr. Hamid Heidarali, Dr. Jeffrey Mahn, and Dr. Denisa Ionescu for their valuable contributions, and whose expertise and experience were always enlightening. My appreciation is also extended to the building science community members who contributed to the completion of this study.

To my fellows in the graduate program, all of you deserve recognition in this work. Often, your doubts were mine, and together we gained deeper knowledge in the building science field. My thanks to the BCIT faculty members for the uncountable hours of wisdom that you shared with us.

I also would like to thank BC Housing and the British Columbia Institute of Technology for the financial support for this research.

Finally, Rodrigo and Leonardo, my thanks to you for being the wonderful people you are. Fabricia, my thank you to you for your huge patience, attention, care, and love. None of this would be possible without your support.

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Table of Contents

Table of Figures

1 INTRODUCTION

Exterior building envelope walls have undergone major changes in recent years to meet energy and moisture requirements. The two most significant modifications in exterior walls are the inclusions of a rain screen cavity and an exterior thermal insulation layer. The sound transmission loss[1] of these current envelope wall assemblies has generally not been evaluated. The rainscreen cavity is the physical separation between the two outer layers of a wood frame wall, the sheathing and cladding, or exterior insulation and cladding, creating an air cavity, which becomes a drainage path for incidental water and increases the drying potential for the walls' materials. The addition of an exterior thermal insulation layer in the exterior cavity (between the sheathing and cladding) is a measure to increase thermal performance and reduce the energy required for thermal comfort in cold climates.

Most research on these current building envelope walls has been concerned with thermal and moisture performance. Sound insulation of the recommended wall assemblies from community and transportation noise has not been evaluated. Providing an additional exterior cavity and the required air gaps to drain or ventilate the cavity along with an exterior thermal insulation in these walls will alter the sound transmission path and create a different response in frequency dependent transmission loss performance.

[1] An increase in Sound Transmission Loss is a positive outcome rather than a negative characteristic, as the discussion of energy loss will show.

The primary concern of this research focus is residential building envelope walls. In British Columbia, where these two changes in wall assemblies have been adopted, the main publications that mandate how buildings are to be constructed are the British Columbia Building Code (BCBC, 2012), the City of Vancouver Building By-law (CVBBL, 2014), and the Building Enclosure Design Guide (HPO, 2011). These documents are primarily focused on air movement, moisture control, and increasing the overall thermal performance (R-value) for efficient single and multi-family housing.

The World Health Organization (WHO) published extensive studies connecting the health impacts on populations to environmental noise in urban areas, citing urbanization, economic growth, and motorized transport as the primary causes of high levels of exposure to noise. The consequences of excessive noise exposure are cardiovascular disease, cognitive impairment in children, sleep disturbance, tinnitus, and annoyance (WHO, 2011).

In any environment, the most efficient manner of reducing noise is by controlling the source generating the noise. If this cannot be done, the next best possible measure is to interfere with the sound path to the receiver. A massive wall is an efficient way of controlling sound that is generated outdoors and may be intrusive in the house. However, construction of massive walls (thicker and denser) are not feasible, and light-weight construction assemblies are prevalent.

The basic configuration of a common wood-frame residential exterior wall assembly that has had widespread use in the past and is still current in some jurisdiction is illustrated in Figure 1.1. The layers, from exterior to interior are cladding, wood sheathing, wood studs, thermal insulation, and gypsum board. This wall includes a vapour/air barrier and a water-resistive barrier (not shown in the cross-section view).

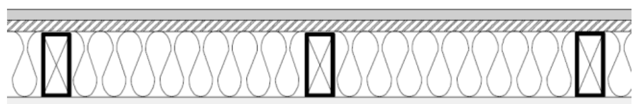


Figure 1.1. Single insulation wall without rainscreen cavity (horizontal cross-section).

The currently recommended wall assemblies and trend in future walls in British Columbia are illustrated in Figure 1.2. The following layers, from exterior to interior are cladding, strapping (wood or metal clips), an air cavity, (optional) exterior thermal insulation, wood sheathing, wood studs with internal thermal insulation, and gypsum board. This wall also includes a vapour/air barrier and a water-resistive barrier (not shown in the cross-section view).

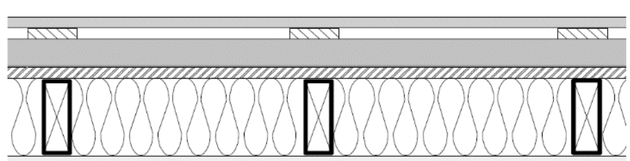


Figure 1.2. Split insulated rainscreen cavity wall (horizontal cross-section).

2 LITERATURE REVIEW

2.1 Sound Transmission

When airborne sound waves reach a wall, three phenomena occur: part of the sound waves is reflected back, part is absorbed by the wall components, and the remainder is transmitted to the other side of the wall. The last represents the focus of this study. The quantity of sound energy transmitted divided by the amount of incident sound energy is represented by the sound transmission factor τ (dimensionless) where

$$\tau = \frac{W_t}{W_i} \qquad \text{Eq. (1)}$$

and where W_t = transmitted sound power (W),

W_i = incident sound power (W).

Thus, in decibel (dB) units, sound transmission loss (TL) can be written as

$$TL = 10\ \log\frac{1}{\tau} = \ 10\ \log\frac{W_i}{W_t} \qquad \text{Eq. (2)}$$

One of the basic concepts that describes the relationship between sound energy and materials is specific acoustic impedance (*z*). This property gives a “measure of the resistance to motion at a given point” (Long, 2006, p. 55). A sound wave that is transmitted through materials (solid, gas or liquid) causes the movement of particles, and there will be measurable resistance to the passage of a sound wave through the material. Acoustic impedance is the “ratio of sound pressure differential existing between the two faces of the structure to its normal velocity” (Sharp, 1973, p. 4). Additionally, the acoustic impedance is directly related to the product of bulk density of the medium (*ρ*) and speed of sound (*c*) as described by the equation

$$z = \frac{p}{u} = \rho\, c \qquad \text{Eq. (3)}$$

where z = specific acoustic impedance ($N.s/m^3$),

p = sound pressure (Pa),

u = acoustic particle velocity (m/s),

ρ = bulk density of the medium (Kg/m^3),

c = speed of sound (m/s).

The product of the density of the material and the speed of sound in the material gives a basic understanding of the acoustic impedance ($N.s/m^3$ – also call rayl), which describes the rate at which the material will accept energy. The product between frequency (Hz, which is 1/s) and surface mass density (kg/m^2) provides the same result in terms of units to the acoustic impedance of a material ($N \times s/m^3 = Kg/m^2 \times 1/s$), illustrating that the acoustic impedance expresses an energy acceptance rate. A sound wave is a pressure variation in air that spreads out at a certain speed. When the sound wave reaches another material (boundary condition), it may be possible for the sound wave to keep the same amount of pressure and speed in this new material, but the new pressure and speed depend on the physical properties of the new material. At a boundary condition, the closer the materials' impedances match each other, the higher the transmission, while a mismatch impedance causes lower transmission and higher reflection (Kim, 2010). Transmission is frequency-dependent. This creates possible combinations of different materials and boundary conditions in which sound transmission loss is low in some frequencies while in other frequencies the transmission loss is high.

As illustrated in Figure 2.1 presented from Long (2006) and also explained by Ginn (1978) and Sharp (1973), the transmission loss for a single thin panel can be divided into five zones according to the frequency of the wave impinging on a panel.

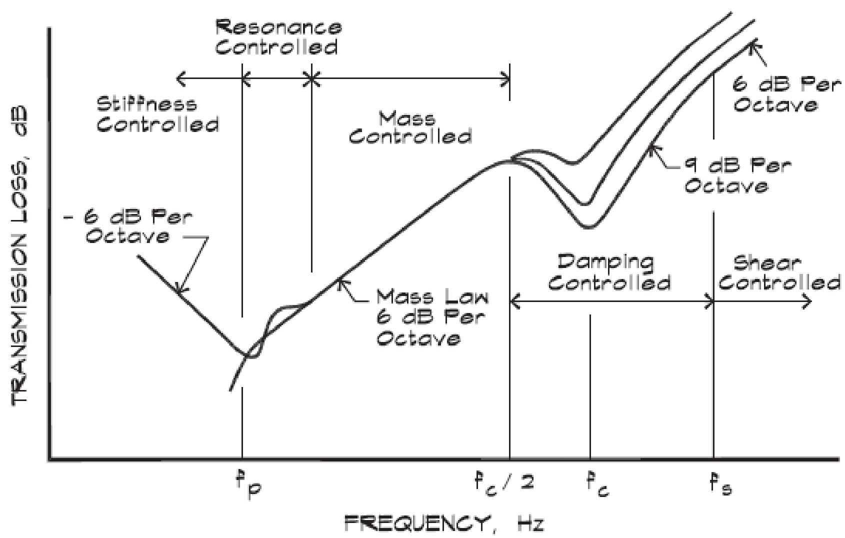


Figure 2.1. Generic graph for sound transmission loss for a single thin panel.(Long, 2006).

The behaviour presented in the graph (Figure 2.1) can be reviewed starting from low-frequency to high-frequency sound to explain the transmission loss. The first region illustrates that below panel resonance frequency (f_p), the transmission loss of a panel is stiffness controlled, and there is an increase in transmission loss with a decrease in frequency. This zone tends to be observed at very low frequencies and usually only where the lowest transmission loss occurs—the panel resonance frequency—is the transmission loss of concern. The equation for the panel resonance is given by

$$f_p = \frac{\pi}{2}\sqrt{\frac{B}{m_s}}\left[\frac{1}{a^2} + \frac{1}{b^2}\right] \qquad \text{Eq. (4)}$$

where f_p = panel resonance (Hz),

a, b = panel dimensions (m),

B = bending stiffness (N.m),

m_s= surface mass density (Kg/m^2).

This effect happens when the incoming sound wave has the same natural frequency as the panel due to its dimensions and physical properties, which causes the panel to vibrate with the same period, creating an effect in which low sound transmission loss is observed. The sound waves do not face any resistance in crossing the panel and can be easily transmitted to the other side of the panel. To control the resonance effect, damping control is required.

Panel resonance is the most critical point of analysis for a building wall because at this frequency we will observe the lowest transmission loss for the whole wall. This situation can limit the overall performance of a wall, impacting the calculated single number ratings STC or OITC. Single-number ratings are further explained in Section 2.2. If the performance of a panel must be improved, the resonance frequency should be lowered as much as possible, preferably below a critical range.

Just above the panel resonance frequency, the second zone presents the phenomenon known as the panel resonance in tandem with mass impedance.

The mass-law region is the third zone illustrated in Figure 2.1. Mass law is a fundamental relation that is useful in understanding the transmission of sound waves striking a panel. By using the acoustic impedance (*z*), we can observe that a single panel will behave differently depending on its surface mass density and the frequency of the incident wave. The sound transmission loss is also a function of the incidence angle of the incoming sound wave. Knowing that transmissivity (τ) is a relation between transmitted and incident power, or in other terms, a relation between the transmitted and incident sound pressures, the following equation describes transmissivity relative to the angle of incidence.

$$\tau_\theta = \left[\frac{p_t}{p_i}\right]^2 = \frac{1}{\left|1 + \frac{\pi\, f\, m_s\, \cos\theta}{\rho_0 c_0}\right|^2} \qquad \text{Eq. (5)}$$

where p_t = transmitted sound pressure (Pa),

p_i = incident sound pressure (Pa),

f = frequency (Hz),

m_s = surface mass density (kg/m^2),

θ = angle between sound wave and surface normal (rad),

$\rho_0\, c_0$ = characteristic impedance of air (N.s/m^3).

Given that from Equation (2), Equation (5) can, therefore, be changed and represent the TL of a panel as a function of the incident angle θ:

$$TL\,(\theta) = 10\log\left[1 + \left(\frac{\pi\, f\, m_s\, \cos\theta}{\rho_0 c_0}\right)^2\right] \qquad \text{Eq. (6)}$$

In a diffuse sound field, all possible angles of incidence must be integrated to obtain the diffuse sound field transmission loss. The equation below integrates the angles up to 78° which, due to the effect of low grazing angles, is the limiting of integration (Sharp, 1973).

$$TL = 10\log\left[1 + \left(\frac{2\,\pi\, f\, m_s}{3.6\,\rho_0 c_0}\right)^2\right] \qquad \text{Eq. (7)}$$

Since the term in the brackets is much greater than 1 for most building materials, the above equation becomes:

$$TL = 10\log\left(\frac{2\,\pi\, f\, m_s}{3.6\,\rho_0 c_0}\right)^2 = 20\log(f m_s) - 20\log\left(\frac{2\,\pi}{3.6\,\rho_0 c_0}\right) \qquad \text{Eq. (8)}$$

The terms on the right-hand side of the above equation are constants; hence, Equation (8) becomes the diffuse field equation for the mass-law sound transmission loss, in dB units, for a single panel:

$$TL = 20\log\,(f\, m_s) - K_{TL} \qquad \text{Eq. (9)}$$

where K_{TL} = 47.3 dB, numerical constant,

f = frequency (Hz),

m_s = surface mass density of the panel material (Kg/m^2).

This equation gives the positive and straight sloped line in the graph, illustrating that when either the frequency or the surface mass density is doubled the overall increase in sound transmission loss is 6 dB per octave.

In the fourth zone, in the range of high frequencies, above where the panel responds solely to the mass-law relation, a dip in the graph is caused by an important phenomenon termed the 'coincidence effect.' In a diffuse sound field, incoming longitudinal waves impinge on a panel and additional waves pattern will occur in the panel. These are the bending and shear waves. Thin panels are more prone to bend than shear, and therefore only the acoustic impedance of bending waves is considered, as they are dominant compared to the acoustic impedance of the shear waves (Long, 2006).

Figure 2.2 below, from Long (2006), illustrates how the coincidence effect occurs.

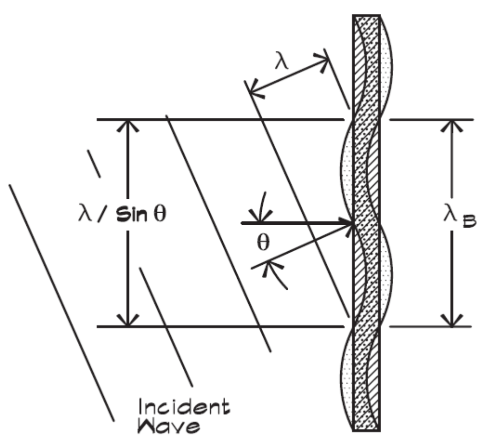


Figure 2.2. Coincidence effect. (Source: Long, 2006)

A wave, with wavelength λ, reaches a panel at an angle θ between the longitudinal wave and the plane of the panel. There will be an angle θ of coincidence at which the ratio of longitudinal wavelength and the wavelength of the bending wave at angle λ_B is equal to sin θ:

$$\sin\theta = \frac{\lambda}{\lambda_B} \qquad \text{Eq. (10)}$$

where λ_B = wavelength in the panel (m),

λ = wavelength in air (m),

θ = angle between wave in air and panel (rad).

When the two waves have the same wavelength, the panel vibrates at the same frequency as the incident wave and sound faces less impedance in the panel, due to the impedance match. In reality, what happens is that the incoming waves vibrate the panel, which, in turn, vibrates the air on the other side of it; this is energy transmission, and the resistance to the sound wave motion is strongly reduced.

There is a frequency, at any angle (θ), called the coincidence frequency (f_{co}). This is the lowest frequency where a coincidence effect occurs at the defined angle of incidence.

$$f_{co}(\theta) = \frac{c_0^2}{2\,\pi\,\sin^2\theta}\sqrt{\frac{m_s}{B}} \qquad \text{Eq. (11)}$$

where f_{co} = coincidence frequency (Hz),

θ = angle between wave in air and panel (rad),

c_o = speed of sound in air (m/s),

m_s = surface mass density of the panel material (Kg/m^2),

B = bending stiffness (N.m).

There is a critical frequency—the frequency where the angle of incidence is at a grazing angle—that is the lowest frequency where the coincidence effect can occur. The equation for critical frequency is given by

$$f_c = \frac{c_0^2}{2\,\pi}\sqrt{\frac{m_s}{B}} = \frac{c_0^2}{2\,\pi\,h}\sqrt{\frac{12(1-\sigma^2)\rho_m}{E}} \qquad \text{Eq. (12)}$$

where f_c = critical frequency (Hz),

h = panel thickness (m),

ρ_m = bulk density of the panel material (kg/m^3),

E = Young's modulus of elasticity (N/m^2),

σ = Poisson's ratio.

Considering Equations (11) and (12), it can be determined that the coincidence effect will always happen at or above the critical frequency.

In the fifth zone, above frequencies where a coincidence effect occurs, the transmission loss is controlled by the shear impedance, which in the case of thin panels happens at high frequencies, usually much higher than the frequency range in building acoustics (greater than 4000 Hz), and the analysis of this region is commonly disregarded.

Moreover, at high frequencies, the transmission loss through building materials is generally quite high and does not require special attention.

In a wall assembly, the layers that can represent an isolated single panel are gypsum board, plywood sheathing, and cladding. These are the layers that tend to behave according to the panel theory for sound transmission. As illustrated in Figure 1.1, the plywood sheathing and the cladding of a single insulated wall without a rainscreen cavity are fully connected through their surface areas, and as such, they behave as if they were one panel. On the other hand, as illustrated in Figure 1.2, there are three theoretically isolated panels in the split insulation rainscreen cavity wall, which are gypsum board, plywood sheathing, and cladding. The thin panel theory is the fundamental explanation for the overall behaviour of light-weight building wall assemblies even with the additional practical construction constraints that are included in more detailed and complex analyses of multi-layer walls. The practical constraints include distance between panels (mass-air-mass resonance), cavity and thermal insulation, and studs and structural connections, such as bracing.

When dealing with two layers of panels, another effect that impacts the low-frequency transmission loss is the mass-air-mass (m-a-m) resonance. This phenomenon occurs when the two mass panels are connected by an air cavity, which acts as a spring. Depending on the frequency of the sound wave, this system—two panels and air cavity—will resonate, generating vibrations at a specific frequency, and thus will not impede sound transmission. To control the acoustical coupling between the two panels, each mass and distance between them must be carefully controlled. Furthermore, the purpose of controlling the masses and distance is to allow them to independently vibrate at a resonance above the m-a-m resonance; the two masses then react as if they were independent, and theoretically the total contribution is a simple contribution of each panel. The equation for the m-a-m resonance of a double panel wall is given by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3.6\,\rho_0 c_0^2}{m' d}} \qquad \text{Eq. (13)}$$

where $m' = \frac{2\,m_1\,m_2}{m_1 + m_2}$, effective mass per unit of area (kg/m^2),

d = panel spacing (m),

ρ_0 = bulk density of air (Kg/m^3).

A second thin panel layer with an air gap in between (two-panel system) improves sound transmission loss, thus increasing the slope of the transmission over frequency curve (Warnock, 1985; Nightingale & Quirt, 1999). The overall result tends to be better; however, in the low-frequency region where resonance happens, this effect needs careful control, as the dip does not change significantly.

Adding a third panel layer creates a mass-spring-mass-spring-mass system, which at specific frequencies, similarly to a double panel system, will present its own resonance modes coupling all three plates (Long, 2006; Sharp, 1973). The equation for the three-panel resonance is given by

$$f_{\alpha,\beta} = \frac{1}{2\pi}\sqrt{3.6\,\rho_0 c_0^2}\,\sqrt{a \pm \sqrt{a^2 - b}} \quad ; \quad (f_\alpha > f_\beta) \qquad \text{Eq. (14)}$$

where $f_{\alpha,\beta}$ = resonance frequencies (Hz),

$a = \frac{1}{2\,m_2}\left(\frac{m_1+m_2}{m_1 d_1} + \frac{m_2+m_3}{m_3 d_2}\right)$,

$b = \frac{M}{m_1 m_2 m_3 d_1 d_2}$,

$M = m_1 + m_2 + m_3$ (Kg/m^2).

In building walls, the interior and exterior cavities on either side of the wood sheathing are the distances between the panels, which determine the practical values for possible resonances. Theoretically, better sound transmission loss can be achieved by adding additional layers of panels separated by an air cavity, but practical construction issues beyond three panels in terms of increased floor area, support system, and cost for the final wall determine a limit to the number of panels that usually can be used (Sharp, 1973).

A third panel in a wall assembly increases the sound transmission loss due to higher mass of the overall configuration. The mass-law for triple panels results in higher TL values than single and double panels of equal masses and thicknesses. Xin and Lu (2011) demonstrated through analytical calculations that unbalanced masses produce higher TL if the incident sound panel is the heaviest panel, whereas Vinokur (1990) performed experimental tests showing same results if the heaviest panel is the incident sound panel.

This effect happens due to an interaction between the incident panel in the mass-spring system for a triple panel, while increasing the middle and inner panels masses does not bring an equal amount of change.

Wall cavity resonances may arise due to standing waves within the wall cavity between the wall panels. These waves are normal to the surfaces and can be calculated according to Equation (15) below. These cavity mode resonances couple the adjacent panels, creating a sound bridge, lowering the transmission loss. Usually, if there is insulation material in the cavity, these resonances are mitigated and do not pose any additional deficiency to the wall. Frequently, due to small distances between panels, these cavity resonances happen at a higher frequency and do not coincide with the lowest transmission loss values at low-frequency ranges, which would contribute to higher losses.

$$f_n = \frac{n\, c_0}{2d} \qquad \text{Eq. (15)}$$

where n = 1,2,3… (modes).

Additional to the double and triple panels' behaviour, another consideration is the structural resonance of the ribbed panels which leads to misinterpreting the values of the mass-air-mass resonance that is measured at low-frequencies for double panel walls (Lin & Garrelick, 1977). The stiffness of a panel is changed when wood studs are attached to it; consequently, there is a difference between single panel and ribbed panel resonances.

In the context of the exterior wall under investigation, the ribbed panels are the wood studs connected to gypsum board and wood sheathing. Xin and Lu (2011) pointed out that for a finite panel, a panel modal resonance happens at frequencies below the lowest mass-spring resonance and is highly influenced by the panel dimensions. Smaller triple panels have higher TL than bigger triple panels. This panel mode resonance frequency might also lead to an ambiguous identification of the lowest TL frequency at a low-frequency range. A proper differentiation between the three distinct resonance effects (mass-spring, structural, and panel mode) is required when the focus of the attention is in the low-frequency range. Recall, the lowest results are in the low frequencies and the single number ratings tend to be largely influenced by low frequencies.

One major concern of walls are the structural connections that walls have in a construction assembly. In wall assemblies, structural connections decrease the total transmission loss to lower than the total theoretical mass model predicts (Ginn, 1978). The theory of thin panel does not include the effect of structural paths for sound transmission. This effect creates what is termed sound bridging and reduces the overall sound transmission loss of walls (Sharp, 1973, 1978; Long, 2006). In a three-panel situation of rainscreen cavity walls, the attachment of the external layer of cladding can be a connection that will, like wood studs, affect sound transmission and change the sound transmission loss. Sharp (1973, 1978) proposed models that included the effect of sound bridging in wood frame walls, and in association with the theory of thin panels created more accurate model solutions. Sharp also proposed some models that took into consideration the “area associated with each point connection” (Sharp, 1973). The models accommodate an influence area, or a connection density, for point connections that correlate the number of connections or proximity among connections, to a change in sound transmission. A higher number of connections (or lower area associated with each point connected) cause higher sound transmission. Quirt and Warnock (1993) and Quirt et al. (1995) showed that screw spacing for screws that attach gypsum boards to wood studs interferes with sound transmission between panels.

Sharp (1973) stated that there is a crossover frequency where triple panel performs more poorly than a two-panel system (usually at a low-frequency range) when the two configurations have equal total mass and equal total thickness. This theory was based only on free hanging panels. Sharp did not take into account the overlapped resonances effect due to structural connections that happen in real constructions.

A sound absorptive material in the wall cavity usually increases overall sound transmission loss. Standing waves that occur within the cavity without an absorptive fill can create acoustical coupling and the final transmission loss may be lower than what is expected from the mass-law theory and for the two- and triple-panel theories. London (1950) pointed out differences in transmission loss for double panel walls with and without sound absorptive material in the cavity and emphasized large improvements for light walls whereas for heavy walls there was little effect. Studies (Bradley & Birta, 2000, 2001;

Nightingale & Quirt, 1999; Quirt & Warnock 1993; Quirt et al., 1995) have showed that the insulation inside the cavity contributes to a higher transmission loss. Cambridge (2012) completed an extensive study on insulation in cavity walls. In general, his findings corroborated with previous studies; however, he noted a caution in the selection of the material type. Vinokur (2011) demonstrated the importance of the insulation material between panels to the overall sound transmission loss. In an assembly of 10 infinite panels separated by air gaps, the gain was only 10 dB higher than a single panel only.

In building envelope wall design, sound insulation materials are frequently specified using their mass density (Kg/m^3). However, the property that better explains the sound absorption characteristic for porous materials is flow resistivity (Bies & Hansen, 1980). This measure can be described as "how easily air can enter a porous absorber and the resistance that air flows meets through its structure" (Cox & D'Antonio, 2016, p. 191). It measures the pressure drop at constant flow velocity for a unit thickness of material. The unit is rayl/m. It describes the resistance for every meter of material. Not coincidentally, the most important properties that explain acoustic impedance and sound absorption have same physical unit—rayl. These two indexes are fundamental in understanding materials' acoustical behaviour. Commonly, absorption is described by a frequency dependent coefficient from 0 to 1.

Occasionally some types of thermal insulation do not provide acoustical benefits due to lack of absorption properties such as those having closed cell structure (e.g., XPS, EPS) or a non-porous structure. Nonetheless, according to Cox and D'Antonio,

> closed cell structures, on the other hand, do not readily permit the passage of sound into the air pockets, and so the absorption is much lower. It is possible, however, to perforate closed foam structures at the end of manufacture and so provide moderate absorption by interconnecting the pores. … While this can increase low-frequency absorption, performance is poorer at mid-high frequencies. (2016, p. 180)

2.2 Single-number Rating of Building Envelopes Transmission Loss

Although transmission loss is frequency dependent, to classify wall assemblies in terms of their transmission loss, single-number ratings were developed to provide a value to quantify the general behaviour of a wall for a quick comparison, specifications, and criteria. Such ratings are calculated from the sound transmission loss (TL) data. The most common and widely used ratings are Sound Transmission Class (STC), and Outdoor Indoor Transmission Class (OITC) and are used to classify walls for commercial and technical purposes. STC is calculated according to the ASTM E413 (ASTM, 2016c), while the OITC is calculated according to the ASTM E1332 (ASTM, 2016d). Although such classifications provide fair representation, they have some drawbacks, which were pointed out by Garc et al. (2013). The main critique regarding of these two ratings is that the frequency ranges data from which the single number is calculated may not include the full range of interest. The STC range is from 125 to 4000, Hz and it was developed within the speech frequency range, whereas the OITC range is from 80 to 4000 Hz. OITC better expresses the low-frequency of transportation and environmental noise and covers the frequency range in which the human ear is able to perceive sound at a lower frequency; some people are more sensitive to this range. Since walls have low performance for low-frequency sound, a close look at this range—below 125 Hz—can be a valuable contribution to the overall behaviour of a wall when designing a high-performance envelope assembly.

Figure 2.3 shows the two embedded relative response curves in dB that are required to obtain STC and calculate OITC. OITC uses the A-weighting correction factor while STC uses a contour line that needs to be fitted into the TL curve as detailed in the standard. Aside from the fact that OITC extends the correction factor two lower 1/3 octave bands, note that both curves have similarities regarding the slopes indicating that they tend to capture the idea of the human hearing system behaviour, yet using different approaches. The STC contour resembles the A-weight factor but in three connected steeped lines.

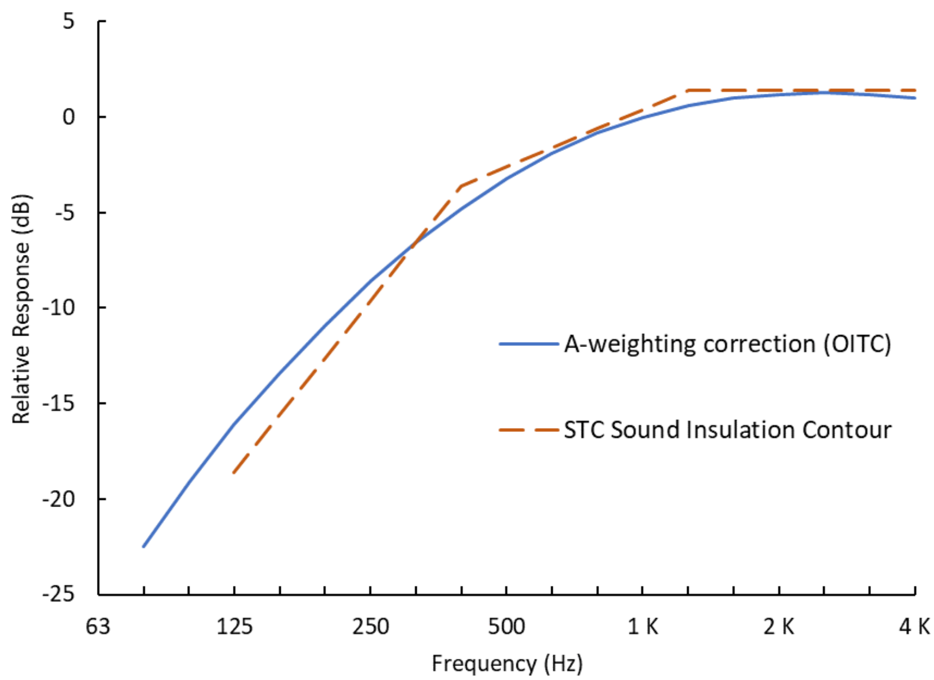


Figure 2.3. Correction factor for calculating OITC and STC sound insulation contour.

Based on the graph from Figure 2.3 it is reasonable to say that the main frequency ranges that predominantly affect the calculated STC and OITC are from 125 to 400 Hz and from 80 to 500 Hz, respectively. This means that small differences in sound levels in these regions will be translated into higher differences in single-number ratings.

In some studies (Sabine & Lacher, 1975; Rudder, 1985; Quirt et al., 1995; Bradley & Birta, 2000), researchers have evaluated and ranked walls according to the STC to make a simpler comparison of material layer. This approach is helpful for selecting wall types to reach a specific STC instead of modelling a predicted frequency dependent performance for each type of wall. Building codes (BCBC, 2012; CVBBL, 2014) present some basic wall assemblies and their respective STC ratings that can be used as a reference to meet code criteria. STC values are available from past field and laboratory studies such as Sabine and Lacher (1975), Rudder (1985), Quirt et al. (1995), and Bradley and Birta (2000).

The current guidelines and codes (BCBC, 2012; CVBBL, 2014; HPO, 2011) have been updated for thermal performance for high-efficiency wood frame assemblies but not updated for acoustical performance. Presented STC values do not represent values for the current wall assemblies (split insulated rainscreen cavity walls); thus, they represent a gap in information and adequate specification for a geographic region of interest.

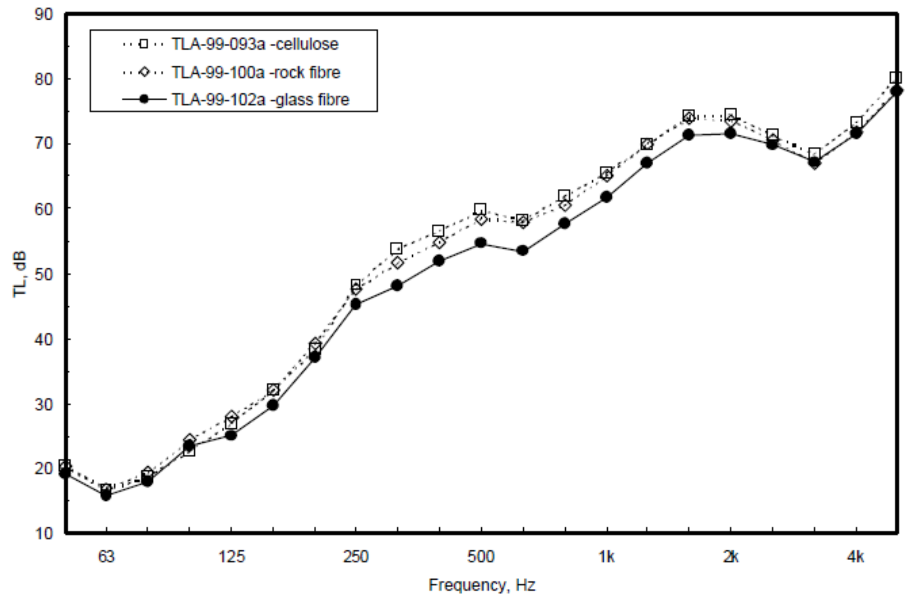
2.3 Material Parameters and Effects in Transmission Loss

2.3.1 Gypsum Board

The use of gypsum board as the interior layer of a wood frame exterior wall assembly is common practice in the construction industry. The lower cost than wood, ease of maintenance, and fire protection are some of the reasons why this standardized board is widely used. In terms of sound insulation, a gypsum board has high density and will behave according to the mass law theory (Sharp, 1973). The acoustic advantage of using gypsum instead of a wood board, which is the sheathing material on the opposite side of the cavity, is that the coincidence effect of both layers will be at different frequencies, and as such they can contribute to a less pronounced dip in this region, flattening the reduced loss (Bies & Hansen, 2005).

2.3.2 Insulation Material

The second material of consideration is the internal insulation in the cavity. Studies (Sharp, 1973; Quirt et al., 1995) show that there is a gain in sound transmission loss when the cavity is insulated. Reviewing an extensive study done by Bradley and Birta (2000), where measurements of sound transmission loss were made in several wall types, findings indicate that there are no appreciable differences between different types of insulation (cellulose – 8.0 Kg/m^2; rock fibre – 5.6 Kg/m^2; glass fibre – 1.4 Kg/m^2) as illustrated in Figure 2.4. Up to 250 Hz, the differences in transmission loss between insulations were negligible and do not significantly impact the final STC or OITC. The differences of insulation type in exterior wall cavities can be seen at frequencies above 250 Hz. Another finding is that the thicker the insulation, the higher the transmission loss. In a situation where an insulation material is compressed in a cavity such that the installed insulation thickness is less than the original insulation thickness, the sound transmission loss may be compromised. Insulation in the cavity attenuates the resonance modes that happen in the cavity due to standing waves. Insulation that allows friction between air and its boundary layer absorbs sound energy. Bradley and Birta (2000) did not refer to any property related to flow resistance of insulation materials even though for interior cavity insulations their surface densities were different, and results were negligible.

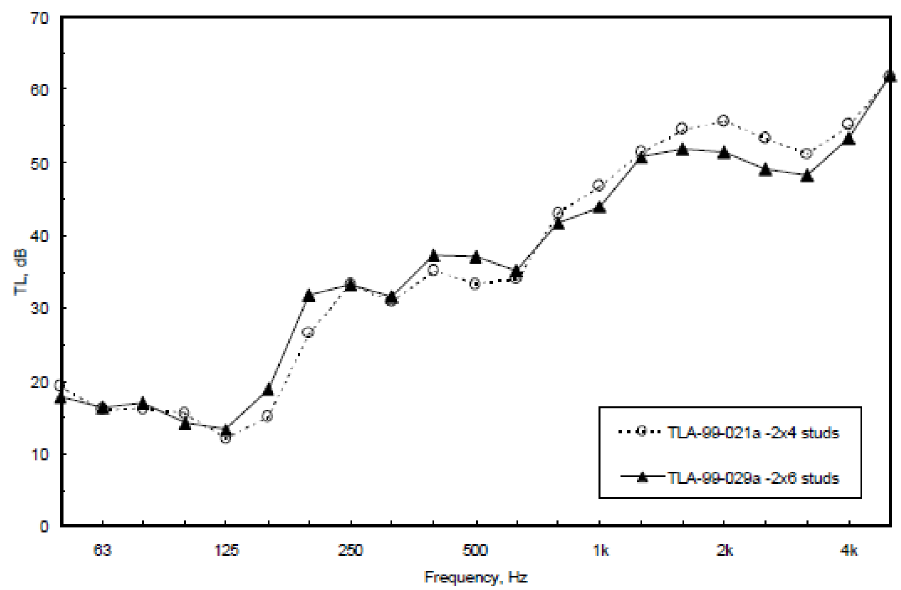


Test ID	Description	OITC
TLA-99-093a	VIN1_OSB11_WS140(406)_CFL140_RC13(610)_2G13	35
TLA-99-100a	VIN1_OSB11_WS140(406)_RFB140_RC13(610)_2G13	36
TLA-99-102a	VIN1_OSB11_WS140(406)_GFB152_RC13(610)_2G13	34

Figure 2.4. Sound transmission loss versus 1/3 octave frequency for walls constructed with 3 types of cavity insulation. (Source: Bradley & Birta, 2000)

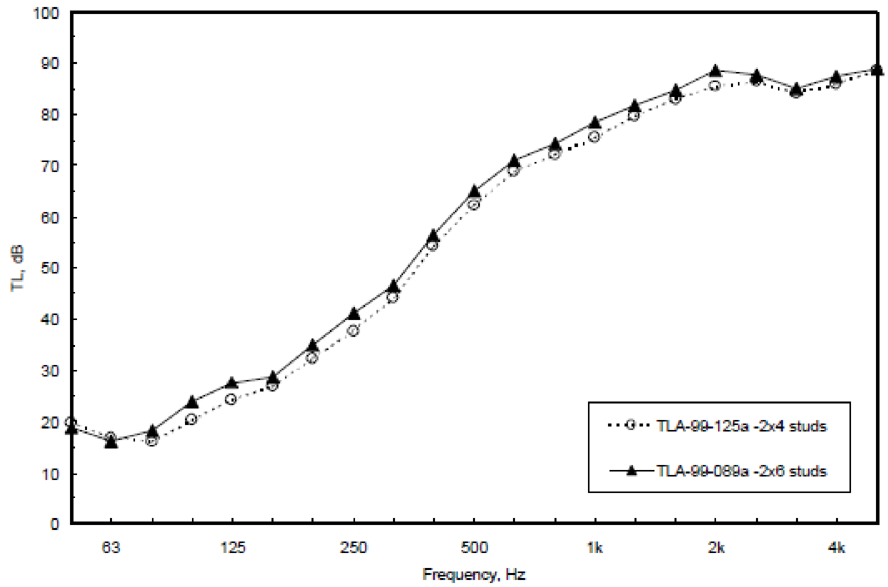
2.3.3 Wood Stud: Size and Spacing

For the stud size and spacing, Bradley and Birta (2000, 2001) showed that for walls having different stud sizes (2"x4" and 2"x6") but the same stud spacing (16" o.c.), the differences in sound transmission loss were minimal (Figure 2.5 and Figure 2.6), whereas walls having same stud size (2"x6") but different spacing (16" and 24" o.c.) presented substantial differences between results (Figure 2.8). They also did a comparison using one stud size (2"x4") but three different spacings (12", 16", and 24" o.c.), which presented better results for transmission loss when the spacing was increased (Figure 2.7). In other words, the 24" o.c. had the best result when compared to 16" and 12". Most noticeable is that the transmission loss curves shift in the low-frequency range to higher values when the spacing was increased. The lowest sound transmission loss level did not change at all, but, in fact, it moves to a lower frequency. This was due to the structural resonance and not to mass-air-mass resonance. In general, the impact of spacing on transmission loss is in the low-frequency range where it already has the lowest values of transmission loss. Studies performed by Rindel and Hoffmeyer (1991), and Quirt et al. (1995) presented similar results.



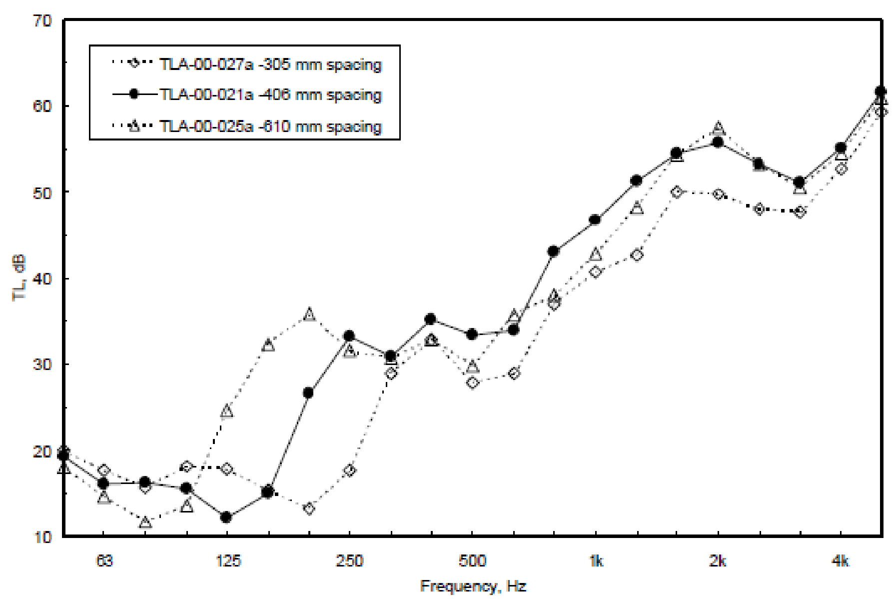
Test ID	Description	OITC
TLA-00-021a	VIN1_OSB11_WS89(406)_GFB89_G13	24
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25

Figure 2.5. Sound transmission loss versus 1/3 octave frequency for walls constructed with either 89 mm or 140 mm wood studs both spaced at 406 mm. (Source: Bradley & Birta, 2000)



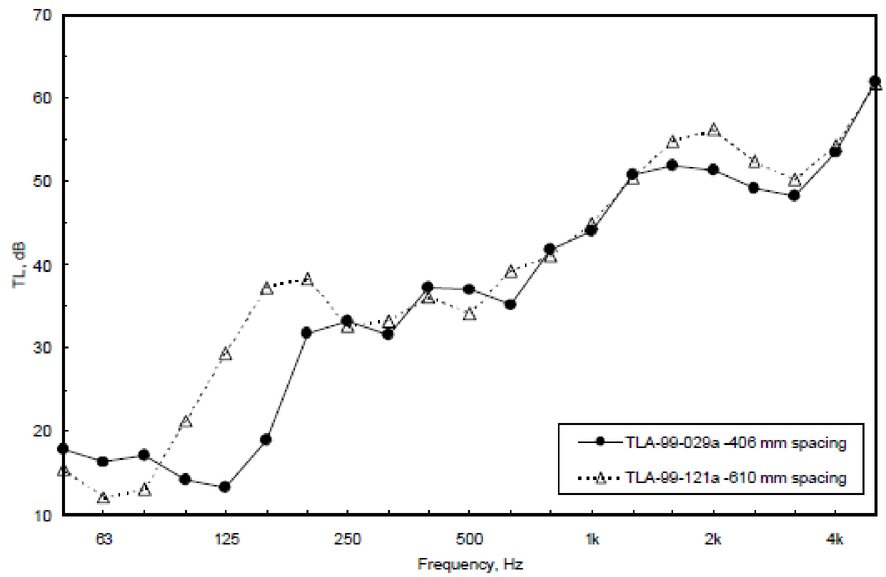
Test ID	Description	OITC
TLA-99-125a	VIN1_GFR25_OSB11_WS89(406)_GFB89_RC13(610)_2G13	48
TLA-99-089a	VIN1_GFR25_OSB11_WS140(406)_GFB152_RC13(610)_2G13	35

Figure 2.6. Sound transmission loss versus 1/3 octave frequency for walls constructed with either 89 mm or 140 mm wood studs both spaced at 406 mm and two gypsum boards mounted on resilient channels. (Source: Bradley & Birta, 2000)



Test ID	Description	OITC
TLA-00-027a	VIN1_OSB11_WS89(305)_GFB89_G13	23
TLA-00-021a	VIN1_OSB11_WS89(406)_GFB89_G13	24
TLA-00-025a	VIN1_OSB11_WS89(610)_GFB89_G13	27

Figure 2.7. Sound transmission loss versus 1/3 octave frequency for walls constructed with 89 mm wood studs spaced at 305, 406, and 610 mm. (Source: Bradley & Birta, 2000)

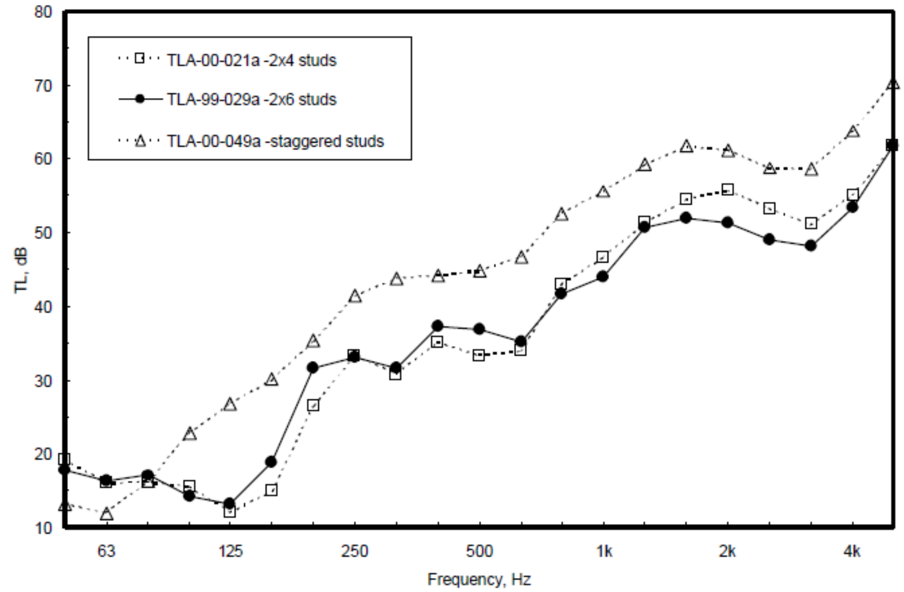


Test ID	Description	OITC
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-99-121a	VIN1_OSB11_WS140(610)_GFB152_G13	31

Figure 2.8. Sound transmission loss versus 1/3 octave frequency for walls constructed with 140 mm wood studs spaced at 406 and 610 mm. (Source: Bradley & Birta, 2000)

2.3.4 Staggered Studs

When staggered studs in the test specimen were evaluated by Bradley and Birta (2000) there was an increase in sound transmission loss, improving performance when compared to the same wall without staggered studs. Staggering the studs provides a similar effect as increased stud spacing with a similar explanation. Additionally, the measured effect of staggering the studs corroborates predictions based on panel resonances theory. Illustrated in Figure 2.9 is a reduction in the resonance frequency, from 125 to 63 Hz.

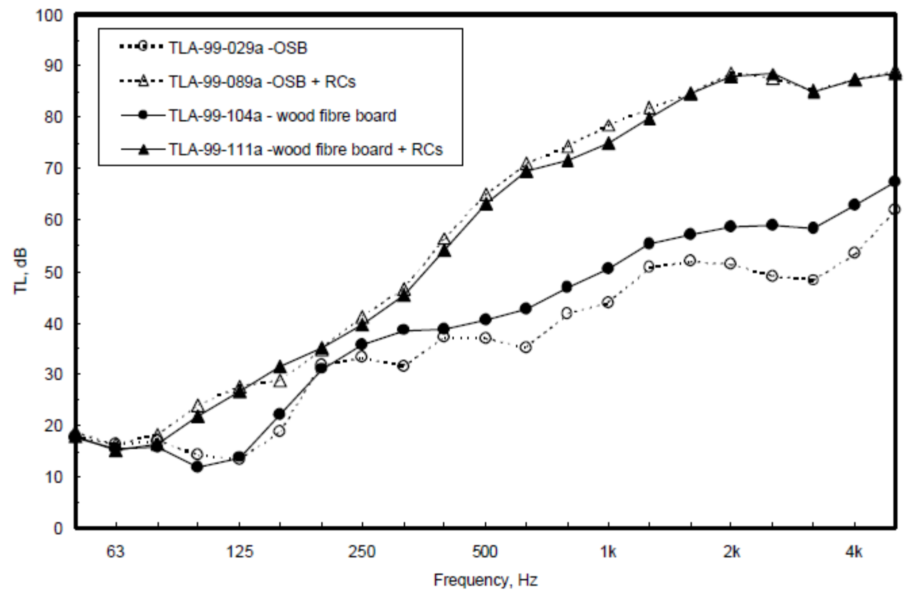


Test ID	Description	OITC
TLA-00-021a	VIN1_OSB11_WS89(406)_GFB89_G13	24
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-00-049a	VIN1_OSB11_SWS140(406)_2GFB65_G13	33

Figure 2.9. Sound transmission loss values versus 1/3 octave frequency for walls constructed with a 406 mm stud spacing. (Source: Bradley & Birta, 2000)

2.3.5 Sheathing

Sheathing is part of the structural system of a wood frame wall and needs to withstand lateral and shear forces. The study performed by Bradley and Birta (2000) was completed with two different types of sheathing materials: Oriented Strand Board (OSB) and wood fiber board with densities of 6.9 Kg/m^2 and 3.5 Kg/m^2, and thicknesses of 11 mm and 13 mm, respectively. Their result showed that there was no significant difference between these two types of wood boards as illustrated in Figure 2.10. The graph also presents negligible differences in transmission loss for two walls with OSB and wood fiber board both having resilient channels and two gypsum boards.

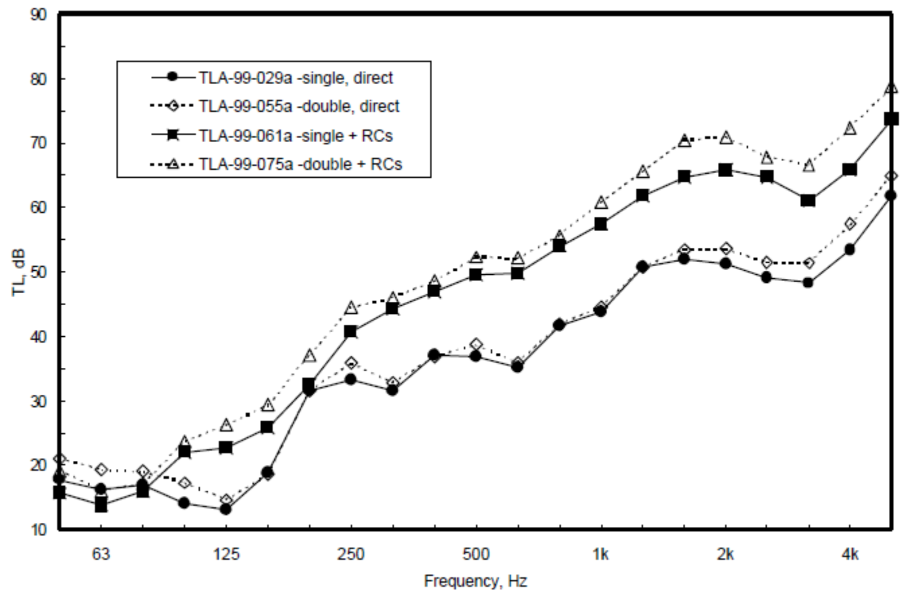


Test ID	Description	OITC
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-99-089a	VIN1_GFR25_OSB11_WS140(406)_GFB152_RC13(610)_2G13	35
TLA-99-104a	VIN1_WFB13_WS140(406)_GFB152_G13	25
TLA-99-111a	VIN1_GFR25_WFB13_WS140(406)_GFB152_RC13(610)_2G13	33

Figure 2.10. Sound transmission loss versus 1/3 octave frequency for walls with wood fibre board or OSB sheathing. The lower two curves are for varied exterior sheathing on the base wall construction. (Source: Bradley & Birta, 2000)

2.3.6 Resilient Channel

Bradley and Birta (2000) further tested walls having resilient channels supporting the gypsum board and confirmed the results from past research (Halliwell et al., 1998; Sabine & Lacher, 1975; Quirt et al., 1995). Figure 2.11 illustrates that resilient channels provide a substantial improvement in the sound transmission loss of a double-leaf wall due to a structural disconnection between the studs and the gypsum board. The resilient channels act as a sound break to the path for vibrations through the stud.



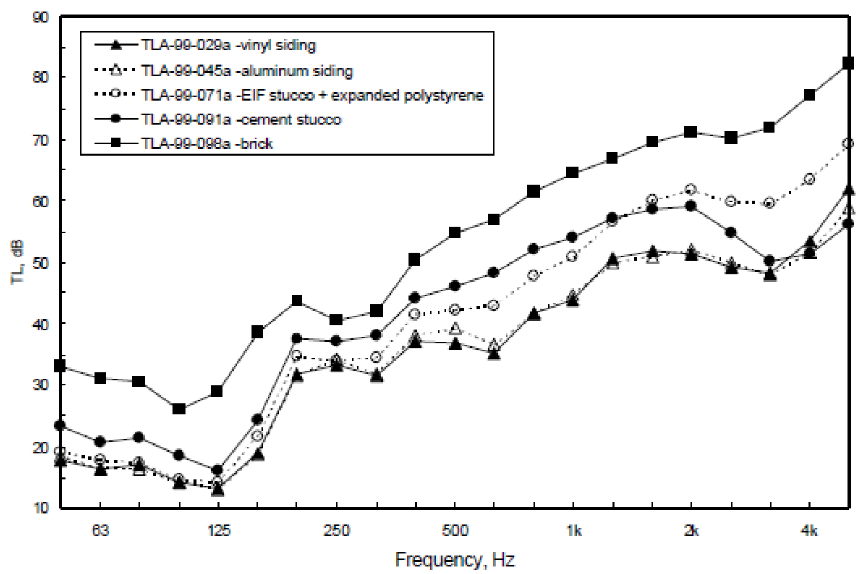
Test ID	Description	OITC
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-99-055a	VIN1_OSB11_WS140(406)_GFB152_2G13	27
TLA-99-061a	VIN1_OSB11_WS140(406)_GFB152_RC13(610)_G13	32
TLA-99-075a	VIN1_OSB11_WS140(406)_GFB152_RC13(610)_2G13	34

Figure 2.11. Sound transmission loss versus 1/3 octave frequency for walls constructed with resilient channels. Combinations of one or two layers of gypsum board with and without resilient channels. (Source: Bradley & Birta, 2000)

2.3.7 Cladding and Cladding Attachment

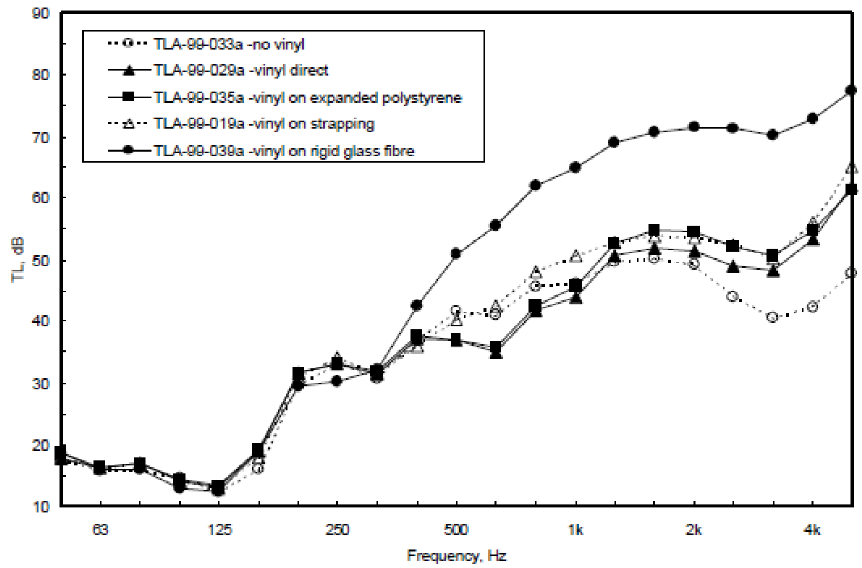
Bradley and Birta (2000) performed a series of tests on their base wall with five different types of cladding materials. They stated that because of differences in surface mass density, the obtained results can be explained by the mass law relation. As illustrated in Figure 2.12 the heavier cladding materials presented higher values for transmission loss than the lighter cladding across all frequencies.

In the same series of tests, the researchers attached vinyl cladding by three different types of cladding attachments (wood strapping, EPS, and rigid glass fibre insulation). Vinyl was selected as the cladding type because it had the lowest transmission loss values for all types of cladding. They found out that for all tests comparing attachments, the transmission loss for vinyl fixed directly on the sheathing without attachment was the lowest result (Figure 2.13) at mid and high frequencies. This result suggests that cladding separated from the sheathing, having an air cavity in between them, tends to improve the transmission loss of a wall assembly. The results also showed that the attachment material has a significant impact on the mid and high frequencies on transmission loss.



Test ID	Description	OITC
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-99-045a	ALM0.6_OSB11_WS140(406)_GFB152_G13	25
TLA-99-071a	G13_WS140(406)_GFB152_OSB11_BPAP0.7_EPS25_EIF6	27
TLA-99-091a	G13_WS140(406)_GFB152_OSB11_BPAP0.7_STUC9.5	29
TLA-99-098a	G13_WS140(406)_GFB152_OSB11_AIR16_BRI89	40

Figure 2.12. Sound transmission loss versus 1/3 octave frequency for varied exterior cladding. (Source: Bradley & Birta, 2000)

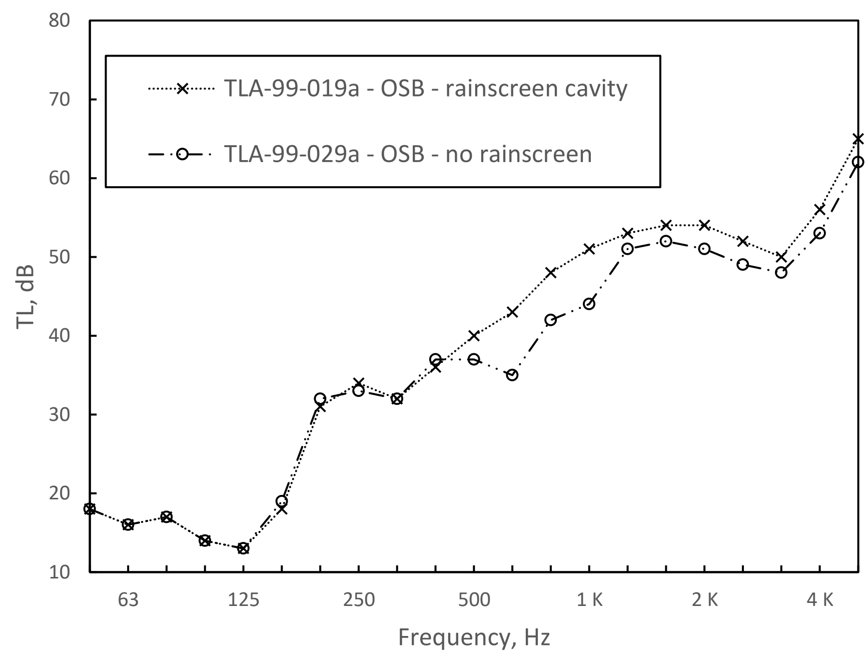


Test ID	Description	OITC
TLA-99-033a	OSB11_WS140(406)_GFB152_G13	25
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-99-035a	VIN1_EPS25_OSB11_WS140(406)_GFB152_G13	26
TLA-99-019a	VIN1_WFUR19(406)_OSB11_WS140(406)_GFB152_G13	25
TLA-99-039a	VIN1_GFR25_OSB11_WS140(406)_GFB152_G13	25

Figure 2.13. Sound transmission loss versus 1/3 octave frequency for varied method of attaching vinyl siding. (Source: Bradley & Birta, 2000)

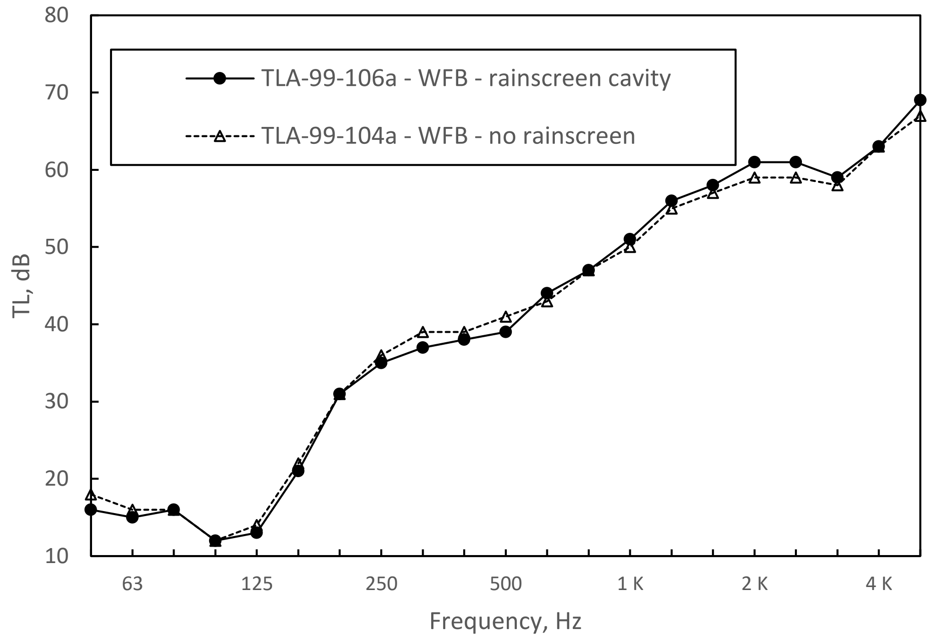
2.3.8 Rainscreen Cavity and Exterior Insulation

Bradley and Birta (2000) compared two sets of walls that were identical except for a rainscreen cavity feature. Findings indicate that between the first set of walls built with OSB sheathing, the rainscreen cavity wall presented a higher sound transmission loss result (Figure 2.14), illustrating that an expected improvement of a second air cavity increases transmission loss. Wood strapping (19 mm – 3/4") was used to attach the cladding, and although this assembly detail provided sound bridging, the overall results were positive. The second set of walls were built with wood fiber board (WFB) sheathing. Figure 2.15 illustrates that the transmission loss differences were smaller for WFB than walls built with OSB. Even being smaller, the measured differences suggested that the insertion of a second cavity had an impact on TL. Moreover, in this WFB case, there was a trend inversion. From 250 to 500 Hz, the rainscreen cavity had lower performance, whereas above 630 Hz the rainscreen cavity wall had higher transmission loss.



Test ID	Description	OITC
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25
TLA-99-019a	VIN1_WFUR19(406)_OSB11_WS140(406)_GFB152_G13	25

Figure 2.14. Sound transmission loss versus 1/3 octave frequency for walls constructed with and without rainscreen cavity and OSB sheathing. (Source: Bradley & Birta, 2000)

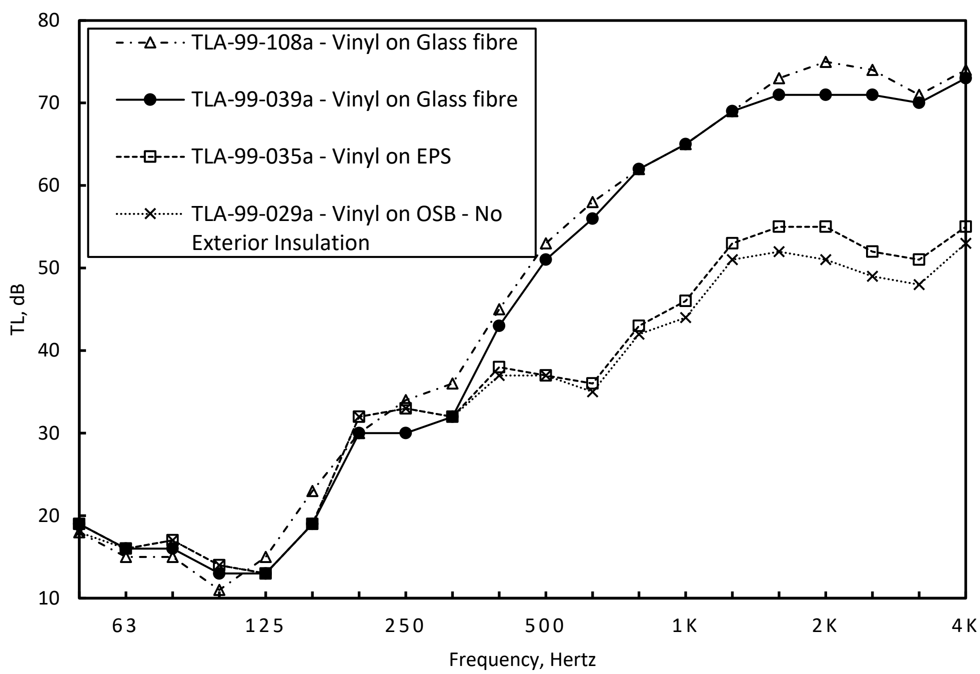


Test ID	Description	OITC
TLA-99-106a	VIN1_WFUR19(406)_WFB13_WS140(406)_GFB152_G13	25
TLA-99-104a	VIN1_WFB13_WS140(406)_GFB152_G13	25

Figure 2.15. Sound transmission loss versus 1/3 octave frequency for walls constructed with and without rainscreen cavity and wood fiber board sheathing. (Source: Bradley & Birta, 2000)

This study included tests in which the external insulation was evaluated. Vinyl cladding was directly installed over sheathing (without insulation), on rigid glass fibre board, and on EPS using the same reference wall (Figure 2.16). As observed in Figure 2.16, the exterior glass fibre insulation considerably increased the transmission loss from 400 Hz, whereas when the wall had vinyl on EPS insulation, the gain was negligible. The effect of external insulation may improve transmission loss to the overall result as illustrated. The possible explanation for the differences in transmission loss between the glass fibre and EPS may be because EPS has a closed cell structure while glass fibre is a porous material. This is an important factor for an insulation material to contribute to sound absorption

(Cox & D'Antonio, 2016). Materials' densities were presented; however, no references to flow resistivity for exterior insulation that could be correlated to sound absorption results were presented in the study by Bradley and Birta (2000).



Test ID	Description	OITC
TLA-99-108a	VIN1_GFR25_WFB13_WS140(406)_GFB152_G13	25
TLA-99-039a	VIN1_GFR25_OSB11_WS140(406)_GFB152_G13	25
TLA-99-035a	VIN1_EPS25_OSB11_WS140(406)_GFB152_G13	26
TLA-99-029a	VIN1_OSB11_WS140(406)_GFB152_G13	25

Figure 2.16. Sound transmission loss versus 1/3 octave frequency for similar walls constructed with vinyl on OSB without exterior insulation, exterior EPS insulation on OSB, exterior rigid glass fibre insulation on wood fibre board, and exterior rigid glass fibre insulation on OSB. (Source: Bradley & Birta, 2000)

2.4 Possible Limits of Previous Tests

All tests performed by Bradley and Birta (2000) were completed with edge-sealed wall assemblies' samples, which did not represent actual rainscreen cavity walls. The rainscreen walls under test were not provided with a horizontal gap at the bottom to facilitate drainage to the bottom. The horizontal gaps in the cladding are needed so the water can drain, and air can freely circulate. It is not well known if the absence of the horizontal air gaps limits the previously discussed findings to wall types which are not based on the complete rainscreen principle.

A recent project (Tamanna, 2017) investigated the effect of both rainscreen cavity and the required horizontal gaps on the sound transmission loss of single insulation walls. Results indicated that some differences in sound transmission loss might be expected from walls having a horizontal gap promoting drainage and air movement. The differences in sound transmission can be around 5 dB less at 500 Hz and 5 dB greater at 2 KHz, and around 3 dB for sound transmission averaged across the range of frequencies.

The fundamentals of sound transmission loss and empirical measurements of light-frame wood walls have been discussed. Knowing each of the variables that impacts the overall wall behaviour can lead to a better and adequate wall design. The promoted impacts by some of the presented variables, such as mechanical coupling, acoustical coupling, sound insulation material, and material properties can be used to hypothesize the performance of walls designed according to current guidelines as previously illustrated in Figure 1.2 of the introduction. However, care must be taken when dealing with novel assemblies, and assigning transmission loss values to a wall demands proper validation and experimental tests.

This study is intended to elucidate some of the practical implications in regard to sound transmission loss of exterior building wall features. These are the influence of a rainscreen cavity in a wall assembly, the impact of an exterior wall cavity and its depth variation, and the effect of cladding attachments.

3 PROBLEM STATEMENT AND HYPOTHESIS

This study examines the sound transmission loss of walls currently recommended in British Columbia by building guides, codes, and envelope engineers. There is a need for empirical data on acoustical properties of the recommended wall assemblies. An evaluation of wall type variations is executed in order to understand the acoustical contribution of the wall materials and components.

This research will investigate transmission loss when exterior split insulation (a third-panel layer) and an air cavity are introduced in a wall according to rainscreen principles. Horizontal gaps are required in the cladding for the air cavity to function. The horizontal air gaps are included in the test samples. The impact on a wall when the exterior cladding is rigidly and non-rigidly connected to the sheathing and opened and closed cell absorptive insulation will be investigated.

3.1 Hypothesis

Based on the theory of sound transmission loss as presented in the literature review and the review of previous evaluations of wall assemblies, it is expected that the type of cladding attachment will have an appreciable effect on the sound transmission loss of cavity walls; it is also anticipated that there will be an increase in sound transmission loss when mineral wool insulation is used as an exterior insulation in the cavity compared to XPS insulation. It is expected that for split insulated walls designed according to the rainscreen principle that thicker exterior insulation, larger rainscreen cavity width, and denser cladding types will increase transmission loss. Finally, the last hypothesis is related to a variable termed sheathing-to-cladding distance. In this case, there will be discernible differences between the greatest distance and the shortest distance.

4 RESEARCH METHODOLOGY

The first challenges of the methodology were to select a limited set of walls systems to be tested and to develop a standard test procedure to follow. The available measurement equipment and lab facility guided the selection of standardized test methods.

The guidelines and codes are prescriptive in that they allow for a wide variance of materials selection and assemblies within a performance matrix. The possible combinations of material layers for wall assemblies created an unfeasible number to evaluate. Due to practical limits of schedule and resources the study scope was limited.

4.1 Test Wall for Evaluation

A steering committee comprised of wide representation from the building science community (see Appendix A) convened in June 2016 to review a proposal of wall assemblies to be investigated. The assemblies included a base wall, reference wall configurations, and the parameters for the assemblies to be evaluated. The variables discussed included rainscreen cavity width, exterior insulation type, exterior insulation thickness, cladding attachment, and cladding type. The following approach was accepted.

4.1.1 Selection

The selection of one base wall, comprised of 13 mm (1/2") gypsum board, 38 x 140 mm (2" x 6") wood studs at 406 mm (16") on center (o.c.), 152 mm (6") glass fibre batt, and 13 mm (1/2") plywood sheathing (illustrated in Figure 4.1 and Figure 4.2) limited the initial total possible permutations for a base wall. A base wall type provided a standard wall section for the assemblies tested. This fixed standard wall section was then complemented by additional layers outboard of wood sheathing.

To approximate a realistic and complete wall assembly, the base wall also had a polyethylene film as a vapour/air barrier between the gypsum board and the interior wood studs, and a spun-bonded polyolefin as a water-resistive barrier outboard of the plywood sheathing (not represented in Figure 4.1 and Figure 4.2).

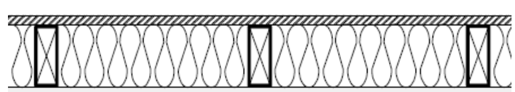


Figure 4.1. Base wall horizontal cross-section.

There was no sound transmission loss measurement for the base wall.

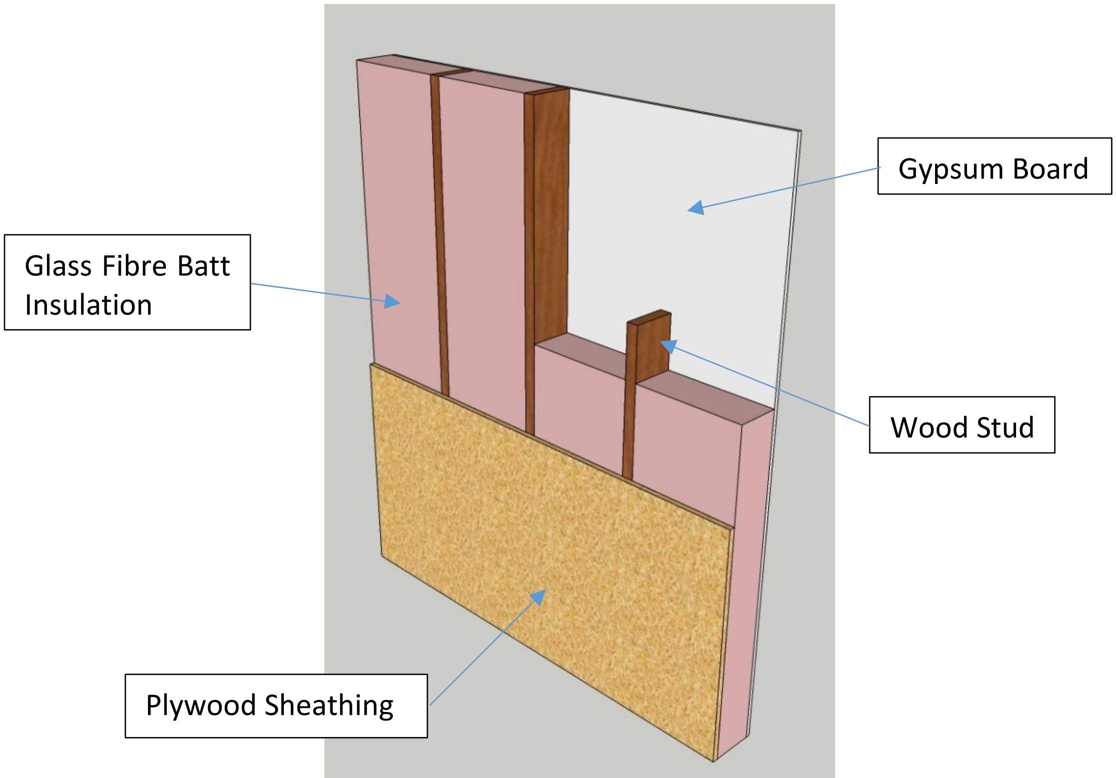


Figure 4.2. Base wall perspective and its components.

Two additional walls were tested as reference walls. The cladding materials were either vinyl or fiber cement board. Both claddings were directly connected to the base wall plywood sheathing without using any cladding attachment. There was neither exterior insulation nor a rainscreen cavity. In these terms, these walls were similar to the wall described in Figure 1.1 in the introduction. Table 1 below presents the reference walls configurations.

Table 1. Reference walls.

Cladding Attachment	Exterior Insulation	Ext. Insulation Thickness	Cavity Width	Cladding
None	None	---	---	Vinyl
				Fiber Cement Board

The nomenclature used in the Building Enclosure Design Guide (HPO, 2011), published by the Homeowner Protection Office, derived from the presence or not of thermal bridges between cladding and sheathing separates walls into two categories: Bridged and un-bridged. Sound bridging is a similar effect in acoustical transmission, and hence the same classifications will be used. The term bridged means that the cladding is attached to continuous structural connections to the plywood sheathing; therefore, the exterior insulation is not continuous. The continuous and solid connection through the exterior attachment system was termed by Sharp (1973, 1978) as a line-line connection. There were two types of cladding attachments for the bridged category. They are type S1, which is wood strapping, and type S2 attachment, which is metal Z-girts and steel furring hat-track. S2 type is illustrated in Figure 4.3. The term un-bridged means that the cladding attachment to the plywood sheathing minimally interrupts the exterior insulation, similarly to thermal bridging. There were two types of attachments for the un-bridged category. They are classified as type S1, which uses a wood strapping over the exterior insulation, and type S3, which is a metal clip and steel furring s-track attachment or a line-point solution (Sharp, 1973, 1978). S1 and S3 attachment types are illustrated in Figure 4.4 and Figure 4.5, respectively. The S1 is used in both categories. What differentiates them is the usage or not of exterior insulation between cladding and sheathing (see Table 2 and Table 3). The selected 3/8" cavity width is code minimum and the 1" cavity width was selected as a reasonable maximum width predicted in industry.

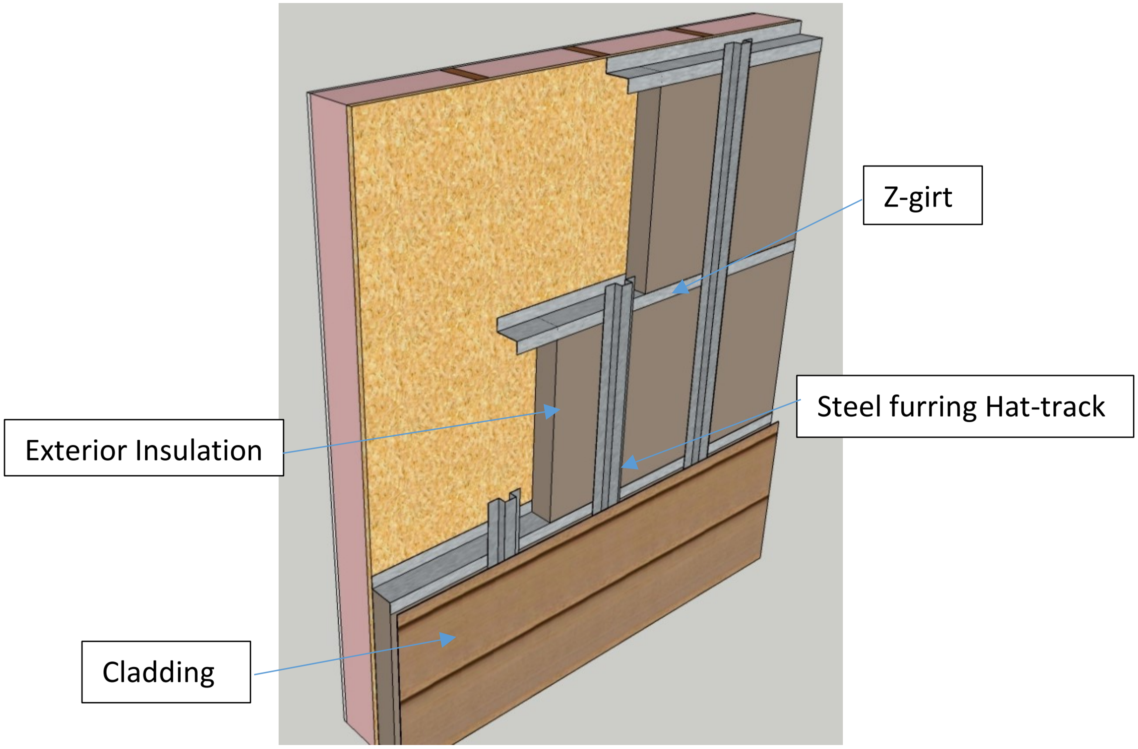


Figure 4.3. S2 Attachment – Z-girt and steel furring hat track

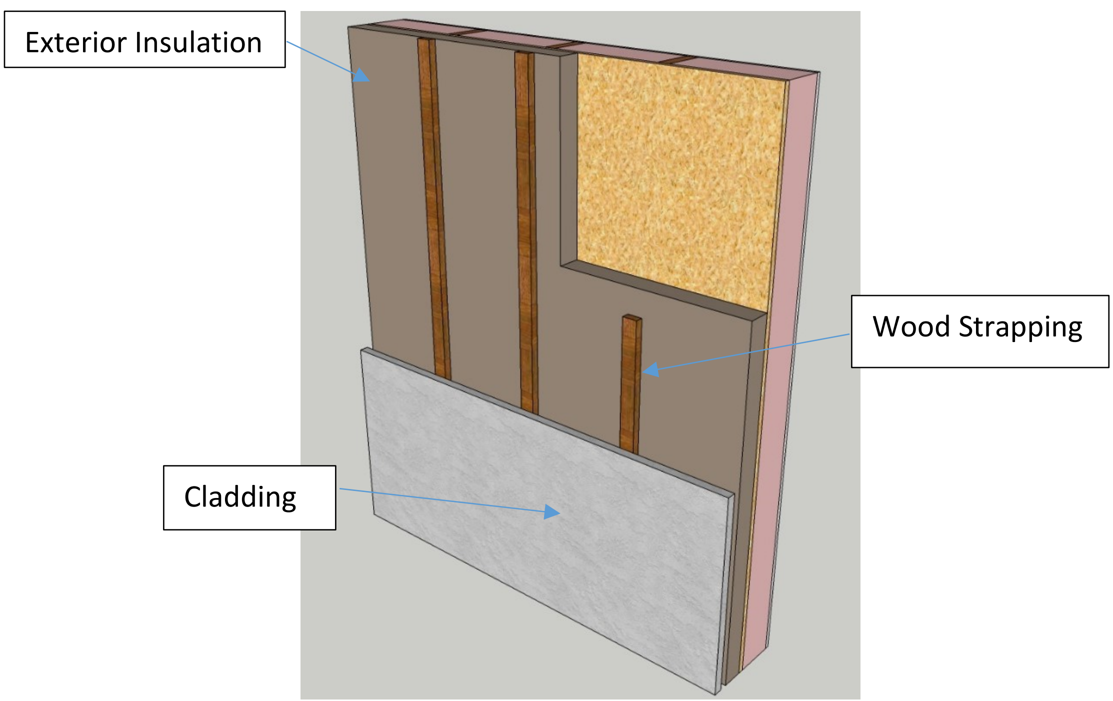


Figure 4.4. S1 Attachment – Wood strapping over insulation.

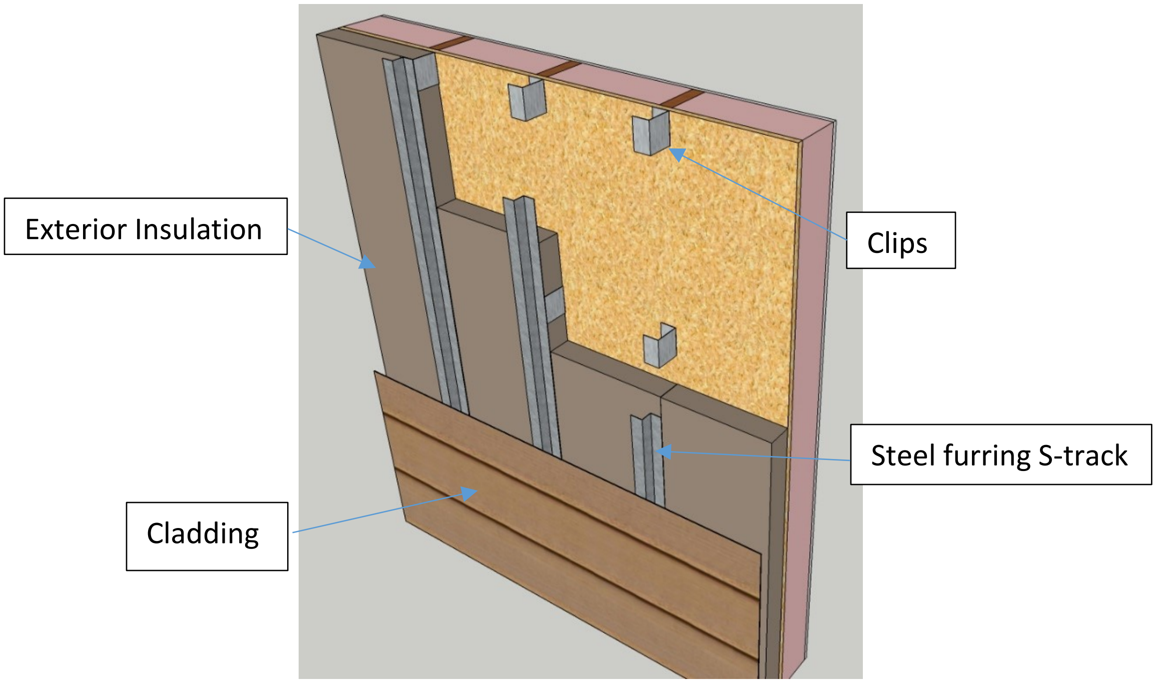


Figure 4.5. S3 Attachment – Metal clips and steel furring S-track.

The bridged wall type had either type S1 (wood strapping) or type S2 (Z-girt) attachment types for cladding attachment. The bridged wall type with wood strapping did not have exterior insulation, yet it had its rainscreen cavity width and cladding material varied. The rainscreen cavity width was either 9 mm (3/8") or 25 mm (1") and the cladding material either vinyl or fiber cement board.

The bridged wall with type S2 cladding attachment had exterior insulation material, exterior insulation thickness, rainscreen cavity width, and cladding material varied. The exterior insulation type included either mineral wool or extruded polystyrene (XPS), exterior insulation thickness of either 38 mm (1 ½") or 76 mm (3"), rainscreen cavity width of either 9 mm (3/8") or 25 mm (1"), and cladding material of either vinyl or fiber cement board. The rainscreen cavity width was determined by a steel furring hat-track height (Figure 4.7). Table 2 illustrates the bridged wall types configuration.

Table 2. Bridged wall types.

<table>
<tr><th>Cladding Attachment</th><th>Exterior Insulation</th><th>Ext. Insulation Thickness</th><th>Rainscreen Cavity Width</th><th>Cladding</th></tr>
<tr><td rowspan="3">S1 (Wood Strapping)</td><td rowspan="3">None</td><td rowspan="3">---</td><td rowspan="2">3/8"</td><td>Vinyl</td></tr>
<tr><td>Fiber Cement Board</td></tr>
<tr><td>1"</td><td>Repeat above</td></tr>
<tr><td rowspan="5">S2 Type</td><td rowspan="4">Mineral Wool</td><td rowspan="3">1 ½"</td><td rowspan="2">3/8"</td><td>Vinyl</td></tr>
<tr><td>Fiber Cement Board</td></tr>
<tr><td>1"</td><td>Repeat above</td></tr>
<tr><td>3"</td><td colspan="2">Repeat above</td></tr>
<tr><td>XPS</td><td colspan="3">Repeat above</td></tr>
</table>

For the un-bridged category, the characteristics that were varied were exterior insulation material, exterior insulation thickness, cladding attachment, rainscreen cavity width, and cladding material. The external insulation type included rigid extruded polystyrene (XPS) and semi-rigid mineral wool boards; the thickness of external insulation was either 38 mm (1 ½") or 76 mm (3"); the attachments were either wood strapping over insulation (S1 type), or clips (metal) connection (S3 type); the rainscreen cavity width was either 9 mm (3/8") or 25 mm (1"); and the cladding was either vinyl, or fiber cement board, or stucco. The rainscreen cavity width was determined by wood strapping thickness when type S1 attachment was used and by steel furring S-track height when type S3 attachment was used (Figure 4.6). Below, Table 3 represents permutations for un-bridged wall types. Only three stucco walls were built due to the constraints of waiting times for the layers to dry. The assembly of the three stucco cladding walls was determined after obtaining measurements results of all other walls.

The stucco walls had wood strapping (S1) as cladding attachment and one rainscreen cavity width of 9 mm (3/8"). The exterior insulation was mineral wool of either 38 mm (1 ½") or 76 mm (3") thick, and XPS of 38 mm (1 ½") thick. The total stucco thickness was 22 mm (7/8"). A first 9 mm (3/8") scratch coat followed by a 9 mm (3/8") brown coat and a 3 mm (1/8") acrylic finishing coat were the stucco layers.

Table 3. Un-bridged wall types.

<table>
<tr><th>Exterior Insulation</th><th>Ext. Insulation Thickness</th><th>Cladding Attachment</th><th>Rainscreen Cavity Width</th><th>Cladding</th></tr>
<tr><td rowspan="5">Mineral Wool</td><td rowspan="4">1 ½"</td><td rowspan="3">S1 Type</td><td rowspan="2">3/8"</td><td>Vinyl</td></tr>
<tr><td>Fiber Cement Board</td></tr>
<tr><td>1"</td><td>Repeat above</td></tr>
<tr><td>S3 Type</td><td colspan="2">Repeat above</td></tr>
<tr><td>3"</td><td colspan="3">Repeat above</td></tr>
<tr><td>XPS</td><td colspan="4">Repeat above</td></tr>
<tr><td rowspan="2">Mineral Wool</td><td>1 ½"</td><td rowspan="3">S1 Type</td><td rowspan="3">3/8"</td><td rowspan="3">Stucco</td></tr>
<tr><td>3"</td></tr>
<tr><td>XPS</td><td>1 ½"</td></tr>
</table>

The attachments S2 - Z-girt and S3 - Clip were fabricated at BCIT and the figures below present the possible used combinations for them. Each attachment system S2 and S3 was composed of two parts. Either a 38 mm (1 ½") or a 76 mm (3") metal profile determined the insulation thickness, and this profile was either a Z-girt (S2) or a Clip (S3). These two profiles were then screwed to either a 9 mm (3/8") or a 25 mm (1") metal profile which determined the rainscreen cavity width, and this profile was either hat-track or s-track. The hat-track was always used in conjunction with the Z-girt (S2) profile while the s-track was always used in conjunction with the Clip (S3) profile. The material was an 18-gauge carbon steel sheet. The mentioned metal profiles yielded four possible sheathing-to-cladding distance combinations. Figure 4.6 (a), (b), (c), and (d) show the combinations for S3 - Clip attachment. Figure 4.7 (a), (b), (c), and (d) show the combinations for S2 - Z-girt attachment. Observe that the Z-girt runs transverse to the hat-track rainscreen cavity profile.

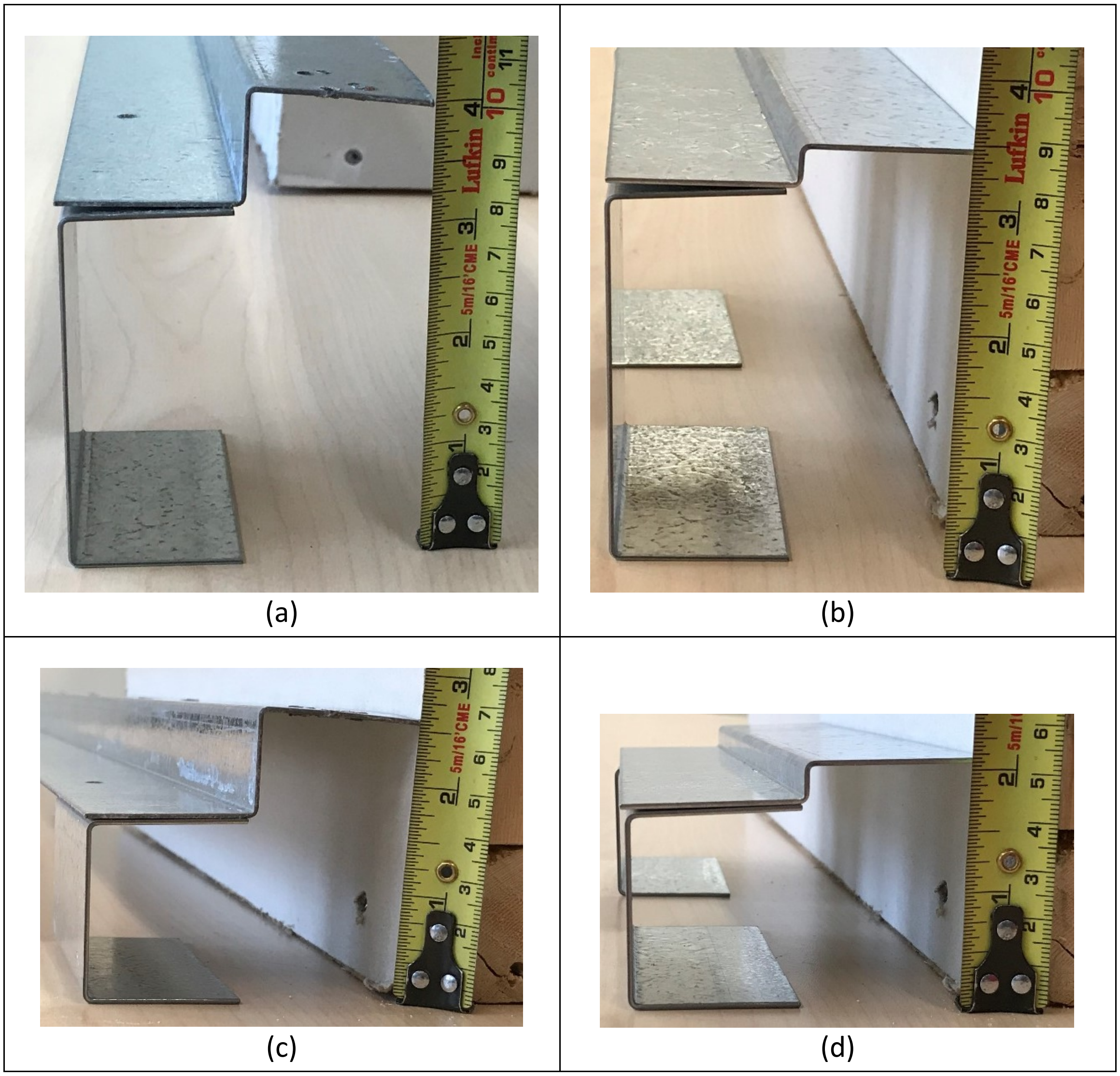


Figure 4.6. S3 - Clip and S-track profiles, and the possible distance combinations. (a) 1"+ 3"; (b) 3/8"+ 3"; (c) 1 ½"+ 1"; and (d) 1 ½"+ 3/8".

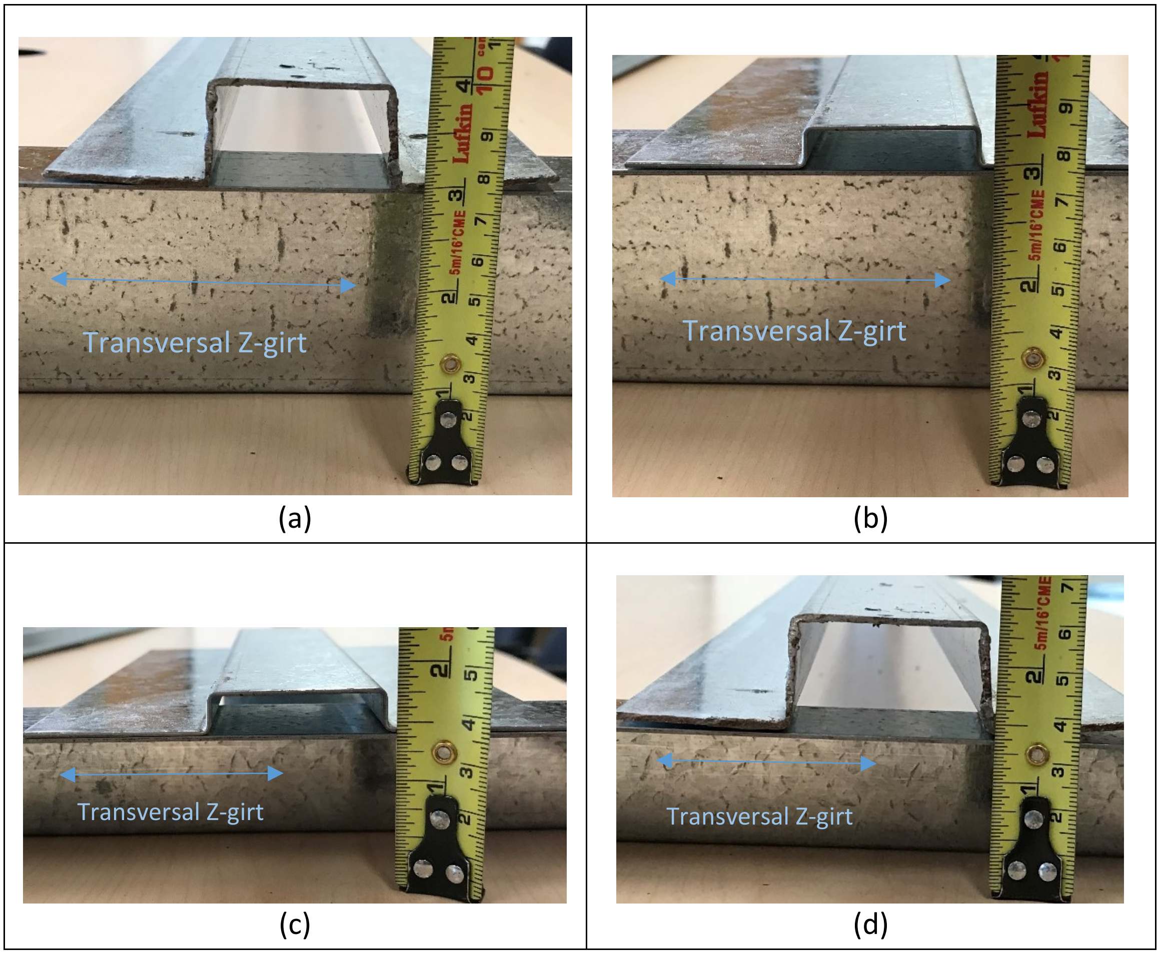


Figure 4.7. S2 - Z-girt and Hat-track profiles, and the possible distance combinations. (a) 1"+ 3"; (b) 3/8"+ 3"; (c) 1 ½"+ 1"; and (d) 1 ½"+ 3/8".

Since the intent of the tests was to verify the influence of the attachment type, in all cases the spacing dimension between cladding attachments, rainscreen profiles, and connector screws was 400 mm (16"). The horizontal distance between wood strappings and their vertical screws were 400 mm (16"). Hence, wood strapping was aligned with interior wood studs and no intermediate strapping was built as seen in real building applications (although for other reasons). The vertical distance between Z-girts was 400 mm (16"), the horizontal distance between steel furring hat-tracks and their respective screws were 400 mm (16"). Finally, the horizontal and vertical distances between clips were 400 mm (16"), the horizontal distance between steel furring S-tracks and their respective screws were 400 mm (16"). Appendix D presents pictures of some of the tested wall assemblies and their layer configurations.

To provide an adequate and logical sequence of changes to the wall specimen, some wall layers were kept fixed while others were varied until all proposed combinations reached the total permutation number. Obviously, due to practical purposes, the outer layers required a higher number of changes.

For the bridged category, beginning from the outermost layer, the variations were cladding, followed by cavity width, insulation thickness, and exterior insulation type. This sequence is detailed in Table 2. For the un-bridged category, beginning from the outermost layer, the variations were cladding, followed by cavity width, attachment, exterior insulation thickness, and exterior insulation type. This sequence is detailed in Table 3.

The physical properties of the tested building materials are presented in Table 4.

Table 4. Physical properties of the tested building materials.

Material	Mass Surface Density (Kg/m^2)	Bulk Density (Kg/m^3)	Thickness (mm)
Gypsum Board	6.5	512	12.7
Plywood	6.9	543	12.7
Vinyl	1.5	1364	1.1
Fiber Cement Board	11.5	1533	7.5
Stucco	41	1847	22.2
Fiberglass Batt	1.4	9	152.0
XPS	1.1	29	38.1
Mineral Wool	4.7	123	38.1

4.2 Evaluation of Wall Assemblies

The measurement method was derived from ASTM and ISO standards. The standards are ASTM E966 - Field Measurement of Airborne Sound Insulation of Building Façade Elements (ASTM, 2010), and ISO 15186 - Measurement of Sound Insulation in Buildings and of Building Elements Using Sound Intensity - Part 1: Laboratory Measurements (ISO, 2000). A hybrid measurement method was developed based on the available lab infrastructure.

4.2.1 Sound Intensity Field Measurements

At BCIT, in an exterior wall opening of 2.44 x 2.13 m (8' x 7'), a sub-frame was built to support the base wall specimen and the subsequent additional layers. The final wall specimen size was 2.08 x 1.83 m (6' 10" x 6'), which gives an area of 3.80 m^2 (40.97 ft^2).

To reduce flanking, the subframe was isolated from the opening with resilient materials. The evaluated specimens were also isolated with resilient material. To eliminate sound leaks, acoustic sealant and gaskets were incorporated. See Appendix E for detailed illustration of installation.

In the interior part of the lab, a partial enclosure was built to reduce reflections and noise from other sources than the testing source itself. Figure 4.8 presents a schematic layout plan view that shows the wall specimen, partition, and the exit door.

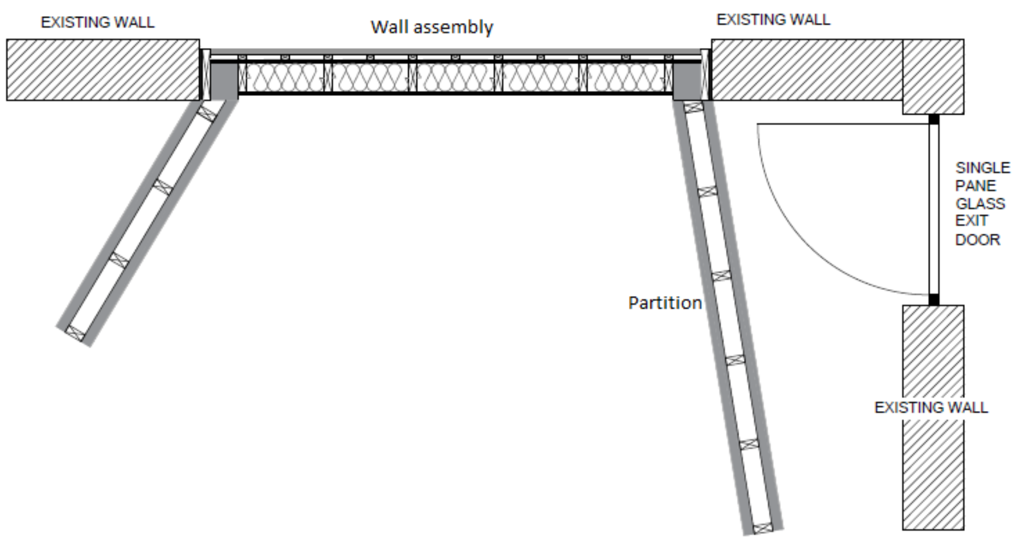


Figure 4.8. Plan view of the lab layout. (Credit: Omid T.)

Figure 4.9 shows the partition with the fiberglass batt insulation and the wall specimen with the painted and sealed gypsum board.

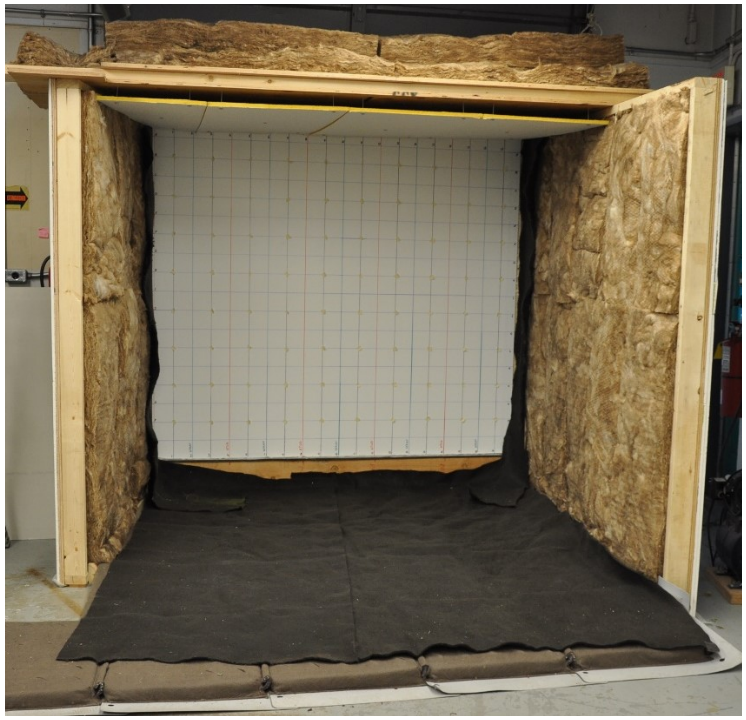


Figure 4.9. Interior picture of the test wall specimen and the partition semi-closure faces.

Since the study was intended to observe the more realistic behaviour of rainscreen cavity walls, all wall permutations had a horizontal opening at the bottom between the cladding and inferior external edge frame of approximately 10 mm (3/8"). This condition was selected to represent a vented condition in a rainscreen wall system, where rain that crosses cladding drains to the bottom of the wall and exits (Figure 4.10).

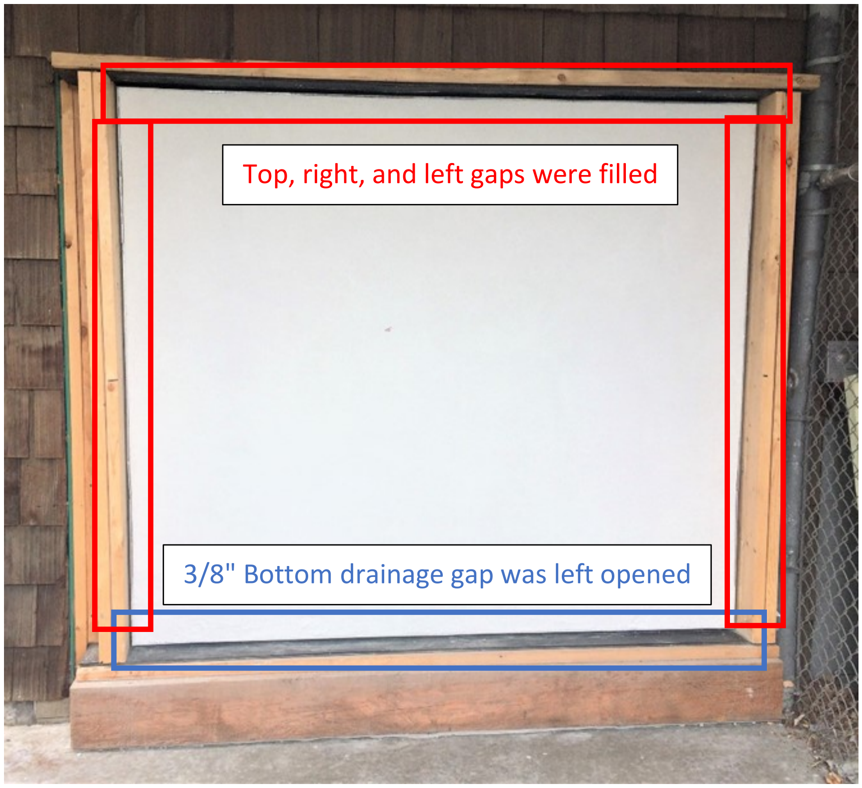


Figure 4.10. Wall assembly and its edges.

4.2.2 Measurement Methods

The measurement technique for scanning the wall was a hybrid of ISO 15186 and ASTM E966. The standards complemented each other; the ASTM provided guidance with speaker position and procedures on how to generate and measure the exterior sound pressure levels while the ISO provided procedures to measure interior sound intensity levels. There are two parts of the ISO 15186 standard that specify test conditions depending on whether the measurements are made in a laboratory (Part 1: Laboratory Conditions) (ISO, 2000) or under field conditions (Part 2: Field Measurements) (ISO, 2003). Both parts refer to the ISO 10140 (ISO, 2010) (superseded ISO 140), which specifies all source room conditions. Regardless of the ISO 15186 adopted to measure indoor sound levels (Part 1 or 2), the requirements needed to generate the sound source referred to in the ISO 10140 are specific. The facility where the experiments took place did not have the source room requirements and the partition between the source room and the receiver room is, in fact, an exterior wall. The main ISO 10140 conditions for the source room are related to room volume and sound diffuseness, among others. As the building element was an exterior wall, the source room was, in reality, an exterior environment and consequently, the requirement for a sound diffuse room source was not possible to achieve. The actual outdoor test condition was analogous to a free field condition. Since diffuse conditions could not be met, an ASTM was adopted to be the guideline to generate the exterior sound levels. Having adopted the ASTM and established the conditions for the exterior sound source, the set up assimilated a similar condition to an existing wood frame building. The adoption of the ASTM E966 instead of the ISO 10140 was a significant deviation from the ISO 15186 standard in the development of the hybrid test method.

Equipment used in this study was comprised of sound level meter, speaker, noise generator, soundbook, laptop, sound analyser software, sound intensity probe equipped with two paired ½" microphones, and a microphone calibrator. A list of the equipment, manufacturers, and serial numbers is presented in Appendix B.

The Flush Method described in the ASTM E966 was the most appropriate to obtain the outdoor sound levels due to the actual test conditions. This configuration requires a speaker positioned as a point source distant from the building element under analysis and the sound levels were taken very close to the specimen surface. Background noise was evaluated by time averaging two minutes, and in all 1/3 octave bands from 63 to 5K Hz the outdoor sound source levels with the speaker turned on were at least 10 dB greater than the ambient noise with the speaker off.

A speaker was positioned on the outside of the building at a 45° angle of incidence, from the normal of the plane of the wall under test distance 2.40 m (95") from the center (Figure 4.11), and the bottom of the speaker was at 1.20 m (47") height. There are two options to measure the exterior sound levels according to the E966. The first requires five different angles—15°, 30°, 45°, 60°, and 75°—to position the speaker from the center of the wall and measure sound pressure levels. These measured values are averaged, and the result is considered the exterior sound source level. This situation allows for an approximate diffuse field that would be comparable to a procedure done in a diffuse sound field (ASTM, 2010). The second option allows for a single angle of incidence to position the speaker, and the standard suggests a 45° angle. This angle of incidence is intended to minimize the number of source locations, and because this test had a large number of wall assemblies to be tested, the second option was chosen. Using only one incidence angle generates an approximate situation to a free-field condition. An outdoor sound field does not tend to be diffuse and the single angle configuration might well represent environmental incident sound even though sound transmission through building elements is angle dependent. The set-up yielded sufficient data to compare the results.

The sound level meter was positioned at a distance lower than 17 mm from the wall surface without touching the specimen, and its microphone was calibrated before the measurements using a microphone calibrator. Sound pressure levels were taken at the center and at four other random locations over the external wall. The measurement time for each of the five points was 60 seconds. For every point location, the sound level was the sound level averaged during measurement time calculated by the sound level meter. Only one sound level meter was used, and consequently, five sound levels were measured in sequence, one after the other. Subsequently, all five results were averaged and presented in 1/3 octave frequency bands and treated as the sole exterior sound pressure level. No weighting decibel curve was adopted. For every wall permutation under test, the exterior sound source (speaker position) was configured to be at the same initial set up in order to provide identical outdoor sound pressure level conditions. This measure was needed because there was no simultaneous real-time data collection for both exterior and interior sound levels. Exterior sound levels were collected only once, and the final calculated value was considered equal for all tested walls to calculate sound transmission loss. This procedure is a deviation from the standard used, which required simultaneous generation and measurement of source and receiver room levels. Available lab equipment did not allow for such procedure.

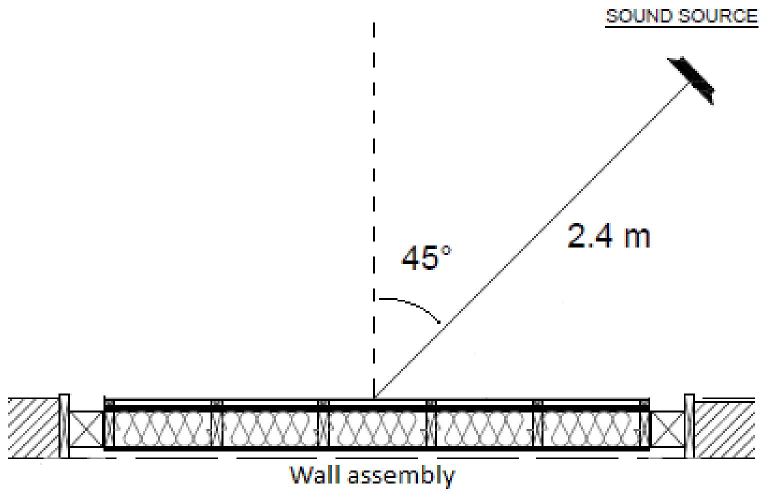


Figure 4.11. Set up for measurement and generation of exterior sound levels. (Credit: Omid T.)

Inside of the building where measurements were made using a sound intensity probe, the scanning method was used, and two orthogonal swept measurements were made, averaged, and presented as the sound intensity level for a wall being tested. The probe paired microphones were individually calibrated before every set of measurements using a sound pressure calibrator. The intensity probe phase calibrator was not available.

For the scanning method, a 20-cm distance between vertical and horizontal parallel lines (orthogonal lines) (Figure 4.12) was used. The intensity probe needed to cover the whole wall area following two independent pattern lines at a time. The measurement time for each scanning line was on average 90 seconds. This time was calculated based on the suggested mean speed in the ISO standard, which is 0.2 m/s. The range for the probe speed is from 0.1 to 0.3 m/s. According to the total measured distance that the probe should cover, the final measuring time was calculated to give the desired probe speed.

The distance from the probe microphone to the gypsum board was 20 cm, and it originated an imaginary parallel plane from the gypsum board which, was considered the measurement surface.

A previous test comparison between scanning and point methods were made. Initially, the intent was to verify if there were any sound leakages through the wall and if the two methods would yield similar responses. Results between the two presented equal results, indicating that both could be confidently used and that there were no sound leakages. The scanning method was adopted rather than the grid point method because it was a fast and straightforward possible measurement method in the ISO standard. No windscreen was used because no drafts were observed in the receiver room.

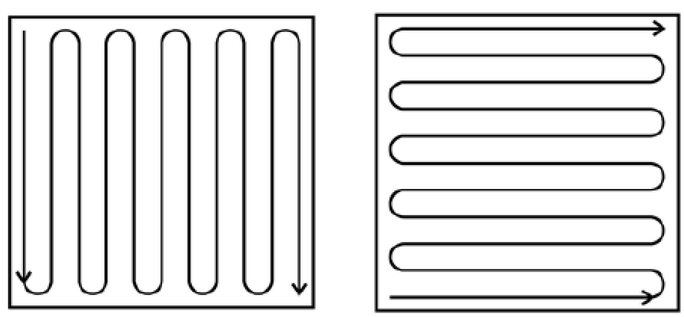


Figure 4.12. Vertical and horizontal parallel pattern lines for scanning the wall.

The measurement surface is illustrated in Figure 4.13. The 20-cm measurement distance was initially selected because it falls under the suggested standard range, which is between 10 and 30 cm. Using the 20-cm distance, results showed conformity, and obtained values from the scanning method had differences in sound intensity level between the two orthogonal measurements less than 1 dB. These results qualified the scanning method.

The Pressure-Intensity Index (F_{pI}) was also evaluated and results showed that the index qualified the measurement surface (See Appendix C for wall measurement data) for the scanning method ($F_{pI} < 10$). The pressure-intensity index was automatically calculated by the sound analysis software. Results from the two orthogonal measurements had an arithmetic average calculated to be the final result of the whole wall surface. Background noise was evaluated by time averaging two minutes, and in all 1/3 octave bands from 63 to 5K Hz, indoor sound pressure levels when the speaker was on were at least 10 dB higher than the ambient noise with the speaker off. The data were presented in one-third octave band frequency levels.

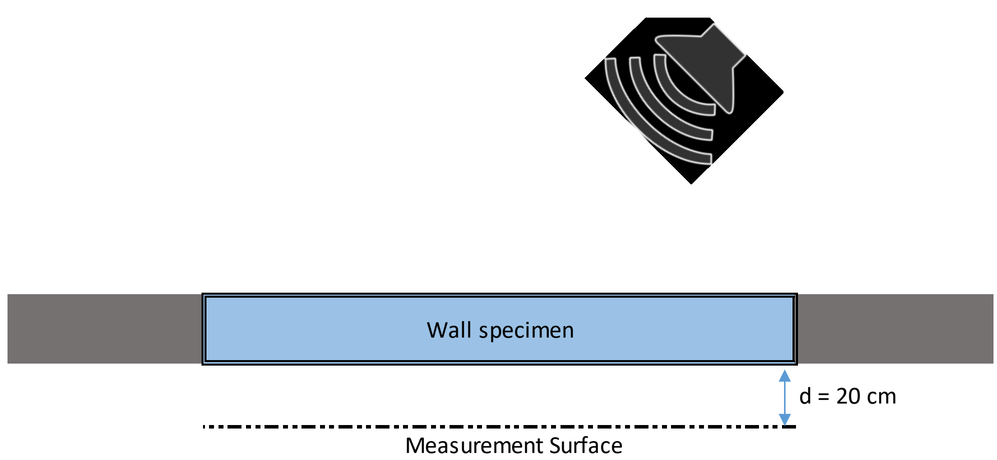


Figure 4.13. Horizontal section of the wall specimen and measurement surface.

The wall assembly was mounted in a niche and, as usual, the surface measurement coincides with the edges of the niche. The standard requires that the perimeter area around the niche between the wall specimen and the surface measurement needs to be fully reflective. In the study, this reflectivity was not fully observed because of the built semi-anechoic indoor environment. Only at right and left areas were the surfaces rigid and reflective; at the bottom and top, the surfaces were covered with an absorptive material. This was a deviation from the standard that might have reduced the indoor intensity levels. But since the study dealt with differences between the transmission losses of the walls, rather than absolute values, the deviations from the standard did not affect the results. The transmission losses of all the walls would be lower than in practice, and the shift would be systematic and would preserve the differences between the results.

Two spacers were used in the intensity probe, between the paired microphones, according to the frequency range needed to be measured. A 25 mm spacer was used for frequencies between 125 Hz and 5000 Hz while a 50 mm spacer was used for frequencies between 63 Hz and 1600 Hz. The 12 mm spacer was not available in the lab. The options for the two spacers and frequency ranges which they cover, including the frequency range of interest, were obtained from the manufacturer's instruction manual (GRAS, 2014). A picture of the graph with the spacers' measures and respective frequency ranges is presented in Figure 4.14. The manufacturer's manual was the primary source for selecting the appropriate spacers and frequency ranges as per Figure 4.14.

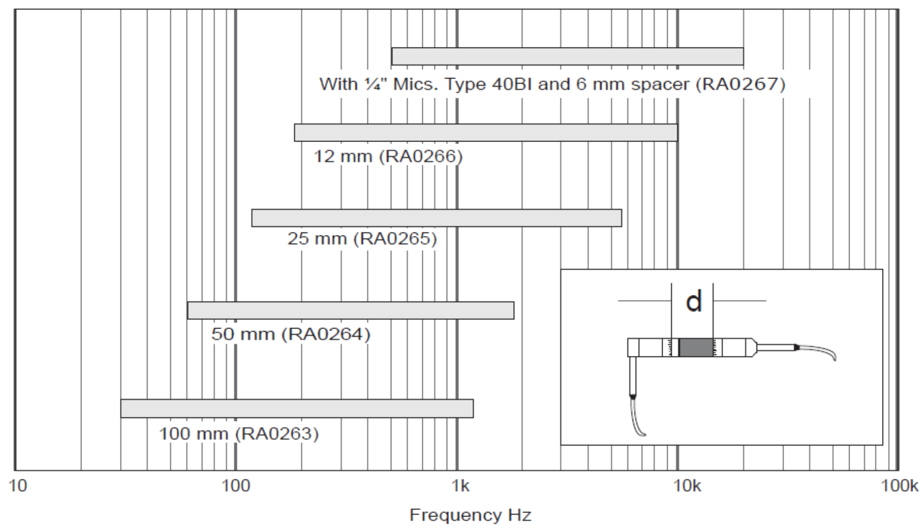


Figure 4.14. Graph showing spacers' measures and frequency ranges for ½" microphones. (Source: GRAS, 2014)

The ASTM E2249 (ASTM, 2016b) was adopted to merge the two measurements from both spacers and obtain only one measurement for the whole range of frequencies, from 63 to 5000 Hz. It was used to deal with the sound intensity levels where frequencies overlapped each other. The standard states that to calculate the overall sound intensity, the following rule (Equation 16) has to be applied according to where the frequencies overlap.

$$L_I = \begin{cases} \dfrac{L_{25} + L_{50}}{2}, & |\, L_{25} - L_{50}| < 1.5\ dB \\ \max\,(L_{25};\ L_{50}), & |\, L_{25} - L_{50}| \geq 1.5\ dB \end{cases} \qquad \text{Eq. (16)}$$

where L_{25} = averaged sound intensity level for the 25 mm spacer (dB),

L_{50} = averaged sound intensity level for the 50 mm spacer (dB),

L_I = wall normal sound intensity level (dB).

In summary, the process of measuring sound intensity level for each wall specimen had a first horizontal and vertical measurement using the 25 mm spacer. The second step was to repeat a horizontal and vertical measurement using the 50 mm spacer. For each spacer, the two orthogonal measurements had an arithmetic mean calculated, and later the two averages were merged according to Equation (16).

The ISO 15186-1 presents an equation (section 3.8, Eq. 7) that calculates the sound transmission loss (TL) between the two adjacent rooms. Since in this study there were no sub-surface measurement areas, the referred equation became, in dB units:

$$TL = L_p - 6 - L_I \qquad \text{Eq. (17)}$$

where L_p = average sound pressure in the source room (dB),

L_I = average sound intensity over the surface in the receiver room (dB).

A variation of the variable L_p presented in the ISO was done due to the actual source environment and conditions. Instead of an averaged sound diffuse pressure level, in this equation, the free-field sound pressure measured at only one angle of incidence was used. This procedure was a deviation from the ISO standards. Transmission loss was calculated in 1/3 octave frequency bands.

The calculated Transmission Loss (TL) from Equation (17) was the reference value to calculate the single-number ratings STC and OITC presented in section 5.1.

As evidence of the valid approach hybrid test method developed to perform the experiment, the graph below (Figure 4.15) presents sound transmission loss comparison between three wood frame wall specimens. All walls had exactly same layer configurations: 13 mm (1/2") gypsum board, 38 X 140 mm (2"x 6") wood studs at 400 mm (16") on center, 150 mm (6") fiberglass batt insulation in the cavity, wood board sheathing, and vinyl cladding. One wall was tested at the BCIT lab with the hybrid method, while the other two were tested at the National Research Council ASTM E90 sound suite facility. At the NRC, the tests were performed using two adjacent reverberation chambers and the source and receiver rooms had sound pressure levels measured. Data were taken from Bradley and Birta (2000). The referred NRC walls are the TLA-99-029a and TLA-99-104a. The differences between the three walls were material type or the surface mass density of the wood sheathing layer. The TLA-99-029a had an 11 mm Oriented Strand Board (OSB) weighing 6.9 Kg/m^2, the TLA-99-104a had a 13 mm wood fiber board weighing 3.5 Kg/m^2, and the BCIT wall had a 13 mm plywood weighing 6.9 Kg/m^2. The BCIT and NRC walls, whose wood sheathing had similar surface mass density, presented very close results even though the methods and the sound fields were different.

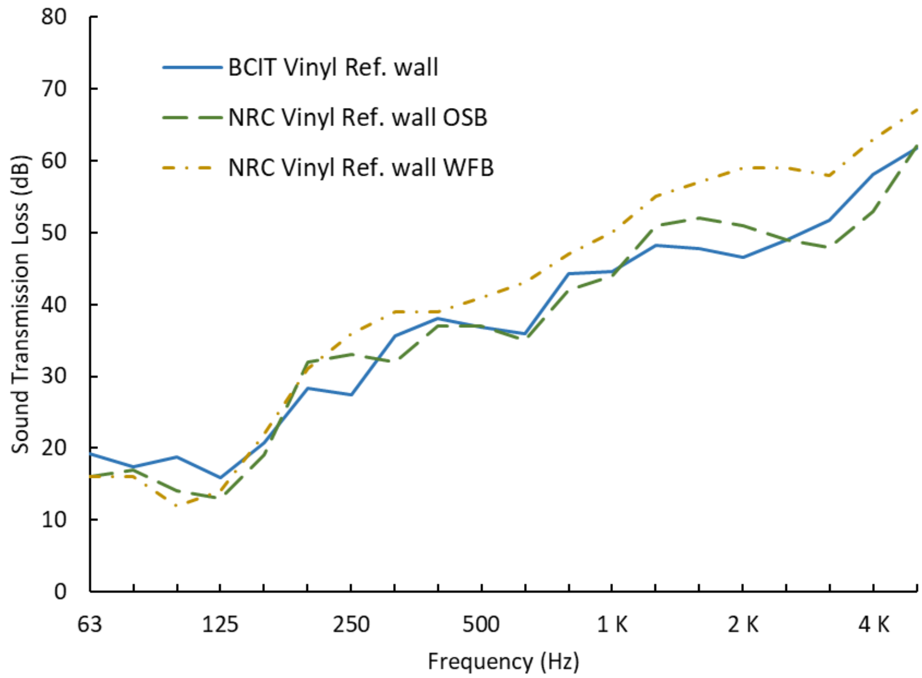


Figure 4.15. Sound transmission loss comparison between BCIT reference and NRC reference walls tests.

To calculate the single-number ratings STC and OITC, the ASTM E413-16 Classification for Rating Sound Insulation (ASTM, 2016c) and the ASTM E1332-16 Classification for Rating Outdoor-Indoor Sound Attenuation (ASTM, 2016d) were followed, respectively.

Remarks

The sound transmission loss result and calculated Sound Transmission Class (STC) and Outdoor Indoor Transmission Class (OITC) ratings were presented and calculated solely for academic and comparative purposes and under any circumstances shall not be used outside of this study scope. The transmission loss results using the hybrid test method described in this thesis cannot directly be compared to tests results from an ASTM E90 or ISO standard. This is primarily due to specimen size and deviations cited in this section.

Limits

The research approach used in these tests was somewhat straightforward. The materials were changed according to a selected combination and results were measured in the indoor room. Even so, there were some limitations to the method. The size of the wall specimen was smaller than an ATSM/ISO standard tests. This size difference might have affected the overall stiffness and edge effects of the whole system and impacted frequency dependent results. Second, the use of the equipment manufacturer recommendation for the spacer superseded the standards. Last, the indoor semi-anechoic room conditions had an intermittent uncontrollable source affecting interior intensity levels. This situation happened in this study frequently at the 1.6 KHz where higher values variation were observed for some of the tested walls.

5 ANALYSIS AND RESULTS

The main objective of this study was to evaluate differences in sound transmission loss for a number of wall assemblies having different variations among their constituent layers. Tests were performed in a sound lab using sound intensity techniques. This section presents results of the tests completed in a graphical representation of the sound transmission loss values. Since there is a large number of transmission loss results, the practical and straightforward analysis approach was to present wall combinations according to the variables or materials being evaluated. The analysis started with the single-number ratings and the following sub-sections analyzed as to how specifically each variable or material impacted the overall wall behaviour.

5.1 Single-number Ratings

A total of 57 sound intensity levels for all tested walls were measured, and the sound transmission loss and single-rate numbers were calculated. Table 5 below compiles the walls and their respective layer configurations, Outdoor Indoor Transmission Class (OITC), and Sound Transmission Class (STC) single-number ratings. The walls were numbered in sequence.

Analyzing the single-rate numbers, it can be seen that OITC varied from 26 to 37 and the STC rating varied from 37 to 52. OITC presented a much narrower range (11 points) than STC (15 points) for the same walls. Developed with distinct approaches, the two ratings intend to indicate how sound will ultimately be sensed by the human hearing system. OITC embeds in its calculation the A-weighted sound level whereas STC does a corresponding weighting factor using the A-weighted level concept through its graphical approach composed of three sloped lines (STC contour line). These ratings cannot give details of how a wall performs in specific frequency bands. OITC extends its frequency calculation range down two additional 1/3 octaves (80 and 100 Hz) compared to STC. At the low frequency range, aside from the stucco cladding walls, the walls had closer transmission loss performance with variations being less disperse than those at mid and high frequencies. Such results and a broader calculation band can likely be the explanation why OITC numbers were tighter than STC. On one hand, this measure can well express the impact at a specific range, in this case low frequency, and perhaps fairly estimate the general performance. On the other hand, such impact in a particular range caused an attention deviation from other as important ranges, underestimating the overall performance. The latter observation may be important when a particular frequency range is of more interest than others, in cases where the environment sound level presents a specific set of frequencies to be attenuated. A simple observation of the OITC and STC might ignore specific ranges; consequently, leading to erroneous specifications.

STC and OITC might provide guidance and reference to selecting construction materials but caution is needed in the selection of building materials. Results indicated that many of the tested walls had similar STC and OITC numbers, yet a detailed observation at their

1/3 octave frequency transmission loss levels showed that variations at mid and high frequencies were consistently high. The results corroborated the assumption that the ratings emphasized narrow frequency bands while underestimating other important frequency ranges. In the absence of a more comprehensive single-number rating, STC and OITC must be carefully used due to lack of frequency dependent data, according to study findings. If provided, further observation and analysis of the frequency dependent TL data of a wall is suggested to verify a satisfactory sound attenuation at a particular frequency range of interest.

STC, as opposed to OITC, had broader rating values. Apparently, this result might be interpreted as a better representation for exterior walls although, in fact, it leads to a misinterpretation of the wall behaviour for low frequency sounds, which are typical from an environmental urban noise.

To illustrate the situation in which STC presents its dual characteristic of good representation at a specific frequency band while not well representing a wall assembly at other frequency bands and consequently inducing poor wall design, Figure 5.1 shows a graph for 16 walls whose STC were equal to 40. These walls represented the middle group taken from Table 6.

The graph clearly showed that there is a convergent point at around 125 Hz, which coincidentally is the STC initial calculation frequency, and all walls had virtually same TL values at this frequency. This likely was very significant to the method of calculating the final STC value. Above 160 Hz, the curves tended to diverge and there was an evident difference between walls' performance at mid- and high-frequencies. If no additional information is provided regarding this set, one can unwittingly select a wall that has a poor performance at mid and high frequencies and potentially deliver higher indoor sound levels rather than a wall that could deal with higher exterior sound levels. As for the OITC, these walls had values ranging from 27 to 29, more precisely 11 out of 16 had a 29 value, four had a 28, and one wall had a 27. Again, the OITC might better capture the lower frequency sound levels yet, similarly to the STC, it needs a comprehensive component.

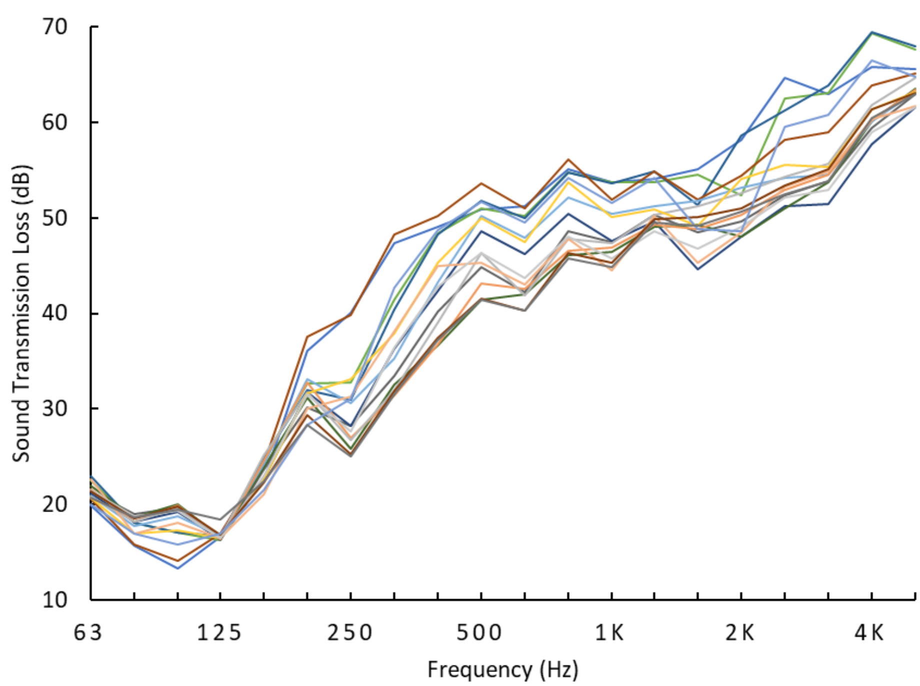


Figure 5.1. Sound transmission loss curves for STC 40 walls.

Hence, such single-number ratings usually emphasise some frequency ranges, not necessarily meaning that the overall performance is poor or compromised. A wall can have low general performance comparable to another whose results were lower at a very narrow band. These ratings are a first measure on how to select and design a specific wall to meet certain code requirements.

Remarks

The sound transmission loss data and calculated Sound Transmission Class (STC) and Outdoor Indoor Transmission Class (OITC) ratings were presented and calculated solely for academic purposes and under any circumstances shall not be used outside of this study's scope.

Table 5. List of walls, their respective configuration, and single-number ratings.

Wall #	Cladding Type	Cladding Attachment	Rainscreen Cavity Width	Exterior Insulation	Exterior Insulation Thickness	OITC	STC
1	Vinyl	Wood Strap.	3/8"	Min. Wool	1 ½"	26	37
2	FCB	Wood Strap.	3/8"	Min. Wool	1 ½"	29	41
3	FCB	Wood Strap.	1"	Min. Wool	1 ½"	27	39
4	Vinyl	Wood Strap.	1"	Min. Wool	1 ½"	27	38
5	FCB	S2 - Z-Girt	1"	Min. Wool	1 ½"	27	40
6	Vinyl	S2 - Z-Girt	1"	Min. Wool	1 ½"	29	40
7	Vinyl	S2 - Z-Girt	3/8"	Min. Wool	1 ½"	29	40
8	FCB	S2 - Z-Girt	3/8"	Min. Wool	1 ½"	28	40
9	Vinyl	S2 - Z-Girt	1"	XPS	1 ½"	29	40
10	FCB	S2 - Z-Girt	1"	XPS	1 ½"	28	38
11	FCB	S2 - Z-Girt	3/8"	XPS	1 ½"	29	40
12	Vinyl	S2 - Z-Girt	3/8"	XPS	1 ½"	29	40

Wall #	Cladding Type	Cladding Attachment	Rainscreen Cavity Width	Exterior Insulation	Exterior Insulation Thickness	OITC	STC
13	FCB	S2 - Z-Girt	3/8"	XPS	3"	29	40
14	Vinyl	S2 - Z-Girt	3/8"	XPS	3"	29	40
15	Vinyl	S2 - Z-Girt	1"	XPS	3"	29	40
16	FCB	S2 - Z-Girt	1"	XPS	3"	28	40
17	FCB	S2 - Z-Girt	1"	Min. Wool	3"	29	43
18	Vinyl	S2 - Z-Girt	1"	Min. Wool	3"	29	43
19	FCB	S2 - Z-Girt	3/8"	Min. Wool	3"	29	44
20	Vinyl	S2 - Z-Girt	3/8"	Min. Wool	3"	29	43
21	FCB	Wood Strap.	1"	Min. Wool	3"	30	43
22	Vinyl	Wood Strap.	3/8"	Min. Wool	3"	28	39
23	FCB	Wood Strap.	3/8"	Min. Wool	3"	30	43
24	Vinyl	Wood Strap.	1"	Min. Wool	3"	28	39
25	Vinyl	Wood Strap.	1"	XPS	1 ½"	28	39
26	FCB	Wood Strap.	1"	XPS	1 ½"	28	40
27	FCB	Wood Strap.	3/8"	XPS	1 ½"	29	40
28	Vinyl	Wood Strap.	3/8"	XPS	1 ½"	28	39
29	Vinyl	Wood Strap.	1"	XPS	3"	28	37
30	FCB	Wood Strap.	1"	XPS	3"	29	41
31	FCB	Wood Strap.	3/8"	XPS	3"	30	42
32	Vinyl	Wood Strap.	3/8"	XPS	3"	29	40
33	Vinyl	Reference Wall				28	39
34	FCB	Reference Wall				29	40
35	FCB	Wood Strap.	3/8"			29	40
36	Vinyl	Wood Strap.	3/8"			28	39
37	Vinyl	Wood Strap.	1"			28	38
38	FCB	Wood Strap.	1"			28	40
39	Vinyl	S3 - Clips	3/8"	Min. Wool	1 ½"	27	39
40	FCB	S3 - Clips	3/8"	Min. Wool	1 ½"	28	43
41	Vinyl	S3 - Clips	1"	Min. Wool	1 ½"	28	40
42	FCB	S3 - Clips	1"	Min. Wool	1 ½"	28	43
43	Vinyl	S3 - Clips	1"	XPS	1 ½"	29	38
44	FCB	S3 - Clips	1"	XPS	1 ½"	28	41
45	Vinyl	S3 - Clips	3/8"	XPS	1 ½"	29	40
46	FCB	S3 - Clips	3/8"	XPS	1 ½"	30	41
47	Vinyl	S3 - Clips	3/8"	Min. Wool	3"	28	42
48	FCB	S3 - Clips	3/8"	Min. Wool	3"	30	47
49	Vinyl	S3 - Clips	1"	Min. Wool	3"	28	42
50	FCB	S3 - Clips	1"	Min. Wool	3"	30	47

Wall #	Cladding Type	Cladding Attachment	Rainscreen Cavity Width	Exterior Insulation	Exterior Insulation Thickness	OITC	STC
51	FCB	S3 - Clips	1"	XPS	3"	29	42
52	Vinyl	S3 - Clips	1"	XPS	3"	29	38
53	Vinyl	S3 - Clips	3/8"	XPS	3"	30	41
54	FCB	S3 - Clips	3/8"	XPS	3"	30	43
55	Stucco	Wood Strap.	3/8"	Min. Wool	3"	36	52
56	Stucco	Wood Strap.	3/8"	Min. Wool	1 ½"	37	51
57	Stucco	Wood Strap.	3/8"	XPS	1 ½"	37	49

Reorganizing Table 5 and sorting only the split insulated walls according to the STC from highest to smallest number, the following Table 6 helped understand the impact due to the wall layers. This table presents the results without stucco, reference, and single insulation walls.

Table 6. List of walls sorted by STC rating.

	Wall #	Cladding	Attachment	Cavity Width	Exterior Insulation	Ext. Insul. Thickness	STC
HIGHER STC GROUP	48	FCB	S3 - Clips	3/8"	Min. Wool	3"	47
	50	FCB	S3 - Clips	1"	Min. Wool	3"	47
	19	FCB	S2 - Z-Girt	3/8"	Min. Wool	3"	44
	17	FCB	S2 - Z-Girt	1"	Min. Wool	3"	43
	18	Vinyl	S2 - Z-Girt	1"	Min. Wool	3"	43
	20	Vinyl	S2 - Z-Girt	3/8"	Min. Wool	3"	43
	21	FCB	Wood Strap.	1"	Min. Wool	3"	43
	23	FCB	Wood Strap.	3/8"	Min. Wool	3"	43
	40	FCB	S3 - Clips	3/8"	Min. Wool	1 1/2"	43
	42	FCB	S3 - Clips	1"	Min. Wool	1 1/2"	43
	54	FCB	S3 - Clips	3/8"	XPS	3"	43
	31	FCB	Wood Strap.	3/8"	XPS	3"	42
	47	Vinyl	S3 - Clips	3/8"	Min. Wool	3"	42
	49	Vinyl	S3 - Clips	1"	Min. Wool	3"	42
	51	FCB	S3 - Clips	1"	XPS	3"	42
	2	FCB	Wood Strap.	3/8"	Min. Wool	1 1/2"	41
	30	FCB	Wood Strap.	1"	XPS	3"	41
	44	FCB	S3 - Clips	1"	XPS	1 1/2"	41

Group	Wall #	Cladding	Attachment	Cavity Width	Exterior Insulation	Ext. Insul. Thickness	STC
	46	FCB	S3 - Clips	3/8"	XPS	1 1/2"	41
	53	Vinyl	S3 - Clips	3/8"	XPS	3"	41
MIDDLE STC GROUP	5	FCB	S2 - Z-Girt	1"	Min. Wool	1 1/2"	40
	6	Vinyl	S2 - Z-Girt	1"	Min. Wool	1 1/2"	40
	7	Vinyl	S2 - Z-Girt	3/8"	Min. Wool	1 1/2"	40
	8	FCB	S2 - Z-Girt	3/8"	Min. Wool	1 1/2"	40
	9	Vinyl	S2 - Z-Girt	1"	XPS	1 1/2"	40
	11	FCB	S2 - Z-Girt	3/8"	XPS	1 1/2"	40
	12	Vinyl	S2 - Z-Girt	3/8"	XPS	1 1/2"	40
	13	FCB	S2 - Z-Girt	3/8"	XPS	3"	40
	14	Vinyl	S2 - Z-Girt	3/8"	XPS	3"	40
	15	Vinyl	S2 - Z-Girt	1"	XPS	3"	40
	16	FCB	S2 - Z-Girt	1"	XPS	3"	40
	26	FCB	Wood Strap.	1"	XPS	1 1/2"	40
	27	FCB	Wood Strap.	3/8"	XPS	1 1/2"	40
	32	Vinyl	Wood Strap.	3/8"	XPS	3"	40
	41	Vinyl	S3 - Clips	1"	Min. Wool	1 1/2"	40
	45	Vinyl	S3 - Clips	3/8"	XPS	1 1/2"	40
LOWER STC GROUP	3	FCB	Wood Strap.	1"	Min. Wool	1 1/2"	39
	22	Vinyl	Wood Strap.	3/8"	Min. Wool	3"	39
	24	Vinyl	Wood Strap.	1"	Min. Wool	3"	39
	25	Vinyl	Wood Strap.	1"	XPS	1 1/2"	39
	28	Vinyl	Wood Strap.	3/8"	XPS	1 1/2"	39
	39	Vinyl	S3 - Clips	3/8"	Min. Wool	1 1/2"	39
	4	Vinyl	Wood Strap.	1"	Min. Wool	1 1/2"	38
	10	FCB	S2 - Z-Girt	1"	XPS	1 1/2"	38
	43	Vinyl	S3 - Clips	1"	XPS	1 1/2"	38
	52	Vinyl	S3 - Clips	1"	XPS	3"	38
	1	Vinyl	Wood Strap.	3/8"	Min. Wool	1 1/2"	37
	29	Vinyl	Wood Strap.	1"	XPS	3"	37

Data from the above table suggests that there is a difference in STC according to the wall layers (or variables). Three groups were formed according to STC ranges to ease the view of such differences. The upper group had 20 walls and STC from 41 to 47 (7 points), the middle group 16 walls and STC 40 (1 point), and the bottom group 12 walls and STC from

37 to 39 (3 points). Since the middle group had 16 walls with only one STC number, it was reasonable to present it as an intermediate group only. Table 7 presents a summary of the total number of walls in each group according to the variables.

Table 7. Number of walls for each variable and group in STC table.

Group	Layer	#	Layer	#	Layer	#	Layer	#	Layer	#	Layer	#	Layer	#
Higher STC	FCB	15	Vinyl	5	Wood Strap.	5	S2	4	S3	11	Min. Wool	13	XPS	7
Middle STC	FCB	7	Vinyl	9	Wood Strap.	3	S2	11	S3	2	Min. Wool	5	XPS	11
Lower STC	FCB	2	Vinyl	10	Wood Strap.	8	S2	1	S3	3	Min. Wool	6	XPS	6

From this table, some trends were observed. Emerging patterns were drawn from the number of walls counted in each variable category and compared within the three groups. The direct inferences from Table 7 do not necessarily consider the effect of confounded variables that might happen according to layer combinations.

As for the OITC rating, Table 8 presents the walls in an OITC descending order.

Table 8. List of walls sorted by OITC rating.

	Wall #	Cladding	Attachment	Cavity Width	Ext. Insul.	E. Insul. Thick.	OITC
HIGHER OITC GROUP	21	FCB	Wood Strap.	1"	Min. Wool	3"	30
	23	FCB	Wood Strap.	3/8"	Min. Wool	3"	30
	31	FCB	Wood Strap.	3/8"	XPS	3"	30
	46	FCB	S3 - Clips	3/8"	XPS	1 1/2"	30
	48	FCB	S3 - Clips	3/8"	Min. Wool	3"	30
	50	FCB	S3 - Clips	1"	Min. Wool	3"	30
	53	Vinyl	S3 - Clips	3/8"	XPS	3"	30
	54	FCB	S3 - Clips	3/8"	XPS	3"	30
	2	FCB	Wood Strap.	3/8"	Min. Wool	1 1/2"	29
	6	Vinyl	S2 - Z-Girt	1"	Min. Wool	1 1/2"	29
	7	Vinyl	S2 - Z-Girt	3/8"	Min. Wool	1 1/2"	29
	9	Vinyl	S2 - Z-Girt	1"	XPS	1 1/2"	29
	11	FCB	S2 - Z-Girt	3/8"	XPS	1 1/2"	29
	12	Vinyl	S2 - Z-Girt	3/8"	XPS	1 1/2"	29
	13	FCB	S2 - Z-Girt	3/8"	XPS	3"	29
	14	Vinyl	S2 - Z-Girt	3/8"	XPS	3"	29
	15	Vinyl	S2 - Z-Girt	1"	XPS	3"	29
	17	FCB	S2 - Z-Girt	1"	Min. Wool	3"	29
	18	Vinyl	S2 - Z-Girt	1"	Min. Wool	3"	29
	19	FCB	S2 - Z-Girt	3/8"	Min. Wool	3"	29
	20	Vinyl	S2 - Z-Girt	3/8"	Min. Wool	3"	29
	27	FCB	Wood Strap.	3/8"	XPS	1 1/2"	29
	30	FCB	Wood Strap.	1"	XPS	3"	29
	32	Vinyl	Wood Strap.	3/8"	XPS	3"	29
	43	Vinyl	S3 - Clips	1"	XPS	1 1/2"	29
	45	Vinyl	S3 - Clips	3/8"	XPS	1 1/2"	29
	51	FCB	S3 - Clips	1"	XPS	3"	29
	52	Vinyl	S3 - Clips	1"	XPS	3"	29
LOWER OITC GROUP	8	FCB	S2 - Z-Girt	3/8"	Min. Wool	1 1/2"	28
	10	FCB	S2 - Z-Girt	1"	XPS	1 1/2"	28
	16	FCB	S2 - Z-Girt	1"	XPS	3"	28
	22	Vinyl	Wood Strap.	3/8"	Min. Wool	3"	28
	24	Vinyl	Wood Strap.	1"	Min. Wool	3"	28
	25	Vinyl	Wood Strap.	1"	XPS	1 1/2"	28
	26	FCB	Wood Strap.	1"	XPS	1 1/2"	28
	28	Vinyl	Wood Strap.	3/8"	XPS	1 1/2"	28
	29	Vinyl	Wood Strap.	1"	XPS	3"	28
	40	FCB	S3 - Clips	3/8"	Min. Wool	1 1/2"	28
	41	Vinyl	S3 - Clips	1"	Min. Wool	1 1/2"	28

Wall #	Cladding	Attachment	Cavity Width	Ext. Insul.	E. Insul. Thick.	OITC
42	FCB	S3 - Clips	1"	Min. Wool	1 1/2"	28
44	FCB	S3 - Clips	1"	XPS	1 1/2"	28
47	Vinyl	S3 - Clips	3/8"	Min. Wool	3"	28
49	Vinyl	S3 - Clips	1"	Min. Wool	3"	28
3	FCB	Wood Strap.	1"	Min. Wool	1 1/2"	27
4	Vinyl	Wood Strap.	1"	Min. Wool	1 1/2"	27
5	FCB	S2 - Z-Girt	1"	Min. Wool	1 1/2"	27
39	Vinyl	S3 - Clips	3/8"	Min. Wool	1 1/2"	27
1	Vinyl	Wood Strap.	3/8"	Min. Wool	1 1/2"	26

In the above sorted table, there are two groups according to OITC. The higher group had 28 walls and OITC's 29 and 30 (2 points), and the lower group 20 walls and OITC from 26 to 28 (3 points). Because of a narrower OITC range, only two groups were formed. Table 9 presents a summary of the total number of walls in each group according to the variables.

Table 9. Number of walls for each variable and group in OITC table.

Group	Layer	#	Layer	#	Layer	#	Layer	#	Layer	#	Layer	#	Layer	#
Higher OITC	FCB	15	Vinyl	13	Wood Strap.	7	S2	12	S3	9	Min. Wool	11	XPS	17
Lower OITC	FCB	9	Vinyl	11	Wood Strap.	9	S2	4	S3	7	Min. Wool	13	XPS	7

Table 9 suggested that similar trends to the STC were observed but they were not so evident. This can be attributed to the narrower range; consequently, the same inferences might not be so conclusive due to the fewer differences between the number of walls in each group and because of confounded variables.

STC and OITC tables show that the vinyl reference wall ratings were OITC 28 and STC 39 and that the vinyl rainscreen cavity single insulation walls were OITC 28 and STC 39, and OITC 28 and STC 38 for 3/8" cavity width and 1" cavity width, respectively. As for FCB, reference wall ratings were OITC 29 and STC 40, and the FCB rainscreen cavity single insulation walls were OITC 29 and STC 40, and OITC 28 and STC 40 for 3/8" cavity width and 1" cavity width, respectively. These results indicated that the addition of a rainscreen cavity itself did not increase transmission loss.

This section analysed the exterior wall cavity, which is comprised of the outer layers that governed the wall sound transmission. Variables to consider were cladding attachment types, cladding material, insulation material (including thickness), rainscreen cavity width, and sheathing-to-cladding distance (cavity depth). The variables interacted with each other, and invariably the many observed phenomena were a result of layer combination. The exterior insulation, cladding material, and cladding attachments are an important part of the exterior wall cavity, and these layers have a specific analysis section due to their crucial impact on the overall wall sound transmission loss behaviour.

Cladding Material

Denser and thicker claddings brought about higher transmission loss and consequently higher single-numbers. Stucco walls presented the highest STC and OITC ratings, which can be explained by the superior low frequency performance. The shift promoted by the cladding raised the curve high enough to substantially improve both STC and OITC. In these two single-number ratings, the primary impact range where minimal changes in TL affect the ratings goes up to approximately 500 Hz, followed by a secondary range from 500 to 1250 Hz. The stucco walls had consistently better results exactly within these two ranges and as such the STC and OITC ratings presented higher values. At mid- and high-frequencies the stucco walls had similar performance to walls with the same layer configurations.

Table 7 showed that there was a higher number of FCB cladding walls than vinyl cladding walls within the higher STC group and a higher number of vinyl than FCB walls within the lower STC group. Stucco walls had the highest STC values among all walls (Table 5) and the highest surface mass density and thickness (Table 4). This trend suggested that thicker and denser material promoted higher sound transmission loss at lower frequencies. Table 9 (OITC) illustrates the same conclusion, although the number range between vinyl and FCB walls is reduced.

Cladding Attachment

Table 7 illustrates an emerging pattern regarding the cladding attachments. The S3 type (Clip) had the largest number of walls within the highest STC group. Wood Strapping (S1 type) had a larger number of walls in the smallest STC group. The S2 type (Z-girts) had its greatest number of walls in the middle group (STC 40). This indicated that the cladding attachments had an impact on the overall STC values. The S3 attachment type tended to achieve higher STC values compared to the S2 (Z-girt) (intermediate performance) and wood strapping (lowest performance) attachments. As for OITC number (Table 9), this trend was not as clear as for STC. The S2 attachment seemed to have the highest number of OITC walls whereas wood strapping kept same low single-number tendency. This outcome might have been because of a narrower difference among walls at the 80 and 100 Hz frequency bands.

Exterior Insulation Material

STC values for exterior insulation materials showed that from Table 7 mineral wool had more walls with high STC than XPS, whereas XPS had a greater number of walls in the lower STC group. On the other hand, surprisingly, from Table 9, the XPS walls had a higher number of walls in the higher OITC group while mineral wool had a higher number of walls in the lower OITC group. This trend suggested that XPS might have some sound insulation effect at very low frequency bands, specifically in this case at 80 and 100 Hz and likely superior to the sound insulation effect of mineral wool. A better sound insulation performance for mineral wool was expected due to the known properties of this material, which were observed from the STC values.

All in all, the best STC configurations were for heavier and denser cladding stucco and FCB, mineral wool insulation, thicker exterior insulation, and resilient cladding attachments S3 and S2.

5.2 Frequency Dependent Transmission Loss

One way to detect and verify why the trends occurred was by examining the 1/3 octave frequency band transmission loss for these wall type constructions. First, the reference walls were also presented for comparison. Second, the introduction of a rainscreen cavity to a vinyl cladding wall assembly and to the FCB cladding assembly is investigated. Third, a preliminary layers' analysis indicated that the dominant factors that affected the overall transmission loss were cladding type and exterior insulation material, and the presented graphs were arranged in a way such that they represented all the possible combinations regarding cladding and insulation while still enabling observation of the differences between cladding and insulation. Fourth, the plotted graphs for comparison among cladding attachment types gave insight with respect to this variable in terms of resiliency of the attachment and the effect of sound bridging. In this section, graphs are presented in a frequency range from 63 to 1250 Hz. Finally, the effect of the sheathing-to-cladding distance is investigated.

5.2.1 Primary Structural Resonance

Figure 5.2 illustrates the two reference TL data for FCB and vinyl cladding walls. The two reference walls indicated where the primary structural resonance occurred, as pointed out by Bradley and Birta (2000). The curves suggested that the frequency where the resonance happened is at 125 Hz for both walls. At this frequency, TL had the lowest values of either type of assembly. The similarity to other published TL data for equivalent wall configurations (Bradley & Birta, 2000; Quirt et al., 1995) indicated the same frequency band. The FCB reference wall at 125 Hz had nearly equal TL to the vinyl reference wall although the FCB higher mass surface density and stiffness were not capable of changing where resonance occurred. A frequency of 125 Hz is considered the reference frequency in the impact analysis of the wall cavity components to the primary structural resonance.

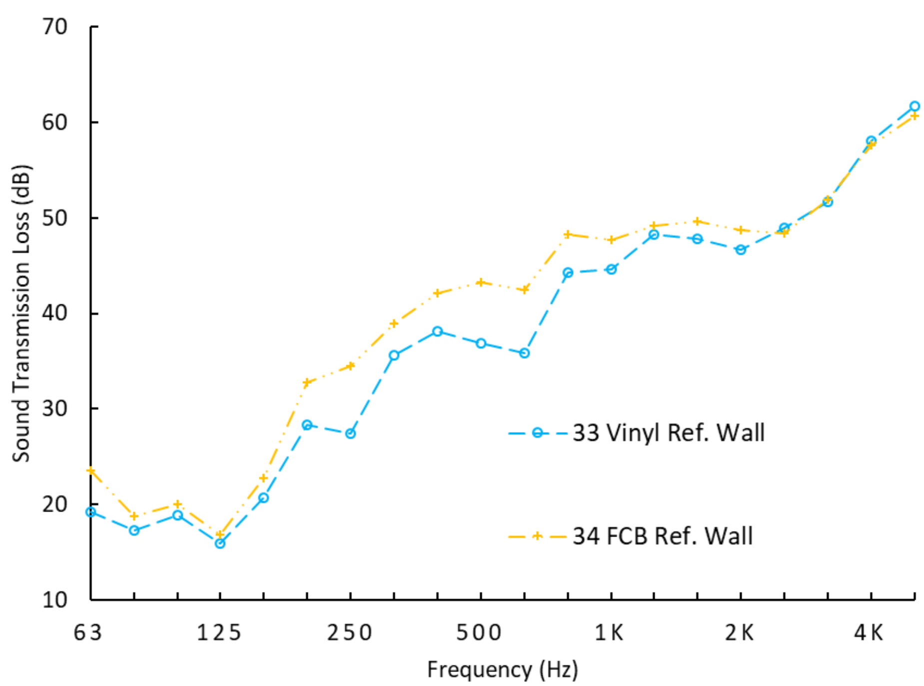


Figure 5.2. TL versus 1/3 octave frequency for Vinyl and FCB reference walls.

The V-shaped figure from the reference walls at 125 Hz would be shifted to the left if a higher disconnection between panels is observed. When this situation happens, usually, there will be lower TL levels at lower frequencies than at 125 Hz and higher TL levels at and above 125 Hz. The panels will tend to work independently, and the lowest TL will lean towards to either the lowest mass-air-mass-air-mass resonance frequency between panels (Bradley and Birta, 2000) or the panel resonance (Xin and Lu, 2011).

5.2.2 Addition of Rainscreen Cavity

The addition of a rainscreen cavity in a wall was analyzed. Starting from the reference wall design, which had cladding attached directly to the plywood sheathing, a rainscreen cavity was added between the two outer panels. This wall feature is meant to work as a drainage path for incidental rainwater and optimize the wall performance in wet conditions. The tested single insulation rain screen cavity walls had wood strapping as cladding attachments and only four variations were built regarding the cavity widths and cladding types (See Table 2).

Figure 5.3 shows the TL differences among vinyl cladding walls: one is the reference wall and the other two had cavity widths of either 1" or 3/8". In these cases, the three walls had equal performance between 63 and 200 Hz. Between 250 and 315 Hz, the reference wall had the highest transmission loss followed by the 3/8" cavity width wall and lastly by the 1" cavity width wall. This trend inverted, and between 400 and 1 K Hz, the 1" cavity width had the highest TL followed by the 3/8" width and finally by the reference wall. The crossover frequency is between 315 and 400 Hz.

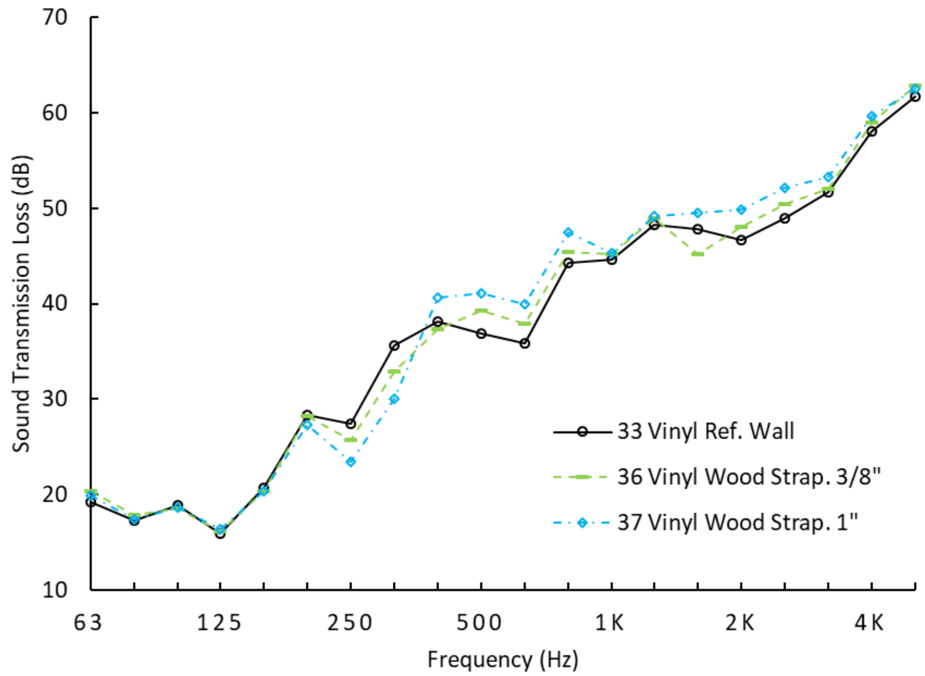


Figure 5.3. Sound transmission loss versus 1/3 octave band frequency for vinyl reference wall and vinyl single insulation rainscreen cavity walls.

Figure 5.4 shows the TL results for FCB walls: the reference, 1" cavity width, and 3/8" rainscreen cavity width walls. From 63 to 200 Hz, the 1" width had slightly lower TL than the other two walls. At 250 and 315 Hz, the 1" and 3/8" cavity widths had very similar TL although lower than the reference wall. At around 400 to 800 Hz, the results inverted and both 1" and 3/8" had marginally higher TL than the reference wall. Again, the crossover frequency is situated around the 400 Hz frequency band.

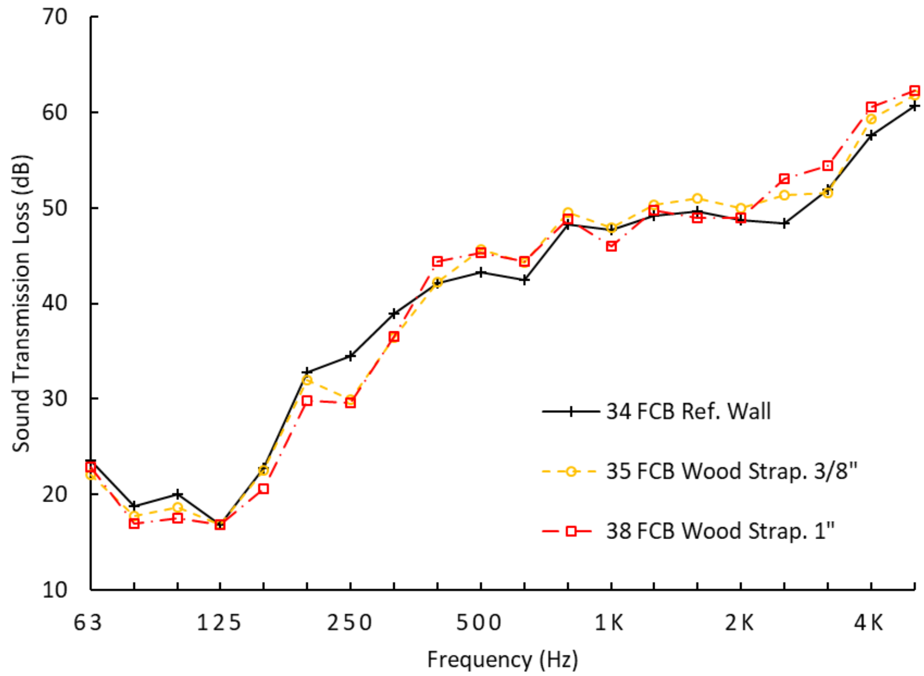


Figure 5.4. Sound transmission loss versus 1/3 octave band frequency for FCB reference wall and FCB single insulation rainscreen cavity walls.

In Figure 2.15 from the literature review, a similar trend was observed from Bradley and Birta (2000) in a rainscreen cavity wall. TL values of a rainscreen wall were lower than a non rainscreen cavity wall from 250 to 500 Hz, whereas TL values were higher above 500 Hz. The similarities between NRC and BCIT results suggested a similar trend, although at the NRC the differences were of much lower variation. There were also differences in the sound field and wood strapping thickness. Figure 2.14 showed higher TL values for the rainscreen cavity wall at and above 500 Hz, and no range where the rainscreen cavity wall presented lower values than a reference wall.

Figure 5.5 presents all vinyl wood strapping mineral wool reference, single, and split insulated wall assemblies. This graph demonstrated that even compared to the split insulated walls, the effect of a rainscreen cavity to a split insulated wall can be prejudicial to a localized frequency range. Aside from the fact that mineral wool had a high impact on the overall performance, two main walls groups were observed, and their TL curves denoted that the TL values at 200, 250, and 315 Hz for the split insulated had slightly lower values due to the rainscreen cavity. These graphs also suggested that the TL variation at these frequencies might have been influenced by the attachment's stiffness and the cladding stiffness and low mass.

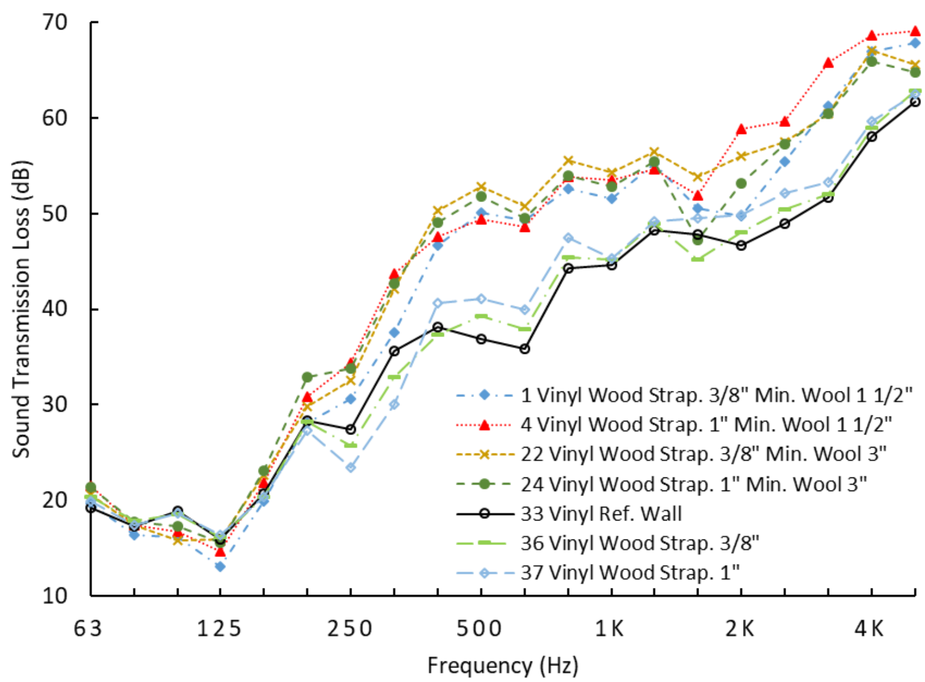


Figure 5.5. Sound transmission loss versus 1/3 octave band for vinyl reference, single, and split insulated walls.

Figure 5.6 presents all FCB wood strapping mineral wool reference, single, and split insulated wall assemblies. This set of curves demonstrated that the FCB split insulated walls did not have a dip analogous to the single insulation. At the least, the curves suggested that the lower performance from 200 to 400 Hz that might have occurred was likely mitigated by cladding stiffness and higher mass. The FCB cladding mass could have contributed to the mass-air-mass resonance for the exterior cavity, as opposed to vinyl, which had much lower surface mass density. Obviously, mineral wool also had a fundamental influence on the higher TL results for the split insulated walls.

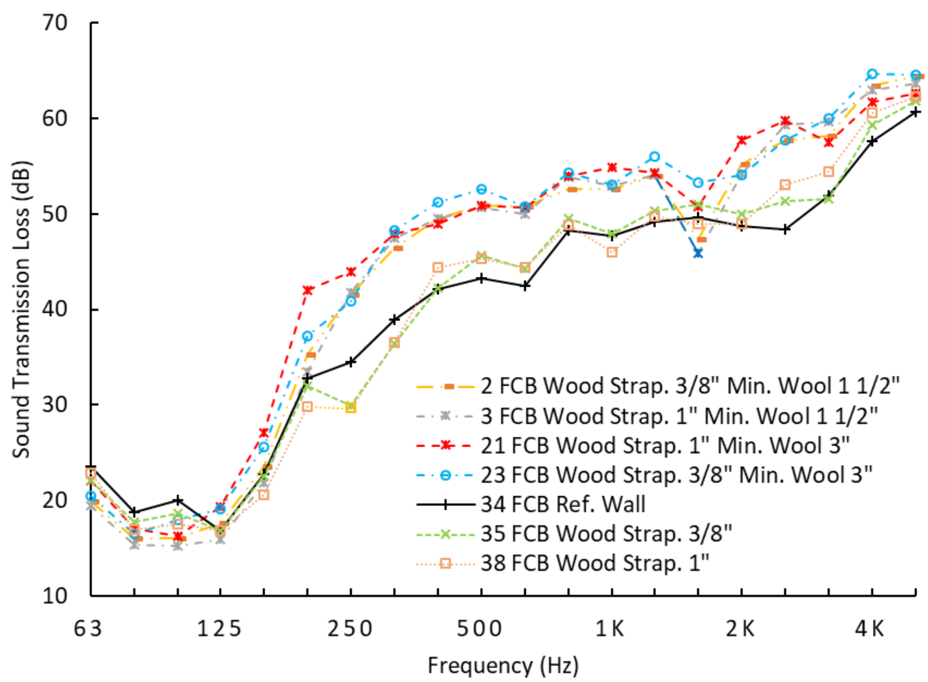


Figure 5.6. Sound transmission loss versus 1/3 octave band for FCB reference, single, and split insulated walls.

Figure 5.7 presents all vinyl wood strapping XPS reference, single, and split insulated wall assemblies. Most importantly, these curves emphasized the insulation material impact if

Figure 5.5 and Figure 5.7 are compared. The TL values at 250 and 315 Hz indicated that the 1" rainscreen cavity walls (single and split insulated) had the lowest values, whereas at and above 400 Hz, the 1" cavity width walls had the highest TL values.

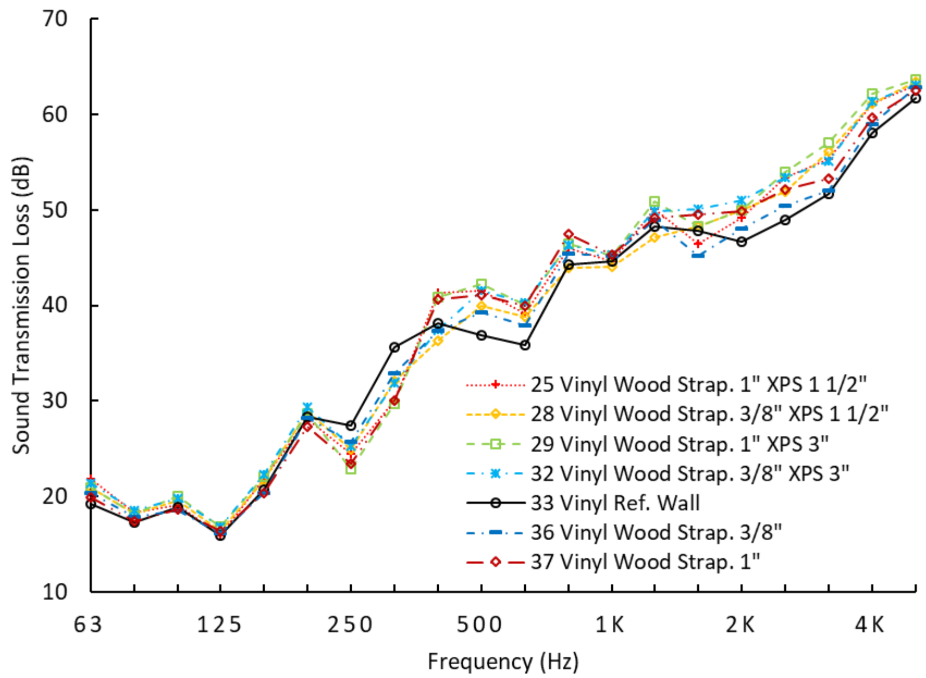


Figure 5.7. Sound transmission loss versus 1/3 octave band for vinyl reference, single, and split insulated walls.

Figure 5.8 presents all FCB wood strapping XPS reference, single, and split insulated wall assemblies. The curves demonstrated the impact of insulation material between mineral wool and XPS walls. The introduction of an exterior cavity lowered the wall performance at 250 and 315 Hz. All walls had lower TL values than the reference wall at 250 Hz. But variations in TL results did not demonstrate a correlation between one specific rainscreen cavity width to a higher or lower TL. The curves presented the same pattern with a dip at 250 Hz and an increase in TL higher than the reference wall at the 400 Hz. Results suggested a correlation to sheathing-to-cladding distance than to rainscreen cavity width after 400 Hz.

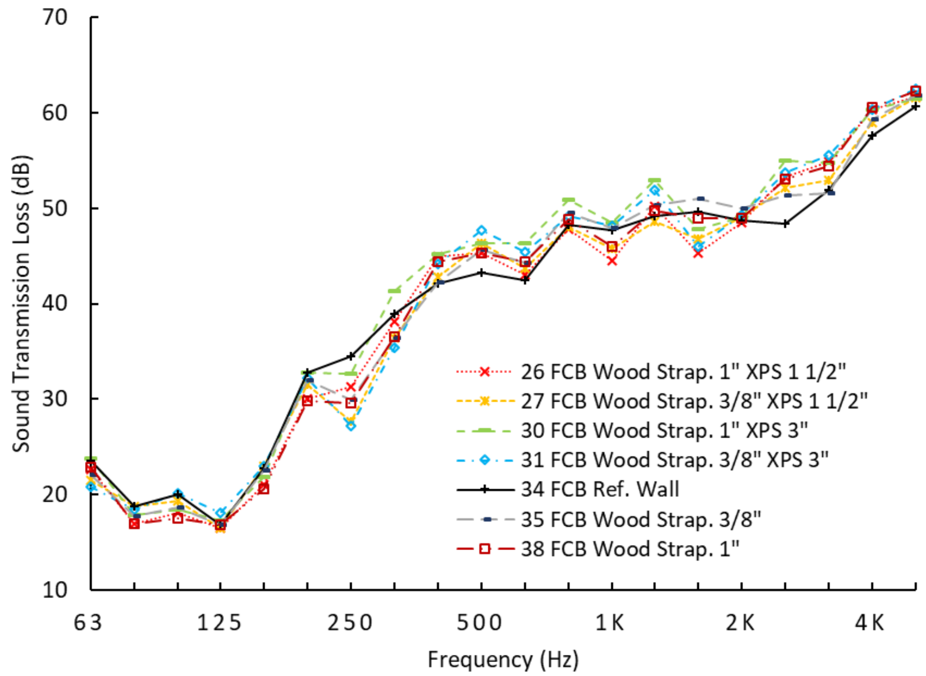


Figure 5.8. Sound transmission loss versus 1/3 octave band for FCB reference, single, and split insulated walls.

Results for the rainscreen cavity width demonstrated that TL can be worsened or enhanced if a rainscreen cavity is provided in a wall. Depending on the layer combination, this effect can be highly influenced. There was a weak correlation between a mass-air-mass effect between insulation material and cladding, a secondary mass-spring effect in the even smaller cavity inside the bigger exterior wall cavity.

Because XPS is a rigid board and mineral wool is semi-rigid, one likely effect of the rainscreen cavity in a split insulated wall is that the wood strappings caused a smaller contact area between the insulation and the cladding. If both boards were attached through their whole surface areas, this might have increased sound transmission (lowering TL), specifically structure-borne sound, which is one of the most degrading sound paths. When cladding is attached on top of strapping and exterior insulation it must be tightly installed. This is the same reason why an insulation should not be compressed in an interior cavity and the final insulation thickness is less than the initial thickness, to not create sound bridging.

A second approach to investigating the introduction of the rainscreen cavity is by looking at differences in transmission loss performance.

Figure 5.9 illustrates the averaged differences between the vinyl reference wall and all walls having vinyl siding, exterior insulation, and rainscreen cavity. The high variability showed by the confidence interval can be partially attributed to other characteristics such as exterior insulation type and insulation thickness.

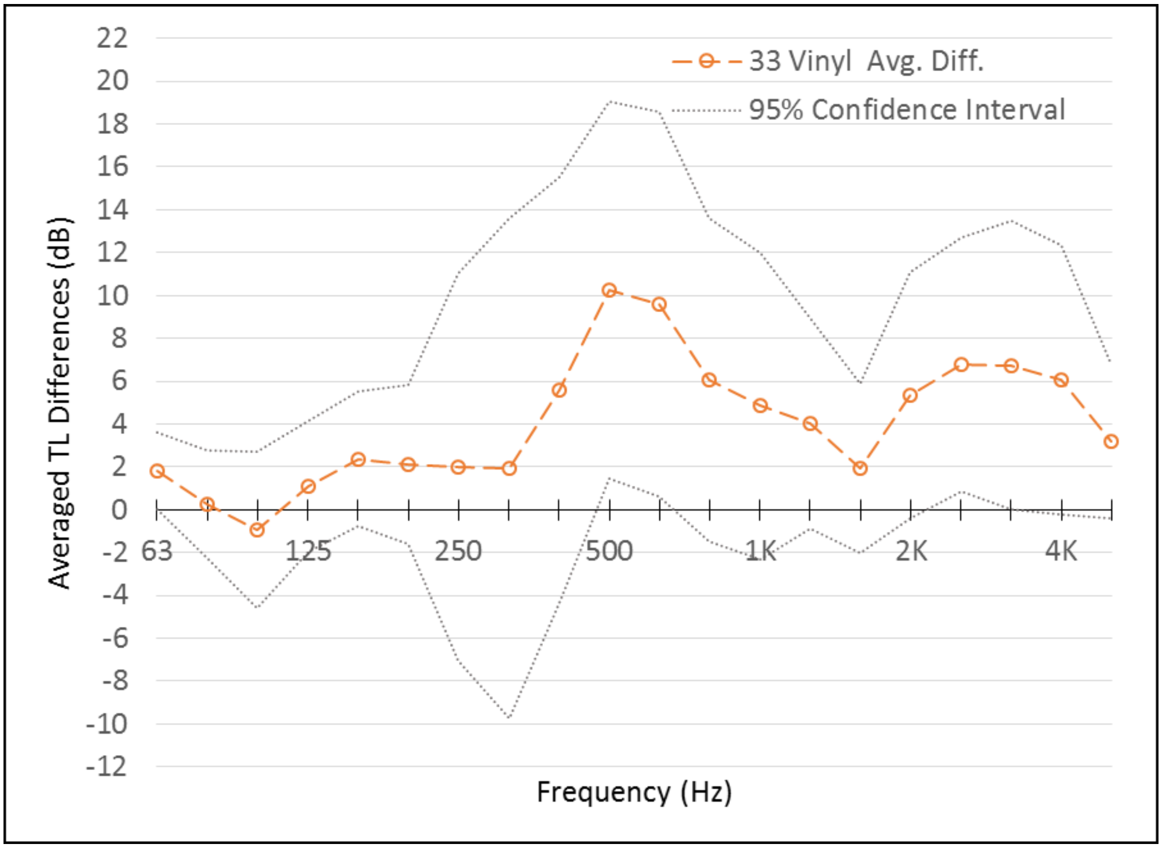


Figure 5.9. Averaged transmission loss differences versus 1/3 octave frequency for vinyl reference wall. Differences between vinyl split insulation rainscreen cavity walls and vinyl reference wall.

As for the reference wall, whose cladding was fiber cement board, Figure 5.10 shows a graph depicting the averaged differences between FCB split insulation rainscreen cavity walls and the FCB reference wall. The overall results for a comparison between single non-rainscreen cavity and split insulation rainscreen cavity walls were superior for the latter.

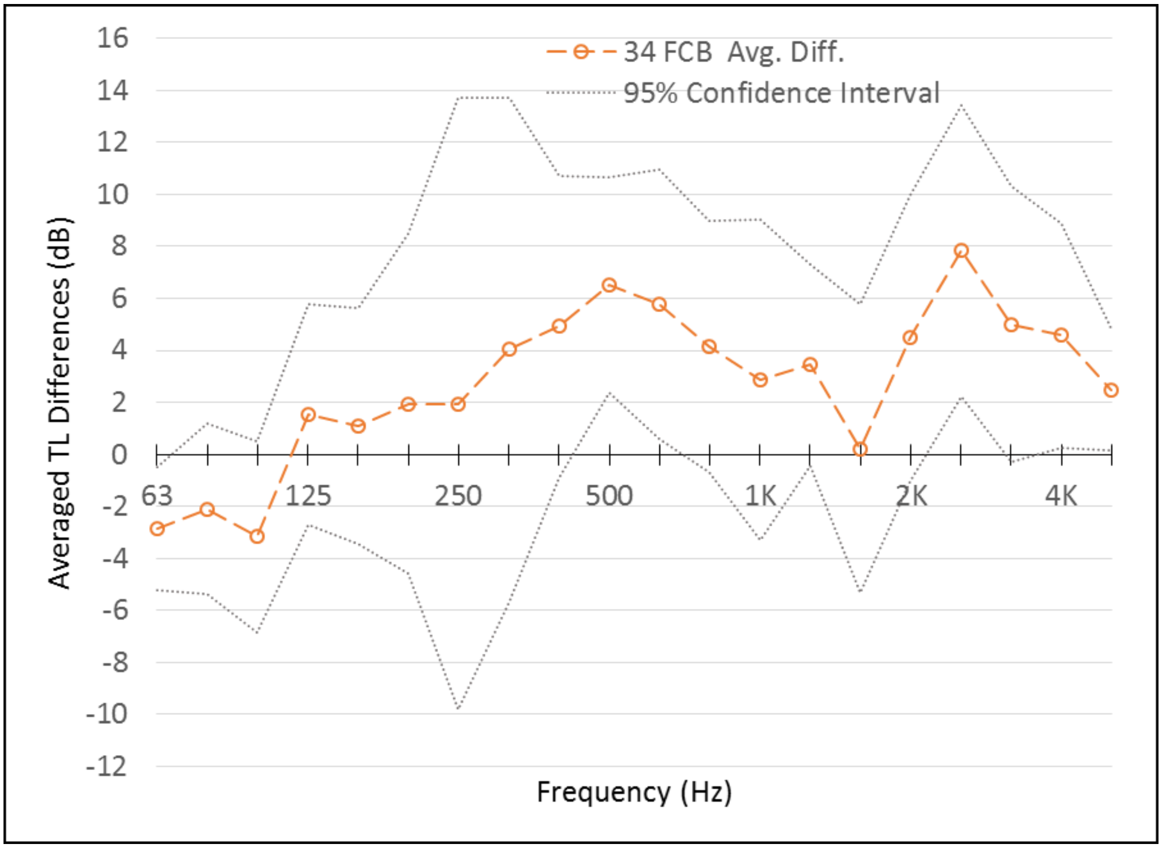


Figure 5.10. Averaged transmission loss differences versus 1/3 octave frequency for FCB reference wall. Differences between FCB split insulation rainscreen cavity walls and FCB reference wall.

5.2.3 Addition of Exterior Insulation

Four walls that were classified as bridged type had only single insulation (in the interior wall cavity) and the rainscreen cavity feature (Table 2). With the addition of an exterior insulation outboard of the plywood, these walls turned to be split insulated rainscreen cavity walls. This section explored the TL effects due to the addition of an exterior insulation through a comparison between the tested single insulation and split insulated walls.

All single insulation rainscreen cavity walls had wood strapping as the cladding attachment. Since the cladding attachment analysis showed that there were differences along the frequency range sufficient to cause variations in STC and OITC numbers among attachment types, the comparisons to single insulation walls were made solely for the wood strapping attachment. In this section, the analysis was made based on the cladding type (FCB and vinyl) and rainscreen cavity width (3/8" and 1") similarities. The variables between the compared walls had exactly same wall configuration aside from the exterior insulation (consequently a deeper exterior cavity).

The first comparison presented in Figure 5.11 shows the sound transmission loss between FCB cladding mineral wool split insulated 3/8" rainscreen cavity walls and FCB single insulation 3/8" rainscreen cavity wall. The next graph (Figure 5.12) shows the sound transmission loss between FCB cladding XPS split insulated 3/8" rainscreen cavity walls and FCB single insulation 3/8" rainscreen cavity wall.

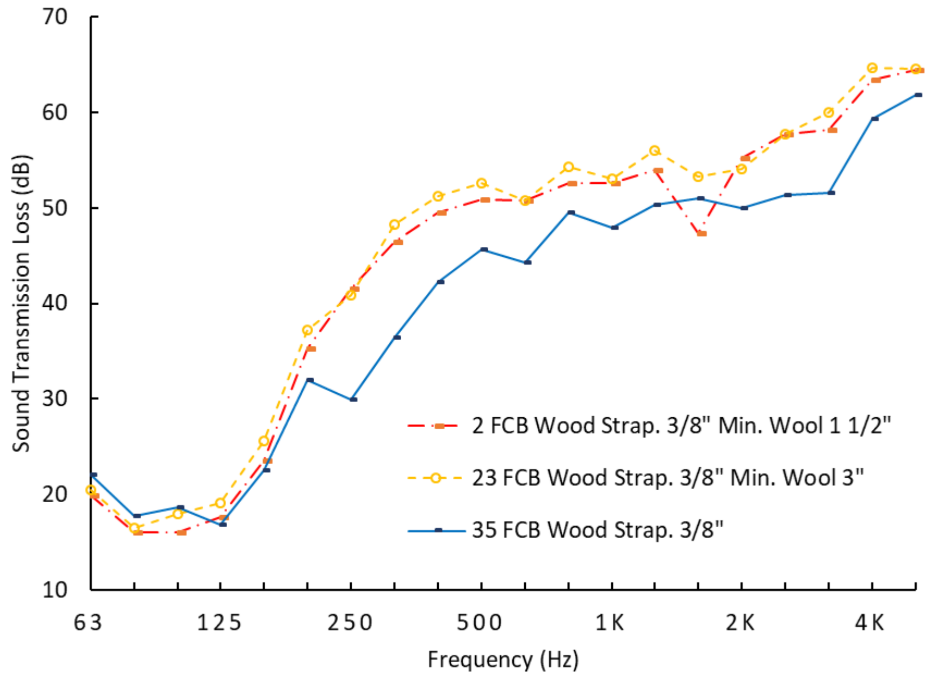


Figure 5.11. Sound transmission loss versus 1/3 octave frequency for FCB single insulation 3/8" rainscreen cavity wall and mineral wool split insulated 3/8" rainscreen cavity walls.

The mineral wool split insulated walls had higher sound transmission loss than the single insulation wall in general for almost the whole frequency range (Figure 5.11). As for the XPS split insulated walls, the sound transmission loss was almost equal to the single insulation wall (Figure 5.12). This result not only corroborated the sound insulation properties between mineral wool and XPS as previously discussed but also emphasised the impact level to the overall wall behavior.

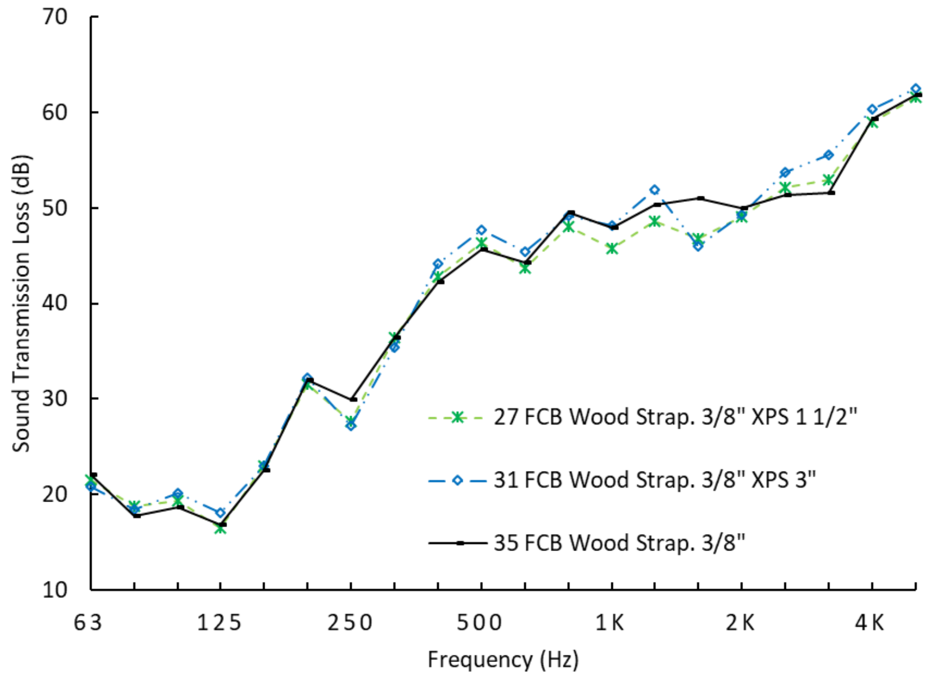


Figure 5.12. Sound transmission loss versus 1/3 octave frequency for FCB single insulation 3/8" rainscreen cavity wall and XPS split insulated 3/8" rainscreen cavity walls.

The fiber cement board single insulation 1" rainscreen cavity wall assembly was the next compared wall, as illustrated in Figure 5.13. The exterior mineral wool promoted higher transmission loss compared to a single insulation wall for this case.

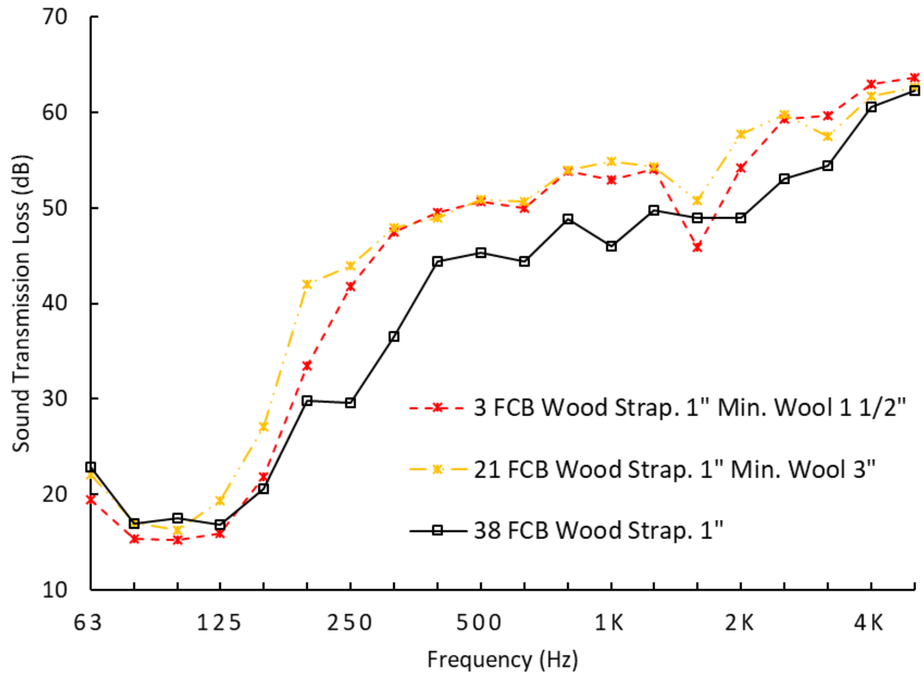


Figure 5.13. Sound transmission loss versus 1/3 octave frequency for FCB single insulation 1" rainscreen cavity wall and mineral wool split insulated 1" rainscreen cavity walls.

On the other hand, XPS did not bring an equivalent level of improvement to the split insulated wall comparable to mineral wool. XPS as exterior insulation seemed to be slightly better than single insulation but these results might have been influenced by the sheathing-to-cladding distance in the case of the 3" XPS. Figure 5.14 presents the results for XPS exterior insulation compared to single insulation wall.

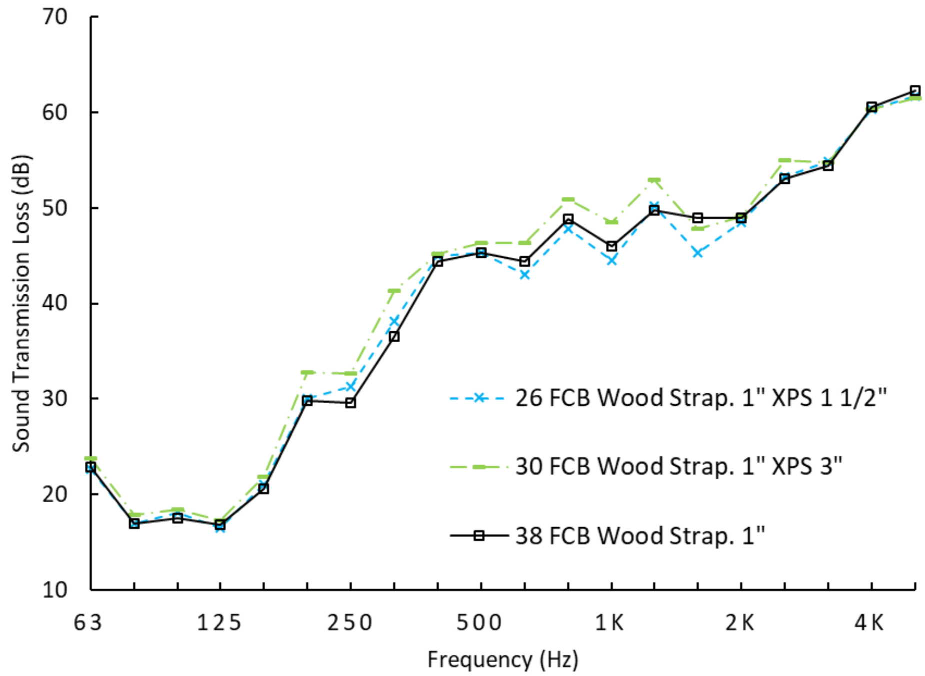


Figure 5.14. Sound transmission loss versus 1/3 octave frequency for FCB single insulation 1" rainscreen cavity wall and XPS split insulated 1" rainscreen cavity walls.

Figure 5.15 shows the sound transmission loss for vinyl cladding mineral wool split insulated 3/8" rainscreen cavity wall and vinyl single insulation 3/8" rainscreen cavity. In general, results for the mineral wool split insulated indicated better performance, or higher transmission loss, than single insulation wall.

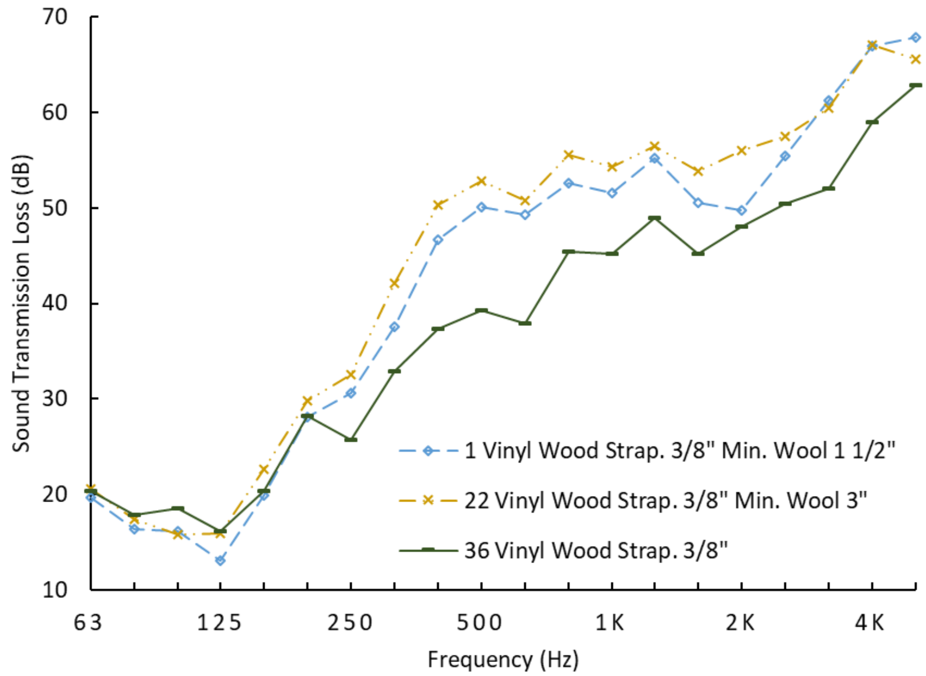


Figure 5.15. Sound transmission loss versus 1/3 octave frequency for vinyl mineral wool split insulated 3/8" rainscreen cavity walls and vinyl single insulation 3/8" rainscreen cavity wall.

Figure 5.16 shows the results for sound transmission loss for vinyl cladding XPS split insulated 3/8" rainscreen cavity wall and vinyl single insulation 3/8" rainscreen cavity wall. As can be noticed, results for the XPS split insulated indicated equal performance to single insulation wall. In the case of a lighter cladding, the sheathing-to-cladding effect was not as effective as for heavier claddings such as FCB and stucco; therefore, when XPS was used, the marginally improved TL was not observed.

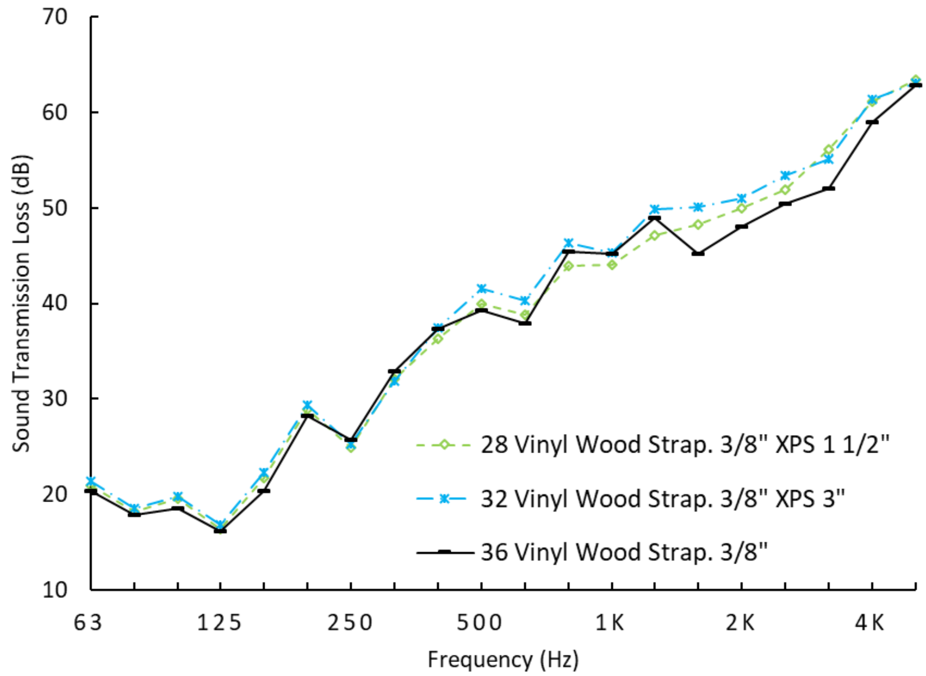


Figure 5.16. Sound transmission loss versus 1/3 octave frequency for vinyl XPS split insulated 3/8" rainscreen cavity walls and vinyl single insulation 3/8" rainscreen cavity wall.

Figure 5.17 shows sound transmission loss for vinyl mineral wool split insulated 1" rainscreen cavity wall and vinyl single insulation 1" rainscreen cavity wall. Similar to the other vinyl mineral wool walls, the change in TL was remarkable, highlighting the importance of materials' combination in a wall if superior performance is needed. Mineral wool helped the wall overcome the low performance of vinyl cladding material.

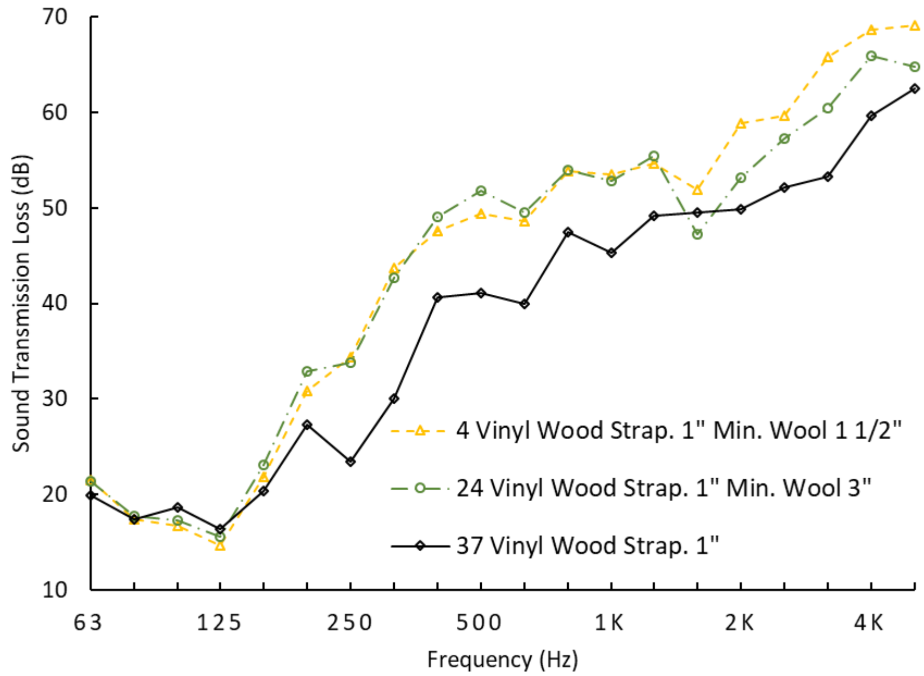


Figure 5.17. Sound transmission loss versus 1/3 octave frequency for vinyl mineral wool split insulated 1" rainscreen cavity walls and vinyl single insulation 1" rainscreen wall.

The last comparison is illustrated in Figure 5.18, which presents the sound transmission loss for vinyl XPS split insulated 1" rainscreen cavity wall and vinyl single insulation 1" rainscreen cavity wall. To a large degree, the XPS split insulated wall had nearly identical transmission loss to the single insulation wall.

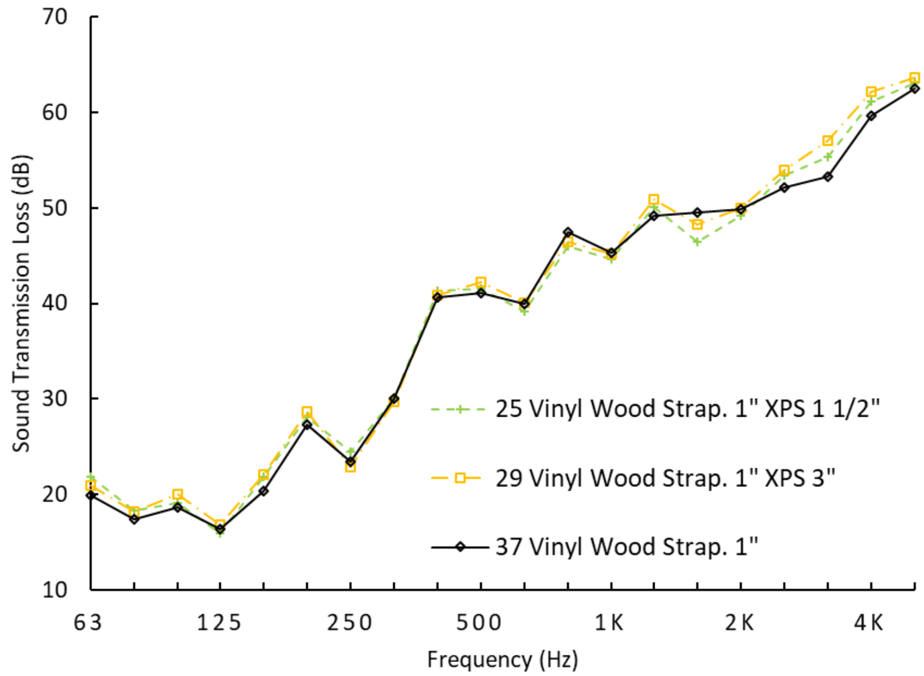


Figure 5.18. Sound transmission loss versus 1/3 octave frequency for vinyl XPS split insulated 1" rainscreen cavity walls and vinyl single insulation 1" rainscreen wall.

5.2.4 Cladding Material

Figure 5.19 presents the result of a comparison among stucco, vinyl, and FCB walls, all having 3/8" wood strapping and 1 ½" XPS exterior insulation.

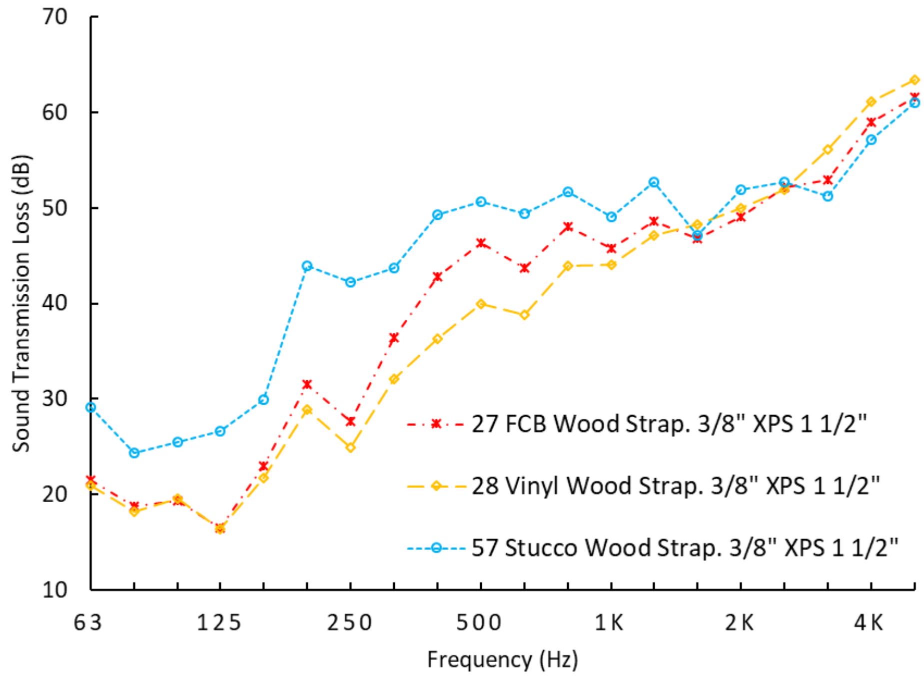


Figure 5.19. Sound transmission loss comparison between stucco 3/8" wood strapping 1 ½" XPS wall and FCB and vinyl walls.

It can be seen that the stucco wall performed significantly better up to 1250 Hz. This result showed the impact of the thicker and denser stucco cladding. Table 4 presented that stucco had nearly four times the mass surface density of FCB and 27 times higher than vinyl. The most significant and important impact was from 63 to 250 Hz where a wall usually poorly performs and which greatly affects the low frequency performance. Certainly, the higher performance for stucco at low frequencies impacted the single-rating numbers OITC and STC.

Figure 5.20 illustrates a comparison between stucco wall 3/8" wood strapping 1 ½" mineral wool and similar walls configured with vinyl and FCB claddings. Again, the stucco wall demonstrated substantial improvement at low frequency bands compared to the other two cladding materials. The superior performance was observed from 63 to 500 Hz. A comparison between the graphs from Figure 5.19 and Figure 5.20 showed that stucco had positive performance between 63 and 1250 Hz, and between 63 and 500 Hz, respectively. The TL difference between 500 Hz and 1250 Hz spectrum from both graphs suggested that the addition of 1 ½" mineral wool instead of 1 ½" XPS was responsible for the difference between the two sound transmission loss curves. The inversion tendency observed at a higher frequency is of minor consideration due to elevated sound transmission loss levels at this range.

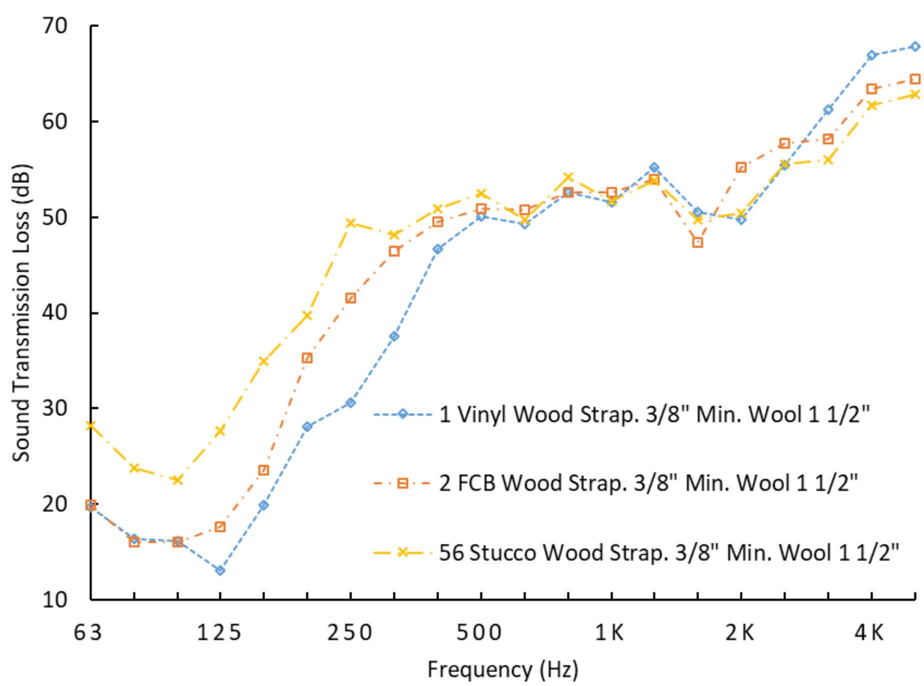


Figure 5.20. Sound transmission loss comparisons for stucco 3/8" wood strapping 1 ½" mineral wool wall. Differences for FCB and vinyl walls.

Lastly, Figure 5.21 compares a stucco 3/8" wood strapping 3" mineral wool to similar walls configured with vinyl and FCB. Like the other two comparisons, the last figure also showed the positive outcomes for low frequency sound transmission loss. The gains were better from 63 to 315 Hz compared to vinyl, and from 63 to 250 compared to FCB, exactly at a low frequency range that can impact STC and OITC, but similar to other stucco walls in a range where some people are more sensitive to sound. A slight reduction in the range where stucco presented a higher impact may be attributed to a thicker mineral wool insulation. The introduction of a 3" mineral wool (or doubling the mineral wool insulation thickness) reduced the range from 630 Hz (Figure 5.20) to 250 and to 315 Hz for FCB and vinyl, respectively (Figure 5.21). Figure 5.21 presents a trend change at 800 Hz, and the stucco wall performed more poorly than vinyl and FCB between 1K and 5K Hz, with a higher TL dip at 1.6K and 2K Hz. Except for the accentuated dip, this lower TL result may be considered of minimal consequences to the overall behaviour because transmission loss at this frequency range was about 50 to 55 dB.

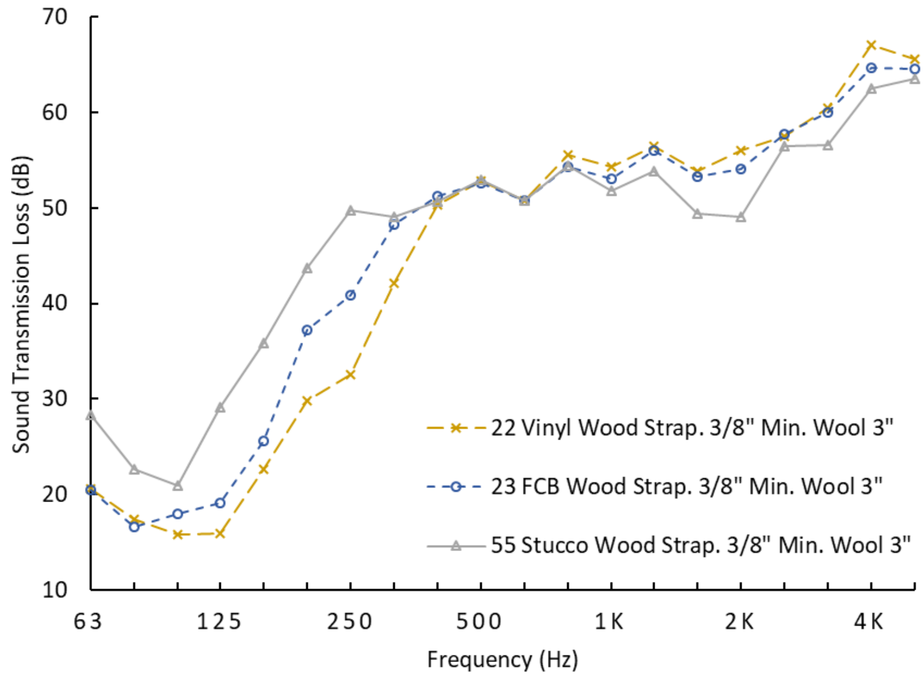


Figure 5.21. Sound transmission loss comparison for stucco 3/8" wood strapping 3" mineral wool wall. Differences for FCB and vinyl walls.

In all 3 comparisons, stucco walls presented their lowest TL values in a lower frequency band and the effect of a massive cladding was the likely cause. Equation (4) described the relation between panel bending stiffness, which, in turn, varies with the cubic of thickness, and panel surface mass density. It implicitly stated that if mass increases, the panel resonance decreases or if thickness increases, the panel resonance increases. There is always a trade-off, and the stucco surface mass density offset the balance between mass density and stiffness and lowered the ribbed structural resonance to lower levels for wood strapping attachment.

Figure 5.22 presents the transmission loss curves for the 3 tested stucco walls. Differences among them suggested, in terms of sound insulation material, accordance with London (1950) that heavier walls would be minimally affected by the addition of insulation. In this study, the stucco XPS wall, with the least sound absorptive material, presented for almost all frequency bands very small differences compared to stucco and mineral wool insulation walls, whereas results indicated higher differences in transmission loss for light panels, specifically FCB and vinyl cladding panel, when compared among XPS and mineral wool insulation walls. Higher differences at 250 and 315 Hz and smaller differences below 200 Hz might be attributed to the stiffness promoted by XPS in combination with wood strapping.

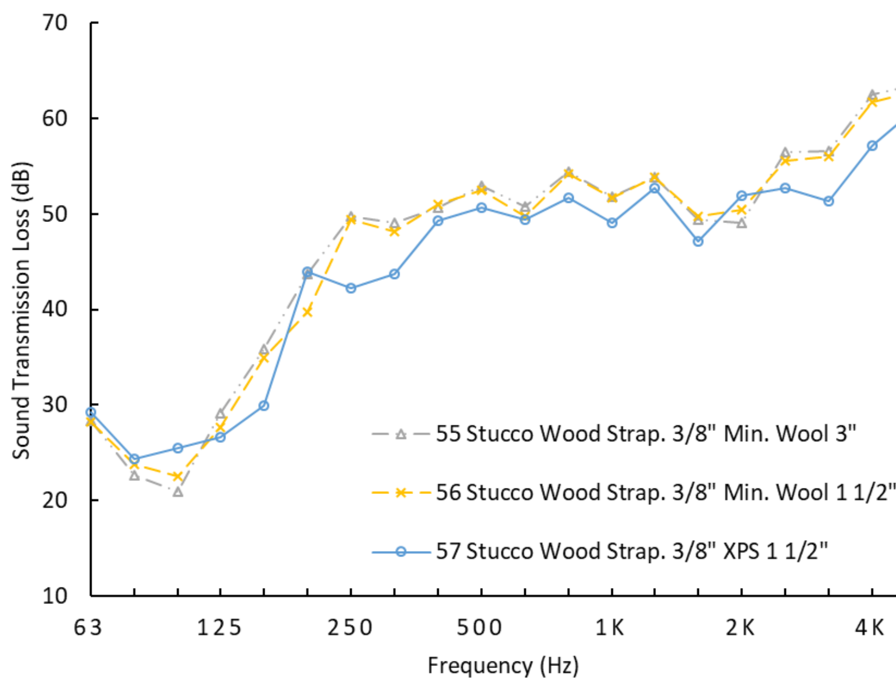


Figure 5.22. Sound transmission loss versus 1/3 octave frequency for stucco walls.

FCB and stucco walls might also have benefitted by their respective wall configurations in which the two cladding materials were simultaneously the heaviest panels and incident sound panel. Particularly in XPS insulation walls, two aspects contributed to a higher TL for these wall types. This benefit comes not only from a higher mass of the overall triple panel system but also from the advantage provided by being at the same time the outer and the heaviest panels as pointed out by Xin and Lu (2011) and Vinokur (1990). Gypsum and plywood boards had nearly equal surface mass densities (see Table 4). Vinyl cladding had much lower surface density whereas FCB and stucco had greater than the two inner boards.

The mass-law herein discussed is the mass impedance of the wall panels. The effect of mass to sound transmission is to serve as a discontinuity medium in which a sound wave being transmitted through air faces a change in pressure and velocity. Mass reacts to the incoming wave, altering pressure and velocity, originating a reflected sound wave and leaving some of the original wave propagating through the material, or a new medium. Depending on the material surface mass density there will high or low reflection, consequently low or high transmission, respectively. The impedance of a massive cladding creates high reflection and low transmission (e.g. stucco and FCB), whereas a lighter cladding (e. g., vinyl) produces low reflection and high transmission through the panel. Results corroborated the mass-law and the mass impedance of the tested walls through TL differences for the three cladding types: stucco, FCB, and vinyl.

The graphs in Figure 5.23 and Figure 5.24 present FCB and vinyl walls' sound transmission loss curves, respectively, and straight lines that fit the mass-law relation (Equation 6) to the measured data in an angle-dependent sound incidence. The 6dB/octave lines showed the range where the measured TL data usually fell into the mass-law relation, consequently supporting the agreement between the mass-law theory and the measured data. The range may vary one or two 1/3 octave bands up or down, and the mass-law line may also rise or lower many dB depending on the wall configuration, mainly on cladding and insulation. These range variations and mass-law parallelism corroborated the influence of cladding attachments and their stiffness, the effect of insulation, and materials' surface mass density. Between the lowest TL level at low frequency and the point where the mass-law takes place, sound transmission is dominated by stiffness. This means that during the ascending curve, flexible attachments allied with heavier cladding and sound absorptive insulation will likely deliver higher TL levels at a lower frequency, resulting in a mid- to high-frequency range of elevated loss. Figure 5.23 resembled Figure 2.1 from the literature review that showed the general graph for sound transmission loss for a single panel. Obviously, being a triple panel wall assembly, this graph needed more complex phenomenon added to the general case of that a single panel.

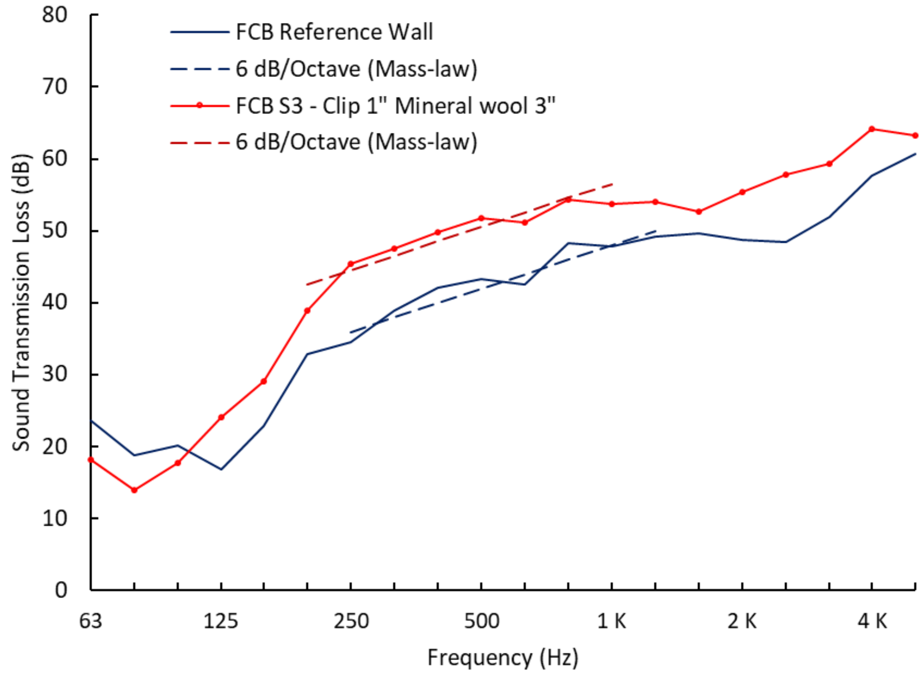


Figure 5.23. Mass-law and FCB walls sound transmission loss curves.

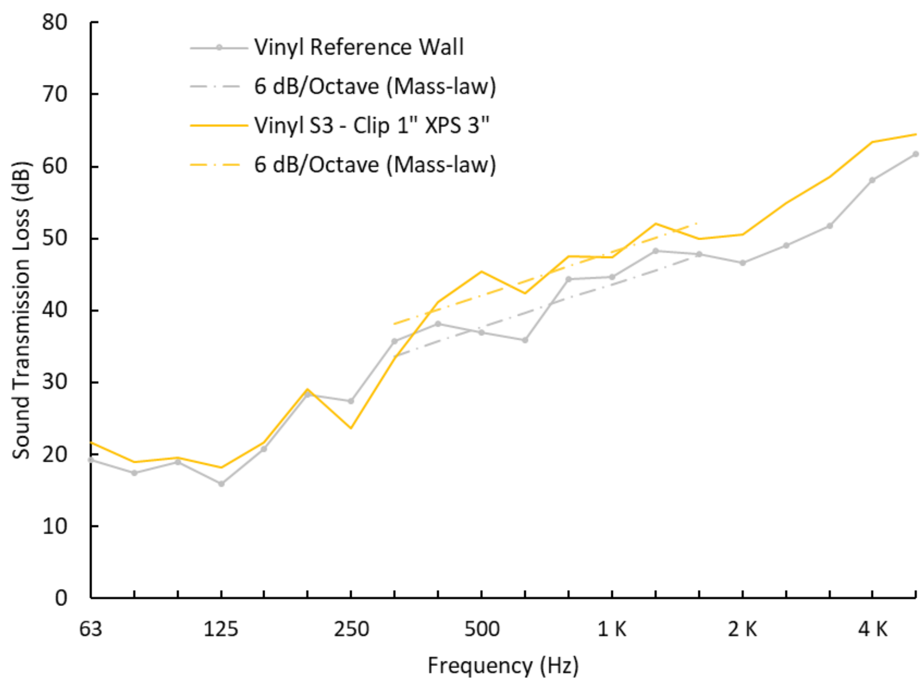


Figure 5.24. Mass-law and vinyl walls sound transmission loss curves.

It must be noted that the fiber cement board and vinyl claddings were installed as siding. The FCB siding was built using cement board planks, and vinyl siding was built with smaller profiled panels. They were not whole, big, and flat boards installed on top of either sheathing or attachments. Theories regarding single panels consider an idealized situation where conditions tend to be uniform and simplistic. The actual conditions might have altered the cladding influence such as stiffness, panel resonance, and small gaps in between the overlapped edge boards.

A second approach to analyzing the cladding materials is calculating the differences and averaging the sound transmission loss data from 48 walls having the exact same configuration aside from the cladding layer.

In general, Figure 5.25 shows that FCB had on average higher transmission loss compared to vinyl from 125 to 2500 Hz. For the three lowest frequencies, vinyl had a slightly better performance than FCB, although it can be considered negligible. On the higher range, from 3150 to 5000 Hz, again the situation inverted and vinyl had better performance. It must be noted that for all walls in general the sound transmission loss at frequencies from and above 2500 Hz was higher than 50 dB. It means that such differences in TL at these levels of losses can be given less significance. The gain associated with the usage of FCB instead of vinyl is of considered value, but inferior to that of exterior insulation itself. The results showed a gain at 250 Hz of approximately 7 dB, and from 200 to 800 Hz it increased above 2 dB.

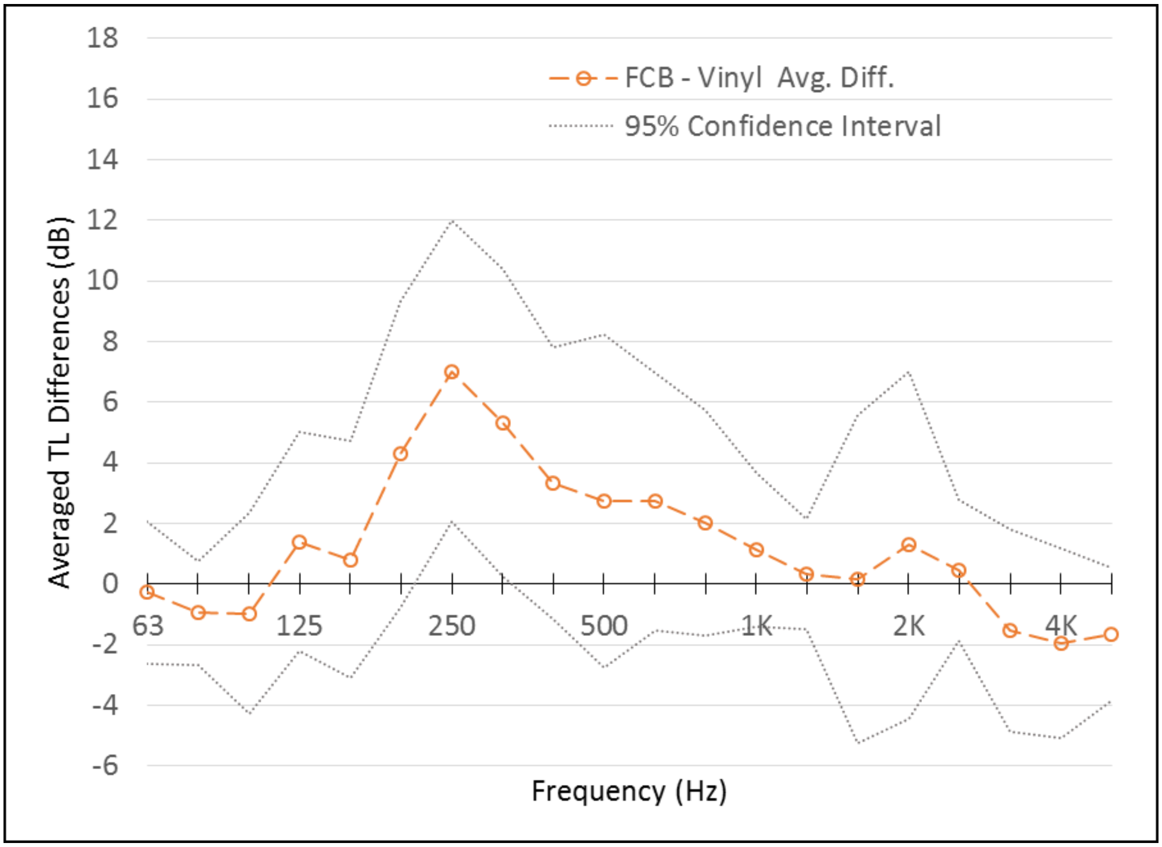


Figure 5.25. Averaged transmission loss differences versus 1/3 octave frequency for cladding material. Values presented for differences between fiber cement board and vinyl.

5.2.5 Exterior Insulation

Figure 5.26 and Figure 5.27 show examples in which the two tested insulation materials (mineral wool and XPS) were compared. Figure 5.26 presents a comparison between 3" mineral wool and 3" XPS while other wall layers were identical. The depicted curves showed that mineral wool had higher TL than XPS for most of the frequency range (from 125 to 5K Hz). This situation was typical for comparisons between insulation materials. As previously noticed, there was a change in TL at 80 and 100 Hz where XPS performed slightly better than mineral wool.

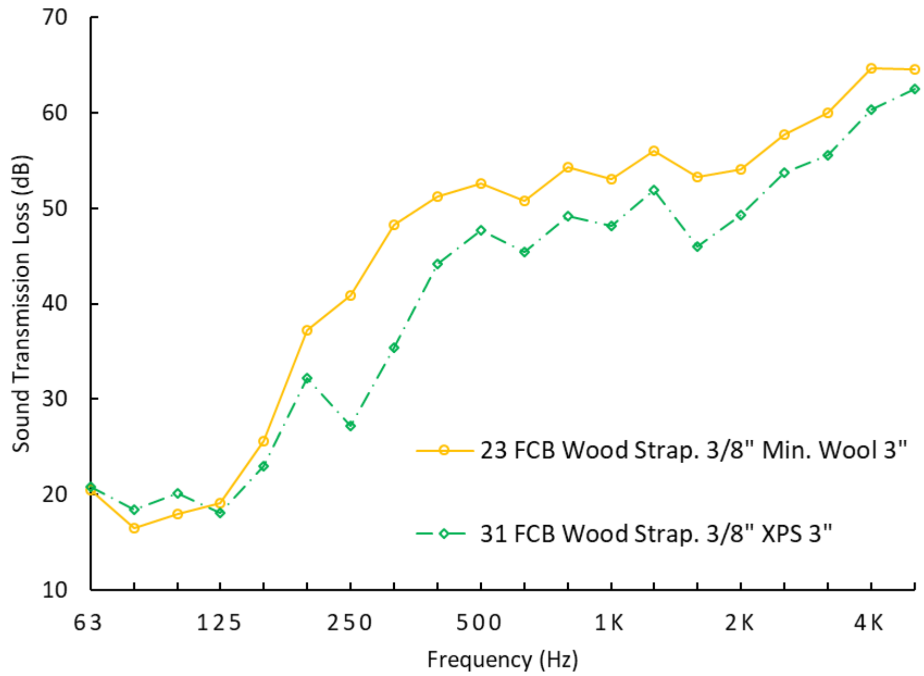


Figure 5.26. Sound transmission loss versus 1/3 octave frequency for FCB S1 - wood strapping 3/8" rainscreen cavity 3" mineral wool and 3" XPS exterior insulation walls.

Figure 5.27 presents another wall configuration in which the insulation materials were 1 ½" XPS and 1 ½" mineral wool. These walls had vinyl wood strapping 1" rainscreen cavity layers in both cases. The observed trend from Figure 5.26 was also repeated in this comparison and for most of the frequency range mineral wool had higher TL than XPS. Again, only at low frequency octave bands, XPS had marginally better TL than mineral wool.

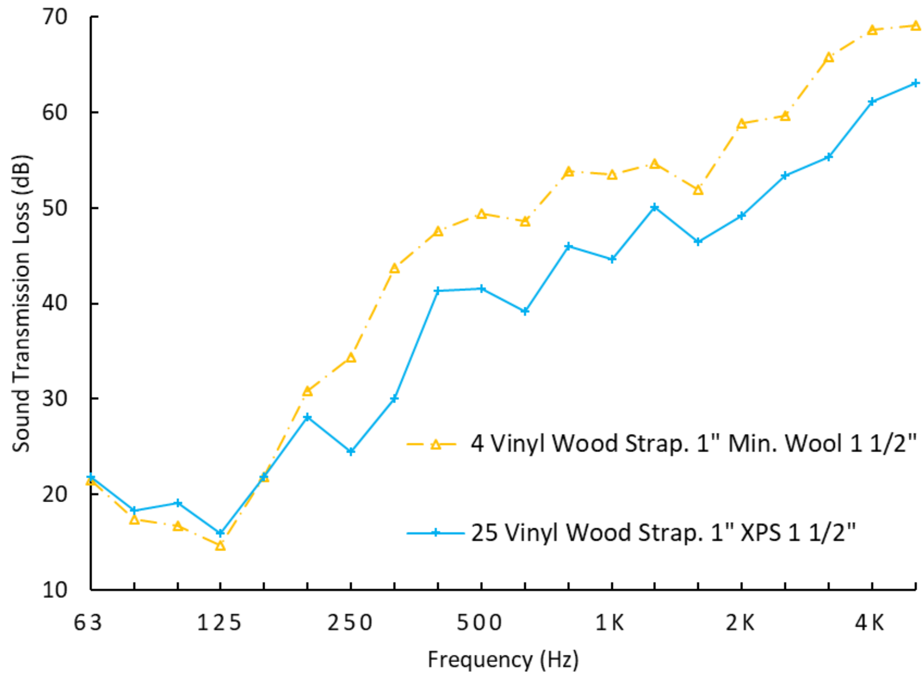


Figure 5.27. Sound transmission loss versus 1/3 octave frequency for vinyl S1 – wood strapping 1" rainscreen cavity 1 ½" mineral wool and 1 ½" XPS exterior insulation walls.

The broad range of higher transmission loss for the mineral wool insulation was clear, starting from 125 up to 5 KHz. A close observation from this graph shows that mineral wool had a slightly poorer performance than XPS for the three lowest frequency bands. As mentioned by Cox and D'Antonio (2016), it might be that this material provided sound absorption to some extent from 63 to 100 Hz. No acoustical properties for the used XPS were found from the manufacturer that could be linked to a higher sound absorption at lower frequencies. It was not possible to analyse the effect of insulation's rigidity between mineral wool and XPS that could have interfered with sound transmission.

Figure 5.28 shows a comparison between vinyl S3 3/8" mineral wool 1 ½" and vinyl S3 1" XPS 3" walls. This graph emphasized the difference between the two insulation materials. A ½" of mineral wool presented better results than a 3" XPS insulation. The mineral wool wall had even a smaller sheathing-to-cladding distance and for most of the mid- to high-frequency range, mineral wool had much better performance. At low frequency (from 63 to 125 Hz) and at two higher frequencies, XPS had slightly higher TL than mineral wool.

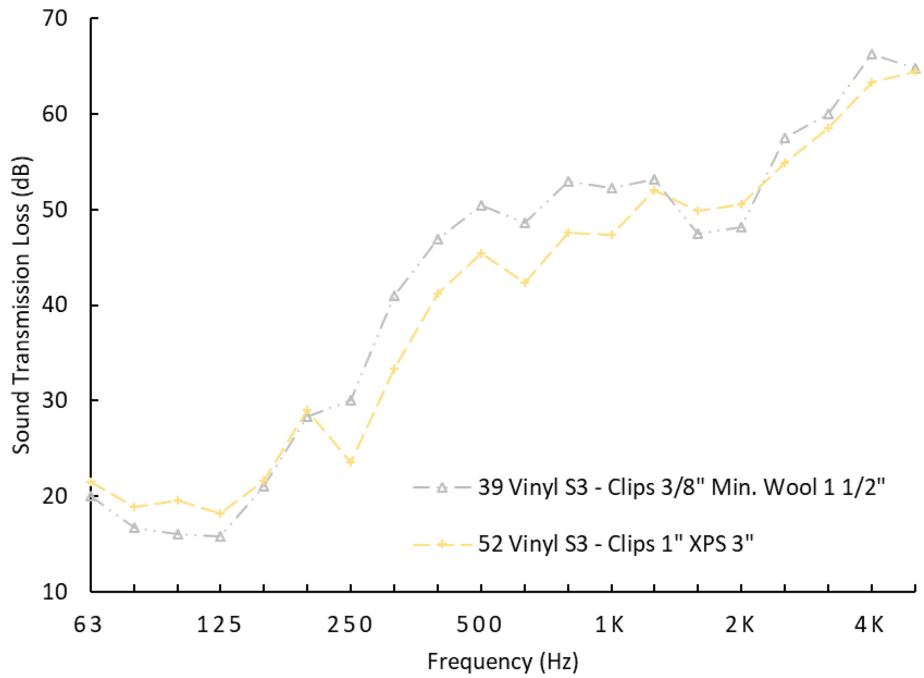


Figure 5.28. Sound transmission loss versus 1/3 octave frequency for vinyl S3 3/8" rainscreen cavity 1 ½" mineral wool and vinyl S3 1" cavity width 3" XPS walls.

Figure 5.29 shows a similar comparison but for FCB and S2 walls. 1 ½" of mineral wool insulation presented higher TL from 160 to 5K Hz frequency bands. Only at the 100 Hz band was XPS better than mineral wool. Again, even a higher cladding to sheathing distance for the XPS wall (whose effect was intensified in an FCB wall) did not offset a poorer performance for XPS insulation.

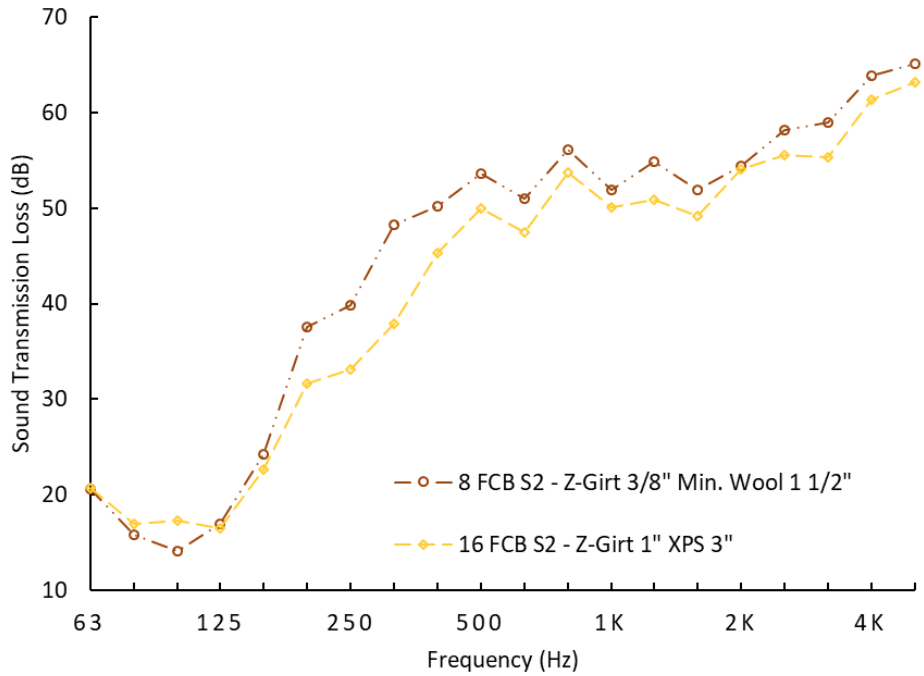


Figure 5.29. Sound transmission loss versus 1/3 octave frequency for FCB S2 3/8" rainscreen cavity 1 ½" mineral wool and FCB 1" cavity width 3" XPS walls.

The last two presented figures highlighted the importance of the insulation material to a split insulated wall. It can be decisive in terms of providing a substantial improvement or not. A proper choice even with a small thickness might be preferred over a thick and non-absorptive material.

Values for flow resistivity were not found for XPS insulation, perhaps due to its non-sound absorptive properties. Only values for opened cell foams were found, such as polyurethane (PU) and melamine foams. For these two foam types, values were from

4,500 to 12,900 rayl/m, and from 10,500 to 17,500 rayl/m, respectively. As for mineral wool, values ranged from 1,000 to 150,000 rayl/m (Cox & D'Antonio, 2016). The mineral wool range was wider and the upper limit much higher than for foams. This might indicate a poorer sound insulation performance for foams. Vigran (2008) presented in a graphical form the correlation between density and flow resistivity for mineral wool insulation. The measured mineral wool density of 123 Kg/m^3 gave an approximate value of 70,000 rayl/m. With this value as a reference, 38 mm (1 ½") and 76 mm (3") mineral wool had flow resistances of 2660 rayl and 5320 rayl, respectively. The flow resistivity and flow resistances values suggested agreement between the beneficial TL results and mineral wool absorption properties. Vigran (2008) pointed out that a high flow resistivity insulation material might offset a higher low-frequency attenuation at the expense of a lower mid- to high-frequency attenuation compared to a low flow resistivity material and both having the same thickness.

Another approach to investigating and quantifying the exterior insulation type is to look at the differences in performance. Mineral wool and XPS have distinct characteristics, consequently dissimilar transmission loss results were expected.

From 48 tested walls, mathematical differences in transmission loss between mineral wool and XPS were calculated. In this process, the only different layer (or variable) was the insulation material while all other variables were kept fixed for every pair of walls. As a result, 24 differences were taken and subsequently their mathematical average and interval confidence were obtained. Figure 5.30 below presents a graphical result for the impact of mineral wool compared to XPS as an exterior insulation material. The broad range of higher transmission loss for the mineral wool insulation is clear, starting from 125 up to 5 KHz. The impact of using this material can add up to 10 dB on average around 250 and 315 Hz, whereas in the mid frequency range from 200 to 1250 Hz, the improvement in transmission loss is quite constant and significant, at least 4 dB higher. A close observation from this graph shows that mineral wool had a slightly poorer performance than XPS for the three lowest frequency bands.

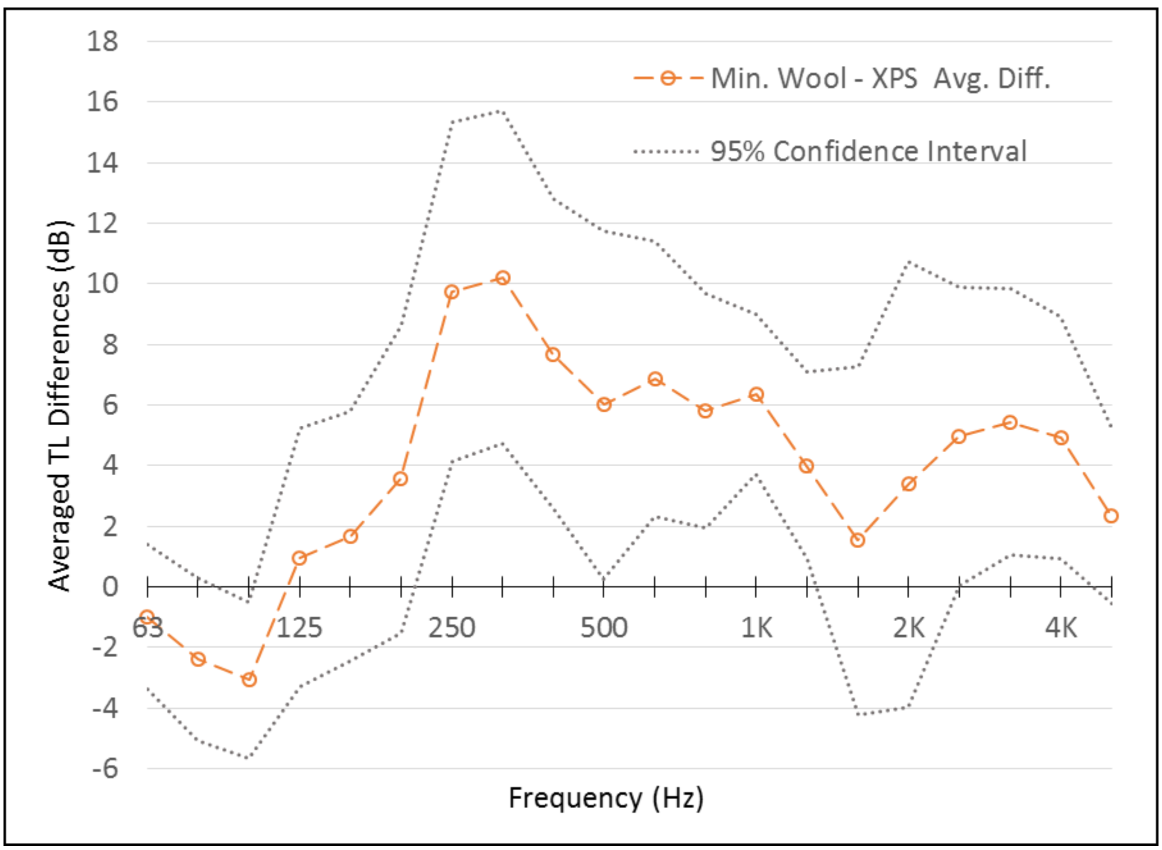


Figure 5.30. Averaged transmission loss differences versus 1/3 octave frequency for exterior insulation type. Values presented for differences between mineral wool and XPS exterior insulation.

5.2.6 Exterior Insulation Thickness

Two insulation thicknesses of mineral wool and XPS (3" and 1½") were tested and evaluated. Figure 5.31 shows an example of two of the tested walls whose insulation were of both thicknesses. This graph presents a comparison of vinyl S3 - Clip 3/8" rainscreen cavity and XPS exterior insulation walls. This graph represented a typical variation from 1½" to 3" of XPS where the observed changes were minimal to no impact. From the previous section about the insulation type, results showed that XPS had a much lower impact than mineral wool, indicating the XPS sound insulation properties. Therefore, in this section, results for differences in XPS thickness did not present remarkable differences.

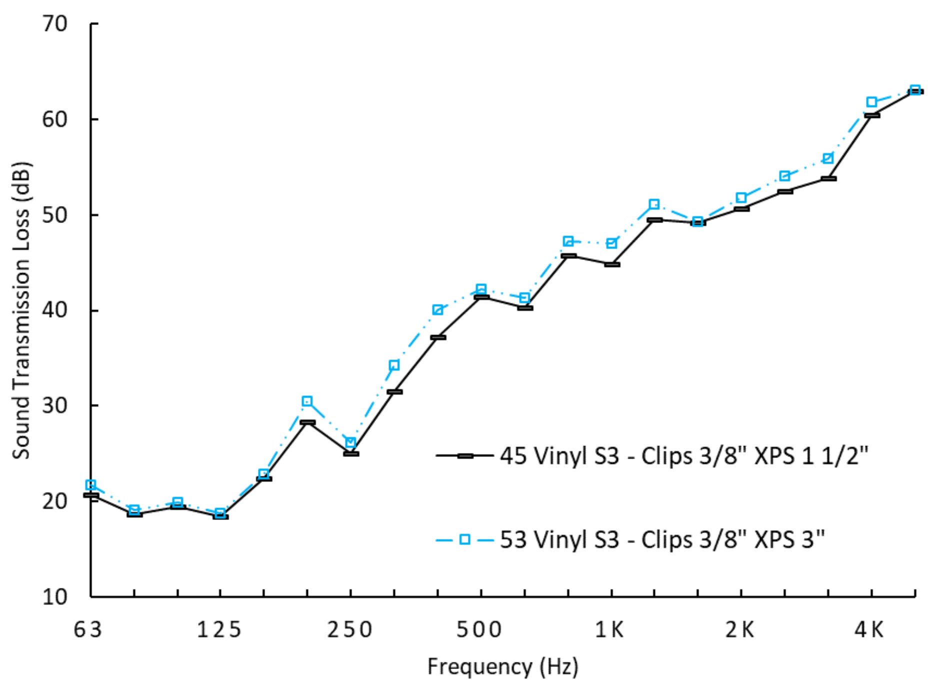


Figure 5.31. Sound transmission loss versus 1/3 octave frequency for vinyl S3 - clip 3/8" rainscreen cavity 1 ½" and 3" thicknesses XPS exterior insulation walls.

Figure 5.32 shows the comparison for FCB S2 – Z-girt 1" cavity width walls between 3" and 1 ½" XPS exterior insulation. Observe that there was virtually no improvement between the two thicknesses for FCB cladding walls.

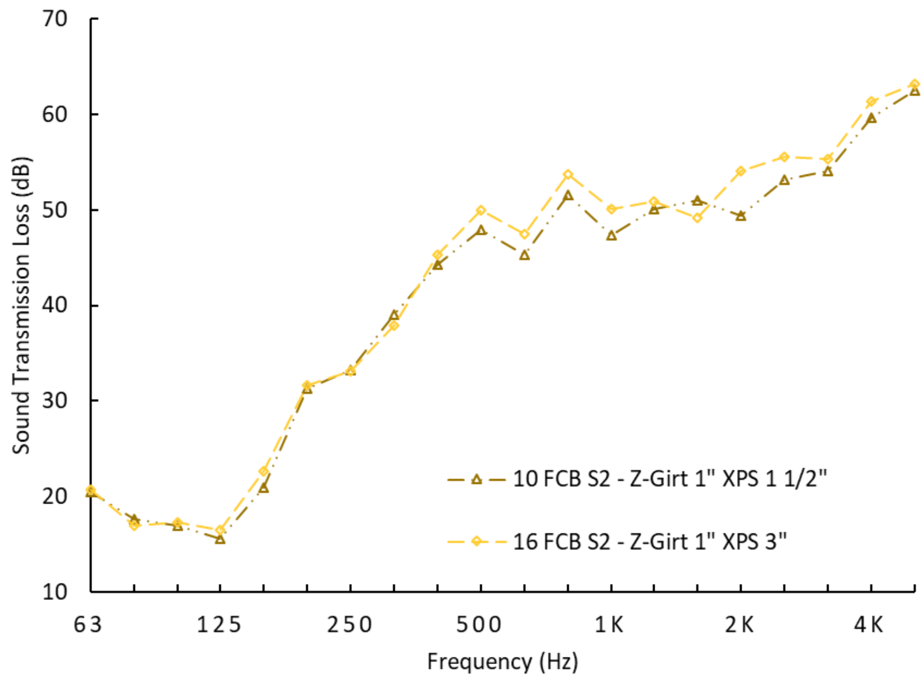


Figure 5.32. Sound transmission loss versus 1/3 octave frequency for FCB S2 – Z-girt 1" rainscreen cavity 1 ½" and 3" thicknesses XPS exterior insulation walls.

Figure 5.33 shows a comparison between mineral wool insulation thicknesses. This graph also represents a typical change from the 3" and 1 ½" thicknesses, in general. Mineral wool had a much higher TL impact than XPS insulation due to its sound insulation properties. 3" of mineral wool promoted small but significant TL changes at low- to mid-frequency bands. This result likely impacted STC and OITC single-number ratings.

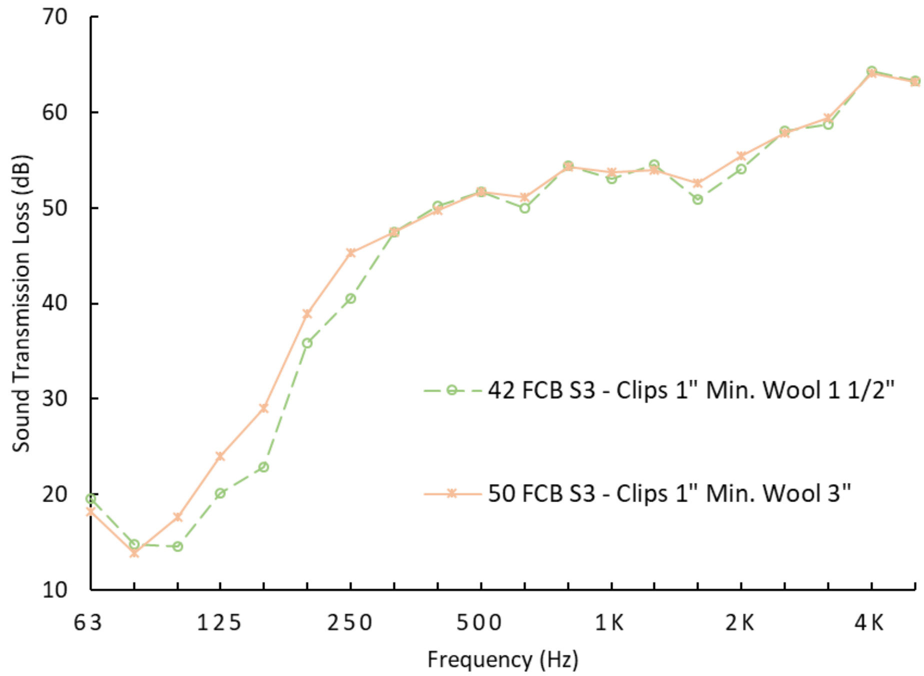


Figure 5.33. Sound transmission loss versus 1/3 octave frequency for FCB S3 - clip 1" rainscreen cavity 1 ½" and 3" thicknesses mineral wool exterior insulation walls.

Figure 5.34 shows another insulation thickness comparison for vinyl and mineral wool walls. Note that the curves indicated improvements at low and mid-frequencies similar to FCB cladding walls, and likely high enough to promote STC and OITC changes.

Doubling insulation thickness resulted in significant TL differences at low- to mid-frequencies mainly for mineral wool walls. Thicker XPS insulation did not provide improvements due to its sound absorption properties. The small changes for XPS might be attributed to a higher sheathing-to-cladding distance than to XPS itself.

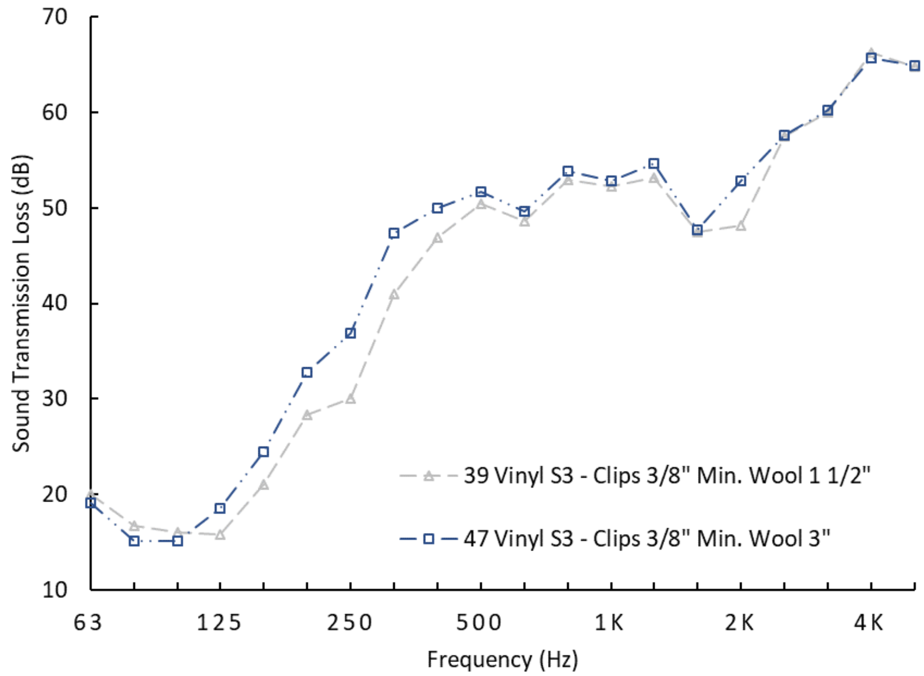


Figure 5.34. Sound transmission loss versus 1/3 octave frequency for vinyl S3 - clip 3/8" rainscreen cavity 1 ½" and 3" thicknesses mineral wool exterior insulation walls.

5.2.7 Effects of Cladding Attachment on Transmission Loss

Due to the introduction of an exterior cavity wall in a triple panel wall system, the outermost panel, or cladding material, needed to be attached to the main structural wall system. In this section, the three proposed attachment types are investigated. To evaluate their effects on TL performance, graphs were plotted in a frequency range from 63 to 1250 Hz. The layout is organized to consider the relationship of cladding type and insulation to cladding attachments: vinyl and mineral wool walls; FCB and mineral wool walls; FCB and XPS walls; vinyl and XPS walls. This presentation is followed by a summary discussion.

Figure 5.35, Figure 5.36, and Figure 5.37 present the transmission loss for vinyl cladding mineral wool exterior insulation walls for the S3, S2, and S1 attachments, respectively.

Figure 5.35 shows that the two 3" clips had the highest TL throughout the presented range. The curve suggested that the S3 attachment stiffness had a pivotal function in the way the curves approached the mid-frequency range. S3 attachment was the highest flexible combination; consequently, it allowed for this higher transition level. The two smallest distances were apart from the two upper curves, and this difference suggested insulation material absorption effect in place. The 1"+1 ½" and 3/8"+1 ½" combinations seemed to keep up with the highest TL levels only at 400 and 500 Hz, respectively. This result might indicate accordance with the calculated resonance frequencies for these cases, which were 414 and 477 Hz, respectively (see Table 10).

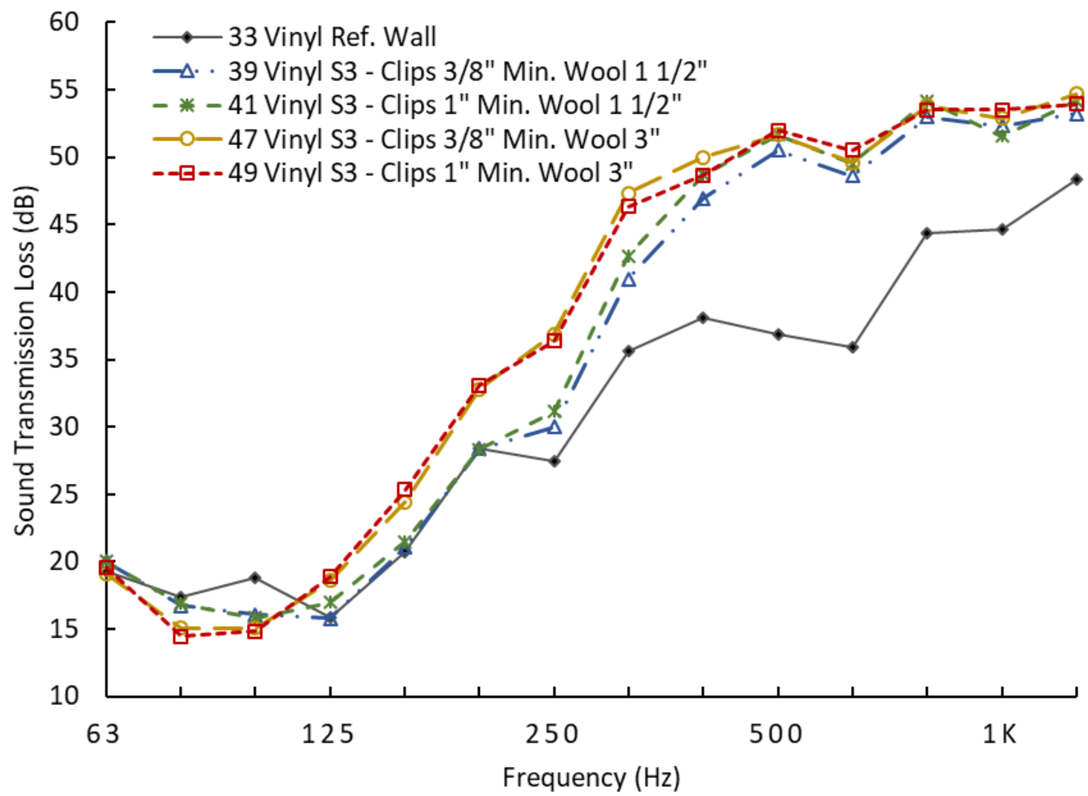


Figure 5.35. Sound transmission loss versus 1/3 octave frequency for vinyl S3 mineral wool walls.

Focusing on the low frequency range, Figure 5.35 shows that TL levels at 125 Hz changed to higher values for the 3" clips, whereas at 60 and 80 Hz, TL values lowered. The presented values suggested that the clip stiffness provided higher flexibility and consequently, a greater change in TL from 80 to 200 Hz. The slight differences in TL for the 3/8" and 1" rainscreen cavities combined with either the 3" and 1 ½" clips showed better results for the 1" profile.

Figure 5.36 shows that S2 attachment stiffness also influenced the low- to mid-frequency transition. Differences in stiffness between S2 and S3 might have influenced the closeness between the 3" and 1 ½" curves for S2 attachment at 200 Hz. At 250 and 315 Hz, the 3" and 1 ½" curves had larger differences that might have been caused by insulation thickness allied with higher flexibility. At 400 to 500 Hz, the four curves seemed to reach equivalent TL levels, indicating that from this point the total distance and insulation thickness difference did not influence the TL.

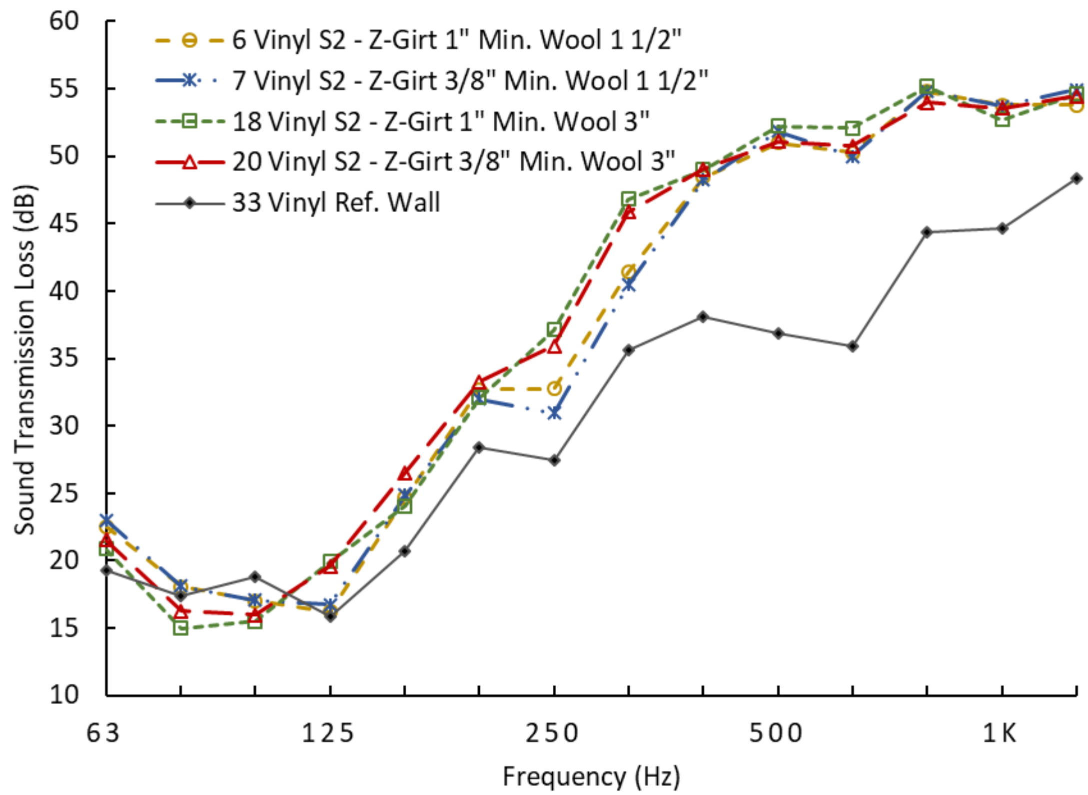


Figure 5.36. Sound transmission loss versus 1/3 octave frequency for vinyl S2 mineral wool walls.

Focusing on the low frequency range, Figure 5.36 suggested, in general, equal behaviour for the S2 attachment compared to S3, but with slightly smaller and higher differences among corresponding frequencies between 63 and 125 Hz. Only at 160 and 200 Hz, in Figure 5.36, did the 1 ½" walls have higher TL than S3 attachment.

Figure 5.37 indicated that the S1 attachment TL levels reached the 200 Hz influenced by its stiffness. At 250 and 315 Hz, the curves tended to suggest that the cavity width was the likely cause for differences when the two 3/8" curves were below the two 1" curves. In fact, the pattern suggested that the TL values were still caused and influenced by stiffness, and likely the wood strapping stiffness. A comparison to Figure 5.40 indicated that the cladding had an important influence. At 400 Hz, in Figure 5.37, there was an inversion and the two 3" curves presented higher TL whereas the two 1 ½" curves had lowest TL, corroborating the idea of thicker insulation material and likely total distance.

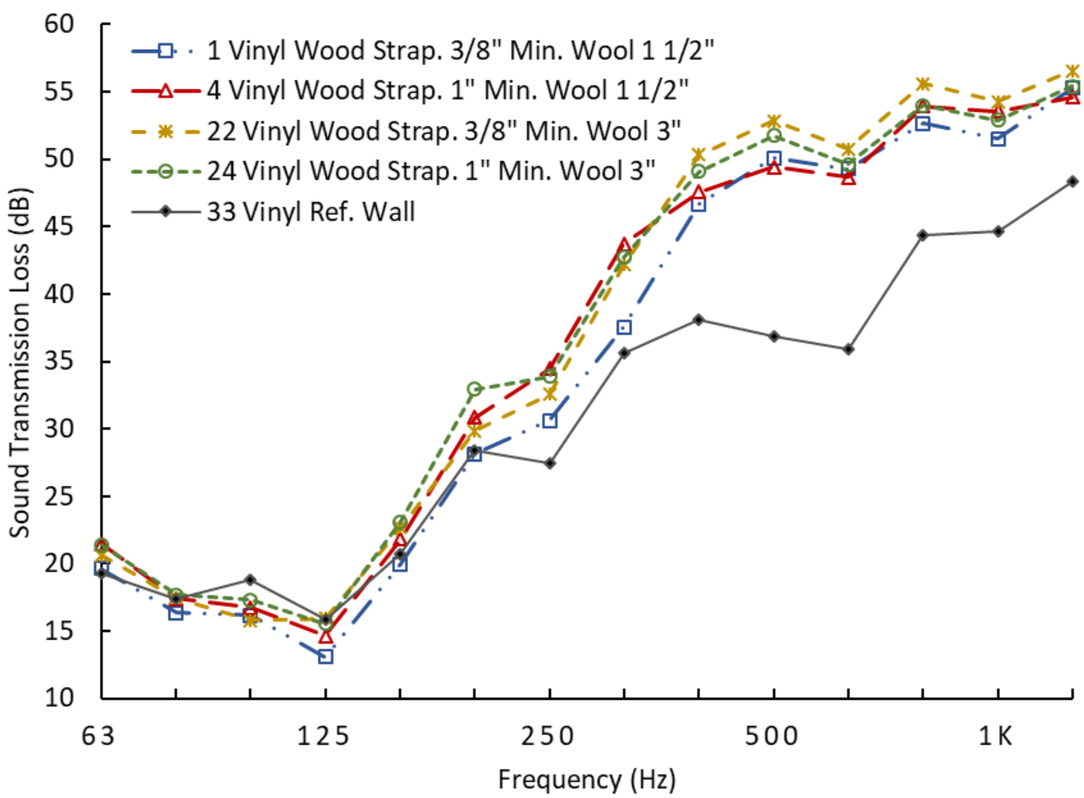


Figure 5.37. Sound transmission loss versus 1/3 octave frequency for vinyl S1 mineral wool walls.

As for S1 attachment, focusing on the low frequency range, Figure 5.37 shows that TL values at 125 Hz lowered, indicating a combined correlation between wood strapping profile allied with insulation thickness stiffness. This combination is of more intricate visualization because unlike S3 and S2, which had two attached profiles that eased the understanding of each stiffness profile, the S1 attachment had to be observed in a wall cross section manner. TL results for the S3 type suggested a stiffness increase in the wall system to all four wall combinations. The combination of 3/8" wood strapping and 1 ½" mineral wool presented the lowest performance, even lower than the reference wall from 80 to 160 Hz, suggesting highest stiffness.

Figure 5.35, Figure 5.36, and Figure 5.37 for vinyl and mineral wool showed significant changes in TL from 80 to 200 Hz range between S1 and the two attachments S2 and S3. The comparison between the three attachments indicated better results for S3 and S2, and that they added flexibility to the wall assemblies compared to S1 attachment. The three figures also suggested that the mass-law relation started when a change in the slope of the curves was observed. There was a visible change, which appeared to be at around 315 Hz and 400 Hz. From this point, the wall approximates a TL increase of 6 dB per octave increase.

Figure 5.38, Figure 5.39, and Figure 5.40 present the transmission loss for FCB cladding mineral wool exterior insulation walls for the S3, S2, and S1 attachments, respectively.

Figure 5.38 shows that the FCB and mineral wool had a similar trend to vinyl and mineral wool for the S3 attachment. The 3" curves approached way higher than the 1 ½" curves. Up to 315 Hz, the stiffness and thicker insulation were in place and results suggested a positive influence from these two variables. At 400 Hz, the four curves seemed to have equal TL levels, indicating equal TL from this frequency regardless of insulation thickness.

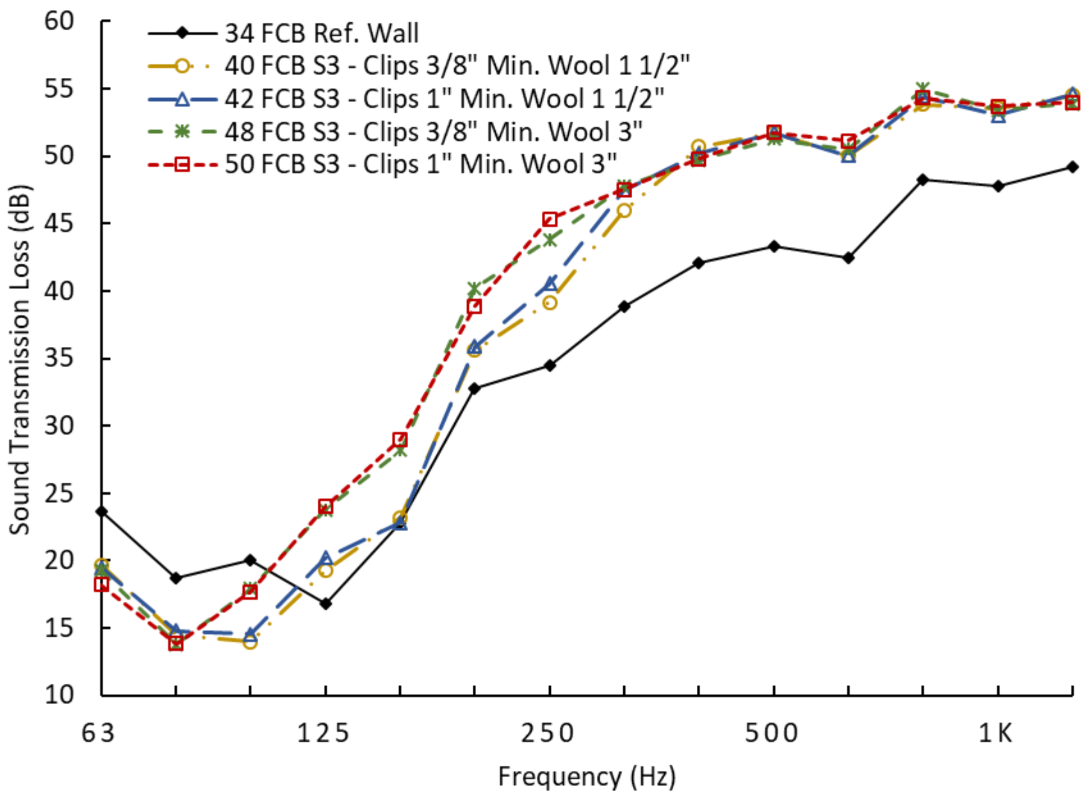


Figure 5.38. Sound transmission loss versus 1/3 octave frequency for FCB S3 mineral wool walls.

Focusing on the low frequency range, Figure 5.38 indicated lower stiffness to the 3" profile; thus, decreasing the lowest TL level to a lower frequency. The 3" clips curves indicated likely correlation to acoustical properties of mineral wool and cladding, taking over where the clips provided higher flexibility. This situation can be seen by comparing the vinyl and FCB graphs with mineral wool—all cases with S3 attachment. The clip which had the highest flexibility was the 3" and as such it allowed higher disconnection between panels.

Figure 5.39 shows that up to 250 Hz there was an influence from attachment stiffness and insulation thickness. The two 3" curves had higher TL than the two 1 ½" curves. This corroborated the broad influence of a less stiff attachment system.

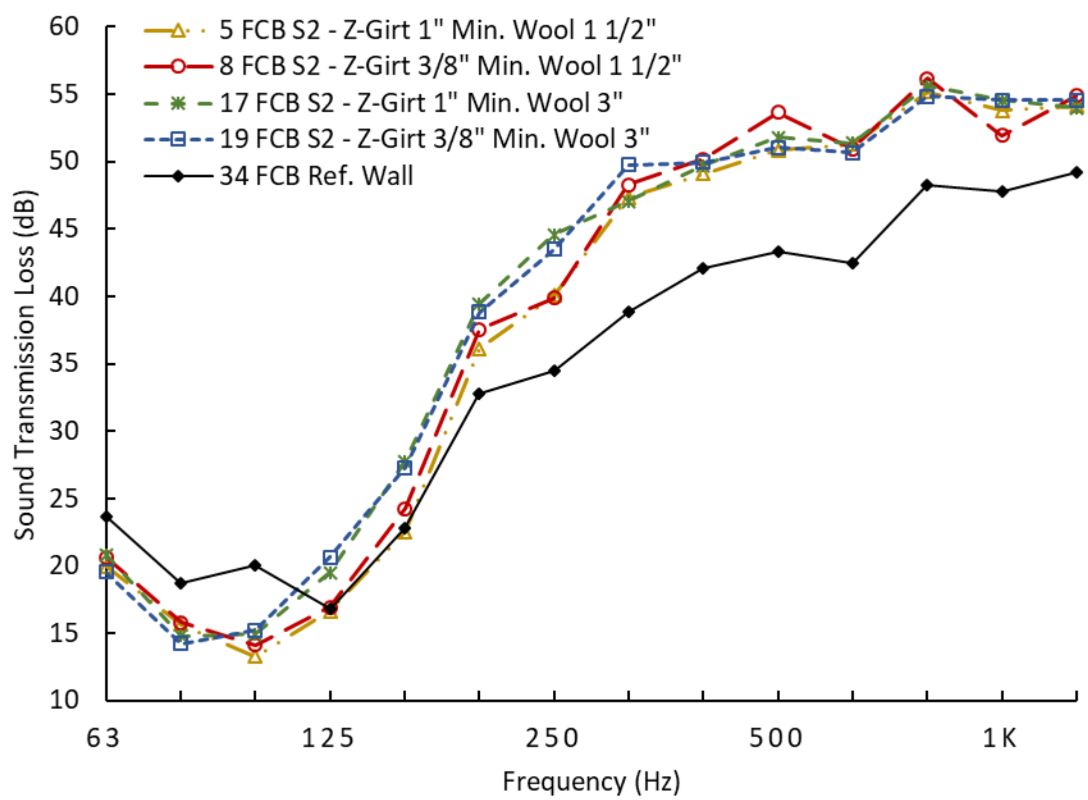


Figure 5.39. Sound transmission loss versus 1/3 octave frequency for FCB S2 mineral wool walls.

Focusing on the low frequency range, Figure 5.39 for the S2 type shows some similarity to the S3 attachment. The S2 presented lower TL values at lower frequencies while higher TL values in a higher frequency. This indicated lower stiffness provided by the 3" profile than the 1 ½" profile.

Figure 5.40 showed that up to 250 Hz the same correlation to stiffness was not clear at 250 Hz. At this frequency, only the 1"+3" had the highest TL value, whereas at 315 Hz the two 3" had slightly higher TL. At 400 and 500 Hz, the 3/8"+3" curve had the highest TL, whereas the other three walls had similar performance. These results suggested poor agreement between rainscreen cavity widths and TL levels. All graphs suggested that, for the FCB and mineral wool walls, the mass-law relation started around 200 Hz for the 1"+3" walls and around 315 Hz for the other walls.

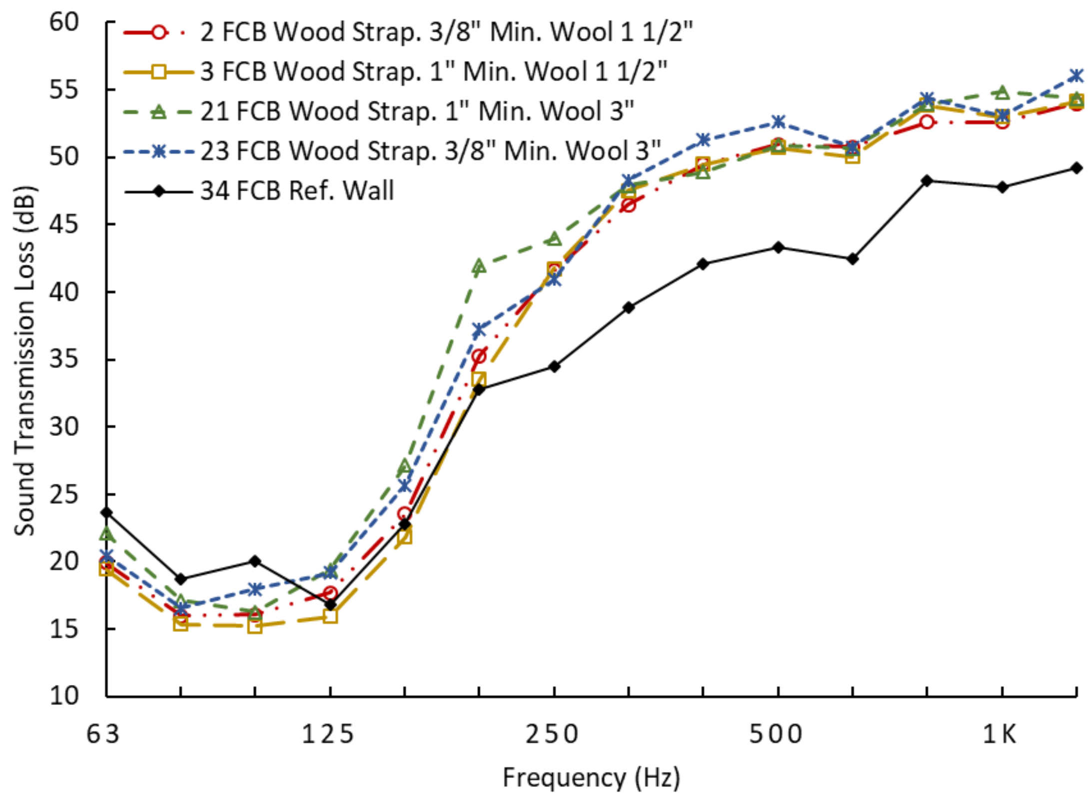


Figure 5.40. Sound transmission loss versus 1/3 octave frequency for FCB S1 mineral wool walls.

Focusing on the low frequency range, Figure 5.40 shows that the S1 type suggested a combined relation between wood strapping profile allied with insulation, or in other terms, the total stiffness. But the cladding material contributed to a higher TL than vinyl. The highest flexibility was provided by 3" insulation and 1" rainscreen cavity width. The lowest flexible combination was the 1 ½" insulation and 1" rainscreen cavity.

Figure 5.38, Figure 5.39, and Figure 5.40 suggested higher resilience for the S3 and S2 attachments compared to the S1 attachment, in general. The S3 and S2 results showed lower TL in a lower frequency band.

Figure 5.41, Figure 5.42, and Figure 5.43 present the transmission loss for FCB cladding XPS exterior insulation walls for the S3, S2, and S1 attachments, respectively.

Figure 5.41 shows a reduction in TL from 200 to 250 Hz followed by an increase up to 500 Hz. This trend resembled the other two attachment type walls. At 250 Hz, the TL levels still indicated correlation to their stiffness. Above 400 Hz the 1 ½" walls had the lowest TL indicating correlation to sheathing-to-cladding distance effect.

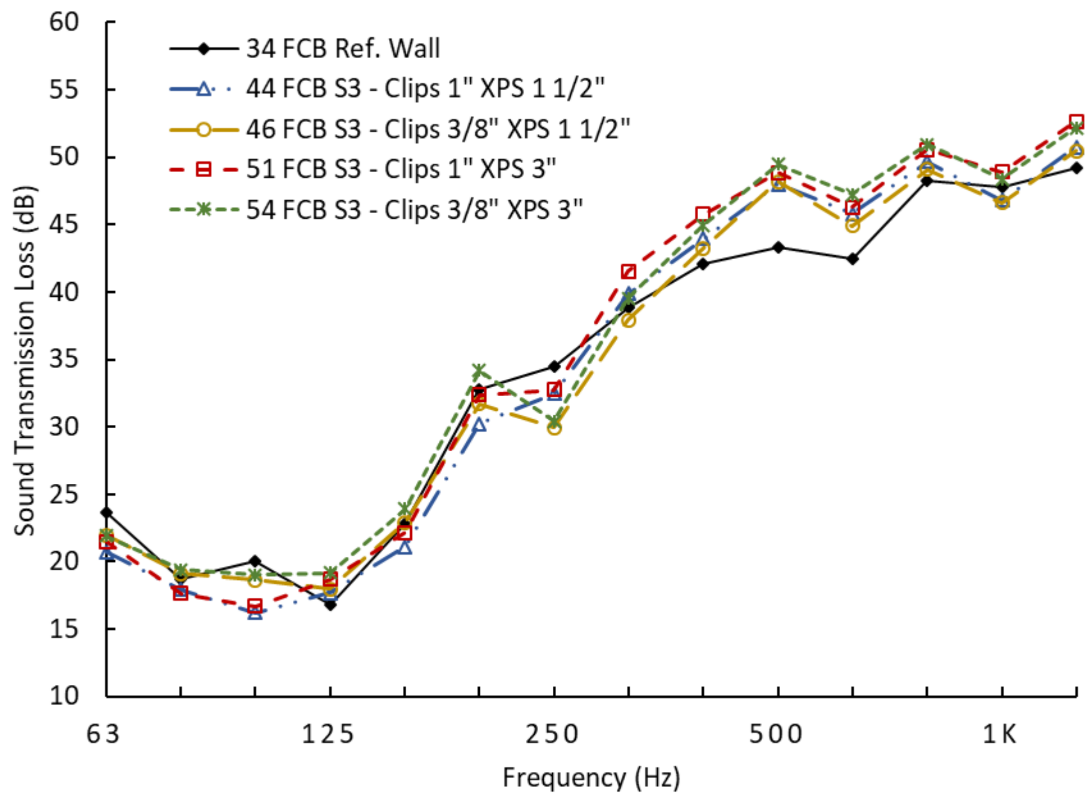


Figure 5.41. Sound transmission loss versus 1/3 octave frequency for FCB S3 XPS walls.

Focusing on the low frequency range, Figure 5.41 showed that FCB and XPS, at 125 Hz, had similar behaviour to vinyl and XPS when higher TL values suggested a slight flexibility of the wall at this frequency. TL values were higher than the respective reference walls at this frequency. The 3" clip presented the highest TL at 125 Hz whereas at 80 Hz the FCB TL curves suggested that the 1" cavity profile influenced the lower TL. This meant that the 1" cavity profile promoted lower stiffness to the system at this frequency level.

Figure 5.42 showed that the S2 Z-girt had a similar trend to the other walls with XPS insulation. A decrease in TL was followed by an increase up to 500 Hz. Above this frequency, the two 3" cavity width walls had the highest TL while the two 1 ½" had the lowest TL, suggesting a correlation to the cladding-to-sheathing increase in TL. At 250 Hz, the 3/8" rainscreen cavity walls had the lowest TL which could be attributed to stiffness and not necessarily to cavity width.

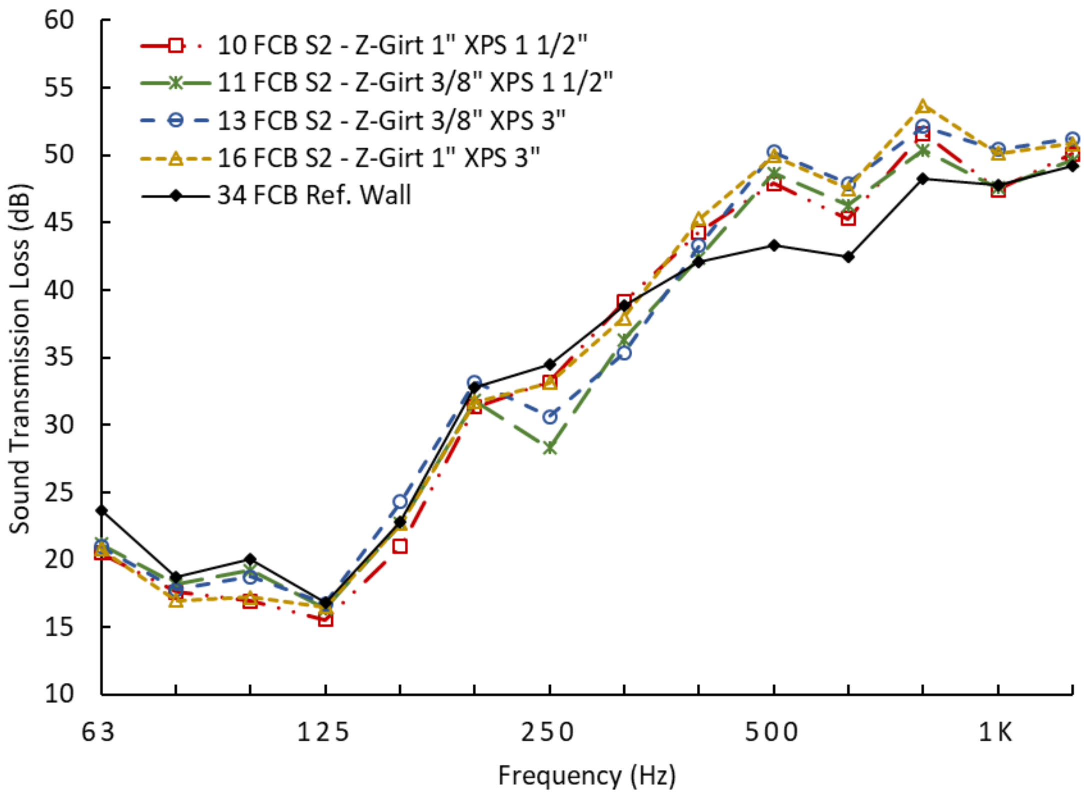


Figure 5.42. Sound transmission loss versus 1/3 octave frequency for FCB S2 XPS walls.

Focusing on the low frequency range, Figure 5.42 for S2 attachments suggested that the combination of rainscreen cavity profile stiffness was the likely cause for differences at 100 Hz when the two lowest TL were obtained from the 1" cavity width. Results from 63 to 125 Hz were worse than the reference wall.

Figure 5.43 showed that above 400 Hz there was a strong correlation of cladding and sheathing distance to TL values. From this frequency, the two 3" walls had highest TL values. At 250 and 315 Hz, differences between TL levels were likely correlated to attachment stiffness.

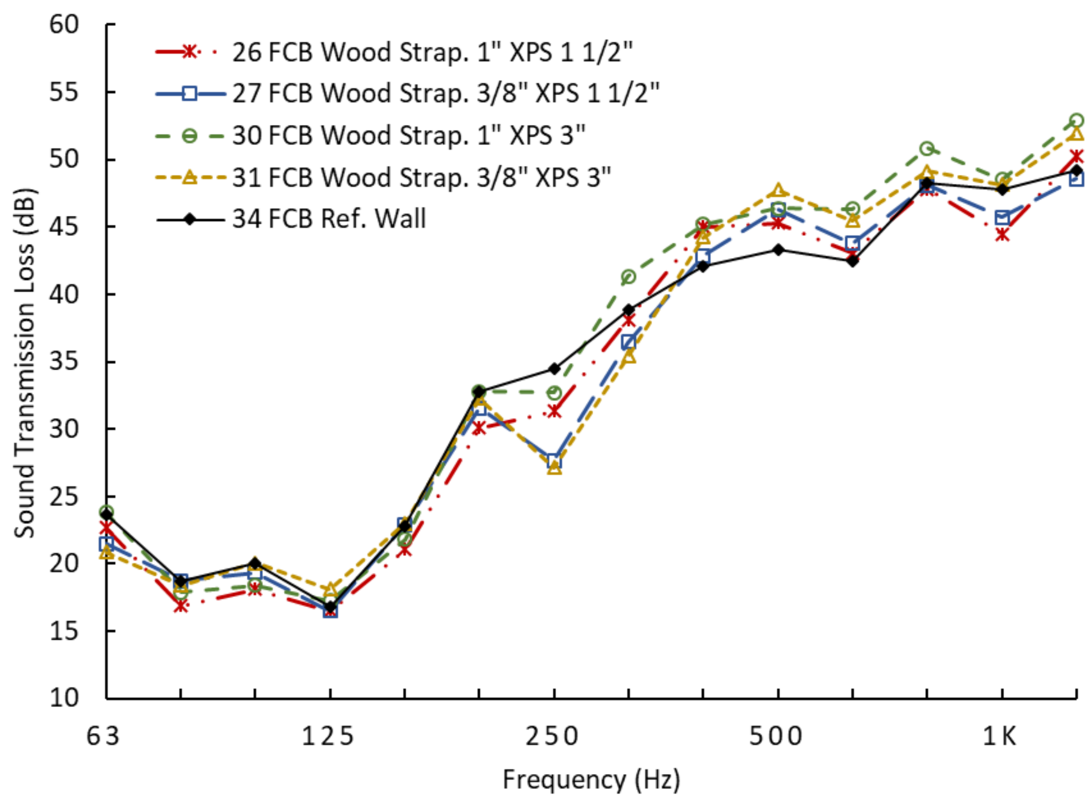


Figure 5.43. Sound transmission loss versus 1/3 octave frequency for FCB S1 XPS walls.

Focusing on the low frequency range, Figure 5.43 shows the results for wood strapping attachment and a similar trend to the reference wall between 63 and 200 Hz. At 125 Hz, the 3/8" wood strapping and 3" insulation was the only wall which had higher TL than the reference wall. Below 125 Hz, all walls had lower TL than the reference. Small TL variations among S1 FCB XPS walls suggested very close stiffness among the four combinations.

Figure 5.44, Figure 5.45, and Figure 5.46 present the transmission loss for vinyl cladding XPS exterior insulation walls for the S3, S2, and S1 attachments, respectively.

Figure 5.44 showed that XPS insulation material had an important effect on the wall behaviour from 200 to 400 Hz. XPS insulation, in this frequency range, did not present sound absorption characteristics, and the main effect on the wall assembly was to create a larger cavity between the sheathing and the cladding. The higher TL that was observed for mineral wool was not observed for XPS. The XPS walls had a strong dip at 250 Hz, which is likely attributed to a resonance around this frequency and the absence of insulation absorption properties. The two 1" cavity width walls had lower TL at 250 Hz while the two 3/8" had better TL, although the four walls had lower TL than the vinyl single insulation reference wall. This result suggested a relation to rainscreen cavity width, even though it was likely related to the cavity width profile stiffness or the total combined stiffness. The introduction of a rainscreen cavity appears to have decreased TL values at a specific frequency range compared to the reference wall.

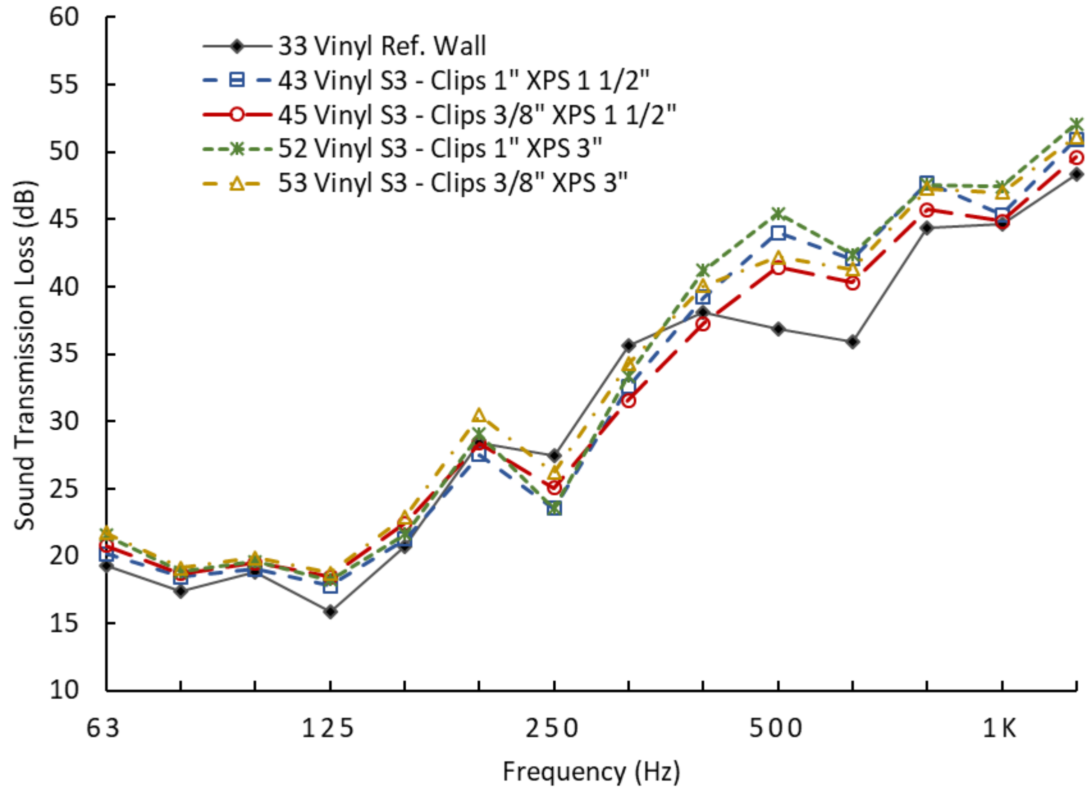


Figure 5.44. Sound transmission loss versus 1/3 octave frequency for vinyl S3 XPS walls.

Figure 5.32 indicated close results among vinyl and XPS wall types between 63 and 160 Hz, while from 63 to 125 Hz, TL levels were higher than vinyl and mineral wool walls (Figure 5.35) and S3 attachments. This better result for XPS insulation at low frequencies compared to mineral wool might be attributed to either a possible better sound absorption property at low frequencies for XPS closed cell insulation (Cox & D'Antonio, 2016) or the XPS board stiffness. XPS is a rigid board insulation, and likely there was interaction with clips and rainscreen cavity profiles that might have influenced the overall flexibility. It could be also a contribution from both hypotheses for the higher TL levels at this frequency range compared to vinyl and mineral wool.

Figure 5.45 showed that from 200 to 400 HZ, TL was still influenced by the attachments' stiffness. At 630 Hz, all walls had equivalent TL, and at and above 400 Hz, the 1" rainscreen cavity width walls had the highest TL levels. TL values at 250 were very close to the reference wall but higher than the S3 attachment. TL values at 315 Hz were lower than the reference wall.

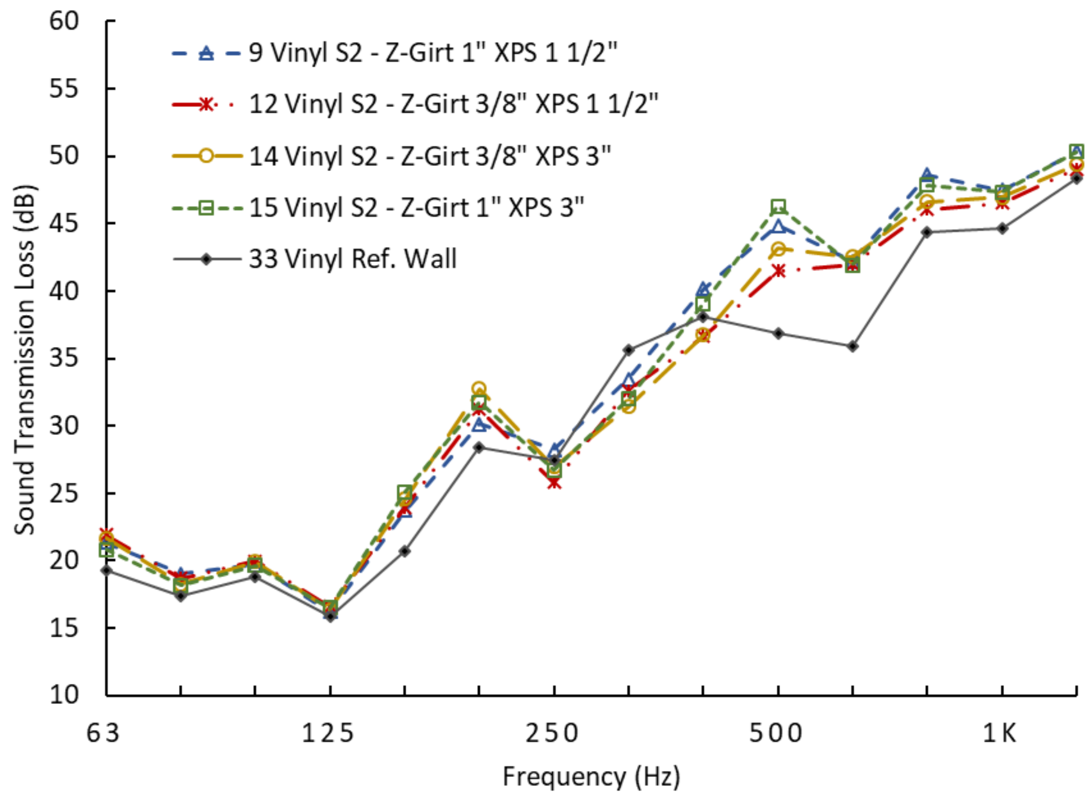


Figure 5.45. Sound transmission loss versus 1/3 octave frequency for vinyl S2 XPS walls.

Focusing on the low frequency range of Figure 5.33 indicated similar behavior between S2 and S3 attachments for vinyl and XPS walls. At 125 Hz, the S2 walls had equal TL levels very close to the reference wall. At 160 and 200 Hz, TL levels were slightly higher than S3 walls. Compared to vinyl and mineral wool walls (Figure 5.36), the vinyl and XPS walls results were better for frequencies below 125 Hz, whereas at 160 and 200 Hz, results presented nearly equal values.

Figure 5.34 showed that wood strapping attachment walls had a similar trend compared to S2 and S3 walls, as well as compared to the reference wall. There was, first, a reduction in TL at 250 Hz, followed by an increase in TL up to around 500 Hz. At 250 and 315 Hz, the 3/8" cavity width walls had slightly higher TL than the 1" cavity width walls, while at 400 Hz, the 1" cavity width had higher TL. From 400 Hz, the 3/8"+1 ½" wall had the lowest TL suggesting a correlation to cladding-to-sheathing distance.

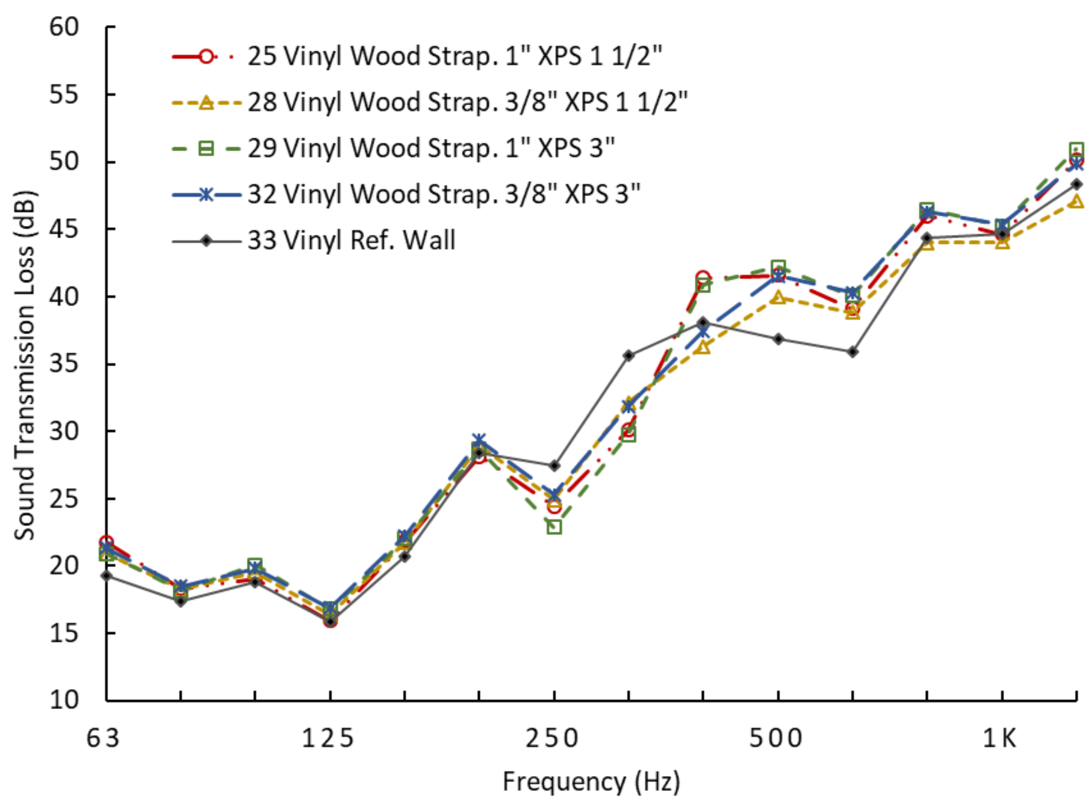


Figure 5.46. Sound transmission loss versus 1/3 octave frequency for vinyl S1 XPS walls.

The low frequency range of Figure 5.34 shows TL levels almost unchanged for the S1 wood strapping compared to the other two attachments and to the reference walls from 80 to 200 Hz. Compared to vinyl and mineral wool (Figure 5.37), the XPS wall provided a better result from 80 to 125 Hz, while at 160 and 200 Hz, vinyl and XPS performed more poorly. This comparison between vinyl S3 XPS and vinyl S3 mineral wool might indicate sound bridging through insulation. Exterior insulation simultaneously touched attachment and sheathing, which might have increased sound transmission for the mineral wool case. XPS was less dense than mineral wool and at low frequency where mineral wool was not providing sound absorption there was a negative outcome from this density difference. This situation resembles to a line-line transmission rather than a point-line configuration, as defined by Sharp (1973).

Figure 5.44, Figure 5.45, and Figure 5.46 clearly showed the impact of the XPS insulation on the three attachment types. As opposed to mineral wool, which presented a higher variation of TL levels, the XPS walls did not present a similar change in TL levels. In general, at lower frequency bands from 80 to 125 Hz, vinyl and XPS walls performed better than vinyl and mineral wool, whereas above 125 Hz, mineral wool performed better. Although apparently small, such found differences influenced the overall single numbers.

A Summary Discussion on Cladding Attachments

The observation of the low frequency range suggested that the attachment system stiffness was a major factor that might affect the sound transmission loss at a low frequency range from 63 to 200 Hz. The analysis suggested that, in general, the outcomes of the structural resonance change influenced TL results beyond one-octave band above the 1/3 octave band where it happened. The overall behaviour suggested, apart from insulation material's key role and cladding material, that the total stiffness was the main cause of the observed TL variations among walls within the same attachment type. Indeed, the underlying effects were greatly influenced by the combination of material layers and their individual stiffness that contributed to the overall stiffness. This situation could be observed from some walls having a 1" cavity width which had lower TL, but the other component of the attachment system was either 1 ½" or 3" profiles. It was also seen in cases from the wood strapping walls with differences in TL among their walls combination. Results did not suggest that a specific rainscreen cavity width, here in terms of distance between cladding and insulation (drainage gap), had any influence at all.

Differences in TL results between vinyl S1 mineral wool (Figure 5.37) and vinyl S1 XPS (Figure 5.46) and differences between FCB S1 mineral wool (Figure 5.40) and FCB S1 XPS (Figure 5.43) suggested that the higher TL for XPS walls might be attributed to lower density of insulation. Mineral wool had higher density and as such it might have caused higher sound bridging at frequencies where it did not provide sound absorption. XPS, on the other hand, was less dense and not capable of transmitting (bridging) sound through its internal structure.

The four wall combinations—FCB and mineral wool, vinyl and mineral wool, FCB and XPS, and vinyl and XPS—suggested a TL pattern according to this grouping and the attachment types. XPS walls had the 125 Hz TL levels usually unchanged or slightly changed among cladding attachments. Below this frequency, for XPS walls, slight changes were also observed. In fact, the reason for the small changes below 125 Hz was likely the same reason correlated to the dip at 250 Hz, indicating that both variations were correlated with higher or lower stiffness. This effect was more prominent for FCB cladding, which might have contributed due to higher mass and stiffness, than for vinyl cladding. Observe that for FCB walls, at 100 Hz, the more flexible attachment combinations had highest TL at 250 Hz while the stiffest attachments at 100 Hz had the lowest TL at 250 Hz. This pattern was not clear for vinyl at 100 Hz, but at 250 Hz, the differences were high enough to suggest correlation to stiffness when contribution from vinyl cladding mass and stiffness were not as high as FCB. Such small differences for vinyl and XPS at 250 Hz were likely attributed to the cavity width stiffness and not necessarily to the gap.

As for mineral wool walls, there was a difference among the cladding attachments. S3 and S2 had, apparently, the highest flexibility and as such imposed higher changes around the 125 Hz. The S3 mineral wool and S2 mineral wool walls had their V-shaped figure at 125

Hz highly shifted to the left, greater for the 3" profiles than 1 ½" (although it indicated a trend). At 250 Hz, the 3" profiles had higher TL than 1 ½" profiles due to higher stiffness and thicker insulation. At this frequency, the 1 ½" had a small dip, indicating a probable resonance in effect. As for the wood strapping (S1) attachment, the general behaviour tended to follow the same pattern but with a notable difference. It indicated that the design of the S1 attachment system highly influenced the overall stiffness. S1 did not have a metal profile that determined the stiffness, but rather the insulation thickness and the wood strapping profile were the system. Aside from that, sound transmission from cladding to sheathing through S1 attachment suggested different behaviour regarding sound bridging.

S2 and S3 behaved as having less sound bridging (line-point connections), whereas S1 behaved as having higher sound bridging (line-line connection). This difference was emphasized when differences between XPS and mineral wool were observed. Walls with XPS usually had higher TL, from 80 to 125 Hz. While this can be counter-intuitive, it might be explained by some reasons. First, as previously cited, this difference could have been linked to higher sound absorption properties at a low frequency (Cox & D'Antonio, 2016). Second, XPS may have introduced some stiffness to the overall attachment system that interfered with the sole attachment stiffness of S3 and S2. XPS is a rigid board insulation, while mineral wool is a semi-rigid insulation board, and as such they allowed for different flexibilities to the system, consequently releasing or not the connections to independently vibrate. Third, in the case of the S1 attachment, since XPS was less dense than mineral wool, the effect of sound bridging through the insulation structure was made less effective than mineral wool, which had higher density. Therefore, TL levels for mineral wool might have been lower for S1 attachments when this insulation material does not provide sound absorption at very low frequencies. Recall, S1 attachment was a line-line connection, and it indicated higher sound bridging than S3 and S2 types. Being denser than XPS, the structure-borne sound effect of mineral wool insulation could have been higher than XPS. Moreover, there was also a stiffness effect interacting with it.

The effect of the used attachments and their stiffness to the wall TL needs a more elaborated conception. If cross sections—both horizontal and vertical—of a wall are drawn with the whole wall assembly (including all elements), the total stiffness needs to consider the intricate contribution of each member to the overall system, not only that the attachment contributed to a higher and lower stiffness. Evidently, in this study, the attachments provided reasonable flexibility and likely were the highest contributors to the overall stiffness. Taking Figure 4.6 and Figure 4.7 as a starting point to analyze the attachment stiffness, it is clear that the profiles' position, dimensions, and fundamentally the plane sections (axes) where bending occurs determined higher or lower stiffness. Invariably, the predominant flexural effect tended to happen following the lowest stiff path, and to determine in what direction and how sound waves will interact requires a more complex calculation and analysis rather than a simplistic image.

Results suggested that the introduction of different cladding attachment systems might affect sound transmission loss levels at low- to mid-frequencies as well as STC and OITC ratings. The outcomes can also be influenced by other wall layers in conjunction with the cladding attachments. Findings for the cladding attachments suggested that, in general, the S3 performed marginally better than S2, whereas the S3 and S2 performed better than the S1.

A correspondence between Bradley and Birta's (2000) and Quirt et al.'s (1995) results for the usage of resilient channels to wood frame walls and this research's results implied that in a triple panel wall the overall change, or improvement in TL, might be reached if a resilient connection is attached to either the outermost wallboard or the innermost wallboard. Indeed, this related to the idea of a mutual effect, where it would not have mattered in this study's set up if both indoor and outdoor panels had been made of the same material and only one was attached to a resilient channel; results would have been equal. This finding has a very practical and advantageous implication to real buildings. Presented results and graphs that depicted the structural resonance frequency change and subsequently better performances to the overall TL, lowering the lowest TL to lower frequencies while allowing for higher TL at higher frequencies, roughly evoked the so-called acoustical reciprocal theorem (Fahy, 2005).

The TL variations that could be linked to the rainscreen cavity widths did not suggest strong correlation or likely cause of great variations. In fact, in the majority of wall combinations where a pattern was observed that could possibly correlate these two variables, other stronger factors might explain the likely cause that justified such changes. In situations of lower TL, for instance, when the 3/8" cavity width at 125 Hz (FCB and XPS) suggested that the cavity width could be the reason, it lacked a systematic pattern among walls. Reasons such as attachment stiffness, cladding type, and cladding to sheathing distance were stronger explanations backed by theoretical arguments. Rainscreen cavity profiles also embedded some of these factors, which were not negligible, the most important being the stiffness. Results did not suggest that there was an interaction between cladding and insulation material in the same sense of a mass-spring system and high enough to overtake other effects. If this effect happened, it would not substantially lower or increase the TL values at a point of being a watershed.

5.2.8 Sheathing-to-Cladding Distance

The sheathing-to-cladding dimension is the addition of the cavity depth dimension and the insulation thickness. To investigate the effect of the sheathing-to-cladding dimension in TL performance, the 63 to 5 K Hz frequency spectrum is presented. The layout is organized to consider the relationship of cladding type and insulation-to-cladding attachments: vinyl and FCB cladding with mineral wool; vinyl and FCB cladding with XPS are reviewed; these are followed by a summary discussion.

Figure 5.47, Figure 5.48, and Figure 5.49 present sound transmission loss for vinyl cladding and mineral wool insulation walls comparing the largest and smallest sheathing-to-cladding distance, or cavity depth, for S3 – Clip, S2 – Z-girt, and S1 – Wood strapping attachments, respectively.

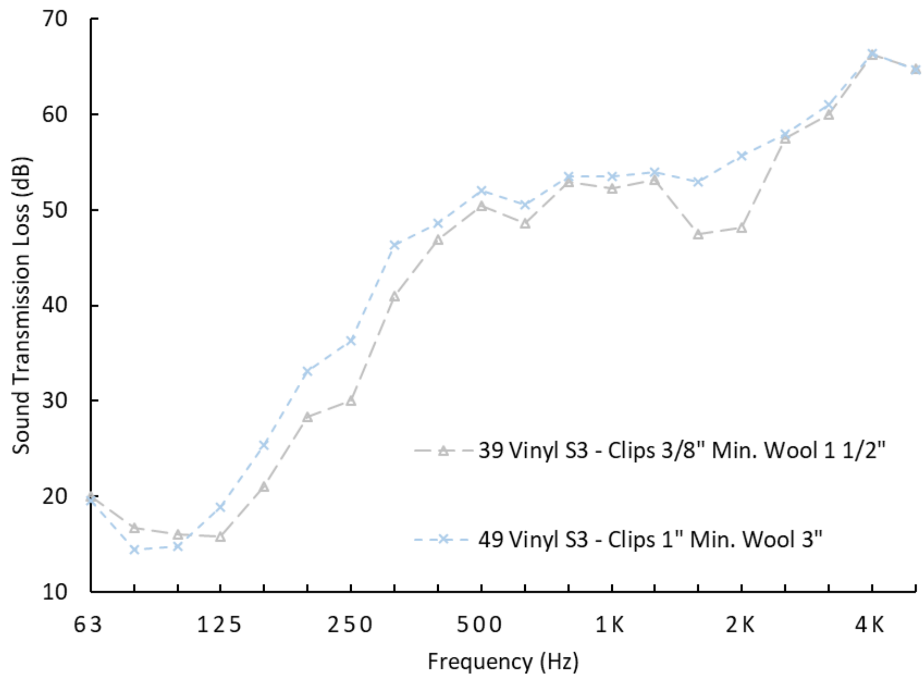


Figure 5.47. Sound transmission loss versus 1/3 octave frequency for vinyl S3 mineral wool – 3/8"+1½" and 1"+3" – walls.

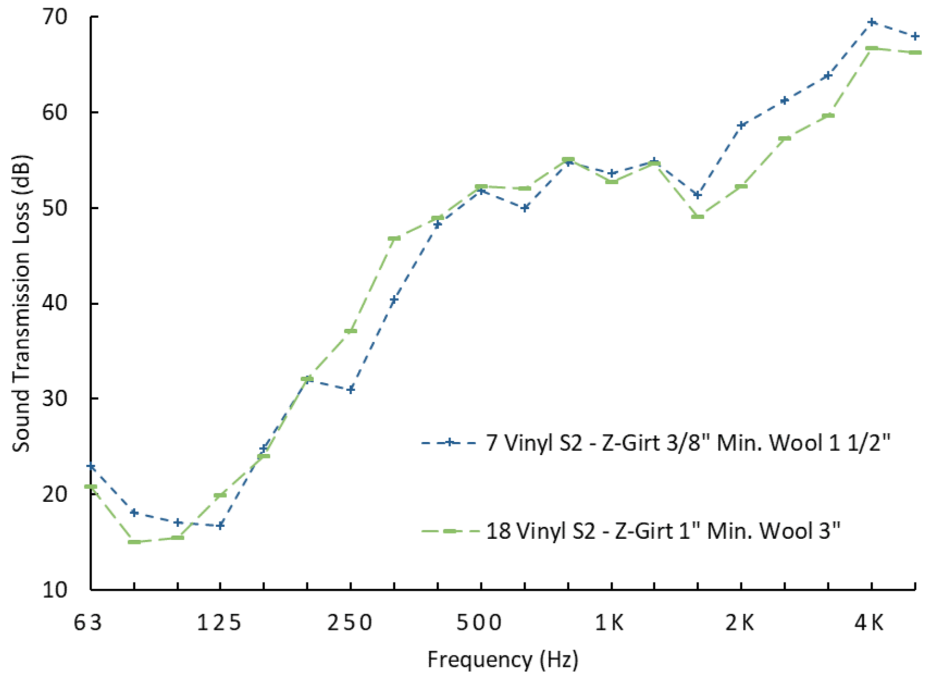


Figure 5.48. Sound transmission loss versus 1/3 octave frequency for vinyl S2 mineral wool – 3/8"+1½" and 1"+3" – walls.

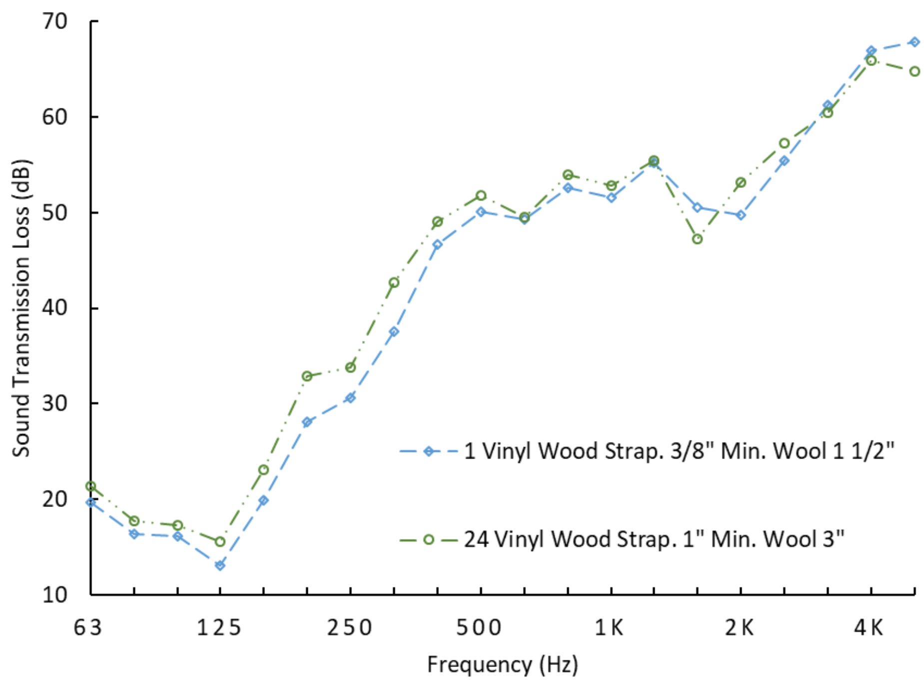


Figure 5.49. Sound transmission loss versus 1/3 octave frequency for vinyl S1 mineral wool – 3/8"+1½" and 1"+3" – walls.

Figure 5.47, Figure 5.48, and Figure 5.49 suggested that for vinyl and mineral wool walls, the 1"+3" (10.2 cm) distance between sheathing and cladding was not the only cause for a higher TL. The general behaviour corroborated that greater distance provided higher TL, although other factors such as insulation material and insulation thickness highly contributed to the observed results. From 63 to 400 Hz, results were favourably influenced by stiffness, as previously demonstrated. The sole observation of the cladding-to-sheathing distance was not clearly conclusive for these wall cases.

Figure 5.50, Figure 5.51, and Figure 5.52 present sound transmission loss for FCB cladding and mineral wool insulation walls comparing the largest and smallest cavity depth for S3 – Clip, S2 – Z-girt, and S1 – Wood strapping attachments, respectively.

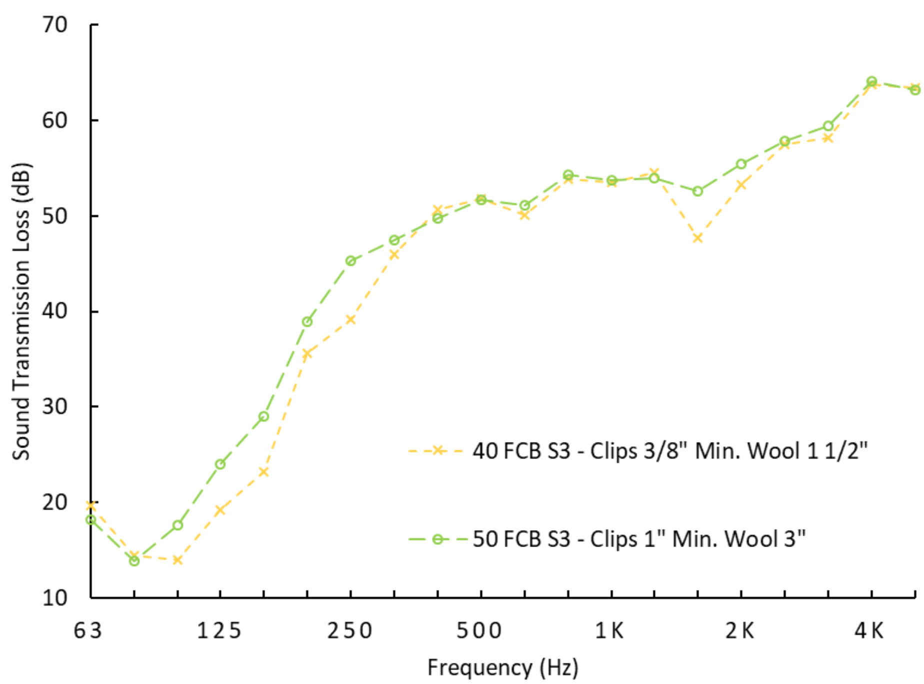


Figure 5.50. Sound transmission loss versus 1/3 octave frequency for FCB S3 mineral wool – 3/8"+1½" and 1"+3" – walls.

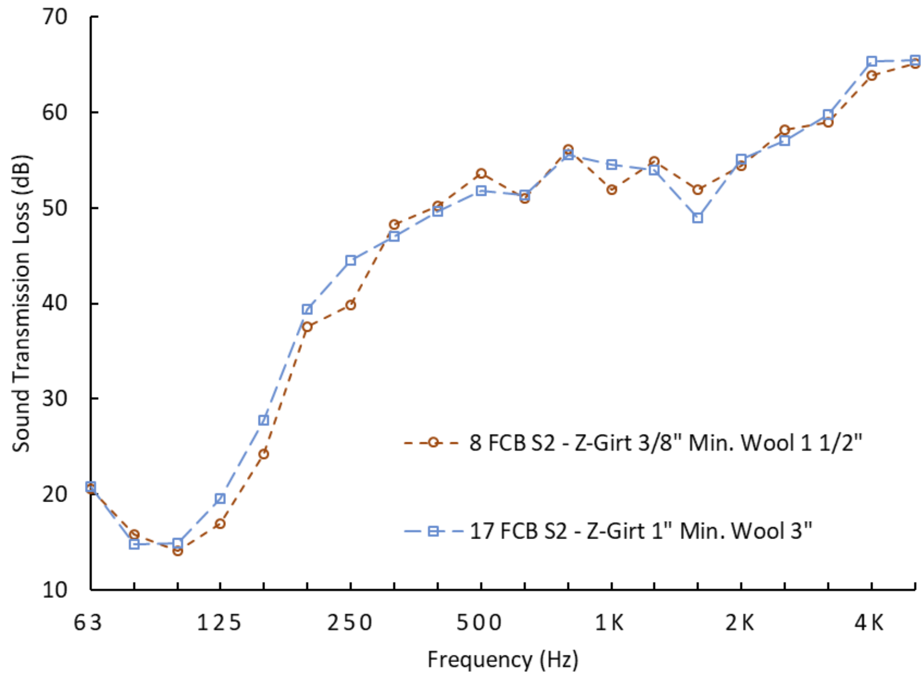


Figure 5.51. Sound transmission loss versus 1/3 octave frequency for FCB S2 mineral wool – 3/8"+1½" and 1"+3" – walls.

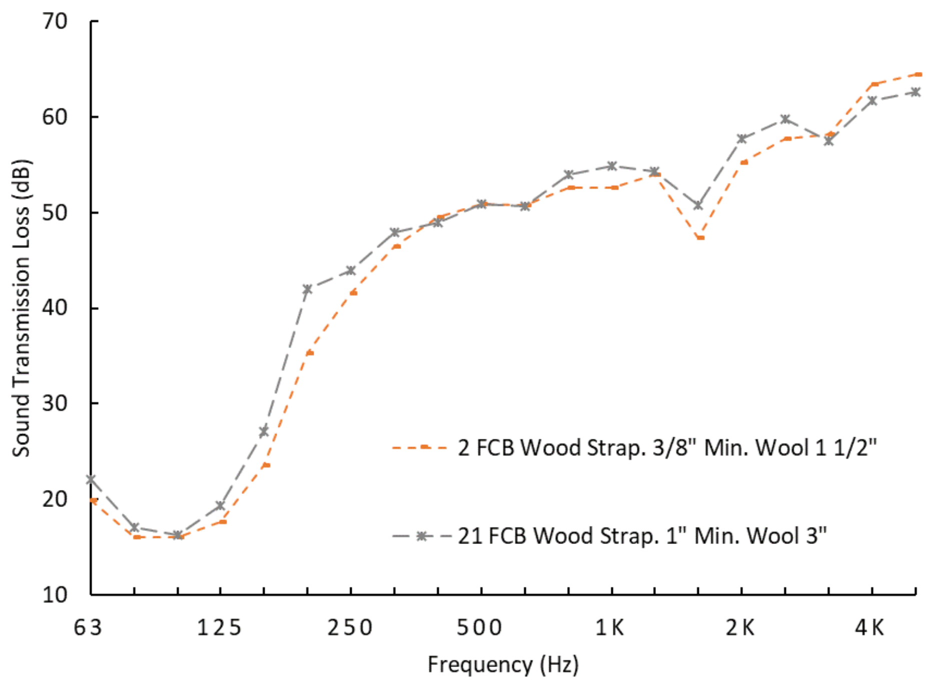


Figure 5.52. Sound transmission loss versus 1/3 octave frequency for FCB S1 mineral wool – 3/8"+1½" and 1"+3" – walls.

Figure 5.50, Figure 5.51, and Figure 5.52 showed that same observation applied to vinyl and mineral wool walls can be applied to FCB and mineral wool walls regarding the influence of other variables that might explain a higher TL for a higher sheathing-to-cladding distance. The sole analysis of sheathing-to-cladding distance is not clear for this wall combination, even though results tended to follow that high distances brought about higher TL.

Figure 5.53, Figure 5.54, and Figure 5.55 present sound transmission loss for vinyl cladding and XPS insulation walls comparing the largest and smallest cavity depth for S3 – Clip, S2 – Z-girt, and S1 – Wood strapping attachments, respectively.

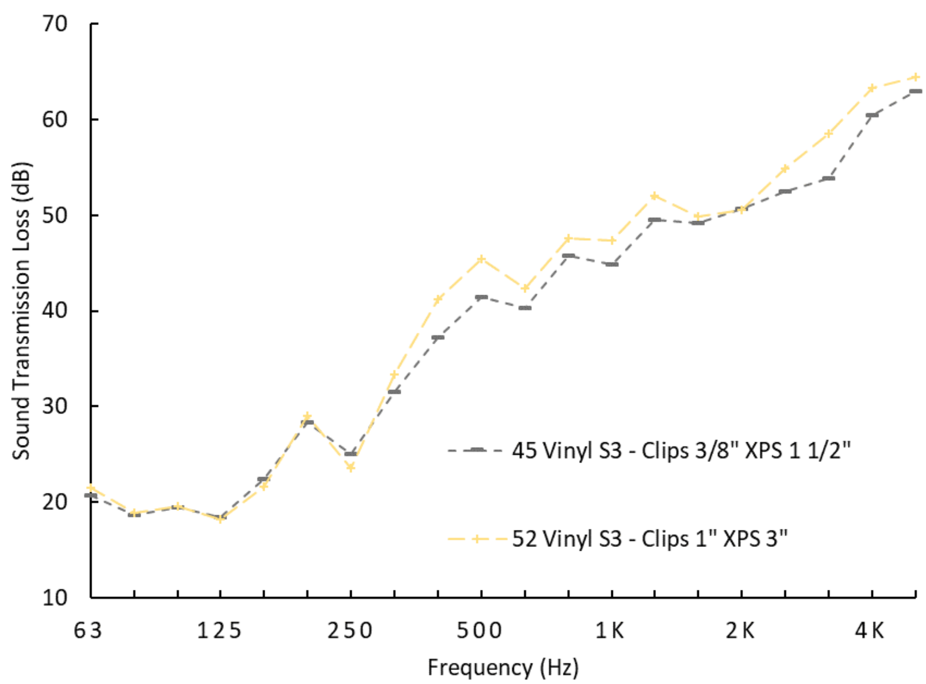


Figure 5.53. Sound transmission loss versus 1/3 octave frequency for vinyl S3 XPS – 3/8"+1 ½" and 1"+3" – walls.

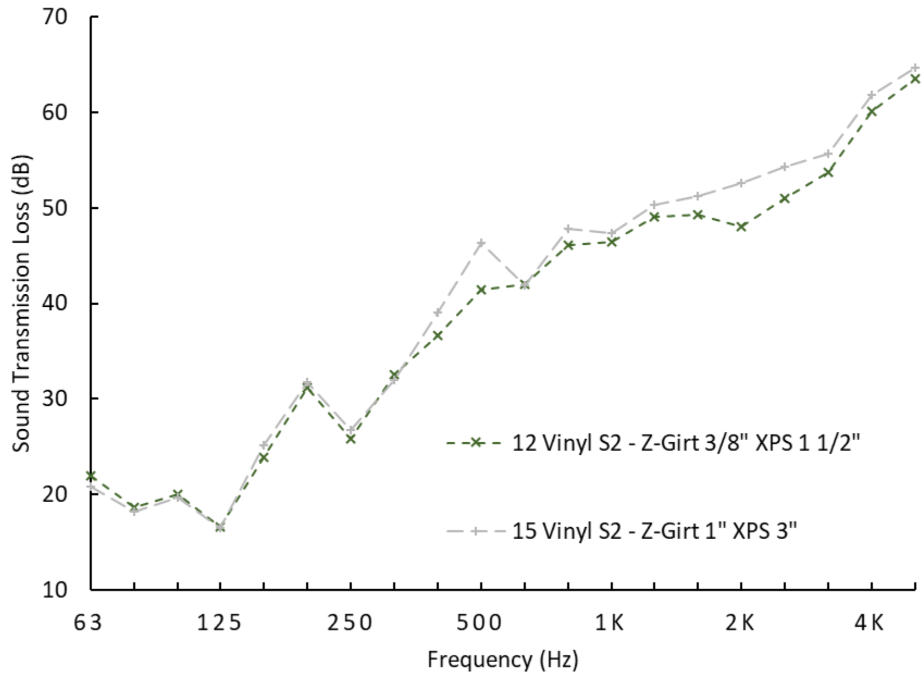


Figure 5.54. Sound transmission loss versus 1/3 octave frequency for vinyl S2 XPS – 3/8"+1 ½" and 1"+3" – walls.

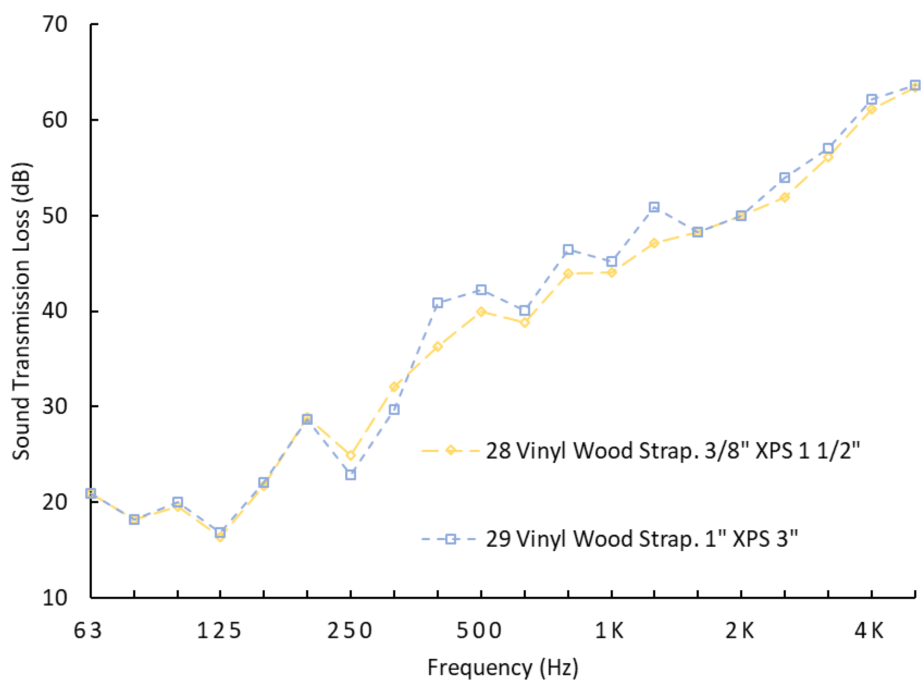


Figure 5.55. Sound transmission loss versus 1/3 octave frequency for vinyl S1 XPS – 3/8"+1 ½" and 1"+3" – walls.

Figure 5.53, Figure 5.54, and Figure 5.55 showed that for vinyl and XPS walls, the 1"+3" (10.2 cm) distance between sheathing and cladding provided higher TL at and above 400 Hz. In the absence of sound absorption properties, walls with XPS insulation provided a better comprehension of the cladding to sheathing phenomenon. Up to 315 Hz, stiffness was the dominant effect and the main cause of small variations between the comparisons. Results indicated that for a lighter cladding such as vinyl, TL gains were small at a mid-frequency range.

Figure 5.56, Figure 5.57, and Figure 5.58 present sound transmission loss for FCB cladding and XPS insulation walls comparing the largest and smallest cavity depth for S3 – Clip, S2 – Z-girt, and S1 – Wood strapping attachments, respectively.

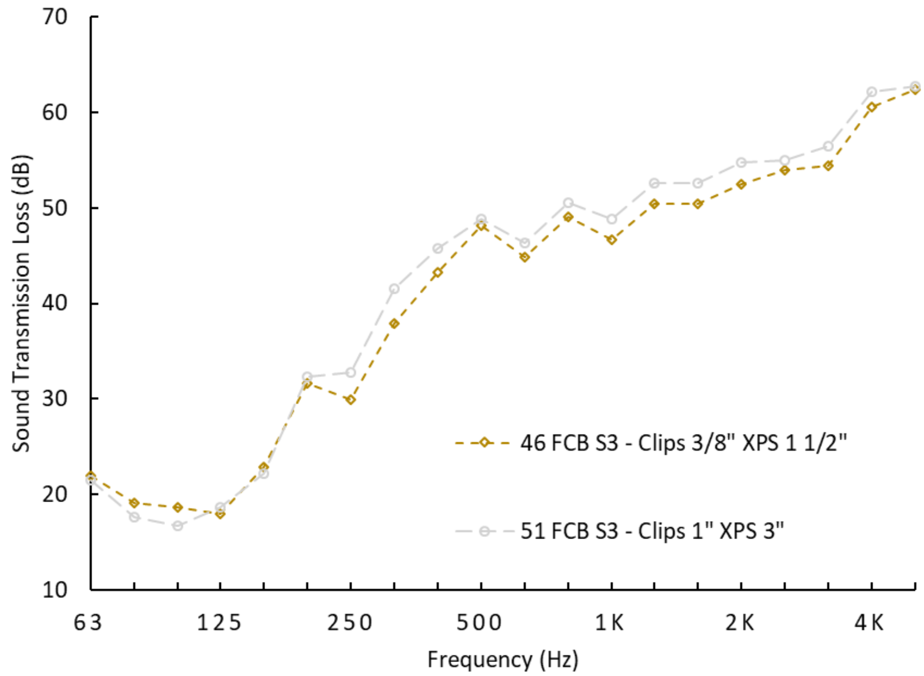


Figure 5.56. Sound transmission loss versus 1/3 octave frequency for FCB S3 XPS – 3/8"+1 ½" and 1"+3" – walls.

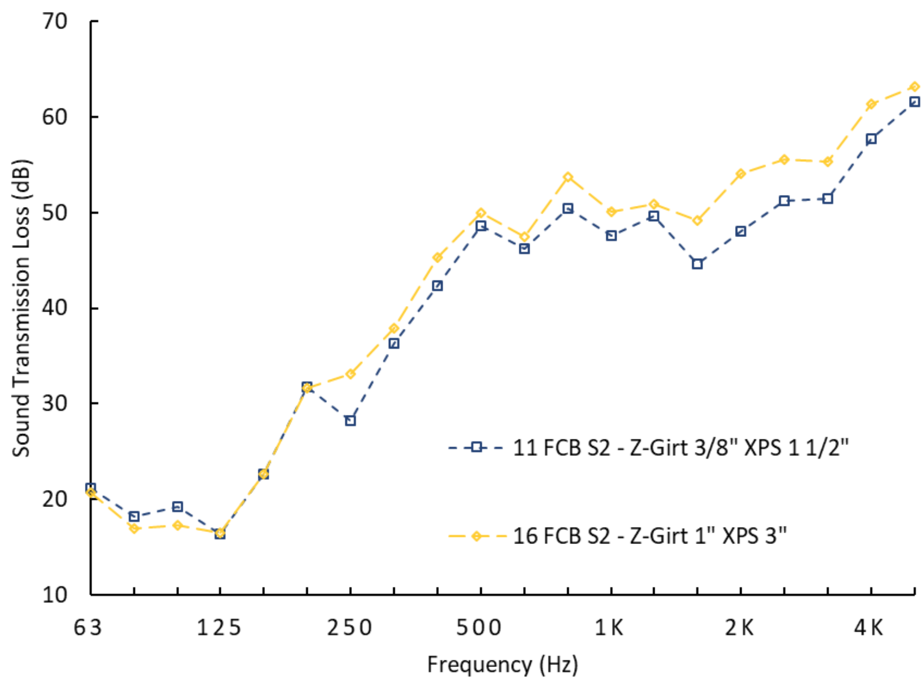


Figure 5.57. Sound transmission loss versus 1/3 octave frequency for FCB S2 XPS – 3/8"+1 ½" and 1"+3" – walls.

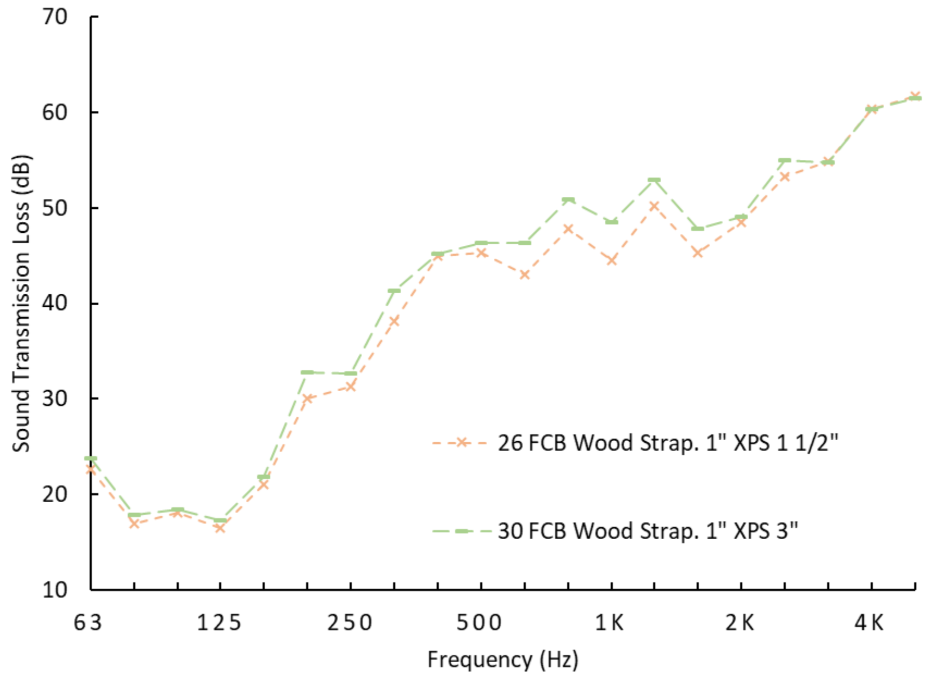


Figure 5.58. Sound transmission loss versus 1/3 octave frequency for FCB S1 XPS – 3/8"+ 1 ½" and 1"+ 3" – walls.

Figure 5.56, Figure 5.57, and Figure 5.58 showed that for FCB and XPS walls, the 1"+3" (10.2 cm) distance between sheathing and cladding provided higher TL at and above 250 Hz. Compared to vinyl and XPS, the graphs suggested that the higher mass for FCB and/or cladding stiffness also contributed more to the higher TL than the smallest cavity depth. In fact, the cladding-to-sheathing distance is controlled by both mass and distance.

Summary Discussion on Sheathing-to-Cladding Distance

A variation of almost double the distance between the two outer panels can produce some improvement. The observed change in mineral wool walls may be attributed not only to the sheathing-to-cladding distance but largely to the insulation sound absorption properties. Since vinyl did not have a same surface mass density as FCB, consequently presenting a poorer performance for sound transmission loss, the observed improvement for vinyl cladding was mostly due to a combination of insulation material and insulation thickness. A similar result was observed for FCB where the improvement was also attributed to the three variables (cladding, insulation, and insulation thickness) combined than to the sheathing-to-cladding distance only.

In the case of XPS, the cladding to sheathing distance effect was made clearer due to the negligible effects of the insulation. Thus, the combination of cladding and its distance to sheathing were the main cause for variations in TL. Greater sheathing-to-cladding distance for vinyl and XPS walls started to positively impact at the 400 Hz band, whereas for FCB and XPS, the impact started from the 250 Hz band. These results showed the extent of the change when a poor sound insulation material (XPS) was used along with a heavier cladding at a larger distance. Results for cladding-to-sheathing distance corroborated Equation (14), which calculates the mass-spring resonances and determines that for higher mass, the resonance frequency will happen at a lower frequency and higher distances give lower resonance frequencies. Results also agreed with theoretical results from Xin and Lu (2011), which evaluated differences in cavity distances and masses and showed similar combinations of results that could be compared to this study's results.

Table 10 shows the calculated mass-air-mass-air-mass resonances for the 3-panel system according to Equation (14). Note that the cited equation did not account for the effect of either insulation material between the panels or structural connections. The first observation from this table is related to distance and mass. Either increasing mass or increasing distance lowers the highest resonance frequency. This indicated that the triple panels tended to reach higher TL levels at a lower frequency for heavier panels and greater distances.

In the tested walls, some trends were observed. The first was that in all walls at 250 Hz there was a reduction in TL with a noticeable dip around this frequency. Mineral wool walls had this effect largely attenuated likely due to insulation sound absorption compared to XPS walls, which had a more evident dip. If Table 10 is used to correlate the dips and the mass-spring resonance in split insulated walls (distances between 4.8 and 10.2 cm), for FCB and stucco walls, it suggested a strong correlation and a likely explanation why the dips occurred. The highest mass-spring resonance frequency (f_{α}) fell into the 250 Hz band. On the other hand, for vinyl walls, there was no correspondence between the resonance frequency and the 250 Hz dip. All highest resonance frequencies (f_{α}) were above this 1/3 octave band. Also, Table 11, which shows the standing wave resonance frequencies, shows that all possible calculated values (for both interior and exterior cavities) were well above the 250 Hz (< 5K Hz are underlined). Table 11 suggested that standing wave resonances were not the likely cause. Looking back to Table 10, the dips might have been reinforced by the mass-spring resonances for FCB and stucco walls, but they did not explain all walls dips at 250 Hz.

FCB and vinyl reference walls had similar dips at 250 Hz; however, for these wall types all highest resonance frequencies (f_{α}) were well above this frequency. This suggested that the main reason for the dips was related to neither rainscreen cavity width nor only mass-spring resonance. These results corroborated an assumption that the main contribution to this dip at 250 Hz was related to a secondary structural resonance. Lin and Garrelick (1977) notably demonstrated the overall impact on TL for a change from primary structural resonance to a ribbed panel resonance if disconnection is provided to one of the panels in a full double wall structure. Notwithstanding, in a double panel stud wall fully connected, they also pointed out that between the first structural resonance and the first wall cavity resonance (standing wave) there was a high order (secondary) structural resonance. Although their results were presented for a fully connected double panel stud wall, and since in this study two of the panels were fully connected to wood studs, the ubiquitous dip at 250 Hz might indicate the occurrence of a secondary structural resonance. Moreover, as in a situation when there is one mass-spring resonance frequency in a double panel configuration and two mass-spring resonance frequencies in a triple panel configuration, it is likely that in a triple panel wall there would be higher order structural resonances. It might be that being the third panel attached through a less stiff attachment, the additional structural resonance found its way and ended up disturbing the 250 Hz frequency.

In Figure 2.15 from the literature review, a similar variation was observed from Bradley and Birta (2000) in a rainscreen cavity wall compared to a reference wall. TL values of a rainscreen wall were lower than the reference wall in a specific frequency range, whereas TL values were higher at a higher frequency range, indicating that another important resonance was possibly in effect. There were differences between the NRC and BCIT tests that might justify such differences. The first was the sound field, and the second was the strapping thickness. These two conditions might have largely influenced this study's results presenting higher differences than the study at the NRC.

As for all lowest mass-spring resonance frequencies (f_β), these values were likely affected by other dominant resonances such as ribbed panel resonance or panel mode resonance.

Table 10. Calculated mass-air-mass-air-mass resonance frequencies for triple-panel walls.

Distance	Vinyl		FCB		Stucco	
	f_α	f_β	f_α	f_β	f_α	f_β
3/8" (1.0 cm)	1060	160	574	138	--	--
1" (2.5 cm)	651	160	361	134	--	--
3/8" + 1 1/2" (4.8 cm)	477	159	275	129	250	111
1" + 1 1/2" (6.4 cm)	414	159	246	125	--	--
3/8" + 3" (8.6 cm)	357	158	223	118	211	98
1" + 3" (10.2 cm)	329	158	212	114	--	--

Table 11. Standing wave resonance frequencies.

	Standing Wave Resonance Frequency (Hz)						
	Distance						
	5 1/2"	3/8"	1"	3/8" + 1 1/2"	1" + 1 1/2"	3/8" + 3"	1" + 3"
n	140 mm	9.5 mm	2.54 mm	47.6 mm	63.5 mm	85.7 mm	101.6 mm
1	<u>1231</u>	18058	6772	<u>3612</u>	<u>2709</u>	<u>2006</u>	<u>1693</u>
2	<u>2462</u>	36115	13543	7223	5417	<u>4013</u>	<u>3386</u>
3	<u>3694</u>	54173	20315	10835	8126	6019	5079
4	<u>4925</u>	72231	27087	14446	10835	8026	6772

To conclude the wall cavity analysis, using Equation (11), values from Table 4, and values from literature about materials properties, Table 12 presents the calculated coincidence frequency for panels at 45° incident angle.

Table 12. Calculated coincidence frequencies.

Coincidence Frequency (Hz) (θ = 45°)				
Gypsum	Plywood	Vinyl	FCB	Stucco
4787	2108	94545	4688	2075

According to Table 12, only plywood sheathing and stucco had their coincidence frequency under the measured frequency range. Reduced TL values were measured around the 1.6K and 2K Hz, and this might justify why some losses were lower. This finding might indicate that the calculated values were closer to the actual coincidence effect. Nonetheless, small variations could be accepted because of variation in materials' properties, and certainly due to the generated sound field. This phenomenon can be observed from the graphs presented throughout the analysis section. Note that not all curves presented a stressed coincidence frequency dip; however, it was perceptible that at around 2K Hz the curves' slope changed to a steeper gradient. Hence, this indicated that the walls were under another dominant effect, neither mass-law nor coincidence, but rather towards a shear-controlled effect. Above 2 K Hz TL levels were usually around 50 dB or higher and at such high levels of losses, further consideration is commonly disregarded in building acoustics unless any particular change is observed.

Table 13 presents the critical frequencies for the used layers. These values represented the lowest possible frequency where a coincidence effect might have happened. Since the study set-up did not have an ideal sound diffuse field and consequently no sound waves at grazing incidence occurred, the observed dips were not likely to happen at these frequencies due to the coincidence effect.

Table 13.Calculated critical frequencies.

Critical Frequency (Hz)				
Gypsum	Plywood	Vinyl	FCB	Stucco
2394	1054	47272	2344	1038

In some TL curves presented in this study, there were ups-and-downs approximately towards the end of the mass-law region and around the coincidence frequency effect area. This might have happened due to the orthotropic condition of panels (Bies & Hansen, 2005) and specifically the orthotropic nature of wood (Forest Products Laboratory, 2010), which could have been influenced by the plywood sheathing board. This condition for plywood affects many variables that govern sound transmission such as direction-dependent modulus of elasticity and speed of sound in the material.

6 SUMMARY AND RESEARCH FINDINGS

Single-number ratings are still largely used by construction professionals as a watershed when selecting a wall, a window, and many building materials. Differences between assemblies are more apparent with the STC than the OITC. OITC walls had a narrower range, from 26 to 37 (11 points), compared with STC, from 37 to 52 (15 points), which could be explained by closer TL differences at the 80 and 100 Hz octave bands. Study findings were in accordance with similar observations made by Garc et al. (2013) regarding the limits of using single-number ratings.

Relative to vinyl and FCB cladding, stucco walls had the highest STC and OITC ratings due to the highest surface mass density and thickness, which predominantly impacted the low frequency range. Results indicated that this much denser material was capable of significant impact on the low frequency sound levels, consequently increasing the single-number ratings of STC and OITC. Depending on the wall layers combination, in a stucco wall, the improved range went up to the 1250 Hz 1/3 octave band. Stucco was able to increase TL levels at mid frequencies and also to reduce the lowest levels to lower frequency bands. If attention is needed in the low frequency range (below 200 Hz) an efficient way to increase sound transmission loss is by using thick stucco cladding on wood-frame walls.

The superior performance for stucco over FCB cladding and for FCB over vinyl cladding aligned with the vast literature about the mass law theory (Sharp, 1973; Ginn, 1978; Long, 2006; Kim, 2010) where a denser and thicker material provides superior performance. Analyzing the measured surface mass densities, stucco had nearly 4 and 27 times higher values than FCB and vinyl, respectively. FCB had nearly 7 times higher surface mass density than vinyl. Since the tested walls had identical layer configurations when comparisons were made, it can be said that the mass law theory was adequately represented. The higher mass for stucco cladding caused an additional impact of much more significance. As discussed by Bradley and Birta (2000, 2001), Sharp (1973), and Lin and Garrelic (1977), the structural resonance was made less pronounced, or in other terms, stucco shifted the lowest level to a lower frequency band. The main contribution of the stucco cladding was in the low- to mid-frequencies whereas at mid- to high-frequencies the overall configuration of the remaining wall layers presented equivalent losses compared to FCB and vinyl. Results for denser cladding aligned with Bradley and Birta (2000, 2001), Nightingale and Quirt (1999), Quirt and Warnock (1993), and Quirt et al. (1995).

Results suggested that stucco and FCB claddings having higher surface mass density than the middle and inner boards (gypsum and plywood boards) in a triple panel wall assembly configuration might have increased TL values to even higher levels, not only due to higher total mass, but for being simultaneously the outer incident sound panel and the heaviest panel (Xin & Lu, 2011; and Vinokur, 1990).

The results for the cladding attachments were the most interesting in this study and apparently suggested agreement with hypothesis. Results for STC and OITC indicated that Clip and Z-girt attachments had higher TL. Sharp (1973, 1978) stated that the connections between panels would modify the sound transmission. The lesser the contact, the higher the loss, basically. Besides from expanding the theory, he performed empirical studies showing alignment with theory. Because of equivalent attachments' screwing distances, the effect of point connection due to these distances was minimized to only allow for the attachments' stiffness to be observed. The used point connection density appeared to be in accordance with Quirt and Warnock (1993) and Quirt et al. (1995).

Findings indicated that the 125 Hz 1/3 octave band was likely the primary structural resonance frequency. Consistent TL changes at and around this frequency, when cladding attachments were changed, suggested that the panels were somewhat released to independently vibrate and likely the panel tended to vibrate according to the ribbed panel resonance frequency (Bradley & Birta, 2000, 2001; Lin & Garrelick, 1977).

The effects of the tested attachments had their results primarily observed at frequencies between 63 and 500 Hz, which was the range where the attachments had higher potential to alter STC/OITC and modify the primary structural resonance. A thorough analysis showed the following findings: i) the S3 - Clip and S2 - Z-Girt attachments were indicated to behave as point-line connections whereas the S1 - Wood strapping acted as a line-line connection, therefore, impacting the sound transmission loss. S3 and S2 attachments provided higher disconnection between panels (at low frequency bands) than the S1 type. S3 and S2 had close TL results between them; and ii) the effect of the S3 and S2 suggested the introduction of meaningful and decisive resilience to the system resembled similar results for those obtained when resilient channels are connected to interior gypsum boards or when the panels tend to work independently.

The first finding was made based on the observation that even though the S2 (Z-girt) connection and its rainscreen profile touched both panels simultaneously (cladding and plywood sheathing) through a line connection, a careful view of a wall cross-section showed that only one point (or a continuous connection path from opposing sides perpendicular to the wall plane) is observed from the connected layers. For the S3 case, which was designed to behave as a point-line connection because of its design, the results suggested alignment as point connection attachment. For the S1 case, the wood strapping touched both cladding and insulation along a line (the strapping length).

The second finding was derived from the fact that the outer wall layer connected to the sheathing and its structural connections were comparable to the same configuration of gypsum boards and resilient channels connected to wood studs but in a backward wall configuration. Instead of using resilient channels to gypsum boards, which is the common practice, they were installed on cladding. The outer layer appeared to be a shell layer connected through reduced stiffness providing lower sound transmission. Or in other terms, the wall assembly system had vibrations transmission reduced, consequently lowering interior sound levels. As noted by Bradley and Birta (2000), the introduction of either resilient channels, staggered studs, or increasing spacing between wood studs (also Rindel & Hoffmeyer, 1991; and Quirt et al., 1995) brings down the lowest transmission loss level to a lower frequency. Many possibilities cause similar and positive results. Resilient channels make the panels in a wall assembly vibrate independently and this study results aligned with the resilient channel solution. These measures act by interacting and attenuating with the structural resonance frequency.

The resilient effect introduced by the S3 and S2 types suggested that the outcomes might be as high as those expected when resilient channels are installed inboard of wood studs. The attachments used in this study mimicked similar commercial designs, but commercial versions likely withstand higher exterior loads and perhaps they end up having a higher stiffness than interior resilient channels. RCs are designed to withstand lighter loads, consequently, they can be designed to provide a high level of flexibility. Therefore, manufacturers might be able to design and provide higher levels of flexibility while being structurally safe. Another measure to improve the effectiveness of commercial cladding attachments would be varying the connection density, but, again, under safety loads.

Mineral wool insulation caused much higher sound transmission loss than XPS insulation, both as exterior insulation in split insulated walls. XPS sound absorption properties were demonstrated to be negligible but at lower 1/3 octave frequency bands XPS presented slightly better results than mineral wool. This might be explained by either some absorption properties at very low frequencies (Cox & D'Antonio, 2016) or by some interaction with attachments that interfered with the system's stiffness. Results for insulation material and insulation thickness aligned with previous studies (Bradley & Birta, 2000, 2001; Nightingale & Quirt, 1999; Quirt & Warnock 1993; Quirt et al., 1995) in terms of the impact of the sound insulation material and its absorption properties on transmission loss. The findings supported the observed effect depending on the physical properties (XPS vs. mineral wool) and showed similar behaviour to Bradley and Birta (2000), which tested EPS and glass fibre, for the insulation material. In terms of insulation thickness, the thicker the insulation, the better the performance at lower frequencies (Long, 2006; Nightingale & Quirt, 1999; Quirt & Warnock, 1993; and Quirt et al., 1995). As for XPS insulation thickness, because it did not provide sound absorption, increasing thickness did not bring about higher TL. The main effect was to increase the cladding to sheathing distance.

Insulation materials tended to be less efficient for stucco cladding walls than for lighter cladding walls (London, 1950). The massive cladding material was not as affected as FCB and vinyl when insulation material was changed. This corroborated the positive association between lighter panels and sound absorptive insulation, whereas for very heavy claddings TL is not strongly influenced by insulation.

Cladding and exterior insulation materials were the most influential variables in this study that interfered with sound transmission for split insulated wall assemblies in terms of the overall sound transmission behaviour. The combination of these two layers might be the difference between high and low sound transmission performances.

The results corroborated the theoretical correlation between transmission loss and cladding to sheathing distance (Long, 2006; Sharp, 1973; Xin & Lu, 2011) that states that either greater distances or greater distances along with heavier claddings cause higher TL. This effect was more evident for XPS walls due to lack of sound absorption properties, although greater distance in XPS walls was not capable of overcoming the negligible effects of this exterior insulation in larger cavity distances compared to mineral wool insulation absorption.

The rainscreen cavity width (3/8" and 1") did not appear to influence the overall sound transmission loss of split insulated rainscreen cavity wall assemblies. The contribution of the cavity widths was to the total cladding-to-sheathing distance and likely to the attachment's stiffness because it was one of the system's components. The sole addition of a rainscreen cavity to a wall might cause dual consequences. Findings indicated that at 250 and 315 Hz frequency bands, TL values were lowered, whereas at higher bands, TL increased. When mineral wool exterior insulation was added to a rainscreen cavity wall, results were significantly better than a single insulation rainscreen cavity wall. As for XPS as the exterior insulation, results showed very little improvement, and TL between single insulation rainscreen and split insulated rainscreen walls were nearly equal.

As a summary, Table 14 illustrates based on the findings from this study, what a high and low performance wall assembly would be for sound transmission loss, in general. Stucco was left out of this table because it did not have all permutations tested.

Table 14. High and low performance wall assemblies.

Sound Transmission Loss	Cladding	Insulation	Insulation Thickness	Attachment	Rainscreen Cavity Width
High	FCB	Mineral wool	3"	Clip / Z-girt	1"
Low	Vinyl	XPS	1 1/2"	Wood Strapping	3/8"

Using the findings as a reference, Table 15 presents a wall layers proposal that could be used to select materials to reach higher sound transmission loss walls. Starting from insulation material, which is the most important choice, the remaining layers should follow the upper row.

Table 15. Wall layers proposal and characteristics.

Sound Transmission Loss	Insulation	Cladding	Insulation Thickness	Attachment	Rainscreen Cavity Width
High	Sound Absorbing	Heavier	Thick	Point-line	Wide
Low	Non-absorbing	Lighter	Thin	Line-line	Narrow

To achieve higher sound transmission loss, the upper row should be followed for selecting building materials in a wall design in a comparison between materials when many options are still available in the design phase. On the other hand, if the chosen materials in a comparative selection had their properties fallen under the second row, the wall will tend to present lower transmission loss.

Future Research

A recommendation for future research is experiments that could solidify field and laboratory tests where the conditions of sound propagation and transmission are not within a diffuse field. In regard to the variables to be tested, a different approach to substantiate the impact of cladding attachments could use different solutions, perhaps currently commercial solutions, such as those for thermal breaking. In recent years, there have been many new advanced systems that seem to work well in providing higher transmission loss. Different types, manufacturers models, dimensions, and attachment distances can be tested.

7 CONCLUSIONS

The sound transmission of wood frame walls has extensively been evaluated in this research. It explored the wall features and their implications to indoors sound levels. A critical function of an exterior wall is to be an efficient sound barrier to environmental urban noise. Using correct materials and knowing acoustical principles, lightweight wood frame walls can be designed to deliver high sound insulation.

Research indicated that the two major factors that affect wall behavior in split insulated walls are the exterior insulation and the cladding material. The insulation material needs to provide sound absorption properties, whereas the cladding needs to be dense enough to reduce transmission. These wall layers might have their beneficial impacts amplified if additional measures are taken. Insulation should be thicker and cladding heavier. Both give additional sound losses to a wall.

In terms of the exterior wall cavity, findings indicated that cladding attachments might boost the sound transmission loss through a wide frequency range and allied with exterior insulation and cladding reach high performance results. With outcomes that can be comparable to measures such as indoor resilient channels connected to gypsum boards, increased stud spacing, and staggered studs, sound break attachments tended to improve sound transmission loss. This might be achieved by using specifically designed profiles that provide point-line connection between sheathing and cladding as well as less stiffness – resilient connections. This cladding attachment design resembles thermal breaking attachments, yet a proper validation of current ones need validation.

The rainscreen cavity was another feature under scrutiny due to the Metro Vancouver ‘s wet weather. An 8-month rainy season makes this building feature a near mandatory solution to prevent damage and increase durability to wood-frame walls. Regarding acoustical benefits, the rainscreen cavity width solely appeared to not contribute to higher or lower transmission loss. Its contribution was found to be indirect through stiffness and width to the overall attachment system.

Lastly, STC and OITC ratings lacked reliable representation of the frequency dependent sound transmission loss data. In the absence of a better comprehensive single-number rating that could also express sound levels in different ranges, these need to be cautiously used by building professionals.

The best performance obtained from this study was from stucco walls regardless of insulation type used, although only wood strapping was used for this wall type. The second best performance were obtained from FCB cladding being used with clip attachment (resilient connection), along with 3" mineral wool insulation, although Z-girt also promoted comparable high sound transmission loss. If vinyl is considered to be used as a cladding material, it must be installed in conjunction with a thick sound absorptive exterior insulation which will overcome vinyl sound transmission deficiencies, and also be used with resilient connections clip or Z-girt.

Since envelope walls are not the only element responsible for reducing exterior sound levels in a home environment, further studies should consider details of wall openings for windows, flues, pipes, vents and flanking paths, which affect the overall sound transmission loss.

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9 APPENDIX

A. Building Science Community

Research collaborators

- BCIT Lead: Maureen Connelly
- BC Housing: Denisa Ionescu
- IRC/NRC: Jeffrey Mahn

Advisory Meetings

- Collaborators: Maureen Connelly, Denisa Ionescu, Jeffrey Mahn
- Building Science Community: Hamid Heidarali, Leslie Peer, Ilona Cervantes
- City of Vancouver: Kevin Lau
- BCIT Building faculty: Ron Krpan
- FP Innovations: Jieying Wang, Ciprian Pirvu, Lin Ho

B. List of Equipment

Equipment	Manufacturer	Model Number	Serial Number
Speaker	JBL	EON-10 G2 Powered Speaker	10G2-20576
Intensity Probe	GRAS	50 AI version B	55684
1/2" Microphone for Intensity Probe	GRAS	40 AK	80391
1/2" Microphone for Intensity Probe	GRAS	40 AK	80459
Toughbook Laptop	Panasonic	CF-19	1BKCA32347
Soundbook MK2	Messtechnik	Sinus	07047
Sound Analyser Software	Samurai	2.6 version	--
Calibrator	Larson Davis	CAL200	3747
Sound Pressure Meter	Larson Davis	831	0003129
Noise Generator	Ivie	IE-20B	2703H272

C. Measurement Data

The data below are the measurements for the Wall # 45, Vinyl S3 (Clip) 3/8" Rainscreen Cavity Width 1 ½" XPS Exterior Insulation. The data present the horizontal and vertical sweeping measurements for 25 mm and 50 mm spacers. Pressure Intensity Index (F_{pI}) required for qualification of the measurement surface using the sweeping method according to the ISO 15186 is also presented for the 4 measurements described. Values are in 1/3 octave frequency band.

Sound Intensity Levels - Measurements

Spectrum (Hz)	50 mm		25 mm	
	Horizontal	Vertical	Horizontal	Vertical
	Leq (dB)	Leq (dB)	Leq (dB)	Leq (dB)
63	(+)53.8	(+)53.9	--	--
80	(+)59.8	(+)60.1	--	--
100	(+)60.3	(+)60.4	--	--
125	(+)64.8	(+)65.2	(+)64.8	(+)65.4
160	(+)59.3	(+)58.9	(+)59.3	(+)58.8
200	(+)52.0	(+)51.9	(+)52.4	(+)52.2
250	(+)54.8	(+)54.6	(+)55.0	(+)54.8
315	(+)49.0	(+)48.6	(+)49.2	(+)49.0
400	(+)45.6	(+)45.3	(+)45.5	(+)45.7
500	(+)44.3	(+)44.1	(+)44.2	(+)44.1
630	(+)42.8	(+)43.0	(+)42.9	(+)43.1
800	(+)39.5	(+)39.8	(+)39.7	(+)39.7
1000	(+)35.5	(+)35.9	(+)35.8	(+)36.1
1250	(+)29.6	(+)29.4	(+)29.6	(+)29.5
1600	(+)25.8	(+)25.9	(+)26.0	(+)26.8
2000	--	--	(+)21.4	(+)22.3
2500	--	--	(+)18.9	(+)18.9
3150	--	--	(+)17.9	(+)18.1
4000	--	--	(+)17.1	(+)17.4
5000	--	--	(+)15.2	(+)15.2

P-I Index (F_{pI}) - Pressure Intensity Index

Spectrum (Hz)	50 mm		25 mm	
	Horizontal	Vertical	Horizontal	Vertical
	Leq (dB)	Leq (dB)	Leq (dB)	Leq (dB)
63	(+)1.4	(+)1.7	--	--
80	(+)5.3	(+)5.3	--	--
100	(+)1.5	(+)1.5	--	--
125	(+)0.7	(+)0.6	(+)0.8	(+)0.6
160	(+)2.3	(+)2.5	(+)2.4	(+)2.5
200	(+)3.1	(+)3.1	(+)3.2	(+)3.2
250	(+)2.6	(+)2.8	(+)2.5	(+)2.8
315	(+)2.5	(+)3.0	(+)2.4	(+)2.9
400	(+)3.5	(+)3.7	(+)3.6	(+)3.8
500	(+)4.0	(+)4.2	(+)4.0	(+)4.3
630	(+)4.0	(+)4.0	(+)4.1	(+)4.1
800	(+)4.9	(+)4.7	(+)5.0	(+)5.0
1000	(+)4.7	(+)4.5	(+)4.6	(+)4.6
1250	(+)4.8	(+)4.6	(+)4.9	(+)4.8
1600	(+)5.1	(+)4.7	(+)4.9	(+)4.3
2000	--	--	(+)5.1	(+)4.3
2500	--	--	(+)6.1	(+)6.3
3150	--	--	(+)5.4	(+)5.3
4000	--	--	(+)4.7	(+)4.6
5000	--	--	(+)5.1	(+)5.1

D. Wall Assemblies Photographs

The following pictures illustrate some of the built wall assemblies and their respective wall layers.

Figure D.1. Metal clips attached to the base wall without exterior insulation.

Figure D.2. Metal clips and mineral wool exterior insulation.

Figure D.3. Metal clips, mineral wool, and S-track steel furring.

Figure D.4. Metal clips and XPS exterior insulation.

Figure D.5. Metal clips, XPS, and S-track steel furring.

Figure D.6. Horizontal Z-girt and mineral wool exterior insulation.

Figure D.7. Horizontal Z-girt, mineral wool, and vertical Hat-track furring.

Figure D.8. Horizontal Z-girt and XPS exterior insulation.

Figure D.9. Horizontal Z-girt, XPS, and vertical Hat-track furring.

Figure D.10. Wood strapping and mineral wool exterior insulation.

Figure D.11. Fiber cement board siding (cladding).

Figure D.12. Stucco wall.

E. Wall Construction and Detailing

At BCIT, in an exterior wall opening (Figure E.13) of 2.44 x 2.13 m (8’ x 7’) a sub-frame was built to support the base wall specimen and the subsequent additional layers.

Figure E.13. BCIT sound lab loading bay opening.

The final wall specimen size was 2.08 x 1.83 m (6’ 10" x 6’), which gives an area of 3.80 m^2 (40.97 ft^2). A sub-frame that supported the wall specimen to be tested was built. Figure E.14 shows the first steps which were the application of an acoustic sealant and a layer of gasket over the sealant. Above this gasket layer, another acoustic sealant was applied (**Error! Reference source not found.**).

Figure E.14. Acoustic sealant and gasket application.

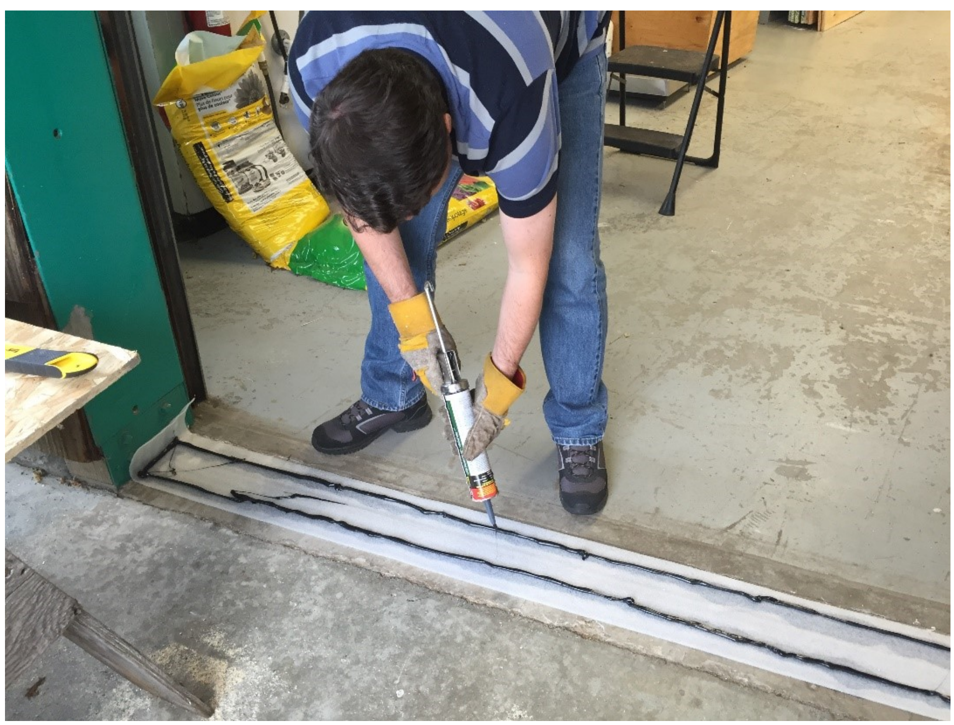

Figure E.15. Acoustic sealant applied over gasket.

Over the second layer of sealant, a 2"x10" plate was installed, and another gasket layer was placed. Between them, the acoustic sealant was also applied (Figure E.16).

Figure E.16. Acoustic sealant and gasket over the plate.

Above the second gasket, another sealant application and a solid and massive 8" x 8" wood column were laid. On top of this piece of wood, Figure E.17 shows a layer of sealant applied.

Figure E.17. Acoustic sealant applied over the 8" x 8" wood.

Figure E.18 illustrates the 2" x 10" plate and 8" x 8" piece sub-frame inferior components that represented a ground concrete foundation wall. This figure also presents a black rubber layer installed above the 8" x 8" that was installed to reduce flanking through vibration. Next step was to install a gasket over the rubber layer. Above this gasket, the bottom plate (2" x 6") of the wall specimen followed by the wood studs (2" x 6") and top plate (2" x 6") were installed (Figure E.19 and Figure E.20).

Figure E.18. Inferior components of the sub-frame wall.

Figure E.19. Wall specimen frame.

Figure E.20. Bottom plate and vertical wood studs.

Over the top plate and laterally to the leftmost and rightmost wood studs, the same rubber layer was installed (Figure E.21).

Figure E.21. Rubber layer between frame and sub-frame for lateral and superior components.

Between the wood frame wall specimen and the sub-frame, on the left and right sides, there were two openings that were completely filled with wood pieces to provide mass and eliminate any possible sound leakages (Figure E.22, Figure E.23, and Figure E.24).

Figure E.22. Wood pieces filling volume between sub-frame and wall specimen frame.

Figure E.23. Gap between the lateral wood stud and sub-frame filled with wood.

Figure E.24. Piece of wood board covering the wood filling laterally.

The next picture (Figure E.25) shows the plywood sheathing applied over the wood studs.

Figure E.25. Plywood sheathing over wood studs.

Figure E.26 illustrates an interior picture of the wall with the fiberglass batts and poly membrane as vapour barrier.

Figure E.26. Interior view of the wall with the fiberglass batts and poly membrane.

In the interior part of the lab, a partial enclosure was built to reduce reflections and noise from sources other than the testing source. The interior partition was constructed with wood frames, gypsum and wood boards, and fiberglass batt insulation on the inside, which along with absorptive floor created a semi-anechoic environment. The intent of this interior partition was to reduce any possible lateral sound that would affect measurements. On the right side of the partition, there was a single pane glass exit door, which could have allowed for unwanted noise entering the building. Figure E.27 presents a schematic layout plan view that shows the wall specimen, partition, and the exit door.

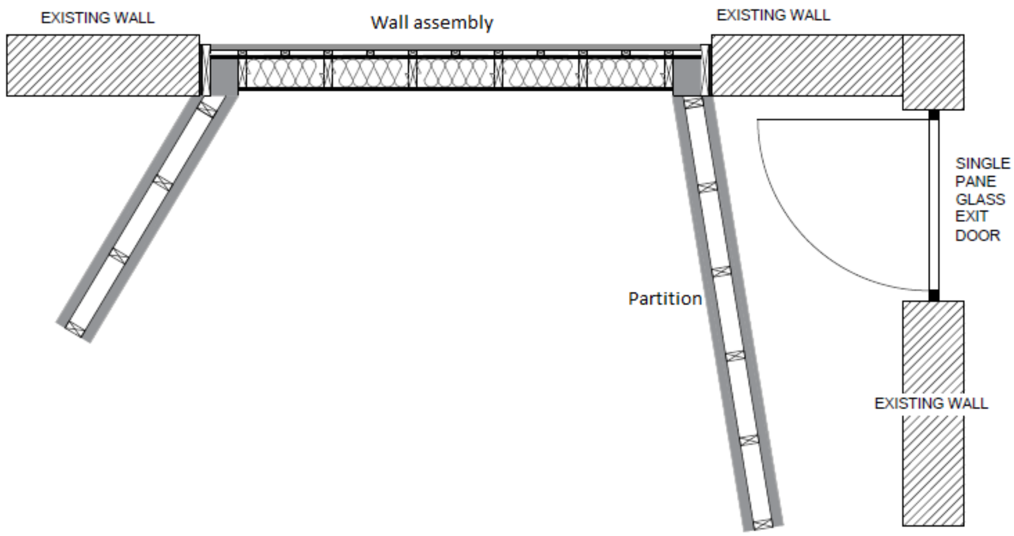

Figure E.27. Plan view of the lab layout. (Credit: Omid T.)

Figure E.28 presents an outside photograph of the lab showing the exit door and the wall specimen.

Figure E.28. External picture of the lab showing exit door (blue) and wall specimen to the right.

Figure E.29 illustrates the interior semi-anechoic partition frame. Figure E.30 shows the partition with the fiberglass batt insulation and the wall specimen with the painted and sealed gypsum board.

Figure E.29. Partition frame.

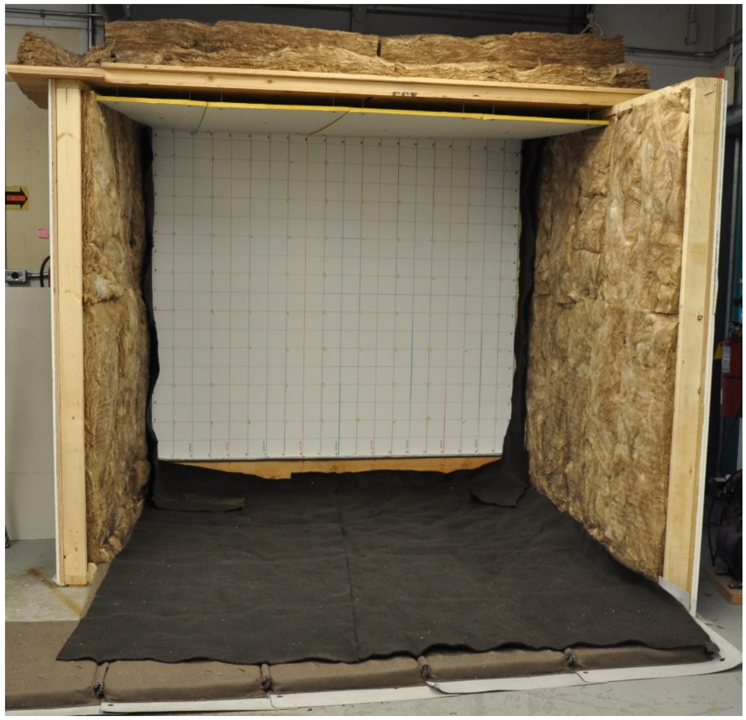

Figure E.30. Interior picture of the test wall specimen and the partition semi-closure faces.

On the exterior part of the test opening, an outer frame was built with the sole purpose of reducing lateral sound directly reaching the side of the specimen under test. The plywood sheathing flushed with the existing wall (Figure E.31) and this configuration could have exposed the outboard layers and their four sides to an undesired sound field. Incoming sound should only impinge the wall through the front side of the wall, and as such an exterior frame was needed. The bottom of the exterior surrounding frame was built with another massive 8" x 8" wood and a 2" x 8" plate, while the right and left sides were built with a double 2" x 8" plates sitting on top of the bottom plate. The top exterior sub-frame had a single 2" x 8" plate. Figure E.32 shows all described elements.

Figure E.31. Plywood sheathing flushing with the existing wall.

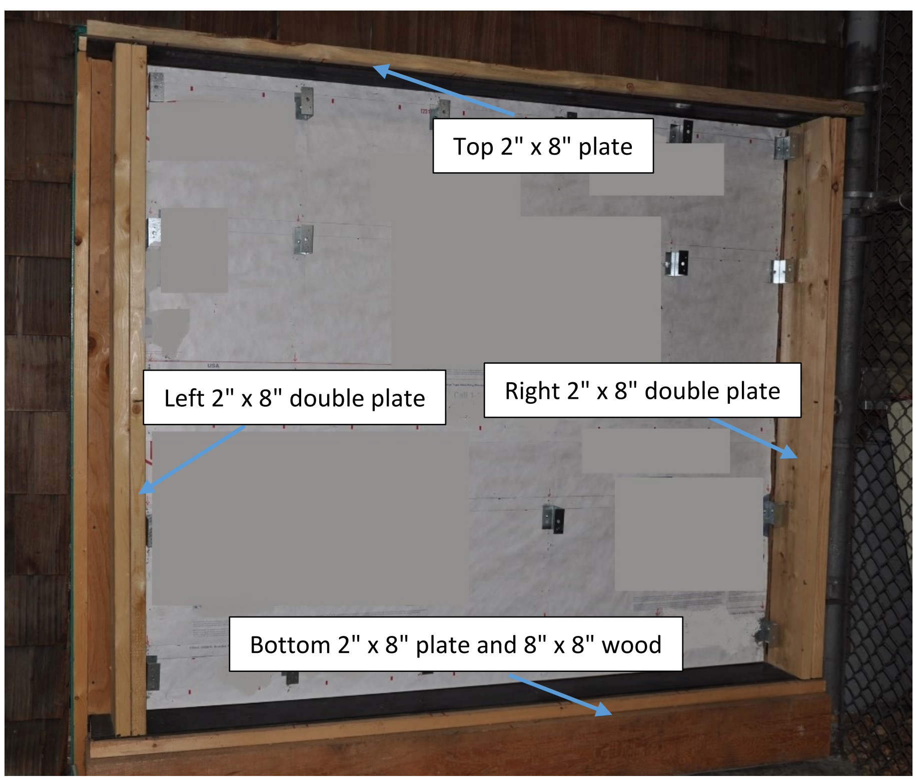

Figure E.32. Exterior frame and components.

During the tests, all walls were sealed with modeling clay between the cladding and the exterior frame on top, left, and right edges because the use of traditional acoustic sealants was not viable due to constraints such as installation, schedule, and cleanness (Figure E.33).

Since the study was intended to observe the more realistic behaviour of rainscreen cavity walls, all wall permutations had a horizontal opening at the bottom between the cladding and inferior external edge frame of approximately 10 mm (3/8"). This condition was selected to represent a vented condition in a rainscreen wall system, where rain that crosses cladding drains to the bottom of the wall and exits (Figure E.33).

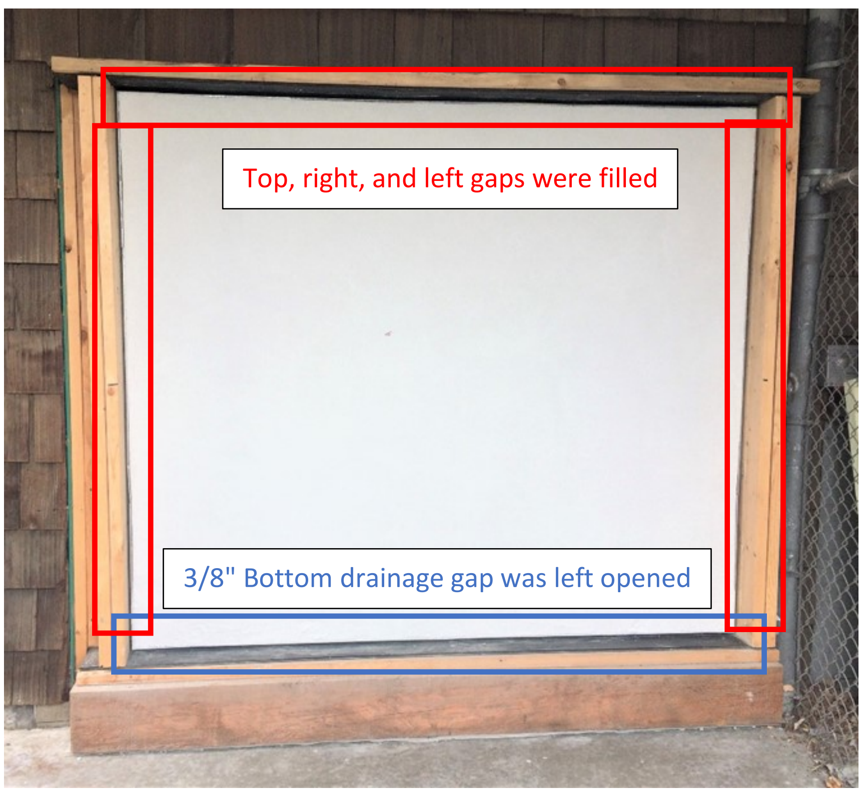

Figure E.33. Wall assembly and its edges.