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Effect of structural changes on acoustic performance of wood frame walls

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Summary

Sometimes in wood frame construction wall assemblies are required that have a higher axial load bearing capacity than conventional loadbearing wall designs. To increase the axial load bearing capacity to carry higher vertical loads, i.e. dead load or traffic load of upper building storeys, the framing has to be stronger, which can be achieved by either decreasing the spacing of the studs or by using stronger studs at a wider spacing. These significant structural measures increase the wall stiffness and thus can also affect the airborne sound insulation of the wall assemblies. The effect of wall stiffness on airborne sound insulation was investigated, by analysing bending wavenumbers measured along the primary axis on the gypsum board leaf of a common staggered stud wood frame wall and of assemblies with smaller than typical stud spacing (i.e. <400 mm), with multi-stud columns at a wider spacing, and with shear membranes in various configurations. A correlation in the change of bending wavenumber results and the change of airborne sound insulation was found in frequency ranges where the wall stiffness was influenced by the design changes. The results are promising and a first step towards a method for the estimation of airborne sound insulation changes from the mechanical properties of the wall.

PACS no. 43.55.+p, 43.40.+s

1. Introduction

In some building situations in modern wood frame construction, walls are required that have a higher lateral load bearing capacity than conventional wall designs. In North America, conventional loadbearing wood frame walls are usually framed with so-called 2x4 wood studs located at every 400 mm. To increase the axial loadbearing capacity to carry higher vertical loads, i.e. dead and traffic loads from upper storeys, framing has to be strengthened and stiffened. This can be achieved by increasing the number of studs per wall length or by using studs with bigger dimensions. Both measures might compromise the sound insulation performance of a wall assembly compared to a conventional assembly. Therefore a method that allows a decision on the performance of the strengthened wall or even an estimate of the change sound reduction index would be desirable. In this paper bending wavenumbers were measured along the various axes of wood frame wall assemblies. The change in the measured bending wavenumber was compared to the difference in the sound reduction index of the wall assemblies and for one case to the measured sound radiation index that relates the velocity on the element surface to the actual radiated sound power.

2. Measurement Methods

2.1. Airborne sound insulation

The airborne sound insulation was measured according to the test protocol in ISO 10140-2 in the NRC-Construction wall sound transmission facility. The facility consists of two adjoining and structurally isolated rooms with a test opening in the partition that can accommodate a test frame with a 3.65 m wide and 2.40 m high wall specimen. The room sizes are 140 m^3 for the small and 250 m^3 for the large room.

Tests were done in forward and reverse direction, i.e. for the first the small room was source room and the large room receiving room and for the second measurement vice-versa. The sound reduction index indices presented in this paper are the average of both directions.

2.2. Bending wavenumber measurements

For the matter of simplicity in this paper, the wavenumber k_B refers to the real part of the complex bending wavenumber that describes propagation of free plane bending waves in structures. It is proportional to the inverse of the bending wavelength and describes the phase relationship between points on a structure with a plane propagating wave.

A procedure for the measurement of the wavenumber on building structures is given by Nightingale et al. in [1] and was already applied earlier successfully to lightweight framed floor [2] and wall assemblies [3].

The wavenumber k_B is the spatial gradient of the phase ϕ of a plane propagating wave in propagation direction as defined in Equation 1.

$$\mathbf{k_B} = \frac{\partial \phi}{\partial \mathbf{r}} \approx \frac{\phi_2 - \phi_1}{\Delta \mathbf{r}}, \qquad (1)$$

The wavenumber can be approximated with a finite difference approach if the phase difference $\Delta\phi$ between two observer points with distance Δr is known as shown in Equation 1.

The applied wavenumber measurement technique uses this approach and the phase relationship between an excitation point and equally spaced observer points on a so-called draw-away line is measured. At the excitation point the structure is excited with an electro-dynamic shaker. The phase of acceleration is measured in 1/3-octave bands with an impedance head at the excitation point and accelerometers at the observer points on the draw-away line.

In theory, the phase difference increases linearly with distance. Hence, a linear curve fit is applied and the slope of the fitted line is an estimate of the wavenumber. To be able to unwrap the measured phase information accurately in all frequency bands of interest, observer points ideally must be spaced less than half a wavelength. For the measurements, 20 points were chosen spaced at 5 cm which usually is appropriate for measurements in the frequency range up to at least 3150 Hz.

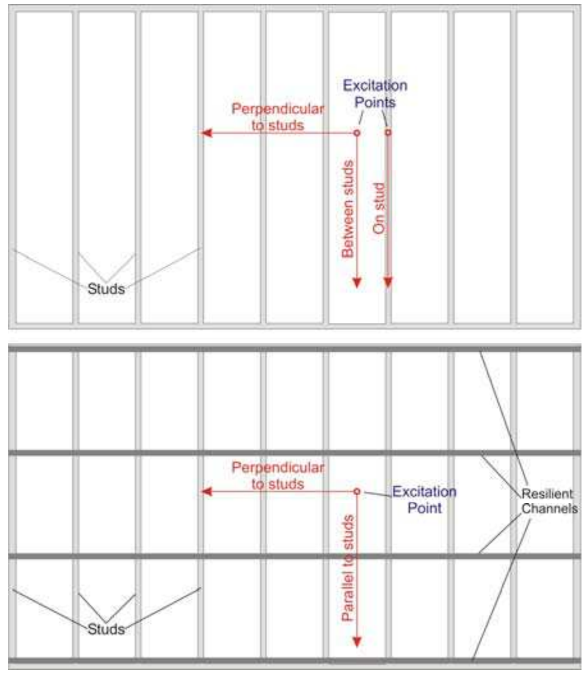

Figure 1. Orientation of draw-away lines; top: gypsum board directly attached to wood frame; bottom: gypsum board mounted on resilient channels

In this paper measurements were done on the gypsum board cladding that was directly attached to the wood frame along lines shown in Figure 1 with following orientation:

- Perpendicular to the wood studs close to centre line of the wall
- On a wood stud
- Along centre between two studs

On gypsum board claddings that were mounted to resilient channels only two lines were used:

- Perpendicular to the wood studs between resilient channels
- Parallel to the wood studs

2.3. Sound radiation index

For one situation the sound radiation index I_R as defined in Equation 2 was measured for further analysis of the sound insulation change. It is the logarithmic value of the sound radiation efficiency σ which is defined as the ratio of sound power W_{rad} that is actually radiated by a surface of area S into a space and the sound power that would be theoretically radiated by an ideal piston moving with the same space average mean square surface velocity $\langle v \rangle^2$ as the radiating surface where ρ_0 and c_0 are the density and sound speed in air.

$$\mathbf{I_R} = \mathbf{10\,lg}\,\sigma = \frac{\mathbf{W_{rad}}}{\rho_0 \mathbf{c_0 S} \langle \mathbf{v} \rangle^2}, \qquad (2)$$

Unfortunately, currently no standard or guideline exists for the measurement of the radiation efficiency itself. Thus, parts of the ISO 10140 protocol were applied for the sound power measurement and parts of the ISO 10848 protocol for the surface velocity measurement.
For measurements, the gypsum board leaf under test was excited at three different excitation positions with an electro-dynamic shaker driven by white noise. The sound pressure was measured as described in Section 2.1. The surface velocity was measured at 8 measurement positions for each excitation position that randomly distributed over the whole element surface. Some points were located on a stud and others in bays between studs.

3. Test specimens

Wood frame gypsum board wall assemblies with four different framing variants were investigated in this paper.

3.1. Wood framing

Framing details are illustrated in the drawings of Figure 2 by horizontal cut drawings through the wall framings. Only the cavities between the studs on one side were filled with glass fiber batts that had the same depth as the studs.

a) <u>2x4 staggered studs @400 mm</u>
The first was a conventional 2x4 staggered stud wall framing with studs (38 mm x 89 mm) attached in two rows to a single 2x6 foot plate (38 mm x 140 mm) and a double 2x6 head plate. The two stud rows were staggered, i.e. one row was flush with one side of the foot- and head plate and one row flush with the other side. The spacing between the studs in each row was 400 mm as for a typical North American loadbearing wall.

b) <u>2x4 staggered studs @100 mm</u>
The second framing was similar to the conventional 2x4 staggered stud wall framing, however, more studs were used in each row and the stud spacing is decreased to only 100 mm.

c) <u>2x4 tripled staggered studs @400 mm</u>
The third framing had columns fabricated out of three 2x4 studs that were connected with screws along their length, instead of single 2x4 studs. The tripled studs were spaced 400 mm on centre.

d) <u>2x6 staggered studs @400 mm</u>
The last framing was similar to the first one in terms of fabrication, but lumber with greater dimensions, i.e. 2x6 studs (38 mm x 140 mm) and 2x8 plates (38 mm x 184 mm), was used.

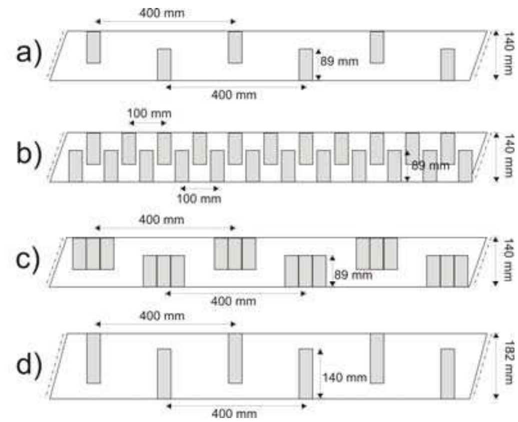

Figure 2. Wall framings (horizontal cut); a) 2x4 staggered studs @400 mm; b) 2x4 staggered studs @100 mm; c) 2x4 tripled staggered studs @400 mm; d) 2x6 staggered studs @400 mm.

3.2. Gypsum board cladding

For all walls two layers of nominally the same 13 mm thick gypsum board were used as cladding on both sides of the framing where it was either directly attached (DA) or mounted to resilient metal channels (RC).
The directly attached cladding was fastened to the framing along each single or tripled stud along a single line and the fastener spacing of was 600 mm for the base layer and 300 mm for the face layer.
The fastening pattern for the gypsum board was the same along the resilient channels. The channels were spaced 600 mm and fastened to each single or tripled stud at a single point.

3.3. Wall assemblies

The following 6 framing and cladding variants are considered in this study:

- 2x4 staggered studs @400 mm:
  1) both sides DA,
  2) one side DA and one side RC,
- 2x4 staggered studs @100 mm:
  3) both sides DA,
  4) one side DA and one side RC,
- 5) 2x4 tripled staggered studs @400 mm both sides DA, and
- 6) 2x6 staggered studs @400 mm both sides DA.

4. Measurement results

4.1. Sound reduction index

The sound reduction index for all framings with directly attached gypsum board on both sides is shown in Figure 3. In the mid- and high frequency range the performance of the wall with the small stud spacing is clearly worst. All the other walls show the same trend, but the 2x6 framing performs slightly better than the 2x4 framings with wide stud spacing. The difference of sound reduction index relative to the conventional 2x4 staggered stud wall shown in Figure 4 reveals that all three strengthened framings have an about 3 to 9 dB lower sound reduction index in frequency range between 100 Hz and 200 Hz. The sound insulation of the framings with the 400 mm spacing increases and the one with the 100 mm spacing decreases further towards higher frequencies.

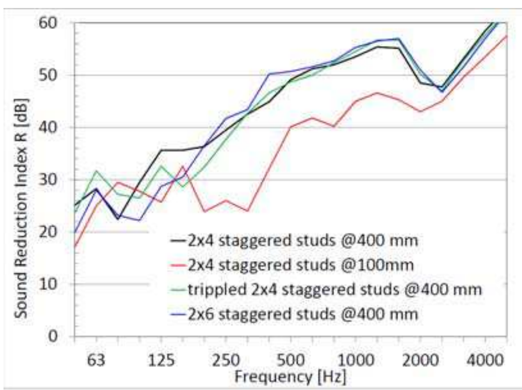

Figure 3. Sound reduction index of wall assemblies with directly attached gypsum board on both sides

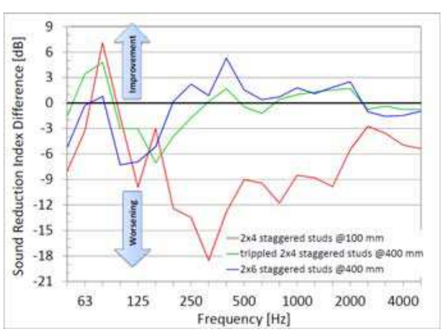

Figure 4. Change of sound reduction index due to framing modifications

The results with the gypsum board mounted to resilient channels on one side in Figure 5 indicate that improvement in sound reduction index is much bigger for the framing with 100 mm stud spacing. In the low in mid-frequency range this assembly performs similar to the conventional wall without resilient channels, then sound insulation increases and in the high frequency range it even performs as good as the conventional framing with resilient channels.

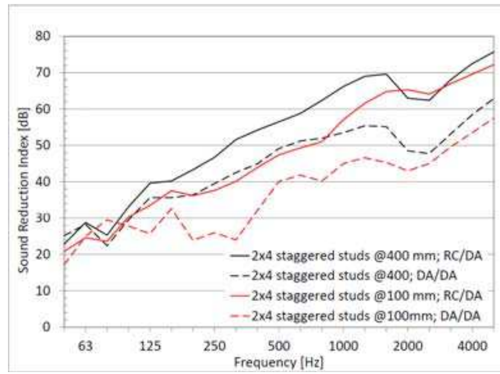

Figure 5. Sound reduction index of walls with one gypsum board cladding mounted to resilient channels

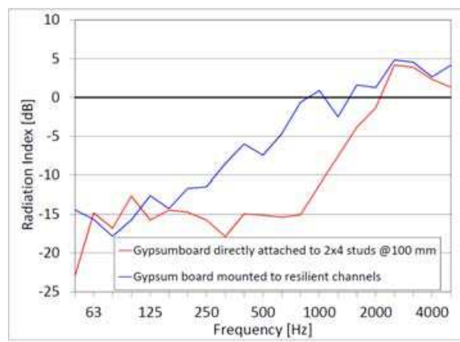

Figure 6. Radiation index for gypsum board directly attached and mounted with resilient channel to 2x4 staggered studs @100 mm

The greater improvement due to resilient channels for the wall with the small stud spacing is the combination of decoupling the gypsum board and reduction of its ability to radiate sound. The measured sound radiation index in Figure 6 is much higher for the directly attached cladding than when resilient channels are used.

4.2. Wavenumber measurements

The radiation index in Figure 6 gives also some first insight in the structural properties of the cladding. At low frequencies the radiation index is negative the wavenumber of the bending waves on the cladding is bigger than the wavenumber in air and sound is radiated only at discontinuities, like the studs and boundaries of the element. At high frequencies above coincidence the radiation index is equal or greater zero and the wavenumber in air is equal or greater than on the cladding and sound is radiated very effectively on the whole element surface. Therefore wavenumber measurements can be very useful to gain insight in the radiation and sound transmission performance of a structure as it is shown in the following.

In Figure 7 wavenumbers measured on gypsum board leaf that is directly attached to the conventional wood frame with 2x4 staggered studs is presented together with predictions for the studs, air and for the gypsum board in both orthogonal directions because of the slight material orthotropy. Globally, the wavenumbers measured perpendicular to the studs are similar to the prediction for plain gypsum board, whereas for orientations parallel to the studs they follow the wavenumbers of studs at low frequencies and of plain gypsum board at high frequencies. As described in [3], transition from one regime to another begins between the studs when half a bending wavelength λ_B in the gypsum board equals approximately the stud spacing d_{stud} and on the studs when half a bending wavelength λ_B is equal to the spacing of the screws d_{screw}. Except for the range below 50 Hz and above coincidence at 2000 Hz all measured wavenumbers are bigger than the wavenumbers in air and thus sound is radiated not efficiently in most of frequency range used for sound insulation measurements.

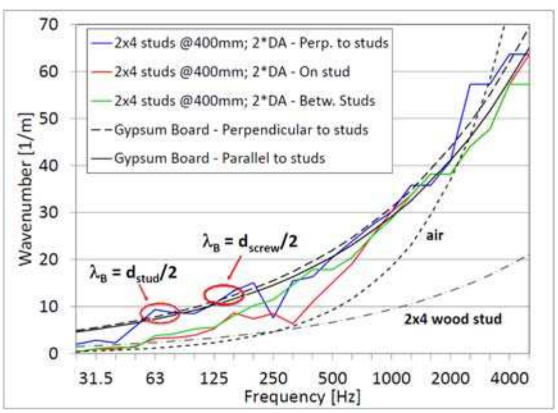

Figure 7. Measured wavenumbers for gyspum board directly attached to 2x4 staggered studs @400 mm

In Figure 8 the measured dispersion curves for the gypsum board cladding mounted with resilient channels to the 2x6 staggered studs @400 mm are shown. They agree very well with the predictions for plain gypsum board in most of the frequency range and the wavenumbers are perpendicular to the studs slightly higher than parallel to studs, which can be attributed to the orthtropy of the gypsum board. The resilient channels decouple the cladding very effectively from the studs so that the gypsum board is not restrained by the frame. Thus, when mounted to resilient channels the wavenumbers on gypsum board are independent from framing details. Since below coincidence the wavenumbers on the cladding are also much greater than for air sound is radiated not efficiently which agrees well with the relative low radiation index in Figure 6.

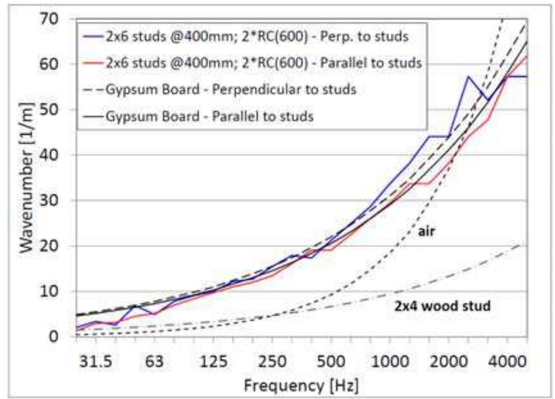

Figure 8. Measured wavenumbers for gyspum board mounted to resilient channels

In Figure 9 the measured wavenumbers in direction perpendicular to the studs are shown for all framings when the gypsum board cladding is directly attached. All curves are almost equal and follow the theoretical predictions for gypsum board very well. Only in some frequency bands lower wavenumbers were measured that can be attributed to standing waves as an inspection of the raw phase data revealed.

The wavenumbers measured along the studs in Figure 10 and the ones between the studs in Figure 11 (unfortunately, this orientation was not measured at 2x4 tripled staggered studs) again follow all the wavenumbers of the framing in the low frequency range and of the gypsum board in the high frequency range. At low frequencies the predicted wavenumbers for single 2x4 studs and tripled 2x4 studs are equal and the difference to 2x6 studs is only marginal. Thus, also all measured wavenumbers are almost equal.

Good agreement is found for the beginning of the transition between the regimes by comparison of stud and screw spacing with the predicted bending wavelength of gypsum board. The only outlier is the framing with the 100 mm stud spacing, with wavenumbers much smaller than for the other framings far above 160 Hz where the screw spacing equals half a bending wavelength. However, the transition frequency for the 100 mm stud spacing is around 1000 Hz which might explain the shift.

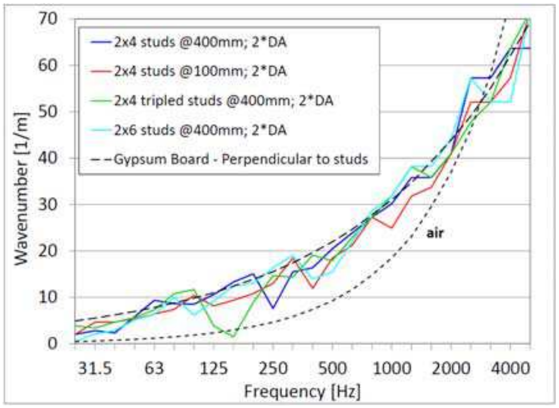

Figure 9. Measured wavenumbers prependicular to studs for gyspum board directly attached to framing.

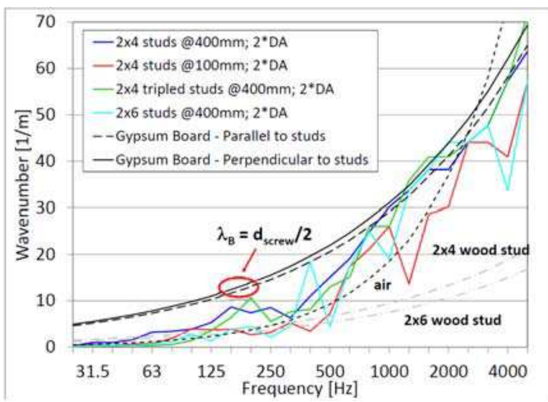

Figure 10. Measured wavenumbers on studs for gyspum board directly attached to framing.

4.3. Wavenumber vs. sound reduction index

Finally, the measured wavenumbers in Figure 9 to Figure 10 are compared to the sound reduction index in Figure 3. The framing with 100 mm stud spacing performs worst in the mid frequencies and the measured wavenumbers on the studs and in-between are also much lower in this range than for the other walls. On the stud the bending wavenumbers are smaller than in air. Bending waves that travel in this direction can be radiated sound effectively which agrees well with the increasing sound radiation index above 125 Hz.

The tripled 2x4 stud framing performs worse than the conventional 2x4 framing around 160 Hz. This correlates well with a dip of the wavenumber perpendicular to the studs where its value is smaller than in air. The dip is attributed to standing waves probably caused by the greater mass of the studs that reflect structure-borne sound travelling perpendicular to the studs more.

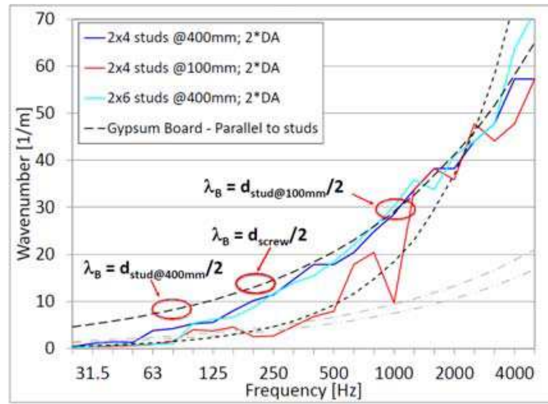

Figure 11. Measured wavenumbers between studs for gyspum board directly attached to framing.

The 2x6 staggered stud framing was expected to have a higher sound insulation than the conventional framing because of the deeper cavity that lowers the mass-spring-mass resonance of the wall assembly that compromises sound insulation. But around 125 Hz the 2x6 stud wall performs even worse. Figure 10 and Figure 11 reveal that because of the stiffer 2x6 studs the wavenumbers are lower than for the 2x4 studs and close to the one in air in this frequency range.

5. Conclusions

A good correlation was found between sound insulation performance and wavenumbers of 6 load bearing wood frame gypsum board wall assemblies with different framings and gypsum board attachment methods which shows that the wavenumber measurement is a powerful tool for analyzing vibration behavior of lightweight framed assemblies. The measured wavenumbers also agreed very well with predicted ones of different structural members in different frequency ranges. Globally, the transition between the regimes occurs as described in [3]. Further, the modal behavior of the structural members must also be taken into account as it affects the wavenumbers in some frequency bands.

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