05 Airborne sound insulation

ELEC-E5640 - Noise Control D

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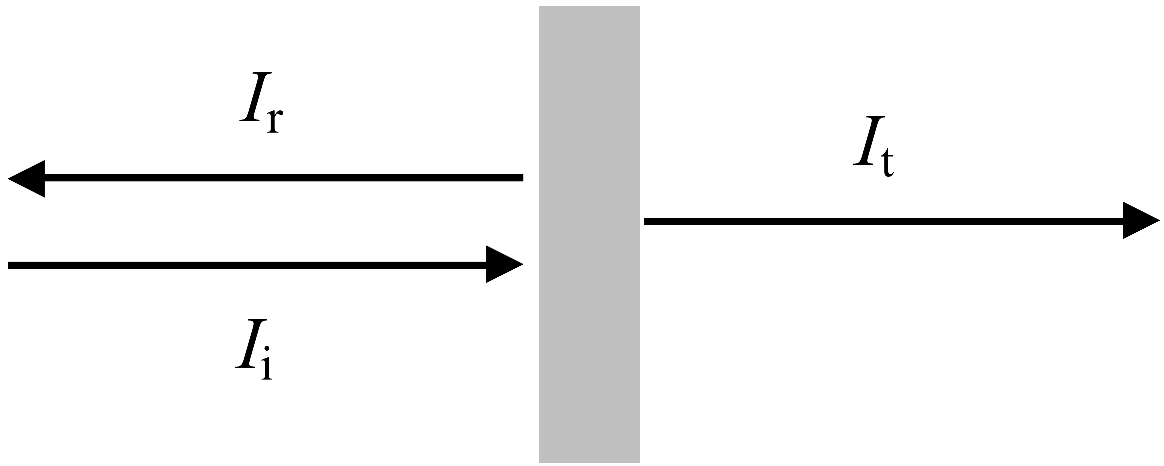
Transmission

- Transmission factor τ is the ratio of transmitted I_t and indident intensity I_r.
- Intensity is the energy per unit area [W/m^2].
- The magnitude of reflected intensity is neglected in this definition.
- The value of τ varies from 10^{-8} to 0.5 for usual constructions, therefore, logarithmic expression is useful.
- **Sound reduction index** *R* [dB] or **SRI** is defined by

$$R = 10\lg\frac{1}{\tau} = 10\lg\frac{I_i}{I_t}$$



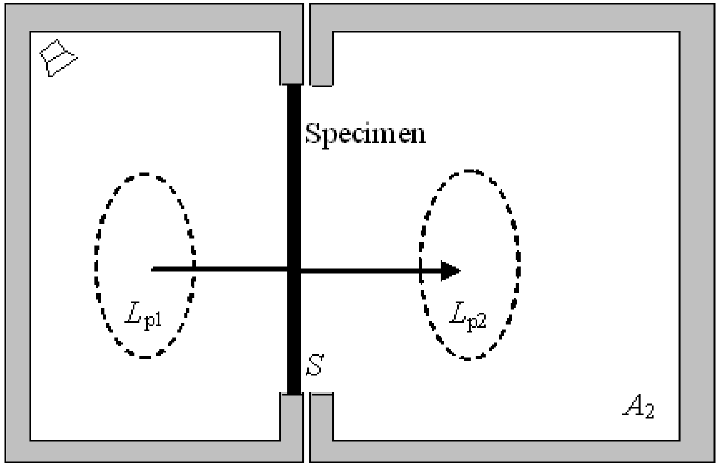
Determination of SRI in laboratory (ISO 10140-2)

- Pressure method means that incident and radiated intensity are derived indirectly using the spatial average of SPL in both rooms.

- R [dB] is sound reduction index, SRI
- τ is the transmission coefficient
- W_1 [W] is the incident sound power
- W_2 [W] is the transmitted sound power
- S [m^2] is the area of the specimen
- A_2 [m^2] is the absorption area of the receiving room (A=0.16V/T)
- $L_{p,1}$ [dB] is SPL in the source room.
- $L_{p,2}$ [dB] is SPL in the receiving room.

ISO 140-3 (pressure method, 50-5000 Hz)

$SRI = L_{p1} - L_{p2} + 10\lg(S/A_2)$



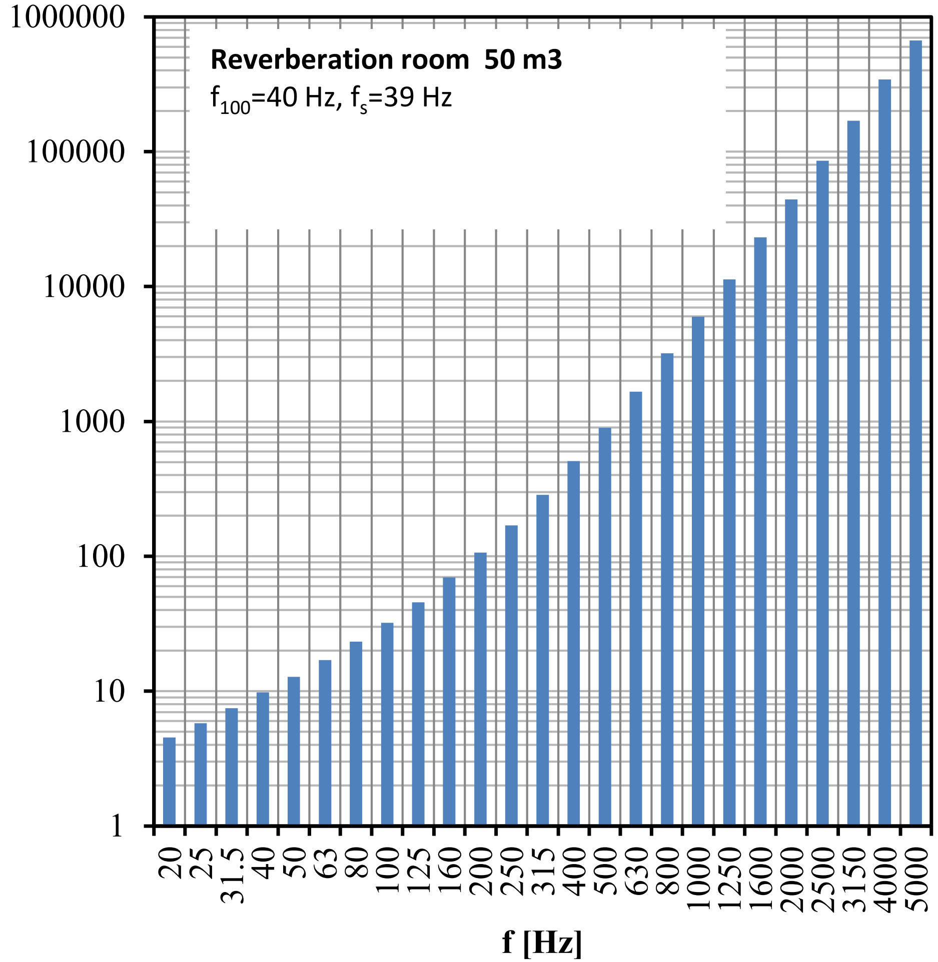
$$R = 10\log\frac{1}{\tau} = 10\log\frac{W_1}{W_2}$$

$$R = L_{p,1} - L_{p,2} + 10\lg\frac{S}{A_2}$$

Room mode analysis

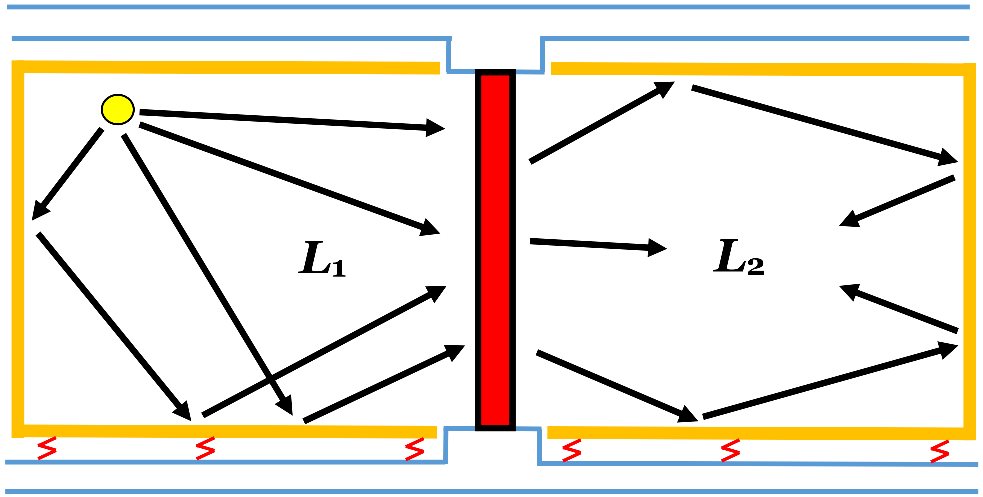
- It has been politically decided that sufficient number of room modes exist at 100 Hz, if the room is reverberant and larger than 50 m3.
- Measurements within 50-80 Hz in such a small room contains obvious risks due to too small (10-25) number of room modes per one-third octave band

Number of modes per third octave band



Determination of SRI in laboratory (ISO 10140-2)

- Specimen is installed between two reverberant rooms of 50 m^3 or more
- Rooms are isolated from building frame flexible mounts to avoid flanking transmission
- Specimen (red) is installed on a mounting frame which is mechanically connected to the building frame
- Specimen size for floors and walls is 10 m^2
- Smaller sizes are used for, e.g., windows, doors, and ventilation supplies

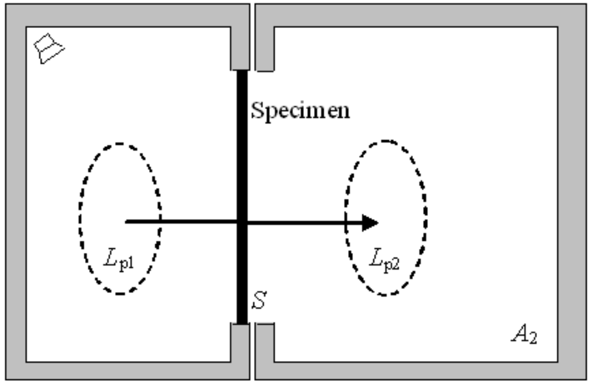


Measurement uncertainty

- A three-pane single-frame window was tested in five Nordic laboratories using both pressure and intensity method

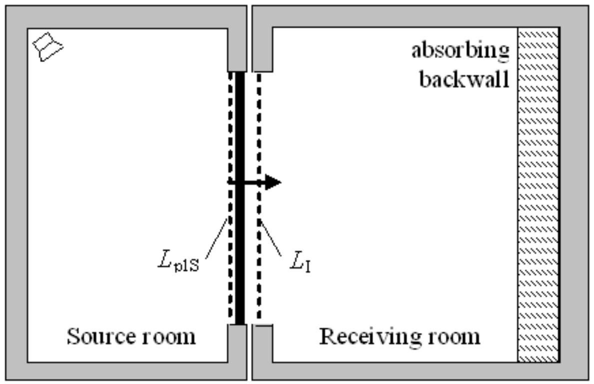
ISO 140-3 (pressure method, 50-5000 Hz)

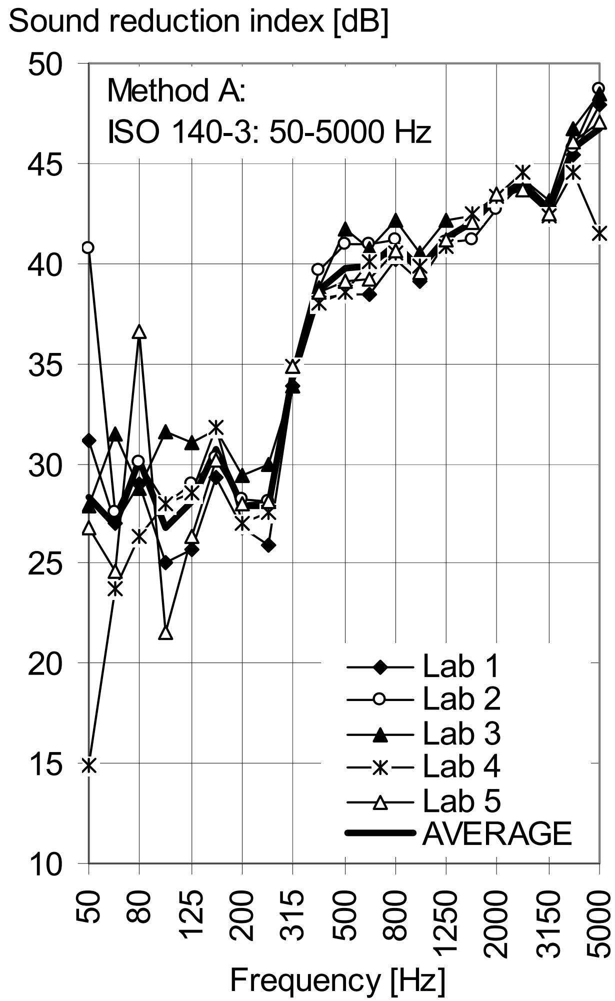
$SRI = L_{p1} - L_{p2} + 10\lg(S/A_2)$

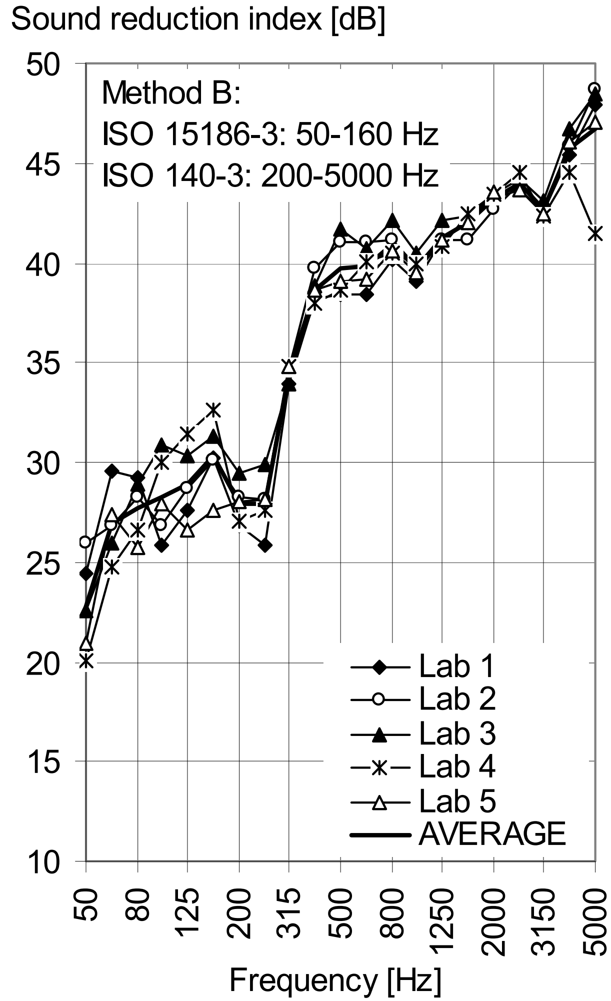


ISO 15186-3 (intensity method, 50-160 Hz)

$SRI = L_{p1S} - 9 - L_I$



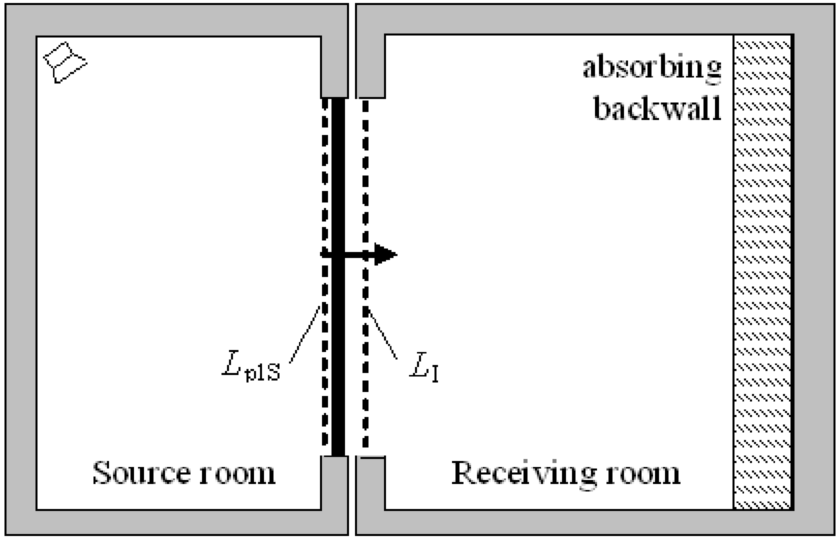




Hongisto et al. (2012) *Acta Acust united Ac*

Sound intensity method

- Sound intensity method is the recommended method to determine SRI at low frequencies
- The backwall of the room is covered with 600 mm thick sound absorber to weaken the reactive sound field (reflections) between the specimen and the backwall



- L_{pIS} [dB] is the SPL right in front of the specimen (10 mm distance)
- L_I [dB] is the sound intensity level radiated by the specimen

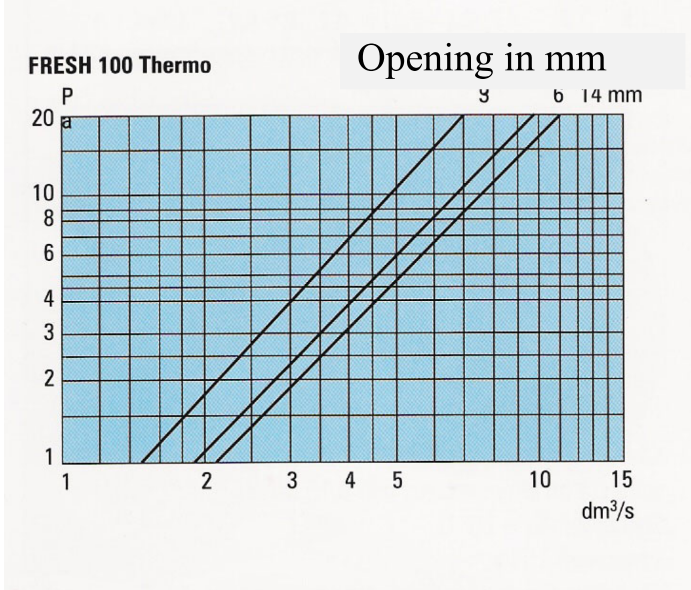
$$R_I = L_{p1S} - L_{I2} - 9$$

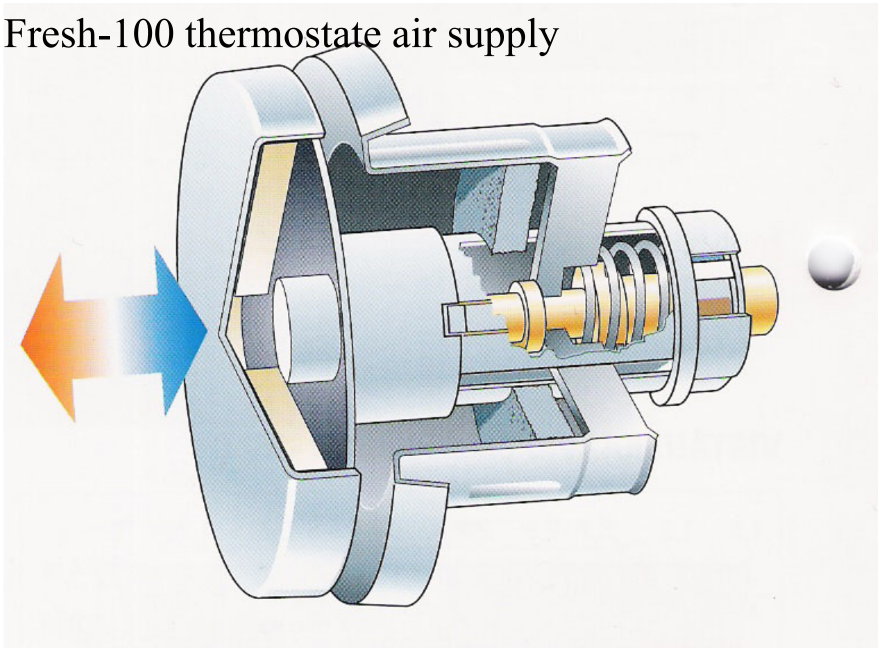
Measurement of small elements in laboratory

$$D_{n,e} = L_{p,1} - L_{p,2} + 10\lg\frac{A_0}{A_2}$$

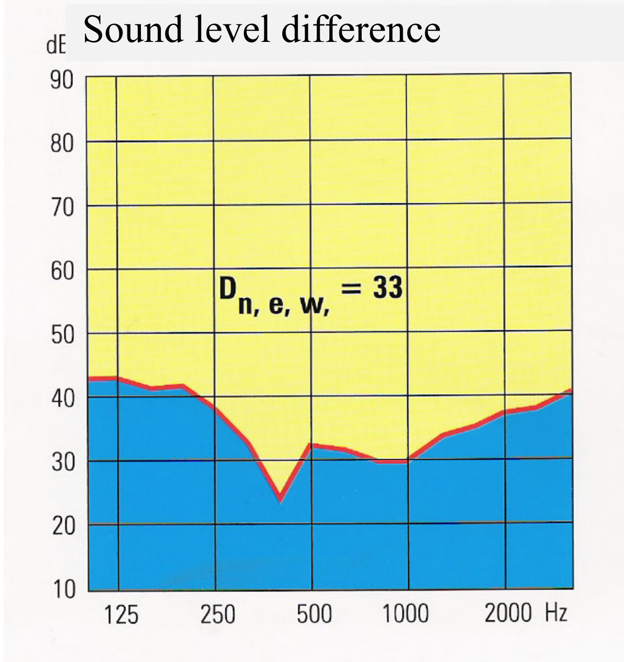
Element-normalized sound level difference

A_0=10 m^2





$$R = L_{p,1} - L_{p,2} + 10\lg\frac{S}{A_2}$$



5.1

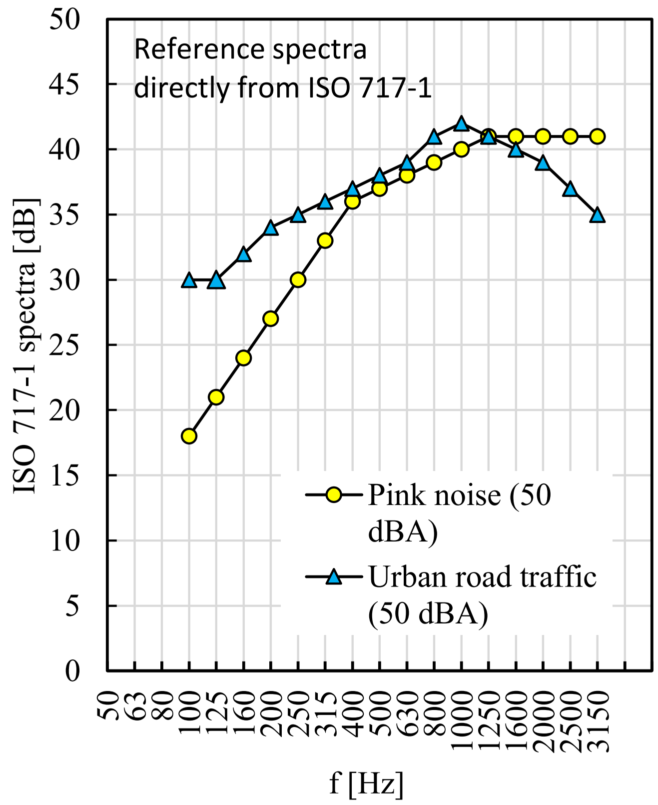
A facade wall is studied in laboratory (S=10 m2).
It involves a ventilation unit (160x200 mm) fully open.
Measurement results were $L_{p,1}$=100 dB, $L_{p,2}$=80 dB and A_2=4 m2.
Determine R and Dn,e.
Why is it more feasible to declare Dne instead of R
although the former does not reflect the physical size?

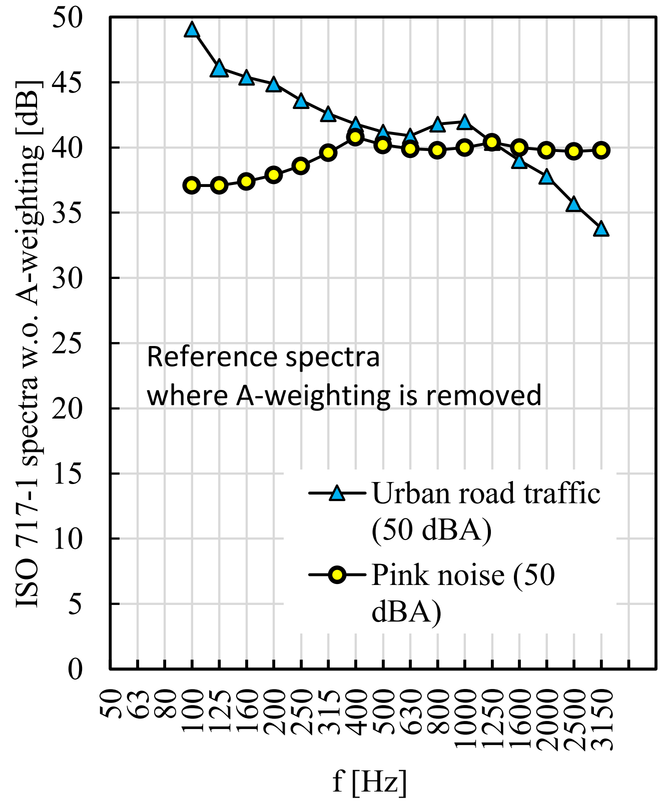
$$R = L_{p,1} - L_{p,2} + 10 \lg \frac{S}{A_2}$$

$$D_{n,e} = L_{p,1} - L_{p,2} + 10 \lg \frac{A_0}{A_2}$$

Single-number quantities (SNQs) for airborne sound insulation

- SNQs are needed to avoid the use of frequency-based data in regulations and business
- ISO 717-1 defines procedures to determine the **weighted sound reduction index, R_w**, and 8 spectrum adaptation terms C from measurement data of R
  - Similar procedure is used for all quantities describing airborne sound insulation: D_{nT}, D_n, R', $D_{e,w}$, R'_{45}.
- **R_w** describes sound insulation performance against noise having spectrum close to pink noise within 100-3150 Hz
- **$R_w + C_{tr}$** describes sound insulation performance against noise having spectrum close to urban road traffic noise within 100-3150 Hz

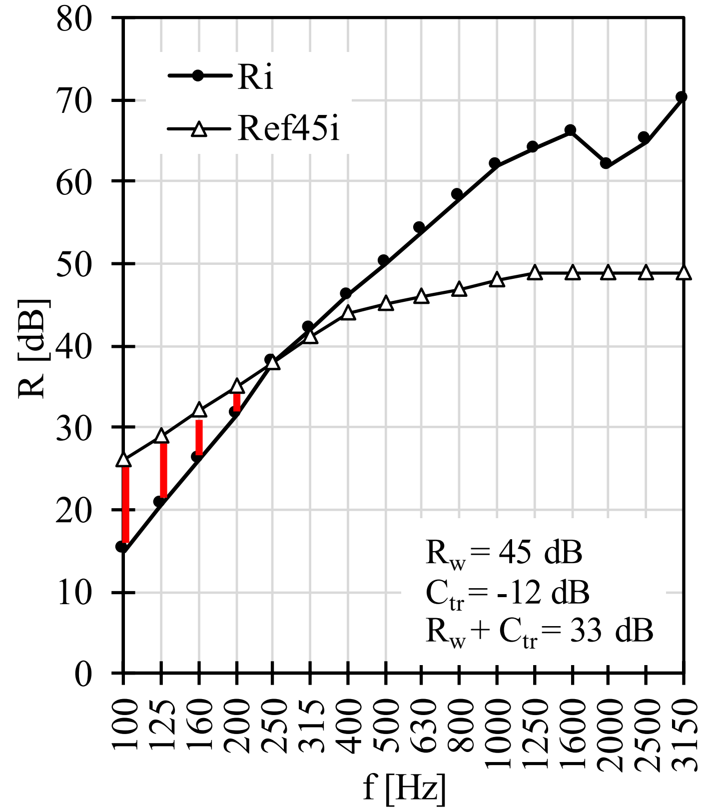




R_w is determined from the measured R values using ISO 717-1. Shape of Ref is always the same but the vertical position depends on the initial value given for 500 Hz (anchor frequency). Anchor frequency is given as high value as possible so that the sum of unfavorable deviations is still under 32 dB. Unfavorable deviation occurs when the reference curve Ref is below the measured value R. Therefore, the initial quess for anchor is 0 dB and the value is increased until the 32 dB limit is broken.

Weighted sound reduction index, R_w, and weighted sound reduction index against road traffic noise, R_w+C_{tr}

f_i	R_i [dB]	Ref_i [dB]	$Ref45_i$ [dB]	Dev_i [dB]	L_{i2} [dB]	$L_{i2} - R_i$ [dB]	$10^{(Li2-Ri)/10}$
100	15.0	*R* w-19	26	**11.0**	-20	-35.0	0.0003162
125	20.5	*R* w-16	29	**8.5**	-20	-40.5	0.0000891
160	26.0	*R* w-13	32	**6.0**	-18	-44.0	0.0000398
200	31.5	*R* w-10	35	**3.5**	-16	-47.5	0.0000178
250	38.0	*R* w-7	38	0.0	-15	-53.0	0.0000050
315	42.0	*R* w-4	41	0.0	-14	-56.0	0.0000025
400	46.0	*R* w-1	44	0.0	-13	-59.0	0.0000013
500	50.0	***R* w**	**45**	0.0	-12	-62.0	0.0000006
630	54.0	*R* w+1	46	0.0	-11	-65.0	0.0000003
800	58.0	*R* w+2	47	0.0	-9	-67.0	0.0000002
1000	62.0	*R* w+3	48	0.0	-8	-70.0	0.0000001
1250	64.0	*R* w+4	49	0.0	-9	-73.0	0.0000001
1600	66.0	*R* w+4	49	0.0	-10	-76.0	0.0000000
2000	62.0	*R* w+4	49	0.0	-11	-73.0	0.0000001
2500	65.0	*R* w+4	49	0.0	-13	-78.0	0.0000000
3150	70.0	*R* w+4	49	0.0	-15	-85.0	0.0000000



R: Measured airborne sound reduction index

Ref: Reference curve shape

Ref45: Ref at 45 dB

Dev: Non-favorable deviation: =Max(0; $Ref45_i$ - R_i)

$Sum=\Sigma[10^{(Li2-Ri)/10}]=$ 0.000473

$X_{A2}=-10\cdot\log_{10}(Sum)=$ 33.3

$C_{tr}=X_{A2} - R_w=$ -11.7

$C_{tr}=$ **-12**

L_{i2} is the reference spectrum used to calculate C_{tr}.

Sum of non-favorable deviations, Dev_i :

29.0 dB argest allowed: 32.0 dB.

Overview of structure types and factors affecting SRI

Single panels

- One material
- SRI is mainly explained by surface mass and Young’s modulus
- Examples:
  - glass
  - gypsum
  - brick
  - Concrete
  - Plywood
  - Chipboard

Sandwich

- Glued rigid composite panels
  - E.g. panel-glue-flexible-glue-panel
- SRI is mainly explained by surface mass
- Examples:
  - steel-wool-steel in facades
  - veneer-rubber-veneer in vehicle floors
  - Honeycomb
  - floating floors

Coupled multilayer constructions

- Two layers separated by a cavity and equally distributed studs
- SRI is mainly explained by surface mass, cavity thickness and dynamic stiffness of studs
- Examples:
  - Light drywalls
  - Windows
  - Douple and triple glazings

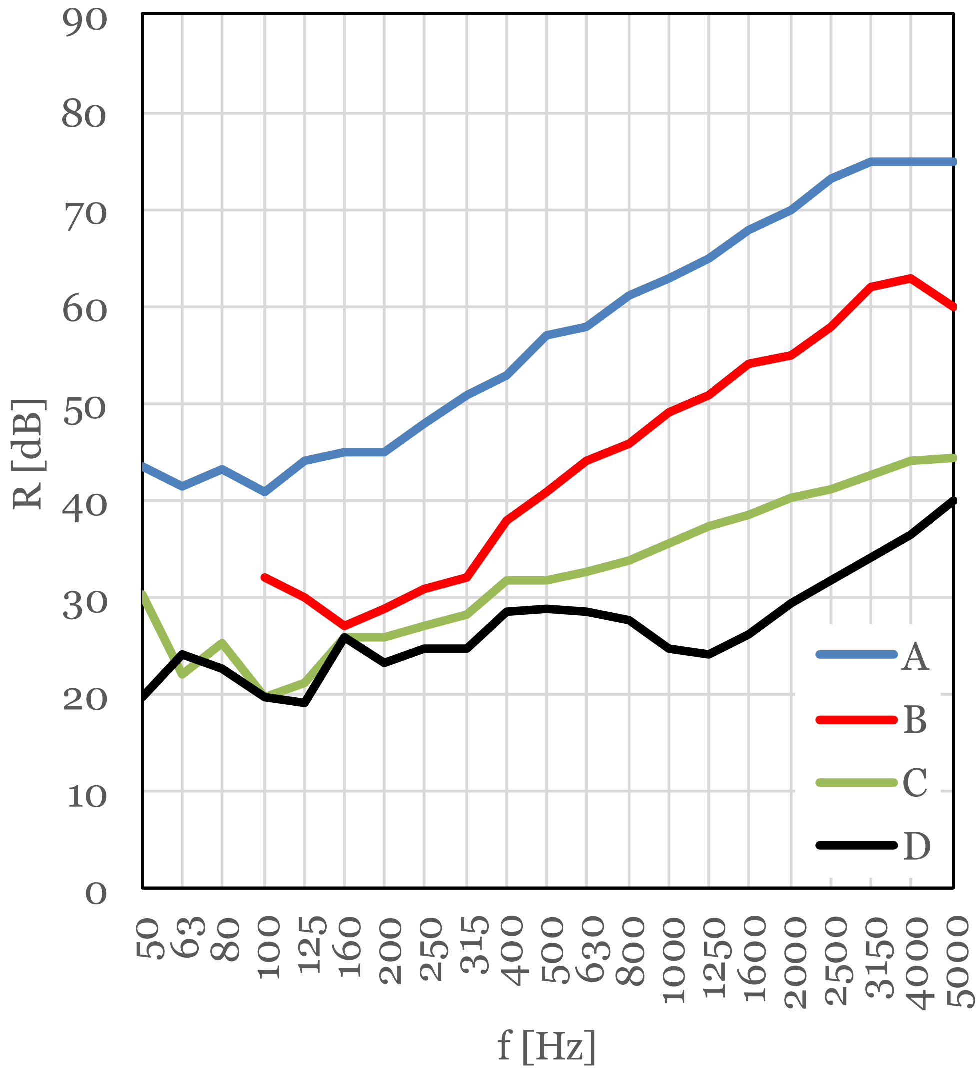
Uncoupled multilayer constructions

- Two layers separated by cavity
  - Cavity usually filled with absorbent
- Separate studs for each layer: no mechanical sound bridges
- SRI is explained by surface mass, cavity thickness, and cavity absorption
- Examples:
  - Double-studded floors and walls

Examples of single panels

A. Steel-reinforced concrete 180 mm
B. Siporex 200 mm
C. Steel 2 mm
D. Plywood 21 mm

	A	B	C	D
m' [kg/m^2]	450	140	15.6	15
h [mm]	180	200	2	21
f_c [Hz]	100	160	>5000	1250
R_w [dB]	60	44	36	28

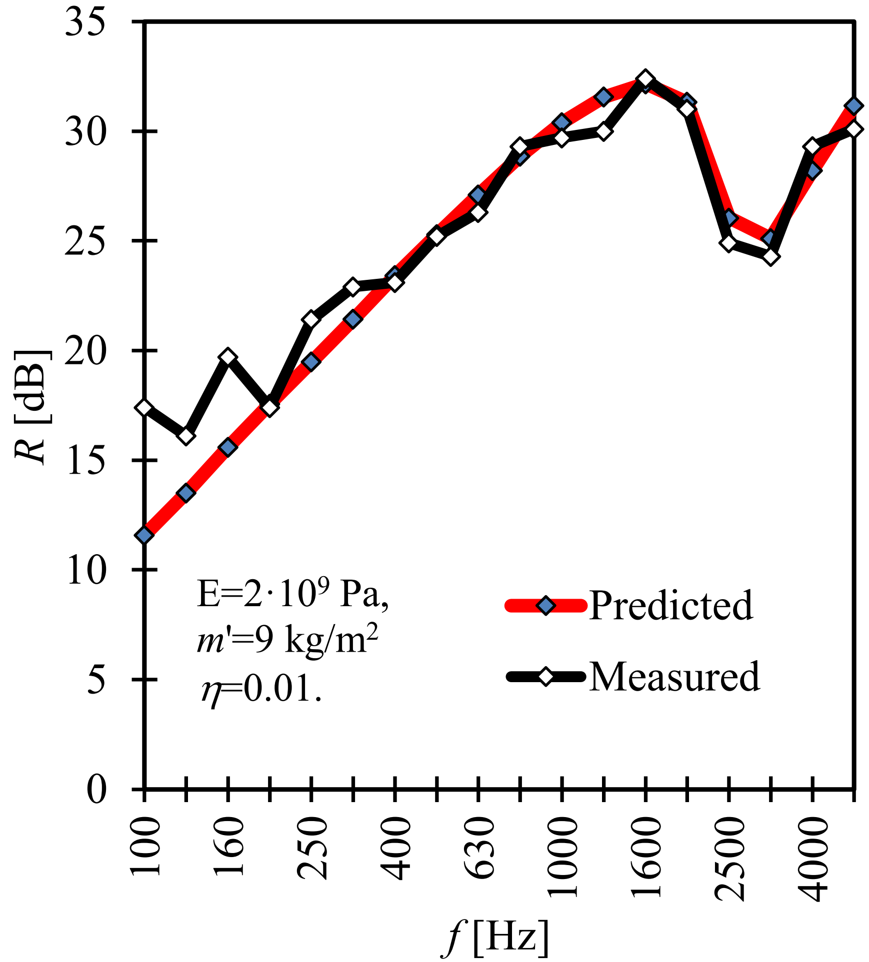


Single panel – prediction model

$$R = \begin{cases} 20\cdot\log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 20\cdot\log_{10}\left(1-\left(\dfrac{f}{f_c}\right)^2\right) - 5, & f < f_c \\ 20\cdot\log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 10\cdot\log_{10}\left(\dfrac{2\eta f}{\pi f_c}\right), & f \geq f_c \end{cases}$$

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{12\left(1-\mu^2\right)m'}{Eh^3}}$$

- surface mass m' [kg/m_2]
- frequency f [Hz]
- lowest critical frequency f_c [Hz]
- Young's modulus E [Pa]
- loss factor η [] (frequency dependent)
- panel dimensions L_x, L_y, h [m]
- Poisson's ratio μ []
- c_0 = 343 m/s, ρ_0 = 1.204 kg/m^3



Young's modulus *E*

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{12(1-\mu^2)m'}{Eh^3}}$$

Hooke's law:

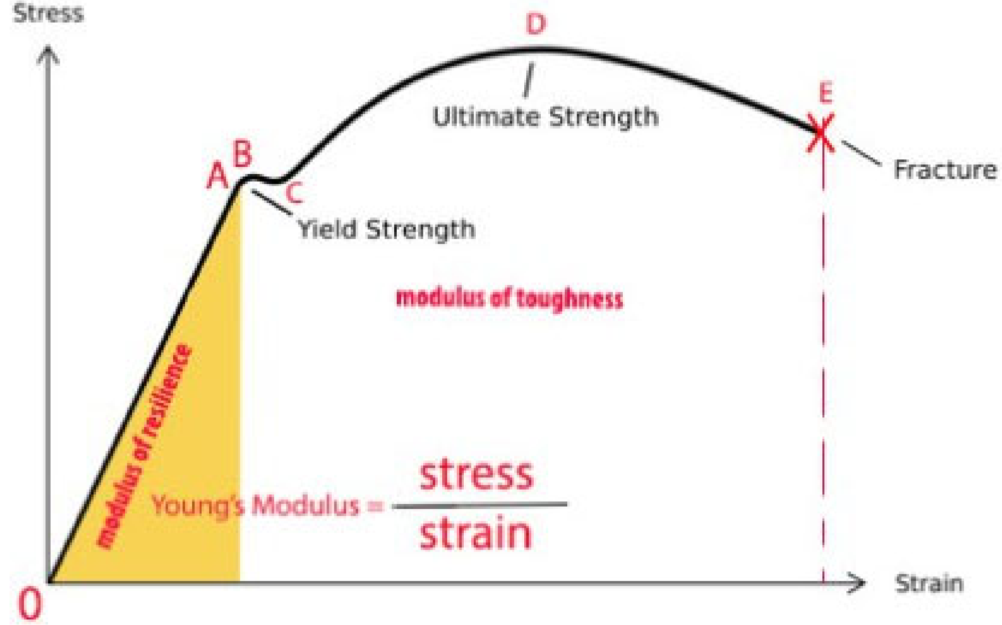
$$F = -kx$$

- x [m] is the displacement
- F [N] is the force
- k [N/m] is spring constant (stiffness)

Stress-strain relationship:

$$\sigma = E\varepsilon$$

- σ [Pa=N/m^2] is the stress
- ε [] is the strain (fractional extension)
- E [Pa] is Young's modulus
  - *Modulus of elasticity*



https://basicmechanicalengineering.com/stress-strain-curve-for-mild-steel-with-stress-strain-relationship/

Examples of material values

Material	ρ kg/m^3	E GPa
steel	7800	210
normal gypsum	670	3.0
hard gypsum	900	4.5
chipboard	630	3.2
veneer coniferous	690	11.0
aluminium	2700	67
spruce	440	10,5
steel reinforced concrete	2500	26
porous concrete	600	2
brick*	625 - 2225	2,2 - 24,7
float glass	2500	70

Usual values: perforated brick 1400 kg/m^2; full brick 1800 kg/m^2.

Propagation speeds of different wave types

- **Thick panel**
  - $h > \lambda$
  - shear wave is dominating
  - independent on frequency

$$c_s = \sqrt{\frac{Gh}{m'}} = \sqrt{\frac{E}{\rho_p 2(1+\mu)}}$$

- **Thin panel**
  - $h < \lambda$
  - bending wave is dominating
  - frequency dependent

$$c_B = \sqrt[4]{\frac{\omega^2 B}{m'}} = \sqrt[4]{\frac{\omega^2 h^2 E}{\rho_p 12(1-\mu^2)}}$$

h [m] is thickness of panel
G [Pa] is shear modulus
B [Nm] is bending stiffness per unit width

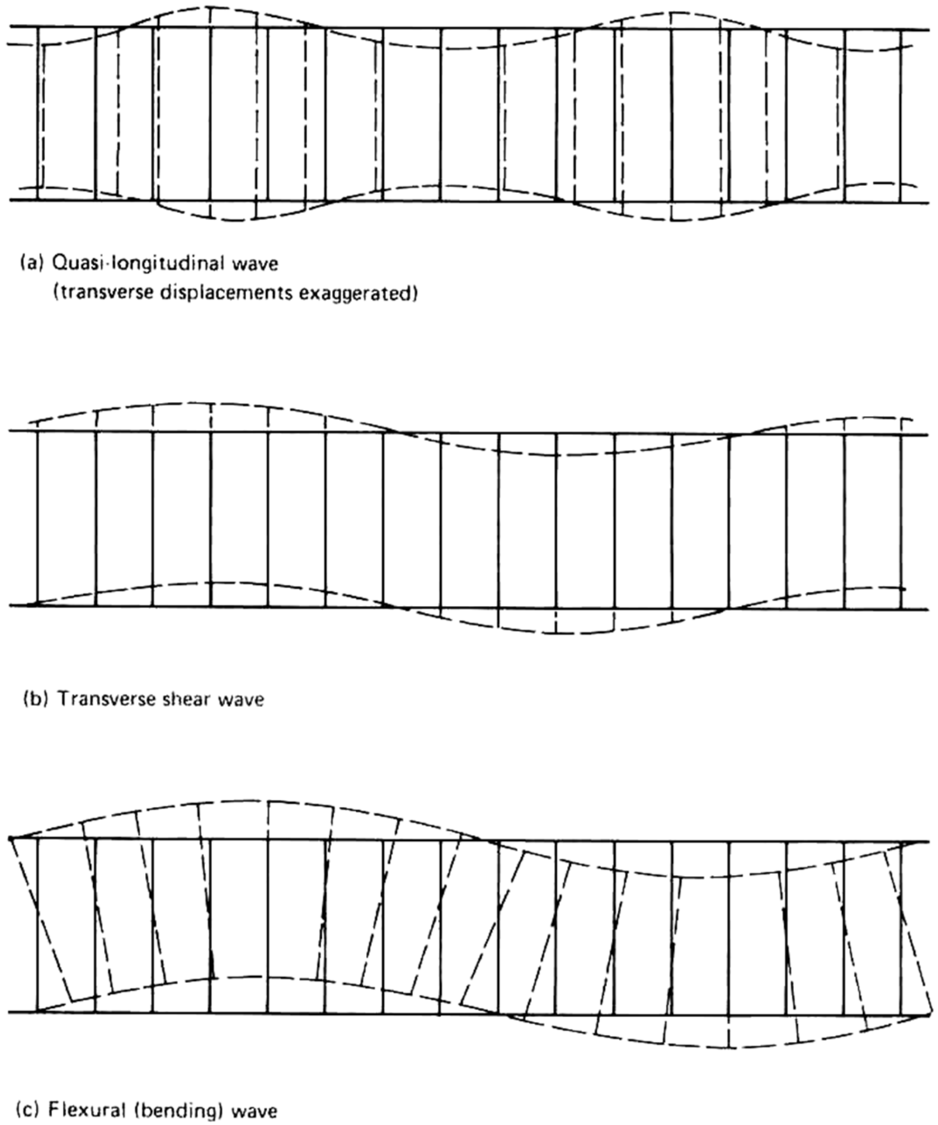
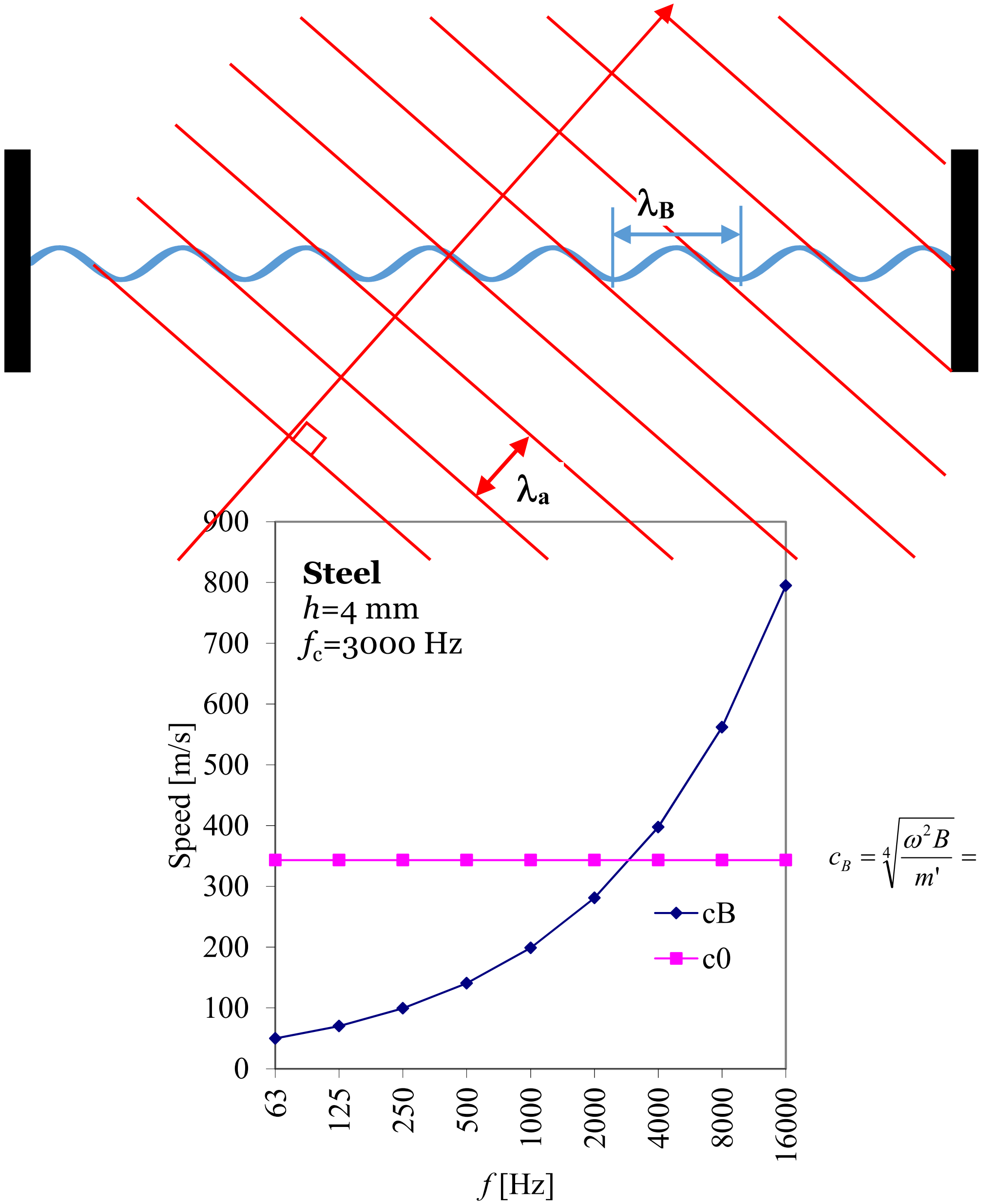


Figure: Fahy F (1985)

Coincidence

- Bending wave is dispersive: i.e. speed of sound depends on frequency
- Dispersion is the reason for the complexity of *R* calculations
- When the speed of bending wave in the panel equals with the speed of sound in air, coincidence phenomenon occurs.
- Sound insulation is nearly zero because the impedances are nearly equal
- The lowest coincidence frequency is called *critical frequency,* f_c. It takes place in the grazing incidence angle 90° at

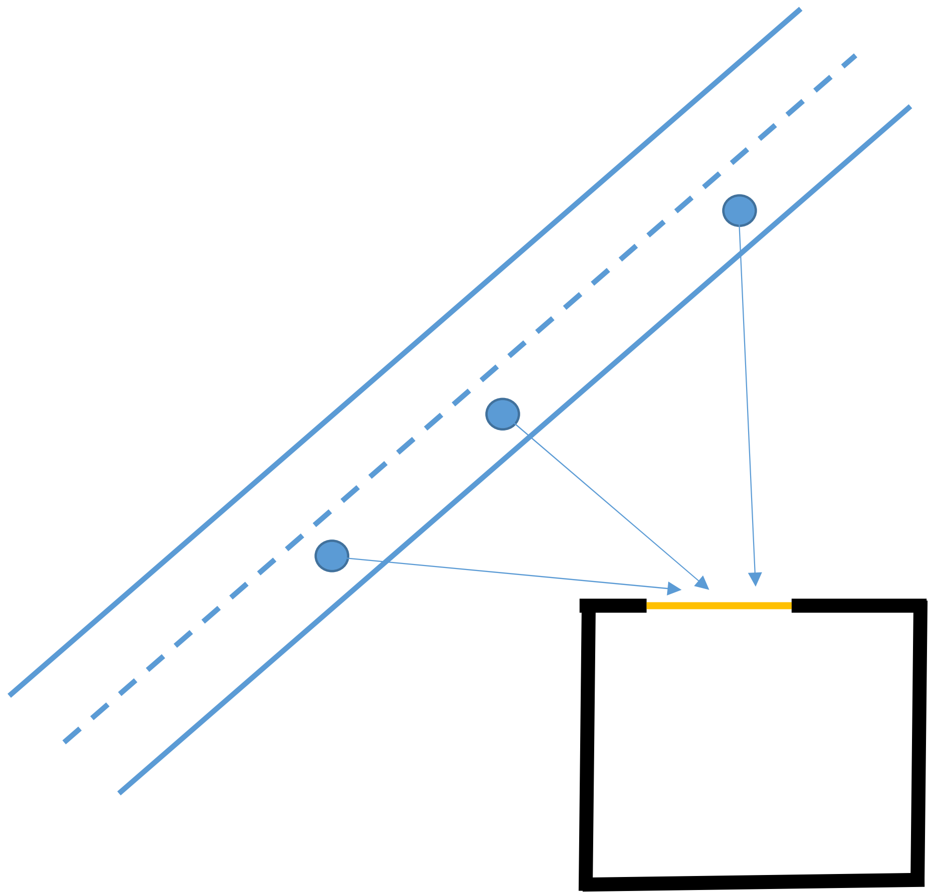
$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{12\left(1-\mu^2\right)m'}{Eh^3}}$$



$$c_B = \sqrt[4]{\frac{\omega^2 B}{m'}} = \sqrt[4]{\frac{\omega^2 h^2 E}{\rho_p 12\left(1-\mu^2\right)}}$$

Angle-dependence of coincidence frequency

- A moving source in the free field can lead to an audible perception of increasing or decreasing coincidence frequency behind the panel
- Coincidence frequency is larger than f_c at at smaller incidence angles than 90°
- Coincidence frequency is infinite at normal sound incidence



Poisson's ratio

- Precise values for different materials slightly depend on the source
- The following values can be safely used:
  - Metals: $\mu \approx 0.30$
  - Others: $\mu \approx 0.20$.

Material	Poisson's ratio
rubber	0.49
gold	0.42–0.44
saturated clay	0.40–0.49
magnesium	0.25–0.29
titanium	0.265–0.34
copper	0.33
aluminium-alloy	0.32
clay	0.30–0.45
stainless steel	0.30–0.31
steel	0.27–0.30
cast iron	0.21–0.26
sand	0.20–0.46
concrete	0.10–0.20
glass	0.18–0.3
metallic glasses	0.28–0.41
foam	0.10–0.50
cork	0.01

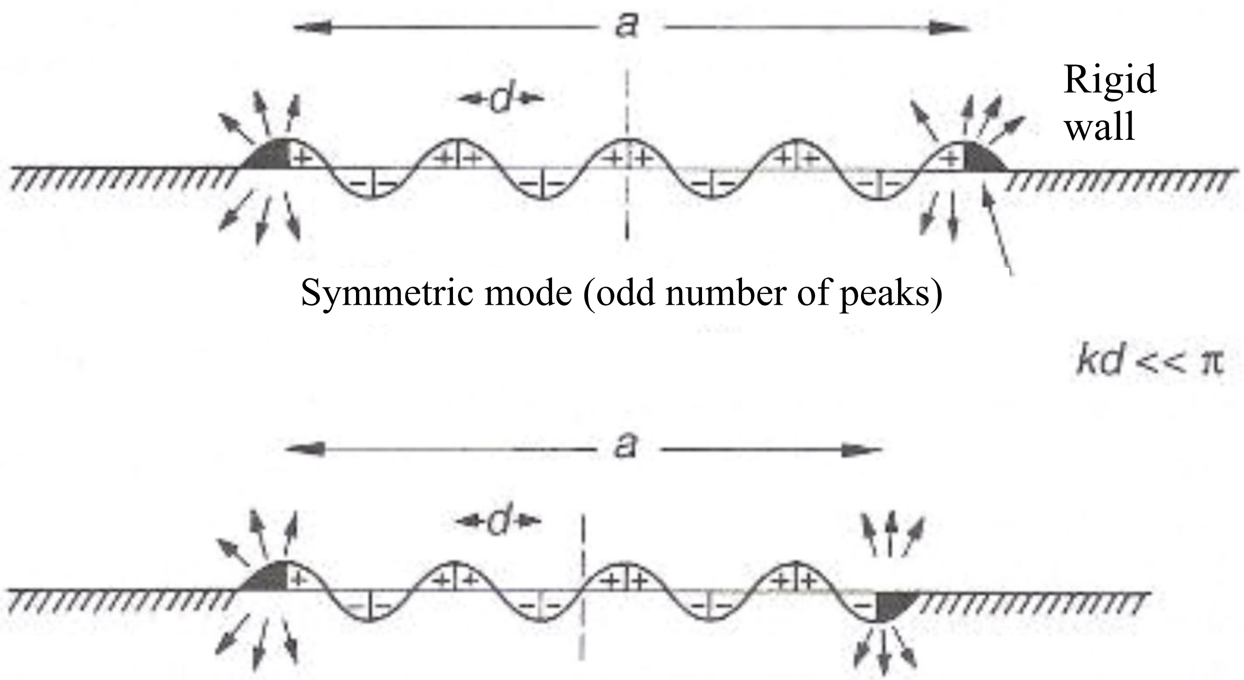
Radiation efficiency

- *Radiation efficiency* σ expresses how well the bending wave field is radiating airborne sound.
  - W [W] is the sound power radiated by the panel
  - v [m/s] is the mean vibration velocity of the panel
  - S [m^2] is the surface area
- σ span is 0.00 —1.00.
  - $\sigma = 1$, when $f > f_c$ (f_c critical frequency)
  - $\sigma = 0 \ldots 1$, when $f < f_c$
- **Thick heavy panels: $f_c \approx$ 100 Hz →** sound power radiated by the structure can be determined from the vibration velocity in the full frequency range (100-3150 Hz), since **$\sigma = 1$**.
- **Thin light panels: f_c 1000 - 3000 Hz →** vibration measurements cannot be used to predict sound emission
- σ is not used on the models of this chapter but it is a concept that should be known: for example: materials with σ=0 radiate very little flanking sound

$$\sigma = \frac{W}{\langle v^2 \rangle \rho_0 c_0 S}$$

Acoustic short circuit in the middle of the panel, when f << fc

- Acoustic short circuit takes place when the wavelength in air, λ_a, is longer than the bending wavelength in the panel λ_m
- Pressure fields caused by nearby maxima and minima of the bending wave interfere and revoke each other (σ << 1)
- Corner modes and edge modes can radiate sound but only in corner and edge areas (σ = 1)
- In overall, the radiation from the panel is weak and the radiation is dominated by corners or edges, depending on frequency, in a complex way.



Symmetric mode (odd number of peaks)

Antisymmetric mode (even number of peaks)

Fahy (1985)

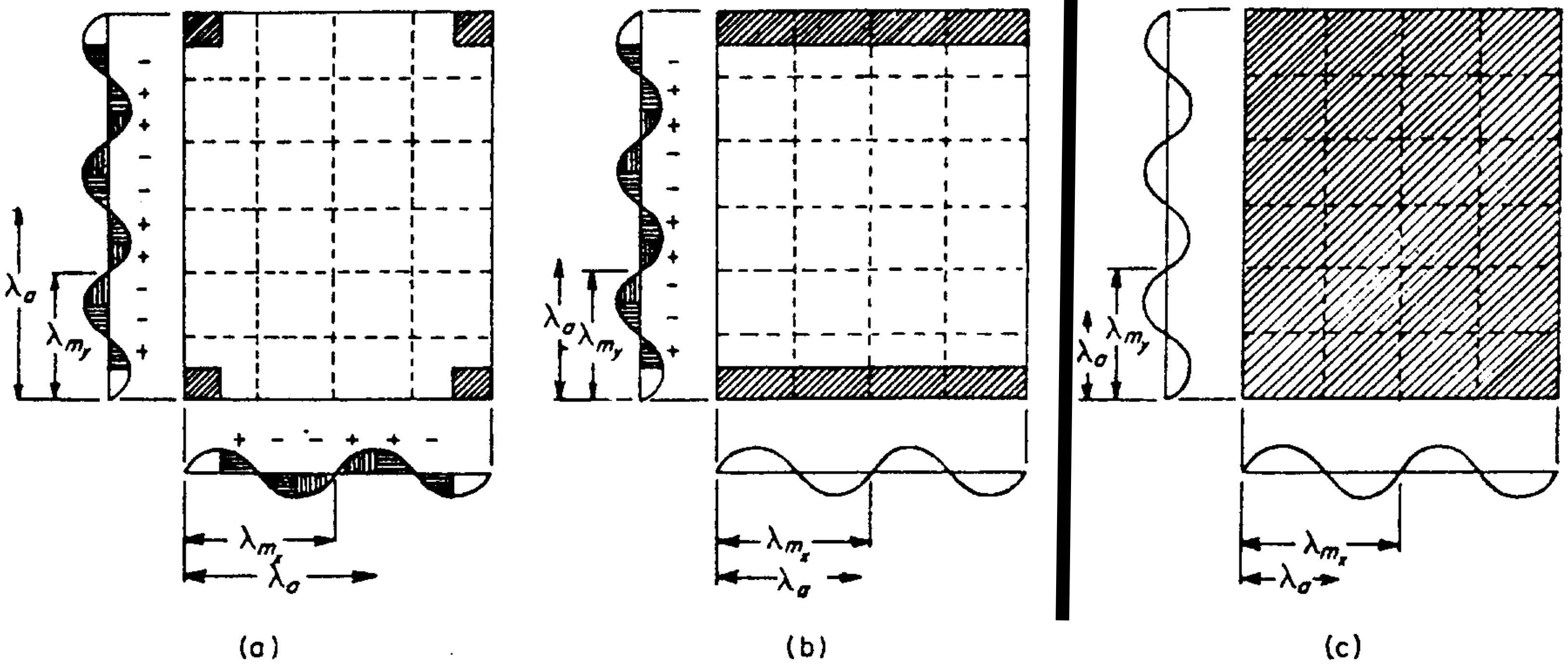
Forced vibration and resonant vibration

Forced vibration; *f* < *f*$_c$

- $\lambda_a > \lambda_m$
- Acoustic short circuit in the middle of the panel
- Individual modes can radiate efficiently from the edge or corners where the short circuit does not occur: low σ
- *R* depends on mass (forced vibration)

Resonant vibration; *f* > *f*$_c$

- $\lambda_a < \lambda_m$
- No short-circuit
- σ=1
- R smaller than mass predicts



Fahy (1985) ??

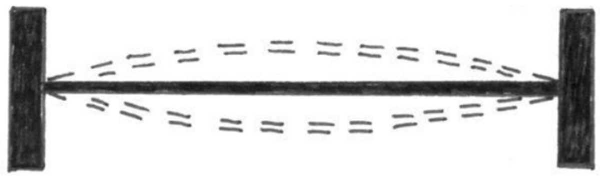
Panel modes

- The lowest axial panel modes are called
  - f_{01}:resonance in horizontal direction
  - f_{10}: resonance in vertical direction
- Radiation at the lowest panel modes is efficient since acoustic short circuit cannot take place. Sound insulation is poor at these frequencies.
- Frequency of panel mode ”mn” is calculated by

$$f_{mn} = \frac{c_0^2}{4 f_c}\left[\left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2\right] \qquad m, n = 0, 1, 2, 3, \ldots$$

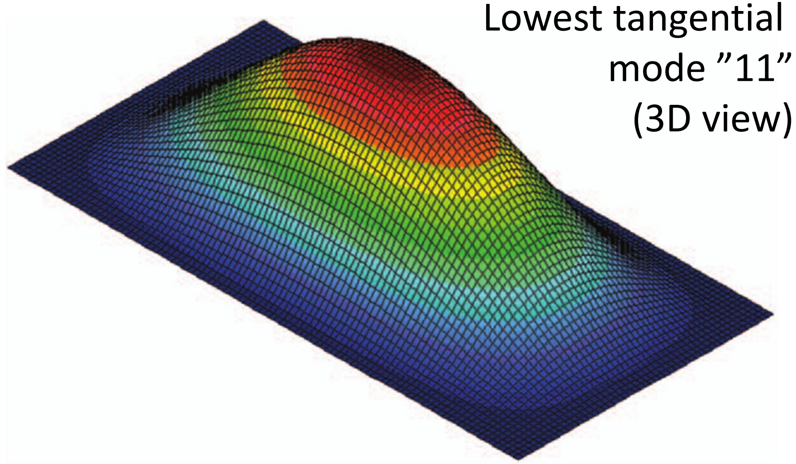
  - L_x [m] is the width of the panel [m]
  - L_y [m] is the height of the panel [m]
  - Dimensions are measured from the fixing points
- The mode is usually under 100 Hz

Lowest axial horizontal mode ”10” (top view)



Lowest axial vertical mode ”10” (section view)

Lowest tangential mode ”11” (3D view)



5.2

Gypsum board (13 mm, 8.8 kg/m2) is attached by screws to the vertical studs. Calculated the lowest panel mode in horizontal direction, when the stud division is

a) 600 mm

b) 400 mm.

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{12(1-\mu^2)m'}{Eh^3}}$$

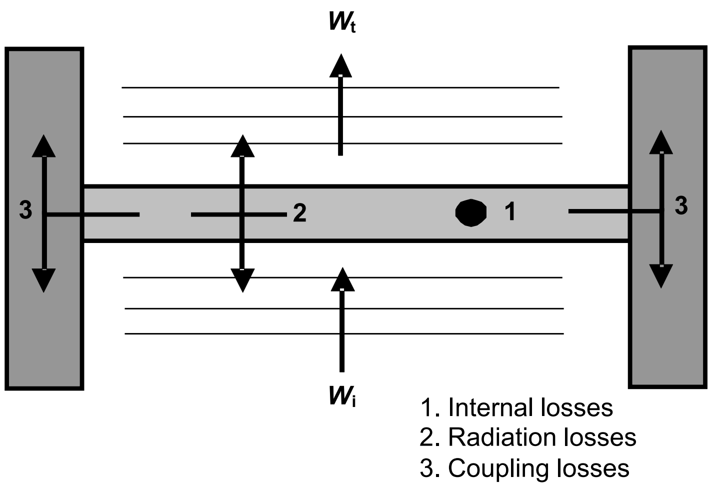
$$f_{mn} = \frac{c_0^2}{4f_c}\left[\left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2\right] \qquad m,n = 0,1,2,3,...$$

Loss factor η

- Loss factor expresses the energy loss per radian angle within the material:

$$E(t) = E_0 e^{-\eta\omega t}$$

- Total loss factor involves three types of losses:
  1. internal losses
  2. radiation losses
  3. coupling losses
- Coupling losses determine the total loss factor for e.g. concrete structures
- Internal losses are important for e.g. sandwich structures
- Total loss factor is measured by vibration transducer from structural reverberation time T.



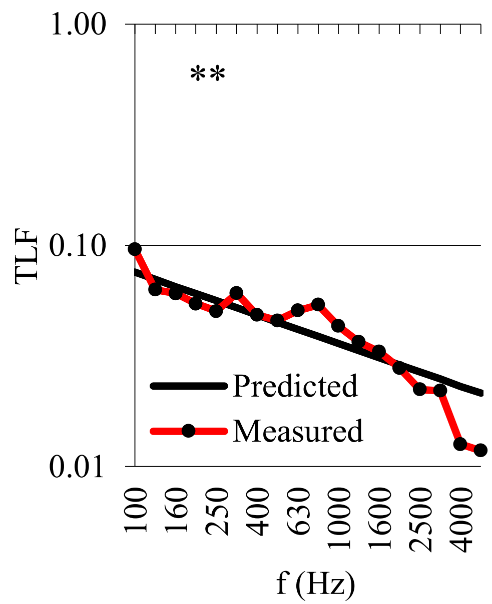
$$\eta_{tot} = \eta_1 + \eta_2 + \eta_3$$

$$\eta_{tot} = \frac{2.2}{f\,T}$$

Loss factor

- Loss factor depends on frequency.
- Trocket (2000) suggested the following analytic form for the presentation of frequency-dependent loss factor:
- Hongisto (2003) experimentally determined A and B for some materials.

$$\eta_{tot}(f) = Af^{B}$$



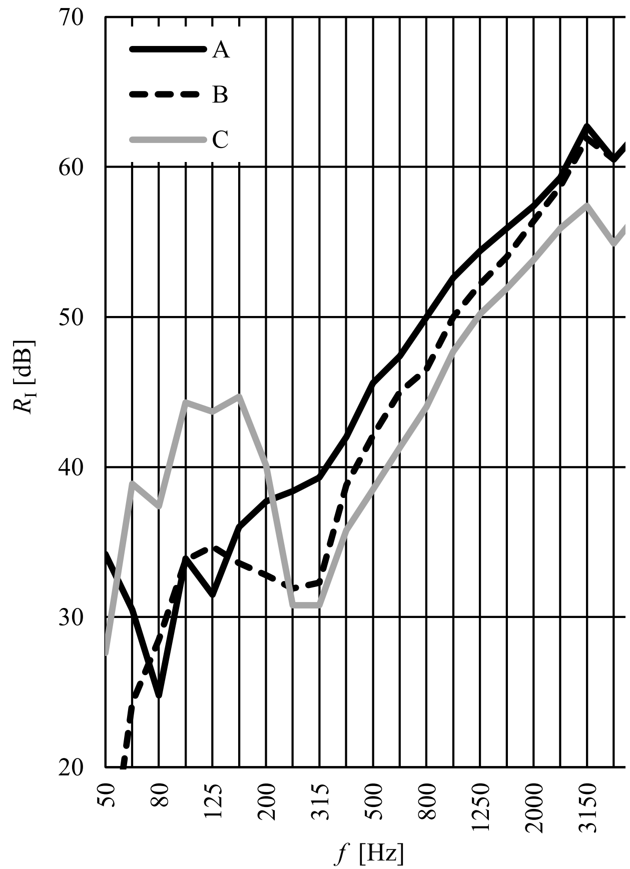
Material	Installation	Dimensions [m]	A	B
Calcium silicate block 130 mm, 260 kg/m2**	Masoned joints	3.6 x 2.8	0.33	-0.32
Calcium silicate block 130 mm, 260 kg/m2	Resilient joints	3.6 x 2.8	0.38	-0.43
Calcium silicate brick 200 mm, 360 kg/m2	Masoned joints	3.6 x 2.8	1.09	-0.52
Steel-reinforced concrete 180 mm	Masoned joints	3.0 x 6.0	0.50	-0.42
Steel-reinforced concrete 160 mm	Slab on steel beams	4.1 x 2.5	0.12	-0.30
Gypsum, 13 mm 11 kg/m2	Screwed cc600	1.2 x 2.2	0.05	-0.10
Gypsum 13 mm 9 kg/m2	Screwed cc600	1.2 x 2.2	0.04	-0.08
Steel 2 mm	Screwed cc1200	1.2 x 2.2	1.66	-0.72
Steel 4 mm	Screwed cc1200	1.2 x 2.2	0.07	-0.25

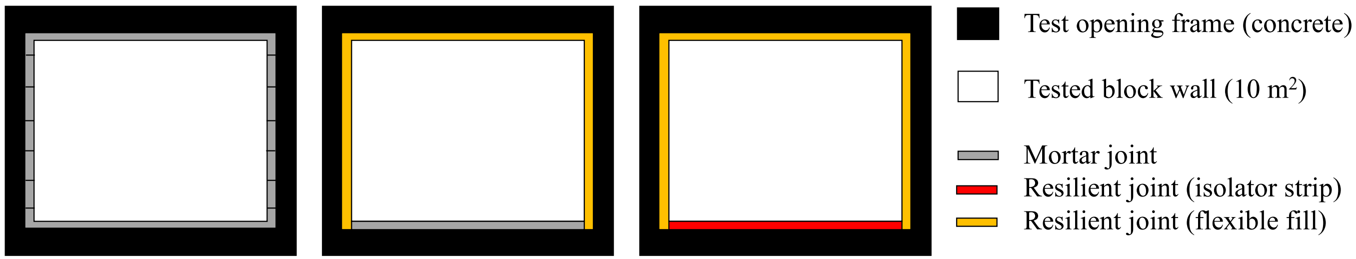
Hongisto (2003) Työterveyslaitos

Effect of total loss factor on SRI

- Calsium-silicate block wall (220 kg/m^2, 140 mm, f_c=180 Hz) was built in laboratory using three different joint types. The highest SRI above 200 Hz was obtained using rigid joints. Why?

Joint type	R_w [dB]	$R_w + C_{50\text{-}5000}$ [dB]
A (All joints rigid)	50	49
B (Floor joint rigid, other joints resilient)	45	45
C (All joints resilient)	43	43





A.
All joints rigid

B.
Floor joint rigid,
other joints resilient

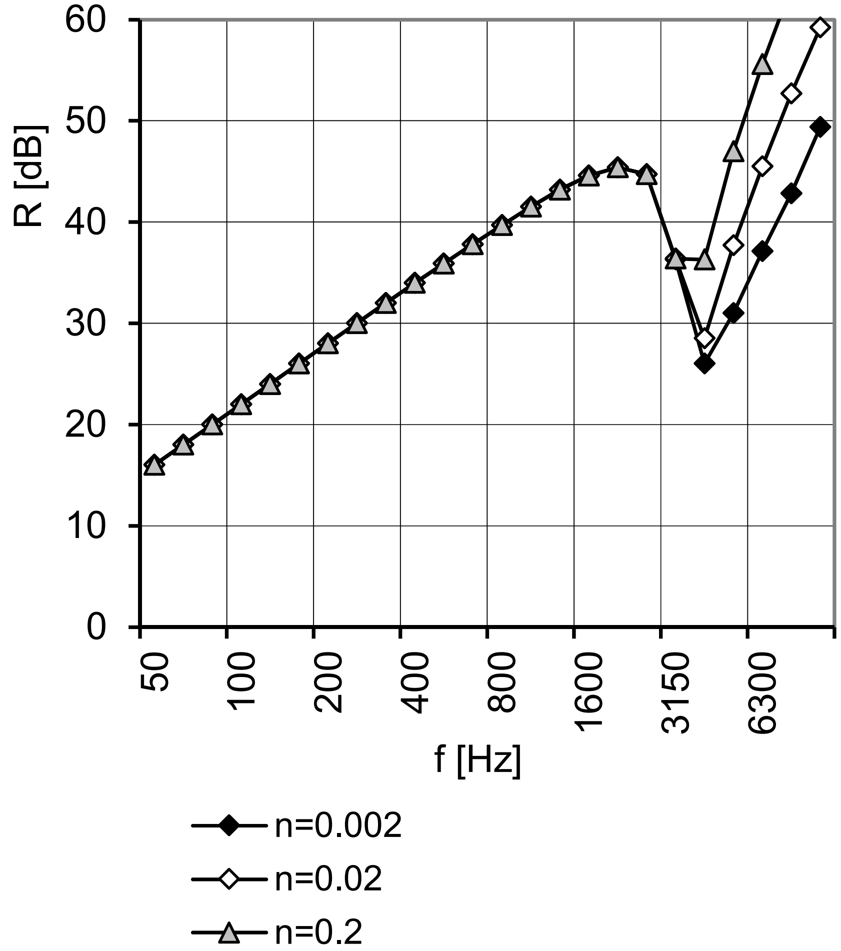
C.
All joints resilient.

Keränen & Hongisto 2022 **Journal of Building Engineering**

Thin panel - the effect of constant total loss factor

- Calculated by previous model
- Material
  - 4 mm steel
  - width L_{zp}=1.25 m
  - height $L_{x,p}$=2.25 m
  - S=2.8 m^2
  - m'=31.2 kg/m^2
  - E=2E11 Pa
  - TLF was modified
- TLF affects only at and above f_c

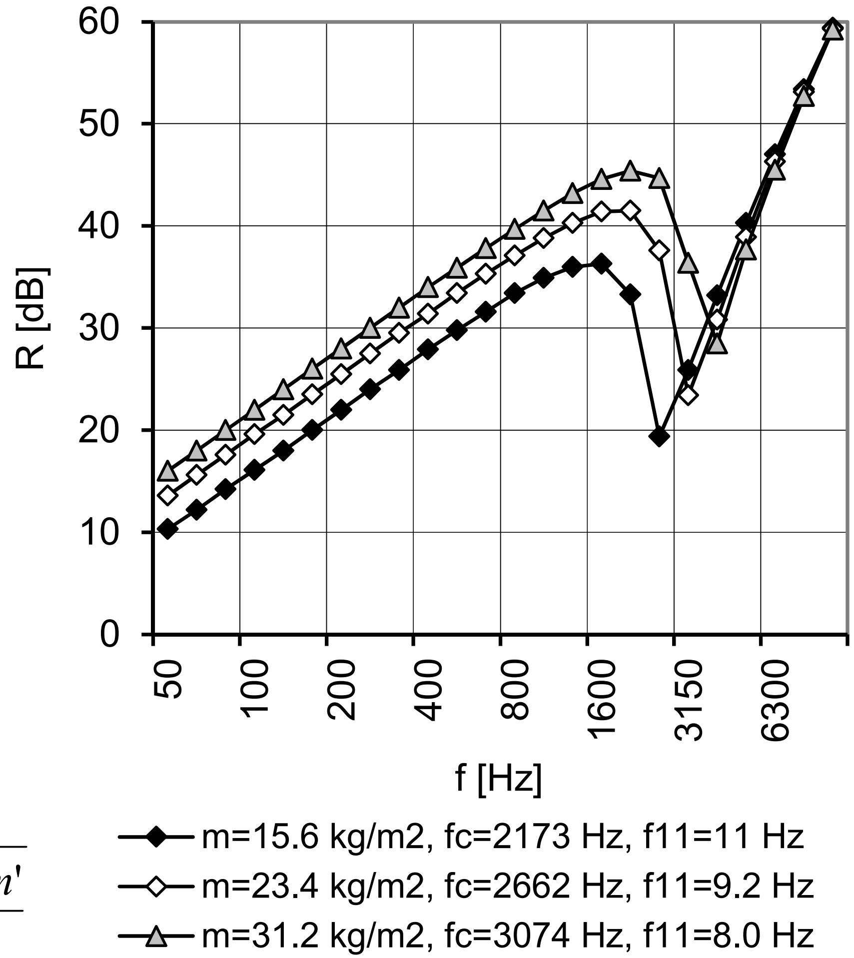
$$R = \begin{cases} 20\cdot\log_{10}\left(\frac{\pi m' f}{\rho_0 c_0}\right) + 20\cdot\log_{10}\left(1-\left(\frac{f}{f_c}\right)^2\right) - 5, & f < f_c \\ 20\cdot\log_{10}\left(\frac{\pi m' f}{\rho_0 c_0}\right) + 10\cdot\log_{10}\left(\frac{2\eta f}{\pi f_c}\right), & f \geq f_c \end{cases}$$



Hongisto (2003) Työterveyslaitos

Thin panel - the effect of surface mass

- Calculated by previous model
- Material
  - 4 mm steel
  - loss factor 0.02
  - width L_{zp}=1.25 m
  - height $L_{x,p}$=2.25 m
  - S=2.8 m^2
  - E=2E11 Pa
  - m' was modified
- Doubling m' increases SRI by 6 dB



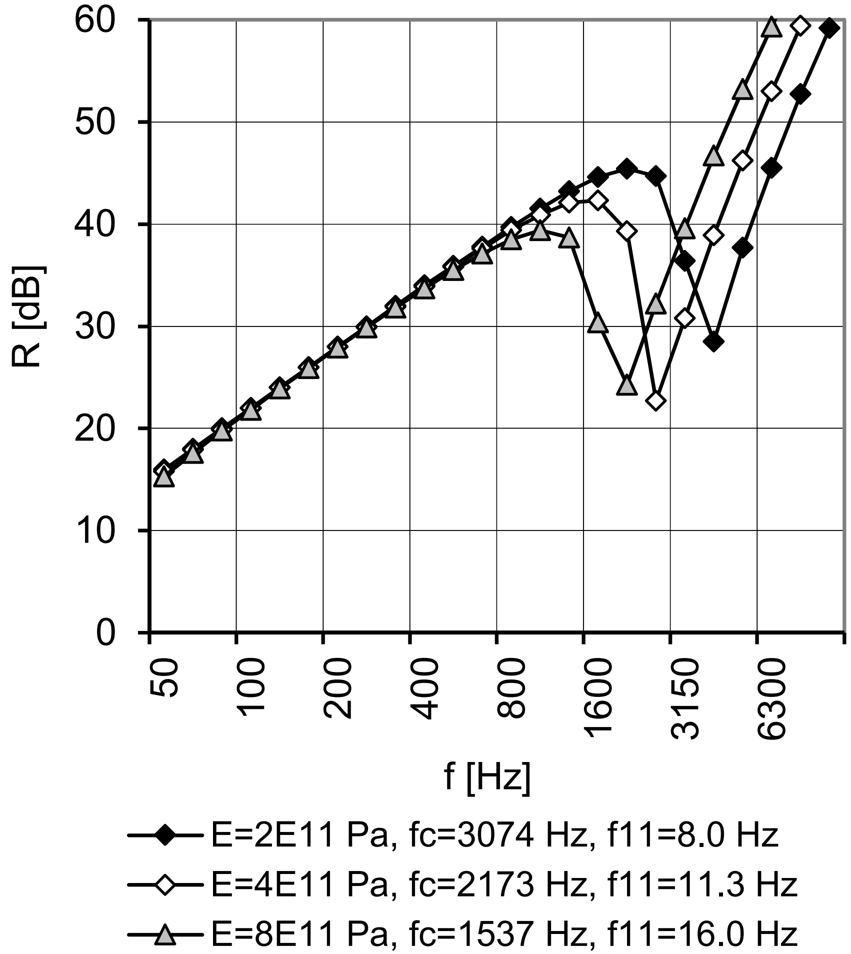
$$R = \begin{cases} 20 \cdot \log_{10}\left(\frac{\pi m' f}{\rho_0 c_0}\right) + 20 \cdot \log_{10}\left(1 - \left(\frac{f}{f_c}\right)^2\right) - 5, & f < f_c \\ 20 \cdot \log_{10}\left(\frac{\pi m' f}{\rho_0 c_0}\right) + 10 \cdot \log_{10}\left(\frac{2\eta f}{\pi f_c}\right), & f \geq f_c \end{cases}$$

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{12\left(1-\mu^2\right)m'}{Eh^3}}$$

Hongisto (2003) Työterveyslaitos

Thin panel - the effect of Young's modulus

- Calculated by previous model
- Material
  - loss factor 0.02
  - width L_{zp}=1.25 m
  - height $L_{x,p}$=2.25 m
  - S=2.8 m²
  - m'=31.2 kg/m²
  - E was modified

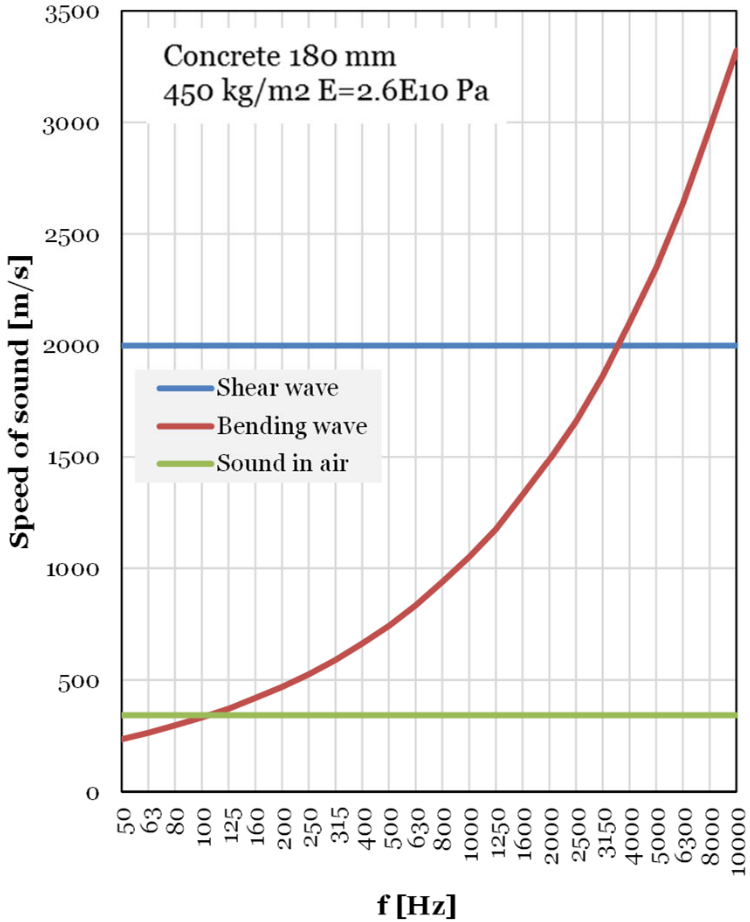


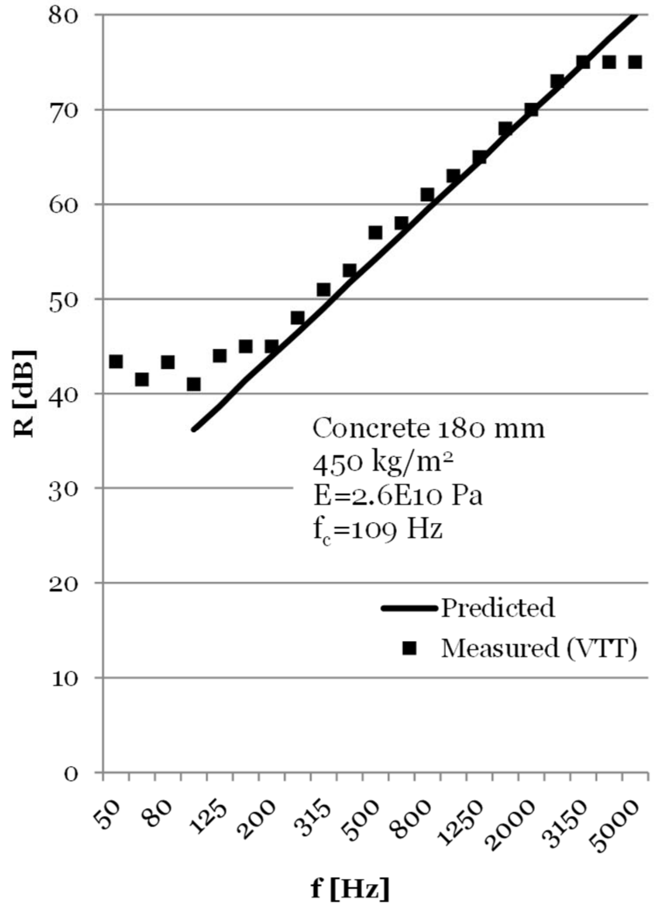
$$R = \begin{cases} 20 \cdot \log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 20 \cdot \log_{10}\left(1 - \left(\dfrac{f}{f_c}\right)^2\right) - 5, & f < f_c \\ 20 \cdot \log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 10 \cdot \log_{10}\left(\dfrac{2\eta f}{\pi f_c}\right), & f \geq f_c \end{cases}$$

Hongisto (2003) Työterveyslaitos

Thick heavy panel

- The SRI of thin panels can be explained by looking at the radiation from *bending waves* below 5 kHz
- When panel thickness *h* exceeds 1/6 of the bending wavelength λ_B, *shear waves* begin to dominate sound radiation and SRI.
  - SRI becomes frequency independent above a certain frequency since c_S is constant while c_B is not.
- Figure shows a prediction assuming only bending waves to radiate sound.
- Ignorance of shear waves seems not to lead in major overestimation of SRI.



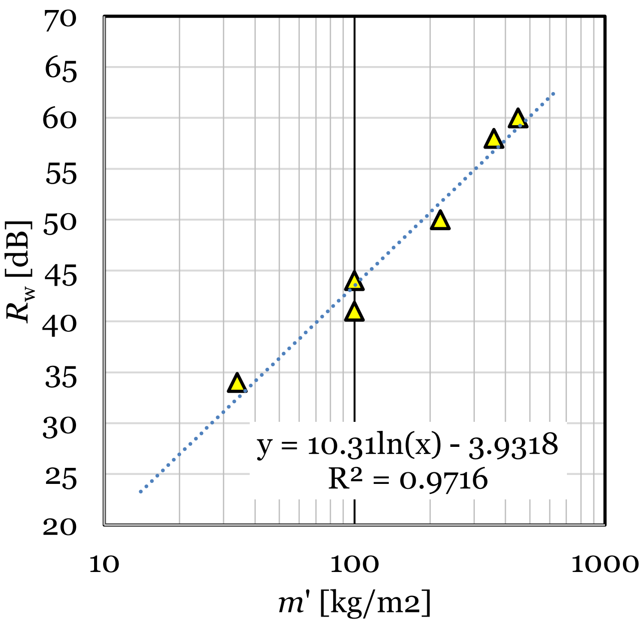


$$R = \begin{cases} 20 \cdot \log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 20 \cdot \log_{10}\left(1 - \left(\dfrac{f}{f_c}\right)^2\right) - 5, & f < f_c \\ 20 \cdot \log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 10 \cdot \log_{10}\left(\dfrac{2\eta f}{\pi f_c}\right), & f \geq f_c \end{cases}$$

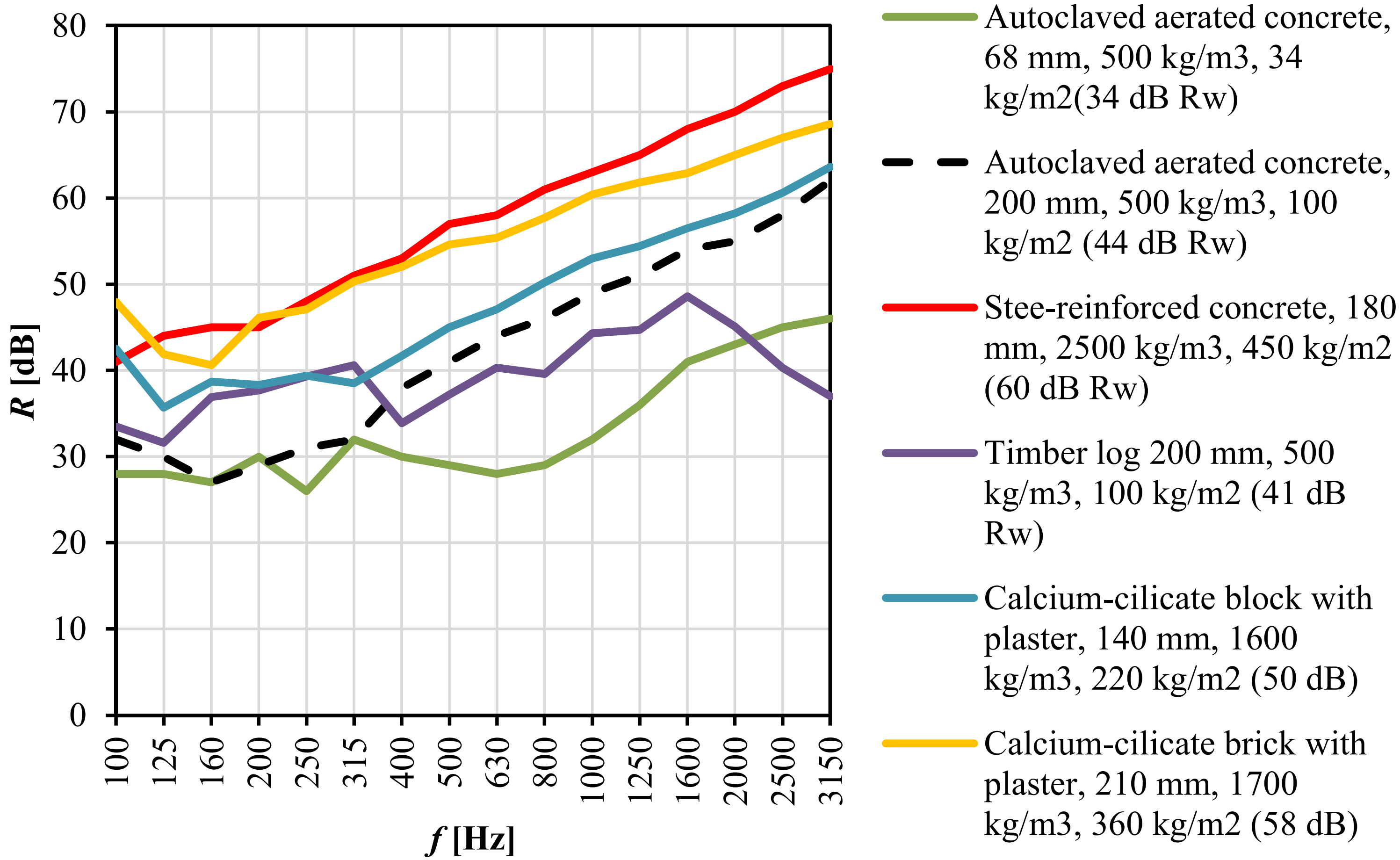
$$\eta(f) = Af^B$$

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{12\left(1-\mu^2\right)m'}{Eh^3}}$$

Examples of some heavy constructions

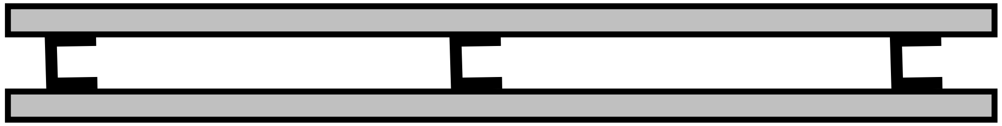


- R_w is almost linearly associated with logarithmic *m'* in this dataset

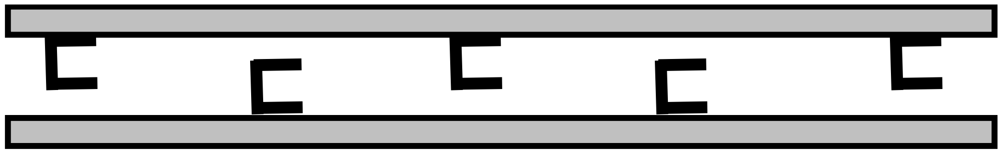


Double constructions

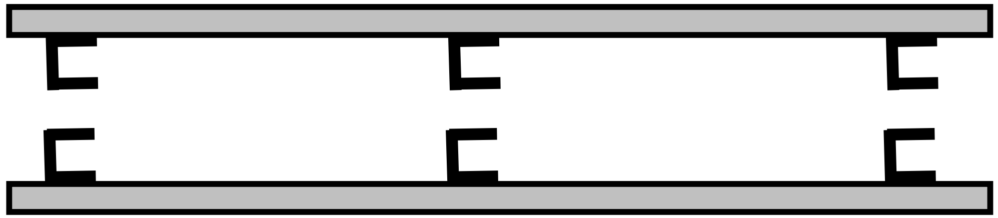
- Single studs (fully coupled)



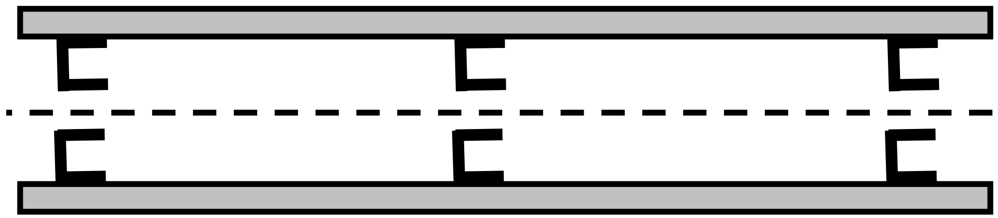
- Staggered studs (partially uncoupled, since common rails exist on top and bottom of the wall)



- Separate studs (uncoupled)

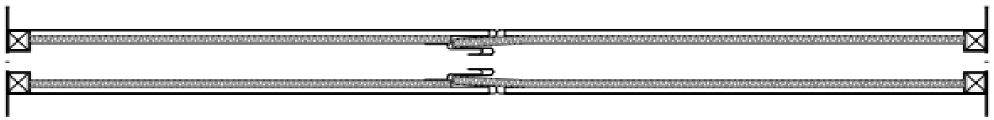


- Separate studs with structural break (uncoupled)

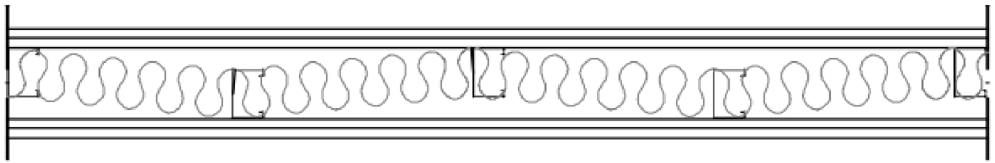


Examples of uncoupled double constructions

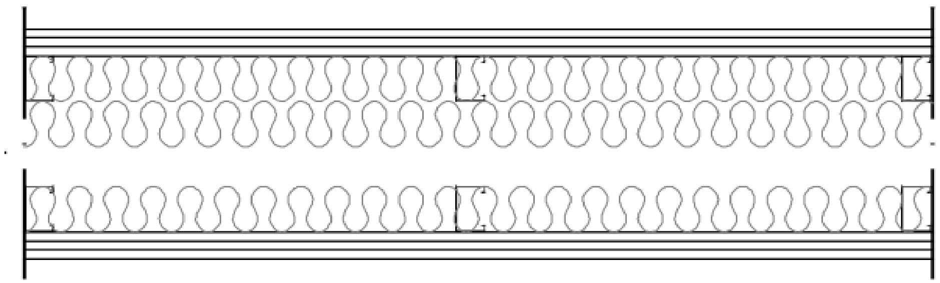
- A: Ship cabin wall

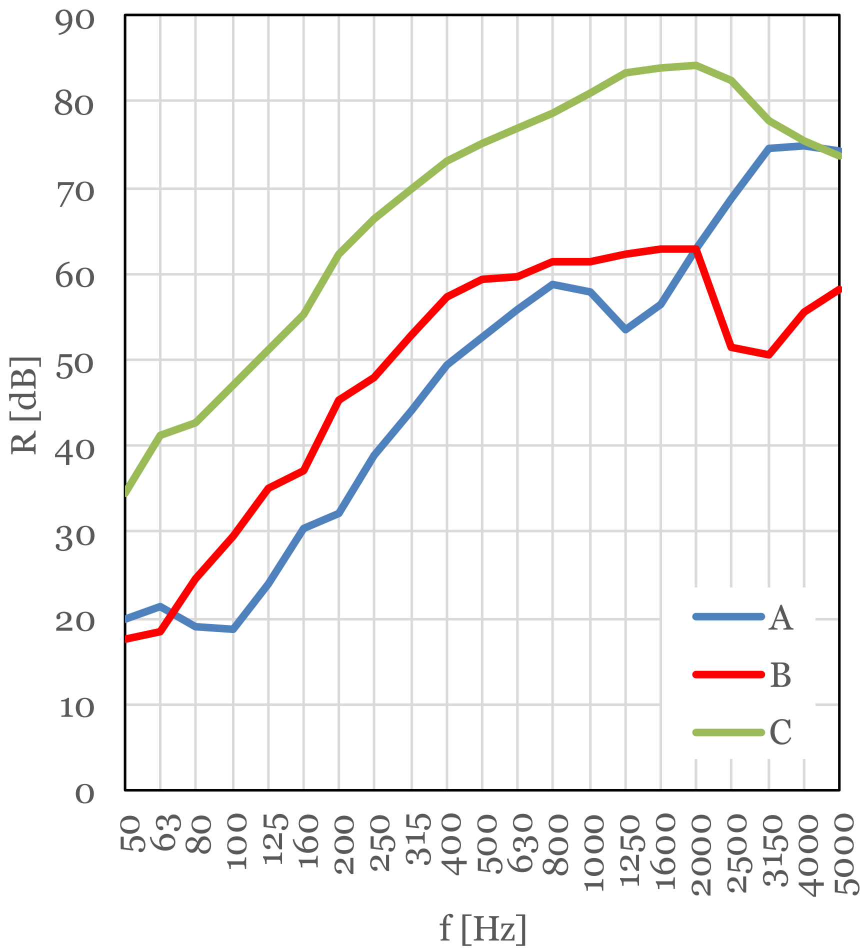


- B: Double wall, staggered studs, common rails
  - 95/66 k600 (4xGN13) M95



- C: Double wall, separate studs, separate rails
  - 2x66 k600 (6xGN13) M190





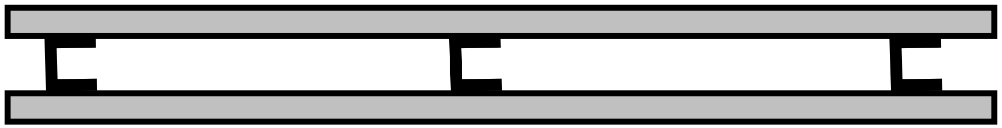
	A	B	C
m' [kg/m^2]	27	37	57
h [mm]	85	147	268
f_{mam} [Hz]	100	63	<50
R_w [dB]	48	55	75

Double construction – 4 steps of prediction

- R [dB] is the superposition of R_c and R_b:

$$R = -10 \cdot \log_{10}\left(10^{-R_c/10} + 10^{-R_b/10}\right)$$

  - R_c [dB] is SRI through the cavity (air path).
    - R_{cI} (fully absorbing)
    - R_{cII} (partially absorbing)
  - R_b [dB] is SRI through the sound bridges (stud path).
    - R_{bI} (rigid)
    - R_{bII} (flexible)



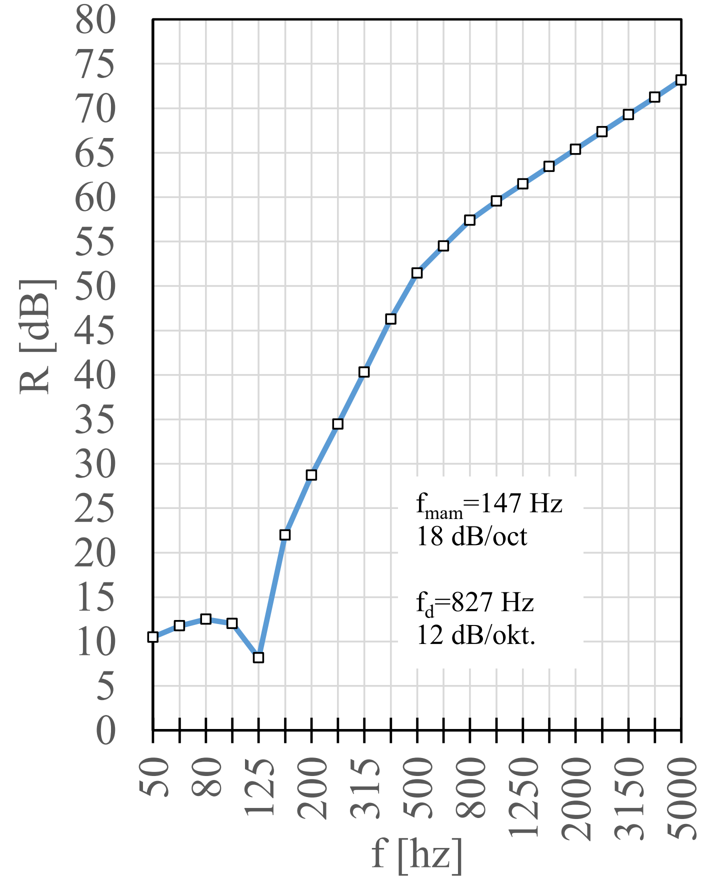
- The weaker path (stud or cavity) dominates the sound transmission.
- Four steps:
  1. Cavity path, perfect absorption, R_{cI}.
  2. Cavity path, non-perfect absorption, R_{cII}.
  3. Stud path, rigid studs, R_{bI}.
  4. Stud path, flexible studs, R_{bII}.

SRI through fully absorbing cavity, no studs, R_{cI}

- Cavity is perfectly absorbing, no reverberation in the cavity

$$R_{cI} = \begin{cases} 20 \cdot \log_{10}\left(10^{R_1/20} + 10^{R_2/20}\right) + R_{mam}, & f < f_{mam} \\ R_1 + R_2 + 20 \cdot \log_{10}(fd) - 29, & f_{mam} < f < f_l \\ R_1 + R_2 + 6, & f > f_l \end{cases}$$

$$R_{mam} = 20 \cdot \log_{10}\left[1 - \left(\frac{f}{f_{mam}}\right)^2\right]$$



d = thickness of cavity [m]

$$f_l = \frac{c_0}{2\pi d}$$

f_{mam} = mass-air-mass resonance frequency [Hz]

f_l = limit frequency [Hz]

R_1 = R of layer 1 [dB]

R_2 = R of layer 2 [dB]

m'_1 = surface mass of layer 1 [dB]

m'_2 = surface mass of layer 2 [dB]

$$f_{mam} = 80\sqrt{\frac{(m'_1 + m'_2)}{dm'_1\, m'_2}}$$

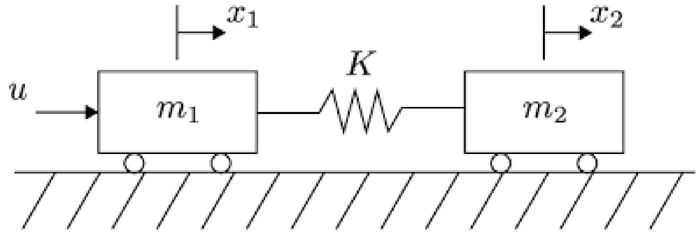
R_1 and R_2 can be measured or predicted.

Layer 1 can also be a double construction in a triple-panel construction.

Mass-air-mass resonance, f_{mam}

- The resonance exists in double constructions because the cavity acts as a spring between the two surface masses of the double panel
- Sound reduction index is usually lower at the frequency band where f_{mam} belongs than on surrounding frequency bands
- The resonance does not occur if the cavity is not air-tight

$$f_{mam} = 80\sqrt{\frac{(m'_1 + m'_2)}{d m'_1 \, m'_2}}$$



- d [m] is cavity thickness
- m'_1 [kg/m^2] is the surface mass of panel 1
- m'_2 [kg/m^2] is the surface mass of panel 2

5.3

Calculate fmam

$$f_{mam} = 80\sqrt{\frac{(m'_1 + m'_2)}{d m'_1\, m'_2}}$$

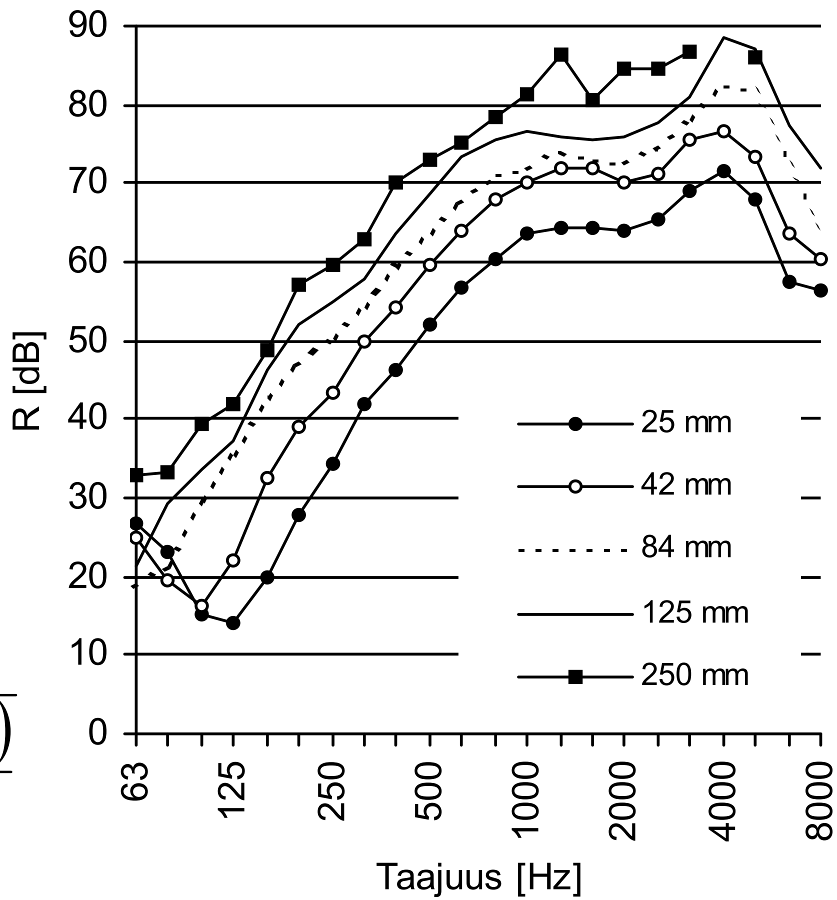
	d [m]	m_1' [kg/m2]	m_1' [kg/m2]	d [m]	f_{mam} [m]
1 x gypsum 13 mm - cavity 66 mm - 1 x gypsum 13 mm					
3 x gypsum 13 mm - cavity 175 mm - 3 x gypsum 13 mm					
1 x glass 4 mm - cavity 12 mm - 1 x glass 4 mm					

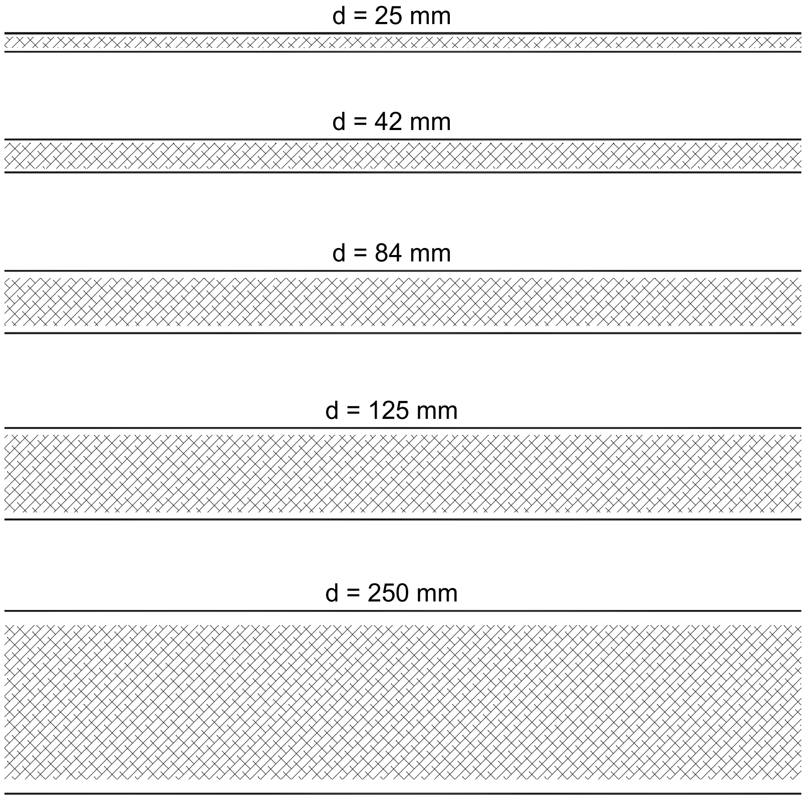
Effect of cavity thickness, uncoupled double panel, sound-absorbing cavity

Double structure

- steel 2 mm
- cavity thickness *d* is varied
- cavity filled with mineral wool
- steel 2 mm

$$f_{mam} = 80\sqrt{\frac{(m'_1+m'_2)}{dm'_1\, m'_2}}$$





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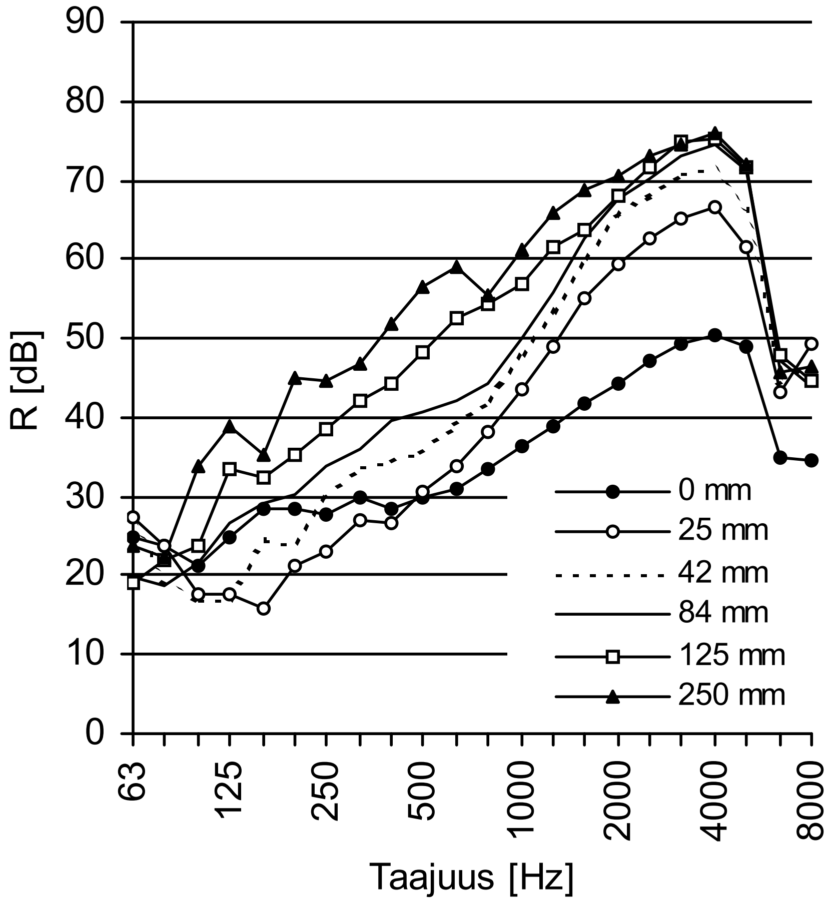
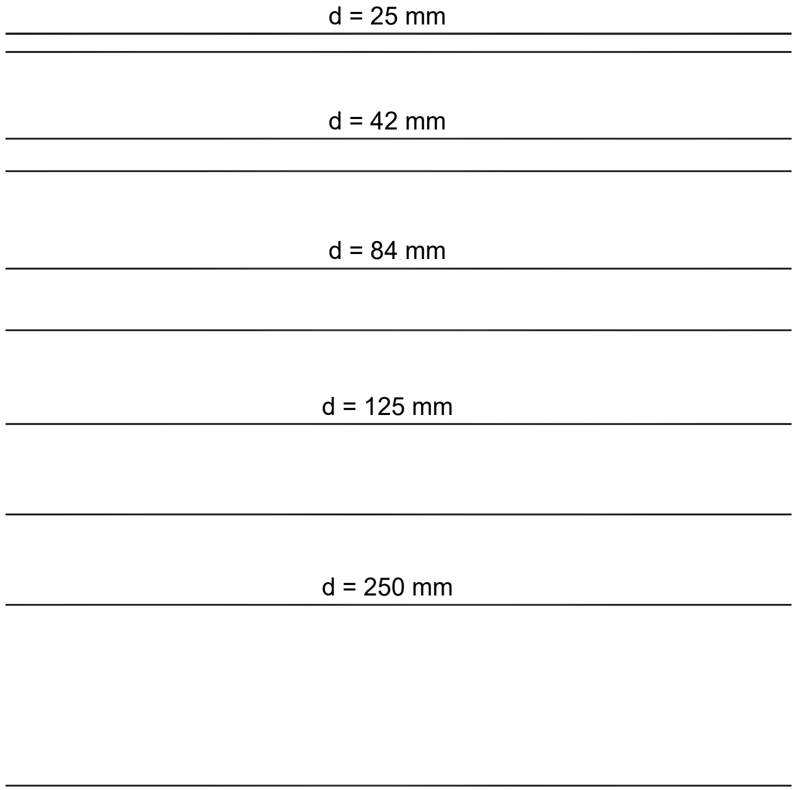
Effect of cavity thickness, uncoupled double panel, empty cavity

Double structure

- steel 2 mm
- cavity thickness *d* is varied
- cavity is empty
- steel 2 mm





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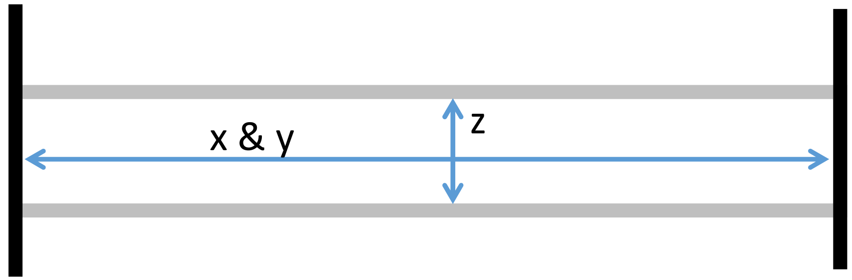
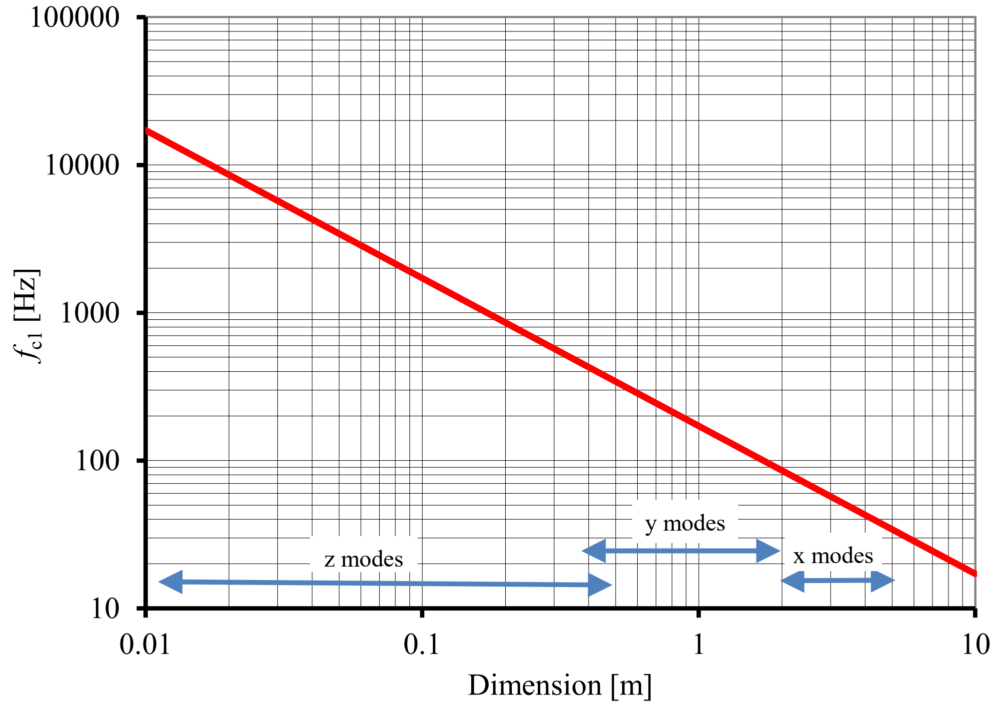
Reverberation of the cavity

- Cavity modes exist in three dimensions, x-y-z
- Modes along the stud/joist span (x)
  - E.g., distance between floor and ceiling, L_{xca} [m]
  - Usual room height is >2.3 m => Under 100 Hz
- Horizontal modes between the studs/joists (y)
  - Horizontal distance between studs, $L_{y,ca}$ [m]
  - Usual stud distances are 300 – 1200 mm => 100-800 Hz
  - In uncoupled structures, $L_{y,ca}$ can be the width of the wall
- Perpendicular modes between panels (z)
  - Distance between the panels, $L_{z,ca}$ [m]
  - Usual distance 10-400 mm
- Higher modes: modes in z direction
- Lower modes: modes in x or y dimensions
  - Strong impact on sound insulation at middle and frequencies if the cavity does not contain absorbents
- The lowest cavity mode, $f_{ca,100}$, exists at:

$$f_{ca,100} = \frac{c_0}{2 \cdot \max\left[L_{x,ca}; L_{y,ca}; L_{z,ca}\right]}$$





SRI through partially absorbing cavity, R_{cII}

- If cavity absorption is imperfect, reverberation leads to reduction of SRI by ΔR_{abs}. This is compensated by R_{cII}:

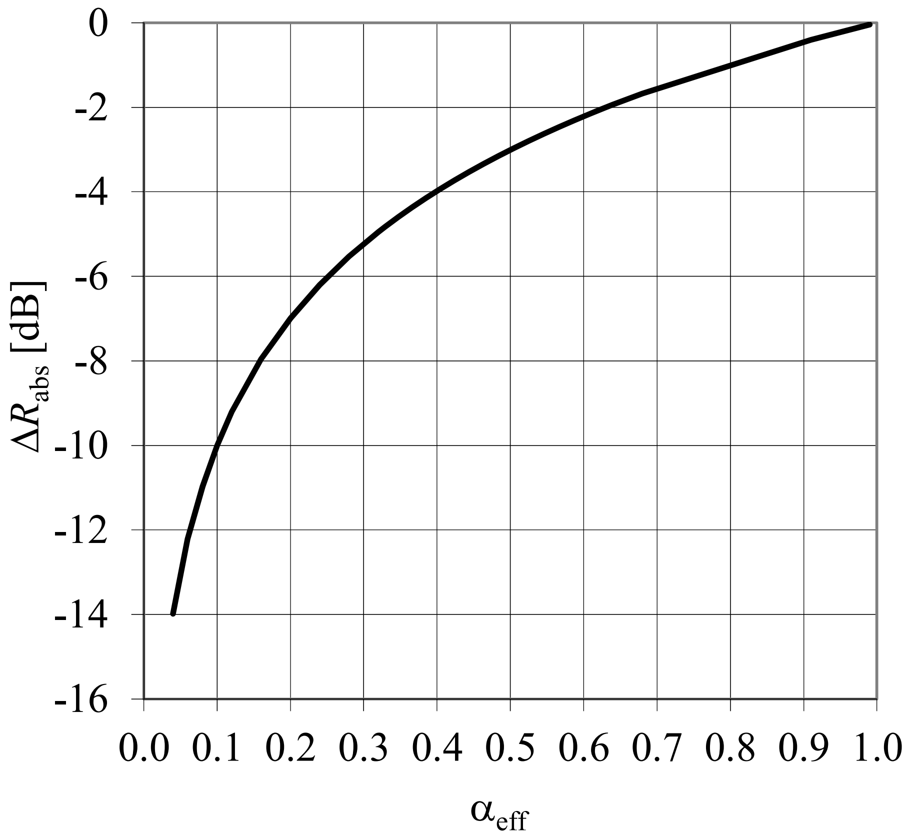
$$R_{cII} = R_{cI} + \Delta R_{abs}$$

$$\Delta R_{abs} = \begin{cases} 0, & f < f_{ca1} \\ 10 \cdot \log_{10}\left(\alpha_{eff}\right), & f \geq f_{ca1} \end{cases}$$

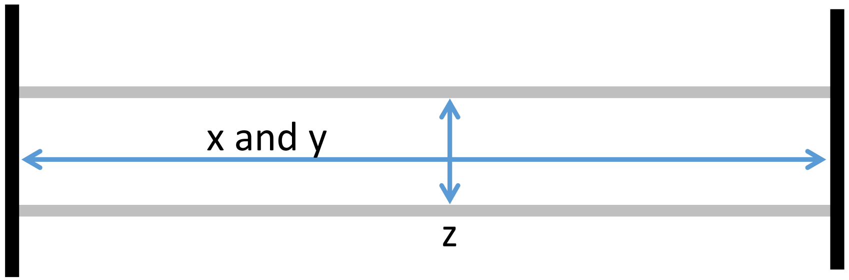
$$\alpha_{eff} = \alpha_{ca} \cdot FR$$

  - α_{ca} = absorption coefficient of the cavity material
  - FR = filling ratio of cavity (0...1)
- Empty cavity has seldom a value under α_{ca}=0.04. The effect of cavity thickness d is estimated for empty cavities by

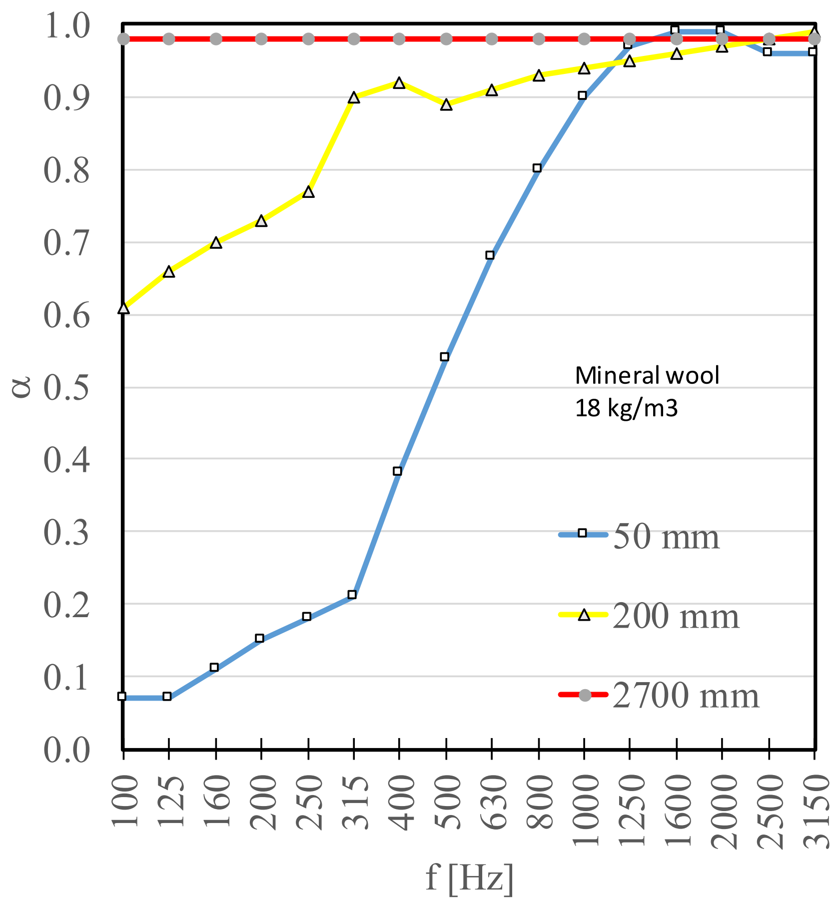
$$\alpha_{eff} = \begin{cases} 0.5, & d \leq 0.02\,\text{m} \\ 0.01/d\,, & d > 0.02\,\text{m} \end{cases}$$



Selection of α_{ca}



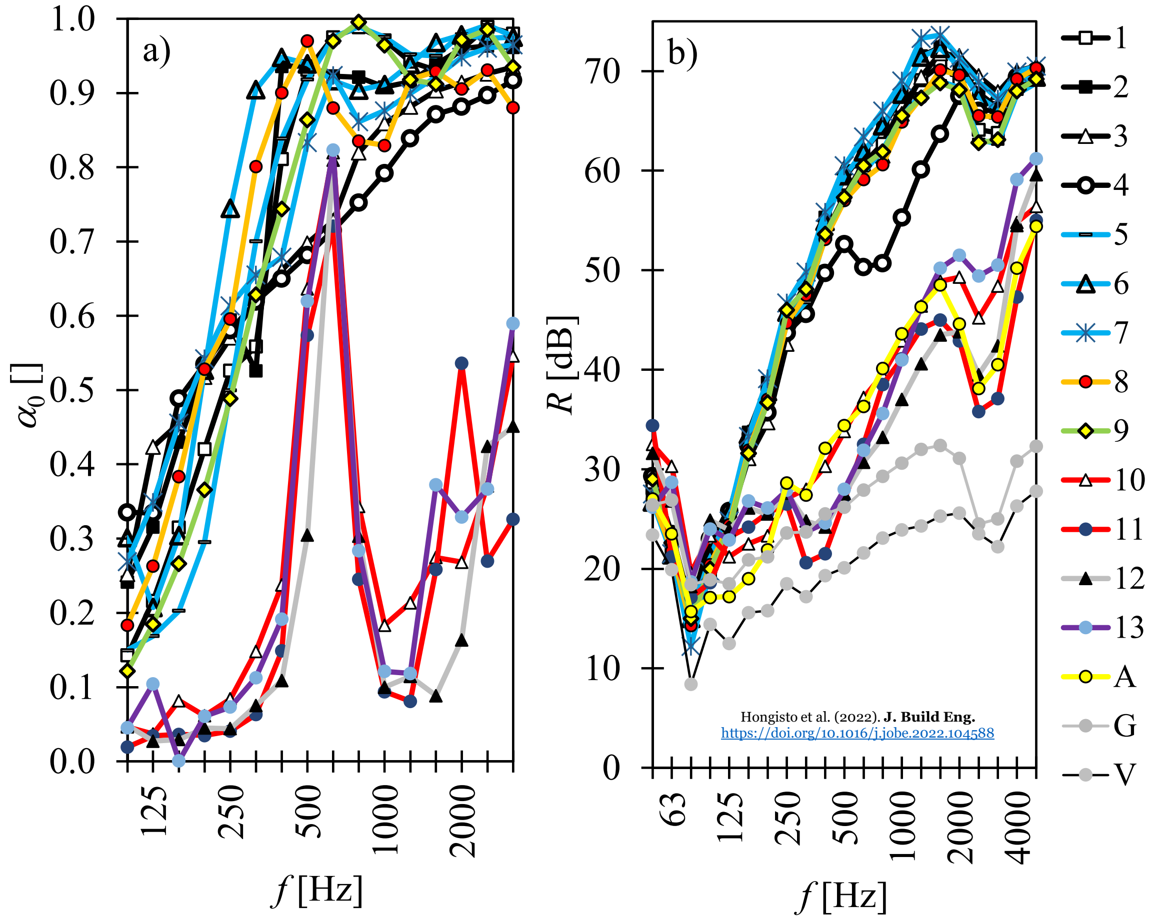
- Sound absorption coefficient of a board is usually known for perpendicular incidence (α_0).
- However, the sound field inside the cavity is parallel to the board below the limit frequency, f_d. If the cavity is filled with absorbent with thickness d, sound propagates inside the material and the α_0 obtained with perpendicular incidence has no meaning.
- The α_0 is valid only above f_d, where the perpendicular sound field comes to play.
- In the direction of the panels, the absorbent thickness is the same as room height (vertical field) or stud spacing (horizontal field).
- Therefore, if $\alpha_0 =$ X above f_d, is is safe to assume $\alpha_{ca} =$ X when $f < f_d$.
- Above f_d, $\alpha_{ca} = \alpha_0$.



SRI of different thermal insulator materials

- There are huge differences between insulator materials w.r.t. sound absorption, and SRI.
- Materials with open pores absorb sound well, since flow resistivity is small.
- Materials with closed pores absorb poorly and the SRI is close to empty cavity (A).

	Insulator material	ρ [kg/m^3]	r' [kPa×s/m^2]
1	Ultra-low density stone wool slab	25	6.6
2	Low density stone wool slab	25	11.6
3	Medium density stone wool slab	75	30.7
4	High density stone wool slab	100	33
5	Ultra-low density glass wool roll	11	3
6	Low density glass wool slab	16	10
7	Medium density glass wool slab	70	15.8
8	Cellulose slab	37	11.1
9	Wood fiber slab	50	5.9
10	Expanded polystyrene board	18	530
11	Polyisocyanurate board	30	2600
12	Phenolic foam board	30	2700
13	Cellular glass board	100	68.3



Absorption coefficient of porous materials 1-13 having 100 mm thickness.

SRI of a double wall having 100 mm cavity filled with porous material or air
- Gypsum 13 mm
- 100 mm porous material or air (A)
- Veneer 9 mm

Cavity absorption

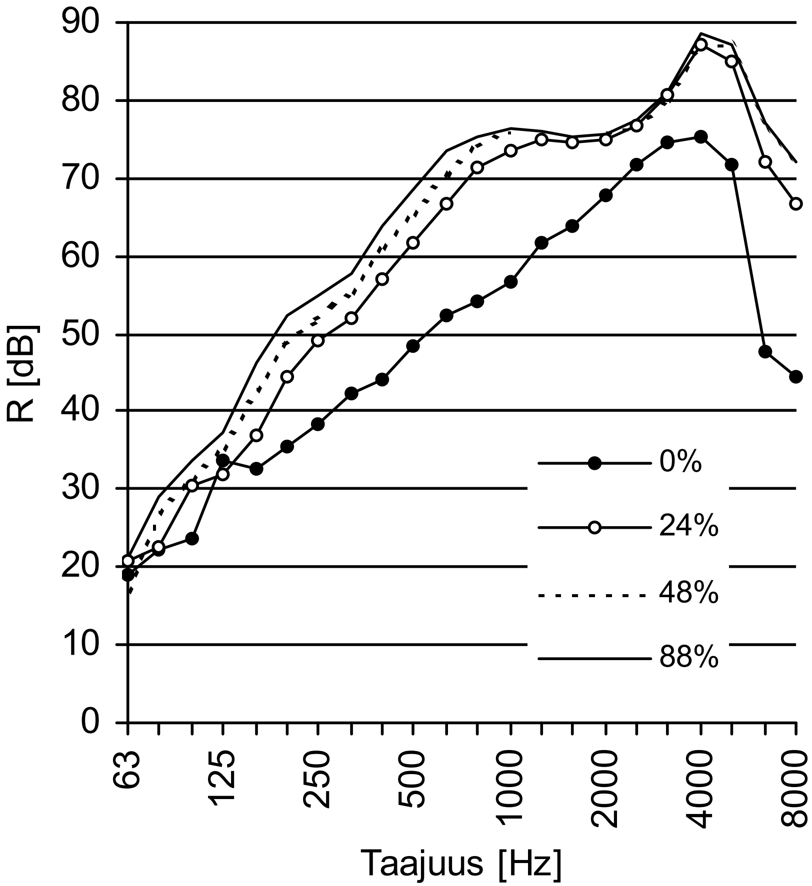
- Absorption can be located in numerous ways
  - full absorption
  - partial absorption
  - strip absorption
  - edge absorption (figure)
- Simple validated prediction models for different alternatives do not exist.
- For example, edge absorption does not eliminate the higher modes (z)

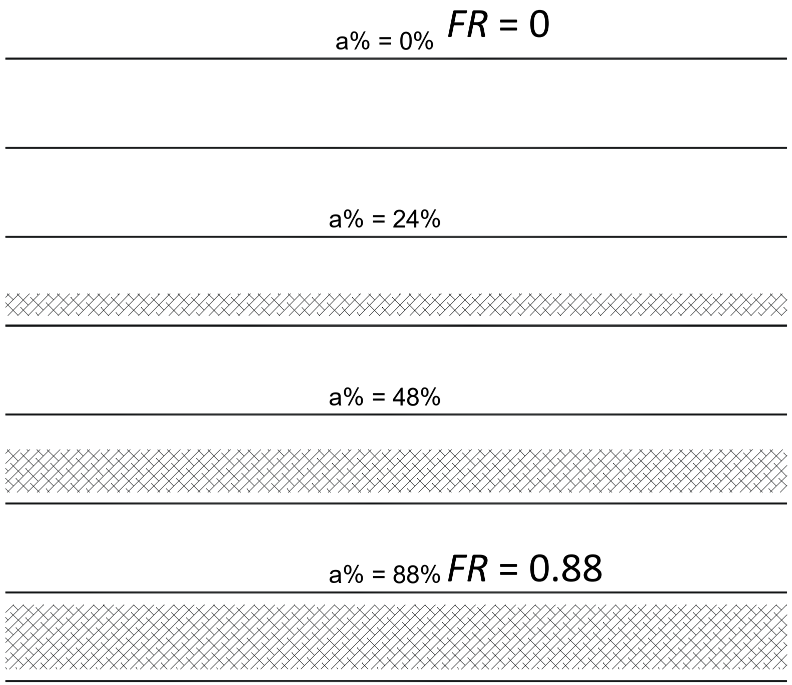
Effect of filling ratio, FR, in an uncoupled double structure

Double structure

- steel 2 mm
- cavity thickness d = 125 mm
- Filling ratio (amount of cavity absorption) is varied
- steel 2 mm

- The specimen size was 2.1x1.1 m, and the lowest cavity mode was f_{c1}=78 Hz.





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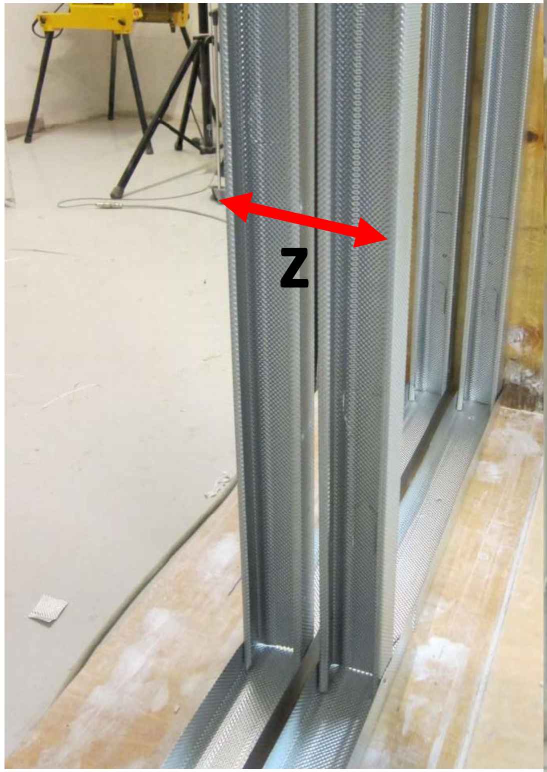
Coupled double structure

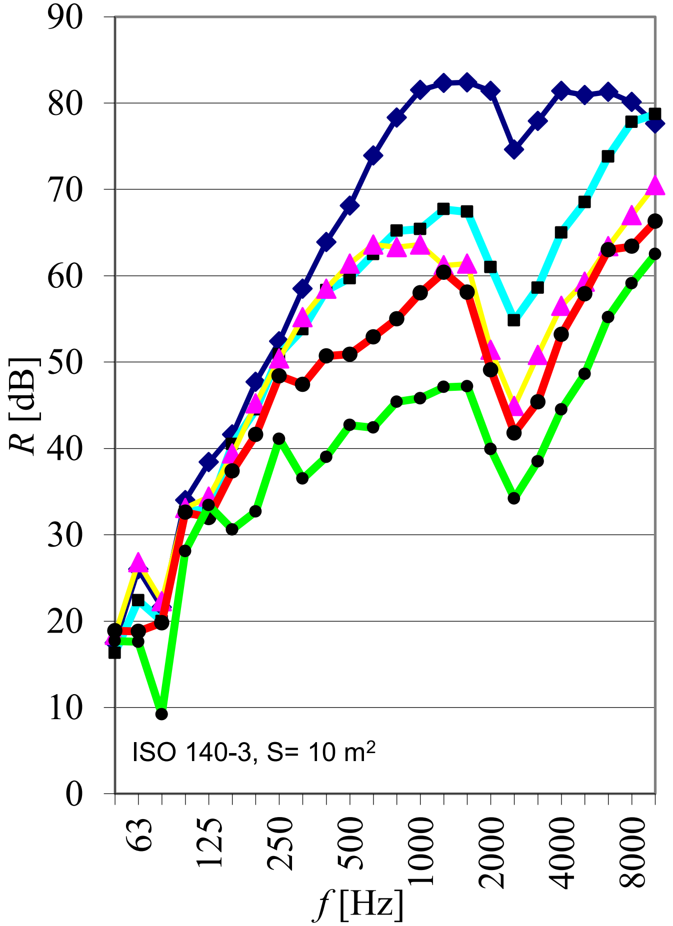
- Rails against ceiling and floor
- Studs are vertical
- Studs and rails are equally thick (common rails)
- Edge studs are screwed to flanking wall and stud resiliency may reduce

Uncoupled double structure

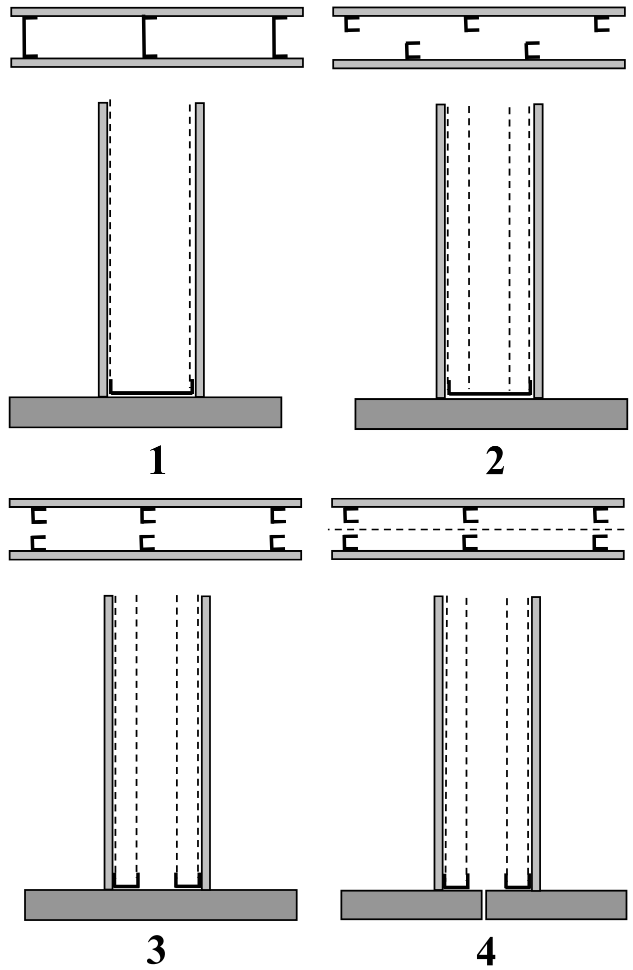
- Double studs on separate rails



Extreme effect of connection types



Structure:
Gypsum 13 mm 11.7 kg/m^2
Cavity 175 mm filled with mineral wool
- coupling was varied
Gypsum 13 mm 11.7 kg/m^2



1 Common rails, common studs
2 Common rails, separate studs
3 Separate rails, separate studs
4 Separate rails, separate studs, construction joint between

- Five different connection types between boards were studied in a 200 mm double wall.
- The effect of connection type on SRI was even 20 dB R_w.

SRI through rigid studs: R_{bI}

Hongisto (2000) **J Sound Vib**
Sharp (1978) Noise Con Eng J
Sharp (1973) NTIS PB 222 829/4

- R_{bI} caused by rigid studs is obtained by summing up the R of both layers, R_1 and R_2, and by adding a constant ΔR_b, which does **not** depend on frequency.

$$R_{bI} = 20 \cdot \log_{10}\left(10^{R_1/20} + 10^{R_2/20}\right) + \Delta R_b$$

- Line connection, i.e. studs:
  - *b* [m] is distance between studs (stud division, cc)
  - f_{cL} is the critical frequency of two boards, weighted by the square of surface mass

$$\Delta R_b = 10 \cdot \log_{10}\left(bf_{cL}\right) + 20 \cdot \log_{10}\left(\frac{m'_1}{m'_1 + m'_2}\right) - 18$$

$$f_{cL} = \left[\frac{m'_1\sqrt{f_{c2}} + m'_2\sqrt{f_{c1}}}{m'_1 + m'_2}\right]^2$$

- Point connection:
  - *N* number of point connections
  - S [m²] is the panel area
  - f_{cP} is the critical frequency of two boards, weighted by the surface mass

$$\Delta R_b = 10 \cdot \log_{10}\left(\frac{S\pi^3 f_{cP}^2}{N 8 c_0^2}\right) = 10 \cdot \log_{10}\left(\frac{S f_{cP}^2}{N}\right) - 45$$

$$f_{cP} = \frac{m'_1 f_{c2} + m'_2 f_{c1}}{m'_1 + m'_2}$$

SRI through flexible studs: R_{bII}

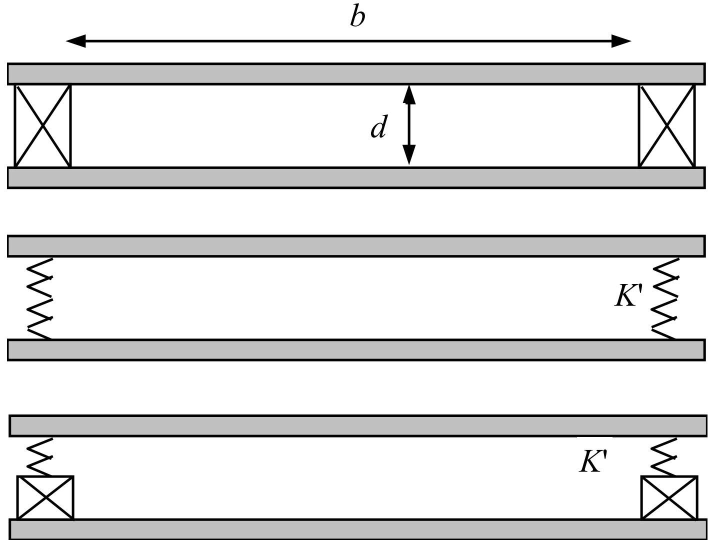
- Flexible stud is a spring. Its effect on SRI can be modeled by adding the vibration reduction index, ΔR_{fb}, to the rigid stud value, R_{bI}:

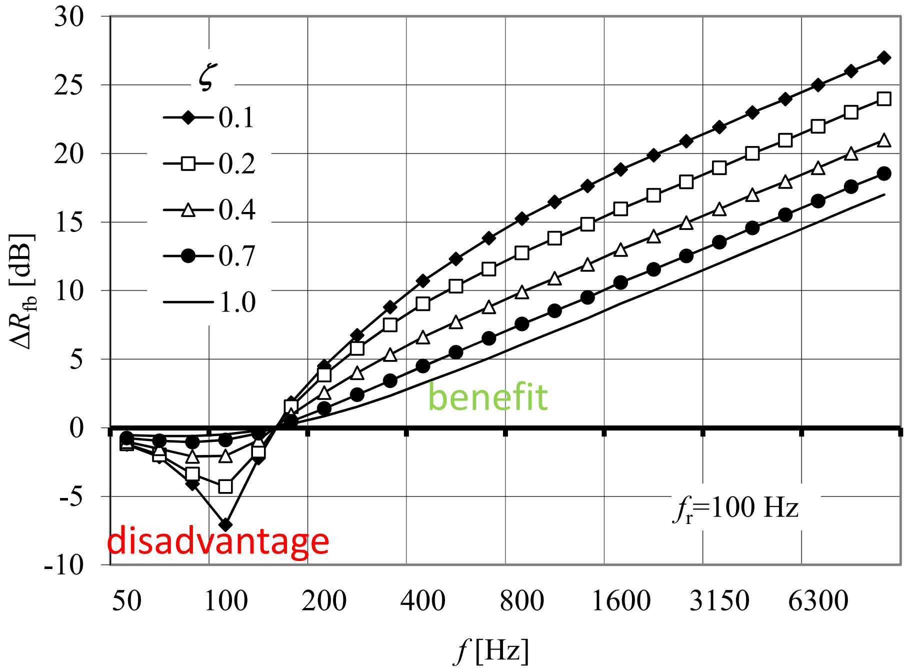
$$R_{bII} = R_{bI} + \Delta R_{fb}$$

$$\Delta R_{fb}(f) = -5\log\left(\frac{1+4\zeta^2\left(\frac{f}{f_r}\right)^2}{\left[1-\left(\frac{f}{f_r}\right)^2\right]^2+4\zeta^2\left(\frac{f}{f_r}\right)^2}\right)$$

$$f_r = \frac{1}{2\pi}\sqrt{K''\frac{m'_1+m'_2}{m'_1 m'_2}}$$

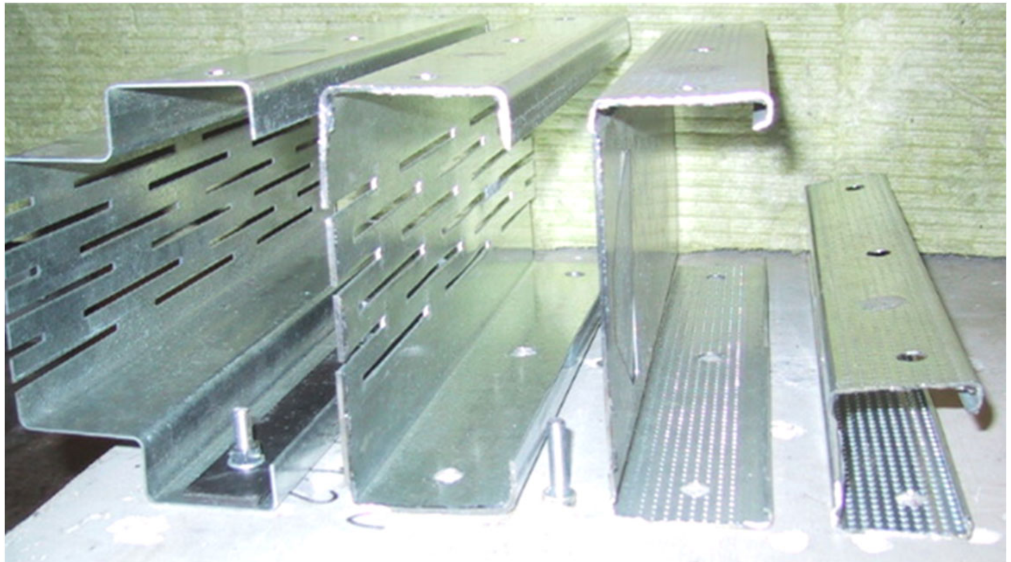
  - f_r [Hz] is the resonance frequency of the double wall with studs
  - ζ is the loss factor of the flexible stud (not the panel)
  - K'' [N/m^3] is dynamic stiffness per unit area of the stud
- Benefit of flexible stud: $R_{bII}>R_{bI}$, when $f > 2f_r$
- Disadvantage of flexible stud: $R_{bII}<R_{bI}$, when $f < 2f_r$





Bradley&Birta (2001) Noise Con Eng J

Examples of resilient studs



- AWS, TC, LR and LPR
- K'' values: 0.2, 2.8, 3.3 and 0,9 MN/m^2
- ΔR_{fb} is usually limited to 8 … 10 dB due to rigid edges of the wall (rigid rails often surround the wall)

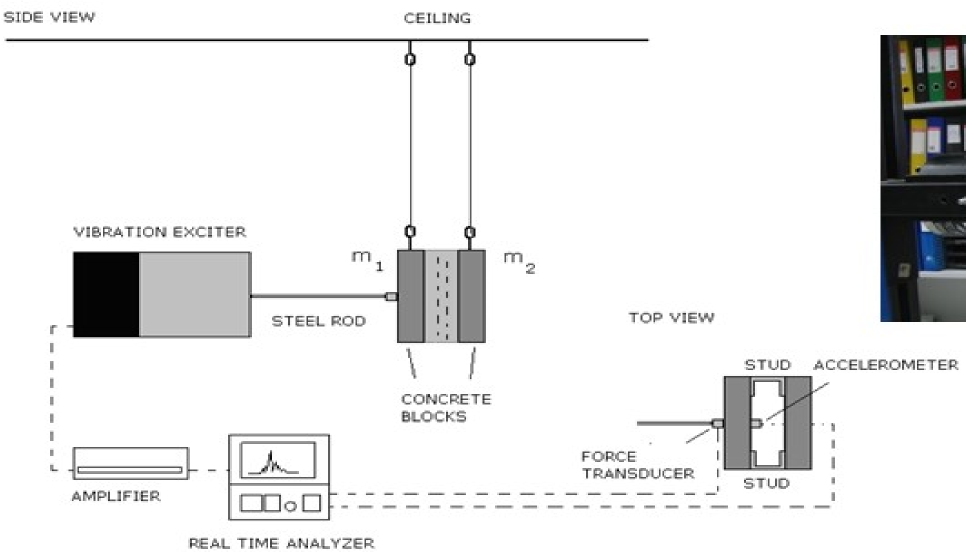
Determination of dynamic stiffness of flexible studs

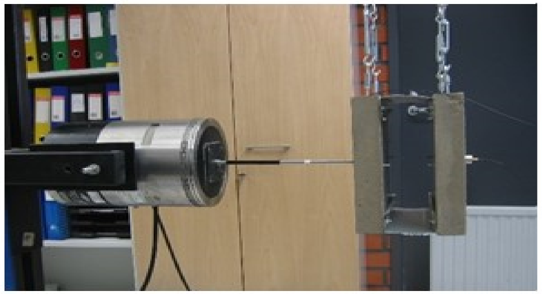
- Test system: Two 30-cm-long studs are installed between two plates (m'_1, m'_2, 30x30 cm) with screws
- The other plate is excited with broad-band vibration shaker
- System's resonance frequency, f_0 [Hz], is determined with FFT analysis
- The dynamic stiffness, or the spring constant, ***K*** **[N/m]**, in test system is
- The dynamic stiffness per unit length, ***K'*** **[N/m²]** is
  - where L=0,6 m
- The modeling of flexible studs in a wall depends on ***K''*** **[N/m³]**, which takes the actual density of studs in the wall into account
  - b [m] is the distance between studs

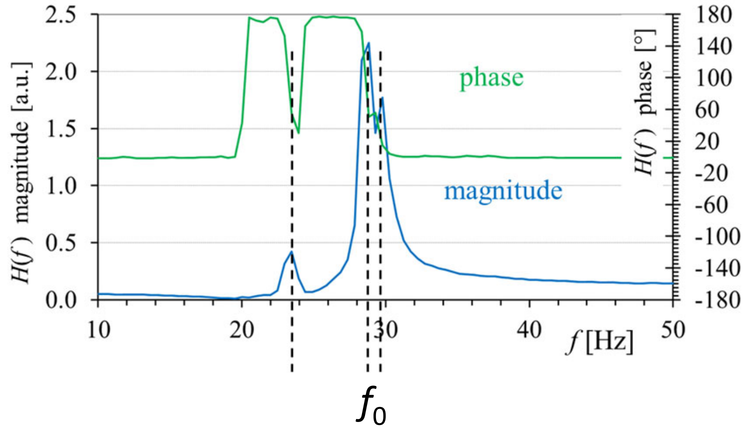
$$K = \omega_0^{\,2} \frac{m'_1 m'_2}{m'_1 + m'_2}$$

$$K' = K/L$$

$$K'' = K'/b$$

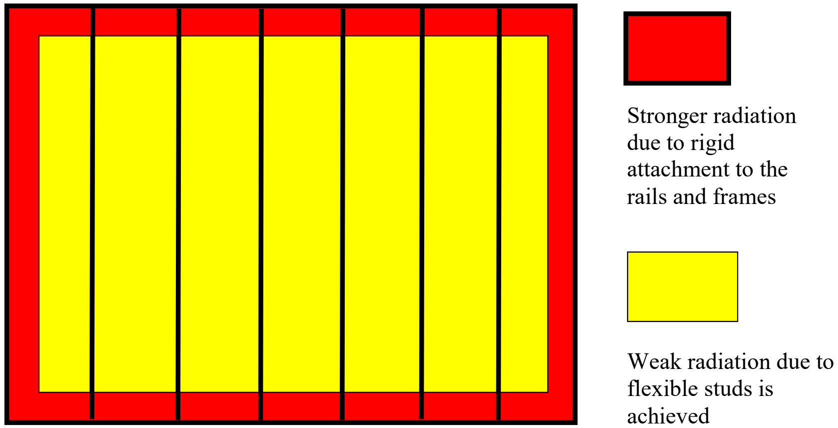


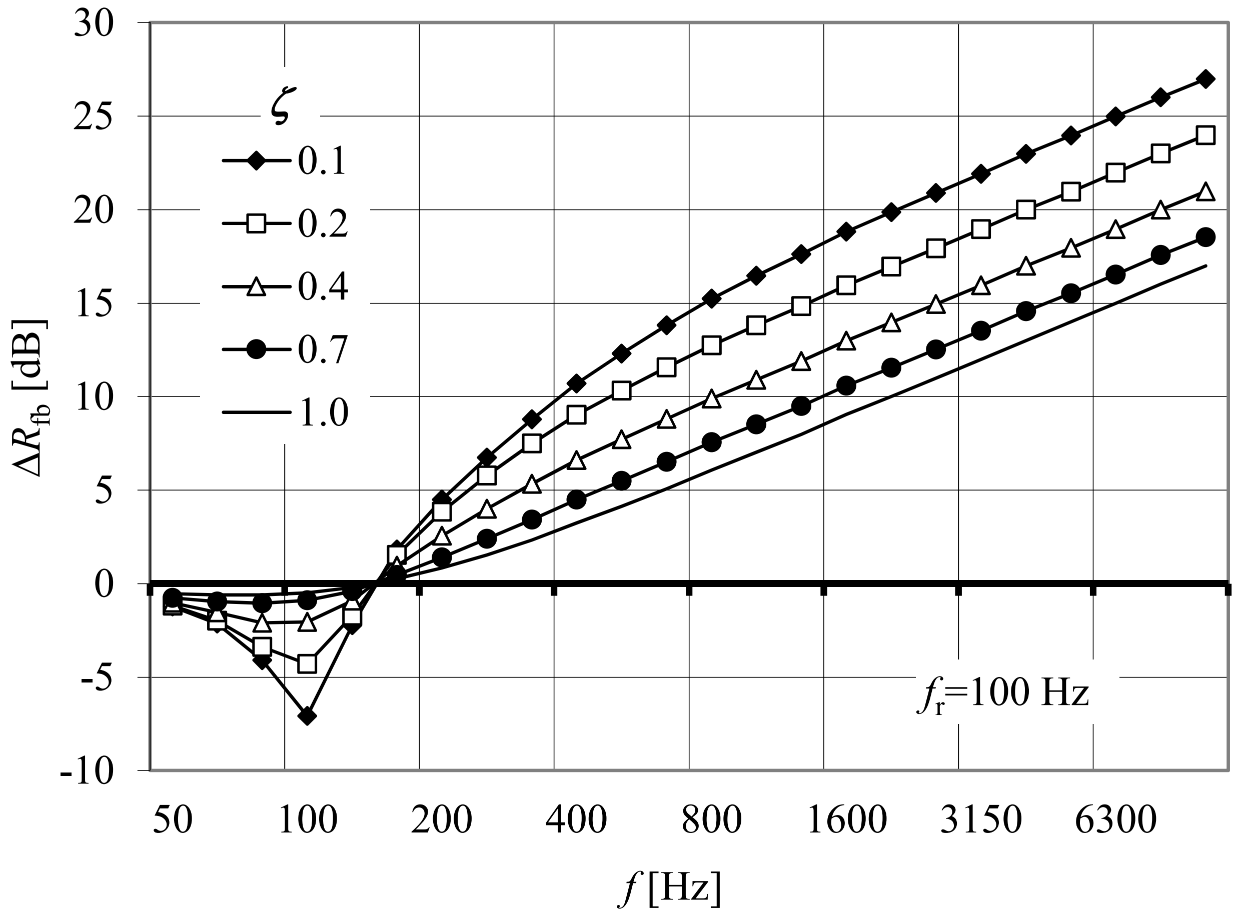




ΔR_{fb}

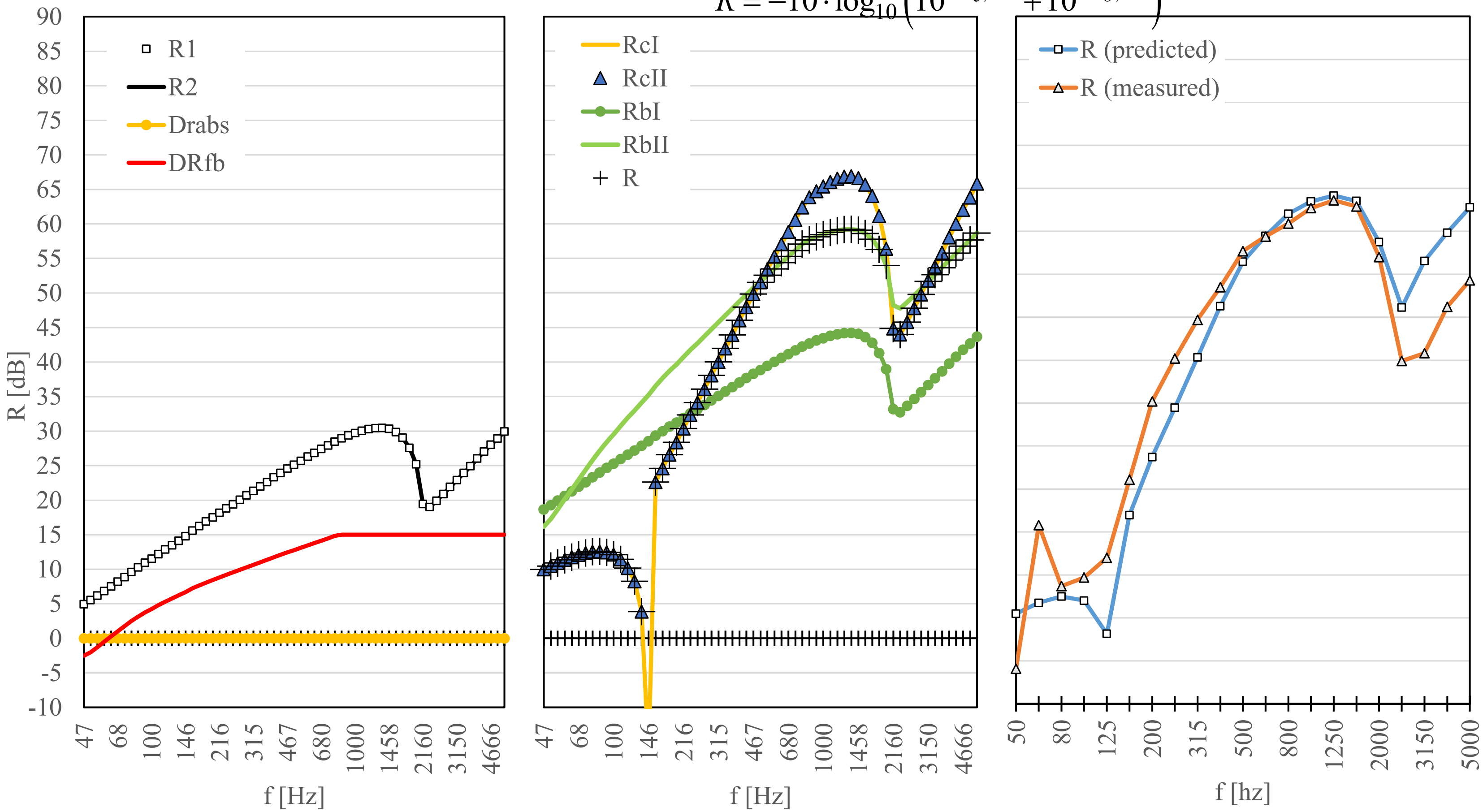
- Although studs were flexible, rails against ceiling and floor are usually rigid. Rigid connection of the flexible stud to the rail locally destroys the advantage of flexible stud
- Full benefit of the flexible stud is only achieved away from the rails.
- Because of this, ΔR_{fb} is seldom larger than 10…15 dB, although equations give larger values at higher frequencies →





m'1	kg/m2	9.0
m'2	kg/m2	9.0
d	kg/m2	0.066
fc1	[Pa]	2500
fc2	[Hz]	2500
fmam	[Hz]	147
fd	[Hz]	827
Lx	m	1
Ly	m	3
fc1	[Hz]	64
FR	0=tyhjä	1.00
α_c	oma	1.00
α_c	tyhjä	0.15
α_{eff}		1.00
Kytkentä: 0 ei,1 viiva, 2 pi		1
b		0.600
Np		10000
S	[m2]	10
fcL	[Hz]	2500
fcP	[Hz]	2500
ΔR_b	[dB]	8
Joustava: 0 ei 1 kyllä		1
K'	[N/m2]	200000
ξ	[ ]	0.30
fr_K'	[Hz]	43
fr_oma	[Hz]	
fr	[Hz]	43
ΔR_{fb} maksimi	[Hz]	15

$$R = -10 \cdot \log_{10}\left(10^{-R_c/10} + 10^{-R_b/10}\right)$$



Example of double wall model

Construction:

- Gypsum 13 mm (R1)
- Flexible stud, 0.2 MN/m^2, cc600, 66 mm cavity, cavity filled with wool
- Gypsum 13 mm (R2)

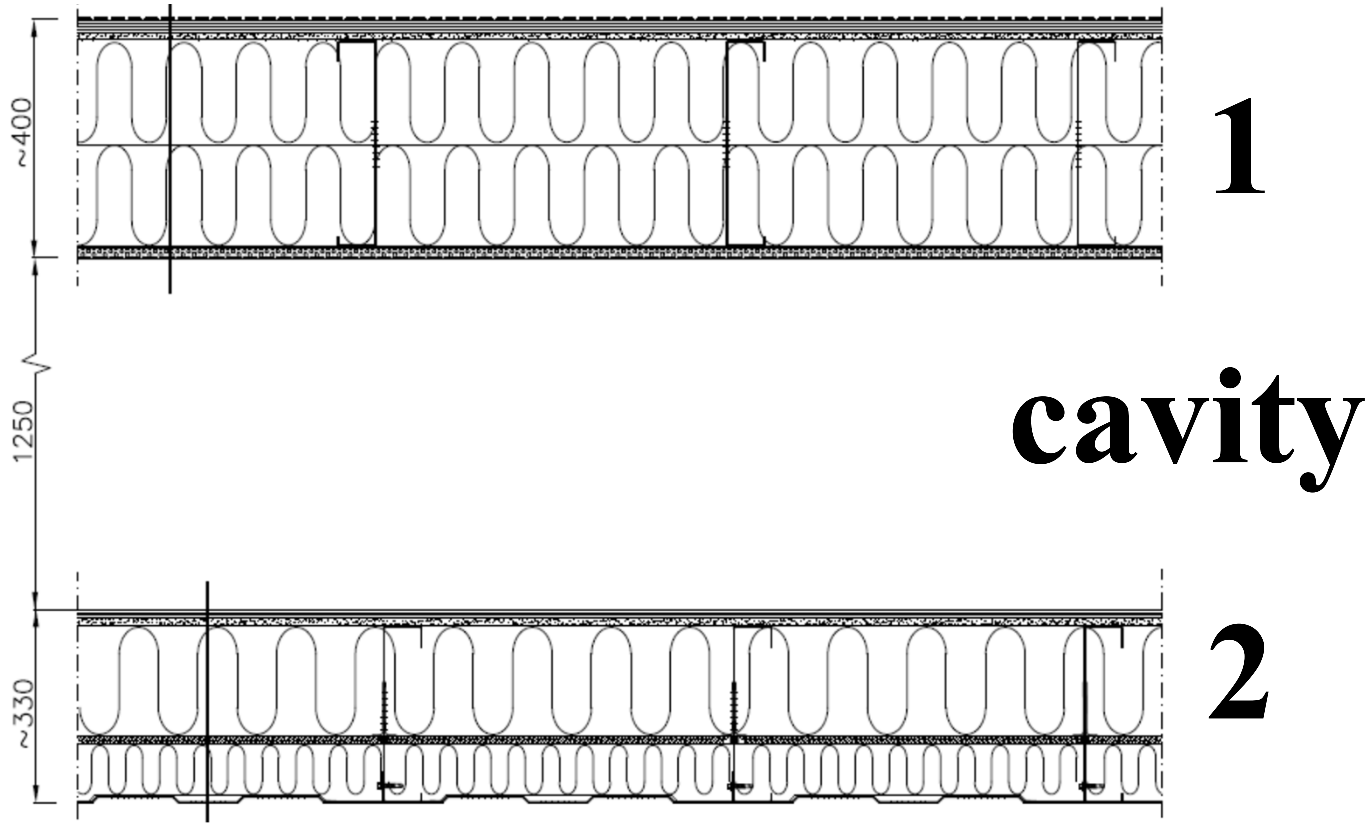
Calculation process:

- 1/9-octave bands for better precision.
- Results are presented in 1/3-octave bands

Extremely thick double panel construction

- Ceiling of a large music arena
- SRI requirement was given in octave bands down to 63 Hz
- Impossible to test in laboratory due to 2 m total thickness
- Layers 1 and 2 were tested separately in laboratory
- Prediction of R was made using the double panel model so that R_1 and R_2 were measured

$$R_{cI} = \begin{cases} 20 \cdot \log_{10}\left(10^{R_1/20} + 10^{R_2/20}\right) + R_{mam}, & f < f_{mam} \\ R_1 + R_2 + 20 \cdot \log_{10}(fd) - 29, & f_{mam} < f < f_l \\ R_1 + R_2 + 6, & f > f_l \end{cases}$$



	63	125	250	500	1000	2000	4000	8000	Rw
Prediction:	51	74	98	118	131	137	143	143	96
Requirement:	46	53	59	64	74	75	75	75	69

Sandwich structure

- Double panel where the cavity consists of elastic core material such as wool, rubber, EPS, polyurethane or honeycomb paper glued to the panels
- Examples:
  - Thermal isolated doors
  - Fire doors
  - Floating floors
  - Concrete sandwich facades
- Dilatation resonance frequency:

$$f_d = \frac{1}{2\pi}\sqrt{K'\frac{m'_1 + m'_2}{m'_1\, m'_2}}$$

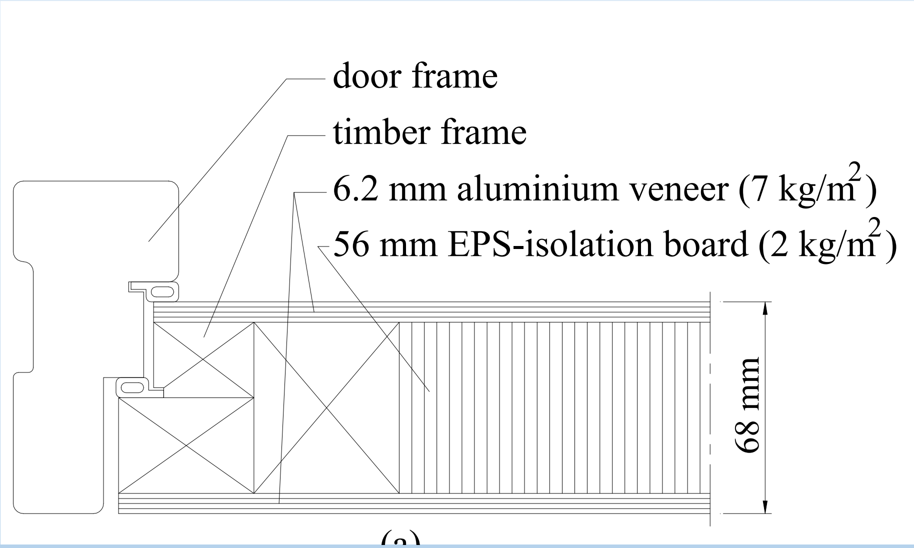
  - K' [N/m^3] is the dynamic stiffness per unit area of the core material
  - m' [kg/m^2] is the surface mass of panel
- It is typical, that f_d is within 100 --- 3150 Hz

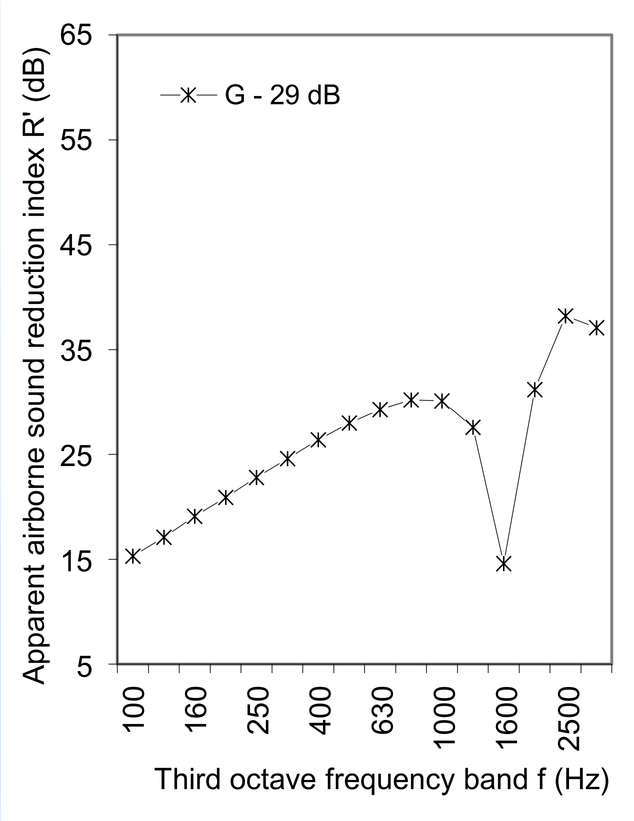
http://www.archiexpo.com/architecture-design-manufacturer/floor-sandwich-panel-21655.html

5.4

Sandwich – door's thermal isolator is EPS.
EPS (s'=330 MN/m3).
Calculate the dilatation resonance.

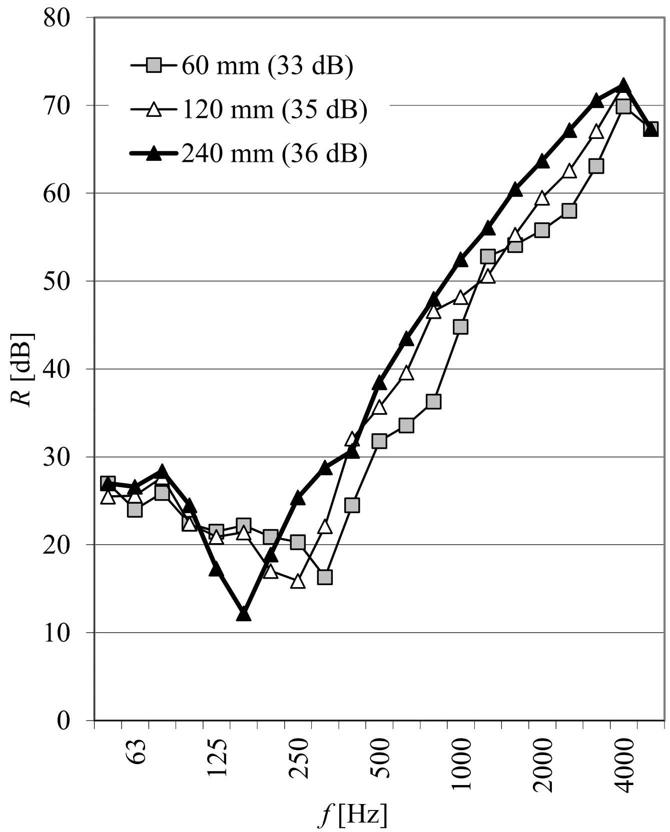
$$f_d = \frac{1}{2\pi}\sqrt{s'\frac{m'_1+m'_2}{m'_1\,m'_2}}$$



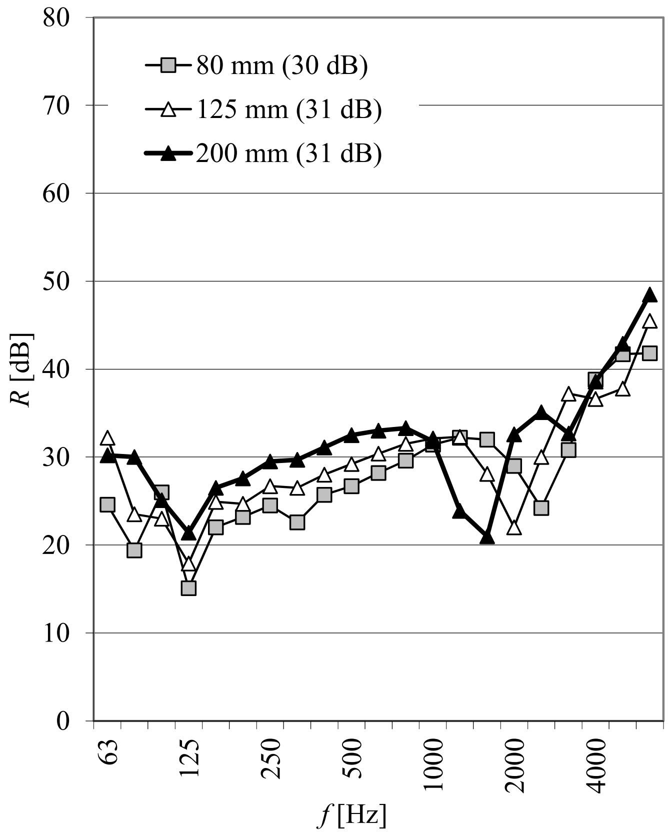


Hongisto 2001 Applied Acoustics

Sandwich panel - effect of core thickness



- steel 1 mm
- mineral wool (100 kg/m^3)
- steel 1 mm
- R_w in brackets

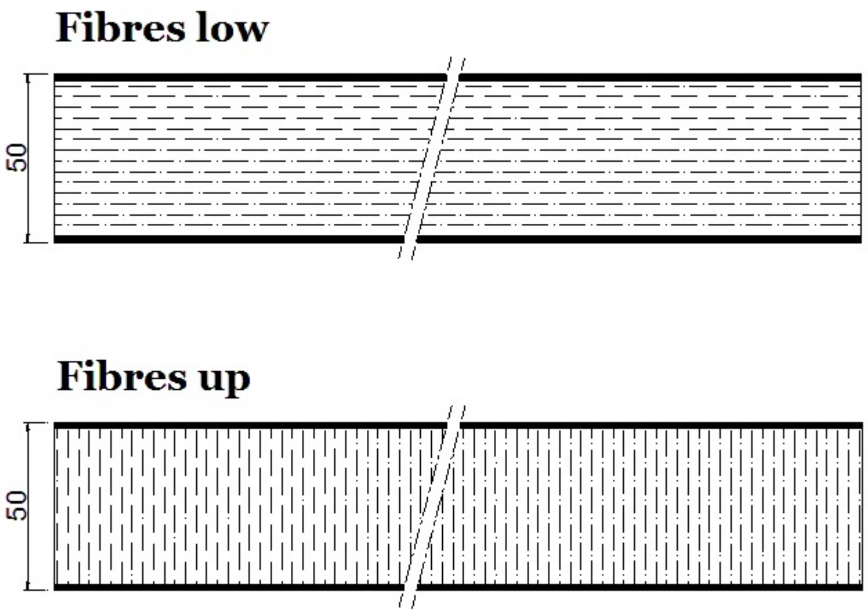


- steel 0.6 mm
- mineral wool (125 kg/m^3)
- steel 0.6 mm
- R_w in brackets

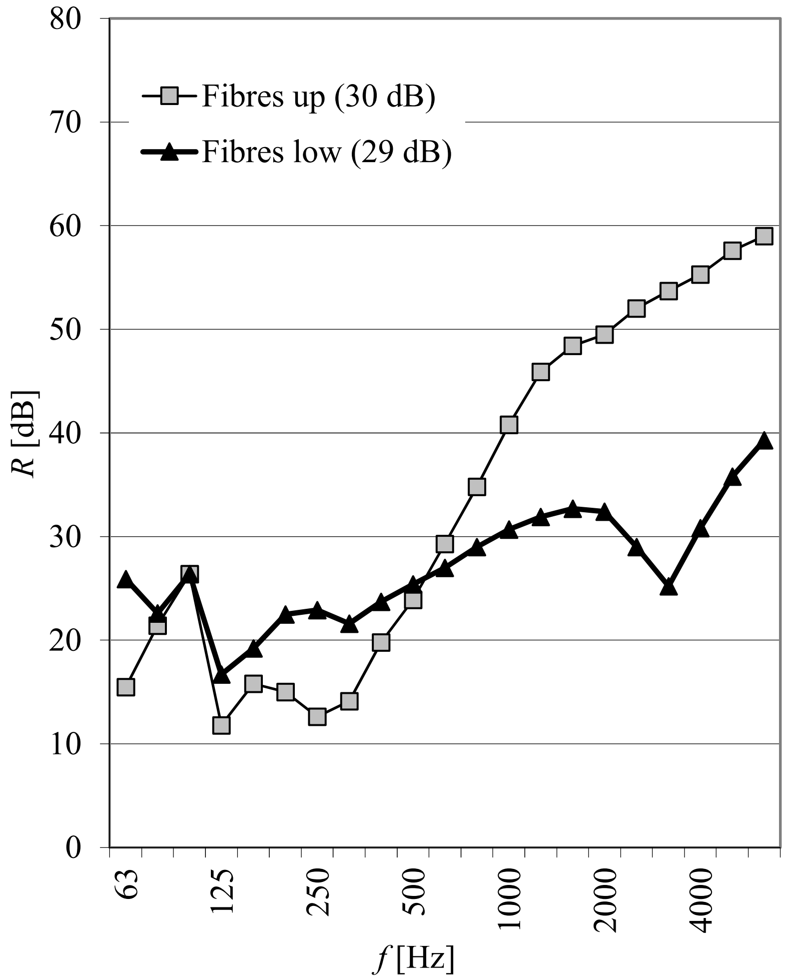
$$f_d = \frac{1}{2\pi}\sqrt{K'\frac{m'_1 + m'_2}{m'_1\, m'_2}}$$

RIL 243-1-2007

Sandwich panel - effect of core stiffness



Fiberglass 2.5 mm
Rockwool 50 mm 110 kg/m3
Fiberglass 2.5 mm
Altogether 14.3 kg/m2



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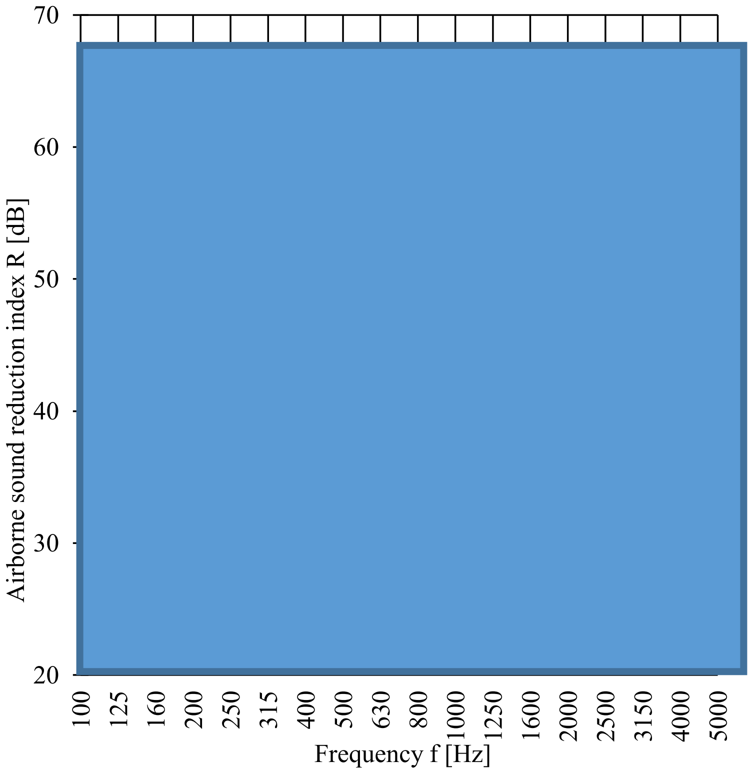
Concrete-EPS-Concrete block

- Describe the SRI performance of a concrete block with EPS core.



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