Aalto University

4 Airborne sound insulation

ELEC-E5640 - Noise Control D

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Why important?

- Sound insulation in buildings is regulated by a **acoustic environment decree** involving at least one apartment and another apartment of any use
- Additional target values can be found from the **acoustic environment instructions** (2018) for schools, offices, health-care buildings, etc.
- Voluntary target values are also found in SFS 5907:2004.
- The regulated values in buildings are presented by a single-number quantity, weighted sound level difference $\mathbf{D_{nT,w}}$.
  - During years 1998–2017, a *single-number quantity* weighted sound reduction index, $\mathbf{R'_w}$, was used and it still concerns buildings licenced before 2018.
- The component properties tested in laboratory are still reported with $\mathbf{R_w}$. The use of different symbols in in buildings and laboratory facilitates the communication.

Decree 796-2017 of the Ministry of the Environment on the acoustic environment of buildings. 24 November 2017, Helsinki, Finland.

- https://www.finlex.fi/fi/laki/alkup/2017/20170796
- In Finnish.

Ministry of the Environment (2018). **Instructions** on the acoustic environment of buildings, Helsinki, Finland.

- http://www.ym.fi/download/noname/%7B2852D34E-DA43-4DCA-9CEE-47DBB9EFCB08%7D/138568
- In Finnish.

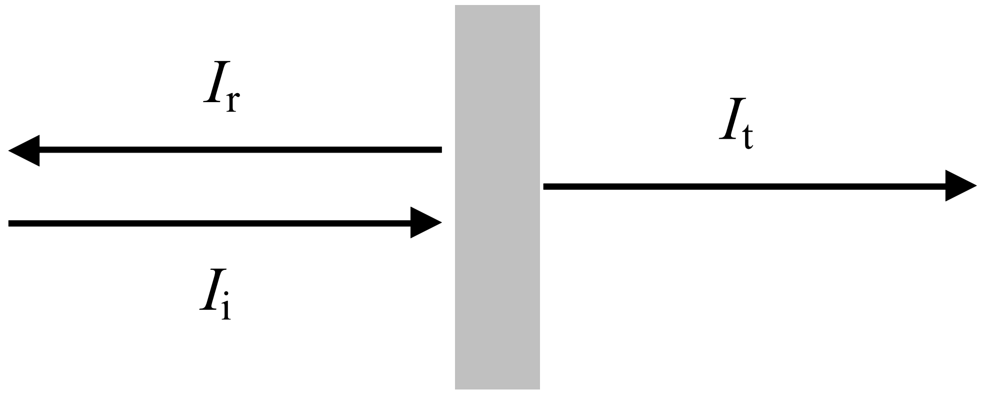
Decree (mandatory)

Room type	**Smallest allowed $D_{nT,w}$ [dB]**
Between residential dwellings and between accommodation rooms	55
From stairway to abovementioned spaces	39

Instruction (mandatory unless otherwise decided)

Room type	**Smallest allowed $D_{nT,w}$ [dB]**		
	To the surrounding spaces in general	To another similar room [b], when they are separated by a door	To the stairway when it is separated by a door
General teaching room [a]	44	42	34
Music teaching room	60	52	44
Teaching room in day-care center	44	42	34
Meeting room	48	42	34
Nursing room such as operation room, reception room, therapy room, rest room [c] [d]	48	42	39
Patient room in hospital or health center[d]	48	42	34
Exercise room	57	48	42
Office room [d]	40	40	30
Between two separate companies in an office buildi	52	-	-
Working room of social worker, psychologist, health nurse or student advisor in a school	48	42	39

Transmission



- Transmission factor τ is the ratio of transmitted and indident intensity.
- Intensity is energy per unit area [W/m^2]
- **Sound reduction index** *R* [dB] or **SRI** is defined by

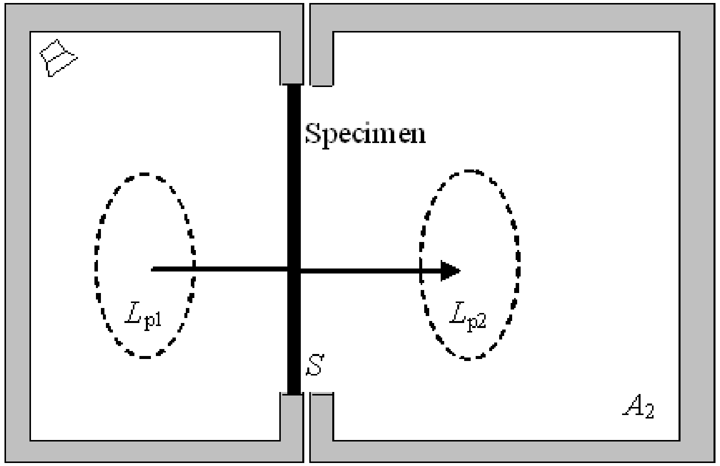
$$R = 10\lg\frac{1}{\tau} = 10\lg\frac{I_i}{I_t}$$

Determination of SRI in laboratory (ISO 10140-2)

- R [dB] is sound reduction index
- 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 sound pressure level in the source room.
- $L_{p,2}$ [dB] is sound pressure level in the receiving room.

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

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

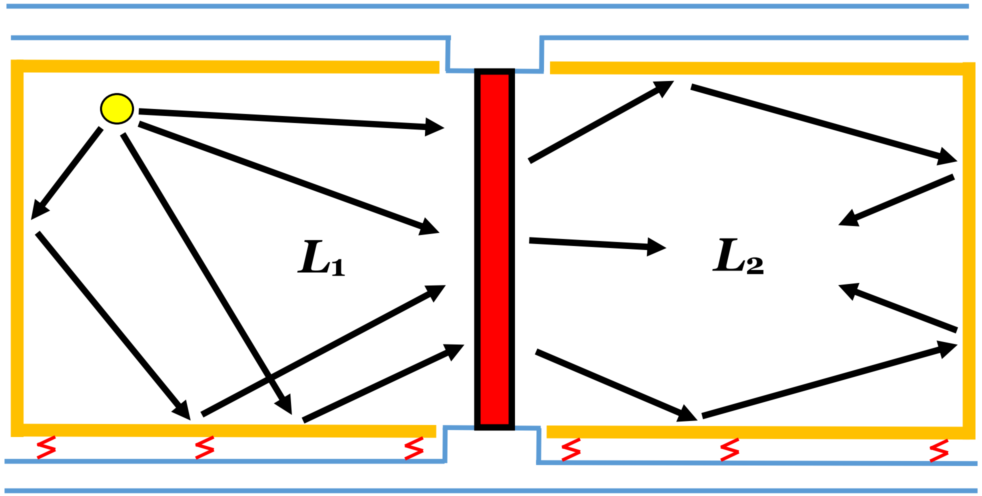


$$R = 10\log\frac{1}{\tau} = 10\log\frac{W_1}{W_2}$$

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

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 of airborne sound insulation in building

- SRI cannot be measured in buildings due to flanking transmission
- Instead, standardized level difference, D_{nT}, is determined.
  - T_2 [s] is the reverberation time in the receiving room
  - T_0 [s] is the reference time 0.5 seconds.

Between rooms by ISO 16283-1

$$\boxed{D_{n,T}' = L_{p1} - L_{p2} + 10\lg\frac{T_2}{T_0}}$$

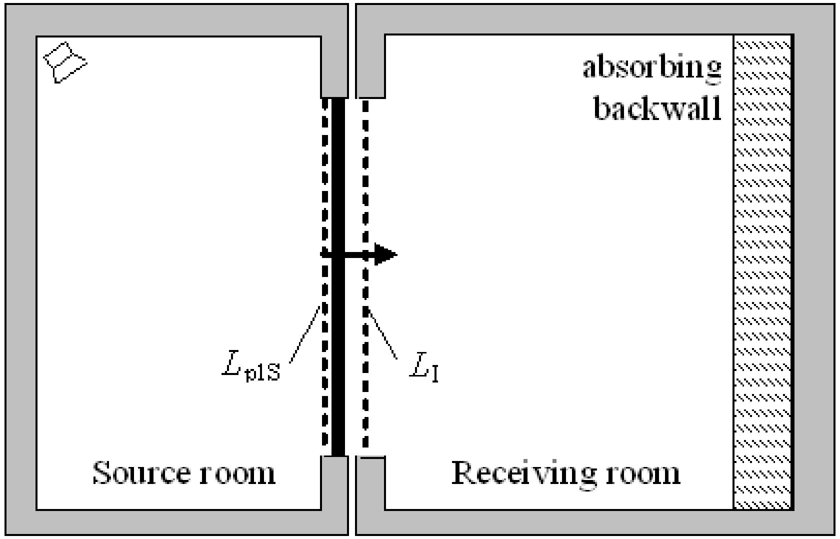
- Facades are measured by R'_{45°:
  - $L_{p1,s}$ [s] is the SPL caused by a loudspeaker in the vicinity (under 30 mm) of facade outdoors

Facades by ISO 16283-3

$$\boxed{R'_{45^o} = L_{p,1,s} - L_{p,2} + 10\lg\frac{S}{A_2} - 1.5}$$

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

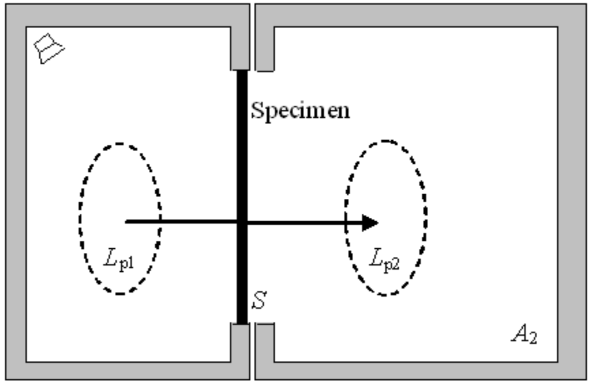
$$R_I = L_{p1S} - L_{I2} - 9$$

Measurement uncertainty

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

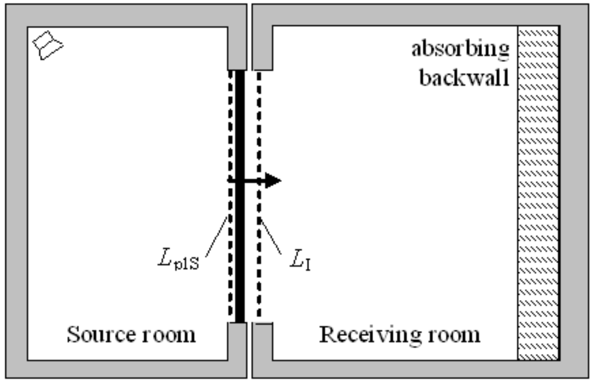
ISO 140-3 (pressure method, 50-5000 Hz)

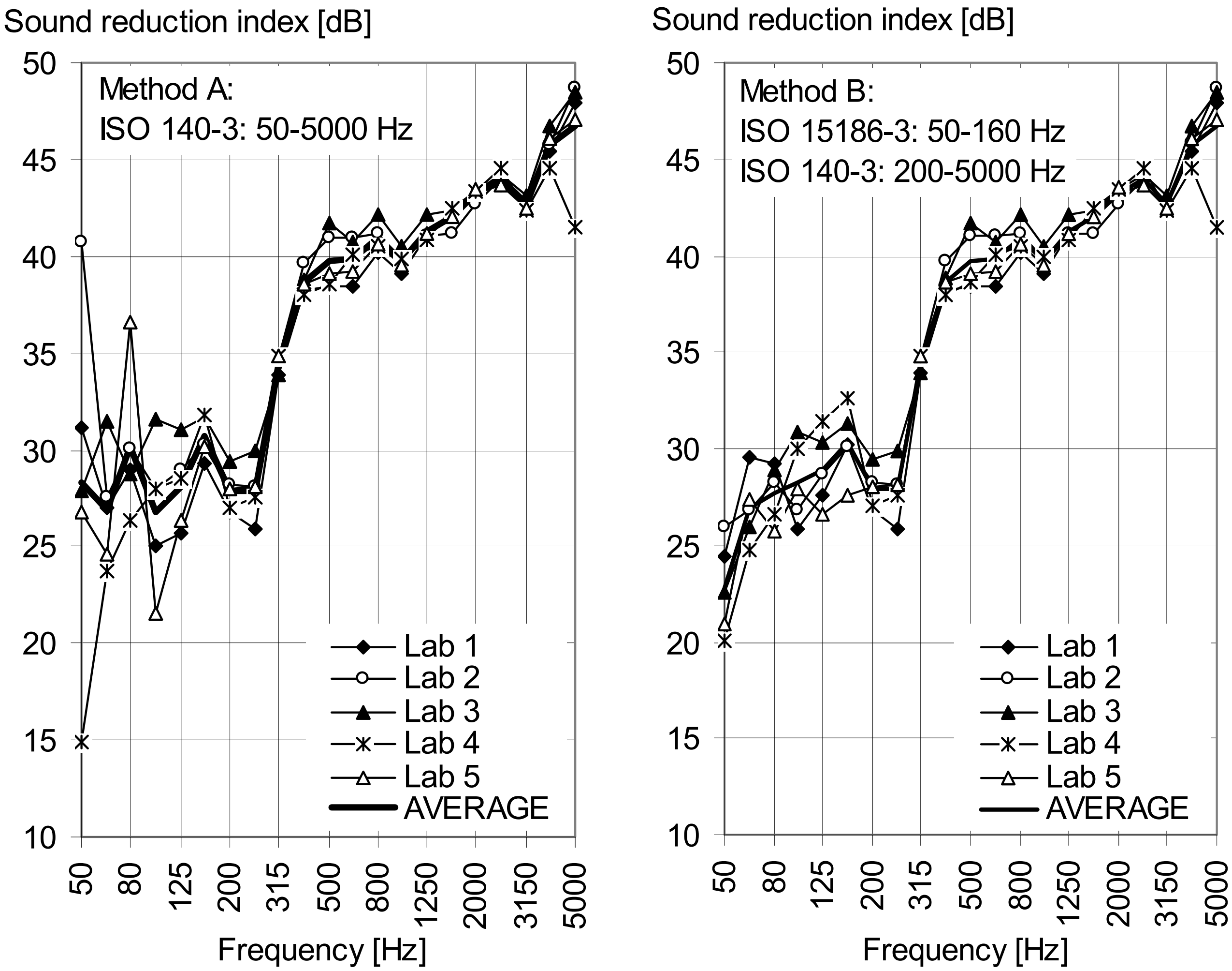
$SRI = L_{p1} - L_{p2} + 10\lg(S/A_2)$



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

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



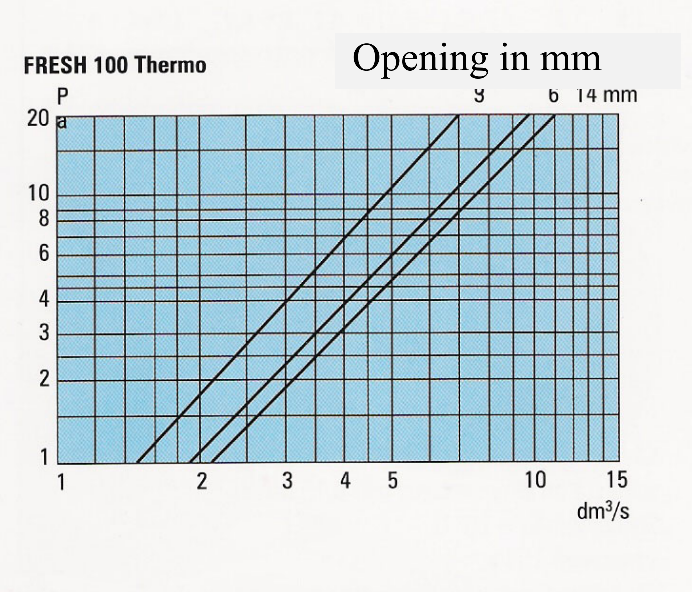


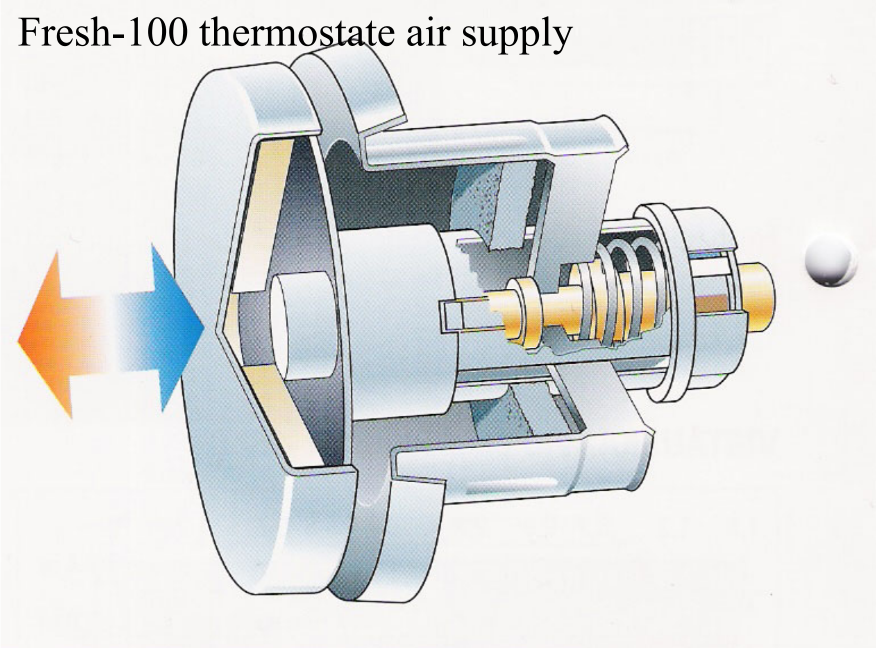
Hongisto et al. (2012) *Acta Acust united Ac*

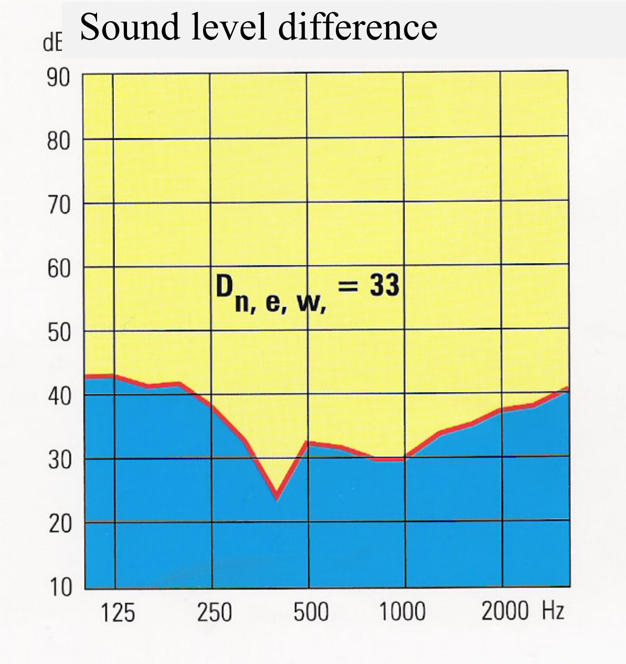
Measurement of small elements in laboratory

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

Normalized sound level difference
A_0=10 m^2


Opening in mm


Fresh-100 thermostate air supply


Sound level difference

4.1

A facade wall is studied in laboratory (S=10 m2).
It involves a ventilation unit fully open.
The dimensions are 160x200 mm.
Measurement results were $L_{p,1}$=100 dB, $L_{p,2}$=80 dB and A_2=4 m2.
Determine R and Dn,e.

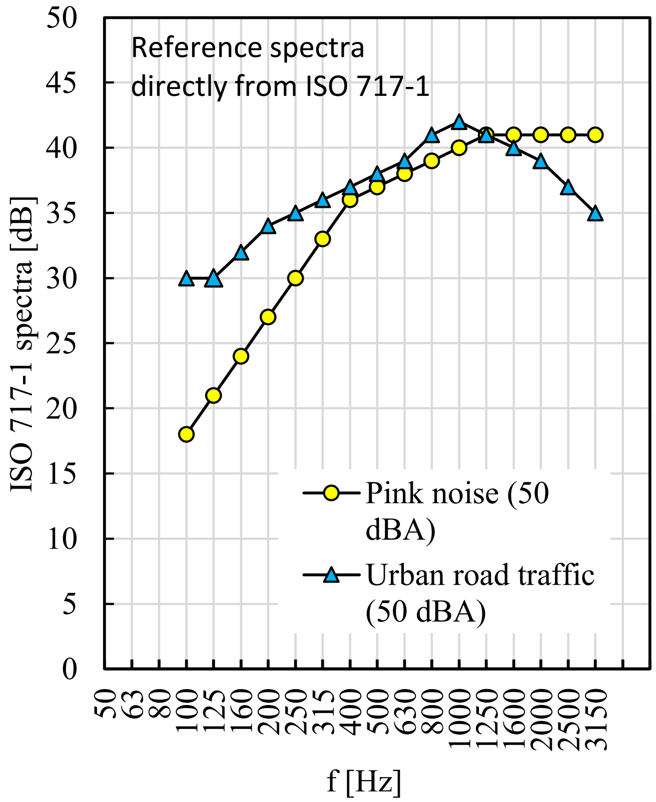
Why is it more feasible to declare Dne instead of R
although the former does not reflect the physical size?

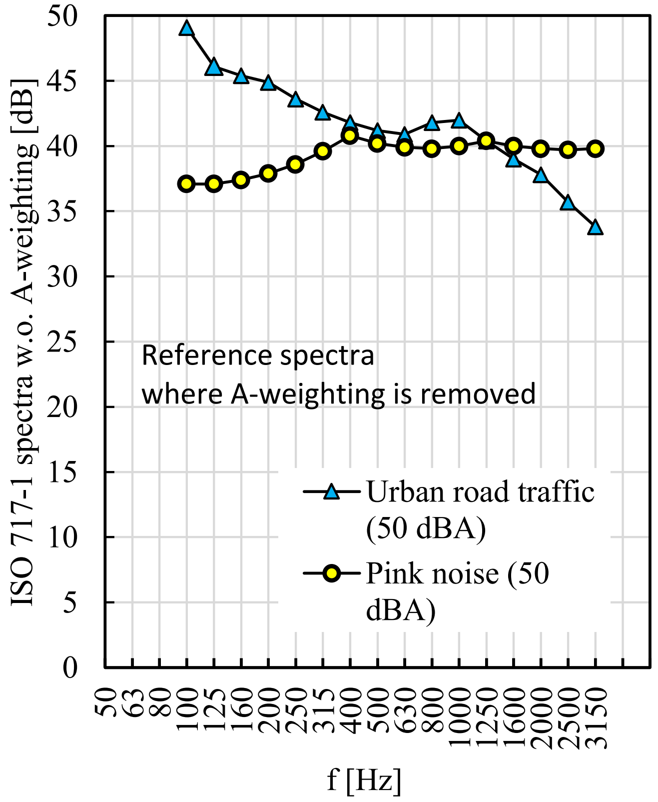
$$R = L_{p,1} - L_{p,2} + 10 \lg \frac{S}{A_2}$$

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

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 procedures are 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
- **$R_w + C_{tr}$** describes sound insulation performance against noise having spectrum close to urban road traffic noise

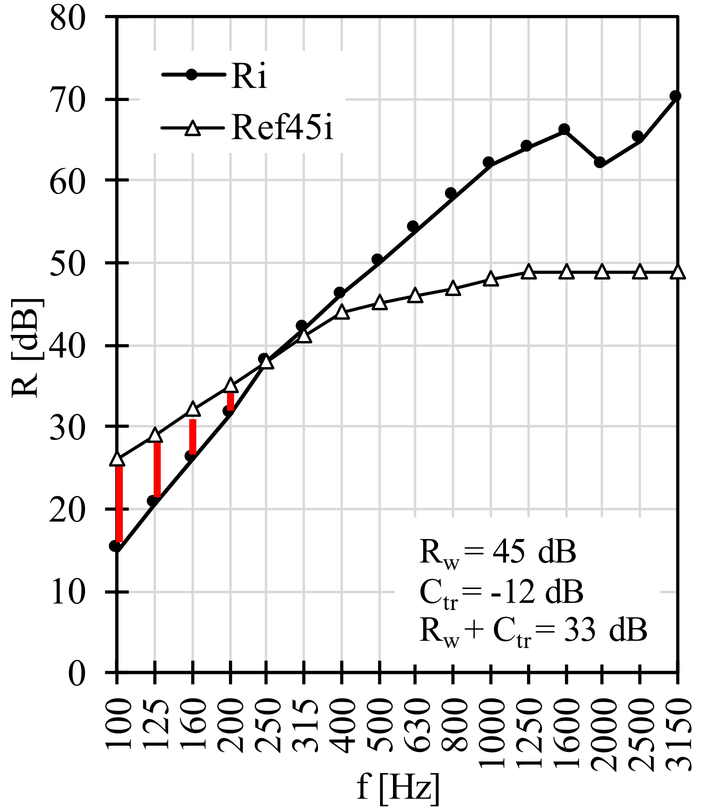




Weighted sound reduction index, R_w, and weighted sound reduction index against road traffic noise, $R_w + C_{tr}$

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.

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

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

$\mathbf{C_{tr} =}$ **-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 R [dB]

Single panels

- One material
- SRI is mainly explained by 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:
  - concrete-wool-concrete in facades
  - steel-wool-steel in facades
  - veneer-rubber-veneer in vehicles

Coupled multilayer constructions

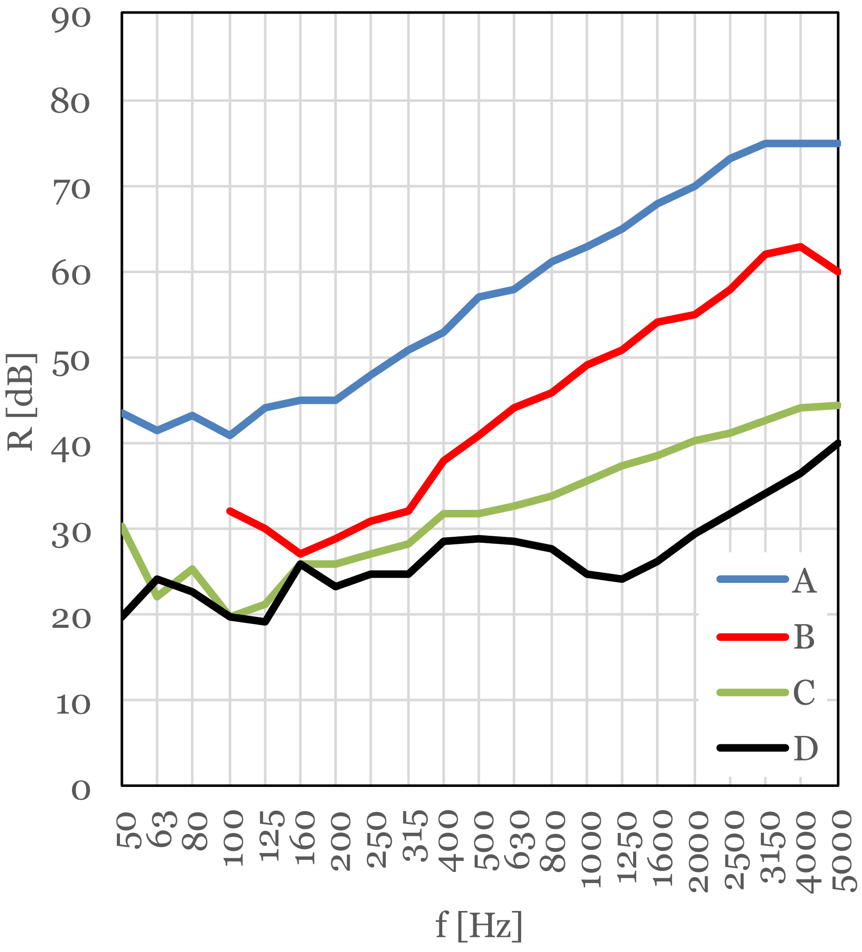
- Two layers separated by a cavity and equally distributed studs
- SRI is mainly explained by surface mass, cavity thickness and dynamic stiffness and density of studs
- Examples:
  - basic walls and floors
  - windows with two frames

Uncoupled multilayer constructions

- Two layers separated by cavity
- Separate studs for each layer: no mechanical sound bridges
- SRI is explained by surface mass, cavity thickness and cavity absorption
- Examples:
  - highly sound insulating 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



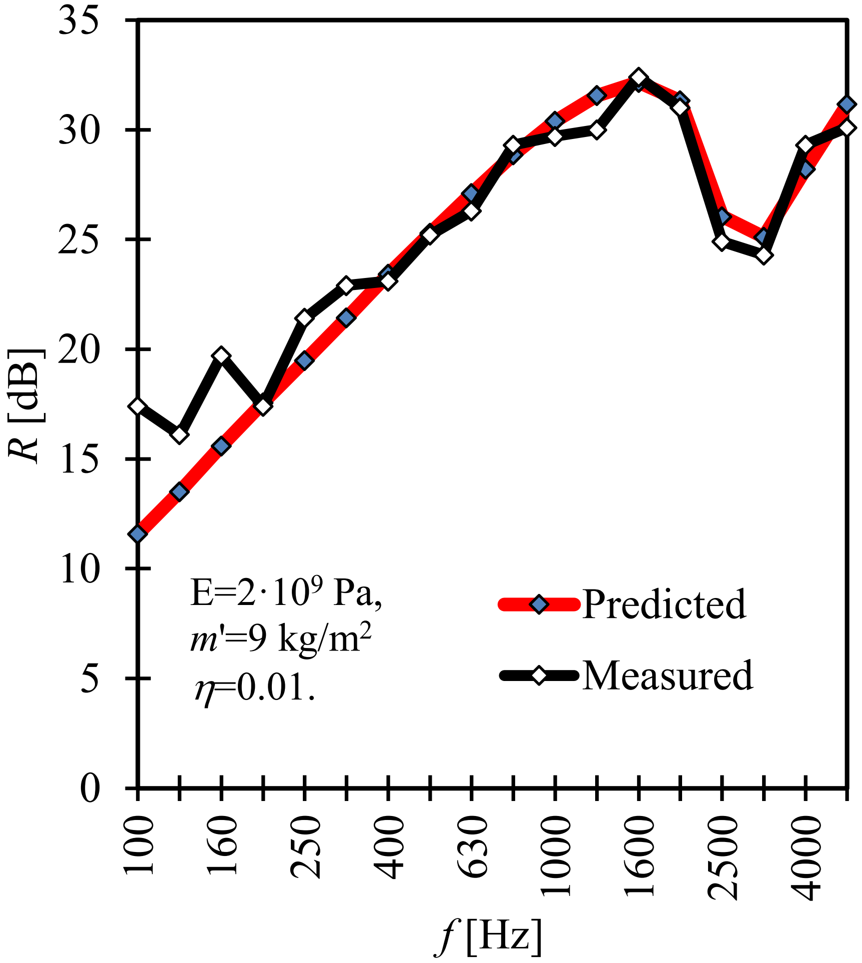
	A	B	C	D
m' [kg/m^2]	450	140	15.6	15
h [mm]	180	200	2	21
f_c [Hz]	100	160	>5000	1250
R_w [dB]	60	44	36	28

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' $[\mathrm{kg/m_2}]$
- 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, $\rho_0 = 1.204\ \mathrm{kg/m^3}$



Young's modulus E

Hooke's law:

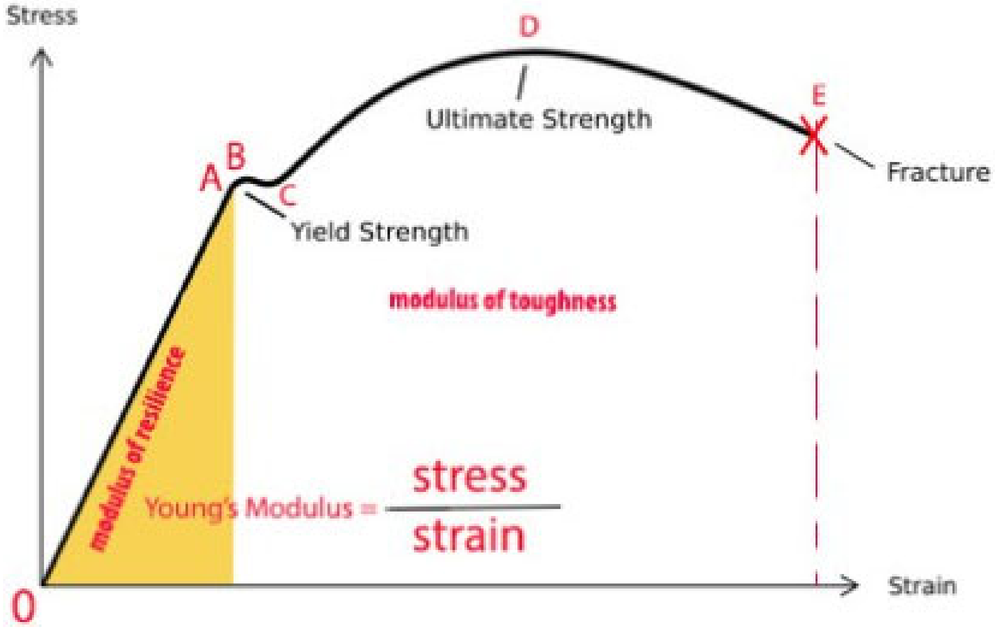
$$F = -kx$$

- 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

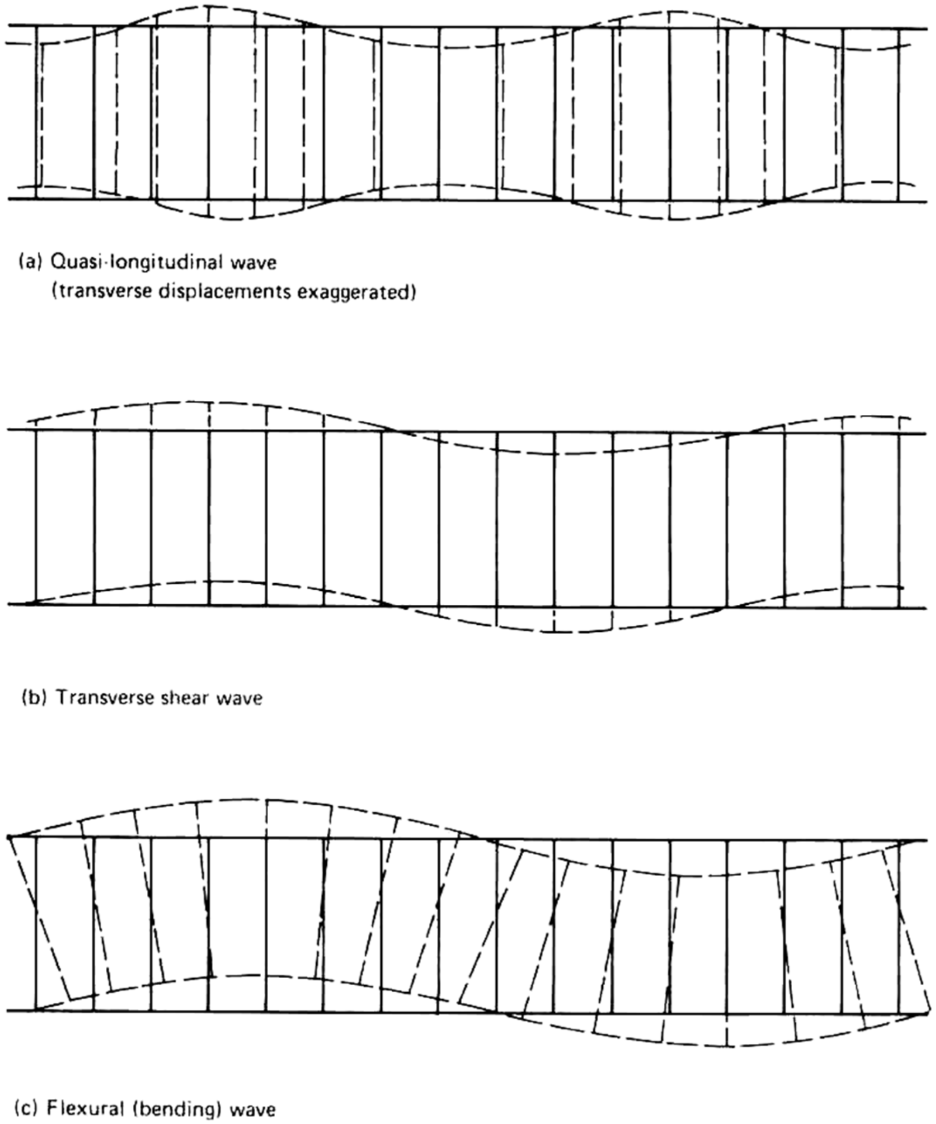
- **Thick panel**
  - $h > \lambda$
  - shear wave is dominating
  - independent on frequency

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

- **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


(a) Quasi-longitudinal wave
(transverse displacements exaggerated)

(b) Transverse shear wave

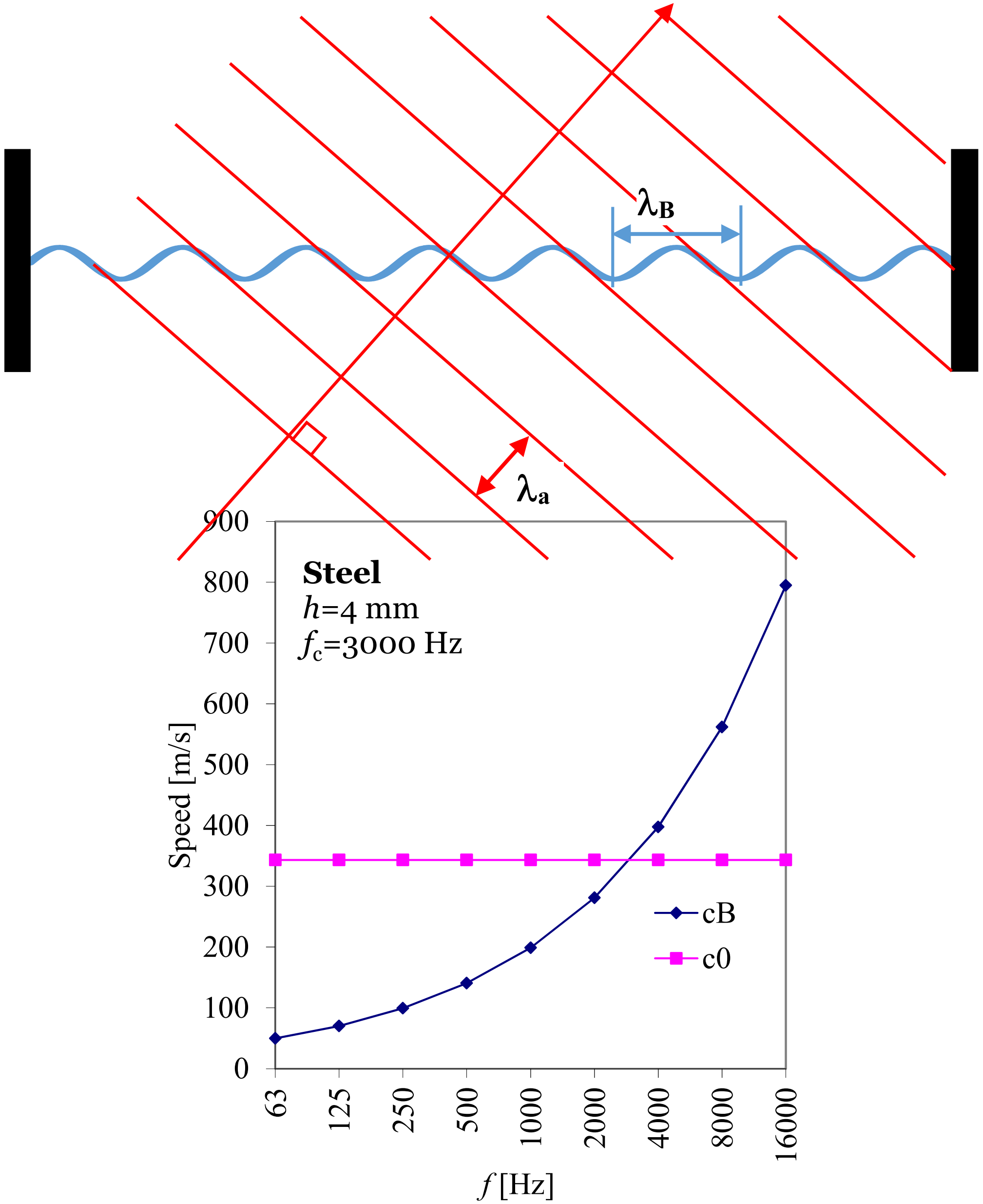
(c) Flexural (bending) wave

Figure: Fahy F (1985)

Coincidence

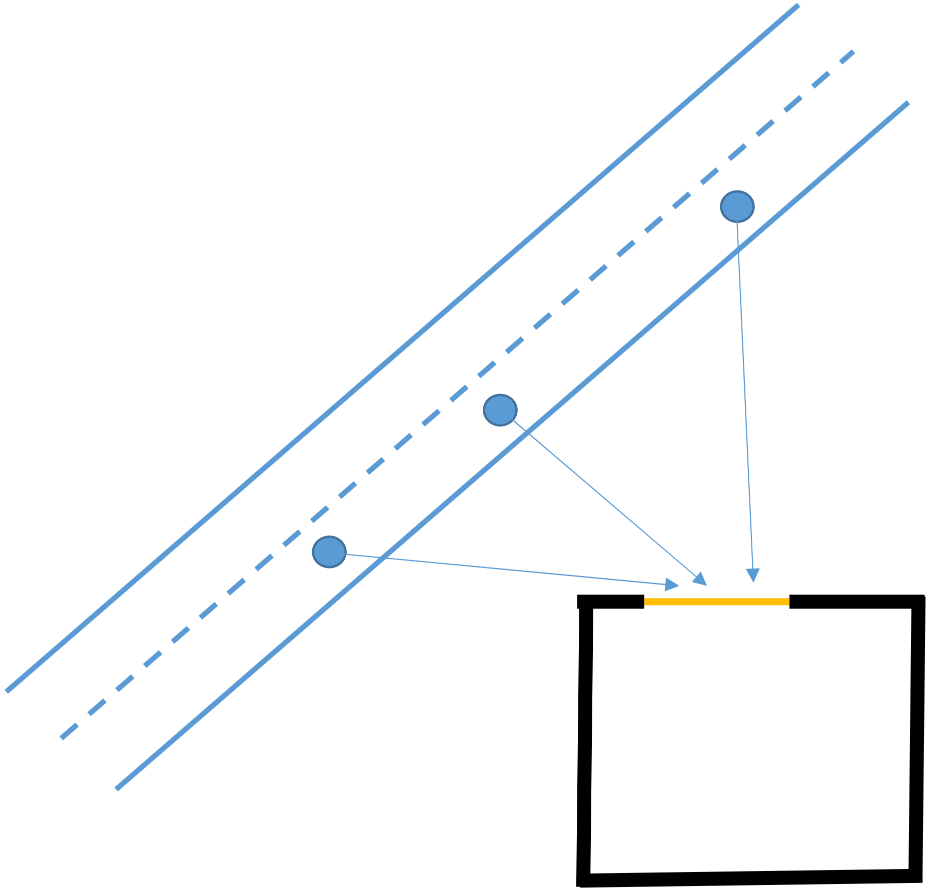
- Bending wave is dispersive: i.e. speed of sound depends on frequency
- Dispersion is the reason for the complexity of *R* calculations
- When the speed of bending wave in the panel equals with the speed of sound in air, coincidence phenomenon occurs.
- Sound insulation is nearly zero because the impedances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

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



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 $f < f_c$

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

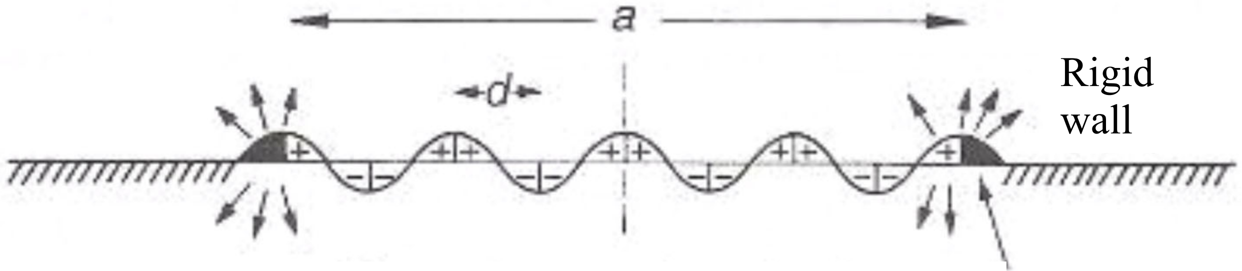
- **Thick heavy panels: $f_c \approx$ 100 Hz →** sound power radiated by the structure can be determined from the vibration velocity in the full frequency range (100-3150 Hz), since **$\sigma = 1$**.

- **Thin light panels: f_c 1000 - 3000 Hz →** vibration measurements cannot be used to predict sound emission

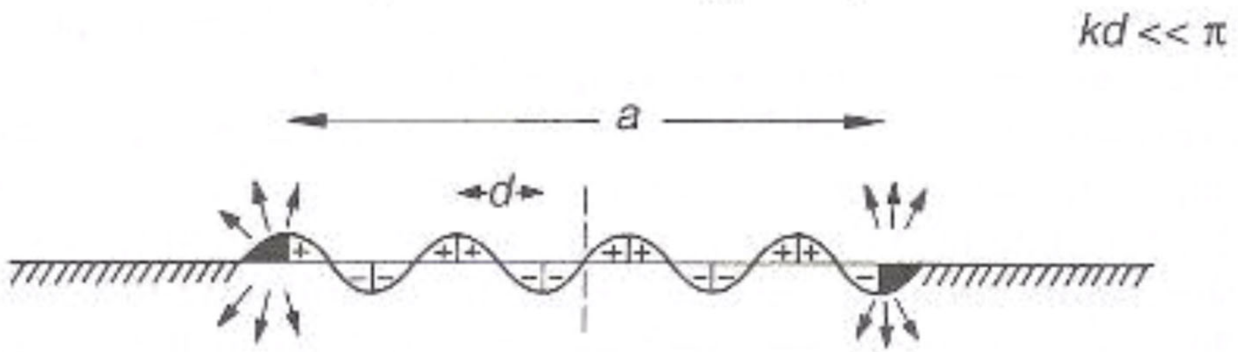
- σ is not used on the models of this chapter but it is a concept that should be known: for example: materials with σ=0 radiate very little flanking sound

Acoustic short circuit in the middle of the panel

- 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 is small)
- Corner modes and edge modes can radiate sound (σ is high)
- This is the situation under coincidence frequency $\boldsymbol{f}_c$: the radiation from the panel is weak and the radiation is dominated by corners or edges, depending on frequency, in a complex way
- Radiation efficiency σ is much below 1



Symmetric mode (odd number of peaks)



Antisymmetric mode (even number of peaks)

Fahy (1985)

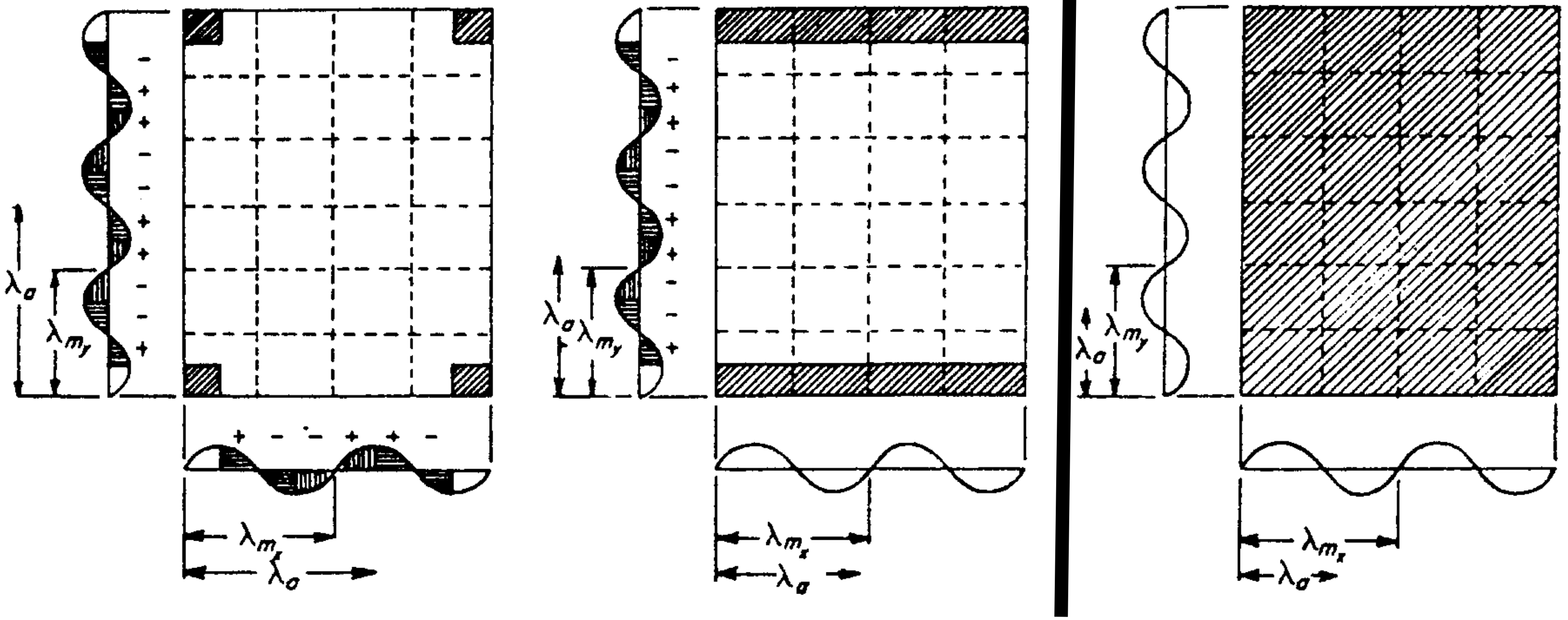
Forced vibration and resonant vibration

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
- $\sigma=1$
- R smaller than mass predicts

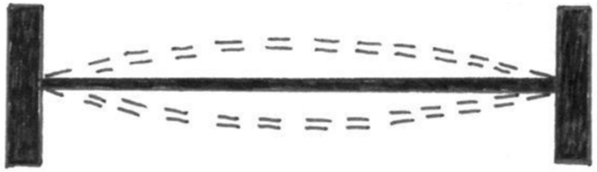


(a) (b) (c)

Fahy (1985) ??

Panel modes

Lowest axial horizontal mode ”10” (top view)



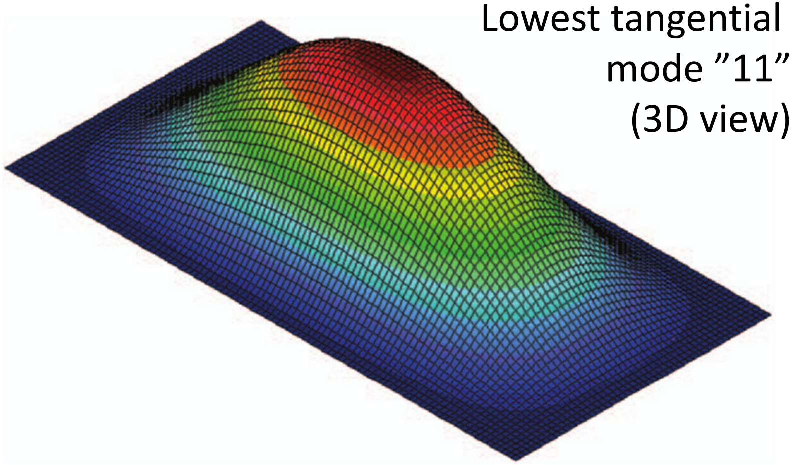
Lowest axial vertical mode ”10” (section view)

- 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 tangential mode ”11” (3D view)



4.2

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

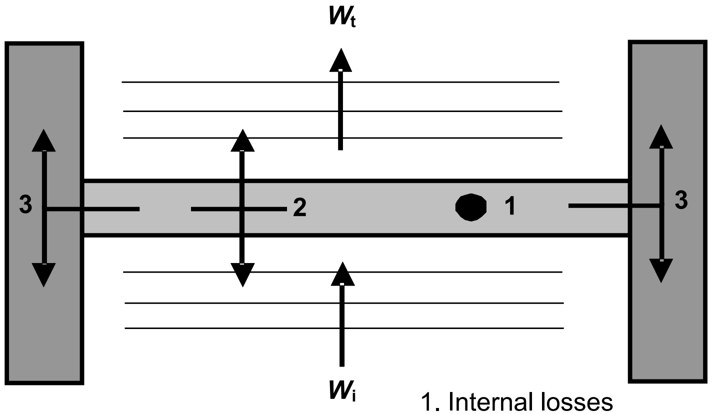
a) 600 mm

b) 400 mm.

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

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

Loss factor η



1. Internal losses
2. Radiation losses
3. Coupling losses

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

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

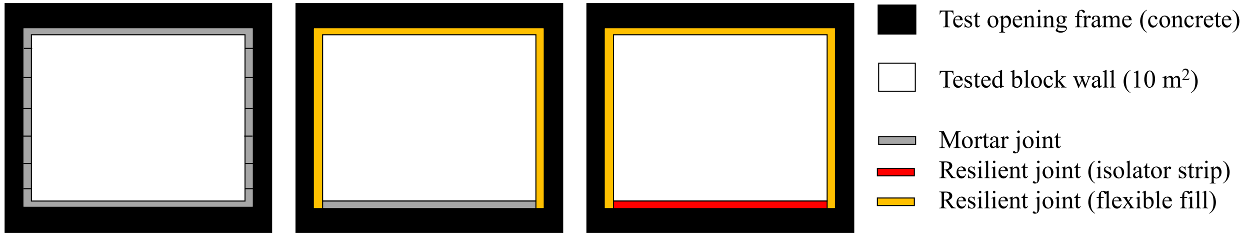
- Total loss factor involves three types of losses:
  1. internal losses
  2. radiation losses
  3. coupling losses
- Coupling losses determine the total loss factor for e.g. concrete structures
- Internal losses are important for e.g. sandwich structures

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

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

Effect of total loss factor on SRI

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



■ Test opening frame (concrete)

□ Tested block wall (10 m²)

▬ Mortar joint

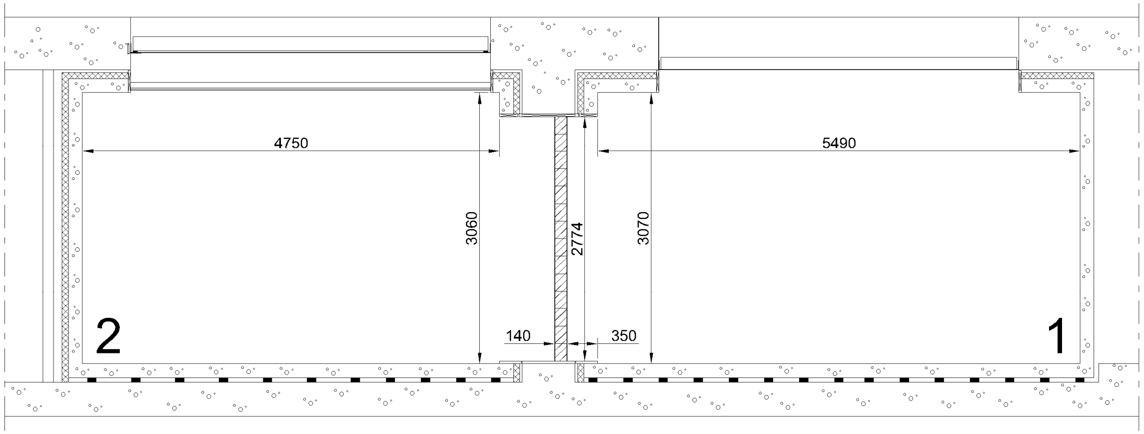
🟥 Resilient joint (isolator strip)

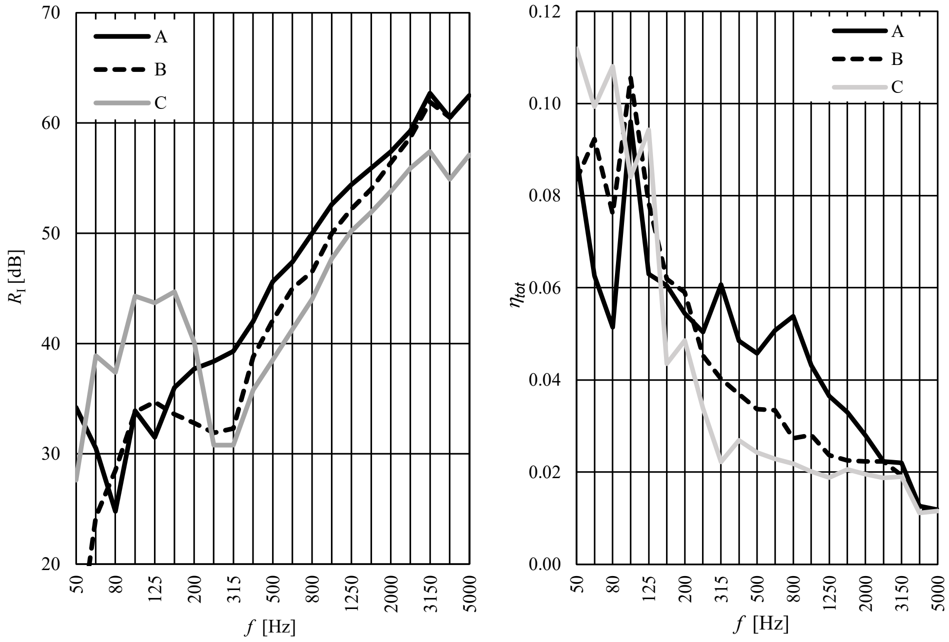
🟨 Resilient joint (flexible fill)

A.
All joints rigid

B.
Floor joint rigid,
other joints resilient

C.
All joints resilient.





- A block wall (220 kg/m², 140 mm, f_c=180 Hz) was built in laboratory using three different joint types
- Best sound insulation above 200 Hz was obtained using rigid joints. Why?

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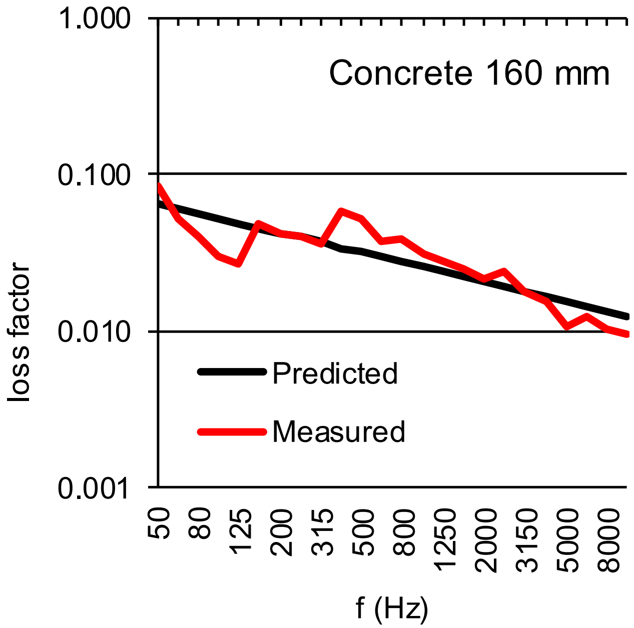
Loss factor

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

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



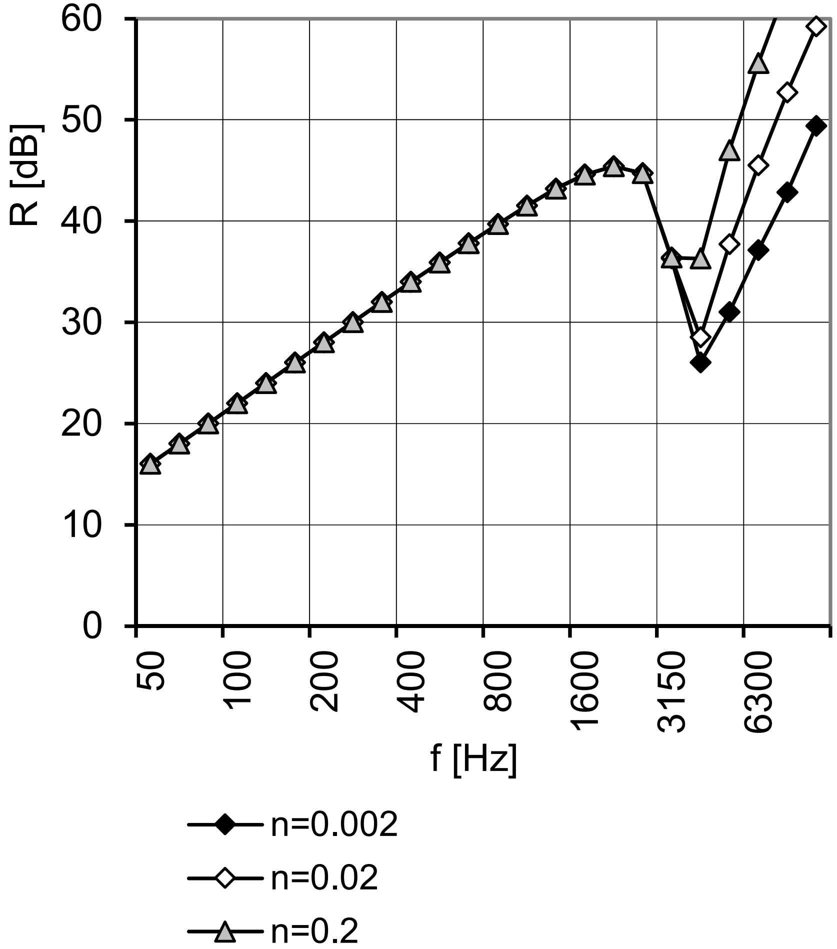
Material	Panel size	Mounting type	A	B	Reference
Leca brick 150 mm	5x4 m	Casted in the building	0.35	-0.40	Hongisto (2003) Työterveyslaitos
Concrete 180 mm	3x6 m	Casted in the building	0.50	-0.42	Hongisto (2003) Työterveyslaitos
Gypsum board 13 mm	1.2x2.2 m	Screwed against wood laths	0.04	-0.08	Hongisto (2003) Työterveyslaitos
Gypsum board, hard 13 mm	1.2x2.2 m	Screwed against wood laths	0.05	-0.10	Hongisto (2003) Työterveyslaitos
					Hongisto (2003) Työterveyslaitos
Steel 2 mm	1.2x2.2 m	Screwed against wood laths	1.66	-0.72	Hongisto (2003) Työterveyslaitos
Steel 4 mm	1.2x2.2 m	Screwed against wood laths	0.07	-0.25	Hongisto (2003) Työterveyslaitos
Steel 6 mm		Welded in a ship	0.41	-0.70	Pertti Hynnä, VTT, 2001
Steel		Welded in a rocket	0.18	-0.63	Troclet B (2000), NOVEM, Lyon, France.

Hongisto (2003) Työterveyslaitos

Thin panel - the effect of constant loss factor

- Calculated by previous model
- Material
  - 4 mm steel
  - loss factor 0.02 (modified here)
  - 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

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

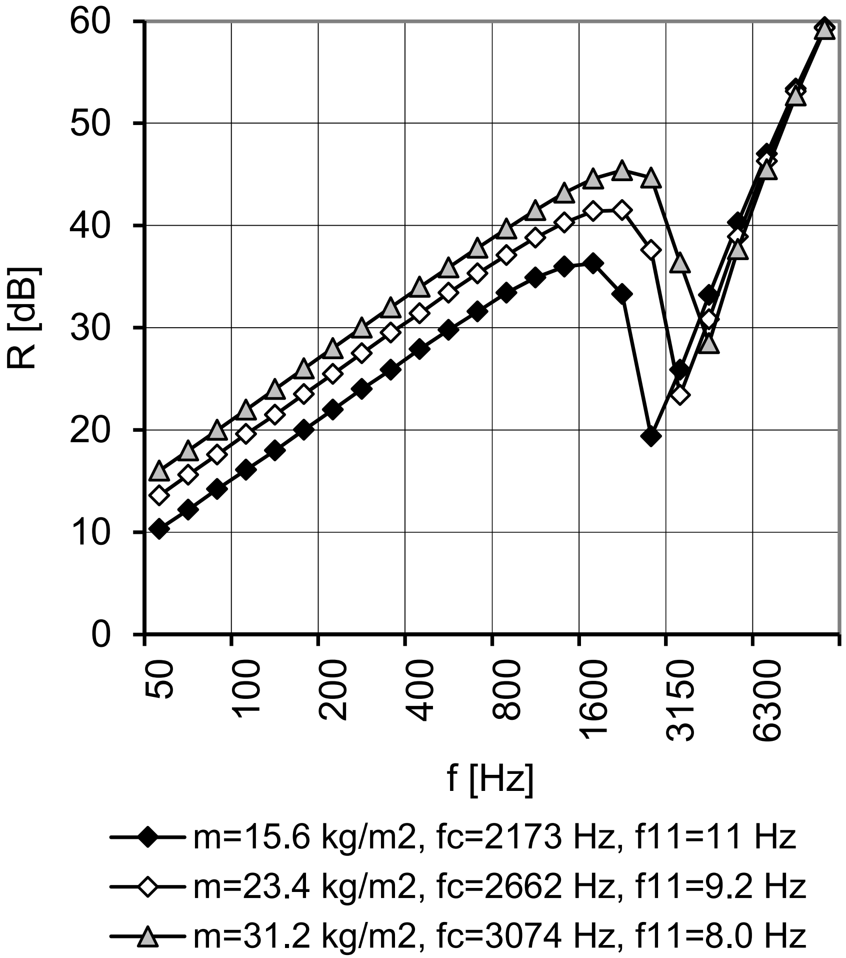


Hongisto (2003) Työterveyslaitos

Thin panel - the effect of 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
  - m’=31.2 kg/m^2 (modified)
  - E=2E11 Pa

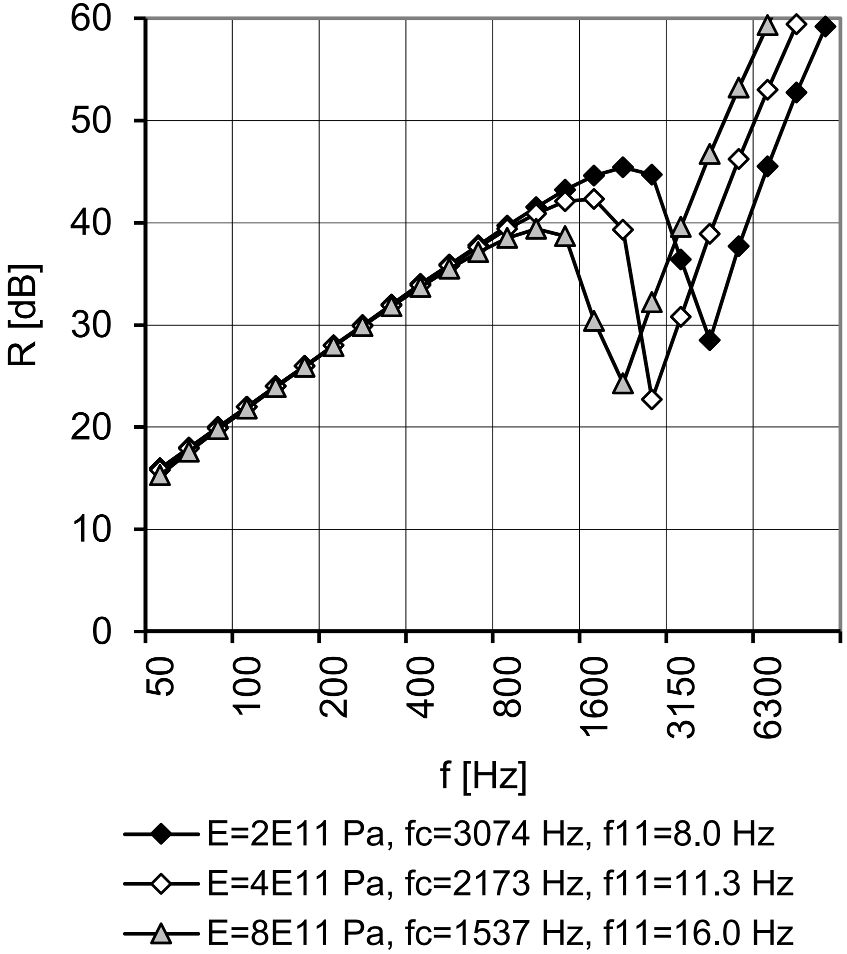
$$R = \begin{cases} 20 \cdot \log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 20 \cdot \log_{10}\left(1 - \left(\dfrac{f}{f_c}\right)^2\right) - 5, & f < f_c \\ 20 \cdot \log_{10}\left(\dfrac{\pi m' f}{\rho_0 c_0}\right) + 10 \cdot \log_{10}\left(\dfrac{2\eta f}{\pi f_c}\right), & f \geq f_c \end{cases}$$



Hongisto (2003) Työterveyslaitos

Thin panel - the effect of Young’s modulus

- 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
  - m’=31.2 kg/m^2
  - E=2E11 Pa (modified)

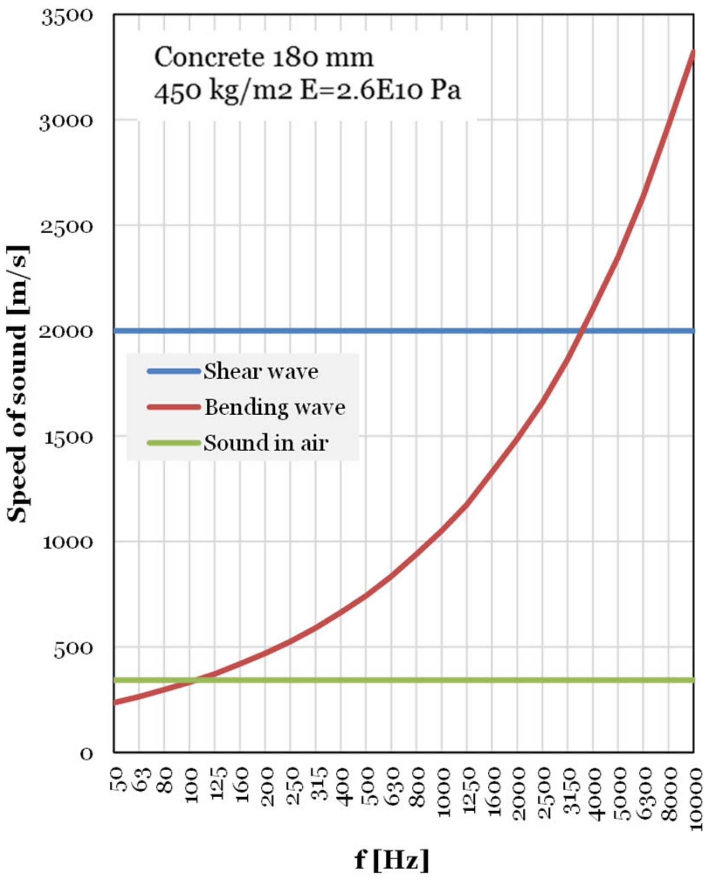


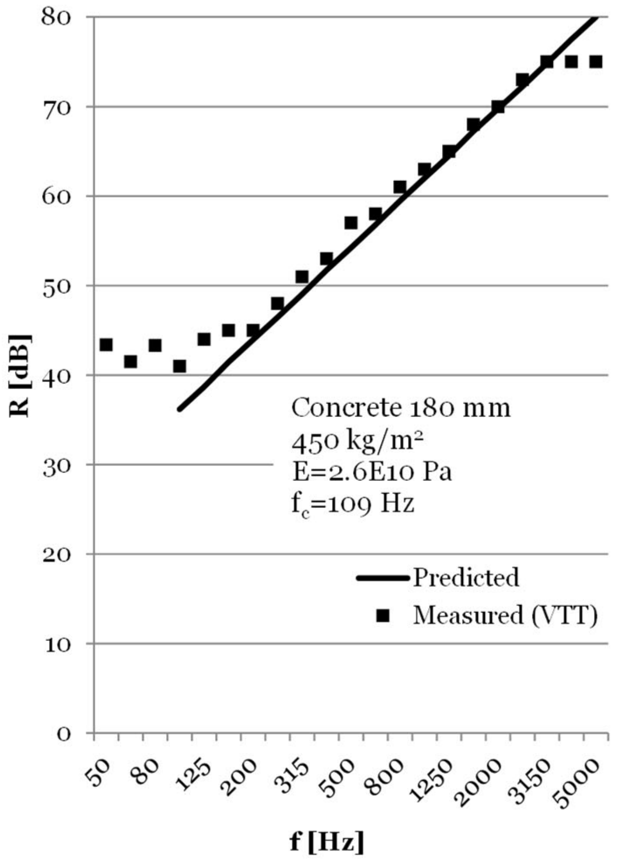
Hongisto (2003) Työterveyslaitos

Thick heavy panel

- The SRI of thin panels can be completely explained by *bending waves* below 5 kHz
- When the panel thickness *h* exceeds 1/6 of the wavelength of bending wave λ_B, *shear waves* begin to dominate sound radiation and determine the SRI.
  - SRI becomes frequency independent since c_S is constant while c_B is not
- Figure shows a prediction using only bending waves: ignorance of shear waves seems not lead major overestimation of SRI.

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

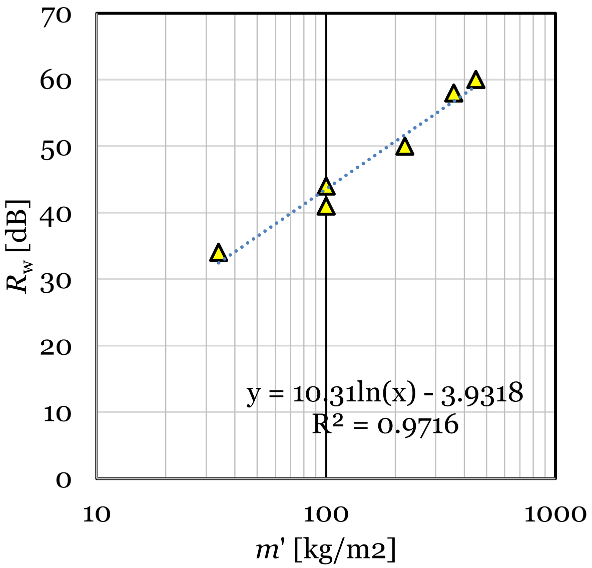


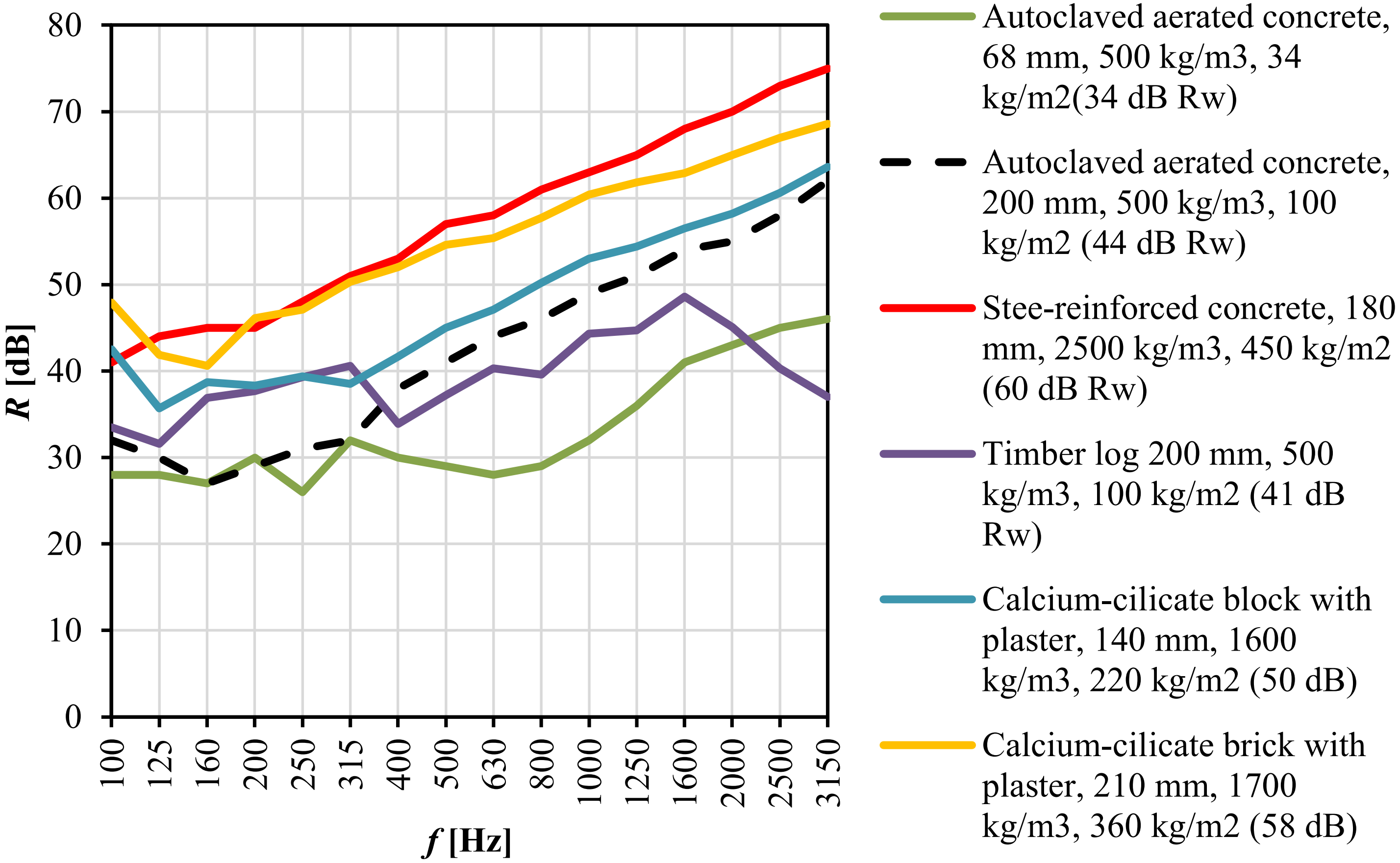


$$\eta(f) = A f^{B}$$

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

Examples of some heavy constructions

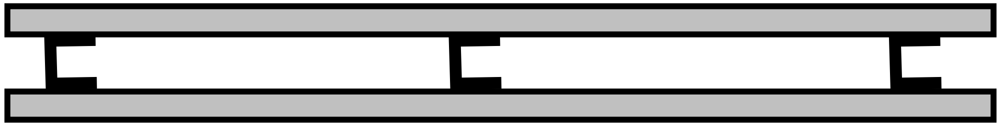




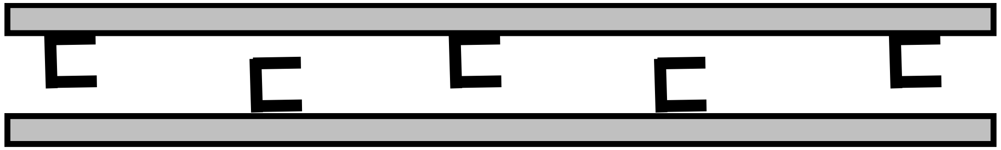
- R_w is linearly associated with logarithmic *m'*

Double constructions

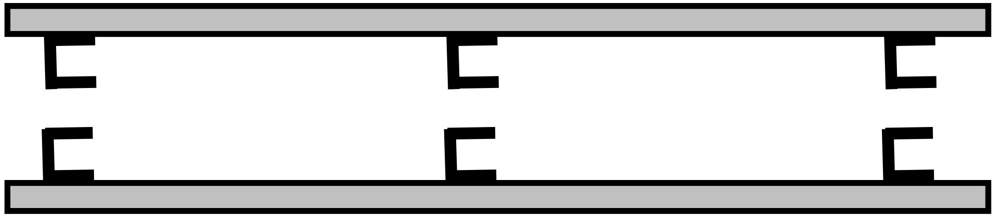
- Single studs (fully coupled)



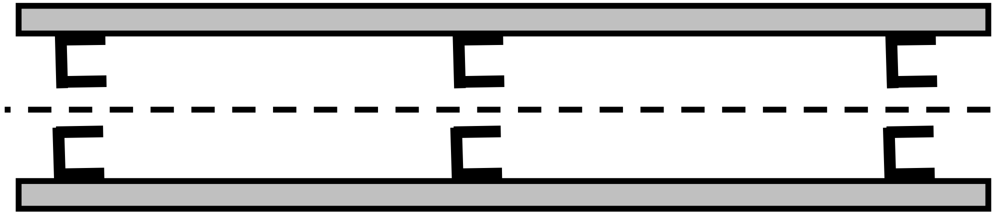
- Staggered studs (partially uncoupled, since common rails exist on top and bottom of the wall)



- Separate studs (uncoupled)

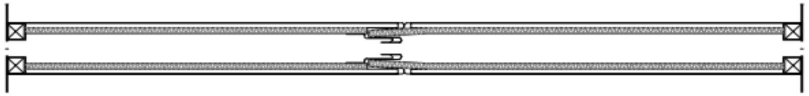


- Separate studs with structural break (uncoupled)

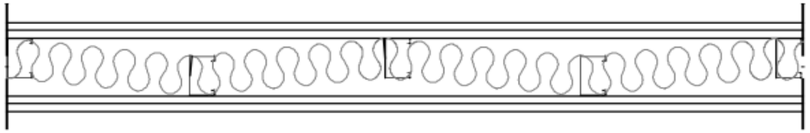


Examples of uncoupled double constructions

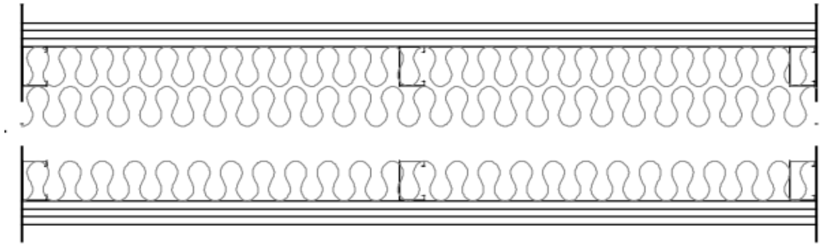
- A: Ship cabin wall

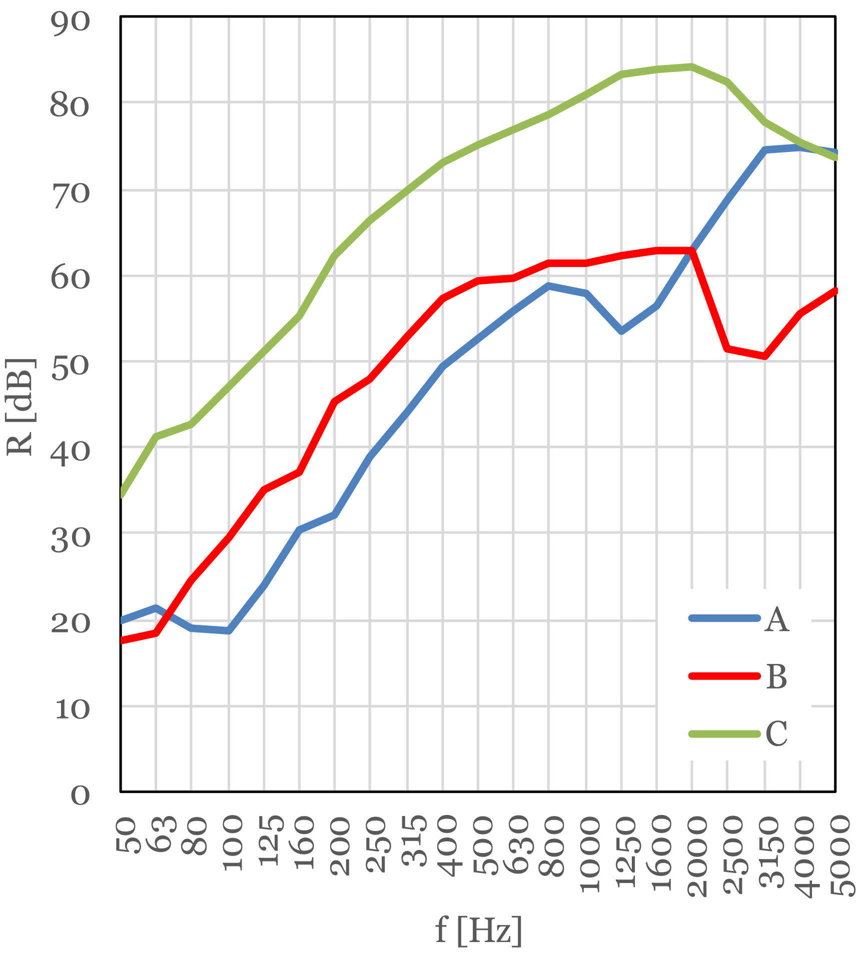


- B: Double wall, staggered studs, common rails
  - 95/66 k600 (4xGN13) M95



- 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

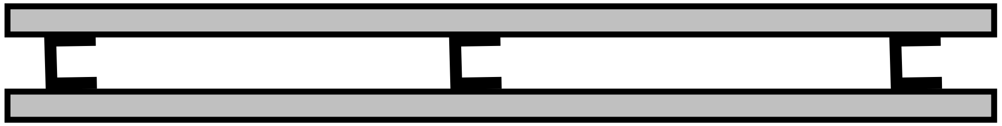
Double construction – 4 steps of prediction

- 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), either R_{cI} or R_{c2}
  - R_b [dB] is SRI through the sound bridges (stud path), either R_{bI} or R_{b2}

- The weaker path dominates.
- Four steps:
  1. Cavity path, perfect absorption, R_{cI}.
  2. Cavity path, non-perfect absorption, R_{cI}.
  3. Stud path, rigid studs, R_{bI}.
  4. Stud path, flexible studs, R_{bII}.

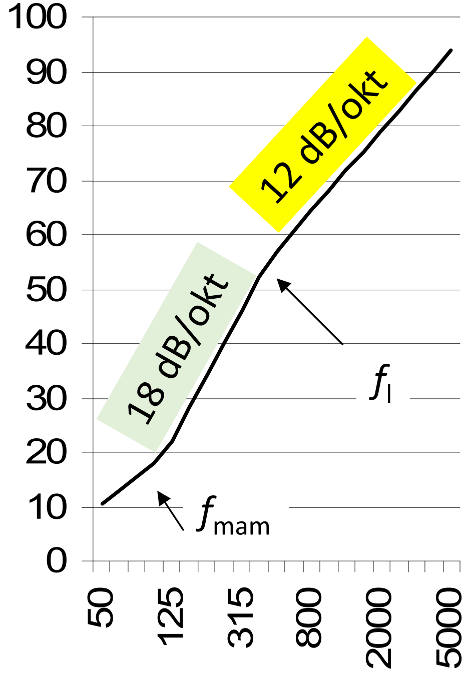


R_{cI}

- 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_{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]
R_1 and R_2 can be measured or predicted.
Layer 1 can also be a double construction in a triple-panel construction.

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

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

Mass-air-mass resonance, f_{mam}

- The resonance is caused 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

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

- 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

4.3

Calculate the mass-air-mass resonance frequency for the following double panel constructions.

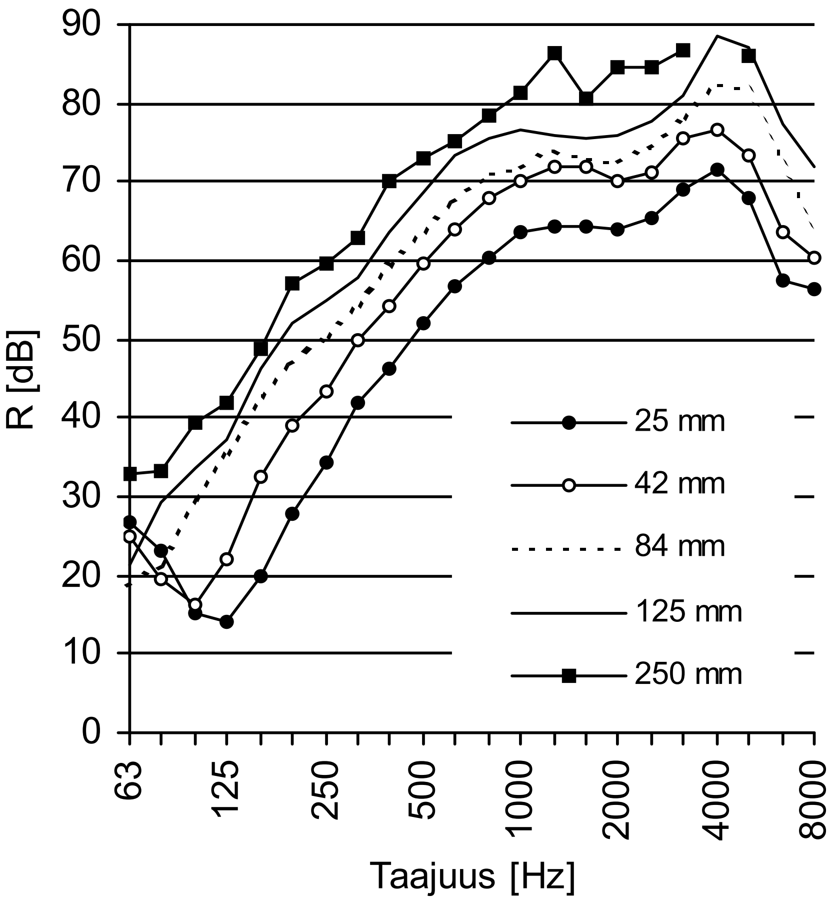
	d [m]	m' [kg/m2]	d [m]	f_{mam} [m]
1 x gypsum 13 mm - cavity 66 mm - 1 x gypsum 13 mm				
3 x gypsum 13 mm - cavity 175 mm - 3 x gypsum 13 mm				
1 x glass 4 mm - cavity 12 mm - 1 x glass 4 mm				

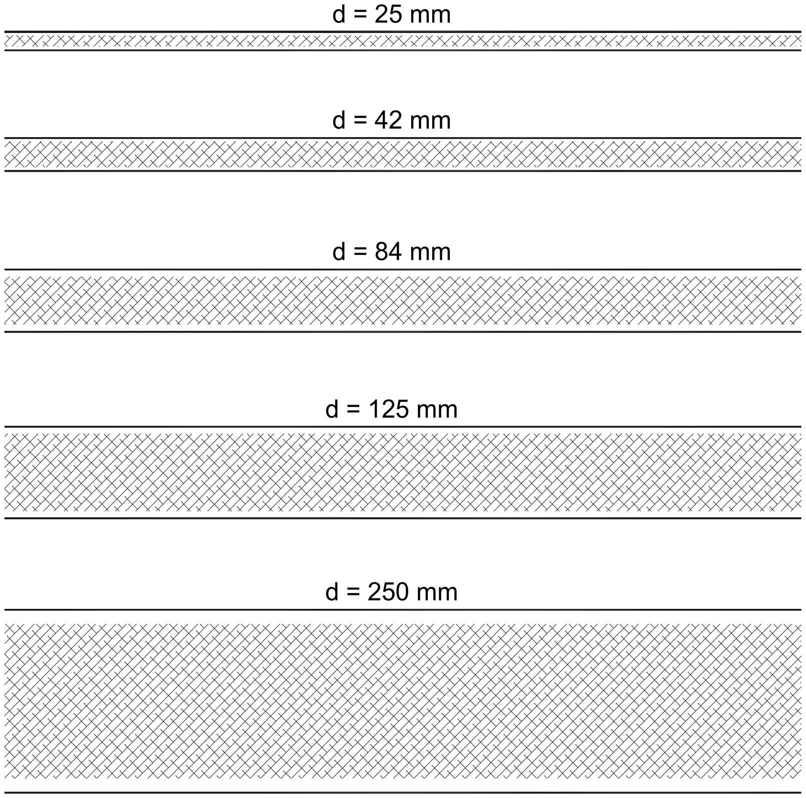
$$f_{mam} = 80\sqrt{\frac{(m'_1 + m'_2)}{dm'_1\, m'_2}} \approx 80\sqrt{\frac{1}{dm'}}$$

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

Structure

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





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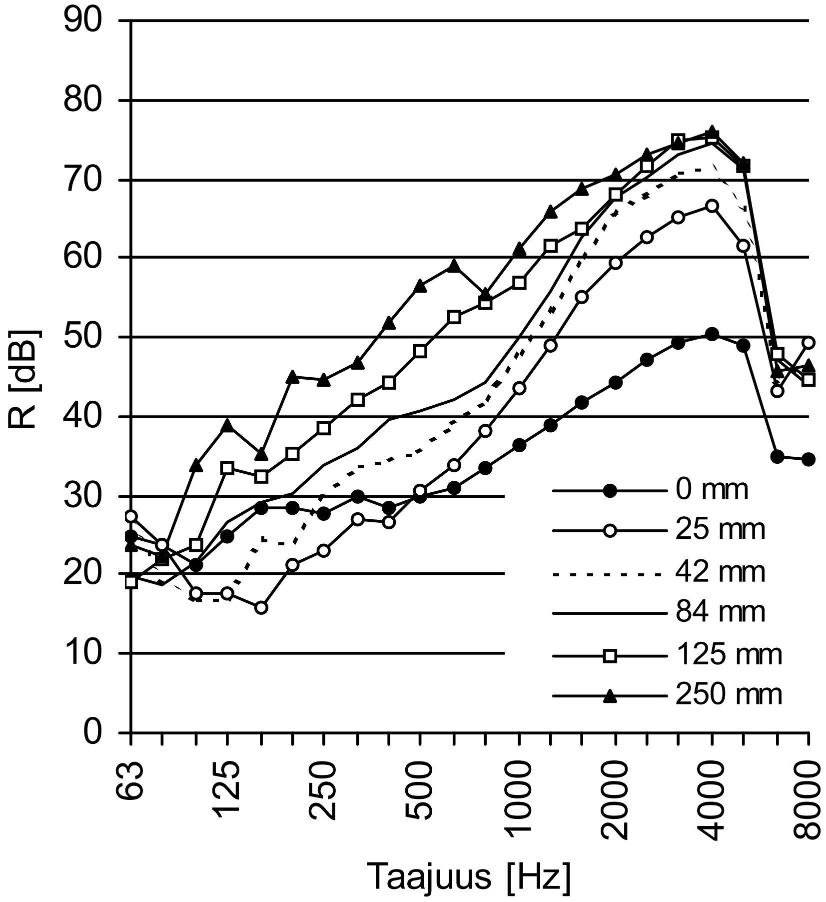
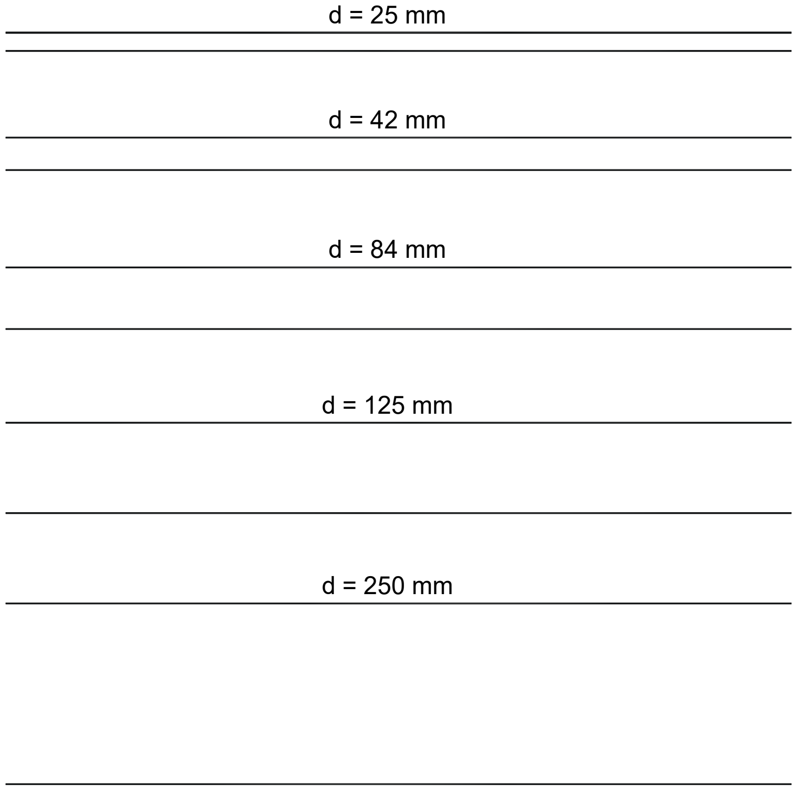
Effect of cavity thickness, uncoupled double panel, empty cavity

Structure

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





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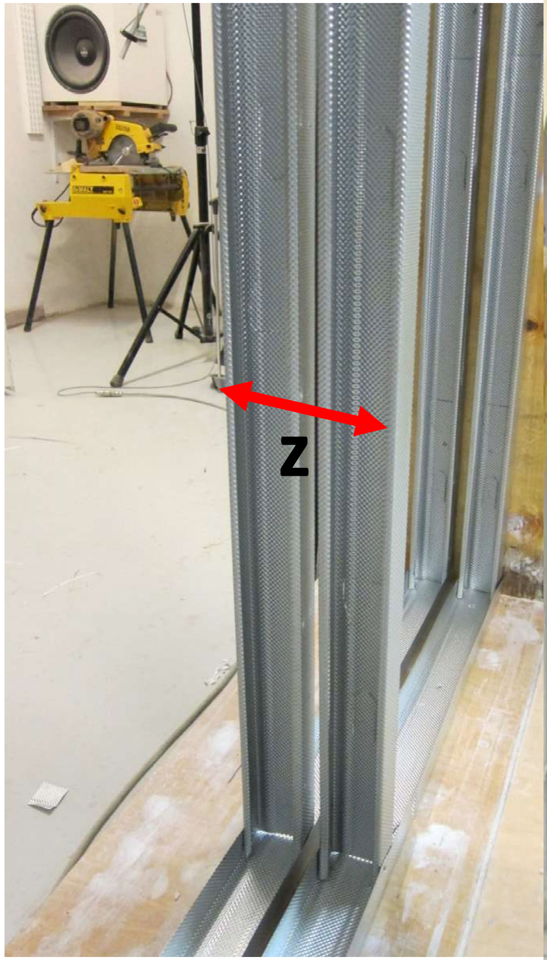
Coupled

- Rails against ceiling and floor
- Studs are vertical, division b=300 mm
- Studs and rails equally thick (common rails)

Uncoupled

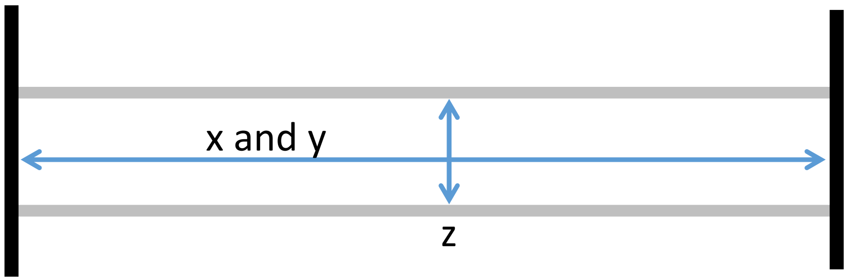
- Double studs on separate rails

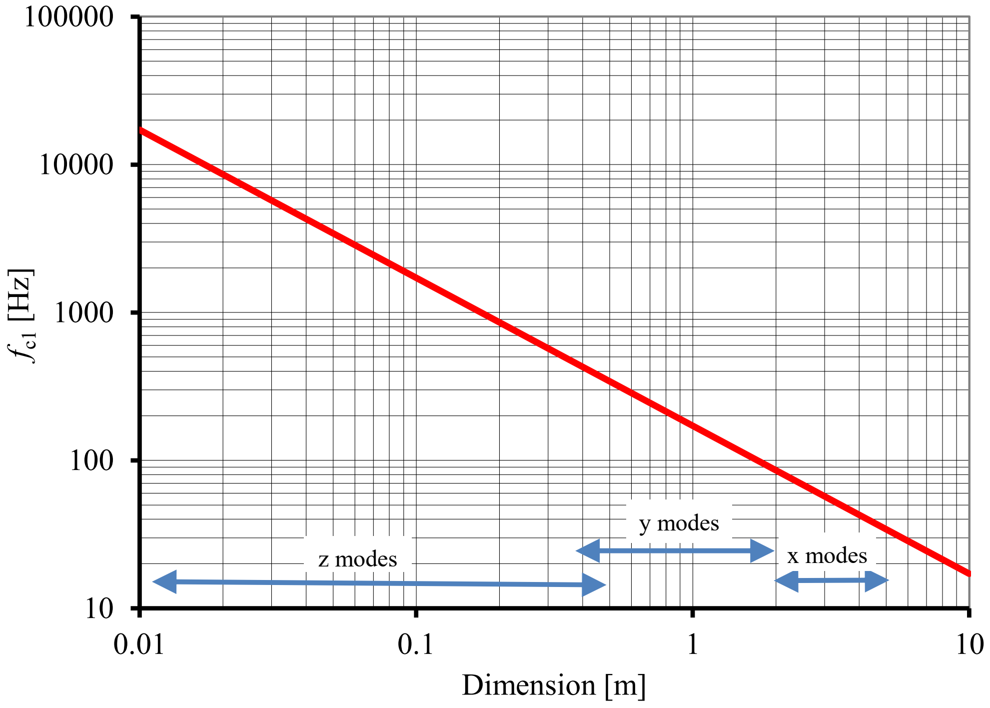


Reverberation of the cavity

- 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 => <u>Under 100 Hz</u>
- Horizontal modes between the studs (y)
  - Horizontal distance between studs, $L_{y,ca}$ [m]
  - Usual stud distances are 300 – 1200 mm => <u>100-800 Hz</u>
  - 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
- Lower modes: modes in x or y dimensions
  - Strong impact on sound insulation at middle and frequencies if the cavity does not contain absorbents
- Higher modes: modes in z direction
- The lowest cavity mode, $f_{ca,100}$, exists at:

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





R_{cII}

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

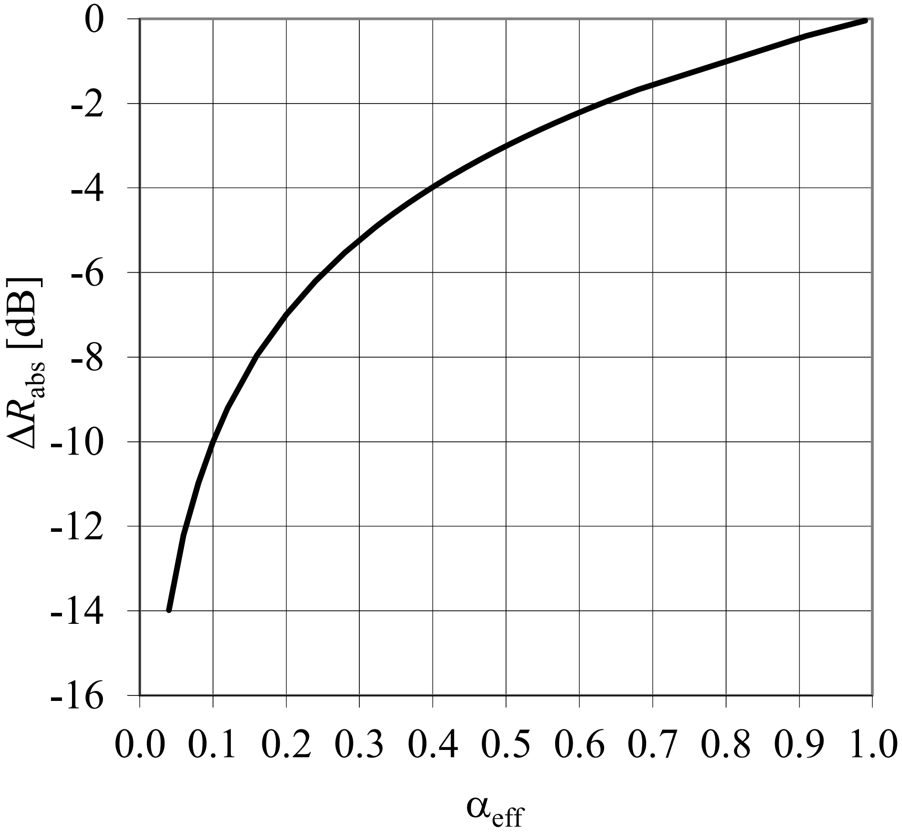
$$R_{cII} = R_{cI} + \Delta R_{abs}$$

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

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

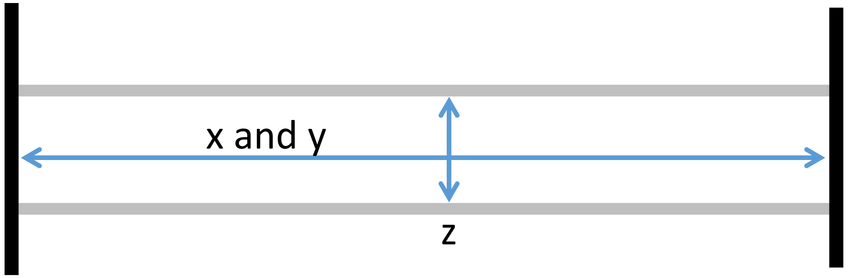
  - α_{ca} = absorption coefficient of the cavity material
  - FR = filling ratio of cavity (0...1)
- Empty cavity has seldom a value under α_{ca}=0.04. The effect of cavity thickness d is estimated for empty cavities by

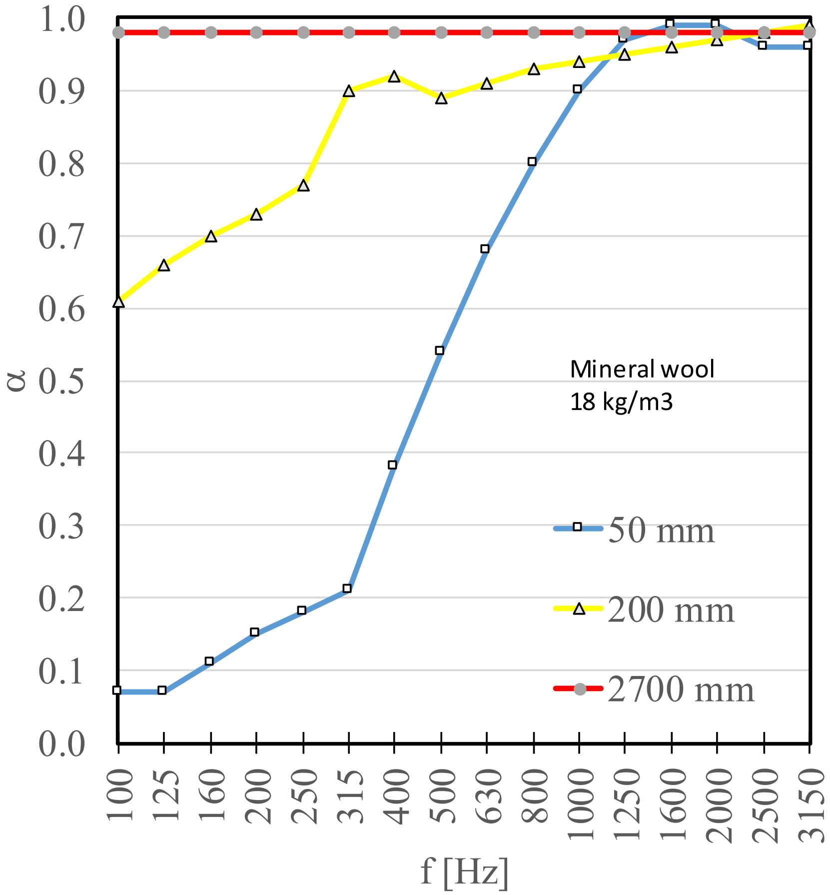
$$\alpha_{eff} = \begin{cases} 0.5, & d \leq 0.02\,\mathrm{m} \\ 0.01/d, & d > 0.02\,\mathrm{m} \end{cases}$$



α_{ca}

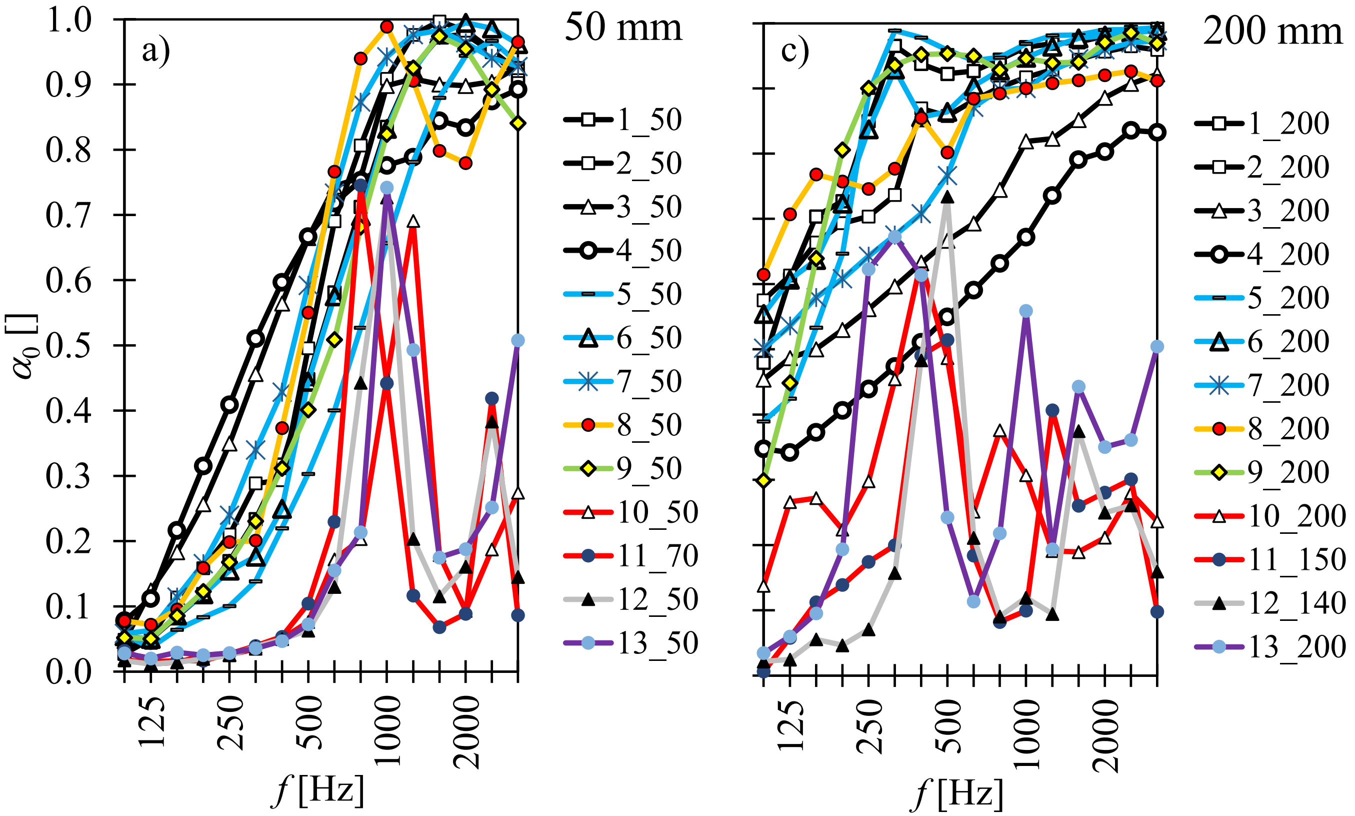
- Sound absorption coefficient of absorption board is usually reported for perpendicular or random sound incidence (α_0 or α_S).
- However, the sound field in the cavity is always parallel to the board below the limit frequency f_d. Perpendicular sound field comes to play above f_d. Because the thickness of sound absorbent parallel to the board is the same as room height or stud spacing, the absorption coefficient is much larger at low frequencies than that obtained perpendicular to the surface because low frequency absorption increases with increasing material thickness.
- Therefore, if $\alpha =$ X above f_d, is is safe to assume $\alpha_{ca} =$ X also at low frequencies.





Hard, non-porous thermal insulators

- Materials with connected pores absorb sound well.
- Materials with unconnected pores are worse.



	Product type (material)	λ [W/mK]	ρ [kg/m^3]
1	ultra low density stone wool slab	0.044	25
2	low density stone wool slab	0.036	25
3	medium density stone wool slab	0.033	75
4	high density stone wool slab	0.037	100
5	ultra low density glass wool roll	0.042	11
6	low density glass wool slab	0.035	16
7	medium density glass wool slab	0.033	70
8	cellulose slab	0.039	37
9	wood fiber slab	0.038	50
10	expanded polystyrene board	0.036	18
11	polyisocyanurate board	0.022	30
12	phenolic foam board	0.020	30
13	cellular glass board	0.036	100

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Cavity absorption

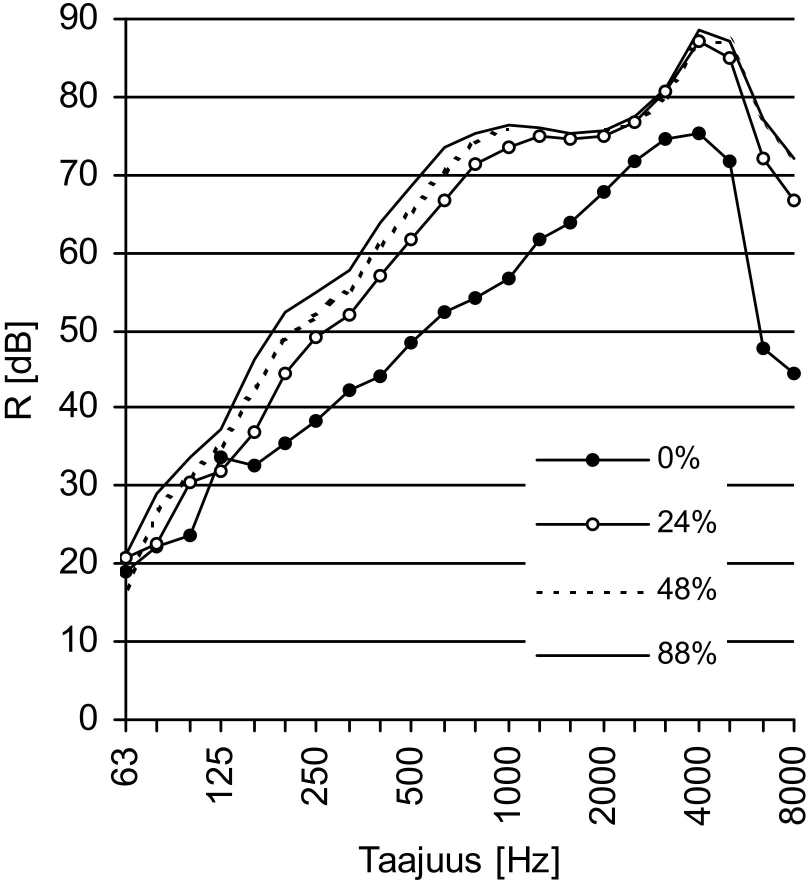
- Absorption can be achieved by many ways
  - full absorption
  - partial absorption
  - strip absorption
  - edge absorption
- Simple validated prediction models for different alternatives do not exist.
- Edge absorption (in Figure) does not eliminate the modes in z direction

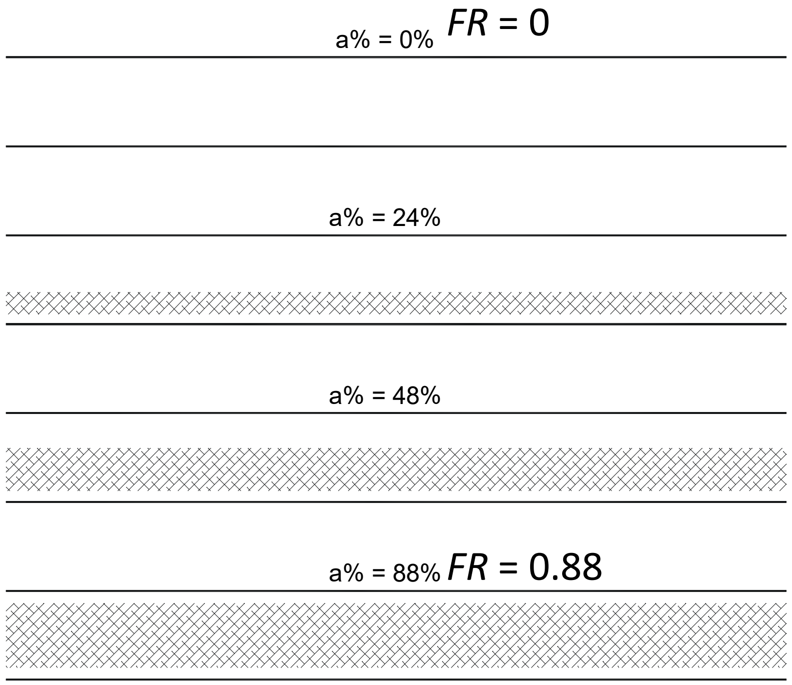
Effect of filling ratio, FR, in an uncoupled double structure

Structure

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

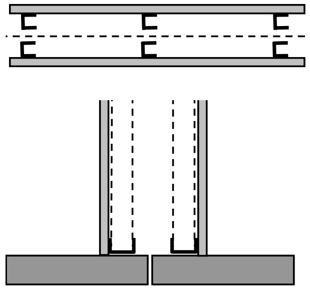
- The specimen size was 2.1x1.1 m, so the lowest cavity mode was f_{c1}=78 Hz.



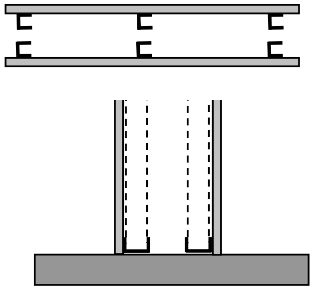


Hongisto ym. 2002 Työterveyslaitos
Hongist et al. 2002 Acta Acust united Ac

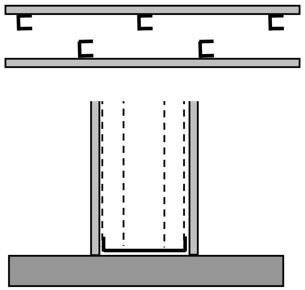
A study of studs and rails



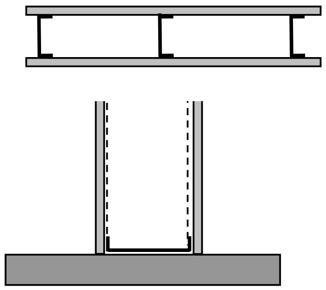
Separate rails
Double studs
Construction joint



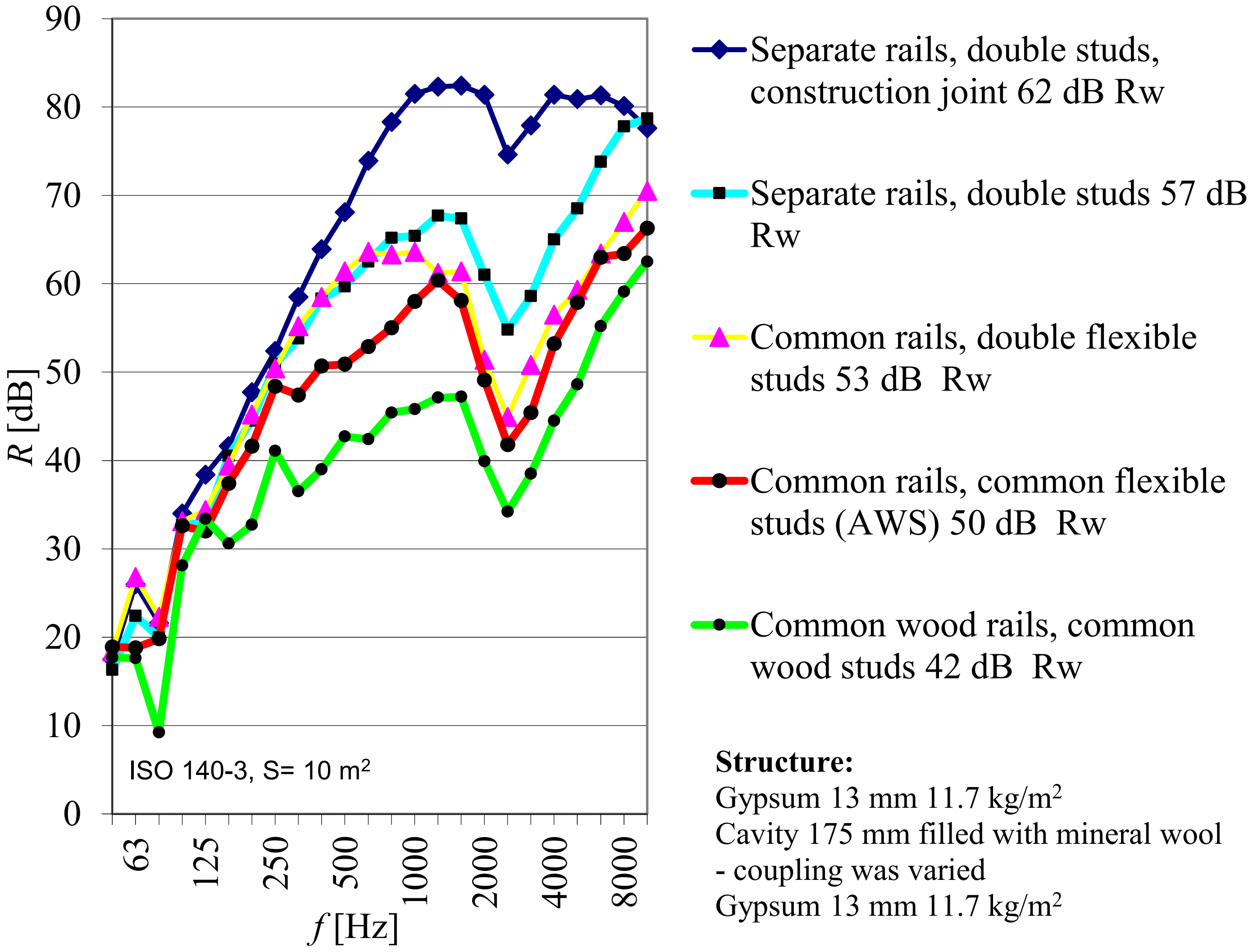
Separate rails
Double studs



Common rails
Double studs



Common rails
Common studs



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

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

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

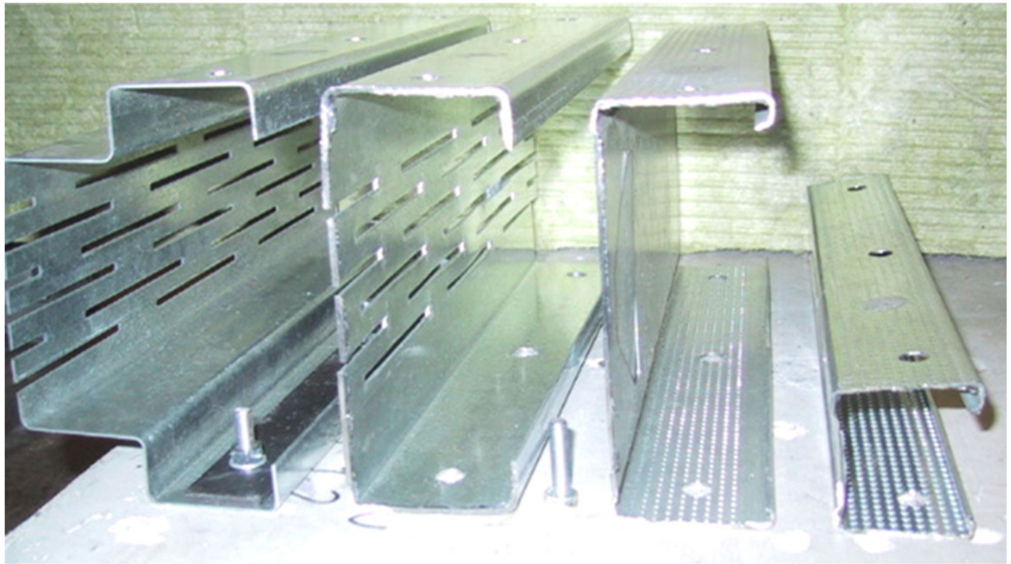
$$f_{cL} = \left[\frac{m'_1\sqrt{f_{c2}} + m'_2\sqrt{f_{c1}}}{m'_1 + m'_2}\right]^2$$

- 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

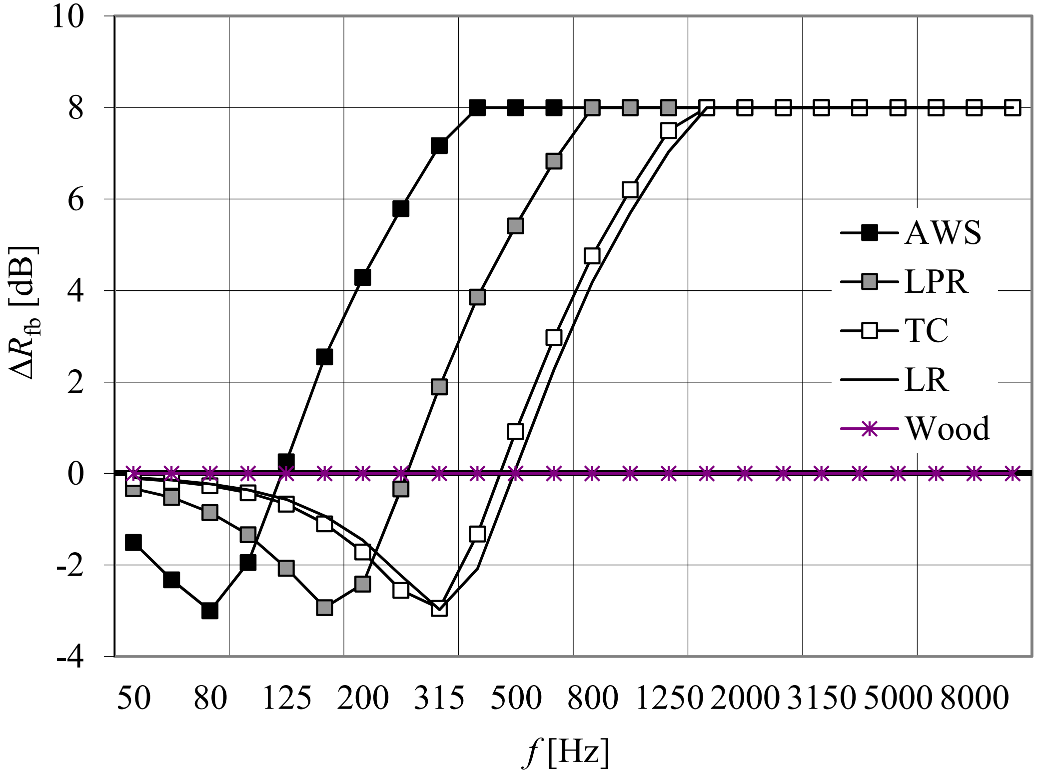
$$\Delta R_b = 10 \cdot \log_{10}\left(\frac{S\pi^3 f_{cP}^2}{N 8 c_0^2}\right) = 10 \cdot \log_{10}\left(\frac{S f_{cP}^2}{N}\right) - 45$$

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

Feasible predictions of ΔR_{fb}



- 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)



R_{bII}

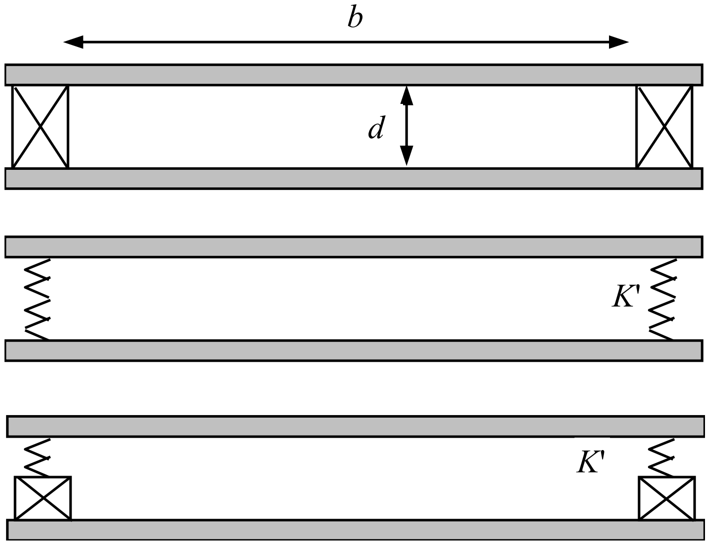
- Flexible stud is a spring. Its effect on R can be modeled by adding the vibration reduction index, ΔR_{fb}, to the rigid stud value, R_{bI}:

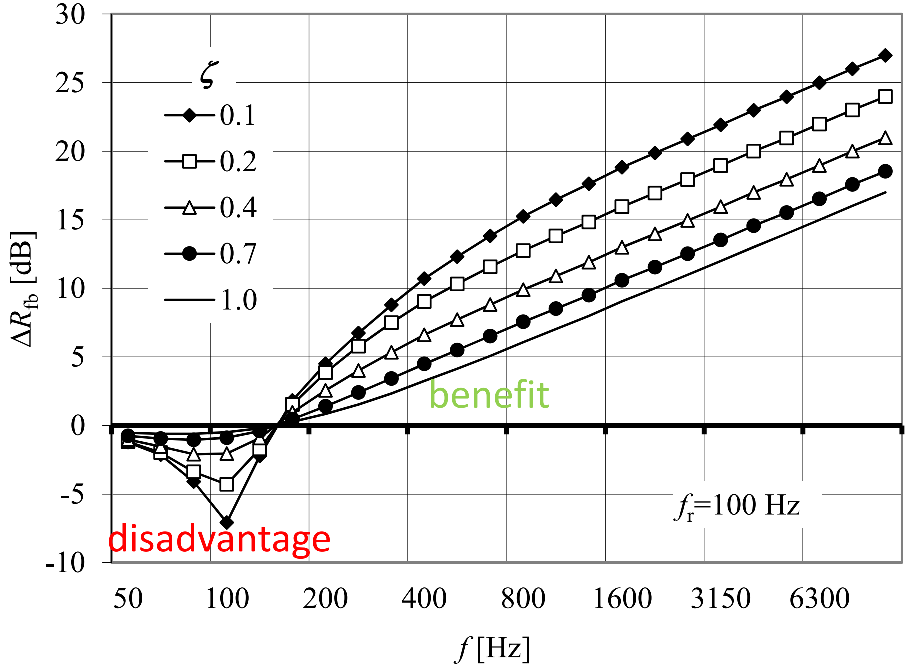
$$R_{bII} = R_{bI} + \Delta R_{fb}$$

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

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

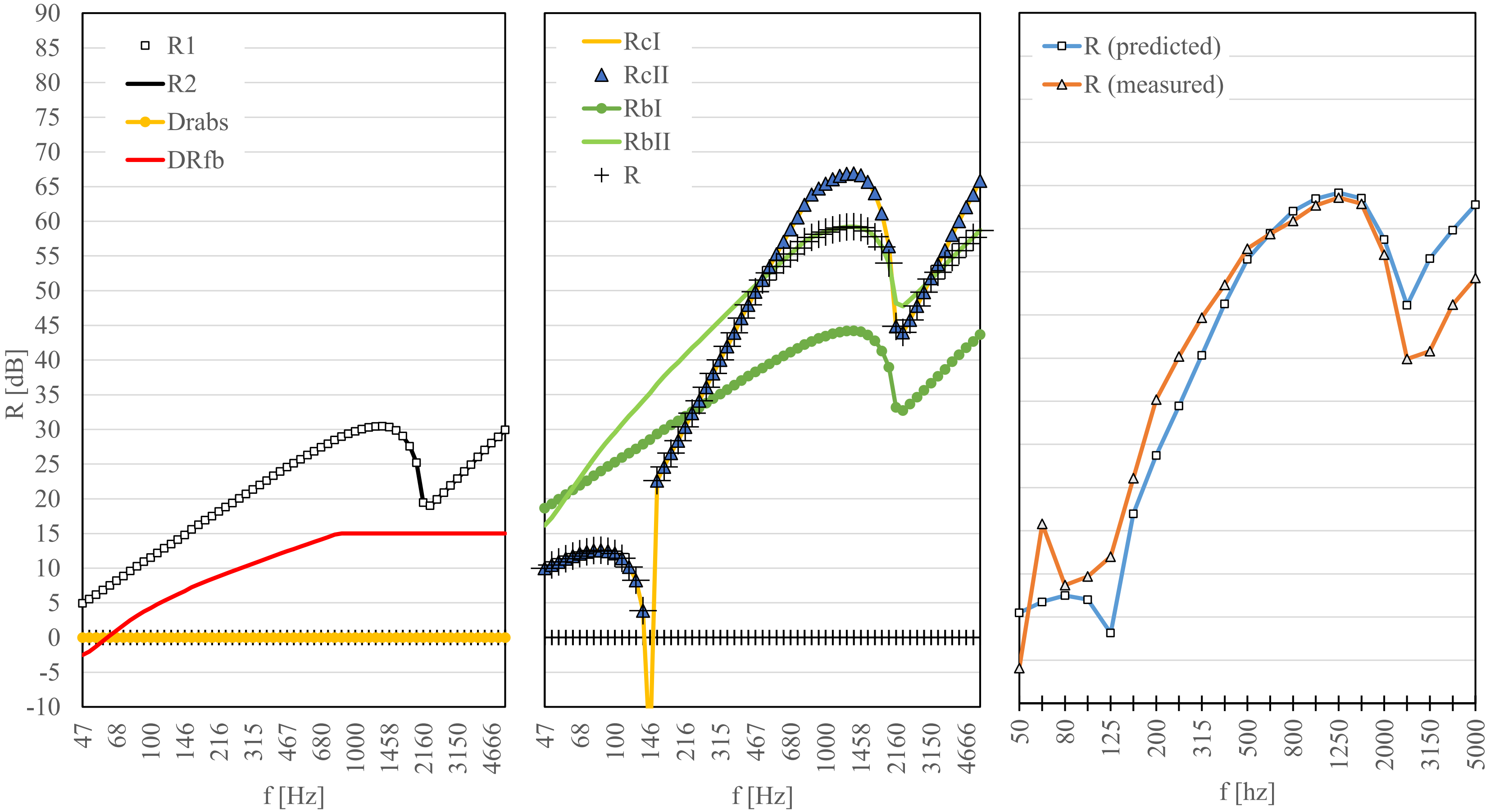
  - f_r [Hz] is the resonance frequency of the double wall with studs
  - ζ is the loss factor of the flexible stud (not the panel)
  - K'' [N/m^3] is dynamic stiffness per unit area of the stud
- Benefit of flexible stud is that $R_{bII} > R_{bI}$, when $f > 2f_r$
- Disadvantage of flexible stud is that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





Bradley&Birta (2001) Noise Con Eng J

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



Construction:

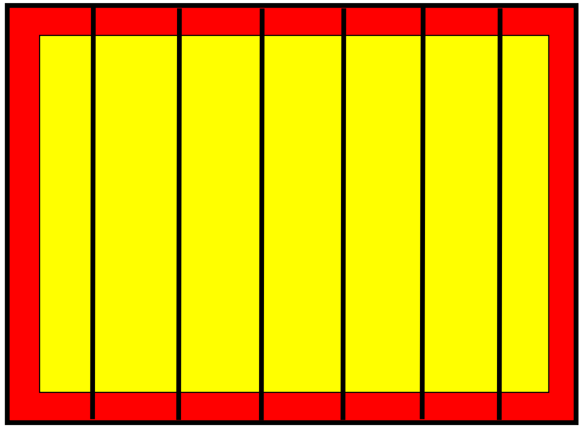
- Gypsum 13 mm
- Flexible stud, 0.2 MN/m^2, cc600, 66 mm cavity, cavity filled with wool
- Gypsum 13 mm

Calculation process:

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

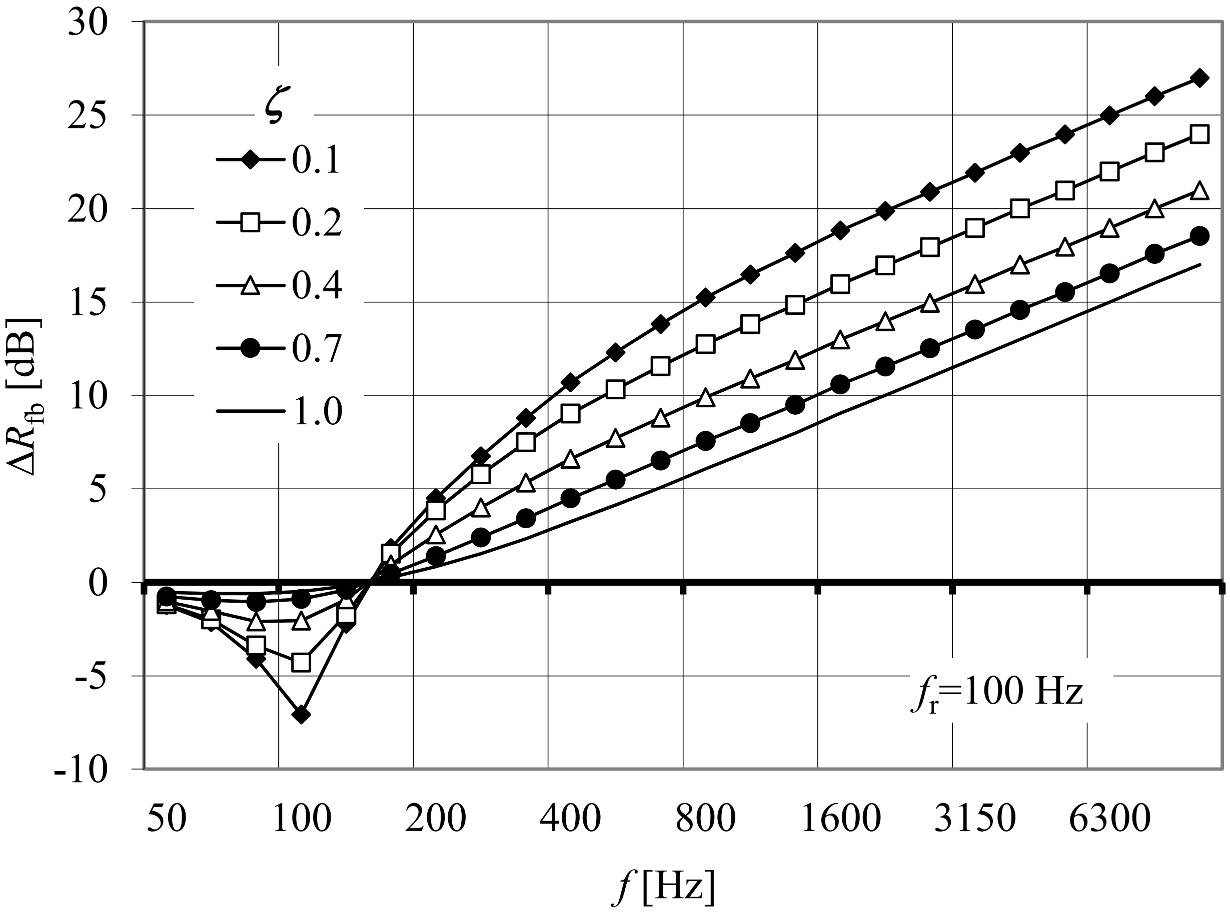
ΔR_{fb}

- Rails in the ceiling and floor are usually rigid. Rigid connections of the flexible studs to the rails destroy the advantage of flexible studs
- Full benefit of the spring is achieved only in the middle part of the double wall.



🟥 Stronger radiation due to rigid attachment to the rails and frames

🟨 Weak radiation due to flexible studs is achieved



Determination of dynamic stiffness of studs

- Two 30-cm-long studs are installed between two heavy plates (30c30 cm) with screws
- The other plate is excited with broad-band vibration shaker
- System's resonance frequency is determined with FFT analysis, f_0 [Hz]
- The dynamic stiffness, or the spring constant, K [N/m], is

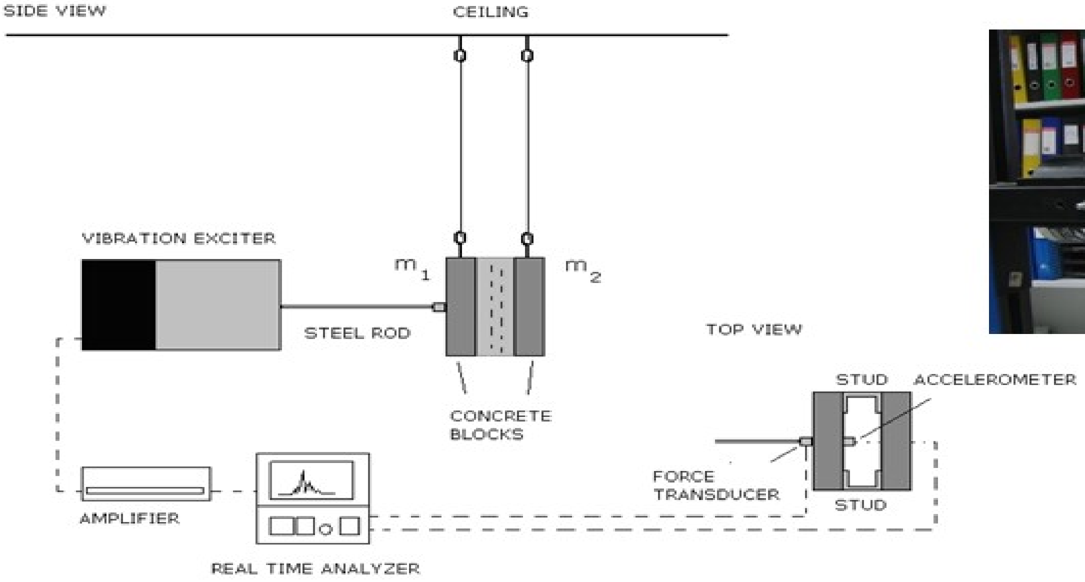
$$K = \omega_0^{\,2} \frac{m'_1 m'_2}{m'_1 + m'_2}$$

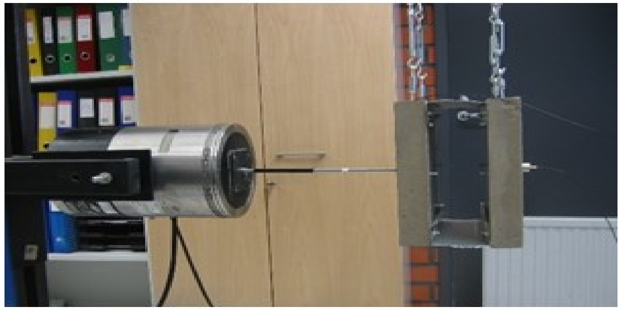
- The dynamic stiffness per unit length, K' [N/m^2] is
    - where L=0,6 m

$$K' = K/L$$

- The modeling of flexible studs is made by K'' [N/m^3] which takes the actual density of studs in the wall into account
    - b [m] is the distance between studs

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

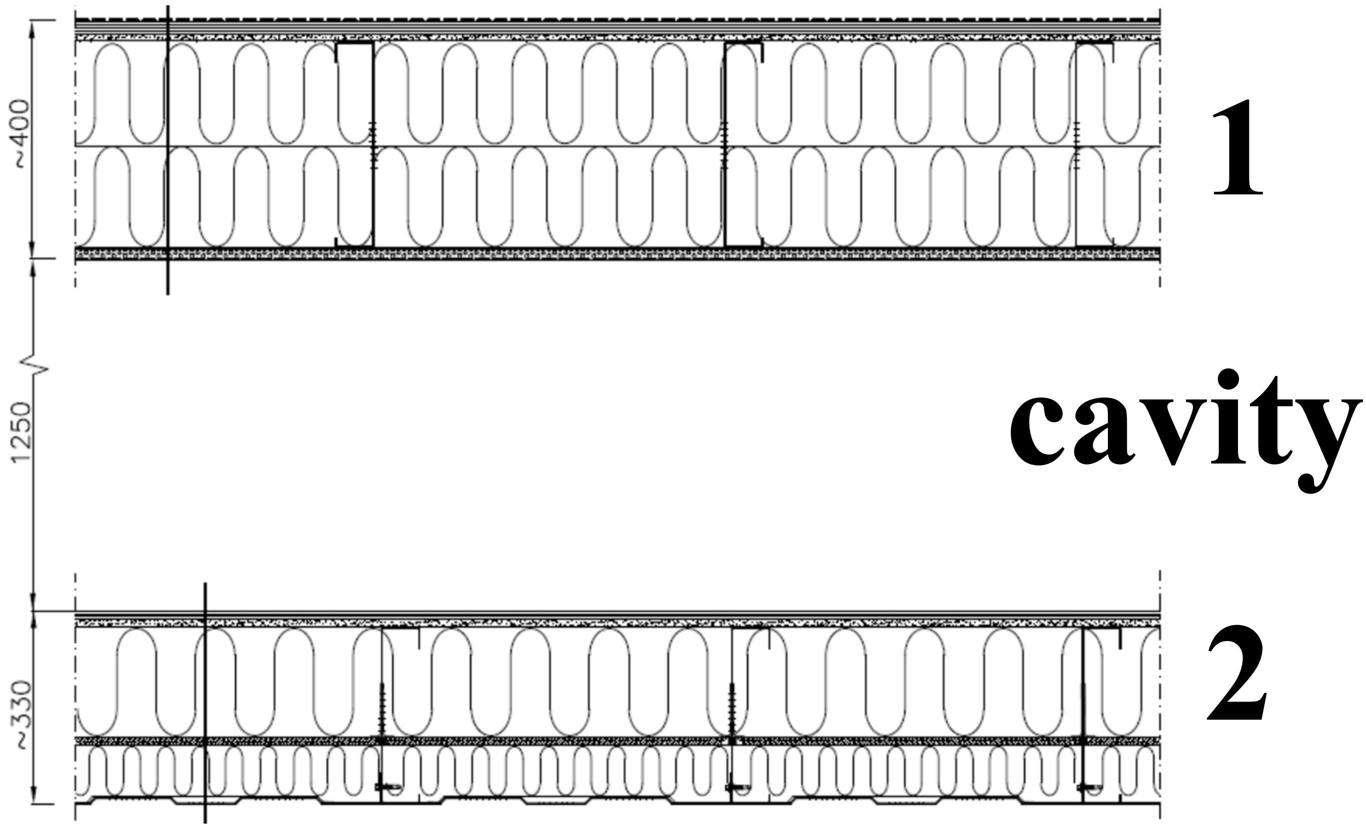




Extremely thick double panel construction

- 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:

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

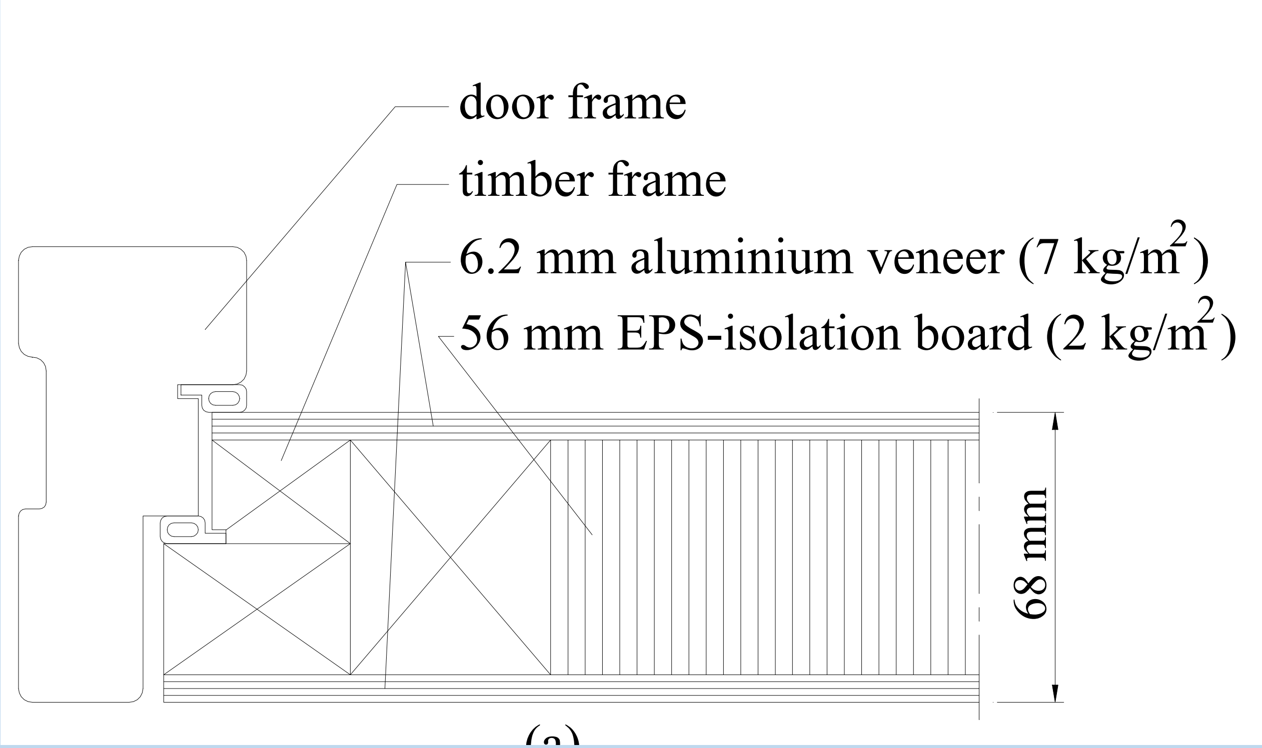
  - K' [N/m^3] is the dynamic stiffness per unit area of the core material
  - m' [kg/m^2] is the surface mass of panel

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

4.4

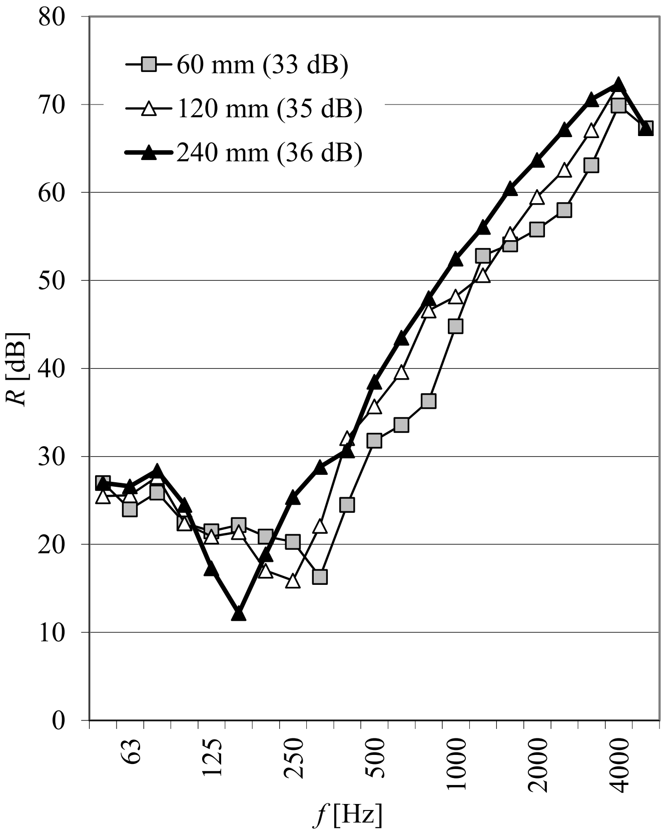
Sandwich – door's thermal isolator is EPS.
EPS (s'=330 MN/m3).
Calculate the dilatation resonance.

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

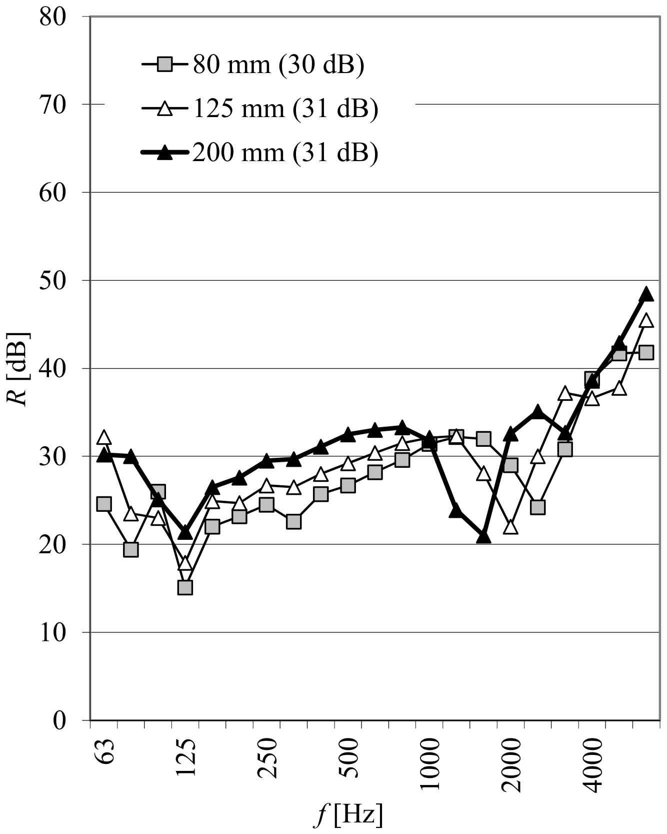


Hongisto 2001 Applied Acoustics

Sandwich panel - effect of core thickness



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

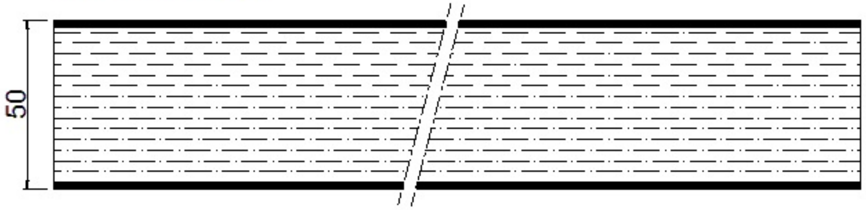


- steel 0.6 mm
- mineral wool (125 kg/m^3)
- steel 0.6 mm
- R_w in brackets

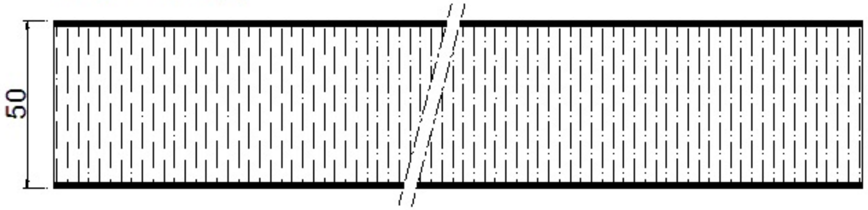
RIL 243-1-2007

Sandwich panel - effect of core stiffness

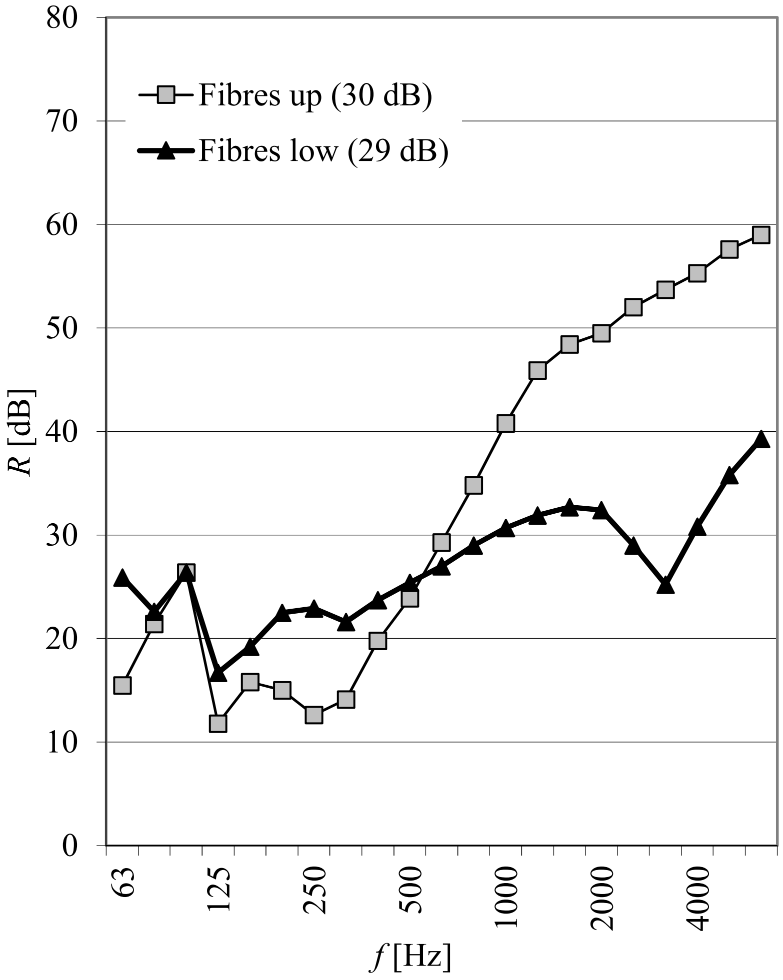
Fibres low



Fibres up



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



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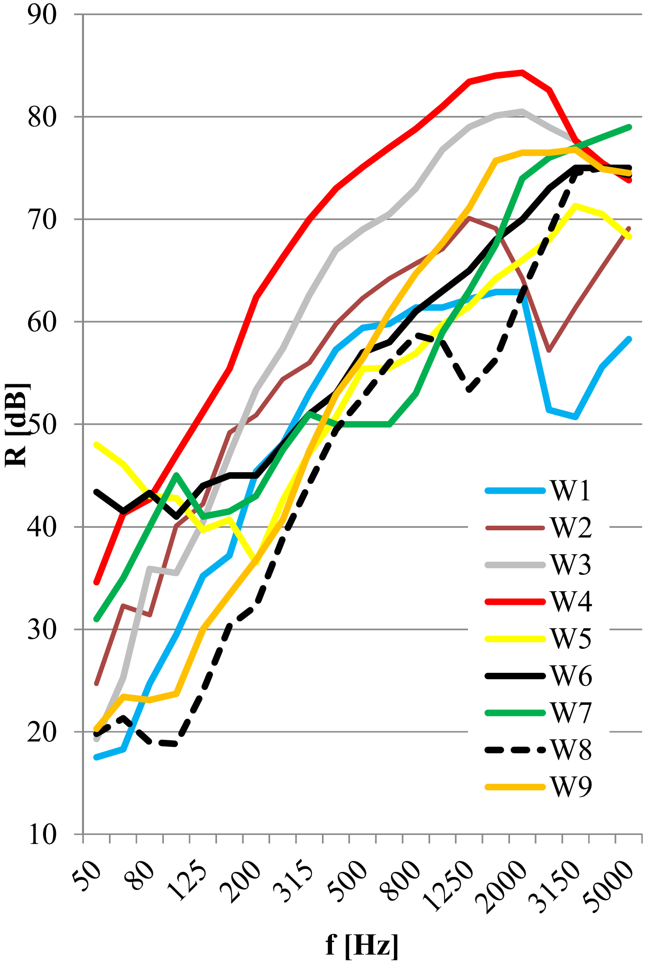
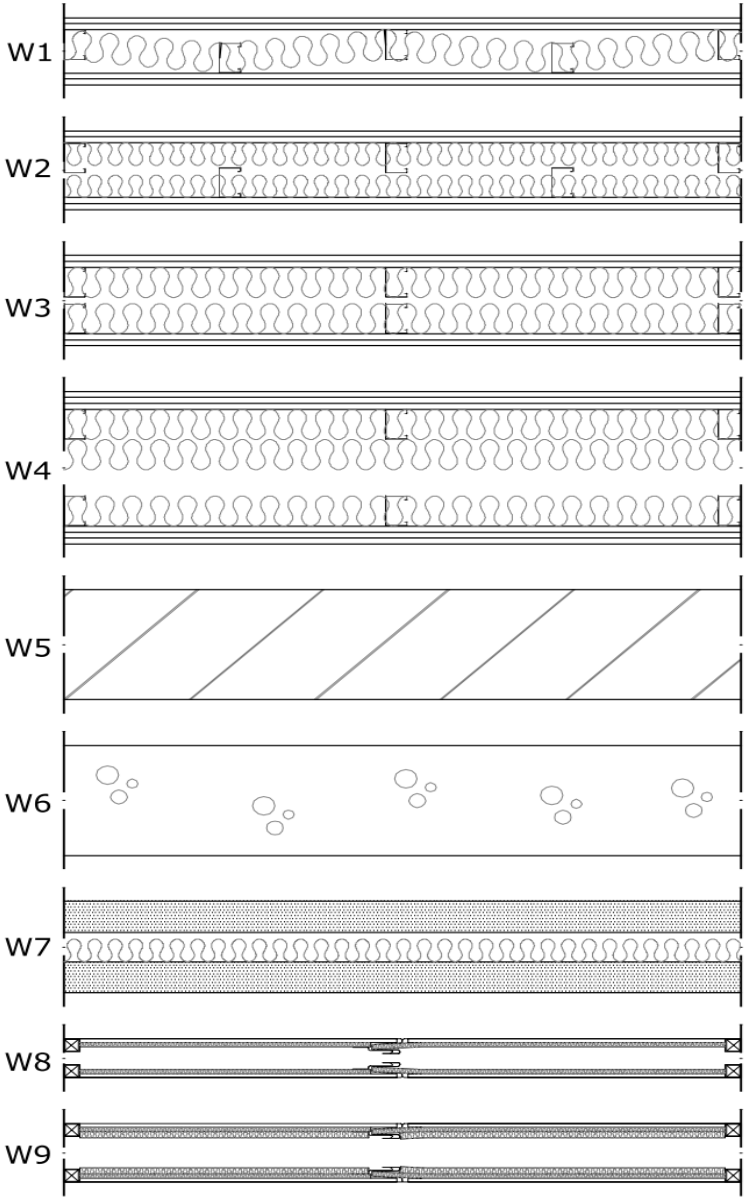
Examples for 9 wall constructions



	W1	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**
R_w	55.1	62.5	66.1	75.1	56.1	60.1	56.2	48.2	52.1
$R_w+C_{100\text{-}3150}$	52.1	59.9	61.1	71.0	53.3	58.2	54.6	43.9	48.6
$R_w+C_{100\text{-}5000}$	52.7	60.7	62.0	71.6	54.3	59.2	55.6	44.9	49.6
$R_w+C_{50\text{-}3150}$	48.7	57.3	55.5	68.0	53.3	58.0	54.4	43.0	47.4
$R_w+C_{50\text{-}5000}$	49.6	58.1	56.5	68.8	54.2	59.0	55.4	44.0	48.4
$R_w+C_{tr,100\text{-}3150}$	47.0	55.9	53.7	64.5	49.0	53.9	51.4	36.8	41.6
$R_w+C_{tr,100\text{-}5000}$	47.0	55.9	53.7	64.4	49.0	53.9	51.4	36.8	41.6
$R_w+C_{tr,50\text{-}3150}$	37.5	46.6	42.3	56.5	48.8	53.1	49.2	34.2	37.9
$R_w+C_{tr,50\text{-}5000}$	37.5	46.6	42.3	56.5	48.8	53.1	49.2	34.2	37.9

Wall	**Mass** [kg/ m^2]	**Thickness** [mm]	**Principal material**
W1	37	147	Gypsum board
W2	44	172	Gypsum board
W3	38	192	Gypsum board
W4	57	268	Gypsum board
W5	440	248	Calcium silicate masonry
W6	450	180	Steel-reinforced concrete
W7	112	200	Autoclaved aerated concrete
W8	27	85	Steel-wool sandwich
W9	33	100	Steel-wool sandwich



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