CHAPTER 4
ACOUSTIC DESIGN OF LIGHTWEIGHT TIMBER FRAME CONSTRUCTIONS

COST Action FP0702

Net-Acoustics for Timber based Lightweight Buildings and Elements

Working Group 4: Building acoustics design

CONTENTS

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Last but not least, we would like to thank IWT for the research project 'optimisation of light weight timber frame constructions AH+' without which it would not have been possible to do this work.

This text is intended for acousticians with less experience in lightweight timber frame construction technology and for people with little background in acoustics working in the building sector with lightweight timber frame constructions. Relatively simplified acoustic concepts will be used to explain how things work acoustically and why the use of some concepts is advised and the use of others might not be such a good idea.

Disclaimer:

This document illustrates the state of the art solutions for buildings using timber and wood materials to achieve satisfactory sound insulations based on research and experience to-date. It is recommended that implementation of the solutions provided in this document, be checked and/or validated with the installation specifications of the various materials with respect to other requirements, such as allowable maximum deformation, moisture stability, etc. Furthermore, in critical situations or when you need assurance or written documentation that the design you have chosen to use meets the specific country regulations, we strongly recommend you engage the services of an acoustical consultant to assist you.

1 - INTRODUCTION

The use of wood for building is growing. This evolution is pushed by the Kyoto protocol. Wood construction presents numerous strong points for sustainability: it allows for CO2 storage, it is a renewable raw material, it provokes only small construction waste on site and it requires little energy to produce. There are other several more pragmatic reasons why lightweight timber frame constructions (abbreviated as LWTF further in the text) are increasing their market share to the detriment of heavy constructions: prefabrication, speed of assembly, new architectural tendencies (fashion trends), and not in the least the possibility of increasing the thermal insulation layers in the façade walls without increasing the traditional thickness of the façades.

In this way lightweight timber frame constructions are becoming ever more popular for free standing or terraced single family houses in Europe. But the share of single family housing in the number of dwellings is diminishing in many European countries: the cost of building plots and construction is rising, transport problems are stimulating people to settle near city centres, public authorities favour the urbananistic approach of more densely built environments to safeguard open spaces and to limit infrastructure costs etc. The dwindling share of single family houses in the construction market, the increase in number of competitors and the growth in size of many of these companies, are pushing LWTF companies to start building other projects than just single family houses. The use of LWTF in multifamily constructions is a fairly recent phenomena in almost all European countries (starting around 1990), even in those with a strong LWTF- tradition for the construction of single family houses.

Thermal insulation is a hot topic and most manufacturers focus on these issues. For single family houses in a quiet environment, this is indeed not a problem. But when it comes to terraced houses or apartments, acoustic quality becomes a major challenge. Unfortunately there are not that many examples of acoustically successful apartment constructions using the LWTF-technology. At least when the goal is to offer a level of acoustic comfort similar to that found in acoustically well- designed heavy constructions.

In most European countries, acoustic requirements have been developed based on the performance of traditional, heavy constructions. Requirements in most countries are based on evaluations of the acoustic performance from the 100 Hz third octave band upwards. Though there is an increasing need to look at the performance of the building below 100 Hz, even for traditional heavy buildings, this is an absolute necessity for lightweight constructions. For the latter it is much more difficult to obtain a performance comparable to that of heavy construction in the third octave bands below 100 Hz. The performance of LWTF constructions in the low frequencies is determined by the acoustic laws for 'double wall constructions'. These are characterized by mass-spring-mass resonances (see further in the text) and modal behaviour below 100 Hz, causing serious dips in the sound insulation in this frequency area.

Although these resonances can also occur in heavy constructions (due to linings, floating floors…), this is far less a problem. Taking in account the measurement reproducibility difficulties in the frequency bands below 125 Hz, most European countries with a tradition of heavy constructions (with the exception of Sweden) opted in the past for requirements that do not take in account the performance below 100 Hz, although this is still very audible for inhabitants (see the reports of WG2 and WG3). This is pretty dangerous for inhabitants of lightweight timber frame constructions: although the LWTF building complies with the acoustic requirements, this is still no guarantee for an acoustic comfort as good as in heavy buildings that also comply with the requirements!

So an 'acoustically good' lightweight timber frame construction is not just a construction that complies with the acoustic requirements. It should be a construction that offers at least the same "experienced" acoustic quality as that of acoustically well designed heavy constructions.

Airborne sound insulation between dwellings – Main requirements in 24 European countries.[a,b]

Country	Descriptor[c]	Multi-storey housing Req. (dB)	Row housing Req. (dB)
Austria	$D_{nT,w}$	⩾55	⩾60
Belgium	$D_{nT,w}$	⩾54	⩾58
Czech Rep.	R'_w	⩾52	⩾57
Denmark	R'_w	⩾55	⩾55
Estonia	R'_w	⩾55	⩾55
Finland	R'_w	⩾55	⩾55
France	$D_{nT,w} + C$	⩾53	⩾53
Germany[i]	R'_w	⩾53[g]	⩾57
Hungary	$R'_w + C$	⩾51	⩾56
Iceland	R'_w[e]	⩾52[h]	⩾55
Ireland	$D_{nT,w}$	⩾53[g]	⩾53
Italy	R'_w	⩾50	⩾50
Latvia	R'_w	⩾54	⩾54
Lithuania	$D_{nT,w}$ or R'_w	⩾55	⩾55
Netherlands	$I_{lu;k}$[d]	⩾0	⩾0
Norway	R'_w[f]	⩾55[f]	⩾55[f]
Poland	$R'_w + C$	⩾50[g]	⩾52[h]
Portugal[i]	$D_{n,w}$	⩾50	⩾50
Slovakia	R'_w	⩾52	⩾52
Slovenia	R'_w	⩾52	⩾52
Spain	$D_{nT,w} + C_{100-5000}$	⩾50	⩾50
Sweden	$R'_w + C_{50-3150}$	⩾53	⩾53
Switzerland	$D_{nT,w} + C$	⩾52[j]	⩾55
UK[k]	$D_{nT,w} + C_{tr}$	⩾45	⩾45

Notes:

[a] Study carried out in 2008. Data verified April 2008.

[b] Overview information only. Detailed requirements and conditions are found in the building codes.

[c] No generally applicable conversion between the different descriptors exists, as the relations depend on characteristics of rooms and constructions. Exact conversion can only be made in every specific case.

[d] $I_{lu;k} = R'_w + C - 52$ dB. Ref. [29].

[e] In addition to the rating procedure described in ISO 717, the Icelandic building regulations prescribe maximum 8 dB unfavourable deviation.

[f] It is recommended that the same criteria are fulfilled by $R'_w + C_{50-5000}$.

[g] Horizontal, requirement for vertical is 1 dB higher (Germany and Poland)/ lower (Ireland).

[h] 55 dB recommended.

[i] Under revision, use of $D_{nT,w}$ has been proposed.

[j] Flats for rent. If owned by occupants, the criterion is the same as for row housing.

[k] England and Wales only. Scotland and Northern Ireland use different descriptors and performance levels.

Impact sound insulation between dwellings – Main requirements in 24 European countries.[a,b]

Country	Descriptor[c]	Multi-storey housing Req. (dB)	Row housing Req. (dB)
Austria	$L'_{nT,w}$	⩽48	⩽43
Belgium	$L'_{nT,w}$	⩽58[g]	⩽50
Czech Rep.	$L'_{n,w}$	⩽58	⩽53
Denmark	$L'_{n,w}$	⩽53	⩽53
Estonia	$L'_{n,w}$	⩽53	⩽53
Finland	$L'_{n,w}$[f]	⩽53[f]	⩽53[f]
France	$L'_{nT,w}$	⩽58	⩽58
Germany[j]	$L'_{n,w}$	⩽53	⩽48
Hungary	$L'_{n,w}$	⩽55	⩽45
Iceland	$L'_{n,w}$[e]	⩽58[h]	⩽53
Ireland	$L'_{nT,w}$	⩽62	None
Italy	$L'_{n,w}$	⩽63	⩽63
Latvia	$L'_{n,w}$	⩽54	⩽54
Lithuania	$L'_{n,w}$	⩽53	⩽53
Netherlands	I_{co}[d]	⩾ + 5	⩾ + 5
Norway	$L'_{n,w}$[f]	⩽53[f]	⩽53[f]
Poland	$L'_{n,w}$	⩽58	⩽53
Portugal[j]	$L'_{n,w}$	⩽60	⩽60
Slovakia	$L'_{n,w}$	⩽58	⩽58
Slovenia	$L'_{n,w}$	⩽58	⩽58
Spain	$L'_{nT,w}$	⩽65	⩽65
Sweden	$L'_{n,w} + C_{I,50-2500}$	⩽56[i]	⩽56[i]
Switzerland	$L'_{nT,w} + C_I$	⩽53[k]	⩽50
UK[l]	$L'_{nT,w}$	⩽62	None

Notes:

[a] Study carried out in 2008. Data verified April 2008.

[b] Overview information only. Detailed requirements and conditions are found in the building codes.

[c] No generally applicable conversion between the different descriptors exists, as the relations depend on characteristics of rooms and constructions. Exact conversion can only be made in every specific case.

[d] $I_{co} = 59 - (L'_{nT,w} + C_I)$ dB $\approx 70 - L'_{nT,w}$ dB for bare concrete floors or $I_{co} \approx 59 - L'_{nT,w}$ dB for other floors like wooden floors, floating floors and floors with soft coverings. Ref. [29].

[e] In addition to the rating procedure described in ISO 717, the Icelandic building regulations prescribe maximum 8 dB unfavourable deviation.

[f] It is recommended that the same criteria are fulfilled by $L'_{n,w} + C_{I,50-2500}$.

[g] From "non-bedrooms" outside the dwelling to a bedroom ⩽ 54 dB is required.

[h] 53 dB recommended.

[i] The same criteria shall also be fulfilled by $L'_{n,w}$.

[j] Under revision, use of $L'_{nT,w}$ has been proposed.

[k] Flats for rent. If owned by occupants, the criterion is the same as for row housing.

[l] England and Wales only. Scotland and Northern Ireland use different performance levels.

Figure1: acoustic requirements in Europe for impact and airborne sound insulation. (Data from Birgit Rasmussen, SBi Danish Building Institute, Aalborg University. Published in Applied Acoustics, no° 71-2010 with the title 'Sound insulation between dwellings – Requirements in building regulations in Europe', pages 373-385.)

Sufficient impact sound insulation and the realisation of satisfying comfort against vibrations in particular appear to be the major challenges. People often complain about buzz or, the almost thunderous sound of someone walking on the floor above. They also complain about the possibility of hearing from where to where someone is walking. Some research shows that the evaluation should go below 50 Hz to explain all of this and to obtain a real description of the acoustic comfort.

But there is also positive news: if the construction allows for similar comfort in the low frequency bands as with heavy constructions, then it will generally offer a much better comfort in the middle and high frequency bands than do heavy constructions, due to the more steep increase in sound insulation with this technology.

All of this has serious consequences on the choice and adaptation of single ratings and measurement techniques. One can even wonder whether it will really be possible to evaluate the acoustic comfort using the same quantity for LWTF and heavy constructions. More information about these problems can be found in the reports of WG 2 and WG 3.

That leaves us, the regulators and the building industry, with some major problems and open questions: *with what measurements should I express the performance of my building to get a good comparison with the comfort of heavy constructions? How high should this performance be to get satisfied customers? How should I build this (robust details?)?* As long as these 'quality' questions remain unanswered, *building multifamily homes in lightweight timber frame remains difficult.*

Market competition can be disturbed by the distance between, on the one hand, an industry trying to build acoustically comfortable houses, and on the other hand people who just want to comply with the acoustic requirements, even knowing that they are inappropriate for LWTF constructions. The latter will create a bad image of the LWTF multifamily home and that is just something we want to avoid.

Many construction models available now in Europe focus only on the existing requirements. Some of these models are discussed below, but their acoustic quality very often dissatisfies inhabitants. The goal of the following chapters is to give an idea of the different construction methods, junctions between building elements and the construction of the building elements. This should allow for the experts in the development of acoustic prediction methods to see what kind of constructions and junctions need to be simulated. For building industry it should offer some explanation why some things work and others just don't. The document also aims to give an overview of 'do's and don'ts' as well as some examples of innovative ideas and solutions. As long as it is unclear what kind of performance should be obtained to get x% satisfied customers, this document does not seek to give THE instructions of how to build an acoustic optimized lightweight timber frame construction. *What we can try to do is to improve existing concepts to get as high as possible acoustic performances while still being in accordance with the other boundary conditions for a well-conceived building (see next chapter).* And of course a document like this is just a snapshot of the actual state of the art; it can never be complete and necessarily refers to on-going work and to databases of performances available on the internet.

2 - GENERAL BUILDING METHODS AND BOUNDARY CONDITIONS

2.1 - General building methods

Lightweight timber frame constructions can be completely built on site, but most lightweight timber frame constructions are made of prefabricated building elements such as walls, floors, etc. that are assembled on site. In some cases, complete rooms or even several rooms are manufactured in an industrial plant and assembled together on the building site. Prefabrication allows for significant cost reductions and for a better quality control in an industrial manufacturing environment. Building time on site can be greatly reduced and is less influenced by weather conditions.

A limited crimp (max 1 cm) is one of the advantages of the lightweight timber frame constructions compared to solid wooden constructions. Crimp in wooden beams occurs due to a reduction in moisture content and takes place perpendicular to the orientation of the wood fibres, i.e. in the width or thickness of the beams and columns. So the crimp in height happens only in horizontal beams and not in the height of the columns and thus remains limited.

Three main prefabricated building methods can be distinguished in Europe:

In the **platform-frame** method, floor elements are fixed on top of the walls of the lower floor and are most often continuous over different rooms. As such, these floors become a working platform for the construction of the next building layer. This is the standard approach in lightweight building frame construction in Europe.

In the **balloon-frame** method (or 'Chicago method'), walls are continuous over many storeys and the floors are hung between these walls. Though this method offers advantages for a better air tightness of the building, it is less used nowadays because of construction limitations in height, prefabrication problems and difficulties in the mounting of the construction on site.

Some mixed balloon/platform-frame methods exist in which the floors are fixed into notches in the walls.

The **box-assembly** method prefabricates box-like elements that are fitted together to realise a complete building. Each box can contain one or several rooms and is very often finished to a large degree in a manufacturing plant so that the work on site is limited to a strict minimum. Transportation costs and difficulties can be the main handicap for this building approach.

Lightweight timber frame constructions can be combined with other traditional constructions and are often used in the retrofitting of buildings or to add additional storeys on existing traditional heavy constructions. There are also all kind of hybrid constructions with e.g. a load carrying steel frame and lightweight timber frame fill-up elements.

Building with wood can also incorporate 'solid wooden' constructions. There are also a large variety of these kinds of building solutions. Some use massive wooden load carrying panels made of cross laminated timber; other 'solid wooden' constructions use superposed beams (e.g. pin and groove fixations) to build walls. The latter need specific solutions to cope with major crimp problems (the accumulation of the crimp in height of each wooden beam). 'Solid wooden' building constructions are not part of the major scope of this COST program and will only sporadically be treated in the following chapters.

The type of building method determines the junctions and will have important consequences for the flanking transmission between adjacent rooms.

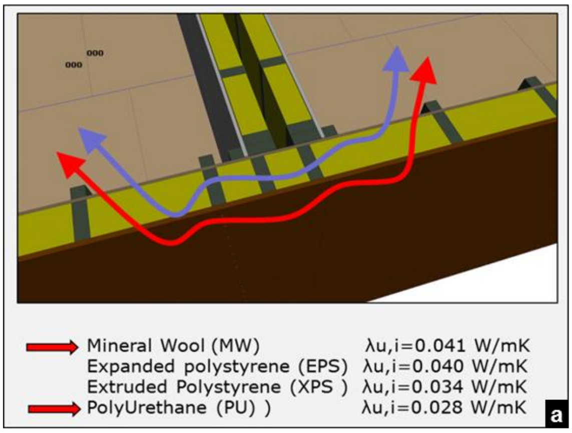
Figure 2: typical examples of light-weight timber frame constructions and junctions used in free-standing houses. Extending this technology towards terraced houses requires some adaptations but the challenges are huge for building apartment constructions.

2.2 - Boundary conditions and possible conflicts with acoustic optimisation

Building is necessarily a technically multidisciplinary activity. The acoustician is therefore used to being confronted with constraints. But in LWTF construction the acoustic challenges are much greater than with heavy constructions and the interactions with other disciplines such as stability requirements, thermal regulations, fire requirements and other can make it particularly difficult to attain goals. In the upcoming pages, ideal acoustic solutions are sometimes impossible because of these constraints and compromises are often necessary. Just let us have a look at some of these constraints that we will encounter.

2.2.1 - Thermal insulation

Most European countries have energy performance requirements and many architects want to go beyond these criteria (e.g. passive houses, o-energy dwellings…). Architects are therefore most inclined to choose the most favourable thermal insulation materials. Unfortunately, PU and EPS have better thermal performances than good acoustic absorption products such as cellulose, mineral wool etc. The use of these rigid, non-porous materials can be extremely problematic for the acoustician leading to a lack of façade sound insulation for vertical walls and roofs. The weak sound insulation of vertical façades and roofs can lead to additional flanking transmission or indirect airborne transmission paths (see red arrows in figure 3 ‘a’).



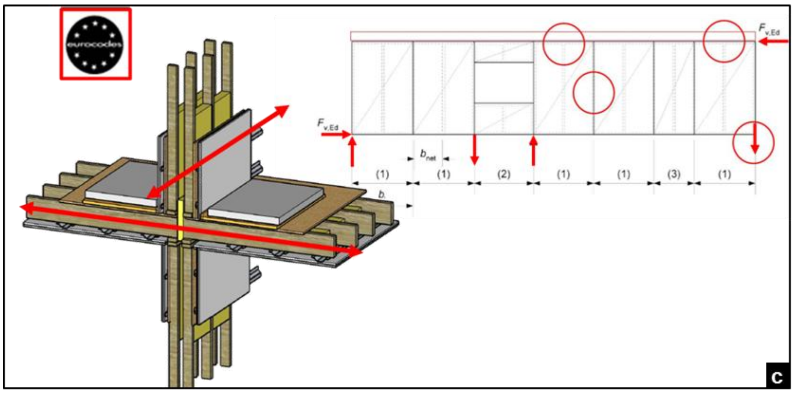


Figure3: some boundary constructions creating problems to optimise the acoustical performance of lightweight timber frame constructions

2.2.2 - The problematic 'idea' of the independence of each terraced house.

An apartment construction is everywhere considered as an entity. But in some countries, blocks of terraced houses are not considered as single building entities, but are required to stand alone after the demolition of the adjacent dwelling. This way of thinking can be criticised, as probably many non-acoustical problems will arise once only one house remains: what about water-tightness, sufficient thermal insulation, hygrothermal effects, aesthetic look….? So if and when the other house were to disappear, inevitably actions would have to be undertaken to create this independence of the remaining dwelling. This 'idea' or even requirement creates some serious low frequency issues (see 'party walls', section 3): wide cavities, good for low frequency sound insulation, are for these reasons difficult to achieve.

2.2.3 - Fire requirements

Fire requirements will largely influence the concept of walls and floors as well as the materials being used. Obvious acoustic solutions are therefore not always applicable. Requirements differ all over Europe, but use in general European classification expressed in minutes ('REI': see figure 'a'). Requirements differ for terraced houses (in general only applicable for the party wall), low rise and high rise blocks.

The requirements for the party wall in terraced houses are in fact expressed for each portion of the party wall, belonging to one of the adjacent houses. The idea is that when one of the houses is on fire, the collapse of one of its floors can work as a lever and provoke the collapse of the burning house or at least destroy its part of the party wall (see figure 4 'c'). The collapse of one house will result in a large fire attacking the adjacent house and its remaining part of the party wall. Most countries require a fire resistance of at least one hour for each part of the party wall (i.e. that part that belongs to each house separately). This explains (together with the reasons expressed in (1)) why LWTF constructions in many countries use extra boards in the cavity, although this is not favourable for the low frequency sound insulation.

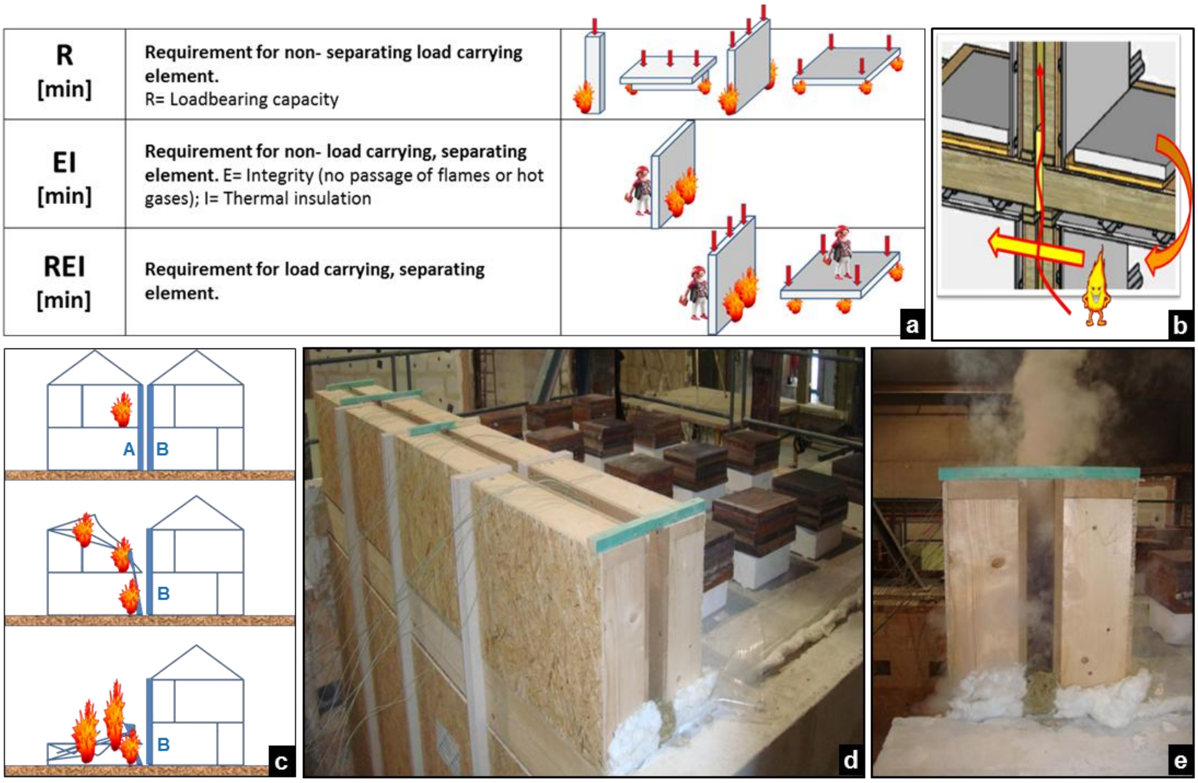


Figure 4: fire and the corresponding requirements have a major impact on how LWTF are conceived. This often leads to choices not very favourable for a good acoustic performance.

Fire requirements in apartments are far more severe and concern all load carrying walls, floors and party walls. In general at least an R or REI 60 is required. The situation is even more complex when a single family house (eventually part of a series of terraced houses) is adjacent to an apartment building. As party walls always exist as a double wall (called wall portions A and B below) with a central cavity, we can give a summary of requirements for party walls in the table below:

Situation	Wall portion (for fire attacking from the inside of the central cavity)	Wall portion (for fire attacking from the inside of the dwelling)
Between two terraced houses	REI 60 to 90 for walls A and B(# of minutes depending on the country)	'/
Between two apartments	'/	REI > 60 to 120 (# of minutes depending on the country)
Between a terraced house (e.g. left) and an apartment building (e.g. right).	REI 60 to 120 on the **side of the apartment, so only on wall portion B** (# of minutes depending on the country)	REI > 60 to 120 on the **side of the apartment** (# of minutes depending on the country)

To avoid chimney effects and fast spreading fire, cavities should be interrupted at least at each floor and all along the junction with the façades and adjacent apartments (see figure 4 'b' and the exploratory fire tests shown in figure 4 'd' and 'e').

Figure 5: automation and large industrial scale production has consequences for assembling techniques and acoustic concepts.

2.2.4 - Structural engineering

Structural engineering determines largely the LWTF concept. The building is not only subject to vertical, gravitational forces: horizontal forces due to wind load and earthquake resistance are major factors in the structural concept. This can cause problems with acoustical optimisation using continuous cavities from foundations to roofs between apartments and terraced houses. Perfect decoupling between apartments or the use of elastic interlayers will also be difficult for these reasons. Because of these shear and vertical forces, boards cannot be fixed in the acoustically optimized way of resilient fixing (using for example, additional resilient channels perpendicular to the studs): to increase the load-bearing capacity of LWTF walls, wood panels are today very often not only screwed to the studs but equally glued increasing the linear contacts and rigidity of the walls (radiation efficiency)

2.2.5 - Industrial production

Last but not least: fabrication can have positive (quality control) and negative effects on acoustic optimisation. The wish to maximize production in factory halls (with robots and automation) and minimize work in situ, has consequences on concepts. The acoustic technology that uses resilient metal channels and studs is a technique typically for in situ finishing. Manufacturers will go for lesser alternatives allowing easier transport and production in factory halls preferring staples in wooden studs to screwing in metal studs (see figure above).

2.3 - Comparison with heavy constructions

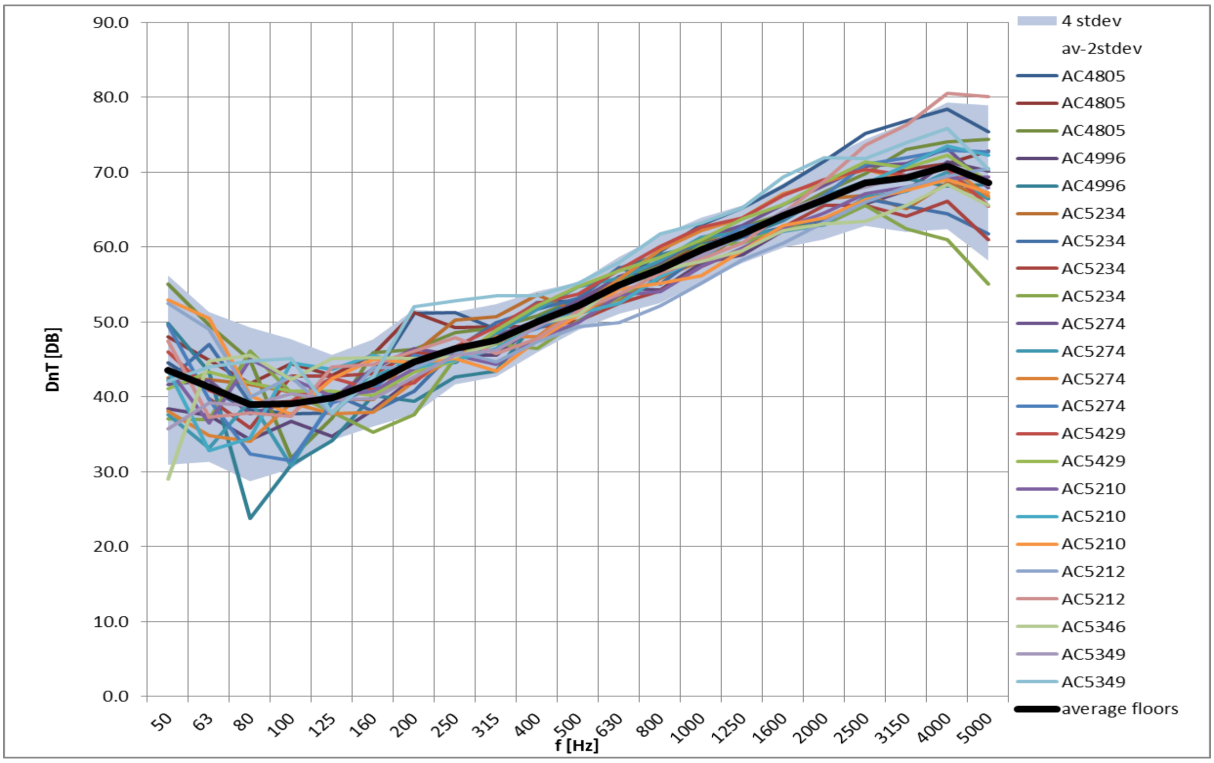
Although an acoustic study is being carried out now in the Scandinavian countries of LWTF constructions and the feeling of satisfaction with regard to acoustic comfort, no results are yet available (project ACULITE).

But people and acousticians know what to expect as acoustic comfort in heavy constructions. One could say that an acoustically good heavy construction will be the reference for inhabitants once they move to a lightweight timber frame construction. . As there is no real agreement on a single rating that could express, at a same absolute value, identical acoustic comfort in both lightweight and heavy constructions, it is vital to compare performances via / across insulation spectra. We propose for this report to confront insulation spectra between light and heavy weight constructions for some in situ and mock-up measurements. This allows also for a better understanding of the typical problems and challenges LWTF are confronted with.

2.3.1 - Vertical sound insulation

For vertical sound insulation, the most critical one in LWTF constructions, an analysis is made based upon field surveys of traditional floating floors in typical heavy built apartments in Belgium. All constructions have complied with a minimal requirement of $D_{nT,w}$>54 dB and

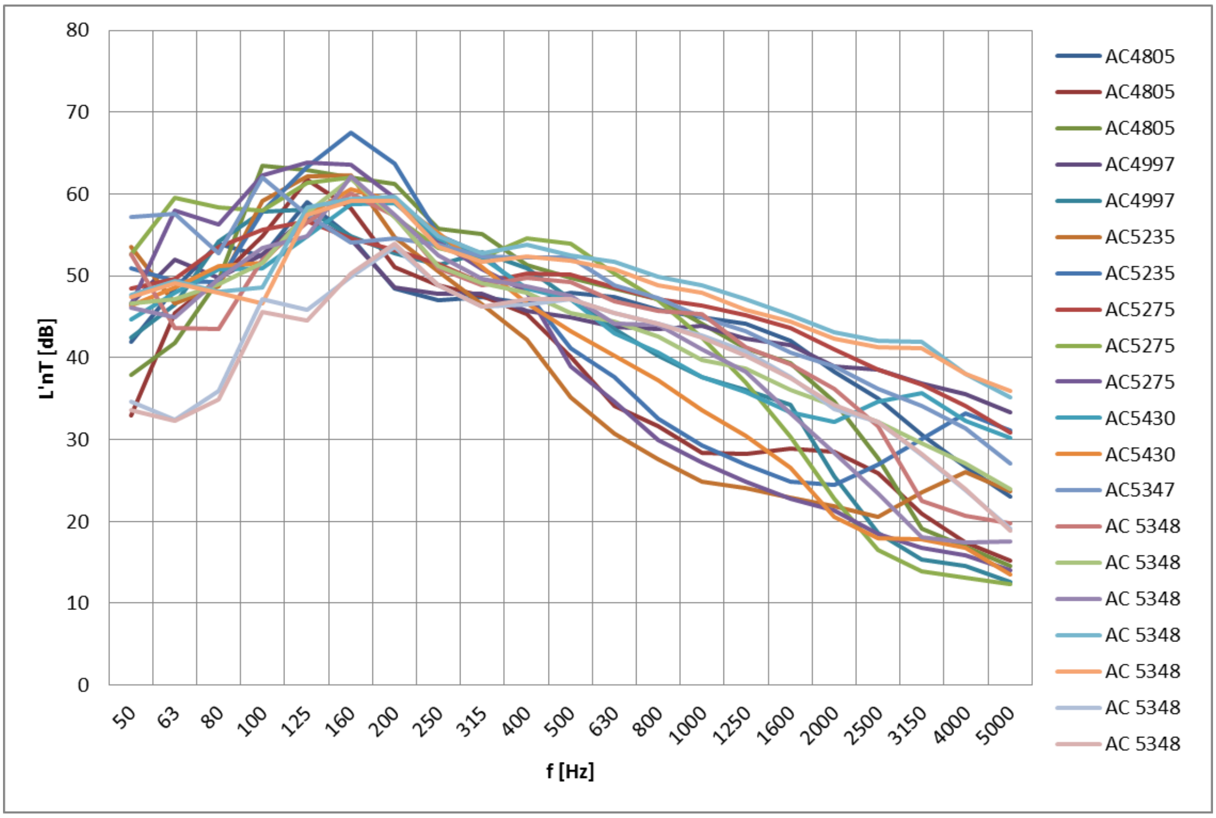
$L'_{nT,w}$ < 54 dB. No real inhabitants' satisfaction enquiry has been made, but there have been no complaints about the sound insulation for these constructions.



Graph 1: Different standardised level difference D_{nT} measured in situ on 23 well-executed traditional floating floors in Belgium. In the shaded zone, 95% of the measured values are situated.

In graph 1 and 3, the results are shown for airborne sound insulation performance while graph 2 and 4 analyse the impact sound level data. The average value for the weighted standardised level difference $D_{nT,w}$ is 57 dB ($D_{nT,w}+C_{50\text{-}5000}$ = 51 dB). The average spectrum will be used as some kind of reference graph for vertical airborne sound insulation DnT measured in some mock-up measurements with LWTF constructions. The average value for the weighted standardised impact sound pressure level $L'_{nT,w}$ is 48 dB ($L'_{nT,w}+C_{I,50\text{-}2500}$ = 49 dB). The average graph will likewise be used as reference graph for the impact sound insulation for in situ measurements.

The fact that the insulation graph for some LWTF construction is lower than the reference graph for the massive construction *does not necessarily mean that there is a lack of acoustic comfort.* More detailed psycho- acoustic studies and surveys should find out about this. *It only means that there can be reason to worry*. On the other hand, if the graph is everywhere above the reference graph, it probably shows good acoustic comfort. Comparing both graphs is also interesting to show the different acoustic behaviour of LWTF constructions compared to heavy weight constructions.



Graph 2: Average spectrum of the standardised impact sound pressure level L'_{nT} measured in situ on 20 well-executed traditional floating floors in Belgium.

The typical floor constructions are as follows (from bottom to top):

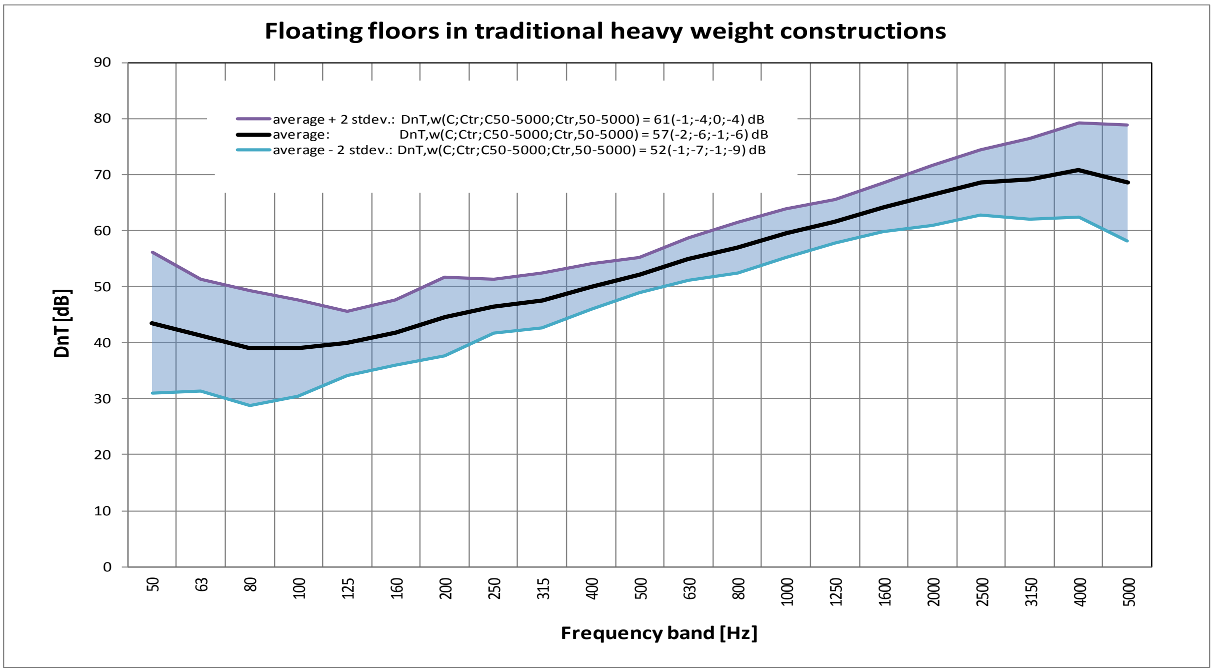
Base floor

- <u>Type 1</u>: 20 to 26 cm concrete, 4-5 cm cement-bounded levelling layer
- <u>Type 2</u>: 13 cm hollow-core concrete elements, 3 cm compression layer, 6 cm porous concrete levelling layer
- <u>Type 3</u>: 20 cm concrete, 3 cm PU foam, 2 cm Polyether foam

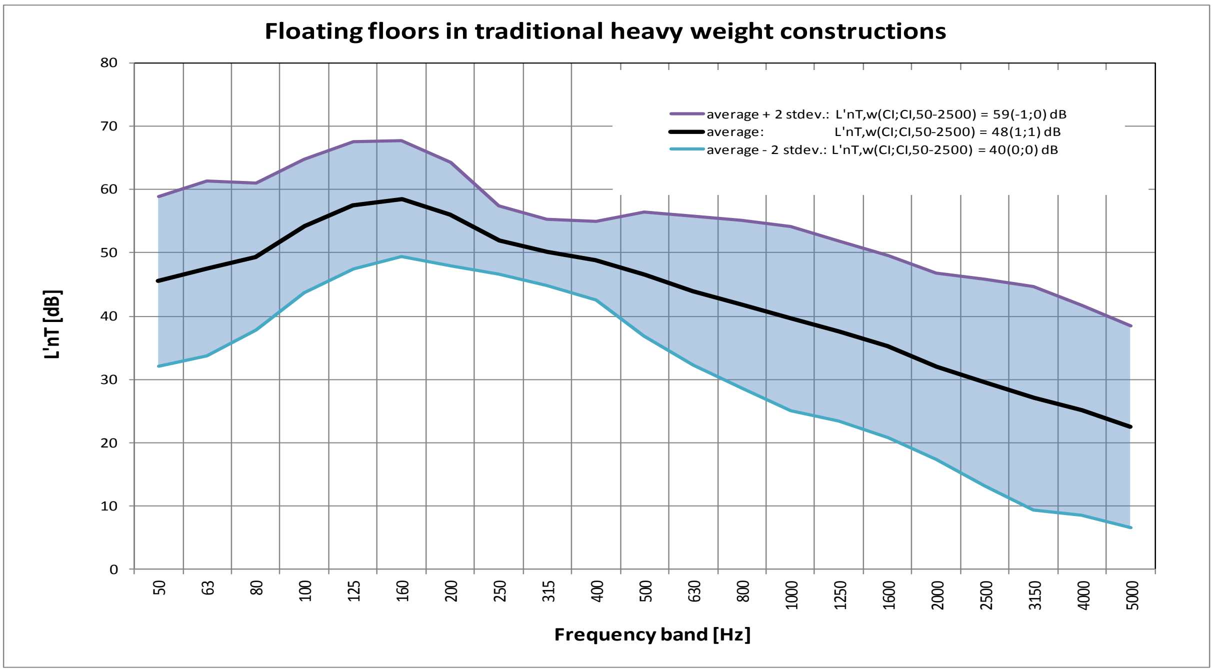
Resilient layer (only on <u>type 1</u> and <u>type 2</u> base floors): 3+3 mm, 5+3mm or 5+5 mm extruded PE membranes

Floating screed: 7 to 8 cm cement-bounded

Floor finishing: tiling or parquet



Graph 3: Average spectrum of the standardised level difference D_{nT} measured in situ on 23 well-executed traditional floating floors in Belgium. 95% of the measured values are situated inside the shaded zone.



Graph 4: Average spectrum of the standardised impact sound pressure level L'_{nT} measured in situ on 20 well-executed traditional floating floors in Belgium. 95% of the measured values are situated inside the shaded zone.

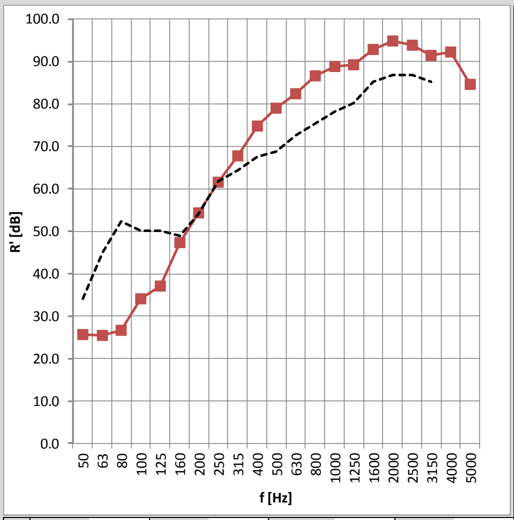
Since the data in both figures is largely based on the same set of floors, it is remarkable that the spread in impact sound level measurements largely exceeds the spread in airborne sound insulation measurements, especially at mid- and high frequencies. This points to the fact that impact sound insulation is particularly sensitive to small variations/errors during execution.

2.3.2 - Horizontal sound insulation

The sound insulation requirements between terraced houses are in several European countries higher than for apartments. The expectations of inhabitants are in general higher as well. In many countries, the sound insulation is solved by the use of tie-less double wall constructions with a complete decoupling from the foundations until the roof. This results in very high sound insulations. Impact noise is then no problem, except at the lowest floor if building guidelines are not well followed (floating floor necessary, special measures to be taken for foundations and concrete slabs). Low–rise apartment buildings most often use the same technique for common walls between apartments.

LWTF-constructions discussed in the next chapters also use techniques of complete horizontal decoupling between apartments and terraced houses.

Unfortunately, we do not dispose of a similar study as the one for the performance in the vertical direction. We will just use a typical result for the sound insulation in the horizontal direction of a construction with two typical brick walls of 14 cm (1200 kg/m³) and a cavity of 4 cm, partly filled up with 2 cm of glass wool. Similar constructions are most often used between apartments. If well executed, these constructions offer sound insulations that are far above what is required. LWTF constructions should not attain such high sound insulations to be good. So if the reference graph is shown, the only purpose is to show the different shape of the insulation graph of the LWTF –construction compared to the heavy weight tie-less wall. A lower LWTF-insulation graph than the reference graph for these horizontal insulations does not say anything about eventual acoustic discomfort.



f [Hz]	1	2
50	25.7	34.1
63	**25.5**	**44.9**
80	26.7	52.3
100	34.0	50.1
125	**37.0**	**50.1**
160	47.3	48.8
200	54.3	54.2
250	**61.6**	**61.7**
315	67.8	64.3
400	74.9	67.5
500	**79.1**	**68.7**
630	82.5	72.7
800	86.7	75.4
1000	**88.8**	**78.3**
1250	89.3	80.3
1600	92.8	85.2
2000	**94.9**	**86.7**
2500	93.9	86.9
3150	91.5	85.2
4000	**92.3**	
5000	84.6	

1	R'_{living}= 56 dB	$C_{50\text{-}5000}$= -9 dB	$C_{100\text{-}3150}$= -6 dB	R'_w= 65 dB
2	R'_{living}= 68 dB	$C_{50\text{-}5000}$= -2 dB	$C_{100\text{-}3150}$= -2 dB	R'_w= 70 dB

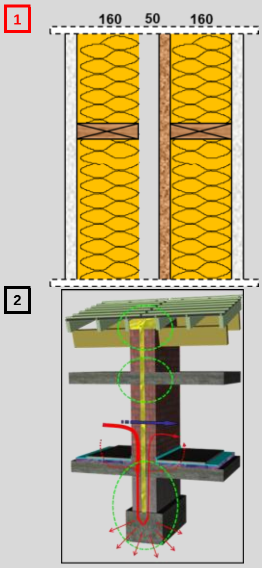
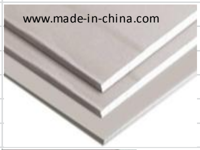
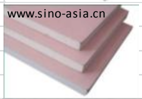
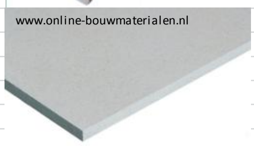
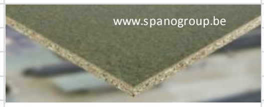
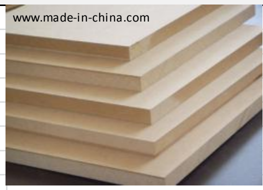
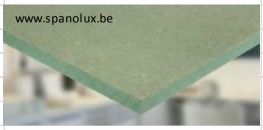


Figure 6: comparison between the sound insulation R' of two compartment walls: (1) of a lightweight timber frame wall; (2) of a traditional tie-less brick construction as a typical compartment wall between two terraced houses or apartments (reference graph)

2.4 - Characteristics of materials used in LWTF constructions

There are a large variety of boards available to be used in LWTF constructions. It is most useful to know there material properties, for instance for the calculations of mass-spring-mas resonance frequencies etc. In the last table, average densities were calculated for common used boards in LWTF constructions.

Gypsum board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
Gypsum board												
standard	9.5	790	7.5		3530	0.5	2114	336	2797		Gyproc	Rigips Bauplatten 9.5
	9.5	740	7.0	> 2200	> 2800						Knauf	GKB A10
	12.5	760	9.5		3530	0.5	2155	766	2085		Gyproc	Rigips Bauplatten 12.5
	12.5	720	9.0	> 2200	> 2800						Knauf	GKB A13
	15	900	13.5								Knauf	GKB A15
	18	915	16.5								Knauf	GKB A18
fire resistant (RF)	12.5	808	10.1								Gyproc	RF 12.5
	12.5	840	10.5								Knauf	GKF 13
	15	866	13.0								Gyproc	RF 15
	15	900	13.5								Knauf	GKF 15
fibre reinforced	10	1150	11.5		3900						Knauf	Vidiwall
	12.5	1150	14.4		3900						Knauf	Vidiwall
	15	1150	17.3		3900						Knauf	Vidiwall
	10	1200	12.0	3500	4500						Gyproc	Rigidur
	12.5	1200	15.0	3500	4500						Gyproc	Rigidur
	15	1200	18.0	3500	4500						Gyproc	Rigidur
	10	1150	11.5								Fermacell	Gipsvezelplaat
	12.5	1150	14.4								Fermacell	Gipsvezelplaat
	15	1150	17.3								Fermacell	Gipsvezelplaat
	18	1150	20.7								Fermacell	Gipsvezelplaat
Particle board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
standard	8	730	5.84		1800						Spano	Standard E1
	10	710	7.1		1800						Spano	Standard E1
	12	690	8.28		1800						Spano	Standard E1
	15	660	9.9		1600						Spano	Standard E1
	18	660	11.88		1600						Spano	Standard E1
	19	650	12.35		1600						Spano	Standard E1
	22	650	14.3		1500						Spano	Standard E1
	25	650	16.25		1500						Spano	Standard E1
	28	640	17.92		1350						Spano	Standard E1
	38	640	24.32		1200						Spano	Standard E1
moisture resistant	10	740	7.4		2550						Spano	Durélis/Populair
	12	720	8.6		2550						Spano	Durélis/Populair
	15	720	10.8		2400						Spano	Durélis/Populair
	18	720	13.0		2400						Spano	Durélis/Populair
	19	700	13.3		2400						Spano	Durélis/Populair
	22	700	15.4		2150						Spano	Durélis/Populair
OSB	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
OSB/2	9	600	5.4	1400	3500						Norbord	Sterling OSB/2 Zero
	11	600	6.6	1400	3500						Norbord	Sterling OSB/2 Zero
	12	600	7.2	1400	3500						Norbord	Sterling OSB/2 Zero
	15	600	9	1400	3500						Norbord	Sterling OSB/2 Zero
	18	600	10.8	1400	3500						Norbord	Sterling OSB/2 Zero
OSB/3	9	600	5.4	1400	3500						Norbord	Sterling OSB/3 Zero
	12	600	7.2	1400	3500						Norbord	Sterling OSB/3 Zero
	15	600	9.0	1400	3500						Norbord	Sterling OSB/3 Zero
	16	600	9.6	1400	3500						Norbord	Sterling OSB/3 Zero
	18	600	10.8	1400	3500						Norbord	Sterling OSB/3 Zero
	22	600	13.2	1400	3500						Norbord	Sterling OSB/3 Zero
	25	600	15.0	1400	3500						Norbord	Sterling OSB/3 Zero
OSB/4	12	620	7.4	1900	4800						Norbord	Sterling OSB/4 Zero
	15	620	9.3	1900	4800						Norbord	Sterling OSB/4 Zero
	18	620	11.2	1900	4800						Norbord	Sterling OSB/4 Zero
	22	620	13.6	1900	4800						Norbord	Sterling OSB/4 Zero
	25	620	15.5	1900	4800						Norbord	Sterling OSB/4 Zero

MDF	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
standard	6	800	4.8		3650	0.25	2136	70	4900		Spanolux	Standaard MDF LA
	7.5	780	5.9		3650	0.25	2163	137	3871		Spanolux	Standaard MDF LA
	9	750	6.8		3650	0.25	2206	237	3163		Spanolux	Standaard MDF LA
	10.5	740	7.8		3650	0.25	2221	376	2693		Spanolux	Standaard MDF LA
	12	730	8.8		3650	0.25	2236	561	2341		Spanolux	Standaard MDF LA
	15	720	10.8		3650	0.25	2252	1095	1860		Spanolux	Standaard MDF LA
	16	720	11.5		3650	0.25	2252	1329	1743		Spanolux	Standaard MDF LA
	17	720	12.2		3650	0.25	2252	1594	1641		Spanolux	Standaard MDF LA
	18	720	13.0		3650	0.25	2252	1892	1550		Spanolux	Standaard MDF LA
	19	720	13.7		3650	0.25	2252	2225	1468		Spanolux	Standaard MDF LA
	22	690	15.2		3650	0.25	2300	3455	1241		Spanolux	Standaard MDF LA
	25	690	17.3		3650	0.25	2300	5069	1092		Spanolux	Standaard MDF LA
	28	690	19.3		3650	0.25	2300	7122	975		Spanolux	Standaard MDF LA
	30	690	20.7		3650	0.25	2300	8760	910		Spanolux	Standaard MDF LA
moisture resistant	6	810	4.9		3000						Spanolux	MDF Umidax
	8	790	6.3		3000						Spanolux	MDF Umidax
	9	760	6.8		3000						Spanolux	MDF Umidax
	10	750	7.5		2800						Spanolux	MDF Umidax
	12	740	8.9		2800						Spanolux	MDF Umidax
	15	730	11.0		2700						Spanolux	MDF Umidax
	16	730	11.7		2700						Spanolux	MDF Umidax
	18	730	13.1		2700						Spanolux	MDF Umidax
	19	730	13.9		2700						Spanolux	MDF Umidax
	22	700	15.4		2600						Spanolux	MDF Umidax
	25	700	17.5		2600						Spanolux	MDF Umidax
	30	700	21.0		2600						Spanolux	MDF Umidax
fire retardant	6	820	4.9		3000						Spanolux	MDF Firax
	9	770	6.9		3000						Spanolux	MDF Firax
	10	760	7.6		2800						Spanolux	MDF Firax
	12	750	9.0		2800						Spanolux	MDF Firax
	15	740	11.1		2500						Spanolux	MDF Firax
	16	740	11.8		2500						Spanolux	MDF Firax
	18	740	13.3		2500						Spanolux	MDF Firax
	19	740	14.1		2500						Spanolux	MDF Firax
	22	710	15.6		2300						Spanolux	MDF Firax
	25	710	17.8		2300						Spanolux	MDF Firax
	30	710	21.3		2300						Spanolux	MDF Firax
Wood fibre cement board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
	8	1250	10.0		4500						Eternit	Duripanel
	10	1250	12.5		4500						Eternit	Duripanel
	12	1250	15.0		4500						Eternit	Duripanel
	14	1250	17.5		4500						Eternit	Duripanel
	16	1250	20.0		4500						Eternit	Duripanel
	18	1250	22.5		4500						Eternit	Duripanel
	20	1250	25.0		4500						Eternit	Duripanel
	22	1250	27.5		4500						Eternit	Duripanel
	24	1250	30.0		4500						Eternit	Duripanel
	25	1250	31.3		4500						Eternit	Duripanel
	28	1250	35.0		4500						Eternit	Duripanel
	32	1250	40.0		4500						Eternit	Duripanel
	36	1250	45.0		4500						Eternit	Duripanel
	40	1250	50.0		4500						Eternit	Duripanel
Organic fibre cement board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
	6	1417	8.5	10000	10000						Eternit	Hydropanel
	9	1411	12.7	10000	10000						Eternit	Hydropanel
	12	1417	17.0	10000	10000						Eternit	Hydropanel
Plywood board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
	12	460	5.5	1200	8400						Finnforest	Spruce plywood
	15	460	6.9	2496	9504						Finnforest	Spruce plywood
	18	460	8.3	3111	8889						Finnforest	Spruce plywood
	21	460	9.7	3464	8536						Finnforest	Spruce plywood
	24	460	11.0	3563	8438						Finnforest	Spruce plywood
	27	460	12.4	4016	7984						Finnforest	Spruce plywood
	30	460	13.8	4224	7776						Finnforest	Spruce plywood

Cross laminated timber panels	dikte mm	ρ kg/m³	m" kg/m²	$E_{\perp}$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
	85	420									Finnforest	Leno
	100	400-550									Egoin	Ego_CLT
	100	470-500									KLH	
	75 - 217	470									HMS	
Wood fibre insulation board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_{\perp}$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
	18	270	4.9								Celit	3D (wanden, vloeren)
	22	270	5.9								Celit	4D (onderdak)
	36	250	9.0								Hunton	Silencio 36

Average density of materials:

Material	class	ρ (average) kg/m³
Gypsum board	standard	750
	fire resistant (RF)	850
	fibre reinforced	1150
Particle board	standard	675
	moisture resistant	720
OSB	OSB/2 & OSB/3	600
	OSB/4	620
MDF	standard	725
	moisture resistant	735
	fire retardant	745
Wood fibre cement board		1250
Organic fibre cement board		1400
Plywood board		460
Cross laminated timber panels		450
Wood fibre insulation board		260

3 - TERRACED HOUSES SOLUTIONS

3.1 - General

3.1.1 - Introduction

All over Europe, minimal requirements exist for the sound insulation between terraced houses. In some European countries, these basic criteria are even higher than for the sound insulation between apartments (see section 1). But only a few countries have criteria for the sound insulation between rooms of the same dwelling and even then these values are easy to attain with LWTF constructions.

So the main focus should be on the acoustic optimisation of the party wall (and of course on other acoustic aspects such as equipment noise…).

Some LWTF manufacturers/contractors use a construction consisting of a heavy wall 'sandwiched' between the LWTF walls of the terraced houses. This gives a very good sound insulation, even in the low frequencies. But this kind of construction is not frequently met, it is moreover expensive and makes for very thick party walls that are time-consuming to construct.

So most constructions have party walls made of studs and boards. Building light and having good acoustic sound insulation is possible. But a general rule in acoustics is that the lighter you build, the more acoustic knowledge and craftsmanship you need to make things work. So if you are not familiar with acoustics, we advise you to read the next chapter to be able to fully understand the rest of this report.

3.1.2 - Some basic notions about the direct airborne sound insulation of walls

There are two main strategies to minimize the airborne sound transmission through a wall. One can use either an 'acoustic single wall', or an 'acoustic double wall' technology.

a) SINGLE WALLS: The acoustic performance of single walls is illustrated by the figures 7 'a' (the sound reduction index R of a single gypsum board of 12.5 mm and of two gypsum boards of 12.5 mm screwed together) and 'b' (examples with 1x18 mm hardboard, 2x18 mm hardboard screwed together and 1x36 mm hardboard). The maximum attainable sound insulation of single walls is mainly determined by the surface mass of the wall and its bending stiffness.

The first part of the sound reduction index spectrum R is governed by the *mass law*: it shows a steady increase of theoretically a maximum of 6 dB for every doubling of frequencies (in practice always a bit less).

In the second part of the spectrum, a deterioration in the sound insulation -called the *coincidence dip*- occurs around the *critical frequency*[1]. The coincidence dip is in both figures indicated by a '**c**'. The critical frequency depends on the surface mass and the bending stiffness of the wall. If boards of the same material are used, then the critical frequency and its coincidence dip will shift towards the lower frequencies for thicker panels (this is less advantageous for the sound insulation). If two hardboards are screwed together (figure 7 'b'), the coincidence dip will remain at the same place as for the individual hardboard as the boards still react independently. If rigidly glued, they will behave as a single hardboard of 36 mm thickness and the critical frequency will shift towards the lower frequencies.

The mass law also states that when the surface mass of the panel is doubled (e.g. figure 7'a'), then the sound reduction index for each frequency will increase theoretically with a maximum of 6 dB (in practice always less and this of course only in the area below the coincidence dip).

In order to obtain sufficient sound insulation for a compartment wall, surface masses of 500 kg/m² are necessary, far above the surface masses typically for LWTF constructions. So the second type of technology, i.e. 'acoustic double walls' is to be used.

b) Just an ordinary double wall will not do. There are some requirements to be fulfilled in order to obtain better performances than that of the single wall with the same surface mass. Perfect double walls behave as *mass-spring-mass systems* and have a sound reduction index spectrum that is characterized by the *mass-spring-mass resonance* provoking a deep dip in the sound insulation at the resonance frequency f_r (in the low frequencies in all the graphs below and indicated by 'r' in figure 7'c'). The sound reduction then increases very rapidly (theoretically with a maximum of 18 dB per doubling of frequency, in practice less). The coincidence dips of both panels of the double wall are visible in the spectrum (dips in the mid or high frequency range of the spectrum). Real walls behave slightly differently and in order to optimize the double wall acoustically, it is necessary to keep in mind the following parameter influences, illustrated by the different figures 'a' to 'g' below.

1) First of all, the *degree of structural decoupling* is important. This is illustrated by figure 7'c': in graph 3 both sides of the wall are rigidly connected by the studs. This results in a 12 dB lower R_w than in graph 1 where both sides of the wall are on separate studs and totally disconnected. The wall of which graph 2 represents the sound reduction index is somewhere in between both previous examples, but with still a 7 dB lower performance than the perfectly disconnected situation represented

[1] The 'why' of this all cannot be explained here. We refer to acoustic literature such as 'Sound Insulation' – Carl Hopkins - Elsevier ISBN 978-0-7506-6526-1 and/or 'Noise and Vibration Control Engineering' – I.M. Vér & L.L. Beranek – Wiley ISBN 13 978-0-471-44942-3

by graph 1: the staggered studs only have a rigid connection above and below the wall.

The more rigid the composing walls/panels, the more each rigid contact will diminish the maximal attainable sound insulation. This has to do with the structural transmission of vibrational power through the rigid connection and the radiation efficiency back to airborne sound of the wall at the reception side. A number of parameters come into play here, but it is good to know that increasing bending stiffness means that good radiation efficiency (the transformation of vibrations back into airborne sound) starts at ever lower frequencies. So a rigid connection between two very bending stiff walls such as masonry will almost annihilate all possible acoustic gain with the double wall construction. Less bending stiff materials such as boards will allow for some structural coupling between the two composing walls and still maintain some acoustic 'double wall' effect.

2) *Increasing the surface mass of the constituting walls* is another important aspect in obtaining not only a higher sound insulation in general, but *in combination with sufficient cavity width*, it also allows for better low frequency sound insulation. This is illustrated in figure 7 'g'. the additional gypsum on both sides of the wall results in an increase of 9 dB in R_{living}!

Both constituting masses will resonate on the spring constituted by the air in the cavity (or eventual elastic fixing) and provoke a sharp diminishment at this resonance frequency.

The sound insulation will increase dramatically beyond this resonance frequency f_r, (theoretically up to 18 dB per doubling of frequency, limited by coincidence effects, high frequency three room transmission…). As low frequency insulation is the problem, the choices of cavity width d [m] and surface masses m_1' and m_2' [kg/m²] of both panels should be made in such a way that the resonance frequency f_r occurs as low as possible and preferably way below 50 Hz. A simple formula (for pragmatic semi-diffuse sound incidence) allows for the calculation of this resonance frequency:

$$f_r \approx \frac{75}{\sqrt{d}} \cdot \sqrt{\frac{1}{m_1''} + \frac{1}{m_2''}} \text{ [Hz]}$$

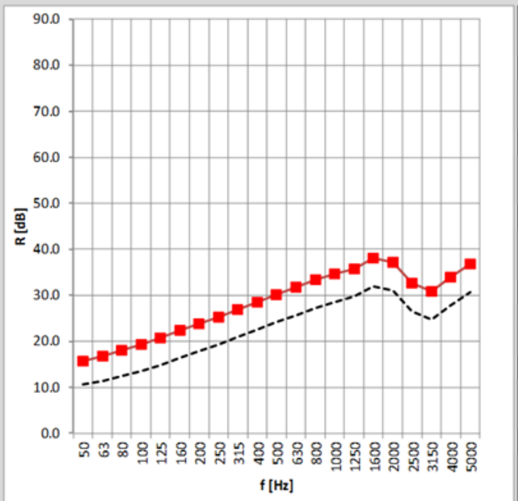
One can easily see that large cavities will be necessary and that an economically optimized choice means symmetrical surface masses at both sides of the cavity. This is illustrated by the figures 7'f' where the wider cavity results in the resonance dip getting situated below 50 Hz with the resulting gain in sound insulation. Adding extra mass has similar effects as illustrated in figure 7'g' with one extra gypsum board on both portions of the wall.

3) The *use of an acoustic absorbing, flexible material* such as mineral wool, cellulose fibres etc. in the cavity also increases greatly the sound insulation when there are no rigid connections between both sides of the wall (figure 7'd'). The acoustically

absorbing material avoids cavity resonances. The greatest gain is obtained with the first centimetres of an acoustic absorbing material, but further filling will still increase the sound insulation in the situation of completely disconnected wall portions.

Unfortunately, this gain can be rather limited or non-existent when major rigid connections exist between both parts of the wall. Inserting 5 cm mineral wool in the cavity in figure 'e' only results in a gain of 5 dB in R_w, far less than the 15 dB in figure 7'd'. This is due to the structural transmission through the studs.

Of course when the whole cavity is filled with this material, it needs to be flexible enough not to increase the coupling between both walls. As thermal and often fire requirements require the placing of some thermal insulation in the cavity, one should take care that this fulfils the necessary conditions mentioned here above. The use of rigid and/or non-acoustically absorbing thermal insulation materials such as certain PU or EPS can dramatically diminish the direct and flanking sound insulation of walls (party walls, façades).



1	R_{living}= 32 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 33 dB
2	R_{living}= 26 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 27 dB

f [Hz]	1	2
50	15.7	10.6
63	**16.7**	**11.4**
80	18.0	12.4
100	19.3	13.5
125	**20.7**	**14.8**
160	22.3	16.4
200	23.8	17.8
250	**25.3**	**19.3**
315	26.9	20.9
400	28.6	22.6
500	**30.2**	**24.2**
630	31.7	25.7
800	33.3	27.3
1000	**34.6**	**28.6**
1250	35.7	29.7
1600	38.0	32.0
2000	**37.1**	**31.0**
2500	32.7	26.6
3150	30.8	24.7
4000	**33.9**	**27.8**
5000	36.8	30.7

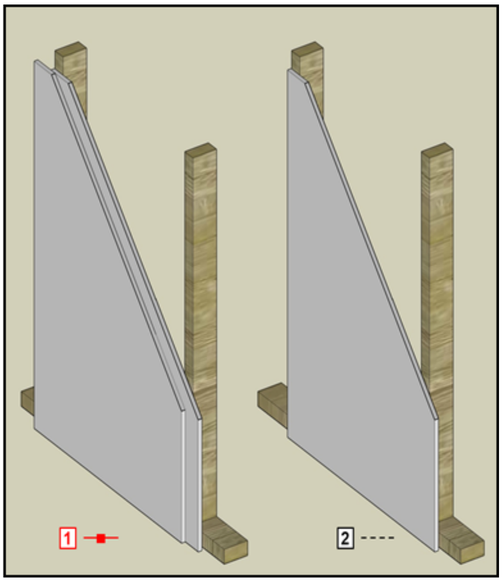
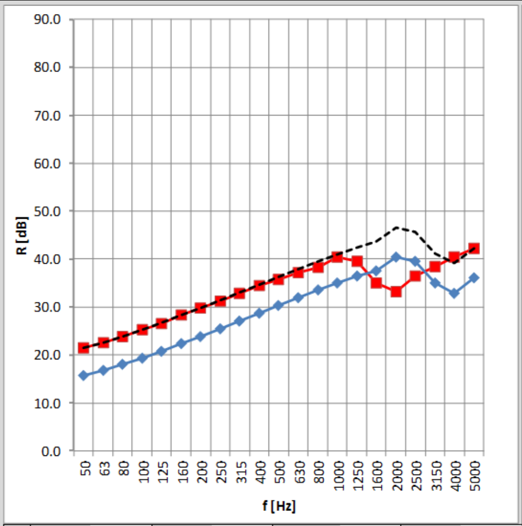


Figure 7a - SINGLE WALLS: illustration of mass law and of the coincidence dip (indicated by 'c'). The critical frequency of two panels screwed together (not glued) remains the same as that of the single panel: R of 1 gypsum board of 12.5 mm (graph 2) en 2 gypsum boards (2 x12.5 mm) screwed together (graph 1). [Simulation by INSUL 6.3 program (Marshall Day Acoustics)]



f [Hz]	1	2	3
50	21.4	21.4	15.7
63	**22.6**	**22.6**	**16.7**
80	23.9	23.9	18.0
100	25.2	25.2	19.3
125	**26.6**	**26.7**	**20.7**
160	28.3	28.3	22.3
200	29.7	29.8	23.8
250	**31.3**	**31.4**	**25.4**
315	32.8	33.0	27.0
400	34.4	34.7	28.7
500	**35.8**	**36.3**	**30.3**
630	37.2	37.9	31.9
800	38.3	39.6	33.6
1000	**40.5**	**41.0**	**35.0**
1250	39.6	42.4	36.4
1600	35.1	43.6	37.6
2000	**33.2**	**46.5**	**40.5**
2500	36.5	45.6	39.5
3150	38.4	41.2	35.0
4000	**40.5**	**39.1**	**32.9**
5000	42.3	42.3	36.1

1	R_{living}= 36 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 37 dB
2	R_{living}= 39 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 40 dB
3	R_{living}= 33 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 34 dB

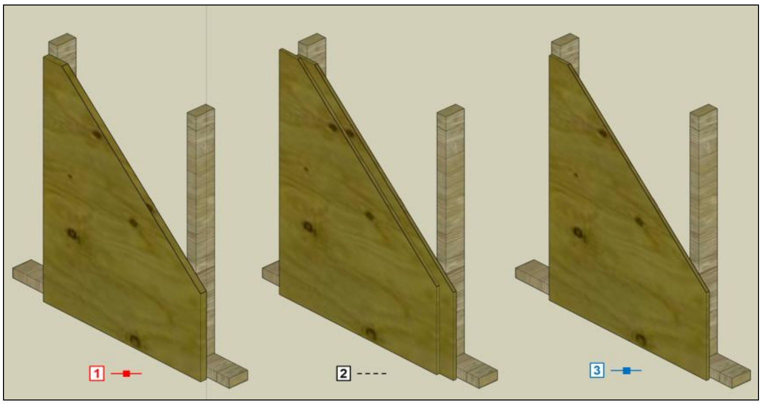
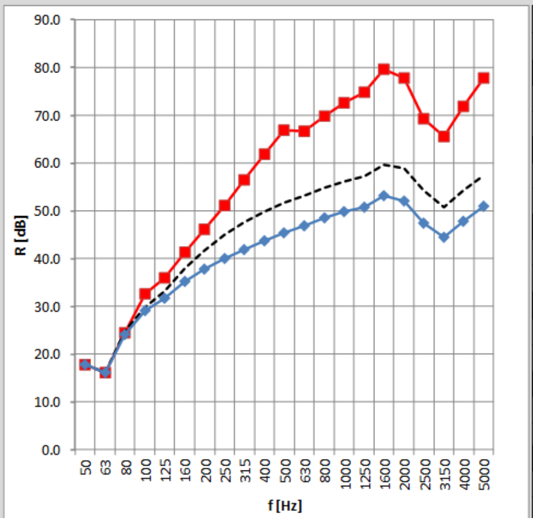


Figure 7b - SINGLE WALLS: the critical frequency decreases with the thickness for the same material. R of a single hardboard of 36 mm (graph 1); R of 2 hardboards of 18 mm screwed (not glued!) together (graph 2); R of a single hardboard of 18 mm (graph 3). [Simulation by INSUL 6.3 program (Marshall Day Acoustics)]



f [Hz]	1	2	3
50	17.8	17.8	17.8
63	**16.2**	**16.2**	**16.2**
80	24.4	24.9	24.1
100	32.6	29.9	29.1
125	**36.0**	**33.1**	**31.6**
160	41.3	37.9	35.2
200	46.2	41.7	37.8
250	**51.2**	**45.0**	**40.0**
315	56.4	47.6	41.9
400	61.8	49.9	43.7
500	**66.8**	**51.7**	**45.3**
630	66.6	53.2	46.9
800	69.8	54.9	48.5
1000	**72.6**	**56.2**	**49.8**
1250	74.9	57.3	50.8
1600	79.7	59.7	53.1
2000	**77.8**	**58.8**	**52.1**
2500	69.2	54.3	47.4
3150	65.6	50.8	44.5
4000	**71.8**	**54.2**	**47.7**
5000	77.7	57.5	51.0

1	Rliving= 50 dB	50-5000= -10 dB	100-3150= -3 dB	Rw= 60 dB
2	Rliving= 48 dB	50-5000= -5 dB	100-3150= -2 dB	Rw= 53 dB
3	R_{living}= 45 dB	$C_{50-5000}$= -3 dB	$C_{100-3150}$= -2 dB	R_w = 48 dB

Figure 7c1 – Graph 1: completely decoupled double wall / Graph 2: staggered constructions only connected on top and below the wall. / Graph 3: studs connect both wall portions. Coincidence dips are marked by 'c', the mass-spring-mass resonance dip is marked by 'r'.

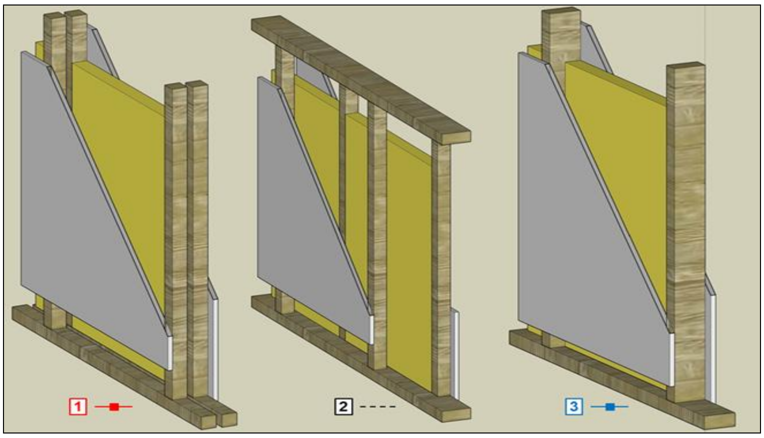
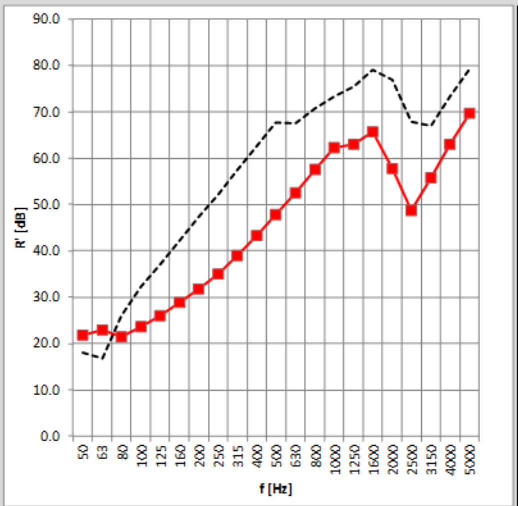


Figure 7c2 – DOUBLE WALLS: the more rigid connections are present, the bigger the losses in sound reduction index.

[Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	21.9	18.0
63	23.0	16.7
80	21.5	25.9
100	23.7	32.3
125	26.0	37.0
160	28.8	42.3
200	31.7	47.2
250	35.1	52.2
315	38.9	57.4
400	43.4	62.7
500	47.8	67.7
630	52.5	67.5
800	57.5	70.7
1000	62.3	73.3
1250	63.0	75.4
1600	65.7	79.1
2000	57.8	76.9
2500	48.8	67.9
3150	55.8	67.0
4000	63.0	73.3
5000	69.7	79.2

1	R'_{living}= 45 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R'_w = 46 dB
2	R'_{living}= 51 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -4 dB	R'_w = 61 dB

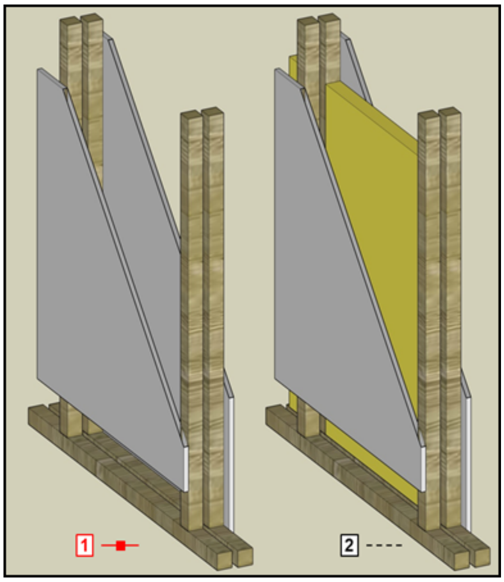
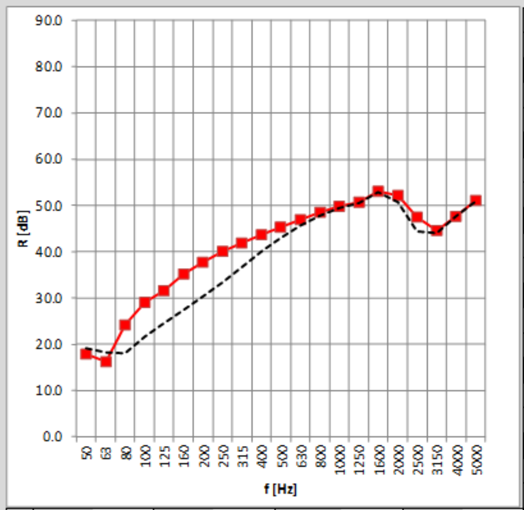


Figure 7d – DOUBLE WALLS: adding an acoustic absorbent increases dramatically the sound reduction index R when both wall portions are disconnected. [Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	17.8	19.1
63	16.2	18.2
80	24.1	18.1
100	29.1	21.7
125	31.6	24.6
160	35.2	27.5
200	37.8	30.3
250	40.0	33.3
315	41.9	36.6
400	43.7	40.1
500	45.3	43.0
630	46.9	45.7
800	48.5	47.9
1000	49.8	49.5
1250	50.8	50.5
1600	53.1	52.8
2000	52.1	50.8
2500	47.4	44.4
3150	44.5	44.1
4000	47.7	47.6
5000	51.0	50.9

1	R_{living}= 45 dB	$C_{50\text{-}5000}$= -3 dB	$C_{100\text{-}3150}$= -2 dB	R_w = 48 dB
2	R_{living}= 42 dB	$C_{50\text{-}5000}$= -1 dB	$C_{100\text{-}3150}$= -1 dB	R_w = 43 dB

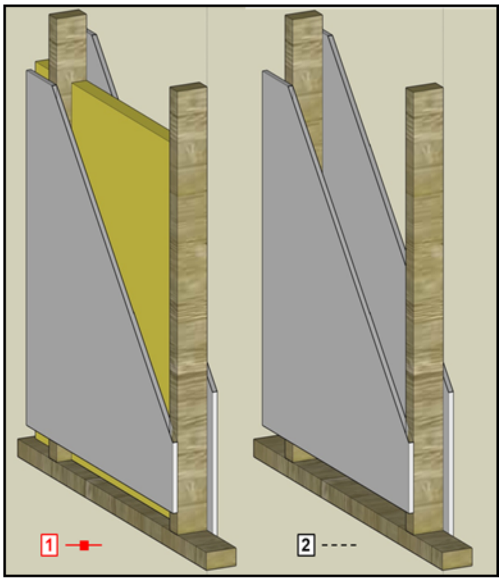
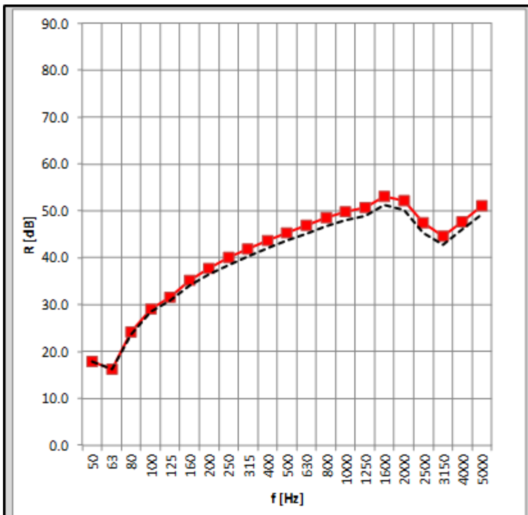


Figure 7e- DOUBLE WALLS: filling up the cavity with some acoustic absorbent can increase the sound reduction index even when there are rigid connections, though the effect is far less important than with disconnected walls (figure d). [Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	17.8	17.8
63	16.2	16.2
80	24.1	23.7
100	29.1	28.6
125	31.6	30.9
160	35.2	34.1
200	37.8	36.4
250	40.0	38.4
315	41.9	40.2
400	43.7	42.0
500	45.3	43.6
630	46.9	45.2
800	48.5	46.7
1000	49.8	48.1
1250	50.8	48.9
1600	53.1	51.2
2000	52.1	50.2
2500	47.4	45.3
3150	44.5	42.7
4000	47.7	46.0
5000	51.0	49.3

1	R_{living}= 45 dB	$C_{50\text{-}5000}$= -3 dB	$C_{100\text{-}3150}$= -2 dB	R_w = 48 dB
2	R_{living}= 44 dB	$C_{50\text{-}5000}$= -2 dB	$C_{100\text{-}3150}$= -1 dB	R_w = 46 dB

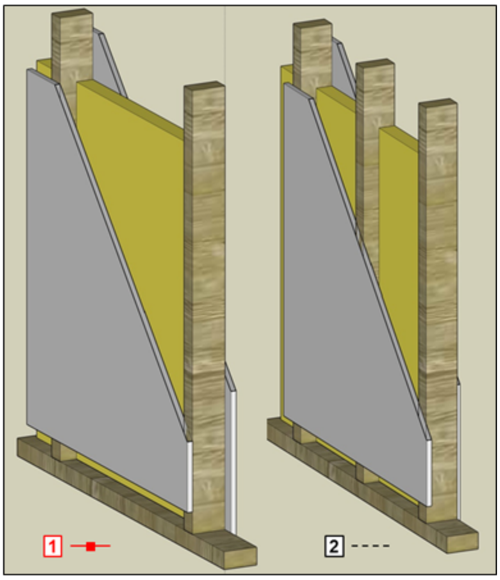
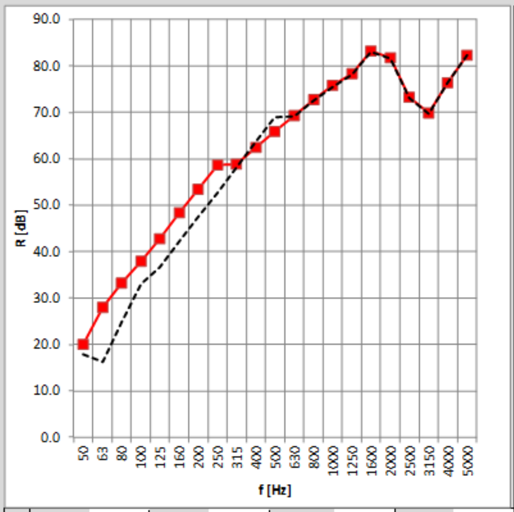


Figure 7f- DOUBLE WALLS: less rigid connections - for instance When the stud spacing increases, the number of rigid connections decreases which leads to a higher sound reduction index R. Graph 1 illustrates this effect for a stud spacing of 60 cm (o.c.), graph 2 shows the result for a stud spacing of 40 cm (o.c.). [Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	20.1	17.8
63	28.0	16.2
80	33.2	24.7
100	37.9	33.1
125	42.8	36.7
160	48.4	42.3
200	53.5	47.4
250	58.7	52.7
315	58.8	58.1
400	62.5	63.7
500	65.9	69.0
630	69.4	69.1
800	72.8	72.5
1000	75.8	75.5
1250	78.3	78.1
1600	83.3	83.1
2000	81.7	81.5
2500	73.2	73.1
3150	69.8	69.7
4000	76.3	76.3
5000	82.4	82.4

1	R_{living}= 58 dB	$C_{50-5000}$= -8 dB	$C_{100-3150}$= -3 dB	R_w = 66 dB
2	R_{living}= 51 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -3 dB	R_w = 61 dB

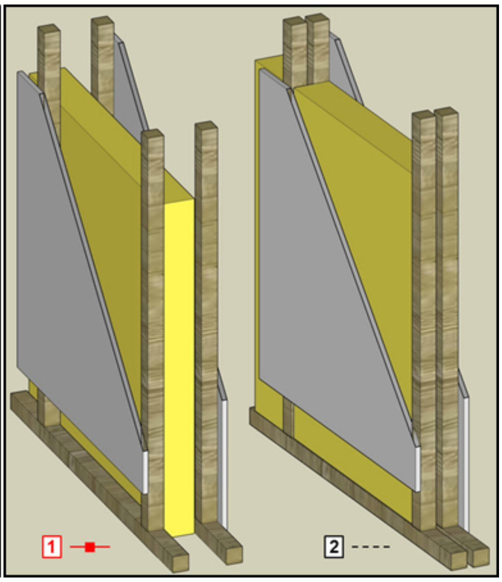
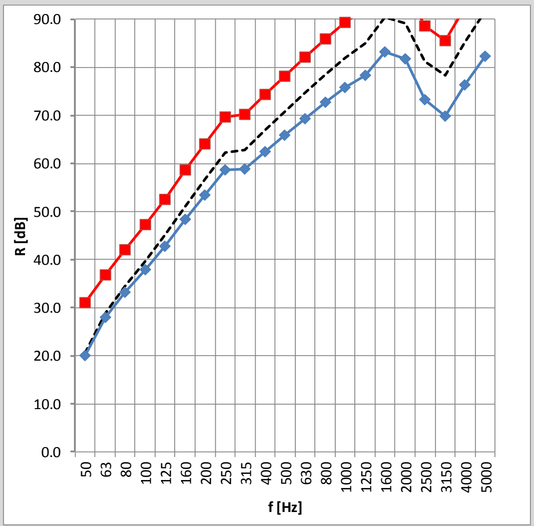


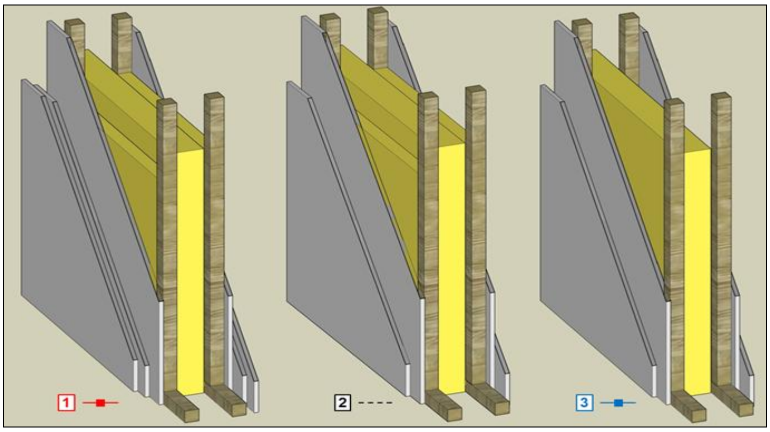
Figure 7f- DOUBLE WALLS: increasing the cavity width increases the sound insulation even in the very low frequencies. [Simulation with gypsum boards of 12.5 mm, mineral wool 10 cm, cavity width 10 cm for case 1 and 20 cm for case 2, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2	3
50	31.1	20.5	20.1
63	36.8	28.9	28.0
80	42.1	34.5	33.2
100	47.2	39.7	37.9
125	52.6	45.1	42.8
160	58.6	51.0	48.4
200	64.1	56.6	53.5
250	69.7	62.2	58.7
315	70.2	62.8	58.8
400	74.3	66.9	62.5
500	78.2	70.8	65.9
630	82.1	74.7	69.4
800	85.9	78.6	72.8
1000	89.3	82.0	75.8
1250	92.2	85.0	78.3
1600	97.7	90.4	83.3
2000	96.5	89.2	81.7
2500	88.6	81.2	73.2
3150	85.6	78.3	69.8
4000	92.5	85.2	76.3
5000	99.0	91.7	82.4

1	R_{living}= 68 dB	$C_{50-5000}$= -8 dB	$C_{100-3150}$= -3 dB	R_w = 76 dB
2	R_{living}= 59 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -4 dB	R_w = 69 dB
3	R_{living}= 58 dB	$C_{50-5000}$= -8 dB	$C_{100-3150}$= -3 dB	R_w = 66 dB

Figure 7g- DOUBLE WALLS: adding a supplementary thickness of acoustic absorbent (from graph 3 to graph 2) and more boards (from graph 2 to graph 1) allows for further increasing of the sound reduction index R. [Simulation with gypsum boards of 12.5 mm, mineral wool of 10 cm (case 3) and 20 cm (case 1 and 2), cavity width 20 cm,, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



3.2 - Internal partitions

As the boards typically used in LWTF constructions have a reasonably low bending stiffness, this means that internal partitions made of boards rigidly connected with wooden studs can be used and still maintain a better sound insulation than what could be deduced from mass law. The calculated performances of some constructions are given in the figures 7'c' (staggered solution), 'e' and 'f'. For internal partitions, this sound insulation is sufficient for basic acoustic comfort and complies with the standard requirements in most European countries (not many countries have requirements for internal partitions).

When the wall is not load carrying, the sound insulation can be increased using metal stud technology (or its improved versions).Some results are given in the table below. This could be a good idea for internal partitions that require a better than usual sound insulation, such as walls between waiting rooms and doctor and lawyers consulting rooms, but also between rooms with technical equipment (technical room with heating, pumps or ventilation devices, restrooms…) and other sensitive rooms.

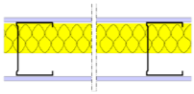
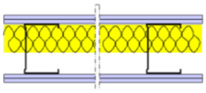
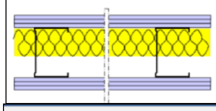
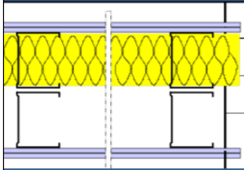
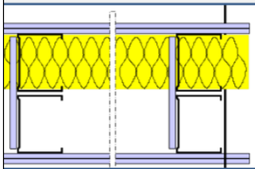
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	1 x 15 mm	40 mm	70 mm	-	34 (-1,-5)
	1 x 15 mm	40 mm	70 mm	30 mm	42 (-2,-7)
	1 x 12,5 mm	45 mm	70 mm	-	34 (-2,-6)
	1 x 12,5 mm	45 mm	70 mm	40 mm	41 (-3,-9)
	1 x 12,5 mm	50 mm	75 mm	-	34 (-2,-6)
	1 x 12,5 mm	50 mm	75 mm	40 mm	42 (-3,-10)
	1 x 12,5 mm	75 mm	100 mm	-	36 (-1,-6)
	1 x 12,5 mm	75 mm	100 mm	60 mm	43 (-4,-10)
	1 x 12,5 mm	100 mm	125 mm	-	38 (-1,-6)
	1 x 12,5 mm	100 mm	125 mm	75 mm	46 (-3,-9)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	2 x 12,5 mm	50 mm	100 mm	-	42 (-2,-7)
	2 x 12,5 mm	50 mm	100 mm	40 mm	50 (-2,-8)
	2 x 12,5 mm	75 mm	125 mm	-	45 (-2,-7)
	2 x 12,5 mm	75 mm	125 mm	60 mm	51 (-2,-8)
	2 x 12,5 mm	100 mm	150 mm	-	47 (-2,-6)
	2 x 12,5 mm	100 mm	150 mm	75 mm	52 (-3,-8)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	3 x 12,5 mm	50 mm	125 mm	-	45 (-2,-7)
	3 x 12,5 mm	50 mm	125 mm	40 mm	56 (-2,-7)
	3 x 12,5 mm	75 mm	150 mm	-	47 (-2,-7)
	3 x 12,5 mm	75 mm	150 mm	60 mm	57 (-2,-7)
	3 x 12,5 mm	100 mm	175 mm	-	49 (-2,-7)
	3 x 12,5 mm	100 mm	175 mm	75 mm	58 (-3,-8)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm	57(-6,-13)
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm + 40 mm	61 (-4,-11)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm	57 (-5,-13)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm + 40 mm	61 (-4,-10)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm	61 (-4,-10)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm + 60 mm	63 (-4,-11)
	2 x 12,5 mm	2 x 100 mm	255 mm	-	52 (-2,-7)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm	62 (-4,-10)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm + 75 mm	63 (-3,-10)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm	52 (-5,-13)
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm + 40 mm	55 (-5,-12)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm	53 (-6,-13)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm + 40 mm	55 (-4,-11)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm	54 (-3,-10)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm + 60 mm	57 (-4,-11)
	2 x 12,5 mm	2 x 100 mm	255 mm	-	52 (-3,-8)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm	55 (-3,-9)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm + 75 mm	57 (-3,-9)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	3 x 12,5 mm	2 x 100 mm	280 mm	-	58 (-2,-7)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm	65 (-3,-9)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm + 75 mm	66 (-4,-10)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	3 x 12,5 mm	2 x 100 mm	280 mm	-	57 (-2,-7)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm	59 (-3,-8)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm + 75 mm	60 (-3,-8)

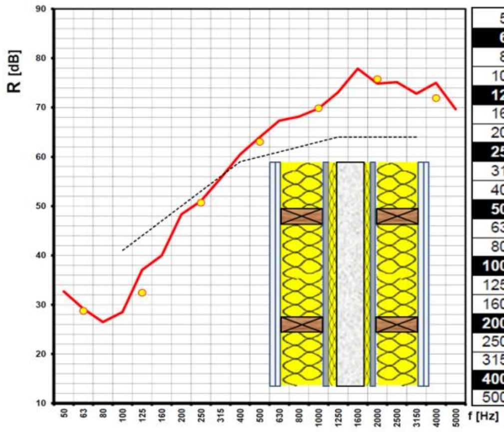
Figure 8: performances of gypsum board constructions (source: Belgisch Luxemburgse Gips Vereniging - Eenduidige geluidisolatie van gipskartonwanden. NBVG-BLGV-ABLG,Rijswijk/Kallo, s.d.)

3.3 - Party walls

The stud connection between the boards will anyhow reduce significantly the maximum attainable direct airborne sound insulation with the materials used. For party walls, this just will not do. Party walls need a complete structural decoupling. In the cases where some structural connection is absolutely necessary, this could be done in a more resilient way using elastic fixations etc.

3.3.1 - The intermediate heavy wall solution

This solution is not frequently met and its disadvantages (width, building cost, time) have already have been mentioned in the introduction. Its low frequency performance though is very good if a heavy concrete block is used. In the example below, only a 5 cm gas concrete element was used, giving moderate results in the low frequency band.



50	32.7
63	**29.2**
80	26.5
100	28.5
125	**37.0**
160	40.0
200	48.3
250	**51.0**
315	55.6
400	60.5
500	**64.0**
630	67.3
800	68.1
1000	**69.8**
1250	73.1
1600	77.9
2000	**74.9**
2500	75.1
3150	72.8
4000	**75.0**
5000	69.6

Figure 9: construction of the party wall composed of 5 cm gas concrete completed symmetrically on both sides with 20 mm glass wool, a cement board of 9 mm, studs of 90 mm x 40 mm and a cavity filled with mineral wool and finally 2 x 12.5 mm gypsum boards. Results: R_w= 60 dB $C_{50-5000}$=-6 dB (R_{living}=54 dB)

3.3.2 - Traditional party walls

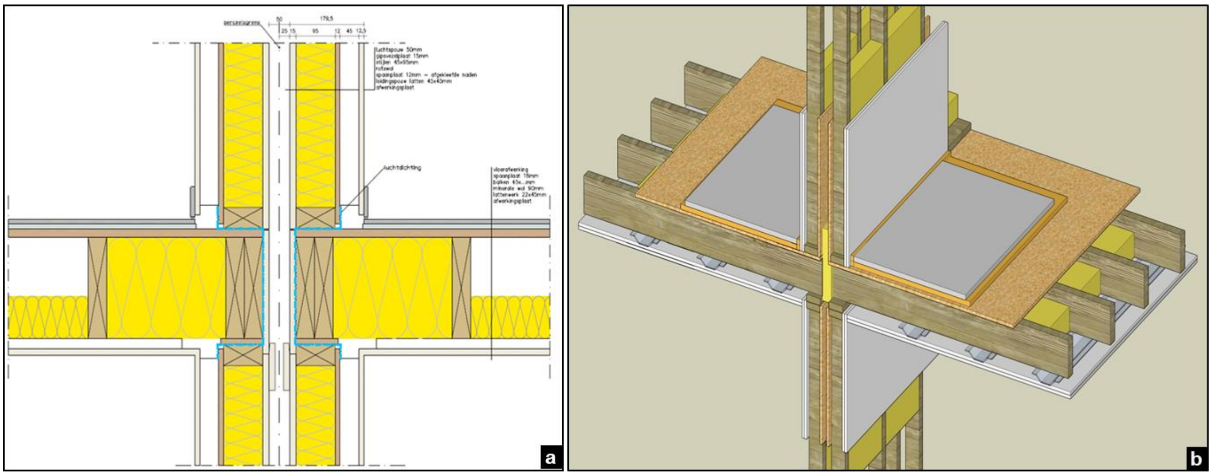
Many manufacturers all over Europe use a similar construction: the party wall is composed of a double stud wall, each stud wall (boards-studs-boards) belonging to one house and separated by a small cavity (e.g. figures 10 'a' and 'c') and allowing for a structural decoupling of both dwellings from the foundations to the roof.

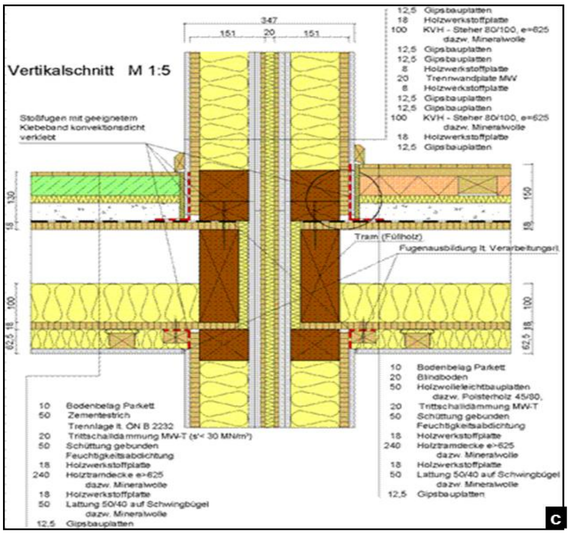
This simple concept has the advantage of solving the 'house independency" problem mentioned in section 2.2 and it offers a good fire protection.

Unfortunately, traditional party walls can have a problem with the low frequency sound insulation.

In several European countries, there are more severe requirements for the sound insulation between terraced houses than between apartments. Though in many countries, the requirements are limited to the frequency range above 100 Hz, this could probably change in the near future as a result of, for instance the on-going work of the prEN ISO 16717 series and the generally accepted view that sound insulation in the low frequency bands is crucial for the comfort of inhabitants (see introduction).

The low frequency sound insulation of the party walls is very much determined by the mass-spring-mass resonances of the different composing layers. These resonances should be well below 50 Hz to maximize comfort. If one wants to limit the number of boards (costs!), this means the necessity of large cavities. The traditional solution discussed here above (figure 10 'a') has normally a poor performance in these low frequencies due to the succession of cavities with a rather limited width.

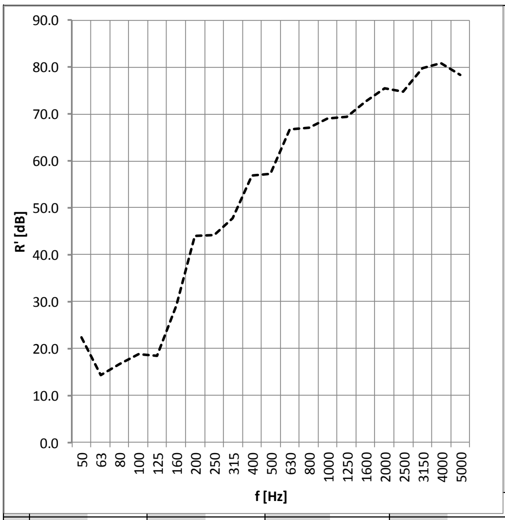




Figures 10: (a) and (b) this type of party wall has a rather poor sound insulation in the lower frequencies. (c) Typical Austrian 'heavy' construction with a small 2 cm central cavity filled with rock wool, surrounded on each side by a complex of an 8 mm rainproof wood panel, a fibre reinforced gypsum board and an RF gypsum board. On the sides of the rooms, the wall is composed of an 18 mm wooden board and a 12.5 mm gypsum board.

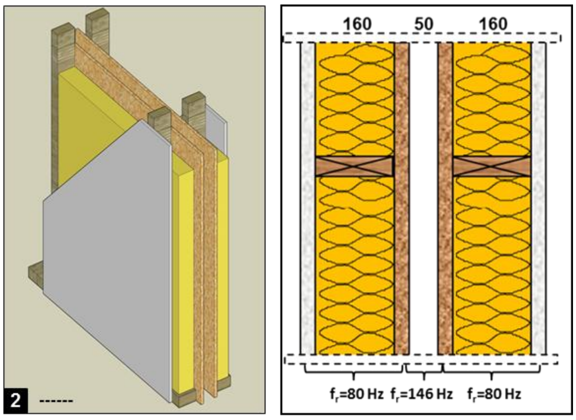
Using more boards ('the heavy' solution as in figure 10'b') allows for a good R_w and moderate performances at the low frequencies. In general, it is also a more expensive solution than the acoustic optimized solution with a large cavity (see below).

Note: in Canada, both leaves of the construction are sometimes connected by the continuous board from the floor of one house to the other. This of course diminishes dramatically the direct sound insulation and induces flanking transmission as well as impact sound to the adjacent dwelling. This continuous board is due to fire requirements to avoid *chimney effects and fire propagation in the cavity. But apparently, the use of rock wool is nowadays also tolerated and is beginning to be applied.*



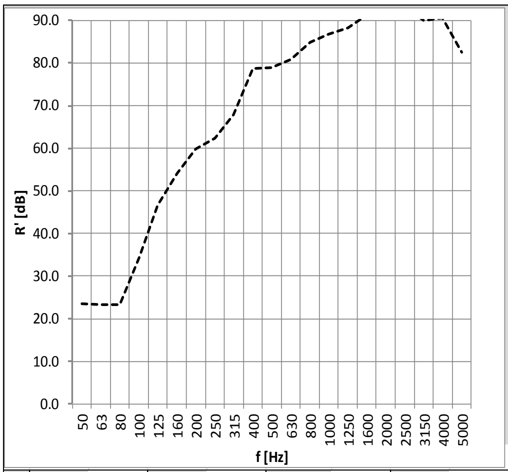
f [Hz]	2
50	22.4
63	**14.4**
80	16.7
100	18.9
125	**18.5**
160	29.1
200	44.0
250	**44.2**
315	47.8
400	56.9
500	**57.2**
630	66.7
800	67.0
1000	**69.0**
1250	69.4
1600	72.6
2000	**75.5**
2500	74.8
3150	79.8
4000	**80.9**
5000	78.3

2	R'living= 42 dB	50-5000= -6 dB	00-3150= -6 dB	R'w= 48 dB



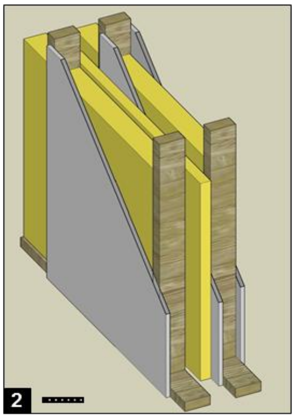
*1 x 12.5 mm fibre reinforced gypsum board *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm *** 1 x 15 mm OSB *** empty central 50 mm *** 1 x 15 mm OSB *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm ***1 x 12.5 mm fibre reinforced gypsum board*

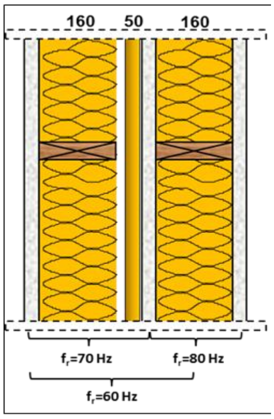
Figure 11- Some traditional party wall constructions have a poor sound insulation, especially in the low frequencies. This is due to the succession of resonance frequencies until the third octave band of 160 Hz (= resonance frequency of the OSB boards resonating on the empty cavity of 50 mm). Once the sound insulation index reaches 75 dB, the reception level becomes so low that the result is being influenced by the background noise (measurements on a mock-up installation project Mobic - BBRI).



f [Hz]	2
50	23.6
63	23.3
80	23.3
100	34.4
125	46.7
160	54.1
200	59.9
250	62.4
315	67.8
400	78.7
500	79.0
630	80.9
800	84.8
1000	86.8
1250	88.2
1600	91.3
2000	93.6
2500	93.3
3150	90.0
4000	90.7
5000	82.5

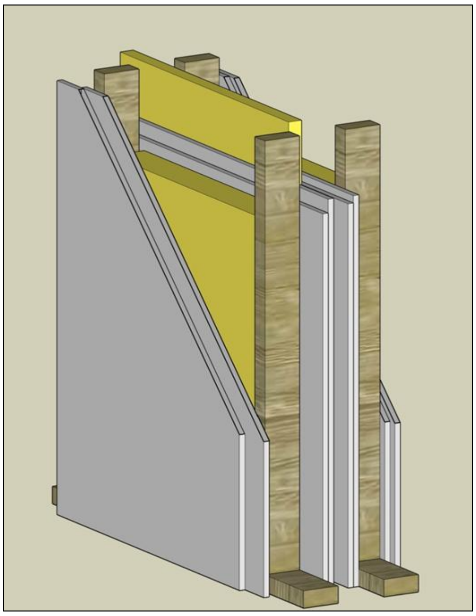
2 R'living= 54 dB 50-5000= -16 dB 100-3150= -7 dB R'w= 70 dB





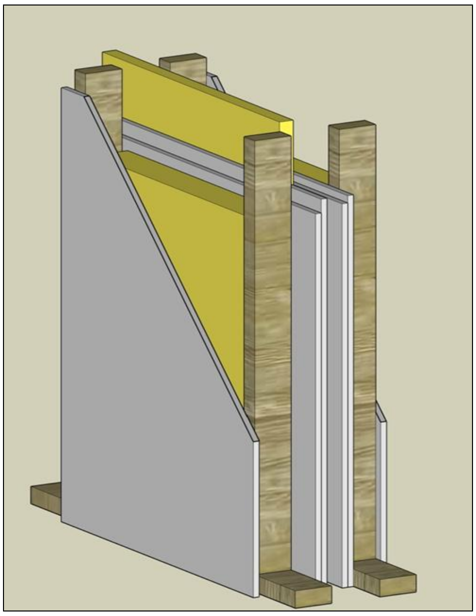
*1 x 12.5 mm fibre reinforced gypsum board *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm *** central cavity of 50 mm cavity filled with mineral wool 3 cm ca. 40 kg/m³ *** 1 x 12.5 mm fibre reinforced gypsum board *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm ***1 x 12.5 mm fibre reinforced gypsum board*

Figure 12-The disappearance of the small cavity of the previous figure greatly increase the sound insulation to $R'_{living}=R_w+C_{50-5000}$ = 54 dB although less boards have been used. These measurements have been done on a mock-up and might be influenced by indirect sound transmission. As such, the result might represent only the lower limit of the sound insulation. Once the sound insulation index reaches 75 dB, the reception level becomes so low that the result is being influenced by the background noise. (Measurements on a mock-up installation project Mobic - BBRI).



Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside):: 2x12.5 mm fibre reinforced gypsum board *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 2x12.5 mm fibre reinforced gypsum board.

Figure 13: typical Austrian party wall Rw (C;Ctr)=59(-2;-10) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).



Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside):: 1x12.5 mm fibre reinforced gypsum board *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 2x12.5 mm fibre reinforced gypsum board.

Figure 14: typical Austrian party wall Rw (C;Ctr)=58(-3;-11) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).

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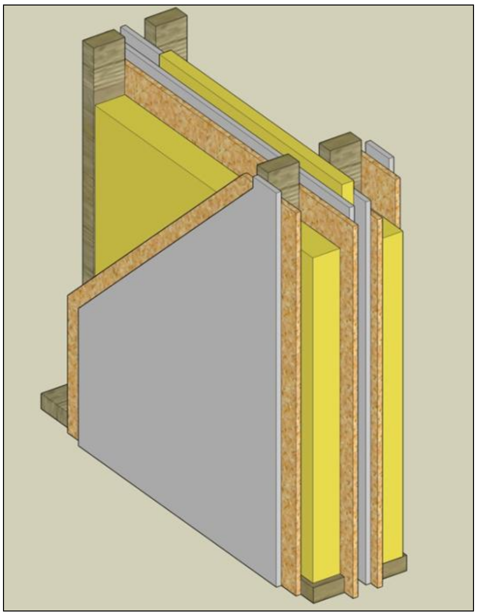

Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside): 1x12.5 mm fibre reinforced gypsum board + 1x15 mm OSB *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 1x15 mm OSB + 1x12.5 mm fibre reinforced gypsum board.

Figure 15: typical Austrian party wall Rw (C;Ctr)=59(-3;-10) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).
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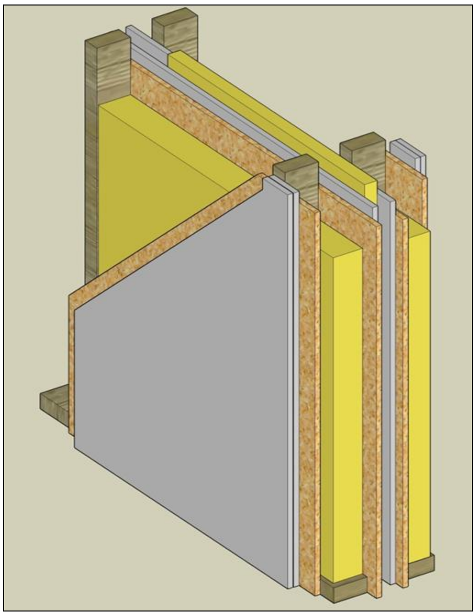

Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside): 1x12.5 mm fibre reinforced gypsum board + 1x15 mm OSB *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 1x15 mm OSB + 2x12.5 mm fibre reinforced gypsum board.

Figure 16: typical Austrian party wall Rw (C;Ctr)=60(-3;-10) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).
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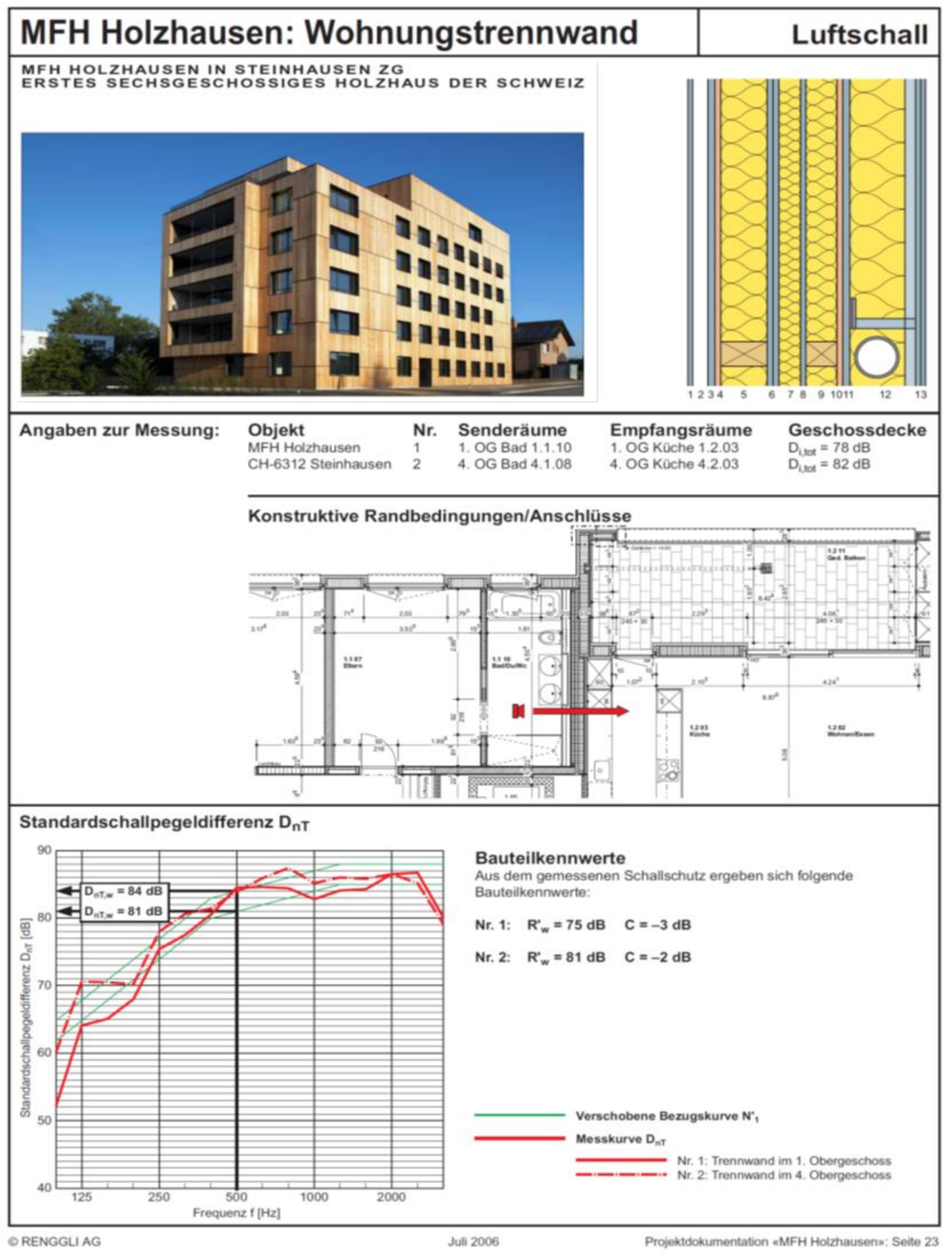


Figure 17: party wall construction in the first 6 floors high LWTF project in Steinhausen, Switzerland (MFZ Holzhausen, © Renggli AG, Sursee). Some words of explanation with the drawing: (1) Gypsum board 12.5 mm; (2) Cavity of 40 mm for technical reasons; (3) Gypsum board 18 mm; (4) OSB 15 mm; (5) Wooden stud and mineral wool 120 mm; (6) Gypsum fibre board 2 x 15 mm; (7) Mineral Wool 55 mm; (8) Gypsum fibre board 15 mm; (9) Wooden stud and mineral wool 80 mm; (10) OSB 15 mm; (11) Gypsum board 18 mm; (12) GYS system 170 mm with cavities filled with mineral wool; (13) Gypsum boards 2 x 12.5 mm.

3.3.3 - Party walls with a single large central cavity (and eventual technical linings)

One way of dramatically improving the low frequency performance is to shift all the boards on both sides of the central cavity of the common solution here above to the extreme sides of the party wall (see pictures in the middle and to the right in the figure below) with the cavity being filled up with rock wool. The possible advantages of this approach are shown in the figure below where the sound insulation increases by more than 20 dB and a with much better low frequency insulation.

This acoustically optimized solution (airborne sound insulation) does not offer a solution to the problematic idea of the 'independent terraced house'. As this approach only occurs in some countries (e.g. Austria) and can be criticized (see above), we can still maintain the idea of regrouping the boards to the extreme sides of the party wall.

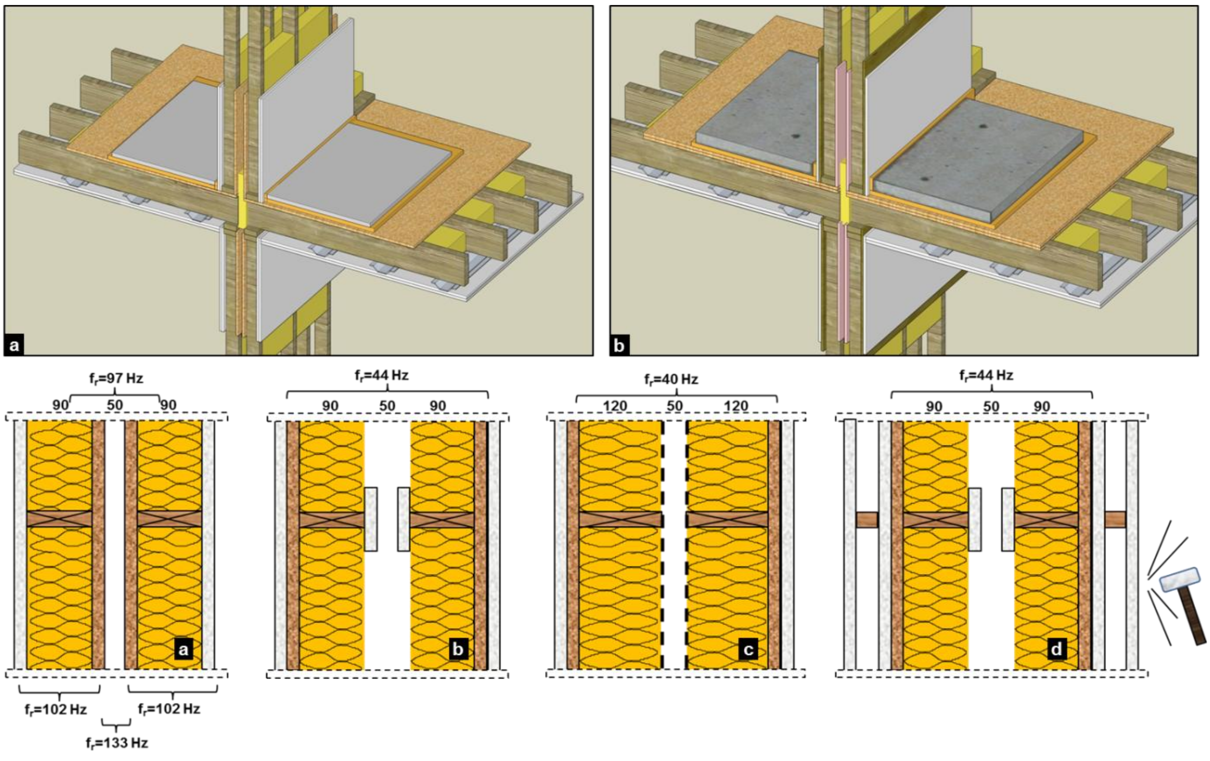
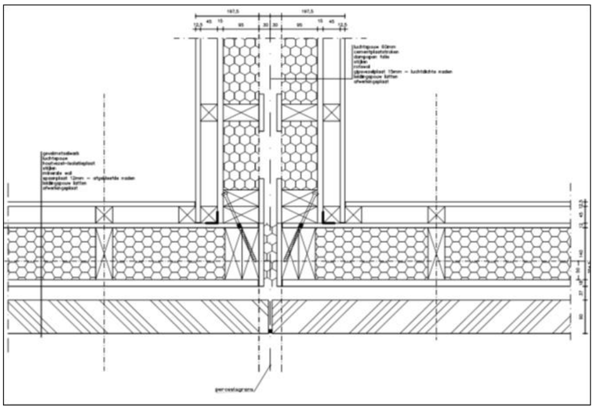


Figure 18: (a) traditional solution; (b) and (c) creating large cavities allows shifting the mass-spring-mass resonance frequency to the very low frequencies increasing considerably the low frequency sound insulation. Fire requirements impose special measures to be undertaken; (d) technical linings help to diminish sound coming from cupboards, tapping against the wall…

But of course the requirements of a fire resistance of one hour, even after the collapse of one of the houses and its part of the party wall, have to be fulfilled. That is why rock wool (or other products with similar acoustic and fire resistance characteristics) is fixed between the studs with at least the same thickness as the height (in section) of the stud. The thermal insulation and fire resistance of the rock wool protects the lateral sides of the studs. Of course this rock wool needs to remain in place (special glue, chicken wire, metal stud profiles….) when the other part of the party wall collapses. The fire will also attack the visible part of the stud (the 'head'). It burns in average depth-wise at a speed of ±1 cm every 10 minutes for traditional wooden studs. To maintain its constructional fire resistance during one hour, fire tests showed that studs of 120 x 45 mm² under a standard load complied. The alternative is the solution which is often used in the construction of technical shafts: small cement fibre or gypsum fibre boards can be fixed on the studs (figure) protecting the studs and maintaining the rock wool in place. These solutions allow for the use of normal, not over-dimensioned studs.



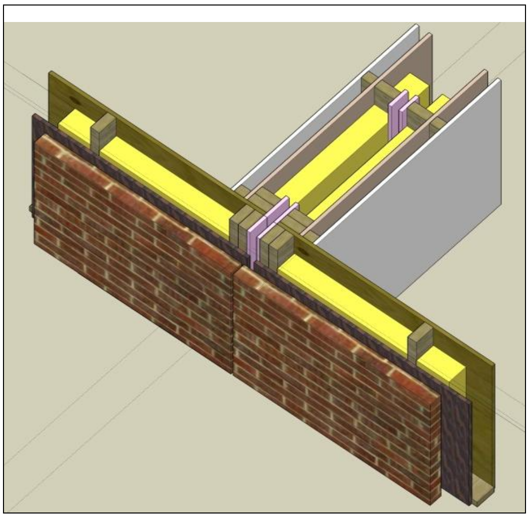
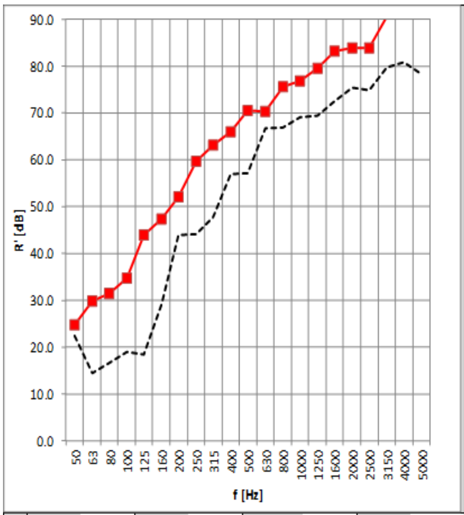
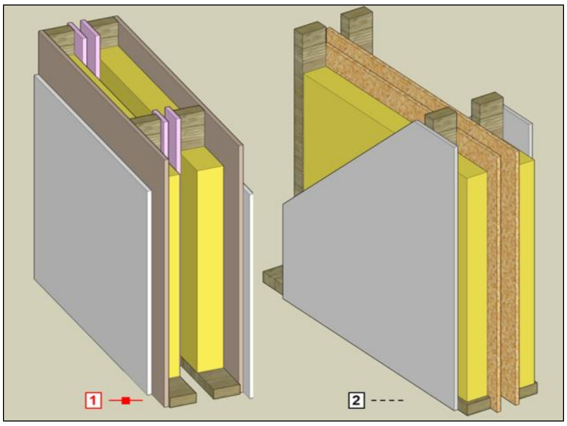



Figure19: fire tests show a resistance of 1 hour with the typical small boards cement boards nailed in the head of the studs. They also maintain the rock wool in place. On top to the right, a picture of half of the party wall belonging to one house and seen from the cavity. The rock wool is protected by a black thin plastic foil to protect the insulation during the construction phase. Down to the right: picture from the social building project in Hechtel-Eksel using this technology (Drawing and pictures from BBRI and Machiels Building Solutions)



f [Hz]	1	2
50	24.8	22.4
63	29.8	14.4
80	31.4	16.7
100	34.7	18.9
125	43.9	18.5
160	47.4	29.1
200	52.2	44.0
250	59.6	44.2
315	63.1	47.8
400	66.0	56.9
500	70.5	57.2
630	70.3	66.7
800	75.6	67.0
1000	76.9	69.0
1250	79.6	69.4
1600	83.2	72.6
2000	83.9	75.5
2500	83.9	74.8
3150	90.6	79.8
4000	92.6	80.9
5000	91.7	78.3

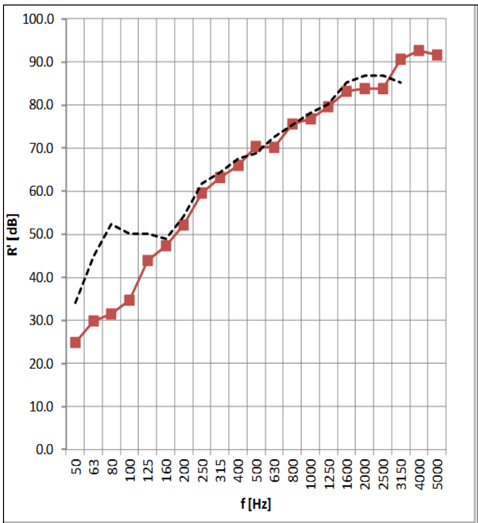
1	R'_{living}= 59 dB	$C_{50-5000}$= -7 dB	$C_{100-3150}$= -5 dB	R'_w= 66 dB
2	R'_{living}= 42 dB	$C_{50-5000}$= -6 dB	$C_{100-3150}$= -6 dB	R'_w= 48 dB



(1) *Central cavity of 60 mm (35 mm between fibre reinforced fire protection boards) and on both sides: 95x45 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board + 1 x 12.5 mm standard gypsum board.*

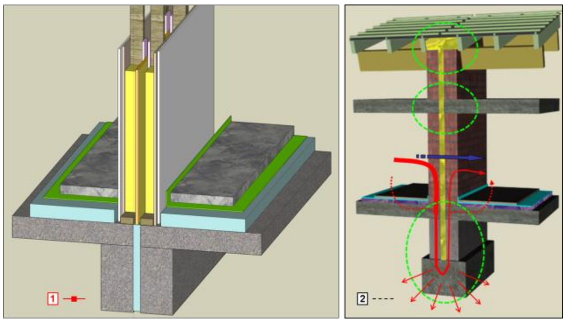
(2) *Central empty cavity of 50 mm and on both sides: 1 x OSB 15 mm *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm ***1 x 12.5 mm fibre reinforced gypsum board*

Figure 20- comparison party walls: (1) optimised system with large central cavity (2) traditional party wall with OSB boards in central cavity. For almost the same surface mass of the total wall, a difference of 17 dB in $R'_{living}=R_w+C_{50-5000}$ is measured in favour of the large cavity! (Measurements BBRI (1) project Hechtel-Eksel MBS liv23liv21; (2) project mock-up BBRI-Mobic)



f [Hz]	1	2
50	24.8	34.1
63	29.8	44.9
80	31.4	52.3
100	34.7	50.1
125	43.9	50.1
160	47.4	48.8
200	52.2	54.2
250	59.6	61.7
315	63.1	64.3
400	66.0	67.5
500	70.5	68.7
630	70.3	72.7
800	75.6	75.4
1000	76.9	78.3
1250	79.6	80.3
1600	83.2	85.2
2000	83.9	86.7
2500	83.9	86.9
3150	90.6	85.2
4000	92.6	
5000	91.7	

1	R_{living}= 59 dB	$C_{50-5000}$= -7 dB	$C_{100-3150}$= -5 dB	R_w= 66 dB
2	R_{living}= 68 dB	$C_{50-5000}$= -2 dB	$C_{100-3150}$= -2 dB	R_w= 70 dB



(1) *Central cavity of 60 mm (35 mm between fibre reinforced fire protection boards) and on both sides: 95x45 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board + 1 x 12.5 mm standard gypsum board.*

(2) *Central cavity of 40 mm filled with 2 cm glass wool and on both sides a 14 cm brick wall (silent brick Wienerberger). There are no ties between both walls and special measures have been taken for the junctions with foundations and façades.*

Figure 21- comparison with the reference heavy party wall construction, see chapter II.3. (Measurements BBRI (1) project Hechtel-Eksel MBS liv23liv21; (2) project Jabbeke – Wienerberger)

The party wall as an optimized acoustic double wall has very good airborne sound insulation - even in the very low frequencies - and can compete with anchorless heavy constructions. Yet the proposed construction can present problems when vibrational power is directly or indirectly injected in one of the walls. To make this more easily understandable for the non-acoustician, imagine the scenario in which one taps with his hand on the party wall. The boards on this side of the party wall will vibrate and radiate sound. So this side of the party wall is not part anymore of the 'acoustic protection' but becomes the sound source itself. Though this is a somewhat simplified explanation (incorrect for the low frequencies), one could say that the remaining part of the party wall acts as an 'acoustic single wall' and could –depending on the injected vibrational power- possibly offer too little protection especially in the lower frequencies.

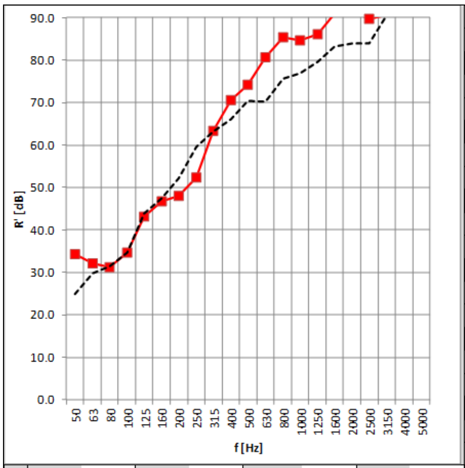
There are many possible sources which fall in this category and will create problems: the injected vibrational power of technical equipment (ventilation units, pumps,…), direct or indirect impacts on the party wall (closing of the door of a cupboard fixed to the party wall, ducts and pipes, sinks…) or structural vibration transmission transmitted from connected walls (closing of doors,…), floors (walking on floors without resilient floor coverings or floating floors), stairs that are fixed to the wall... In Switzerland a specific test method has been developed to measure this kind of noise.

Figure 22: Horizontal and vertical measurement with the pendulous hammer. This device was developed by the research institute EMPA in Switzerland. The aim was to evaluate impact noise of building service equipment in a simple and reproducible manner. The usage of the "pendulous hammer" is described in detail in the appendix B.3.5 of the SIA181:2006 standard.

Solutions are therefore needed. These will be provided by the use of technical linings.

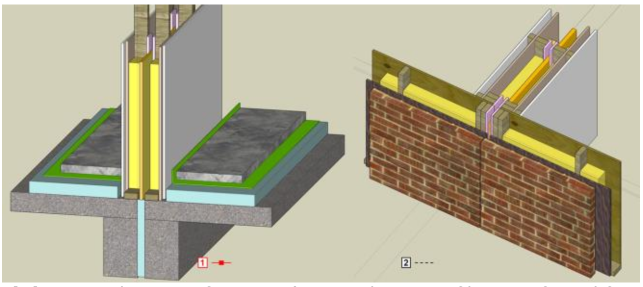
Technical linings will almost always be present in front of the party wall. These are necessary for electric wiring, electricity plugs, piping etc. … Indeed, any perforation of the basic party wall in the acoustically optimized solution is prohibited for fire reasons and concerns about air tightness (Energy Performance Requirements). The use of technical linings (gypsum board, small cavity of 4.5 cm normally containing no porous acoustic absorption material) on both sides of the party wall *will* improve the resistance against the passage of the above-mentioned sounds.

Direct impacts (cupboards, tapping against the wall etc.) will first strike against the technical lining, protecting the party wall behind as injected vibrational energy will only be passed on in a diminished way owing to the extra mass and more complicated structural transmission paths. The technical lining on the receiving side will act as an additional barrier (acoustic lining) except in the proximity of the mass-spring-mass resonance frequency around 125 Hz where its effect might even be slightly negative.



f [Hz]	1	2
50	34.2	24.8
63	32.1	29.8
80	31.2	31.4
100	34.6	34.7
125	43.1	43.9
160	46.8	47.4
200	48.1	52.2
250	52.4	59.6
315	63.4	63.1
400	70.6	66.0
500	74.1	70.5
630	80.6	70.3
800	85.4	75.6
1000	84.6	76.9
1250	86.1	79.6
1600	91.0	83.2
2000	91.7	83.9
2500	89.7	83.9
3150	90.5	90.6
4000	94.8	92.6
5000	96.5	91.7

1	R'_{living}= 59 dB	$C_{50-5000}$= -5 dB	$C_{100-3150}$= -3 dB	R'_w = 64 dB
2	R'_{living}= 59 dB	$C_{50-5000}$= -7 dB	$C_{100-3150}$= -5 dB	R'_w = 66 dB



(1) *Central cavity of 60 mm (35 mm between fibre reinforced fire protection boards) and on both sides: 95x45 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board + 1 x 12.5 mm standard gypsum board.*

(2) *Central cavity of 60 mm (30 mm between fibre reinforced fire protection boards) and on both sides: 95x40 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board *** studs 40x40 mm² with empty cavity *** 1 x 12.5 mm standard gypsum board.*

Figure 23: comparison between two constructions with equal surface mass. Case 2 has a technical lining while case 1 hasn't. (Measurements BBRI (1) project Hechtel-Eksel MBS liv23liv21; (2) project Hechtel-Eksel MBS slk23slk21)

These linings also have an impact on the *direct airborne sound insulation (figure above)*. The added mass will lower even more the mass-spring-mass resonance frequency of the party wall on the spring presented by the air in the widest cavity, resulting in even better performances in the very low frequencies. An economic choice is drawn in the above figure with a single fibre reinforced gypsum board for the basic party wall and a 12.5 mm standard gypsum board for the technical lining.

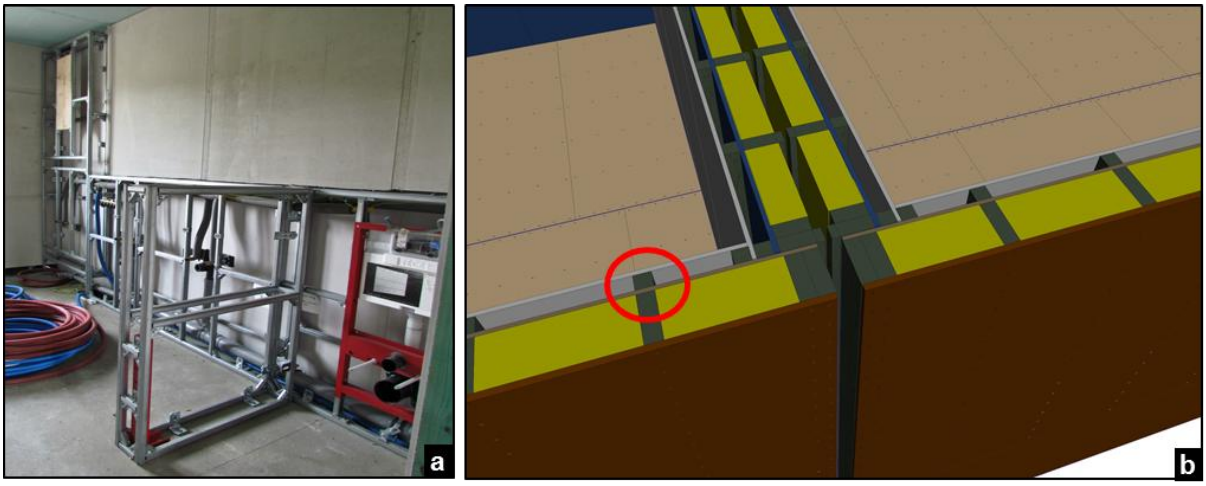


Figure 24: technical lining can be beneficial (picture b) but can present dangers such as the heavy technical lining for bathrooms with thick, very rigid steel studs, to which vibration sources (sinks, toilet…) will be attached (picture a).

Specific rigid metallic technical linings are sometimes used in bathrooms and kitchens. Typical terraced houses have a limited width, and in typical plans, the staircase and bathroom are next to the party wall. There are specific technical linings for bathrooms, lavatories and kitchens which have a reinforced frame so as to be able to cope with the weight of sinks, cupboards etc. Pipes too are fixed into this rigid frame. As this reinforced frame of course needs to be fixed to the lightweight timber frame construction, it can be a dangerous source of vibrational energy. If possible, the easiest way to avoid problems is to adapt the plan of the bathroom/kitchen… so that this rigid frame is connected to a non-common, internal wall. The alternative is the elastic decoupled fixing of this technical rigid lining to the floor and ceiling next to the party wall.

For the same obvious reasons, it is strongly recommended not to fix stairs directly to the party wall. Even 'elastic fixations' are insufficient to avoid acoustic discomfort in the neighbouring dwelling. Ideally, stairs should only be fixed in the floors and/or internal walls of the dwelling. Even in these cases elastic fixations using washers are necessary to obtain enhanced acoustic comfort in the neighbouring dwelling. An even better solution is a stair case with an independent carrying construction.

3.3.4 - Junction of the party walls with the façades and roofs

Light weight party wall constructions need to use 'acoustic double wall' technology to attain sufficient airborne sound insulation. Optimized width of cavities as a function of the surface masses of both wall partitions is one aspect here. Another is avoiding structural connections between the constituting walls if the maximum insulation possible is to be attained. Structural vibration transmission *can* indeed dramatically limit the airborne sound insulation. Even contacts at the edges of the double wall construction can limit the maximum attainable sound insulation. So attention is needed at the edges of the party wall, i.e. in its junctions with the roof and the façade. In the drawings below, one can see the interruptions in the boards in these junctions. The interruption in the façade masonry, useful in heavy constructions, is not really necessary in light-weight timber frame constructions, at least not for acoustic reasons.

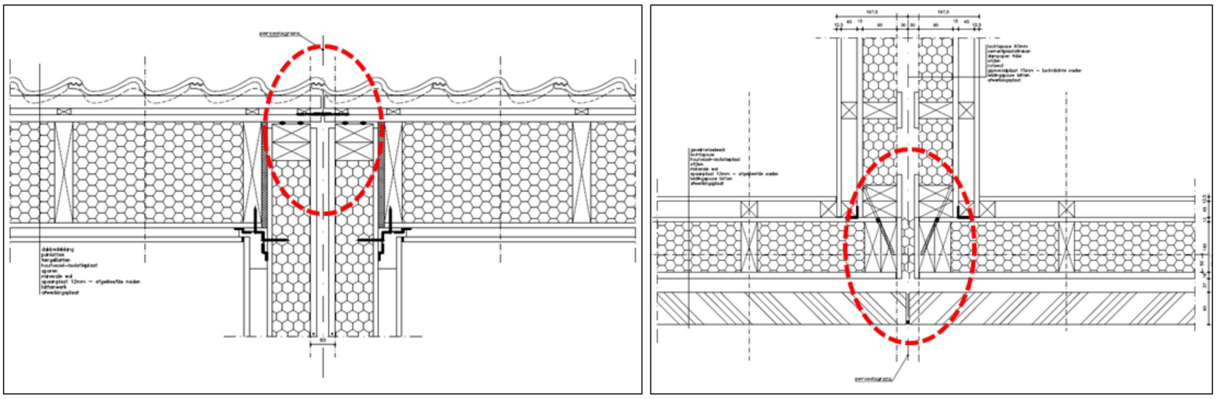


Figure 25: the decoupling should also be respected at the borders of the party wall (junction with the roof to the left, junction with the façade to the right)

3.3.5 - Junction of the party walls with the foundation or lowest floor

Depending on the condition of the building plot, i.e. its load carrying possibility versus the weight of the new construction, the depth of the phreatic surface, the nature of the layers of which it is composed and the risks of differential settings, the strategy of thermal insulation etc. or even the building technique used, many types of foundations can be found. Some examples are given below.

The junction at the foundation can influence the direct sound insulation of the party wall. In the figures 26 'c' and 'd' both wall portions are connected by the continuous concrete from respectively the concrete beam and concrete slab. This will diminish the maximum possible sound insulation of the party wall. The separation of the concrete slabs in figures 26 'a' and 'b' is more favourable for optimal "acoustic double wall effect" and clearly interrupts a possible transmission path between the two wall portions. Even rigid thermal insulation as EPS or XPS will do as a separating element to obtain this positive disconnection effect.

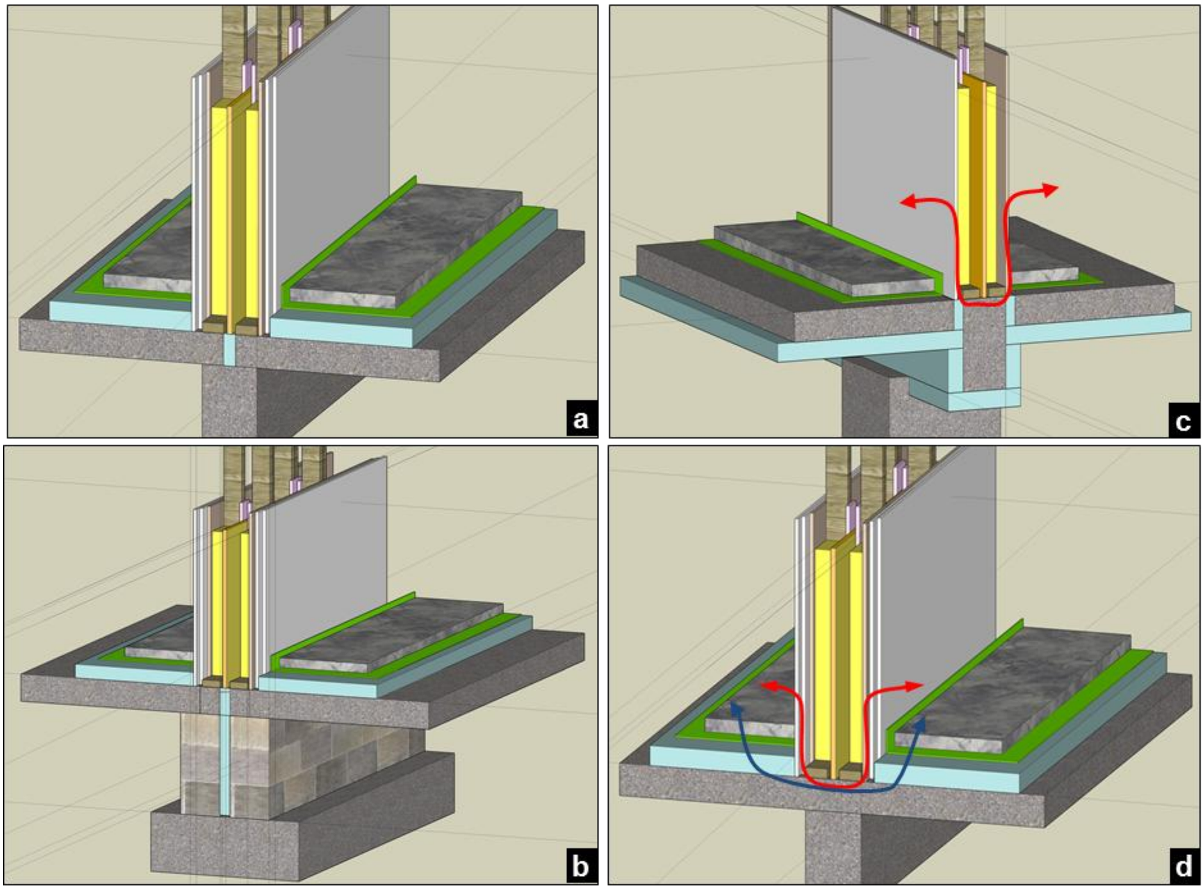
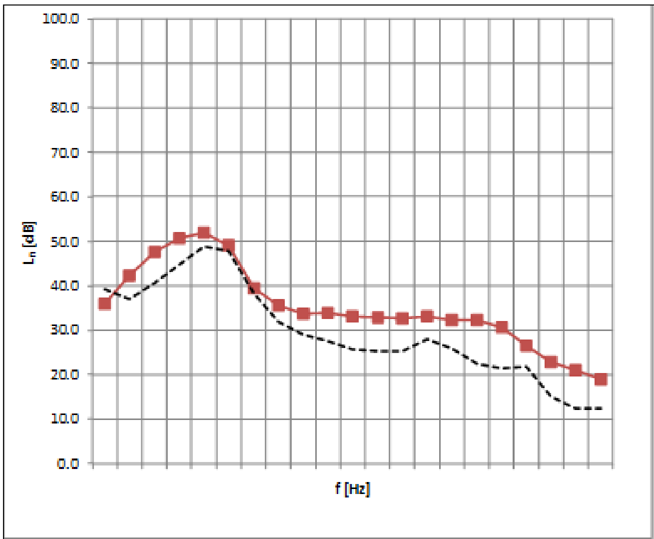


Figure 26: some possible foundations and junctions with the party wall. The use of floating floors is everywhere recommended to avoid impact sound. In figures 'c' and 'd' the maximum possible sound insulation that can be obtained with the party wall will not be attained due to a connecting path between both wall portions via the concrete slab/ beam.

In figure 26 'd' there is more to worry about: first there is the risk of excessive impact sound transmitted through the continuous concrete slab and secondly important flanking transmission is something to worry about. Although a good floating floor in both dwellings could reduce the impact and airborne flanking sound transmission, this is a risky solution we would certainly not recommend. There is always the risk of a not perfectly executed floating floor and of course this solution certainly limits the direct sound insulation of the party wall. Imagine the case with this solution with no floating floor or a badly executed one. The light weight party wall will only have a very low vibrational reduction effect on the transmission path ‘Ff’ (floor to floor) and even other flanking transmissions paths (‘Fd’, ‘Df’) might influence the sound reduction between both adjacent dwellings.

The vibration gaps in figures ‘a’, ‘b’ and ‘c’ certainly diminish the impact sound transmission and eliminates most of the airborne flanking transmission. The installation of a floating floor is still highly recommended for optimal comfort against impact sound. In figures 26 ‘a’, ‘b’ and ‘d’, the thermal insulation has been placed on top of the concrete floor. When this thermal insulation is rigid, a supplementary resilient layer needs to be placed on top of the thermal insulation.



f [Hz]	1	2
50	36.0	39.2
63	42.2	37.0
80	47.6	40.7
100	50.6	44.8
125	52.0	48.8
160	49.0	47.8
200	39.4	38.2
250	35.5	31.8
315	33.7	29.0
400	33.9	27.6
500	33.0	25.7
630	32.8	25.4
800	32.7	25.2
1000	33.0	28.0
1250	32.3	25.8
1600	32.3	22.5
2000	30.6	21.5
2500	26.5	21.9
3150	22.8	15.1
4000	20.9	12.5
5000	18.9	12.4

1	$L_{n,w}+C_{I,50-2500}=$	42 dB	$C_{I,50-2500}=$	2 dB	$C_{I,100-2500}=$	1 dB	$L_{n,w}=$	40 dB
2	$L_{n,w}+C_{I,50-2500}=$	38 dB	$C_{I,50-2500}=$	3 dB	$C_{I,100-2500}=$	3 dB	$L_{n,w}=$	35 dB

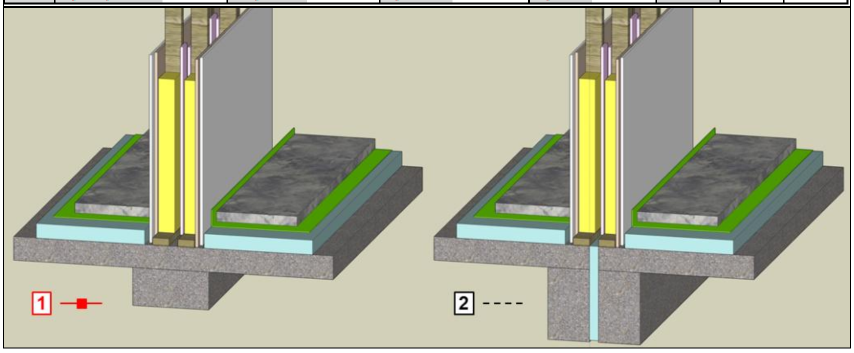


Figure 27: comparison avec the impact sound insulation with well executed floating floors. Both results are excellent, but the interrupted concrete slabs have a 4 dB better performance and offers some additional ‘insurance’ for the case when something goes wrong with the floating floor. (Measurements BBRI-MBS RE Hechtel-Eksel liv23liv21 for case 2 and liv19liv21 for case 1)

Last but not least: absolutely to be avoided is a continuous wooden floor on a concrete foundation between two dwellings. Indirect sound transmission, the coupling of both party wall portions, very important airborne and impact flanking transmission are disastrous for the acoustic comfort.

3.3.6 - Remark: indirect sound transmission to the adjacent house via façades and ventilation ducts

Thanks to the above discussed concept of the party wall, no structural flanking transmission is possible between the two terraced dwellings. But problems can arise with indirect airborne sound transmission.

A very classical problem is the transmission path across ventilation grids that lack or have insufficient acoustic damping. This is also a frequently encountered problem in heavy constructions. Even in very calm environments, if natural ventilation using ventilation grids is chosen, ventilation grids should have a minimal sound transmission loss both for privacy reasons and to avoid indirect sound transmission to adjacent houses/apartments. The same reasoning is valid for all weak points in the sound insulation of the façades.

Typically for light weight timber frame constructions, two further paths for these indirect airborne transmissions are possible as well in the horizontal (terraced houses) as in the vertical direction (to be avoided in the case of apartment constructions):

- TRANSMISSION PATH 1: Across the internal visible wall of the emission room to the exterior cavity (a gap 2 to 3 cm between the façade cladding and the 'wind screen panel'), propagation throughout this cavity and finally across the internal visible wall to the room at the reception side.
- TRANSMISSION PATH 2: Across the façade/roof of the emission room to the outside and finally across the façade/roof of the reception room.

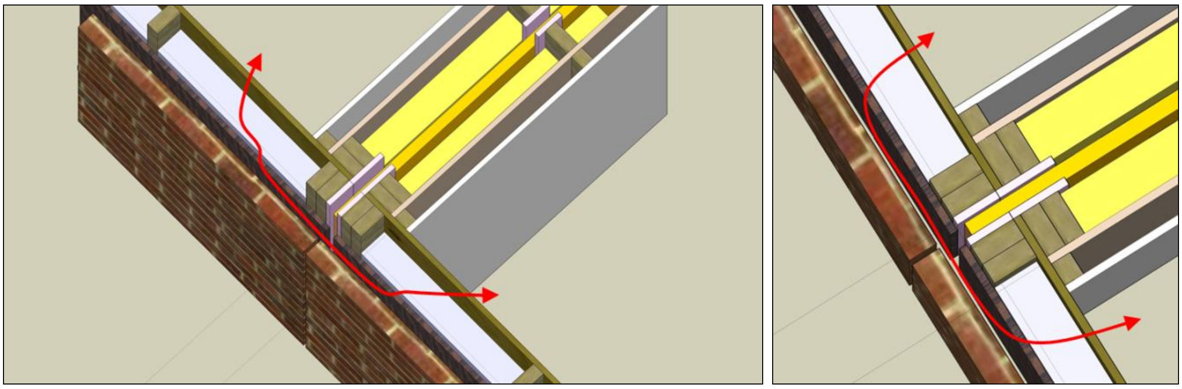


Figure 28: transmission path 1 for the indirect sound transmission, this transmission path is important when thermal insulation is used with no acoustic absorbent characteristics.

This needs some explanation: the inside façade wall is normally a stud wall construction with the typical traditional board fixed at the side of the room, giving strength (also laterally) to the construction. On the outside though, very often a low density (200 to 250 kg/m³) wood fibre panel of 18 mm is used, adding to the thermal insulation and fulfilling the task of windscreen but still allowing for vapour permeability. The use of these light panels results in a rather low direct sound insulation of the stud wall construction. This is even worse when PU or EPS (see figures above and below) is used to optimize the thermal performances. Sound penetrates across this construction and - depending on the exterior finishing - both above-mentioned transmission paths are possible.

When the exterior finishing is made of a heavy material (brick finishing, cement boards with stucco finishing…), only the first indirect airborne transmission path will occur in the cavity (if present, which is normally the case) between the exterior finishing and the low density board.

In the case of a light-weight (wooden planking…) or non-acoustically tight finishing (tiles…) the second path also will occur.

The indirect airborne transmission path in the cavity inside the stud construction is normally negligible due to the studs of the façade wall that connect this wall with the studs of the party wall

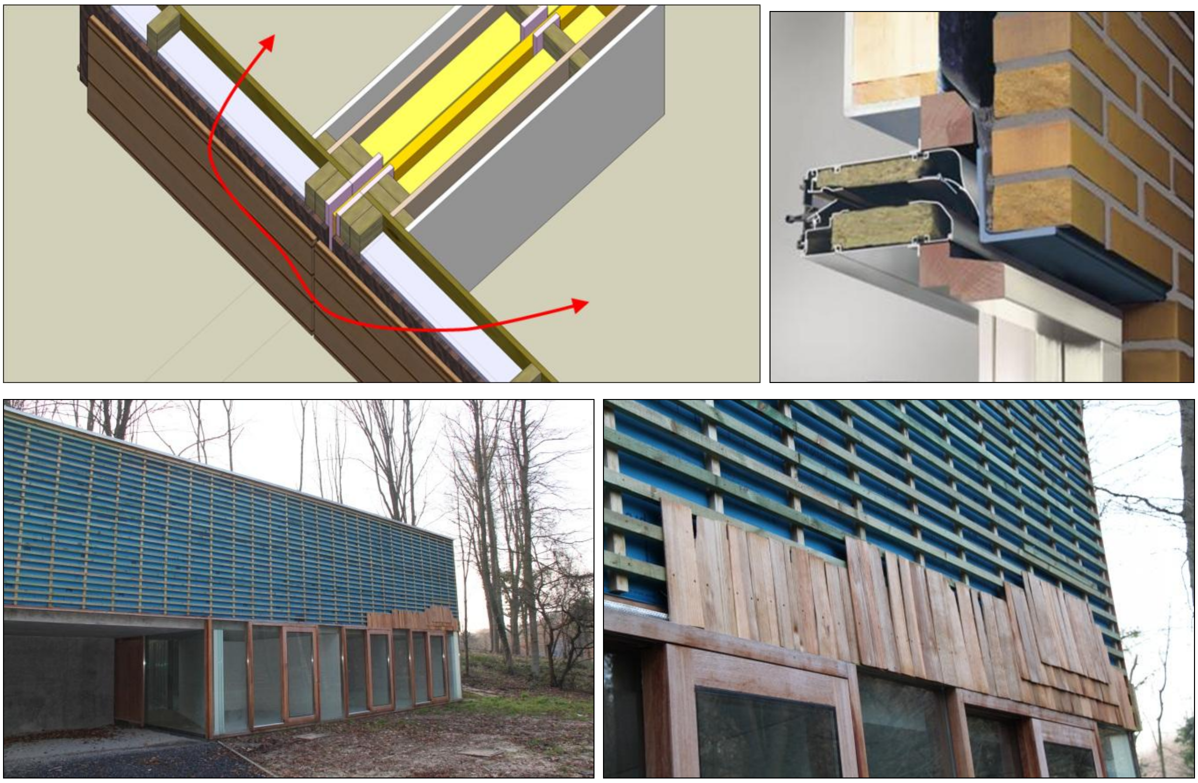


Figure 29: transmission path 2 when the sound façade insulation is low (rigid thermal insulation with closed cells, cladding, cedar tiles,…). Ventilation grids should have a minimal acoustic sound insulation to avoid indirect sound transmission

3.4 - Floors

Most acoustic requirements in European countries for the sound insulation between rooms of the same dwelling are rather low or even inexistent.

For minimal comfort reasons, $D_{nT,w}$ > 35 dB and $L'_{nT,w}$ < 60 dB are often imposed or advised.

Many solutions comply with these requirements. In some countries, resilient floor coverings or floating floors are standard tradition not only in apartment constructions but even in terraced houses. This increases the acoustic comfort for the inhabitant.

But if your country has low or no requirements for the sound insulation between rooms in the same dwelling, are these floating floors or resilient coverings necessary for the impact sound insulation to the adjacent dwelling? Or can parquet be glued or nailed straight into the boards of the load carrying floor, saving height and money? Indeed if a floating floor is necessary and parquet is desired, a resilient interlayer and an extra board (or lattices) are necessary to be able to nail/glue the parquet…. increasing as such the cost of labour and materials.

In *traditional party walls (boards-studs-boards/cavity/ boards-studs-boards)*, there is also a perfect structural disconnection from the foundations to the roof. The vibrational power injected by footsteps (or the impact machine) can propagate to the first partial wall of the party wall where it can radiate sound (and transmit vibrations via mass-spring-mass coupling to the second wall). The second partial wall is a double wall (though with rigid wooden studs) and a sufficient barrier against the radiated sound of the first wall. So, with this kind of party walls, floating floors are eventually not necessary (but still highly recommendable) in countries where no acoustic requirements exist between rooms/floor levels of the same dwelling. We do advice, though, to have a floating floor on the lowest level. The disconnection between the two dwellings is always weaker or inexistent at the lowest level (sometimes a continuous concrete slab) and acoustic discomfort due to impact sound or non-compliance with acoustic requirements is a major risk if no floating floors are applied.

Using the same simplified (and definitely incorrect for lower frequencies) reasoning of a 3 room-model approach, one can understand that the situation is different for *the party wall construction with a single large cavity*. The partial wall at the reception side consists of an 'acoustic single wall' composed of boards, offering a rather weak sound barrier especially in the low frequencies. When no technical linings are applied (to be avoided, one is well advised to provide them, see above), there is a major risk that transmitted impact levels are too high and not comply with local requirements for the sound insulation between terraced dwellings. Even when technical linings are applied, this could still generate problems. As technical linings have rigid stud connections with the party wall, have a mass-spring-mass resonance frequency around 125 Hz and have no absorption material in the cavity, it is unclear how much the technical lining can improve the impact sound insulation. Unfortunately, no measurements of these situations are available, so it is a safe precaution to have floating floors on all levels. This is indeed different in the case of heavy tie-less constructions. Here, floating floors are necessary only on the lowest floor (for these countries which do not have requirements covering internal impact sound insulation within the same dwelling).

4 - APARTMENT CONSTRUCTIONS

4.1 - General

For terraced dwellings, the acoustic problems have mainly to do with the horizontal airborne and impact sound transmission.

Multifamily constructions imply in most cases dwellings on top of each other. Total structural decoupling is then of course not possible any more. This implies a direct impact sound transmission path (which we did not have with terraced houses), numerous flanking transmission paths and greater difficulty in obtaining direct airborne sound insulation in the vertical direction. For countries using the D_{nT} quantity, the relation with R' also becomes less favourable as the term 10.lg(V/3.S) is much less advantageous (V/S≈average height) than in a horizontal direction (V/S≈average depth perpendicular to the separating wall) for larger rooms.

Sound insulation in a vertical direction is crucial for the experienced acoustic comfort, but is unfortunately rather complicated to optimize. The lack of acoustic comfort most complained about is low frequency impact noise.

Larger lightweight timber frame apartment constructions are a relatively recent phenomenon. Smaller constructions, of the kind of terraced units with one or two apartments on top of each other in each unit, are more frequently met. Standard constructions of this type all over Europe pretty much look structurally alike and are largely determined by Eurocode 5 structural calculations. Façade finishings, section of joists and studs and layers of thermal insulation differ, but real acoustic optimisation can only be seen in more recent projects. Lots of details (floors, walls, façades and even some junctions) and corresponding acoustic, thermal and fire data can be found in the excellent database www.dataholz.com and in many different publications (see literature list) such as 'Robust Details', 'Acoustic performance of party floors and walls in timber framed buidlings', etc. (see literature list). Some innovative systems (the use of elastic joints to reduce flanking transmission, special damping constructions within floors, etc..) will be shown later on.

In many countries, technical building guidelines covering lightweight timber frame constructions exist, but the acoustic information mostly remains scarce and limited to single ratings based upon the frequency range down to 100 Hz. Moreover, building guidelines stick to solutions that comply with building regulations. As these requirements are suitable to guarantee acoustic comfort for heavy constructions, but not necessarily for lightweight constructions, there still are quite a lot of problems to be solved and improvements to be made.

In the figure below, a Finnish construction (Ylojärvi apartments) is presented with an overall great acoustic performance. In the charts, spectral information of normalized impact sound levels and apparent sound reduction indices are compared with the average results in heavy apartment constructions with floating floors (see discussion in chapter 2). Both impact and airborne sound insulation of the Finnish construction are more than ‘respectable’ but remain in the low frequency bands below the traditional heavy constructions.

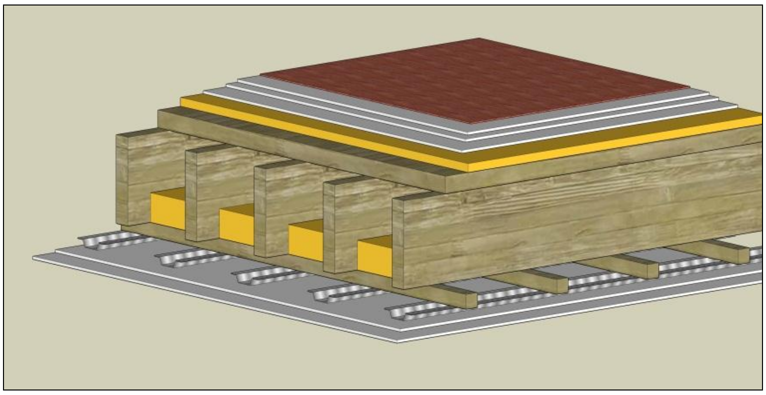
Outline of this section 4:

In the next sections, we will first have a quick look in 4.2. at the party wall construction, being quite similar as to the party walls discussed in the part of this text about terraced houses. Next, compartment floors are being examined in 4.3. The impact sound insulation is extensively treated with topics such as:

(1) the choice between resilient floor coverings and floating floor;
(2) some words explaining how floating floors acoustically work and how this can be different compared to floating floors with heavy floors;
(3) possible errors with the characterisation of the efficiency of floating floors;
(4) current craftmanship errors in the field;
(5) types of floating floors in LWTF construction;
(6) the effectiveness of dry floating floor systems used in LWTF constructions
(7) the necessity of false ceilings

Section 4.3. also gives some information about the airborne sound insulation and some basic information about comfort against vibrations. A series of solutions / examples with the acoustic performance closes this chapter.

Section 4.4. takes a closer look at junctions and the flanking transmission that occurs in these. Techniques to reduce the flanking transmission are being discussed. In the report of WG 1, a methodology to estimate the flanking transmission has been described. In this document, measurements give some indication about the importance of the flanking transmission for some junctions.



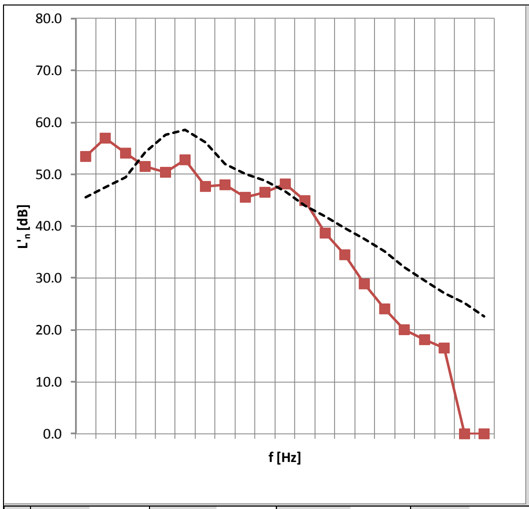
*REF.: Sound insulation structures of beam-to-column framed wooden apartment buildings *** Asko Keronen – Mikko Kylliäinen *** Tampere University of Technology (1997) *** ISBN 951-722-776-0 *** Ylöjärvi apartments, appendix 3 page 1 (L'n) and appendix 5 page 1*

Topping: *Vinyl *** 3x12.5 mm fibre gypsum boards (30.8 kg/m²)*** mineral wool 30 mm (100 kg/m³)*

Floor: *ribbed slab (thickness 6 cm), joists ca. 30 x 6 cm²*

Cavity: *mineral wool 100 mm (30 kg/m³)*

Ceiling: *wooden spacers 5x5 cm² *** resilient channels *** 2x12.5 mm gypsum boards(ca. 2x9.4 kg/m²)*



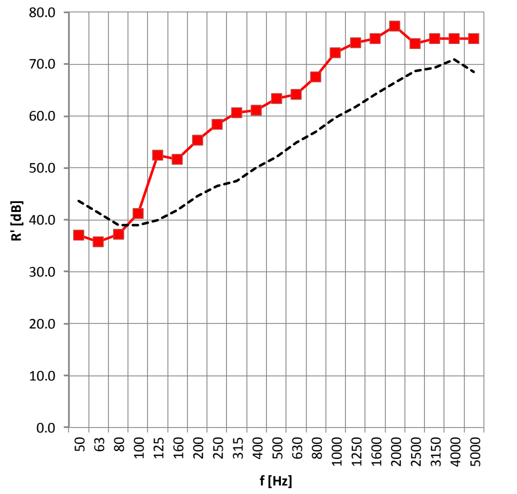
f [Hz]	1	2
50	53.4	45.6
63	**56.9**	**47.5**
80	54.1	49.4
100	51.5	54.2
125	**50.3**	**57.6**
160	52.8	58.5
200	47.6	56.1
250	**47.9**	**52.0**
315	45.6	50.1
400	46.6	48.8
500	**48.2**	**46.6**
630	45.0	44.0
800	38.7	41.9
1000	**34.5**	**39.7**
1250	28.9	37.6
1600	24.0	35.2
2000	**20.0**	**32.1**
2500	18.2	29.5
3150	16.6	27.0
4000	**0.0**	**25.1**
5000	0.0	22.6

1	$L_{n,w}+C_{I,50}$ 47 dB	$C_{I,50\text{-}2500}$= 3 dB	$C_{I,100\text{-}2500}$= dB	$L_{n,w}$= 44 dB
REF	$L_{n,w}+C_{I,50}$ 49 dB	$C_{I,50\text{-}2500}$= 2 dB	$C_{I,100\text{-}2500}$= 2 dB	$L_{n,w}$= 47 dB

1 LWTF construction described above

2 Average performance heavy floor constructions with floating floors in Belgium (see chapter 2)

(part of Figure 30)



f [Hz]	1	2
50	37.1	43.6
63	**35.7**	**41.3**
80	37.3	39.0
100	41.2	39.0
125	**52.4**	**39.9**
160	51.7	41.9
200	55.3	44.7
250	**58.4**	**46.5**
315	60.6	47.5
400	61.2	50.0
500	**63.3**	**52.1**
630	64.1	54.9
800	67.6	57.0
1000	**72.2**	**59.6**
1250	74.2	61.7
1600	75.0	64.2
2000	**77.3**	**66.4**
2500	73.9	68.6
3150	75.0	69.3
4000	**75.0**	**70.8**
5000	75.0	68.6

1	R'_{living} = 64 dB	$C_{50-5000}$ = -3 dB	$C_{100-3150}$ = -2 dB	R'_w = 67 dB
2	R'_{living} = 56 dB	$C_{50-5000}$ = -1 dB	$C_{100-3150}$ = -2 dB	R'_w = 57 dB

1 LWTF construction described above

2 ------ Average performance heavy floor constructions with floating floors in Belgium (see chapter 2)

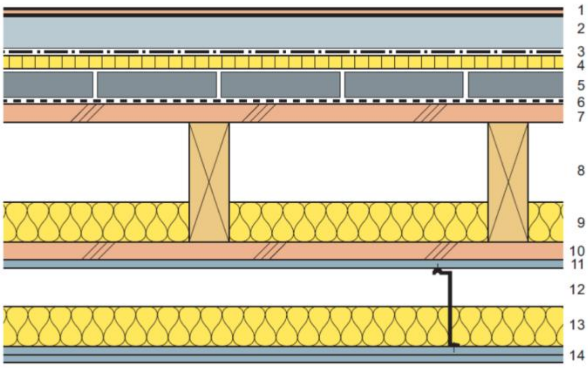
Figure 30: comparison of normalized impact sound levels and apparent sound reduction indices between an acoustically very well performing Finnish LWTF floor construction and the average result in heavy apartment constructions with floating floors (see discussion in section 2).

MFH Holzhausen: Geschossdecken

© Renggli AG, Sursee

Konstruktionsaufbau

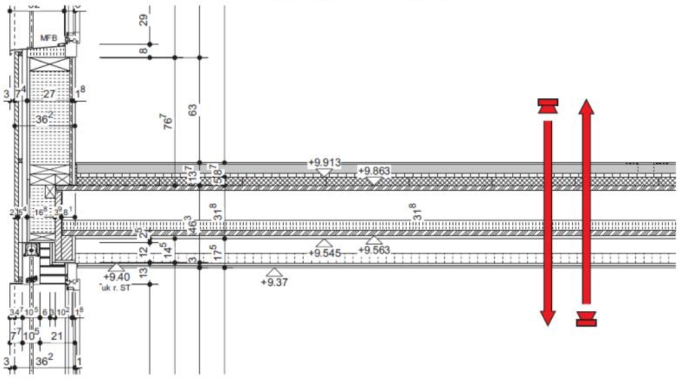
1 Bodenbelag variabel (Parkett, Plattenböden)
2 Anhydrit-Fliessestrich 55 mm
3 Trenn- und Gleitlage
4 Trittschalldämmschicht ISOVER ISOCALOR 20 mm
5 Zementplatten 50 mm (Beschwerung)
6 Vlies
7 OSB-Platte 30 mm
8 Holzbalken 80 mm/240 mm (e = 600 mm)
9 Mineralwollplatte 60 mm (Hohlraumdämpfung)
10 OSB-Platte 30 mm
11 Gipskartonplatte 18 mm
12 Abhängekonstruktion, Installationshohlraum 90 mm
13 Mineralwollplatte 60 mm (Hohlraumdämpfung)
14 Gipskartonplatten 25 mm



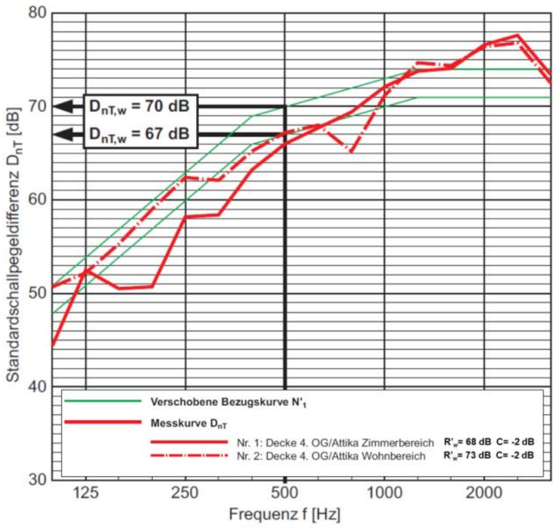
Angaben zur Messung:

Objekt	Nr.	Senderäume	Empfangsräume	Geschossdecke
MFH Holzhausen	1	5.OG Zimmer 5.1.07	4. OG Zimmer 4.2.06	$D_{i,tot}$ = 65 dB
CH-6312 Steinhausen	2	5. OG Wohnen 5.1.02	4. OG Wohnen 4.1.02	$D_{i,tot}$ = 68 dB

Konstruktive Randbedingungen/Anschlüsse



Standardschallpegeldifferenz D_{nT}



Standardtrittschallpegel L'_{nT}

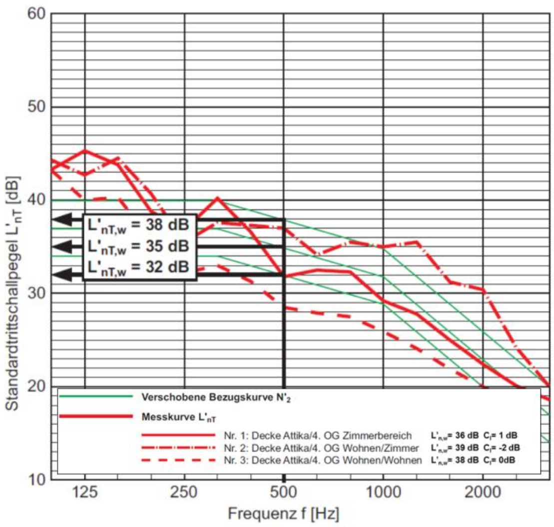


Figure 31: floor construction in the first 6 floors high LWTF project in Steinhausen, Switzerland (MFZ Holzhausen, © Renggli AG, Sursee).

4.2 - Party walls

In the horizontal direction, we can refer to the discussion of party walls in terraced houses, at least for small scale buildings. For larger projects, the required horizontal stability under wind load or earthquake resistance might mean that using the same total separation construction is just not feasible. But in different projects in Europe, we have seen that this problem in large-scale projects is often solved by having a rigid concrete or steel core inside the building containing staircases and lifts (necessary in any case for lifts), although this increases building time. All horizontal forces of the LWTF construction are then brought to bear on this steel or concrete core (e.g. Limnologen Växjö).

Another problem can be penthouses whose floor plans can stretch out over several apartments situated below. No particular details and measurements as a solution for this are available, though one could imagine a locally elastically coupling of the load-carrying floors each time at the party walls of the apartments below. The floating floor could then continue above these party walls so that visually no gap occurs, while acoustically no real structural coupling occurs between the two constituent walls of the lower party walls.

4.3 - Compartment floor constructions (incl. ceilings)

4.3.1 - Introduction

Before considering the junctions and the problems with the numerous flanking transmission paths, it is useful to study in detail the direct insulation against airborne and impact sound. Particularly impact sound, mainly in the low frequencies (drumming sound) can be a major problem in LWTF constructions.

Most compartment floor systems (separating two apartments) consist of 3 structured layers: a floating floor or resilient floor covering is built up on top of the load carrying floor (a combination of joists and boards) and a ceiling mostly made of gypsum boards. A problem could be the thickness (exceeding standard thicknesses of 30 cm to 35 cm in heavy weight constructions) and the weight of these floors when really high performances are required.

4.3.2 - Impact sound insulation

A basic structure without any kind of resilient floor covering or floating floor just will not offer sufficient acoustic comfort against impact sound.

Using floating floors to reduce impact sound has some additional benefits compared with resilient floor coverings; this is discussed in point (1) here below.

It is important to understand how floating floors reduce impact sound (paragraph 2) and how it is correctly characterized to avoid mistakes and to optimize constructions or to look for innovations. But the choice of kind of floating floor is less easy than for heavy constructions and design mistakes are quickly made (paragraph 3).

Next (paragraph 4) we will look at the professional placing of the floating floor so as to avoid frequently-made errors. As small errors almost entirely eliminate the benefits of the floating floor, good craftsmanship is absolutely necessary. Finally (paragraph 5), we will take a closer look at the different families of floating floor concepts and their acoustic performances.

4.3.2.1 - ***Reducing impact noise: the choice between resilient floor coverings and floating floors***

Resilient floor coverings such as carpets and laminate floors on elastic underlays are sometimes used in LWTF constructions. These solutions work out fine in terraced houses where the obtained impact sound reduction can be sufficient. Applying these in apartment constructions is also feasible but presents certain disadvantages: solutions with resilient floor coverings require a much better performance of the rest of the construction of the floor. In some countries, the necessary impact sound insulation must be attained even without the resilient floor covering (e.g. Belgium) owing to legal concerns and discussions: the change of carpets towards parquet or tiling is sometimes considered as an interior decoration change and the concept of the building should be such that these changes have no impact on the building physics of the construction. Floating floors are in this case not only an advantage but a must.

Last but not least, floating floors are very interesting for limiting flanking sound transmission, an advantage resilient floor coverings do not offer. There exist constructions with resilient floor coverings showing sufficient impact reduction in the laboratory to allow one to hope that they will comply with acoustic requirements in situ. But there is the problem of the flanking transmission 'Df'[2]. Without the floating floor, the load-carrying floor and especially the boards will be excited directly by the tapping machine (or walking persons…) and this energy will be transmitted to the load-bearing walls below where it will radiate as impact noise and added to the directly transmitted impact noise ('Dd'). There are four of these flanking paths 'Df' and that can add up quite a lot of sound. Two of these flanking paths 'Df' can be more important than the remaining ones. Indeed the propagation of the vibrational energy injected by the tapping machine will be more rapidly attenuated by distance in the direction perpendicular to the load-bearing joists (at each crossing of a joist an extra attenuation happens). So using linings in front of the floor-carrying walls could possibly be of some help (though we have to take into account perverse effects of the mass-spring-mass-resonances of the linings). But the best way to cope with these flanking transmissions is to install optimised floating floors.

4.3.2.2 - ***How do floating floors reduce impact noise?***

Floating floors are mass-spring-mass systems (see figure below). They may reinforce vibrations at the resonance frequency of the system, but above this frequency, the

[2] An international convention is to indicate transmission ways using capitals for the start of the flanking path at the emission room (with 'D' indicating the direct separating floor or wall between the two rooms seen from the emission side, 'F' represents a flanking wall in the emission room most of the time perpendicular to the direct separating wall or floor). Minuscules are used for the end of the flanking path at the reception side. (with 'd' indicating the direct separating floor or wall between the two rooms seen from the reception side, 'f' represents a flanking wall in the reception room most of the time perpendicular to the direct separating wall or floor').

transmission of vibrations (and the afterwards radiated impact sound) is ever more reduced with increasing frequency (see figure below). Good floating floors are designed in such a way that the resonance frequency is as low as possible (where the sensitivity of the human ear is lower or inexistent) generating an important reduction of the impact sound in the greatest part of the audible spectrum.

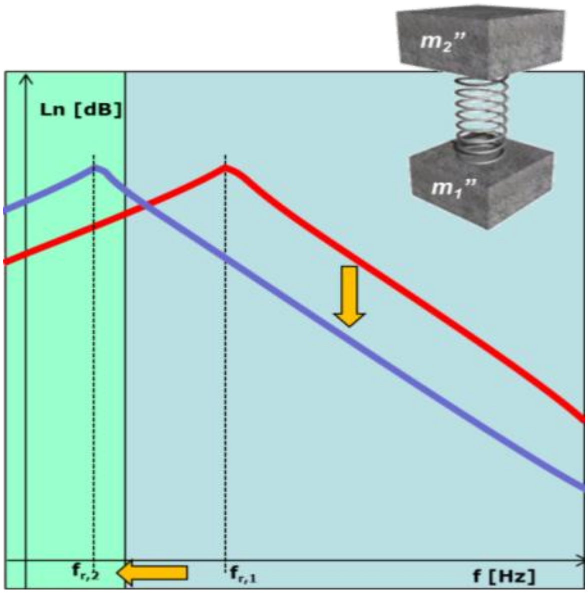


Figure 32: Shifting the resonance frequency in the figure from $f_{r,1}$ to $f_{r,2}$ reduces considerably the impact noise. Although we try to avoid formulas in this WG 4 report, the following simple formula is very useful to calculate the mass-spring-mass resonance frequency f_r. It allows for a better understanding of how the floating floor system works. The resonance frequency f_r resulting from the system composed of the load bearing floor with surface mass m''_1 [kg/m²], the spring with dynamic stiffness s [MN/m³] (normally an elastic interlayer) and the floating floor with surface mass m''_2 (surface mass refers to the mass that acts per surface unit of the spring), can be calculated by:

$$f_r = \frac{1}{2\pi}\sqrt{s.\left(\frac{1}{m''_1}+\frac{1}{m''_2}\right)} \text{ [Hz]}$$

Other mechanisms such as internal and surface damping will also influence the final impact reduction obtained with the system.

Unfortunately, this model is only so simple and valid for rigid concrete constructions. For less rigid light weight timber frame floors, the behaviour can be unexpectedly slightly different. Dynamic impacts on the topping can sometimes be unable to cause the interlayer to compress but instead cause the direct deformation of the supporting subfloor. As such, subfloor and topping are not sufficiently decoupled and the resonance frequency can be less influenced by changing for instance the stiffness of the elastic interlayer. This effect has been noticed in measurements in the National Research Council Canada[3] and in the measurements by BBRI discussed in chart 10 in this section 4.3.2.

4.3.2.3 - *Floating floors to be used in LWTF-construction are often wrongly characterized, leading to wrong concepts and too much impact noise. Moreover most floating floors are often less efficient when applied in LWTF constructions than identical ones used in heavy constructions.*

The efficiency of a floating floor system is expressed by ΔL_w (see EN ISO 717-2). One could describe this quantity as a *single rating that expresses the reduction of the impact sound of*

[3] On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012)

a floor system due to the use of the floating floor. Owing to the still dominant heavy way of building, most products used in floating floors have been characterized for use on heavy floors of ca. 14 cm thick concrete (EN ISO 10140 parts 3 and 5), though these standards also permit a characterization for three types of lightweight timber floors. *One has to be careful not to use the ΔL_w (the weighted reduction of impact sound level) determined on the reference concrete floor in applications with lightweight timber frame constructions!* The correct ΔL_w of the floating floor applied on lightweight timber floors can be quite a bit smaller. One should always keep in mind that the ΔL_w characterizes the total mass-spring-mass system (load-carrying floor – resilient interlayer –floating floor) and not the resilient interlayer alone. So the same elastic interlayer applied on and under different masses and types of materials will have a totally different efficiency in reducing impact sound! There are two reasons for this:

Floating floors equally work as a mass-spring (here the elastic interlayer)-mass system, with the mass of the concrete load-bearing floor being considerably different from the lightweight constructions. Moreover, typical screed like solutions (6 to 8 cm at a density of 1800 kg/m³) put on top of the resilient layer in heavy constructions are often much heavier than the classical floating floor types (e.g. boards) installed in LWTF constructions. That means that the mass-spring-mass resonance frequency for the same elastic interlayer is much lower for the heavy type of construction than for LWTF construction. The lower the mass-spring-mass resonance frequency, the better the impact sound insulation will be. This is therefore a problem from the outset for LWTF constructions.

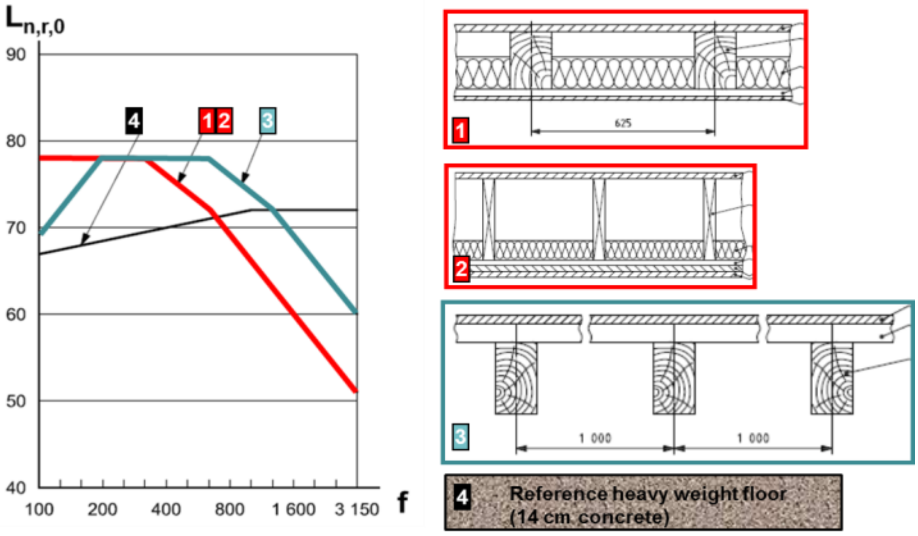


Figure 33: impact sound on reference floors as specified in EN ISO 10140-5. The improvement of the impact sound represents the difference between the impact sound measured directly on the reference floor and measured with the floating floor.

But there is another reason why it is more difficult to reduce impact sound with a lightweight basic floor than with the heavy concrete reference floor. When the tapping machine is positioned on the concrete floor, it generates more sound in the higher frequencies than in the lower frequencies. For the same tapping machine placed on the bare wooden floor (without a ceiling finishing), the opposite is true: more sound power is radiated in the lower frequencies than in the higher frequencies (see figure here above). The attenuation effect of a mass-spring-mass system increases with the frequency above its resonance frequency. Even if one had floating floor systems with the same mass-spring-mass resonance frequencies, the above reasoning explains why the reduction of the impact sound offered by the floating floor will still be much larger for heavy floors than for LWTF constructions.

All this means that one has to be very careful with ΔL_w –values proposed in technical documentation. Most of them were measured on standard concrete floors and show an efficiency that is way above what can be attained with lightweight wooden floors. There are two possible options if one has to choose a floating floor system (or for manufacturers to characterize their product): one could ask manufacturers for the ΔL_w-value measured on the most suitable type of reference wooden floor described in EN ISO 10140-5 represented in the figure above; the even better alternative is to measure the impact noise level $L_{n,w}$ of the complete floor with its ceiling in a laboratory construction.

4.3.2.4 - *Of course floating floors should 'float' and execution errors must be avoided. No hard contacts should link the floating floor to the adjacent walls or to the load-carrying floor. Even small hard contacts will almost entirely eliminate all beneficial effects of the floating floor. In general, the same rules apply as for the placing of floating floors in heavy constructions.*

Resilient strips should be placed between the floating floor and the adjacent walls so as to avoid a hard connection. Where foils are used as an elastic interlayer, this can simply be done by folding the foils up to the wall (figures 34 'a' and 'b'). Especially when working with screeds and concrete floating floors, these resilient border strips should be placed with extreme care. They should only be cut off after the tiling or the parquet has been placed so as to avoid any hard contact with the wall through the floor finishing. Architects and work surveyors should check that the border strips are still visible after placing the floor finishing and before placing the plinths (see figure 34 'e'). Plinths should be fixed to the walls and make no hard contact with the floating floor. If desired, an elastic joint filling (silicones…) can be applied between plinths and floors.

Pipes passing through the floating floor should be detached from the floating floor using again resilient strips around the pipes. Fixations of whatever equipment (radiators, etc.) should not make any hard bridges between the floating and the basic floor (see figure 34 c).

The surface on which the elastic interlayer is to be placed should be horizontal. If electric tubes or water pipes are fixed on top of the load-carrying floor and foils or mats are used as an elastic interlayer, then a levelling layer should be installed so as to provide a flat surface for the correct placement of the elastic interlayer. Before placing the foils or mats, the surface should be cleaned and free of all objects (nails, screws, debris,…).

Elastic interlayers placed as mats should connect well without gaps in between them. Foils should have sufficient overlap and are ideally taped together (see figure 34 'a'). If two superposed elastic interlayers are used, it is recommended to superpose them in crossed orientations (see figure 34 ‘a’). All of this is especially important when screed or concrete is used for the floating floor. Its ‘liquid placing’ is most sensitive to even small gaps as it does not have the advantage of bridging gaps as boards do. Small perforations are again no problem for boards, but can be catastrophic for screeds. Work project leaders should pay attention to all manipulations that could create holes in the elastic interlayer before the placing of the screed. This latter should be done as soon as the elastic interlayer is in place and all other actions in between should be avoided (perforations created by ladders, wheelbarrows, falling objects….). Care should also be taken during the placing of the screed (shovels!), using elastic foil around the tripod to avoid punctuating the foils (see figure 34‘d’).

When porous mats in glass wool, rock wool, cellulose fibres or similar materials are used as elastic interlayers, a plastic foil should be placed on top of these materials to avoid the liquid screed or concrete penetrating inside the pores and producing a hard contact between the two floors (figure 34 ‘f’).

The correct placing of the floating floor is not only crucial for impact but also for airborne direct and flanking insulation!

Figure34: the correct placing of the floating floor is vital. Even small hard contacts will eliminate all positive effects! If a material with open cells is used as an elastic interlayer (e.g. mineral wool, see right picture), a plastic foil should be applied before installing the screed.

4.3.2.5 - ***Types of floating floor systems used in LWTF constructions***

Paragraph (2) explained how floating floors reduce impact sound. The lower the mass-spring-mass resonance frequency, the better the impact sound reduction due to the floating floor in general will be (though some internal and surface damping mechanism will also be a significant parameter). The simple formula that calculates the resonance frequency shows us two possible strategies to optimize the floating floor for impact sound insulation.

We can try to reduce the dynamic stiffness 's' in the formula. This will indeed reduce the resonance frequency, but we cannot do this indefinitely: beyond an optimization value of this dynamic stiffness practical reasons quickly limit the possibilities of this strategy. First of all, the static stiffness should be such that the resilient layer is not overly compressed locally under the influence of furniture or even persons (otherwise the floor wouldn't be a horizontal surface anymore), secondly walking on a too resilient floor can give a strange heaving feeling!

The second strategy is to lower the resonance frequency by adding mass (more boards, screed), preferably both symmetrically below and on top of the elastic interlayer. Increasing the weight of only the basic floor or only of the floating floor will soon become inefficient as the formula for the mass-spring-mass resonance frequency shows. (It is only in heavy constructions that increasing the weight of the floating floor leads to a lower resonance frequency and hence a better performance. This is of course due to the considerably higher surface mass of the load-carrying floor in these constructions, so that $1/m_1''$ becomes negligible compared to $1/m_2''$ in the resonance frequency formula.)

Good floating floors display an optimization of the surface masses and the dynamic stiffness of the elastic interlayer. Lots of products exist that serve as elastic interlayers.

Increasing surface mass for the load-carrying floor can be done by adding extra boards, by using or adding extra heavy boards (fibre cement boards, extra heavy fibre reinforced gypsum board,…), by using sand fillings between the joists (a typical German technique) or on top of the boards (National Research Council of Canada), by grit fillings in honey comb elements on top of the boards (Fermacell), sand or concrete in case elements (Lignatur), dry concrete blocks in case elements (Lignatur) with optimization of the damping (to limit drum sound)…

Similar actions can be undertaken to increase the mass of the floating floor itself. Very often though, a screed of 6 to 8 cm thickness of concrete is used as this is a relatively cheap and very efficient way to increase the surface mass. Moreover, this also gives the possibility to install floor heating.

Up to now, we have always been considering that in a section of 1 m² of the floating floor system that 1 m² of elastic interlayer covers 1m² of the basic load-carrying floor and supports 1 m² of the floating top floor. Let's call this SYSTEM 1 -solutions.

By reducing the surface of the spring, we can also increase the total mass per surface of the spring (m_1'' and m_2''), lowering as such the mass-spring-mass resonance frequency of the system and improving the impact sound insulation. This can be done by concentrating mass so that it bears down line- or point-wise on the elastic pad/interlayer, resulting in a lower resonance frequency and thus to a better performance. The obvious advantage is that with existing reasonable masses of load-carrying and floating floors, quite low resonance frequencies can be obtained. In this e-book we will call the line-wise solutions SYSTEM 2-solutions and the point-wise solutions SYSTEM 3-solutions. The figure below shows some of these SYSTEM 2- and SYSTEM 3-solutions.

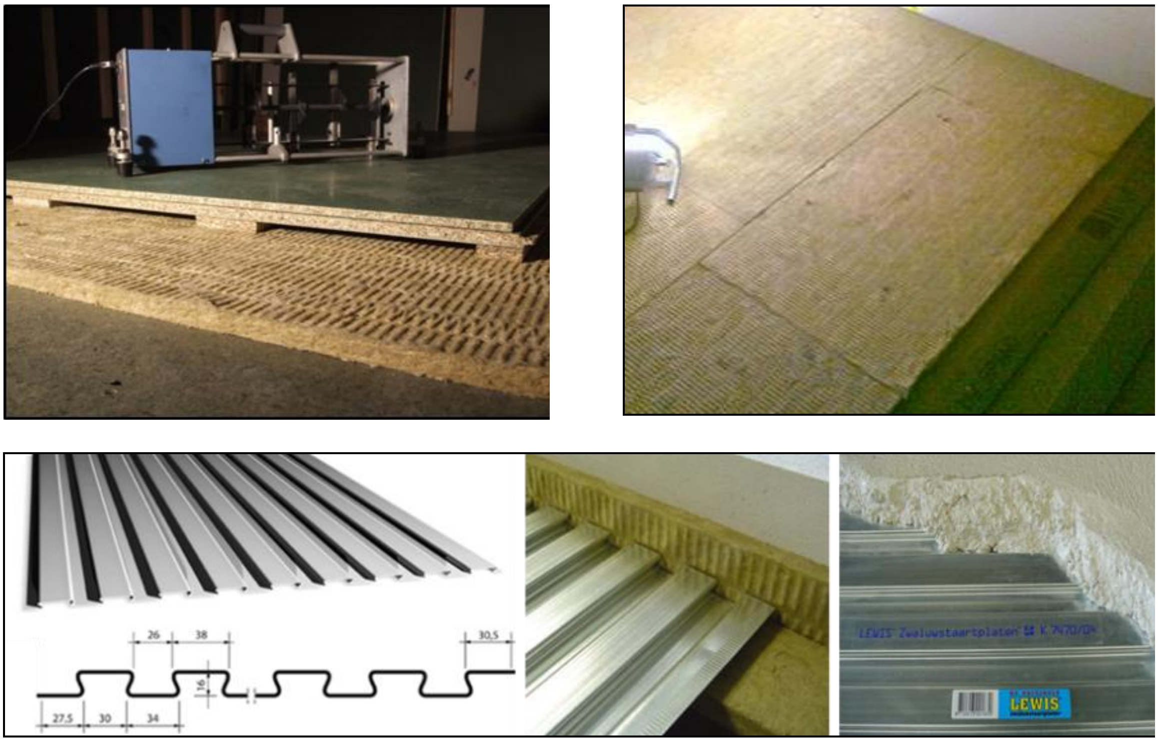


Figure 35: illustrations of floating floors SYSTEM 2 solutions based upon the principle of concentrating mass carrying line-wise on an elastic interlayer.

<u>Picture a:</u> Using the extra 100 mm wide board strips (18 mm high) on centre every 400 mm instead of placing the 2 particle-boards (Spano 12 mm +18 mm) straight on the rock wool (Rockwool 504, 140 kg/m³) reduces the impact sound by 4 dB ($L'_{nT,w}$ + $C_{I,50-2500}$) . In order to 'robotize' the prefabrication of the floor elements, the alternative way <u>(picture c)</u> of fixing the 100 mm wide boards directly on the basic floor (putting the rock wool and boards on top of these strips) was examined and showed identical gains (which is logical in a mass-spring-mass system).

<u>Pictures b:</u> Lewis steel plates have a ribbed surface less than 20 mm high and are placed perpendicular to the joists of the load-carrying floor upon high density mineral wool (140 kg/m³) fixed itself on top of the joists and boards system. A concrete mortar is poured on top of these ribbed plates resulting in a thin layer of concrete (normally around 100 kg/m²). The steel ribs are specifically shaped so as to act as reinforcement steel for the concrete. The ribbed structure perpendicular to the joists channels the load partly line-wise and partly point-wise (dominant mass at the points of crossing with the joists) onto the mineral wood. ***www.reppel.nl***

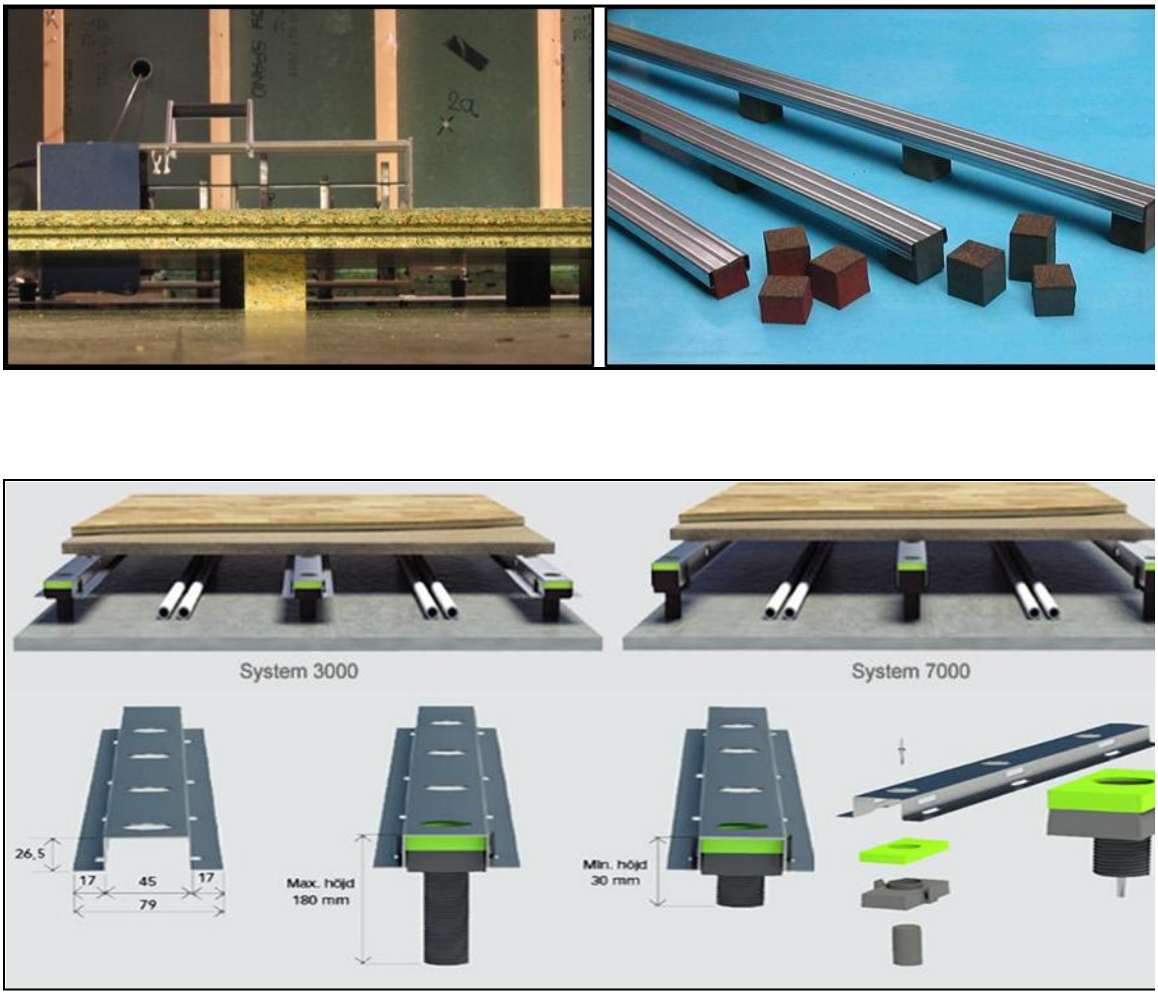


*Figure 36: illustrations of SYSTEM 3-solutions based upon the principle of concentrating mass carrying point-wise on elastic pads. Pictures c is from from CDM company (pads and iso-lats) see **www.cdm.be**. Pictures d is from Granab Subfloorsystems **www.granab.se***

4.3.2.6 - *Effectiveness of dry floating floor systems used in LWTF constructions*

Field measurements with the standard tapping machine were carried out in a two-storey timber frame mock-up construction. The goal was to compare different dry floating floor systems on the same reference floor. The mock-up contained a reference timber floor construction separating two transmission rooms. From top to bottom the basis floor construction was composed as follows (see figure below): 18 mm particle board, timber joists (section: 240 mm x 45 mm, centre-to-centre distance: 400 mm), timber battens (section: 45 mm x 22 mm, centre-to-centre distance: 400 mm), 12.5 mm gypsum boards, directly screwed on the timber battens. A mineral wool filling (90 mm, 16 kg/m³) was applied in the cavity between the timber joists.

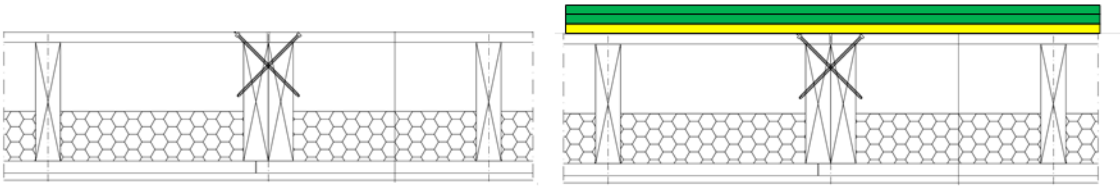


Figure 37: LEFT: construction of the reference timber floor. RIGHT: example of a floating floor on top of the reference floor.

Different (dry) floating floor systems were installed on this reference floor and examined for their impact sound reduction capacity. The examined flooring complexes consisted of a resilient layer loaded with one or two flooring boards (see figure RIGHT). Different types of resilient layers and board materials were tested in this set-up.

For reasons of time and cost savings, more than 40 different samples were tested on a limited surface, defined by typical board dimensions, e.g. 120 cm x 260 cm, 122 cm x 244 cm. In this phase of the study, only impact sound insulation measurements were made. For certain high performing complexes, airborne transmission of the radiated impact noise in the upper room became noticeable in the high frequencies (but without influence on the single ratings).

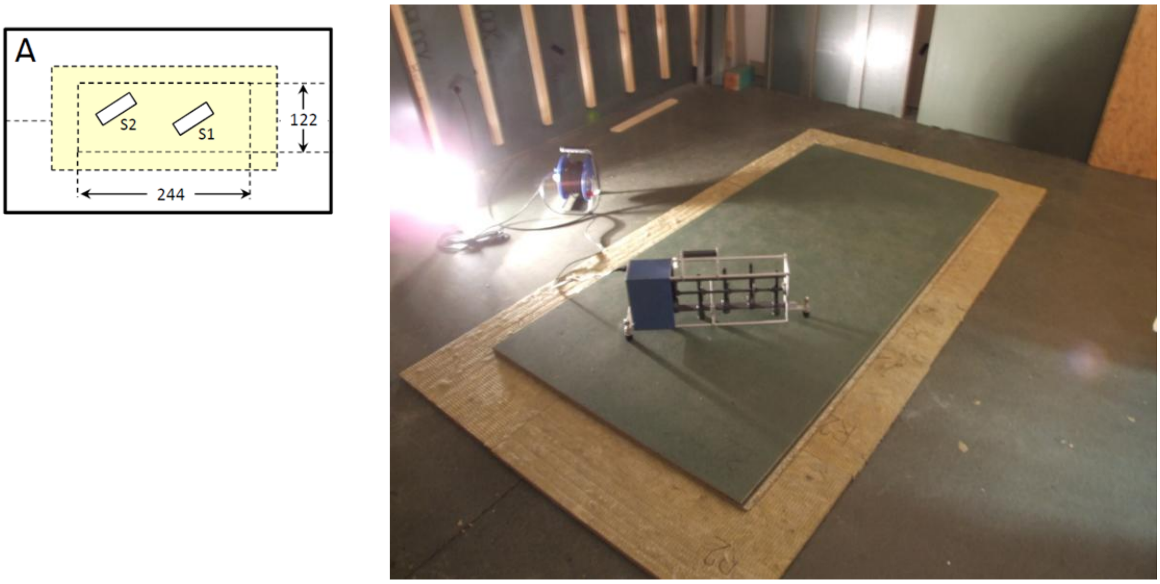


Figure 38: setup of the comparative measurements

First we examined the influence of the different board materials. Tests were carried out on different combinations and types of boards using the same 20 mm mineral wool (140 kg/m³). The following types were examined: particle boards (720 kg/m², 12 mm and 18 mm), OSB boards (600 kg/m³, 12 mm and 18 mm), wood fibre cement boards (1250 kg/m³, 18 mm), fibre cement boards (1180 kg/m³, 12 mm) and fibre reinforced gypsum boards (1140 kg/m³, 2x 10 mm).

Eight different complexes were tested in this way. In terms of $L'_{nT,w}$ the results are situated between 58 dB and 63 dB, while the surface mass of the top layers varies from 11 kg/m² to 45 kg/m². This indicates that surface mass is not the only influence parameter, and certainly internal and surface damping mechanisms need to be taken into account. For this reason we did not necessarily find worse results for boards with lower surface mass. Ranking the tested complexes by their surface mass (see figure chart 1 below), we observe only slightly higher impact noise levels (1 to 2 dB) for simple OSB and particle boards (11 to 13 kg/m², 63 dB) compared to nearly twice as heavy complexes such as an additional 12 mm board (18 to 22 kg/m²) or 18 mm wood fibre cement boards (23 kg/m²). On the other hand, for the same surface mass (23 kg/m²) we observe a difference of 2 dB between the 18 mm wood fibre cement board and the double layer of fibre reinforced gypsum board, in favour of the latter. This indicates clearly the importance of the nature of the board material. The lowest impact noise level (58 dB) was found for the heaviest complex (45 kg/m²) being a double layer of 18 mm wood fibre cement board. Though compared to the double layer of 10 mm fibre reinforced gypsum board, one had to double the surface mass to obtain a negligible improvement of only 1 dB in terms of $L'_{nT,w}$.

Of course, in order to maximise the gain using more and/or heavier boards, this mass should be equally/symmetrically distributed to both masses in the mass-spring-mass system as we explained earlier. For comparison reasons this was not done here, maintaining always the same reference floor.

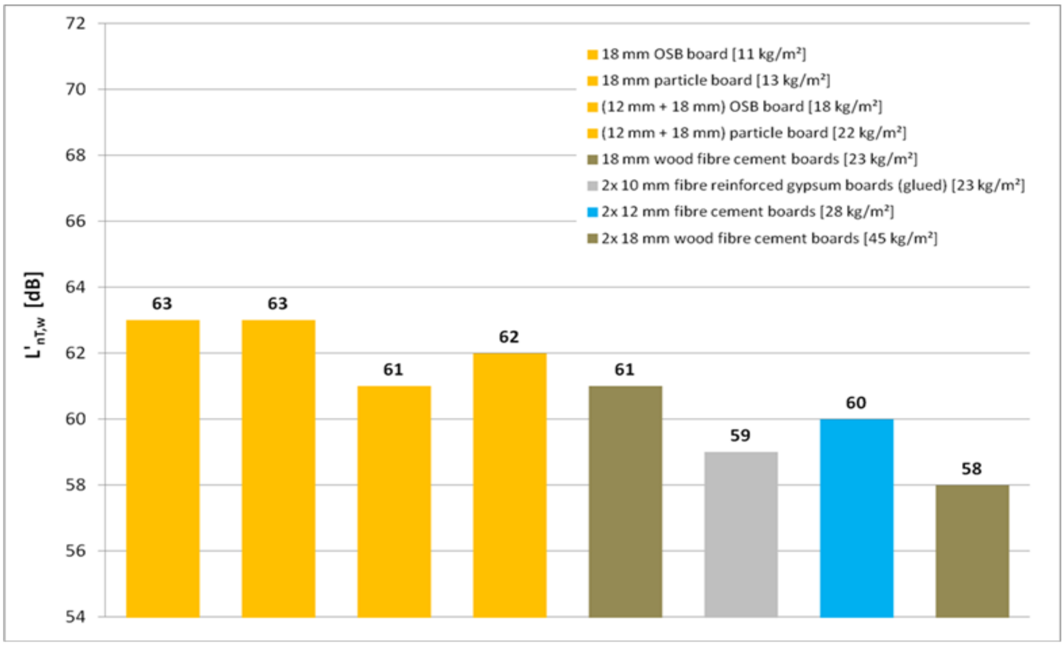


Chart 1: different board types tested on top of a 20 mm thick mineral wool layer (140 kg/m³)

Staying with one type of material, in this case particle boards and OSB boards, the single isolated influence of the surface mass could be observed (see chart 2 below). Tests were carried out on the mineral wool layer loaded with an 18 mm board and with an additional 12 mm board, screwed to the first board. Although important improvements are found between 1250 Hz and 2500 Hz, hardly any improvement of the low frequent efficiency is obtained. In terms of $L'_{nT,w}$ the improvements are confined to 1 or 2 dB. So adding boards is a sure way to improve the impact sound reduction, but not the most efficient one if no equivalent mass increase is applied to the load-carrying floor.

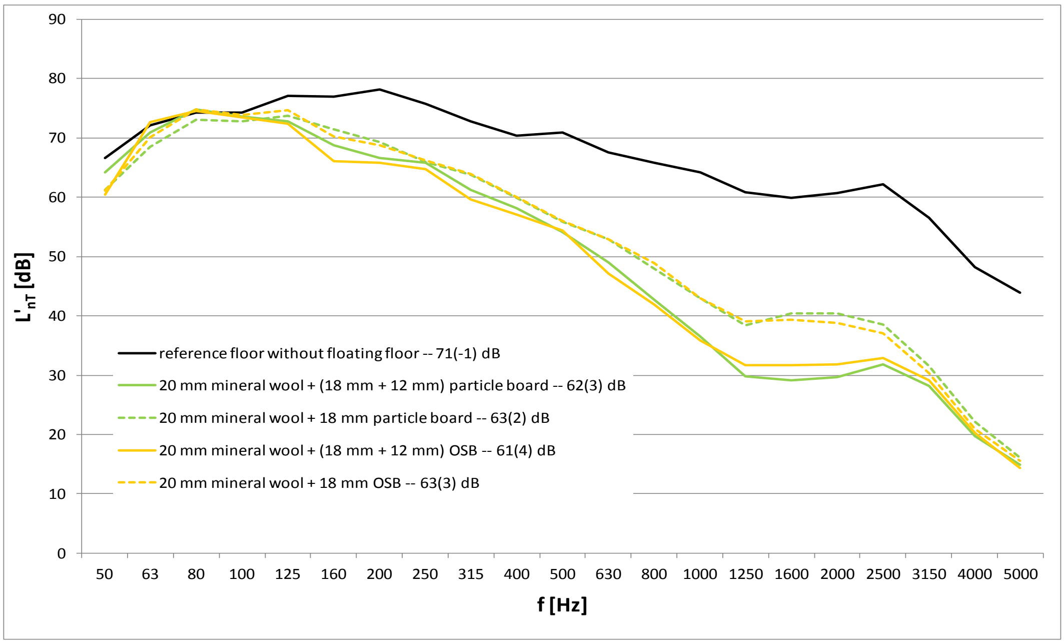


Chart 2: loading effect on 20 mm mineral wool for two different board types

In order to increase the loading effect, an experimental set-up was put into place consisting of 100 mm wide particle board strips (c-t-c distance 400 mm) screwed underneath the top layer so as to obtain a SYSTEM 2-construction. An important performance gain was now observed for the low and mid frequency range (below 1250 Hz, see figure chart 3). This tells us that combining both measures, extra boards and intermediate strips, permits a considerable overall improvement of the impact sound insulation. In terms of $L'_{nT,w}$ a gain of 5 dB due to the intermediate strips is found. Compared to the initial single value of 71 dB for the 'naked' floor, a considerably lower impact sound level of 57 dB is now obtained.

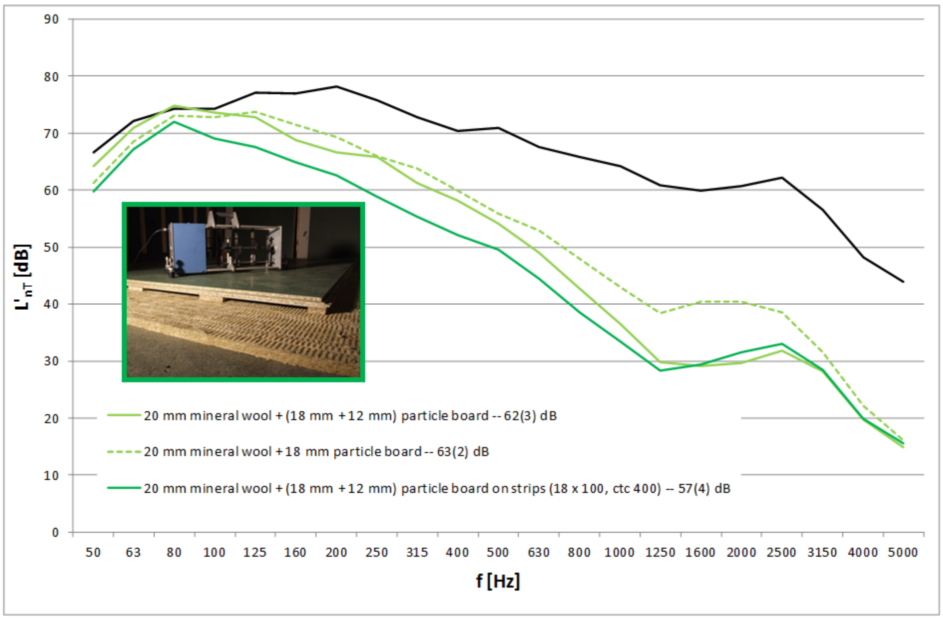
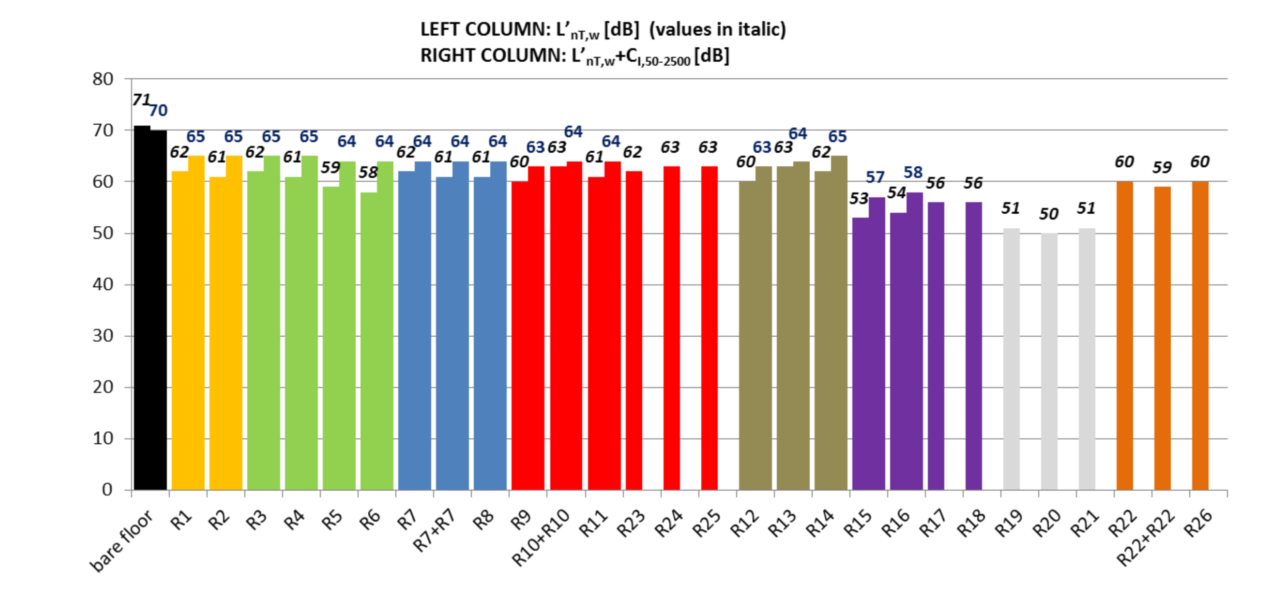


Chart 3: effect of concentrating load by means of wooden strips between boards and resilient layer

Focusing now on the nature of the resilient layer, tests were carried out on several materials, classified into eight different 'material groups'. The following colour codes were used to indicate them:

- Yellow: mineral wool layers (20 mm) – 140 kg/m³, 100 kg/m³
- Green: rubber flake foams (10, 20, 30, 40 mm) – 120 kg/m³
- Blue: PU flake foams (10, 2x10 mm) – 80 kg/m³, 100 kg/m³
- Red: (multi-layered) PE foam membranes (2x 3.5 mm, 4x 2 mm, 2x 3 mm, 5 mm, 6 mm, 9 mm)
- Brown: resin-bound rubber membranes (corrugated 8/4 mm, 3 mm, 4.5 mm)
- Purple: elastomer pads (30 mm, 50 mm)
- Grey: PU flake foam pads (50 mm)
- Orange: Wood fibre insulation boards (18 mm, 36 mm) – 270 to 250 kg/m³

Almost 40 different resilient layers were tested under a complex of 12 mm and 18 mm particle boards, in order to compare their effectiveness regarding impact noise. A brief look at the single value results ($L'_{nT,w}$), shows rather small differences between the tested samples, except for the 'purple' and 'grey' group, containing all the 'pads-based' solutions (SYSTEM 3) (see figure chart 4). Again this indicates that effective solutions have to be looked for in 'discrete' applications, such as strips or pads, optimizing the mass-spring-mass effect for the floating floor. In this way, values in the range of 50-56 dB are obtained for $L'_{nT,w}$, still with a rigidly connected gypsum board ceiling as described above. However, the PU flake pads solutions were found to be too resilient to be used in practice. For the other, more traditional resilient layers, impact noise values ranging from 58 to 63 are found.

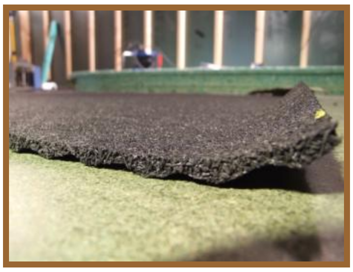


Mineral wool sample

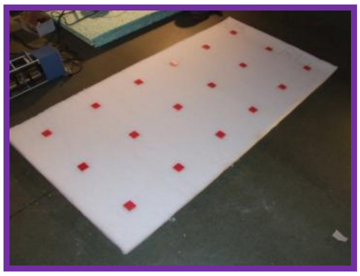
Rubber flake foam

PU flake foam

PE foam membrane



resin-bound rubber membrane



elastomeric pads in polyester wool

Sample of PU flake foam pad

wood fibre insulation boards (under particle fibre boards

Chart 4: L'$_{nT,w}$ results for different type of resilient layers combined loaded with a double layer particle boards (12 mm + 18 mm)

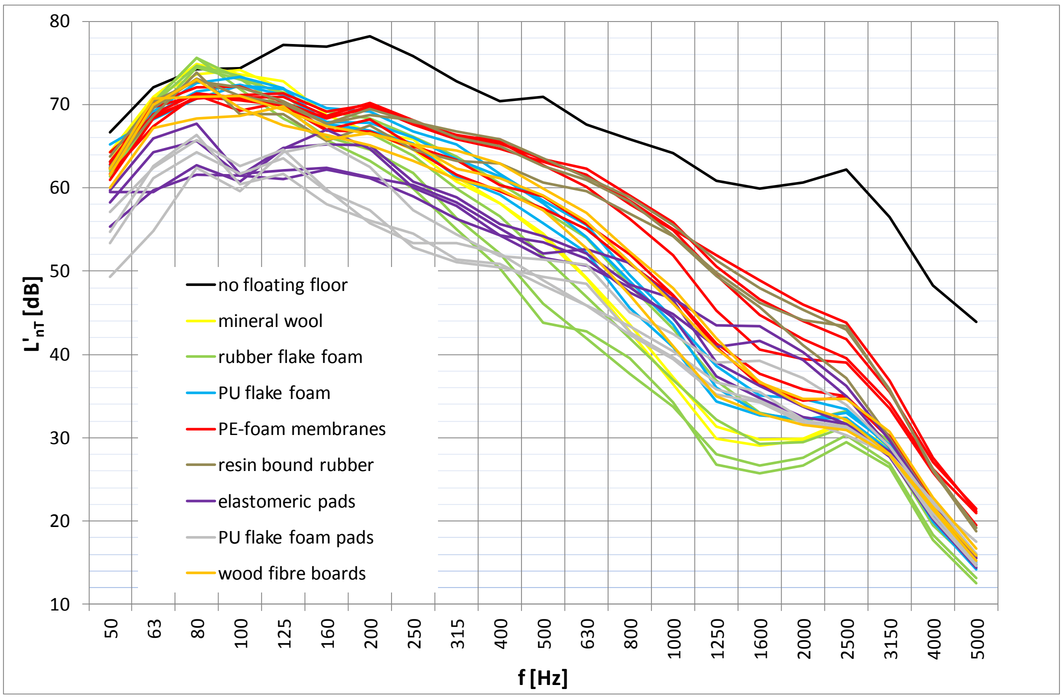


Chart 5: spectral comparison for different type of resilient layers tested under (12 mm + 18 mm) particle boards

A comparison based on spectral information (see figure chart 5) indicates a mainly low and mid frequency improvement in the case of the pad solutions (SYSTEM 3 solution).

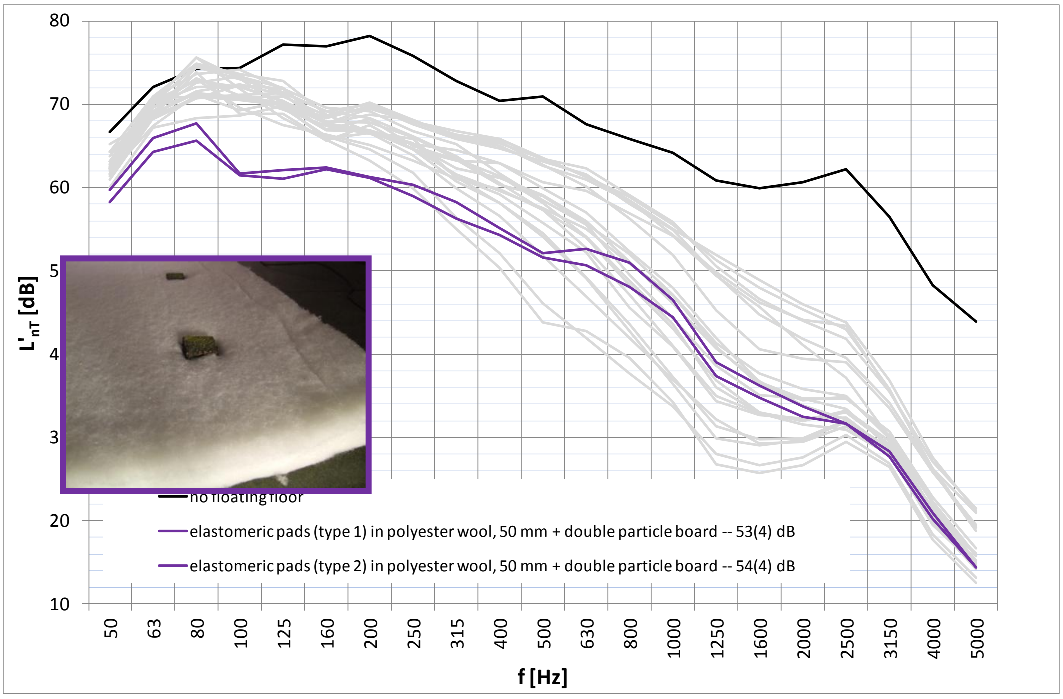


Chart 6: two different types of elastomeric pads tested in polyester wool

Two different types of elastomeric pads (both 50 mm) were tested. When embedded in a polyester fibre wool layer, suppressing standing waves in the cavity, 53 dB and 54 dB were reached in terms of single values. It should be noted that in spite of certain other samples leading to higher gains in the 200-2000 Hz frequency range, the pad solutions remain the best-scoring solutions due to their effectiveness below 200 Hz (figure chart 6). In this frequency range, even for the most effective (thick) membrane (SYSTEM 1), the spectral values remain in the region of 70 dB, leading to relatively high $L'_{nT,w}$ values in spite of their effectiveness in the higher frequencies.

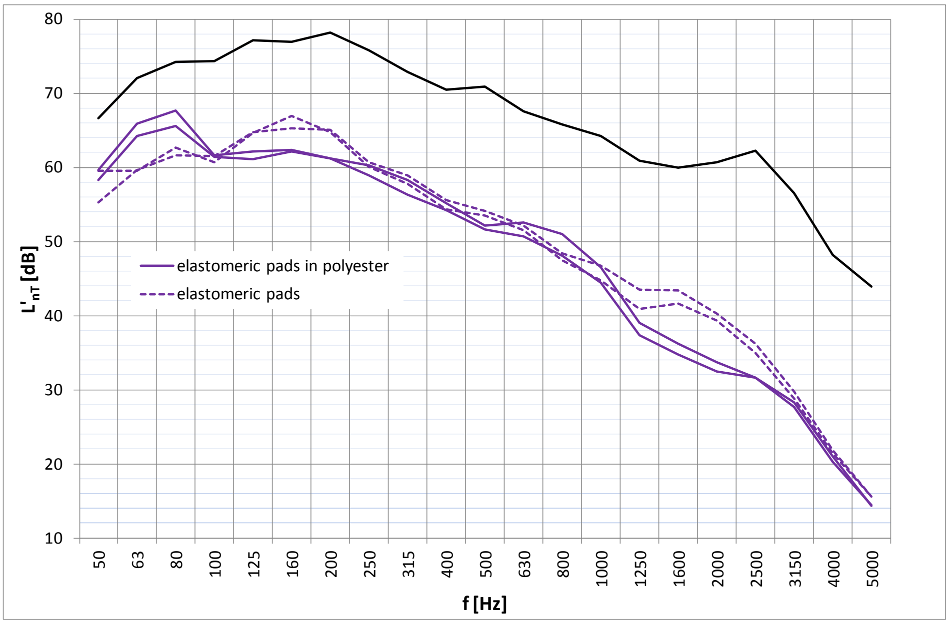
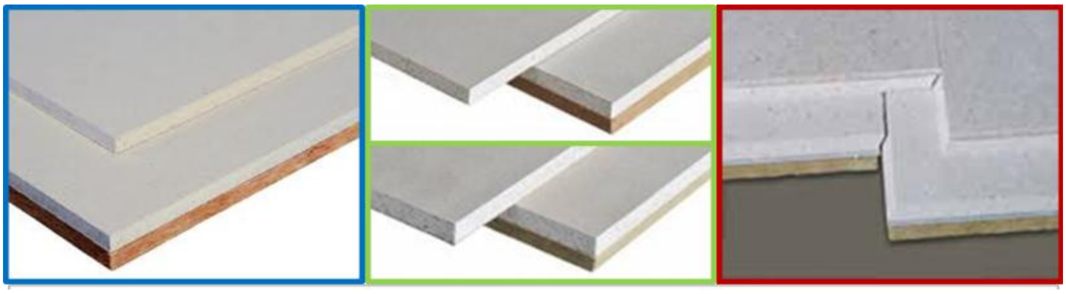


Chart 7: influence of polyester wool layer as cavity absorption with pad solutions (SYSTEM 3 solution)

When no sound absorbent cavity filling surrounds the elastomeric pads (and steel channels are used to support the floating floor), a shift of the resonance peaks is observed in the low frequency region as well as an increase of the impact noise levels in the high frequencies (cavity standing waves, see figure chart 7). In terms of single values, a loss of 2 to 3 dB is recorded ($L'_{nT,w}$ = 56 dB) compared to the pads solutions with cavity filling.

Considering again the more traditional resilient layers tested under a 12 mm + 18 mm complex of particle boards (see figures chart 4 and chart 5), the lowest value (58 dB) was found with the thickest solutions, 40 mm rubber flake foam. The least effective solutions (63 dB) turned out to be the thinnest PE foam membrane solutions. Nevertheless, a value of 60 dB was recorded for a specific 2x3.5 mm PE foam membrane, while comparable results (single values) are obtained for the 18 to 36 mm thick wood fibre insulation boards and a 2 dB higher (!) single value was found for the 20 mm thick mineral wool layer (140 kg/m³). In spite of their impressive performances in the high frequencies, the mineral wool layers do not seem to be well adapted to the relatively small load from the boards resulting in rather high levels at low frequencies (resonance zone). Comparable results (61-62 dB) were found for equivalent thicknesses of PU and rubber flake foams.

A second series of samples was tested for impact noise insulation in the above described mock-up, using commercially available preassembled floating floor systems. The 8 different samples were examined with different kinds of resilient layers: mineral wool (10 mm), wood fibre board (10 mm) or felt (9 mm). All systems consist of fibre-reinforced gypsum boards of different thicknesses: 2x 10 mm, 2x 12.5 mm or 18 mm. Depending on the manufacturer of the specific system, the nature of the fibres used to reinforce the gypsum boards may differ (same colour indicates same manufacturer).



Large deviations are recorded in the high frequency range when comparing systems with similar top layer but different resilient layer (figure chart 8). Felt and wood fibre board seem to be less effective sub layers, in favour of the more resilient mineral wool.

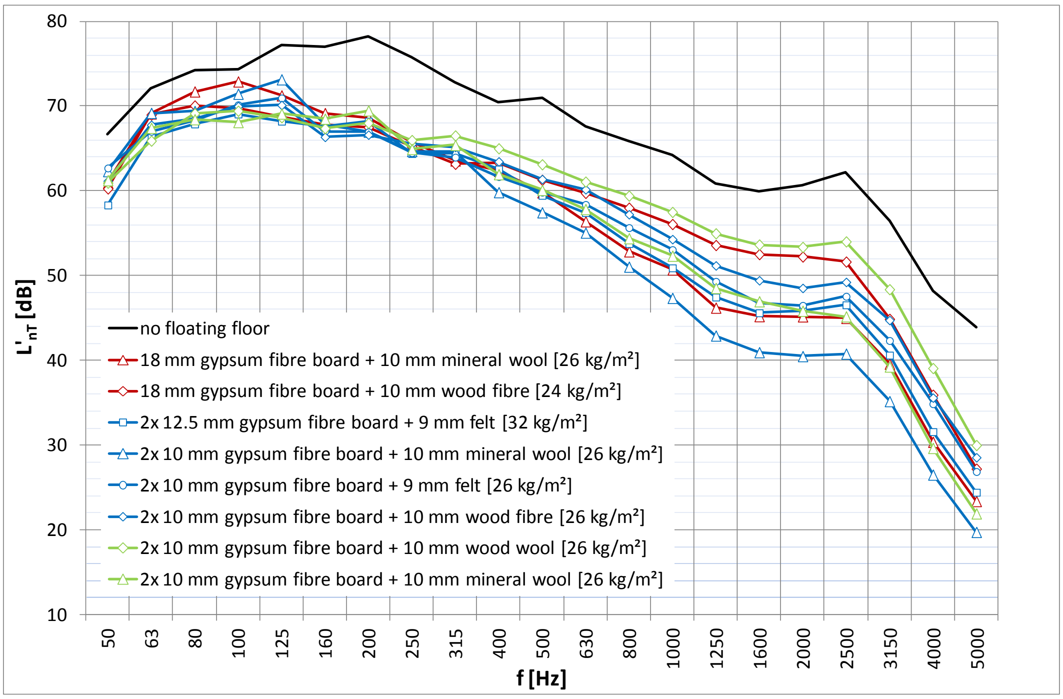


Chart 8: spectral comparison of different pre-assembled dry floating floor systems on reference floor

In spite of the large high frequency spectral deviations, the single values differ only slightly and are situated between 61 dB and 63 dB (figure chart 9). The similar, rather poor effectiveness of these 'ready made' systems in the low frequencies, limits the results in term of single values.

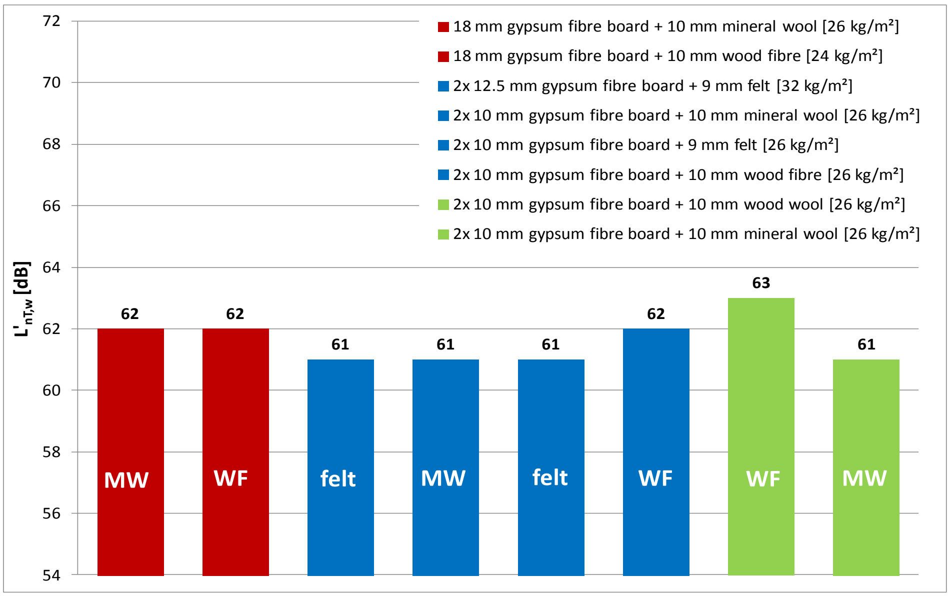


Chart 9: single value results for different pre-assembled dry floating floor systems tested on reference floor

The limits of the mass-spring-mass model for lightweight timber frame floors can be seen in chart 10. Reducing the stiffness ‘s’ of the elastic interlayer by increasing its thickness does not lead towards a downward shift of the resonance frequency. The explanation for this is to be found in the lack of rigidness of the subfloor and was already mentioned with the introduction of the mass-spring-mass model. Dynamic impacts on the topping can sometimes be unable to cause the interlayer to compress but instead cause the direct deformation of the supporting subfloor. As such, subfloor and topping are not sufficiently decoupled and the resonance frequency can be less influenced by changing for instance the stiffness of the elastic interlayer. Creating rigid load-bearing subfloors is not only a good idea for vibration comfort (see section 4.3.4.), it will also improve the impact sound insulation with floating floors due to the above mentioned effect.

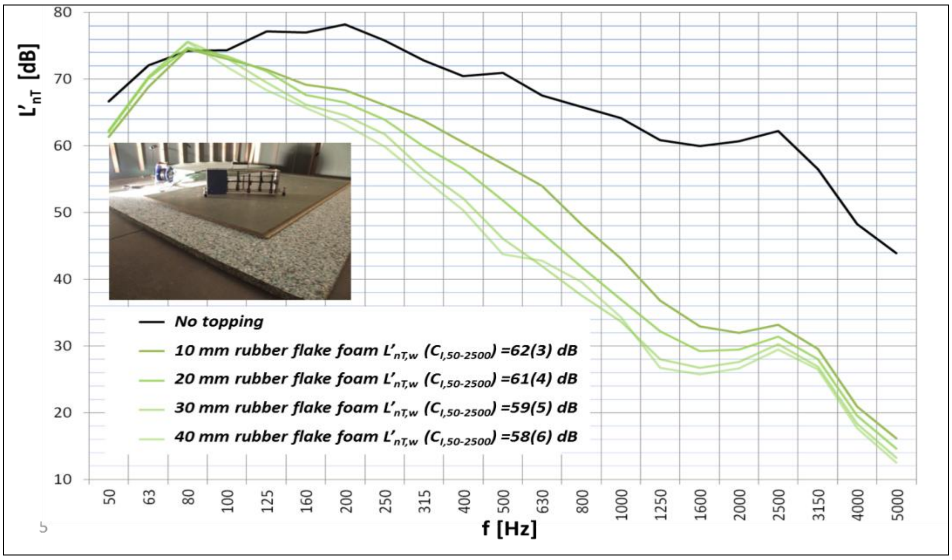


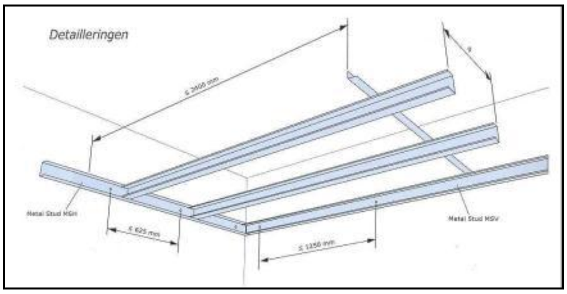
Chart 10: influence of the thickness of the elastic interlayer. Increasing the thickness of the rubber flake foam diminishes its stiffness. Doubling the thickness from 10 mm to 20 mm reduces the stiffness with 2; 40 mm thick foam only has a quarter of the stiffness of 10 mm foam. One would expect a downwards shift of the mass-spring-mass resonance with diminishing stiffness, but this was not noticeable in the measurements.

4.3.2.7 - ***The necessity of false ceilings***

We have seen in paragraph (3) that the same floating floor placed on top of a lightweight timber floor offers a less efficient reduction than installed upon a heavy (concrete) floor. This lack of efficiency explains also why impact sound in most solutions cannot be solved only with a floating floor on top of a light joist/boards system: an additional suspended ceiling will be almost always necessary.

In single family houses, ceilings are often fixed directly on wooden battens (wood furring strips) identical to the reference floor in the previous paragraph. This is not such a problem within the same dwelling, but if the floor separates two apartments (compartment floor), then this solution might not be such a good idea. Although there is some decoupling by the wood furring strips fixed perpendicularly to the joists, reducing the structural coupling to point contacts, too much structural sound transmission still occurs.

The ideal solution is a suspended ceiling that has no structural contacts at all with the load-carrying floor. This is possible to achieve with metal stud systems (see technical manuals of manufacturers), but only for limited spans. For spans above 4 m, stud heights of 15 cm are necessary. As this all comes below the joists, very quickly important floor thicknesses are the consequence (at least when the joists are perpendicular to the metal profiles). One possibility for increasing the span is to subdivide the span into two or more smaller spans using wooden beams (on which the metal studs are fixed just as if it were a wall) that can be placed between the joists of the load-carrying floor. The alternative is a wooden joist system from wall to wall and completely independent from the load-bearing floor joists.



KNAUF	Knauf CW double profile as ceiling profile					
	Maximum room width with max. axial spacing of ceiling profiles b					
	500 mm				625 mm	
	Cladding thickness in mm					
Metal thickness 0.6 mm	12.5	+ extra load 1)	2x 12.5	+ extra load 1)	18	+ extra load 1)
CW 50	**3**	2.75	**2.5**	2.25	**2.75**	2.25
CW 75	**3.75**	3.5	**3.25**	3	**3.25**	3
CW 100	**4.25**	4	**3.75**	3.5	**4**	3.5
CW 125	**5**	4.5	**4.25**	4	**4.5**	4
CW 150	**5.5**	5	**4.75**	4.5	**5**	4.5

GYPROC Plafonds (code)		Dubbele beplating Gyproc A			
		MS 75P/ 50.2(A)	MS 100P/ 75.2(A)	MS 125P/ 100.2(A)	MS 150P/ 125.2(A)
Plafondsamenstelling					
Hoogte constructie in mm		75	100	125	150
Opbouw frame:	Metal Stud MSH	50	75	100	125
	Metal Stud MSV	50	75	100	125
Aantal & dikte platen		2 x 12,5 mm Gyproc A			
Gewicht in kg/m²		23	24	24	24
Maximale overspanningen					
H.o.h.-afstand van de plaatdragende Metal Stud MSV-profielen in mm	300	2200	3000	3750	4350
	400	2000	2750	3400	3900
	500	1900	2550	3200	3650

*Figure 39: maximum room widths of free-spanning fireboard ceilings are limited (see documentation **www.gyprocplafonds.nl** and **www.knauf.de**)*

The alternative of a completely independent ceiling is the use of resilient metal channels that are fixed directly in the joists of the load-carrying floor (see figures 40 'a-f' below).

Figure 40: (a) Wood furring strips fixed directly and perpendicular to the joists of the floor, this is only suitable for floors within the same building. (b) Mounting device to fix any heavy boards (c) (d) Ceiling metal profiles (Knauf) allowing a resilient connection with the joists (e) The finishing of the joint between wall and ceiling has an influence on the direct and flanking insulation. (f) Another type of fixation of metal ceiling profiles allowing for a larger cavity (Gyproc).

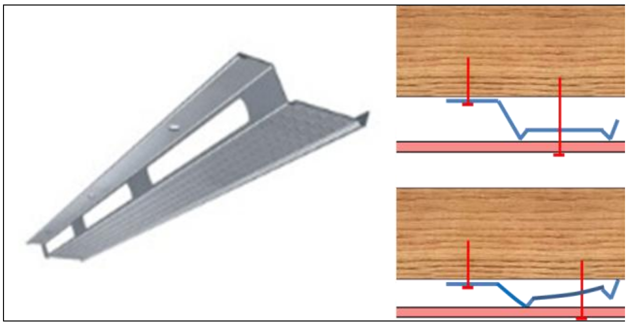


Figure 41: So-called resilient Z-channels (picture from PrimeWall® Resilient Channel). Possible mistakes can deteriorate the acoustic performance. Using the wrong screws that are too long and enter the joists can block the resiliently hung ceiling (this can also happen with the channels in the above picture d). Especially the first screws fixed through the gypsum board can push the 'free end' of the Z-profile against the joists. Even well-dimensioned screws can then enter in the joists, blocking the resilient system.

There are still other alternatives of rigid, 'punctual' fixation clips fixed to the channels (in which finally the gypsum boards are screwed).

Research work in NRCC showed the very beneficial effect of increasing the spacing of resilient channels from 406 mm to 610 mm. The improvement is quite large and ranges from 4 to 6 points in all cases (see table below). This large increase occurs, because by reducing the number of resilient channels, the overall stiffness of the connection decreases, meaning the resonance frequency shifts downwards also. This means that the improvement due to adding resilient channels starts earlier.[4]

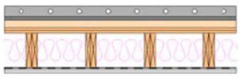
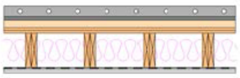
Floor ID	Sketch (not to scale)	Heavy impact (Ball)		Light Impact (Hammer)	
		$L_{iFavg,Fmax}$ (63-1k Hz)	$L_{i,Fmax,AW}$	$L_{n,W}+C_I$ (50-2500 Hz)	$L_{n,W}$
NRC-K23	2G + RC406 	**46**	**49**	**50**	**47**
NRC-K15	2G + RC610 	**42**	**44**	**44**	**43**
NRC-K23 – NRC-K15	Difference	**4**	**5**	**6**	**4**

Table 1: increasing the spacing between the resilient channels results in large improvements of the impact sound insulation (data from table 5 of the article referenced to in the footnote).

Specially developed clips with elastic fixations are also available although the possible gain in insulation remains more limited than when used with concrete floors (see figures and tables below).

The impact sound insulation will improve with the surface mass of the ceiling. In practice this means more (fire resistant) gypsum boards or fire resistant gypsum boards combined with heavier boards. The added mass will lower the resonance frequency and hence increase the sound insulation.

Inside the cavity, flexible porous material should be added to avoid standing waves and to help increase the sound insulation. Taking into account fire requirements, very often rock wool and cellulose fibres are used. The effect of adding these materials inside the cavity will increase with thickness only if the decoupling from the load-carrying floor is sufficient (if not, the structural transmission path will be dominant).

[4] On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012)

	TEST 01				TEST 02				TEST 03				TEST 04				TEST 05				REFERENCE FLOOR	
	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	R
100	68.3	13.7	34.3	12.3	69.8	12.2	35.4	13.4	70.9	11.1	35.8	13.8	69	13	35.1	13.1	69.9	12.1	34.2	12.2	82	22
125	**73.6**	**15.6**	**33.4**	**13.6**	**73.2**	**16**	**34.8**	**15**	**74.9**	**14.3**	**33.7**	**13.9**	**74.2**	**15**	**36**	**16.2**	**73.7**	**15.5**	**36.3**	**16.5**	**89.2**	**19.8**
160	74.7	15.8	31.1	13.1	72.6	17.9	33.8	15.8	74.5	16	32.9	14.9	73	17.5	32.7	14.7	73.7	16.8	32.3	14.3	90.5	18
200	74.7	18	35	16.7	73.5	19.2	34.9	16.6	74.8	17.9	34.2	15.9	73.9	18.8	34.7	16.4	74	18.7	34.1	15.8	92.7	18.3
250	**74.8**	**19.8**	**37.5**	**17.6**	**72.9**	**21.7**	**38.5**	**18.6**	**73.9**	**20.7**	**38.6**	**18.7**	**73.3**	**21.3**	**37.8**	**17.9**	**73.6**	**21**	**37.7**	**17.8**	**94.6**	**19.9**
315	70.9	21.8	41.6	20	69.4	23.3	43.8	22.2	70.1	22.6	43.7	22.1	69.8	22.9	42.9	21.3	71.2	21.5	41.5	19.9	92.7	21.6
400	70.9	19.8	45.5	21.2	69.6	21.1	46.5	22.2	70.7	20	46.2	21.9	69.9	20.8	46.5	22.2	70.9	19.8	45.6	21.3	90.7	24.3
500	**72**	**20.6**	**45.6**	**21.3**	**71.3**	**21.3**	**47.3**	**23**	**72.1**	**20.5**	**46**	**21.7**	**71.3**	**21.3**	**46.8**	**22.5**	**71.7**	**20.9**	**44.9**	**20.6**	**92.6**	**24.3**
630	70.6	23.4	47.6	24.1	70.1	23.9	48.6	25.1	70.6	23.4	48.2	24.7	71.2	22.8	47.1	23.6	70.9	23.1	47.1	23.6	94	23.5
800	70.7	20.1	46.6	21.1	69.3	21.5	48.5	23	70.1	20.7	47.4	21.9	69.9	20.9	47	21.5	70.5	20.3	46.7	21.2	90.8	25.5
1000	**67.3**	**22.6**	**47.9**	**22.8**	**66.1**	**23.8**	**50.1**	**25**	**66.4**	**23.5**	**49.8**	**24.7**	**66.6**	**23.3**	**49.1**	**24**	**66.2**	**23.7**	**49.2**	**24.1**	**89.9**	**25.1**
1250	64.2	23	49.8	24.7	62.7	24.5	51.9	26.8	63.4	23.8	51.2	26.1	63.7	23.5	50.7	25.6	64.1	23.1	50.2	25.1	87.2	25.1
1600	59.6	25.5	52.8	27	59.2	25.9	54	28.2	59.3	25.8	53.3	27.5	59.9	25.2	53.3	27.5	60.1	25	52.7	26.9	85.1	25.8
2000	**55.1**	**27.2**	**54.6**	**28**	**55.2**	**27.1**	**55.6**	**29**	**54.8**	**27.5**	**54.9**	**28.3**	**56**	**26.3**	**54.6**	**28**	**55.7**	**26.6**	**54.6**	**28**	**82.3**	**26.6**
2500	53	25.3	54	25.6	53.5	24.8	54.9	26.5	53.5	24.8	54	25.6	54.5	23.8	54.2	25.8	54.1	24.2	54	25.6	78.3	28.4
3150	49	24.5	55.4	24.7	49	24.5	56.8	26.1	49.6	23.9	56.2	25.5	50.5	23	56.1	25.4	50.3	23.2	55.7	25	73.5	30.7
4000	**41.3**	**26.9**	**60.2**	**28**	**41.1**	**27.1**	**61.2**	**29**	**43.6**	**24.6**	**60.8**	**28.6**	**42.8**	**25.4**	**60.2**	**28**	**42.8**	**25.4**	**60**	**27.8**	**68.2**	**32.2**
5000	34.2	28.1	61.7	26.9	32.9	29.4	62.2	27.4	36.9	25.4	62.5	27.7	34.3	28	62.1	27.3	36.1	26.2	61.6	26.8	62.3	34.8
	69	25	48	22	68	25	50	24	69	25	49	23	69	23	49	23	69	24	48	22	91	26
	-1	-5	-1		-1	-4	-2		-1	-5	-1		-2	-3	-2		-2	-4	-1		-4	-1
			-5				-5				-5				-5				-5			-2

Table 2: direct airborne insulation of different resilient ceiling suspension systems and profiles. The reference floor is a simple wooden floor made of joists and a single OSB panel of 18 mm. Although no measurements are available below 100 Hz, as a conclusion one can say that the difference between all the systems (carrying two gypsum boards of 12.5 mm) is rather negligible. The last two lines represent the single ratings and the spectrum adaptation terms for the frequency area between 100-3150 Hz (airborne sound insulation) and between 100 H-2500 Hz (impact sound).

Where the suspended ceiling touches the walls, a hard connection can arise between the load-carrying floor and the suspended ceiling. Moreover, extra flanking transmission paths will occur. So the use of an elastic joint between ceiling and wall is from an acoustic point of view preferable. Unfortunately problems might arise with fire requirements. In some countries, the use of an elastic junction is allowed in combination with rock wool in the cavity (forming an extra fire barrier), but in other countries, this is not the case.

4.3.3 - Direct airborne sound insulation

The direct airborne sound insulation of floors is very similar to what can be said about party walls. Due to the height of the floor joists and the need for an independent or resilient fixing of the false ceiling (creating extra cavity height), large cavities that can be filled up with flexible porous materials are present, allowing for a very low mass-spring-mass resonance frequency. For the lower frequencies, this is of course ideal.

In party walls, all structural coupling can be avoided except near the foundations. The same perfect structural decoupling cannot be attained with floors. So the ultimate performance of the direct airborne sound insulation will always be slightly influenced by some form of structural sound transmission. In order to obtain ever better performances, cavity width can be increased and the surface masses of the composing mass-spring-mass system can be increased (heavier ceilings, heavier complex of basic floor and floating floor). These strategies have already been commented on above in terms of further increasing impact sound insulation.

In well-structured decoupled systems, adding thicker porous flexible materials (rock wool, cellulose fibres,…) will further increase the direct airborne sound insulation. In general, it is not the direct airborne sound insulation that causes the major worries. Impact sound, vibrations and flanking airborne sound transmission are the topics in LWTF apartment constructions that are most difficult to master

4.3.4 - Floors and comfort against vibrations

Not only impact sound is a worry, also vibrations can be experienced in the same and adjacent rooms when someone is walking around or when children are playing and jumping around (cups starting to tremble, …). In accordance with EC5 'Serviceability under vibrations of wooden floors', an accurate design and calculation of lightweight constructions such as wooden floors is most important. Calculation aspects and requirements are treated in the reports of WG2 and WG3.

Lightweight constructions are far more sensitive to vibrations than heavy constructions: For a given vibratory energy, the amplitude of vibration will increase for the lightweight structural parts of the building. So for a given induced energy, coming either from normal users of the floor or from external sources, the vibration velocity will be much greater than in the case of a normal concrete floor.

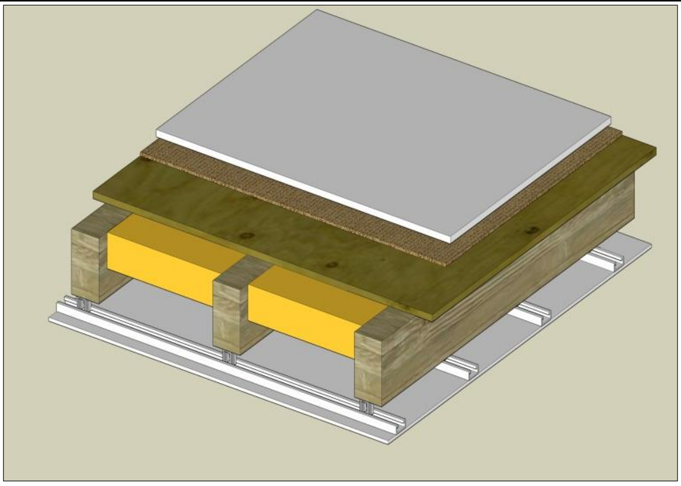
The second drawback of wooden floors is the anisotropy coming from the great contrast between the flexural rigidity in the two directions of the floor. There is a direct mathematical link between the contrast of rigidity and the number of flexural modes of the floors under 40 Hz. From this number of flexural modes, the accelerance of the floor, which is the ratio of acceleration and induced force, can directly be deduced. The accelerance expresses a kind of 'deformability' or 'flexibility' and is a good parameter for the quantification of discomfort for users. If the number of flexural modes is low, the floor will be in compliance with EC5 and users will not experience any kind of vibration inconvenience. For example, in the case of an isotropic concrete floor of classical size there is only one mode lower than 40 Hz. A wooden floor which fails to respect the rules of good design will reveal up to 7 modes!

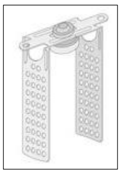
Good rules of design in accordance with EC5 are:

- creating floors that are as rigid as possible (especially reinforcing the flexural rigidity perpendicular to the joists (diminishing the effects of orthotropic behaviour that otherwise exists);
- keeping the first mode of vibration as high as possible in the frequency domain in which vibration energy is induced by normal walking of users. The stipulated minimal limit in EC5 is 7 Hz;
- calculation is always necessary, given that simple building guidelines are just not enough.

Vibratory energy from walking, dancing etc. is well known in terms of induced force and in terms of frequency content. In this way the rules of good design have been established in Eurocode 5. But there can also be problems with exterior sources of vibrations induced by traffic (especially near places where speed bumps are installed or in the proximity of deteriorated road infrastructure). In the case of external sources of vibration, frequency content and amplitude depend on the environment and possibly cannot be met by the calculation design of EC 5. So discomfort can be experienced by people, even when the rules of good design of EC 5 have been respected.

4.3.5 - Complete floor systems and their direct airborne and impact insulation: examples



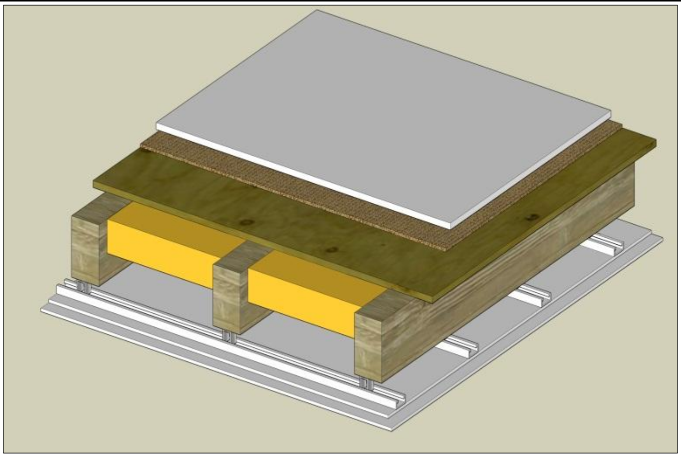


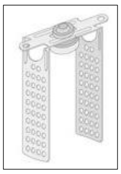
R'_{w}=	67.5 dB
R'_{living}=	57 dB
$C_{50\text{-}5000}$=	-10.6 dB
$C_{100\text{-}3150}$=	-2.5 dB
$C_{tr,100\text{-}3150}$	-8.4 dB

$L_{n,w}$=	49.4 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	57.5 dB
$C_{I,50\text{-}2500}$=	8.1 dB
$C_{I,100\text{-}2500}$=	0.4 dB

Ref. SDH 08098-03-R (Anlage 9), Bauphysik Iphofen

Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 22 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: 100 mm mineral wool
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a space of 70 mm between joists and ceiling. *** 1x12.5 mm 'K diamant board' (ca. 13 kg/m²)



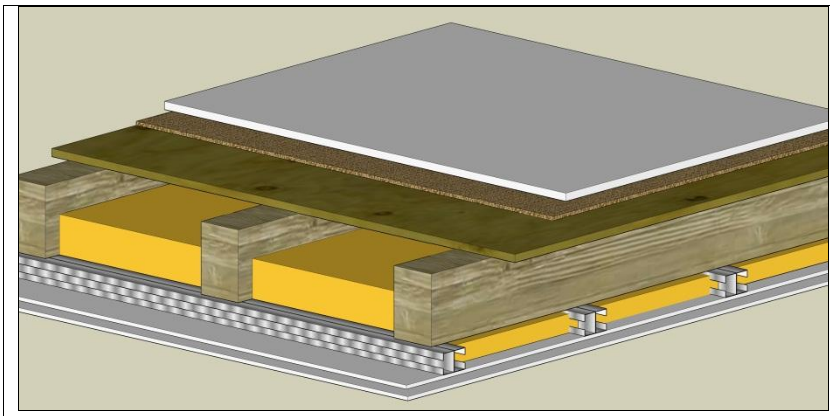


R'_{w}=	71.0 dB
R'_{living}=	62.2 dB
$C_{50\text{-}5000}$=	-8.8 dB
$C_{100\text{-}3150}$=	-2.3 dB
$C_{tr,100\text{-}3150}$	-7.8 dB

$L_{n,w}$=	45.0 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	51.7 dB
$C_{I,50\text{-}2500}$=	6.7 dB
$C_{I,100\text{-}2500}$=	-0.1 dB

Ref. SDH 08098-03-R (Anlage 16), Bauphysik Iphofen

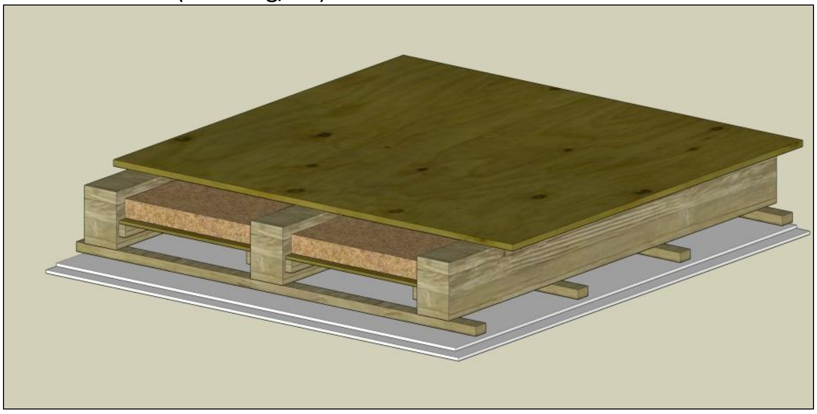
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 22 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: 100 mm mineral wool
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a space of 70 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf diamant board' (ca. 13 kg/m²)



R'$_{w}$=	74.6 dB
R'$_{living}$=	70.1 dB
$C_{50-5000}$=	-4.5 dB
$C_{100-3150}$=	-2.1 dB
$C_{tr,100-3150}$	-6.7 dB
$L_{n,w}$=	37.8 dB
$L_{n,w}$+$C_{I,50-2500}$=	43.9 dB
$C_{I,50-2500}$=	6.1 dB
$C_{I,100-2500}$=	1.3 dB

Ref. SW 07024-10R, Bauphysik Iphofen

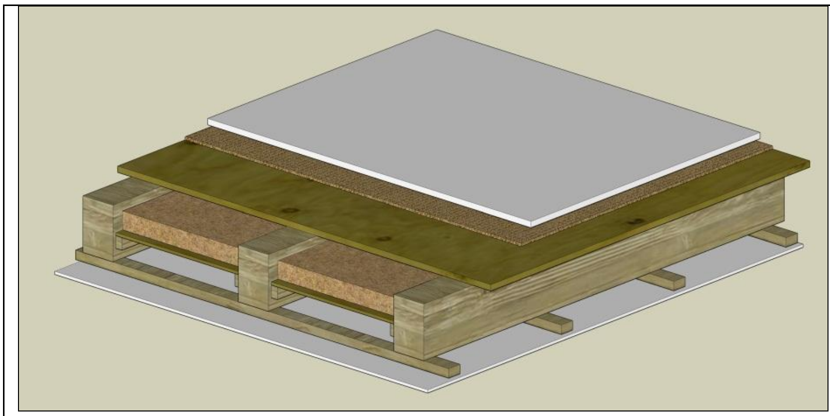
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 22 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: 100 mm mineral wool
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 25 mm below the joists *** 2x12.5 mm 'Knauf diamant board' (ca. 13 kg/m²)



R'$_{w}$=	not avail.
R'$_{living}$=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	71 dB
$L_{n,w}$+$C_{I,50-2500}$=	71 dB
$C_{I,50-2500}$=	0 dB
$C_{I,100-2500}$=	0 dB

Ref. 01 011-T-48, Bauphysik Iphofen

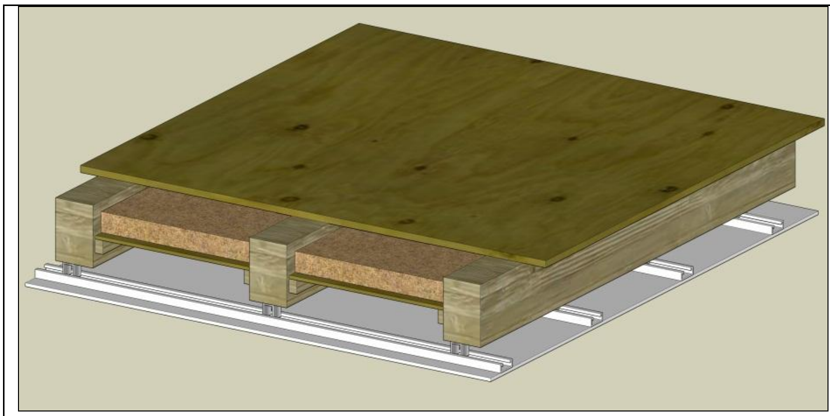
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'$_{w}$=	not avail.
R'$_{living}$=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	68 dB
$L_{n,w}$+$C_{I,50-2500}$=	70 dB
$C_{I,50-2500}$=	2 dB
$C_{I,100-2500}$=	1 dB

Ref. 03 026-T-12, Bauphysik Iphofen

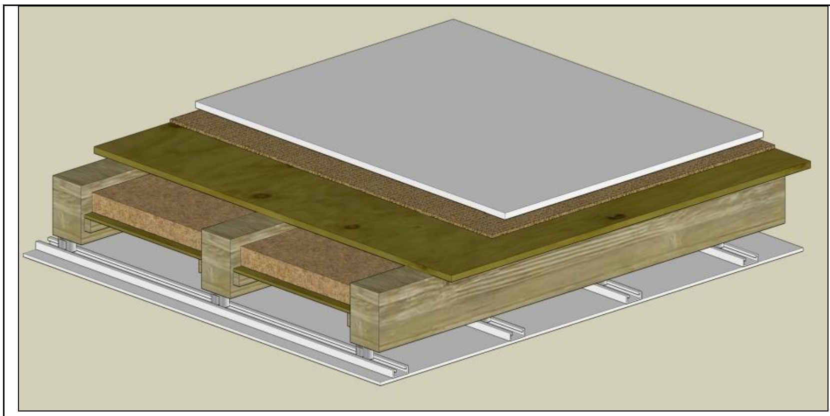
Topping: 20 mm fibre gypsum board (Gipsfasern Integral) + 10 mm wood fibre insulation (Steico)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	62 dB
$L_{n,w}+C_{I,50-2500}$=	63 dB
$C_{I,50-2500}$=	1 dB
$C_{I,100-2500}$=	0 dB

Ref. 06 026-T-43, Bauphysik Iphofen

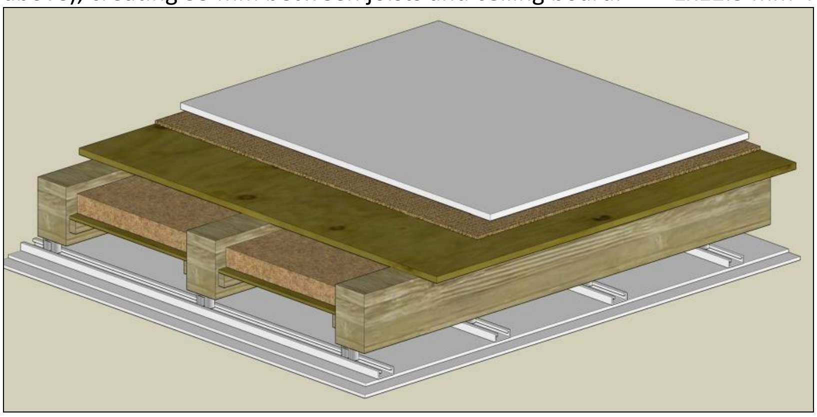
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a 35 mm between joists and ceiling board. *** 1x12.5 mm 'GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	55 dB
$L_{n,w}+C_{I,50-2500}$=	60 dB
$C_{I,50-2500}$=	5 dB
$C_{I,100-2500}$=	3 dB

Ref. 06 026-T-43, Bauphysik Iphofen

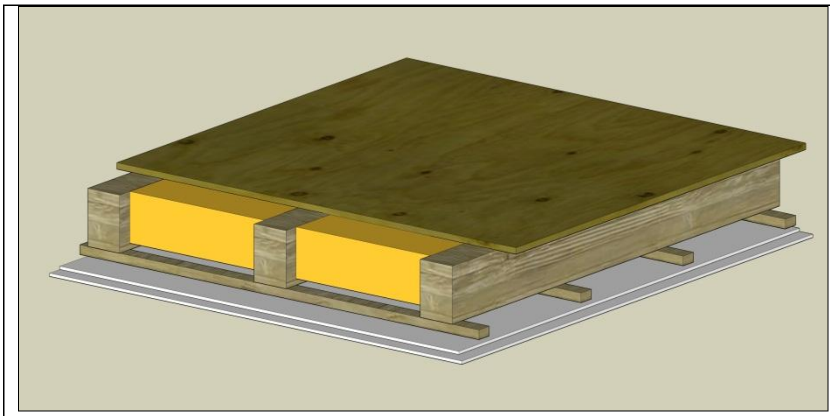
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 35 mm between joists and ceiling board. *** 1x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	49 dB
$L_{n,w}+C_{I,50-2500}$=	56 dB
$C_{I,50-2500}$=	7 dB
$C_{I,100-2500}$=	1 dB

Ref. 06 026-T-43, Bauphysik Iphofen

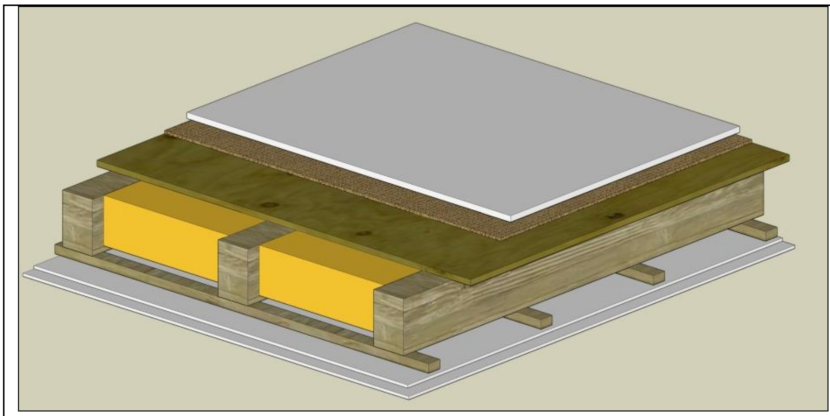
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a space of 35 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	74 dB
$L_{n,w}+C_{I,50-2500}$=	75 dB
$C_{I,50-2500}$=	1 dB
$C_{I,100-2500}$=	0 dB

Ref. 03 026-T-17, Bauphysik Iphofen

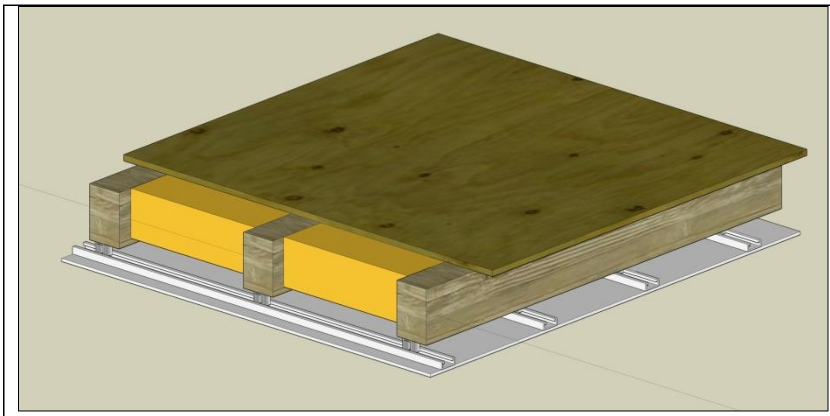
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	65 dB
$L_{n,w}+C_{I,50-2500}$=	67 dB
$C_{I,50-2500}$=	2 dB
$C_{I,100-2500}$=	1 dB

Ref. 03 026-T-11, Bauphysik Iphofen

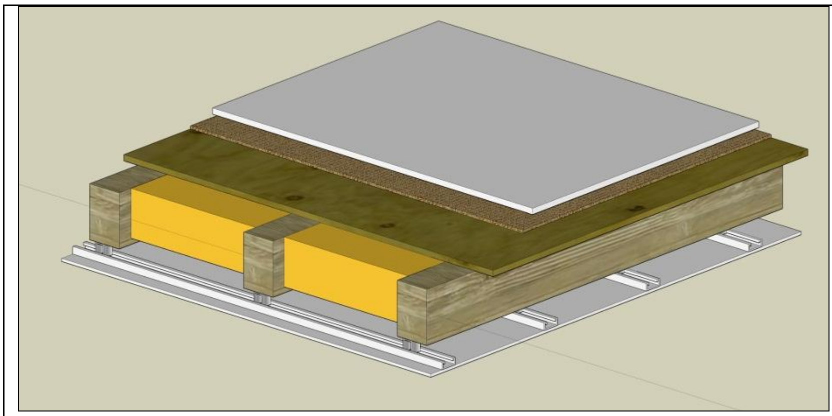
Topping: 20 mm fibre gypsum board (Gipsfasern Integral) + 10 mm wood fibre insulation (Steico)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	60 dB
$L_{n,w}+C_{I,50-2500}$=	69 dB
$C_{I,50-2500}$=	9 dB
$C_{I,100-2500}$=	2 dB

Ref. 05 007-T-43, Bauphysik Iphofen

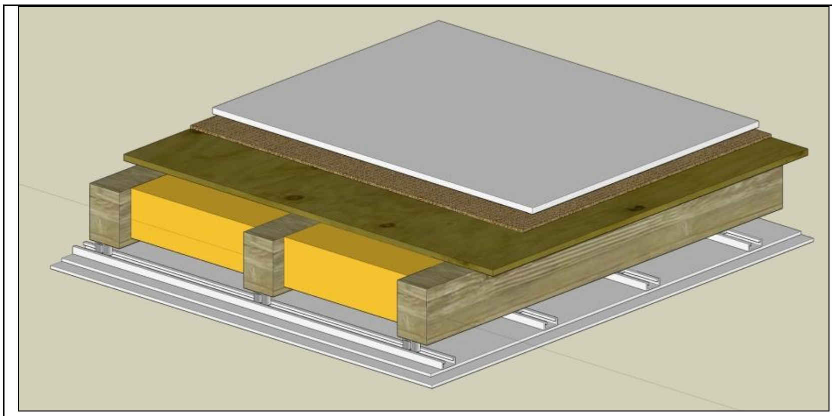
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 1x12.5 mm 'Knauf GKB' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	54 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	63 dB
$C_{I,50\text{-}2500}$=	9 dB
$C_{I,100\text{-}2500}$=	2 dB

Ref. 05 007-T-44, Bauphysik Iphofen

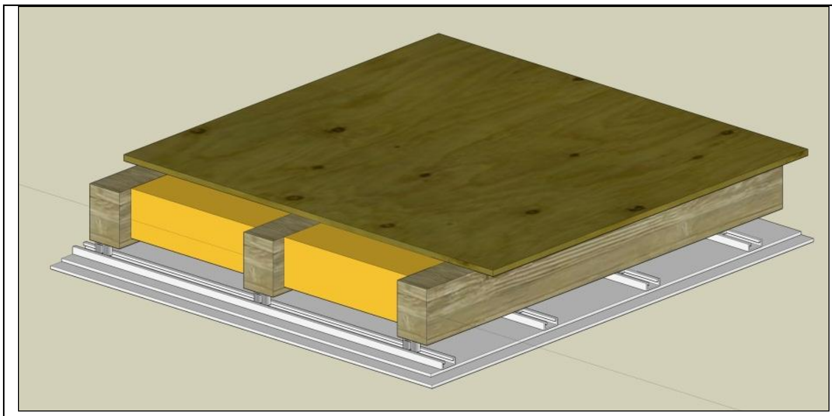
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 1x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	49 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	60 dB
$C_{I,50\text{-}2500}$=	11 dB
$C_{I,100\text{-}2500}$=	1 dB

Ref. 05 007-T-45, Bauphysik Iphofen

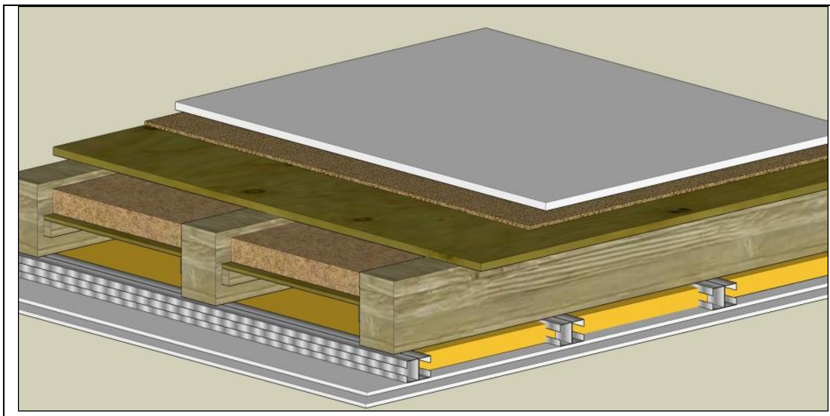
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	55 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	65 dB
$C_{I,50\text{-}2500}$=	10 dB
$C_{I,100\text{-}2500}$=	2 dB

Ref. 05 007-T-46, Bauphysik Iphofen

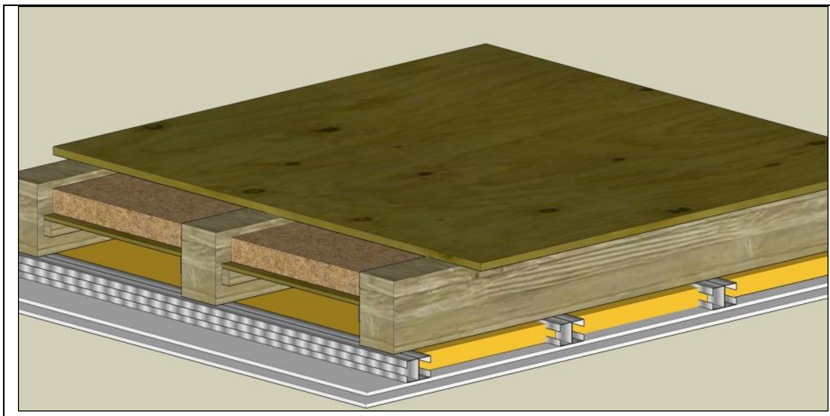
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	38 dB
$L_{n,w}+C_{I,50-2500}$=	48 dB
$C_{I,50-2500}$=	10 dB
$C_{I,100-2500}$=	0 dB

Ref. 06 026-T-06, Bauphysik Iphofen

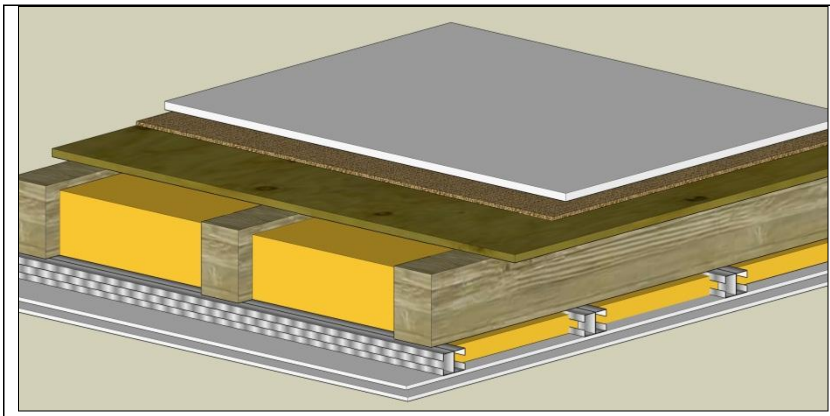
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board and mineral wool 60 mm
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	45 dB
$L_{n,w}+C_{I,50-2500}$=	50 dB
$C_{I,50-2500}$=	5 dB
$C_{I,100-2500}$=	-1 dB

Ref. 06 026-T-05, Bauphysik Iphofen

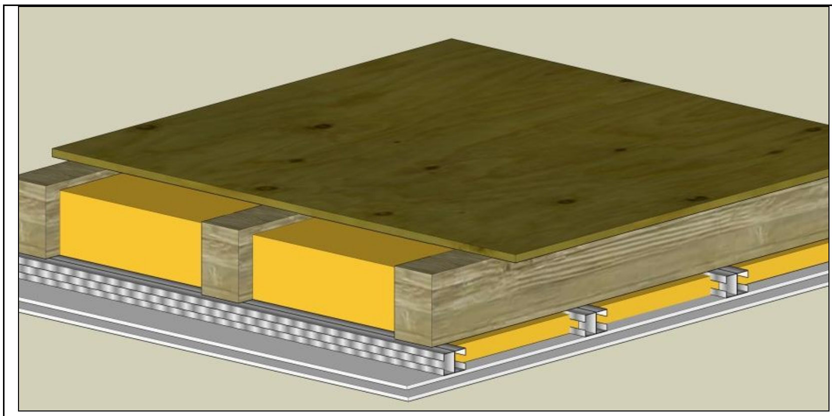
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board and mineral wool 60 mm between channels
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	41 dB
$L_{n,w}+C_{I,50-2500}$=	50 dB
$C_{I,50-2500}$=	9 dB
$C_{I,100-2500}$=	1 dB

Ref. 05 007-T-6, Bauphysik Iphofen

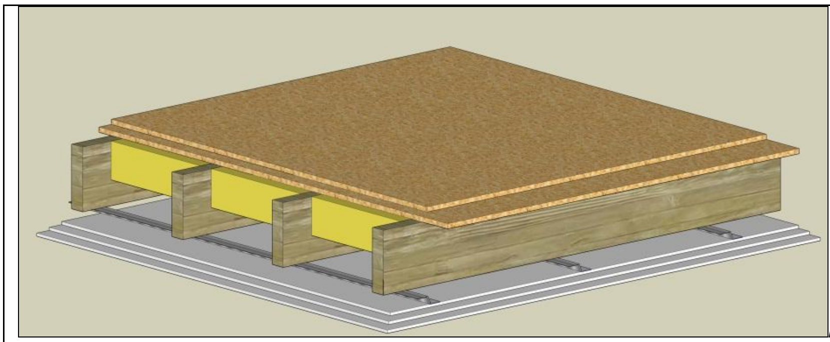
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'$_w$=	not avail.
R'$_{living}$=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	51 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	56 dB
$C_{I,50\text{-}2500}$=	5 dB
$C_{I,100\text{-}2500}$=	1 dB

Ref. 05 007-T-5, Bauphysik Iphofen

Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)

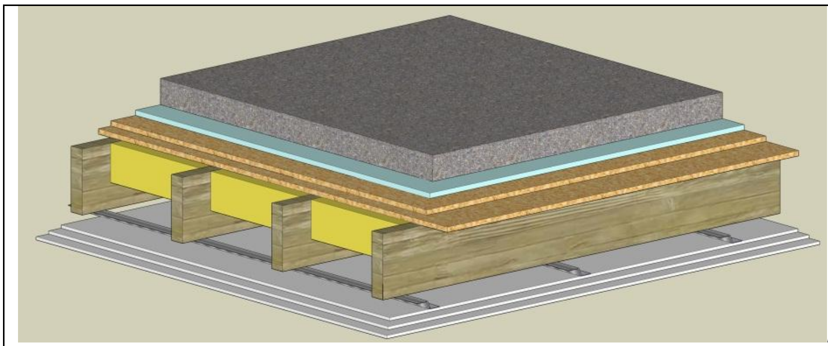


R'$_w$=	not avail.
R'$_{living}$=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	54 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	56 dB
(1) $L_{iFavg,Fmax}$=	59 dB
(1) $L_{i,Fmax,AW}$=	57 dB

(1) *Heavy impact Ball measurement*

REF.:
On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K01 NRCC

Topping: none
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

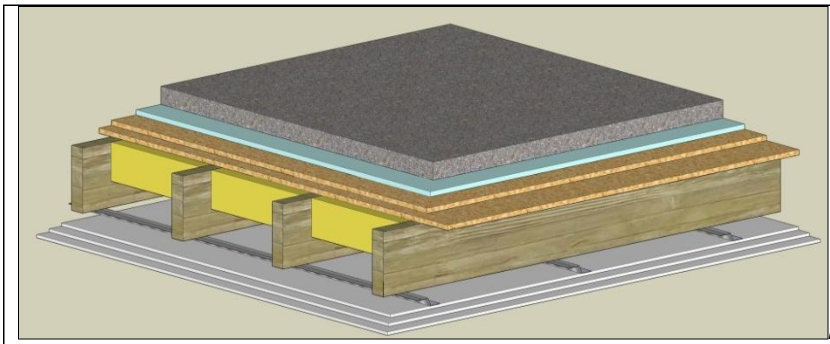


R'$_w$=	not avail.
R'$_{living}$=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	43 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	44 dB
(1) $L_{iFavg,Fmax}$=	42 dB
(1) $L_{i,Fmax,AW}$=	39 dB

(1) *Heavy impact Ball measurement*

REF.:
On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K12 NRCC

Topping: Prefab concrete slab(100 mm) *** 20 mm closed cell foam resilient (no more information available)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

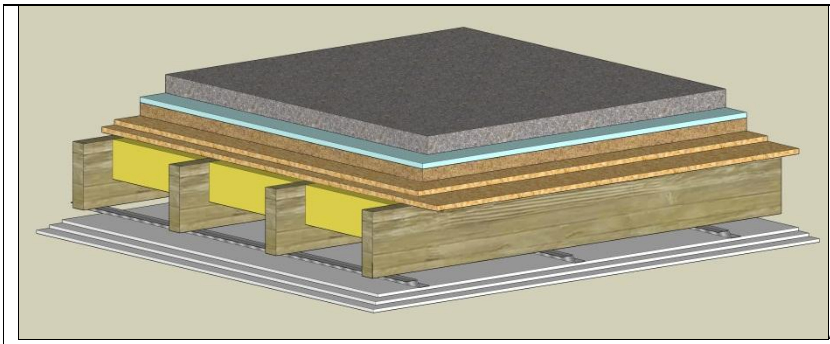


R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	44 dB
$L_{n,w}+C_{I,50-2500}$=	44 dB
(1) $L_{iFavg,Fmax}$=	44 dB
(1) $L_{i,Fmax,AW}$=	41 dB

(1) *Heavy impact Ball measurement*

REF.:
On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K11 NRCC

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient (no more information available)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

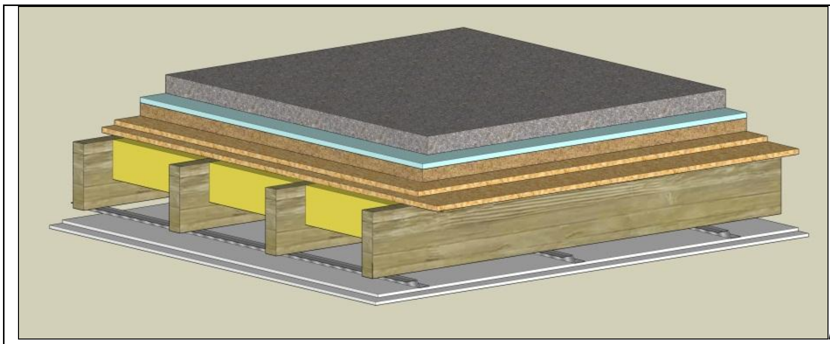


R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	40 dB
$L_{n,w}+C_{I,50-2500}$=	42 dB
(1) $L_{iFavg,Fmax}$=	41 dB
(1) $L_{i,Fmax,AW}$=	41 dB

(1) *Heavy impact Ball measurement*

REF.:
On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K14 NRCC

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient *** 50 cm sand (ca. 80 kg/m²)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

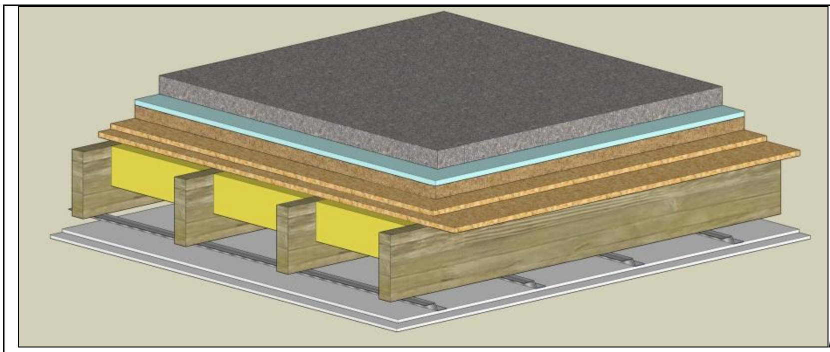


R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	43 dB
$L_{n,w}+C_{I,50-2500}$=	44 dB
(1) $L_{iFavg,Fmax}$=	42 dB
(1) $L_{i,Fmax,AW}$=	44 dB

(1) *Heavy impact Ball measurement*

REF.:
On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K15 NRCC

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient (no more information available) *** 50 cm sand (ca. 80 kg/m²)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 2 x 12.5 fire rated gypsum boards.

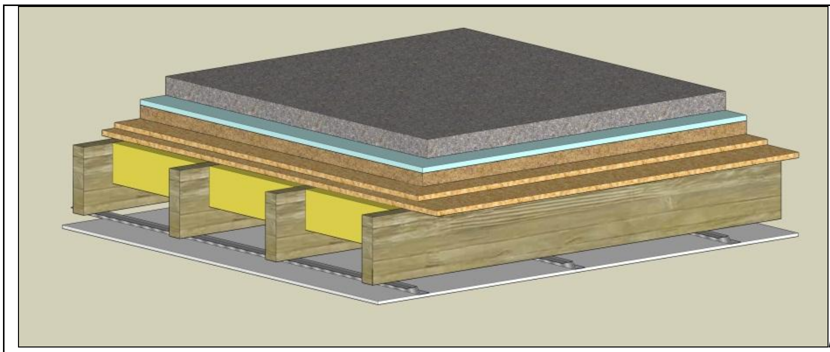


R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	47 dB
$L_{n,w}+C_{I,50-2500}$=	50 dB
(1) $L_{iFavg,Fmax}$=	46 dB
(1) $L_{i,Fmax,AW}$=	49 dB

(1) *Heavy impact Ball measurement*

REF.: On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K23 NRCC

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient *** 50 cm sand (ca. 80 kg/m²)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: RC spaced 403 mm o.c.! 2 x 12.5 fire rated gypsum boards.

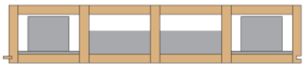
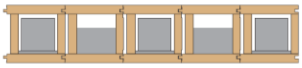
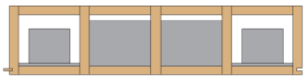
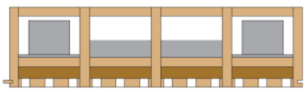
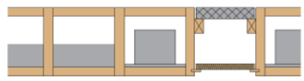


R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	47 dB
$L_{n,w}+C_{I,50-2500}$=	48 dB
(1) $L_{iFavg,Fmax}$=	46 dB
(1) $L_{i,Fmax,AW}$=	48 dB

(1) *Heavy impact Ball measurement*

REF.: On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K16 NRCC

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient *** 50 cm sand (ca. 80 kg/m²)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: RC spaced 610 mm o.c.! 1 x 12.5 fire rated gypsum boards.

	$R_{w,P}$	$L_{n,w,P}$	$C_{I,50-2500}$ / $C_{I,100-2500}$		$R_{w,P}$	$L_{n,w,P}$	$C_{I,50-2500}$ / $C_{I,100-2500}$
1 3 4 8 13		37 dB	+12 dB +1 dB	2 7 10 14		44 dB	+2 dB ±0 dB
2 3 4 8 13		37 dB	+17 dB +1 dB	7 10 14	71 dB	52 dB	-3 dB -5 dB
3 4 8 13	69 dB	46 dB	+7 dB -3 dB	2 5 6 11 14		45 dB	+5 dB -1 dB
2 7 9 13		40 dB	+8 dB ±0 dB	5 6 11 14	68 dB	50 dB	+1 dB -2 dB
7 9 13	75 dB	44 dB	+5 dB -1 dB		II 		
2 7 9 12		47 dB	+7 dB -1 dB				
7 9 12	69 dB	56 dB	-1 dB -6 dB	7 10 14	73 dB	50 dB	-3 dB -5 dB
	I 				III 		
7 10 14	68 dB	52 dB	-1 dB -5 dB	7 10 14	72 dB	51 dB	±0 dB -2 dB
	IV 				V 		

1 Parquet flooring laid floating
2 Fermacell Powerpanel 20mm glued
3 Fermacell Powerpanel 20mm unitised
4 Fermacell screed element 25mm
5 Wood chipboard 28mm
6 Isover EP2, 20 mm, s'<20MN/m³
7 Gutex Thermofloor, 20mm, s'<30MN/m³
8 Isover EP2, 30mm, s'<15MN/m³
9 Fermacell honeycomb fill 30mm

I LIGNATUR box element (LKE)
II LKE with fill 45kg/m² (possible as of element height h = 160mm)
III LKE with fill 90 kg/m² (possible as of element height h = 200mm)

11 Parquet flooring laid floating
12 Cement screed 50mm
13 Isover PS81, 30mm, s'<6MN/m³

IV LIGNATUR surface element (LFE)
V LFE with 50kg/m² fill (possible as of element height h = 160mm)
VI LFE with 100kg/m² fill (possible as of element height h = 200mm)

Figure: the Swiss company 'Lignatur' has some specific solutions for compartment floors. Box and surface elements constitute the load-bearing floor. Different types of toppings allow attaining a wide variety of acoustic performances. The picture down left shows a highly damped solution with dry concrete blocks and grit fillings, optimizing the low frequency sound insulation and acoustic comfort (damping the modal peaks and resonances). Source: http://www.lignatur.ch/2011/en/planning/workbook/

4.4 - Junctions and flanking transmission

4.4.1 - Techniques used to reduce the flanking transmission

In the optimized acoustic concept for party walls of a continuous cavity from foundations to roofs, no flanking transmission between horizontally adjacent apartments is possible. But for apartments one above the other, flanking transmission is definitely present and will limit the overall airborne sound insulation. The main questions are: '*how important is this flanking transmission (see section 4.4.2) and how can we reduce it?*'

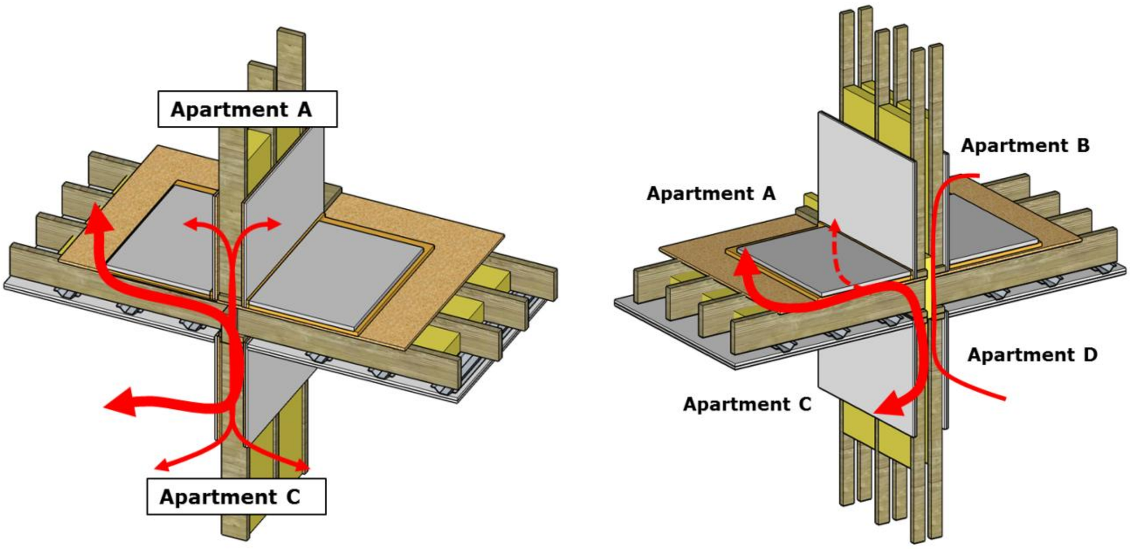


Figure 42 a: flanking transmission paths exist vertically in all junctions, so also through room dividing walls of an apartment (left) or via the façades. In the horizontal direction, the flanking transmission to the adjacent apartment can be eliminated by a party wall such as described in section 3.

1) The most obvious technique to reduce the flanking transmission is to make a disconnection / vibration interruption

We have seen this technique being applied to its full extent in the party wall (see above figure 42 'a'), reducing flanking transmission to the adjacent apartment almost totally.

But also smaller disconnections like the use of an elastic joint between the ceiling boards and the walls (see figure 42 'b') will reduce the flanking transmission from the walls and floor from the apartment above to the ceiling and walls below. Caution: we were told that there can be problems with fire safety acceptance in several European countries, making it necessary to still have a rigid joint.

If the sound insulation is important between two rooms, boards should never continue from one room to the adjacent room to avoid flanking transmission. This is illustrated in figure 42 'c' with an evaluation of the flanking transmission through a metal stud wall with gypsum boards/

Figure 42 b: creating an elastic joint between the ceiling and the walls can reduce the flanking transmission 'Fd' and 'Df', but can create problems with the fire safety requirements in some countries.

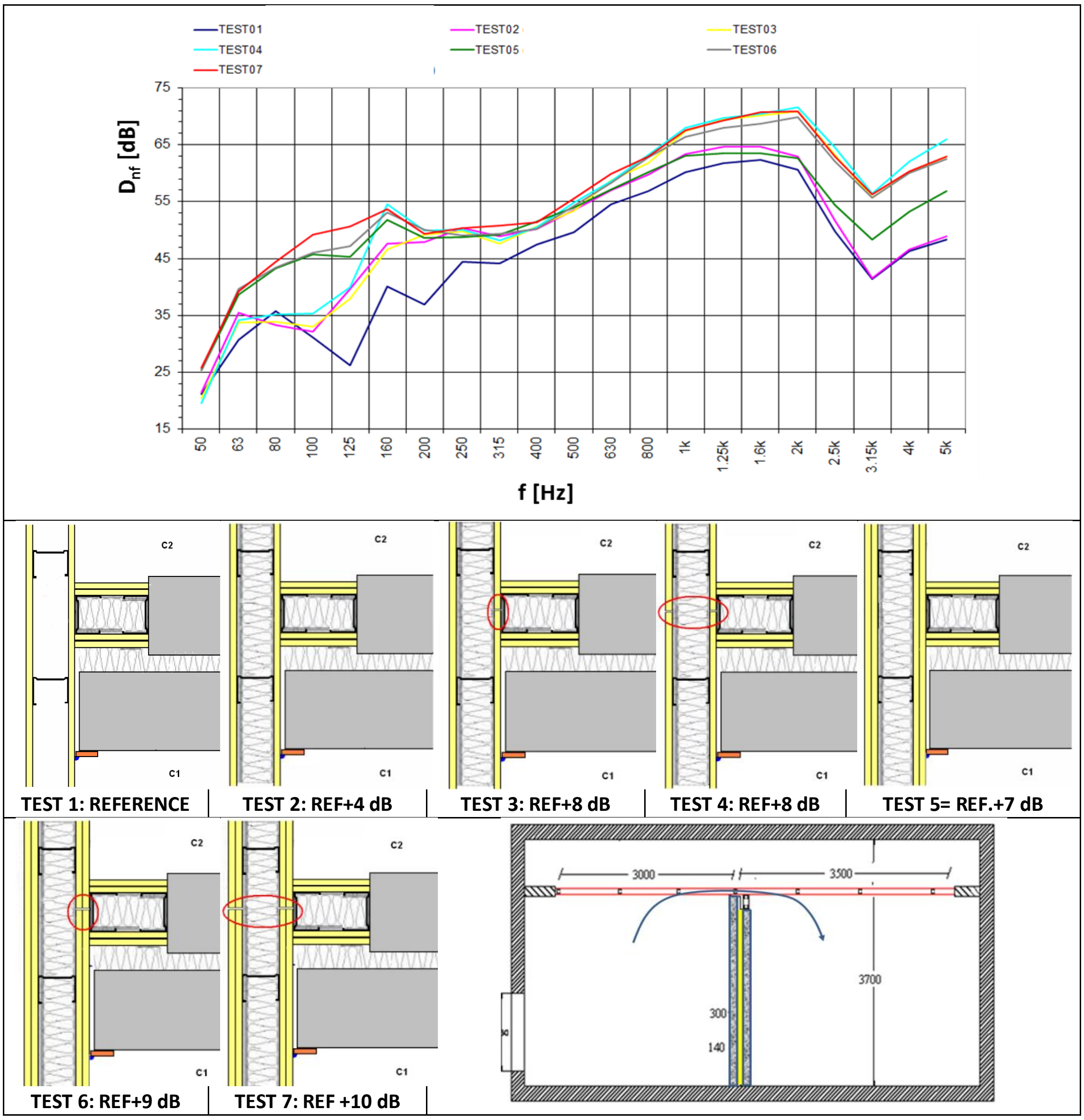


Figure 42 c: evolution of the flanking sound insulation for different constructions. The basic construction was a T junction. The flanking wall was composed of a single layer gypsum board (12.5 mm) on a single Metal frame (75 mm thick). The cavity was empty in the reference setup (Test 1). In test 2, the cavity was filled up with mineral wool. In test 3, the inner leaf was interrupted. The same was done with the outer leaf in test 4. In the tests 5, 6 and 7, the same interventions were made but on a flanking wall consisting of 2x12.5 mm gypsum boards.

2) Linings will have some effect. We already discussed the effect floating floors can have on the 4 flanking transmission paths 'Df'. Technical linings before the walls in the emission and the reception rooms will have some effect if fixed with resilient bars, preferably perpendicular to the wooden studs (see figure 42 'd'). Unfortunately no measurements are known to us to quantify this effect. The empty cavity (necessary to allow the passage of electric wiring or piping) and the limited width of the cavity will unfortunately limit the possible benefits, especially in the low frequency bands.

Figure 42 d: technical linings using resilient studs fixed perpendicular to the wood studs can also diminish some flanking transmission. We do not dispose of any measurements quantifying this, but we expect the improvement to be only in the mid and higher frequencies.

3) Using more 'wood mass' in the junction apparently also has some effect. In Canada a 'heavy' junction with a concentration of wooden beams, showed some improvement even in the low frequencies (see figure 42 'e'). Unfortunately no measurement data is available that isolates this aspect from other influences. So this hypothesis still has to be verified with a dedicated setup.

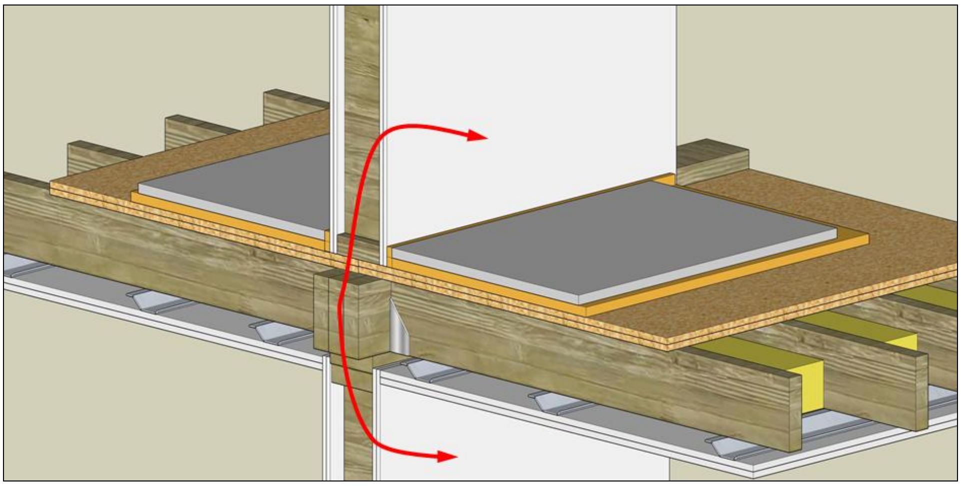


Figure 42 e: creating heavier junctions apparently reduces the flanking transmission. Unfortunately no measurement data is available to verify this statement (information from Zeitler Berndt, National Research Council Canada).

4) Apparently several research groups and consulting offices have tried to use elastic interlayers to reduce the flanking transmission. Two ‘families of solutions’ can be seen: the first uses continuous linear elastic interlayers on top of walls and below floors (or just only below the floors and not interrupting the walls in the project Limnologen in Växjö, Sweden, figure 42 ‘g’), a second solution uses discontinuous fixations on top of the load bearing floors (figure 42 ‘h’). This last solution is apparently only possible with cross laminated timber, the load pressure with punctual charges being too high for the wood fibres in the horizontal beams of timber frame constructions. A pragmatic research (figure 42 ‘f’) showed only a small improvement above 200 Hz that even became negligible when screws were fixed every 40 cm (necessary to take on the horizontal forces within the construction). The inefficient behaviour in the low frequencies can be explained by a too small disruption for the long structural wavelengths of low frequency bending and transversal waves. In the construction in Limnologen (figure 42 ‘g’), the linear elastic interlayer seems to have a beneficial effect on the flanking impact sound. Unfortunately, no measurement results or additional information about this was communicated.

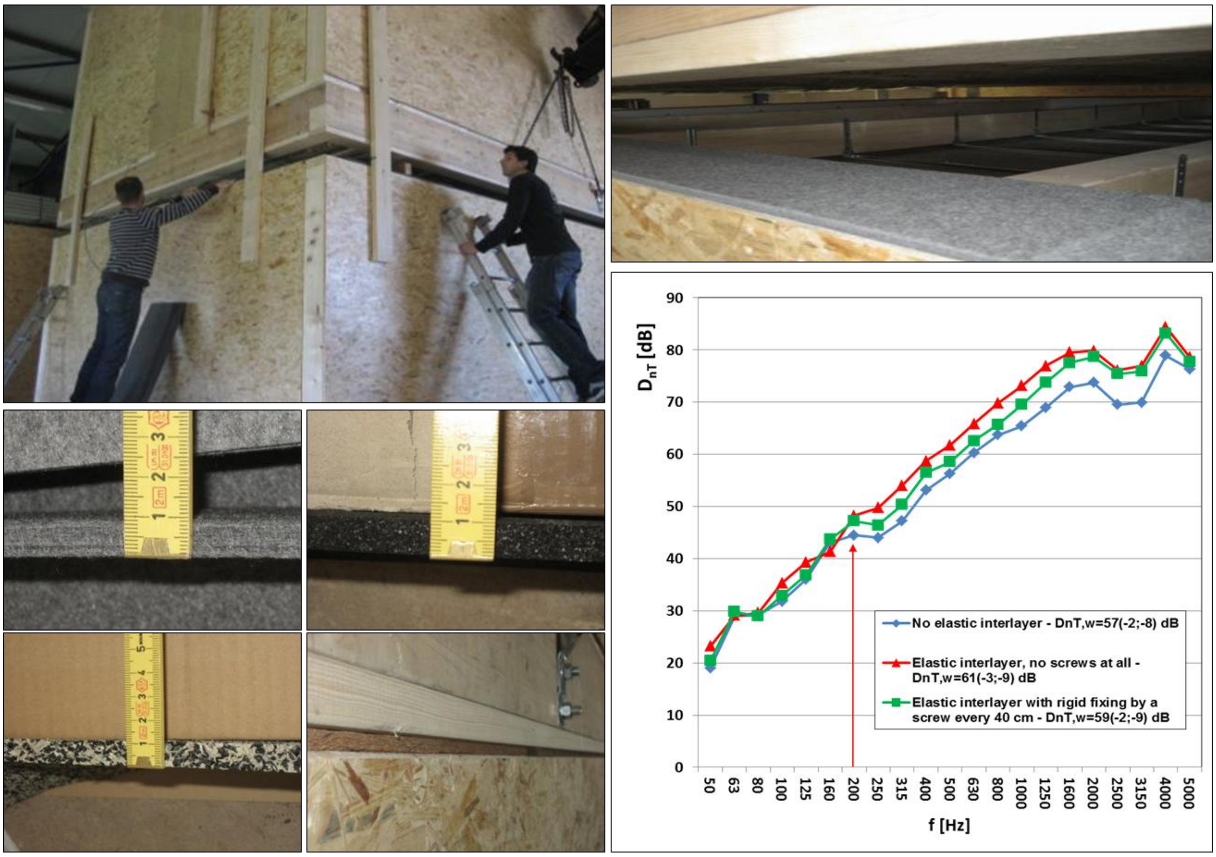


Figure 42 f: a pragmatic research examined the effect on the airborne standardised sound insulation D_{nT} of different linear and continuous elastic interlayers on the walls just below the floor of the room above. The system proved to be only effective above 200 Hz, showing no difference at all for the low frequencies.

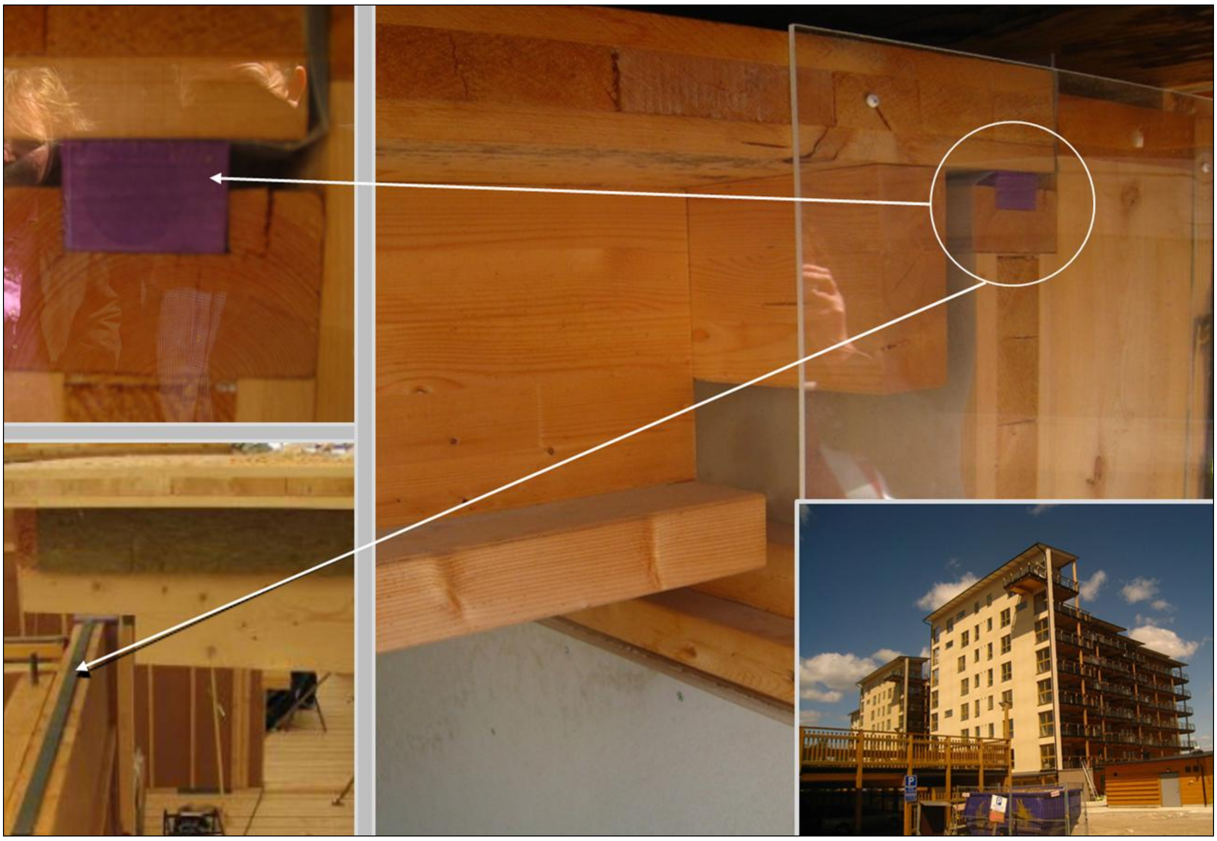


Figure 42 g: a huge multi-storey lightweight timber frame apartment building in Limnologen Växjö, Sweden, also uses linear continuous elastic interlayers to reduce flanking impact sound transmission. All floors bear on the purple elastic interlayer.

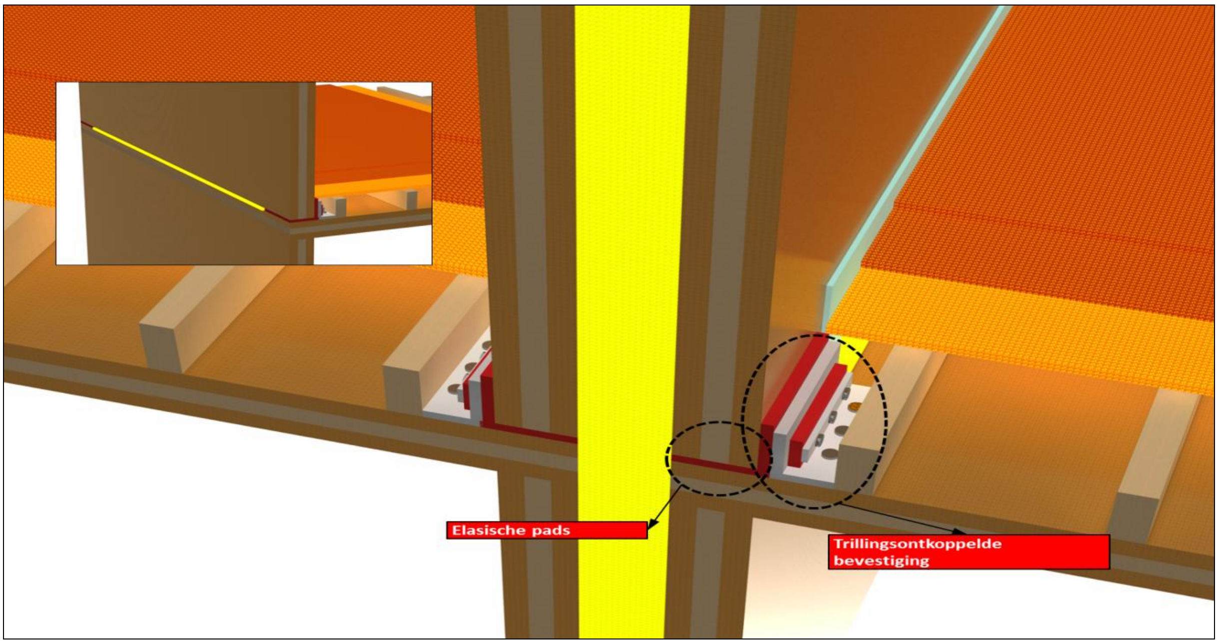


Figure 42 h: the use of elastic pads, creating only discontinuous elastic contact points every 150 cm appears to have a better effect in the low frequencies (BBRI-La Maison Idéale Project).

4.4.2 - Quantifying the flanking transmission

(1) Example 1: quantifying the flanking insulation of some lightweight timber frame junctions in a laboratory setup with and without elastic joints.

Methods to predict the total sound transmission (and the insulation against it) have been developed. A more detailed description can be found in the report of WG 1.

In this chapter some measurements results are given that quantify this flanking transmission (and vice versa the flanking sound insulation).

Special setups have been built in the BBRI's laboratories allowing the following measurements: R, σ, R_{ij}, δ, T_s, D_{nf}. The measurement of the $D_{n,f}$ was carried out with the intensity technique. The sound generated in the source room (C1) was steady and had a continuous spectrum in the considered frequency range. The radiated power by the reception wall was measured with an intensity probe. In order to avoid the background noise from the acoustic hall, we had to use a semi-anechoic box which disrupted the values below 350 Hz. The D_{nf} and R_{ij} were then obtained by the following formulas: $D_{nf,I} = (L_{p1} - 6) - \left(\overline{L_{In,f}} + 10lg\left(\frac{S_{mf}}{A_0}\right)\right)$ and $R_{ij} = D_{nf} + 10lg\frac{S_s l_{ij,lab}}{A_0 l_{ij}}$

Figure 43: LEFT: laboratory setup; MIDDLE and RIGHT: a semi-anechoic box (protecting against the noise influence from the acoustic hall) was used to measure the radiated sound of the wall via the intensity technique

The measurement procedures and the result analysis are reported in other documents. This report here summarizes the results measured on (1) lightweight timber frame constructions in the laboratory, (2) on a research mock-up (built to comply with the EOTA-testing procedure) and (3) on cross laminated timber constructions.

The first setup to get an idea of the importance of the flanking transmission, was built in the (former) acoustic laboratory facility in Limelette. Figures 44 'a' to 'c' first give a description of the separating floor and the acoustic performances going from its basic load-bearing construction (figure 44 'a') to the finished construction in figure 44 'c'. Next (figure 44 'd'), a wall is constructed upon this floor creating a L-junction for which the flanking sound insulations have been determined. In figure 44 'e', the construction has been extended to a T-junction with a wall on top and below the floor, rigidly connected to the load-bearing construction and the ceiling. In figure 44 'f', the effect of an elastic interlayer (reducing the linear rigid contact to punctual rigid contacts) on the flanking transmission is examined.

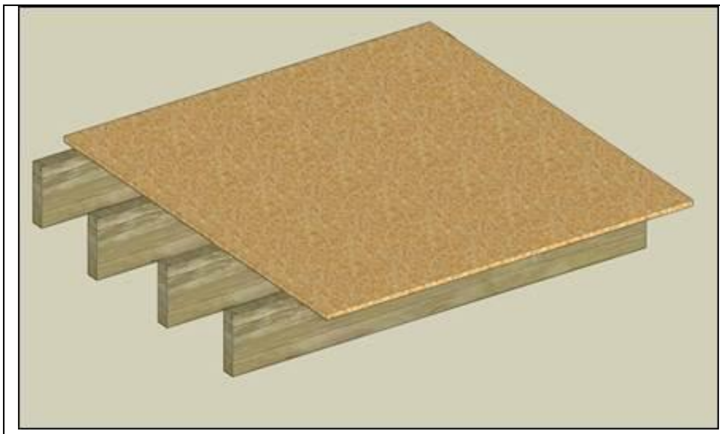
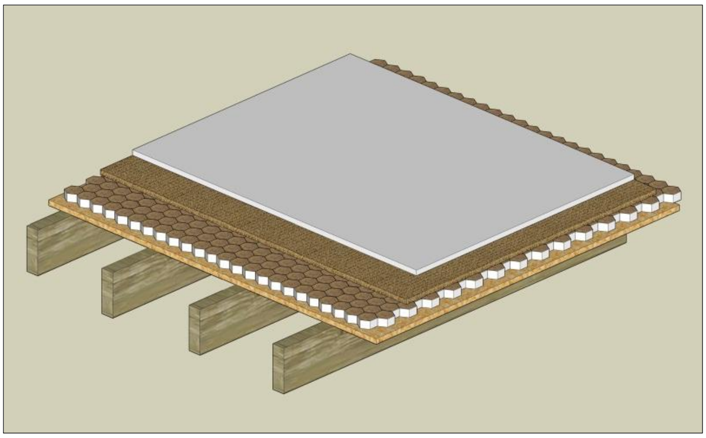
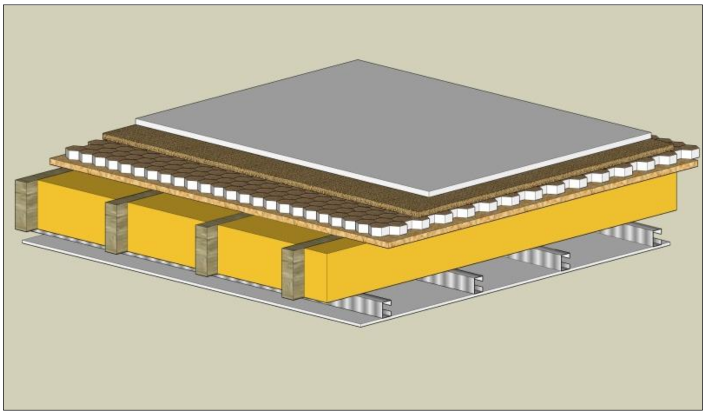
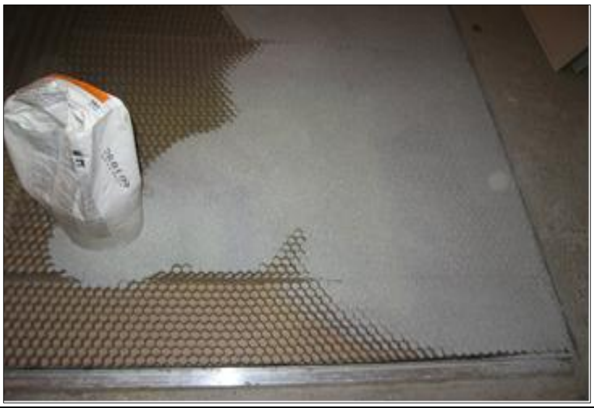
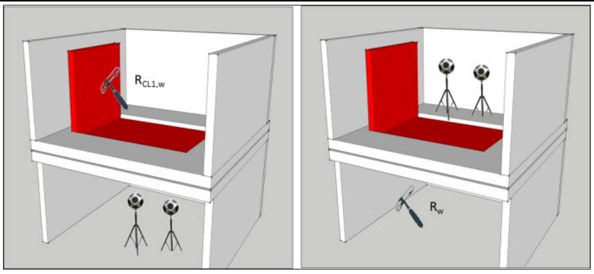
 *Figure a: load carrying floor*	**Reference floor** 3750 x 2400 mm²: OSB 22 mm (13 kg/m²) *** joists 165x65 mm², 40 cm o.c. **Topping: /** **R_w (C;C_{tr})=28 (-1;-2) dB** **$L_{n,w}$ (C_I)=92(-5) dB** Ref. BBRI – OSABOIS TEST0
 *Figure b: with topping of honeycomb boards filled with gravel*	**Floor** 3750 x 2400 mm²: OSB 22 mm (13 kg/m²) *** joists 165x65 mm², 40 cm o.c. **Topping:** honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board) **R_w (C;C_{tr})=52 (-2;-8) dB** **$L_{n,w}$ (C_I)=59(1) dB** Ref. BBRI –OSSABOIS TEST1
 *Figure c: with an independent ceiling (1 board of 10 mm Fermacell)*	**Floor** 3750 x 2400 mm²: OSB 22 mm (13 kg/m²) *** joists 165x65 mm², 40 cm o.c. **Topping:** honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board) **Ceiling:** totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³) **R_w (C;C_{tr})=68 (-3;-9) dB** (intensity measurement, side ceiling) **$L_{n,w}$ (C_I)=43(1) dB** Ref. BBRI –OSSABOIS TEST2

Figure 44: Floors a, b and c





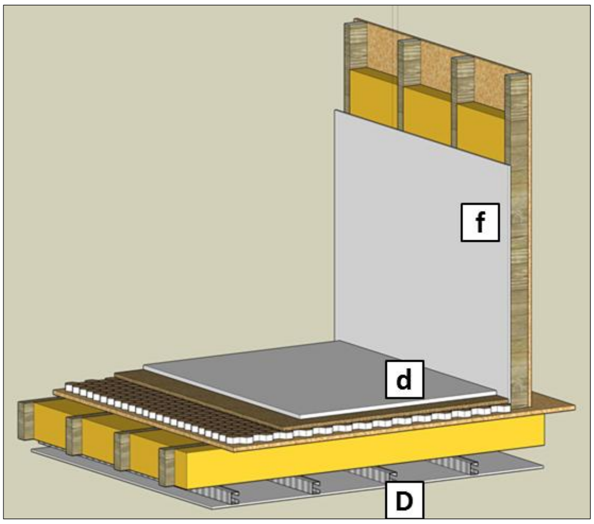


Figure d: L-junction with the studwall rigidly fixed on top of the floor

$R_{w,Dd}$ = R_w ($C;C_{tr}$)=68 (-3;-9) dB
(direct sound insulation, measured in the situation corresponding with figure ‘c’, BBRI – OSSABOIS TEST2)
$R_{w,Df}$ > 73 dB (flanking sound insulation for the transmission from the ceiling ‘D’ to the flanking wall ‘f’, determined via intensity measurement on the gypsum board side of the ‘f’ wall, Ref. BBRI –OSSABOIS TEST4)

<u>Floor</u> 3750 x 2400 mm²:
OSB 22 mm (11.7 kg/m²) *** joists 165x65 mm², 40 cm o.c.
<u>Topping ‘d’:</u> honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board)
<u>Ceiling ‘D’:</u> totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³)
<u>Wall ‘f’</u> 12.5 mm gypsum board, studs 90x40 mm² 60 cm o.c., MW 90 mm, OSB 18 mm

Figure 44: junction d

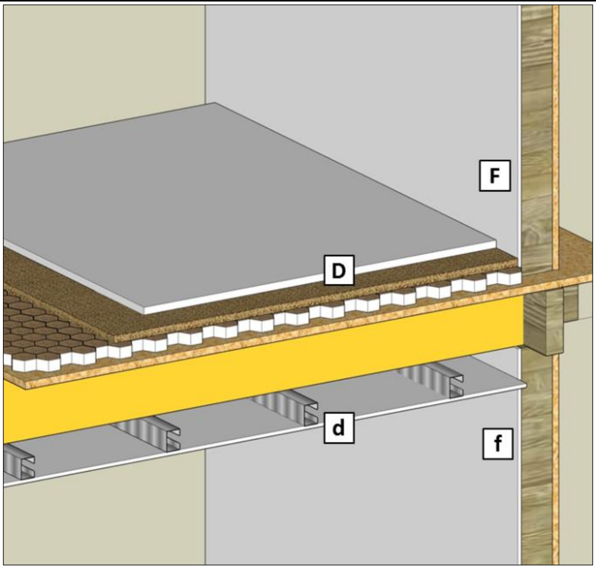


Figure e: T-junction with the studwall rigidly fixed on top of and below the floor

$R_{w,Dd}$ = R_w (C;C_{tr})=68 (-3;-9) dB
(direct sound insulation, measured in the situation corresponding with figure 'c', BBRI – OSSABOIS TEST2)
$R_{w,Fd}$> 76 dB (flanking insulation for the flanking transmission from the flanking wall 'F' to the ceiling 'd', value obtained by the energetic subtraction of the value determined by the intensity measurement result on the ceiling minus $R_{w,Dd}$. Ref. BBRI –OSSABOIS TEST11)
$R_{w,L1L2}$ > 69 dB (flanking insulation for the flanking transmission from the flanking wall 'F' to the flanking wall 'f', value obtained by the intensity measurement result on the wall 'f', we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path 'Df'. Ref. BBRI –OSSABOIS TEST11)

Floor 3750 x 2400 mm²:
OSB 22 mm (11.7 kg/m²) *** joists 165x65 mm² 40 cm o.c.
Topping 'D': honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board)
Ceiling 'd': totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³)
Wall 'F' and 'f': 12.5 mm gypsum board, studs 90x40 mm² 60 cm o.c., MW 90 mm, OSB 18 mm

Figure 44: junction e

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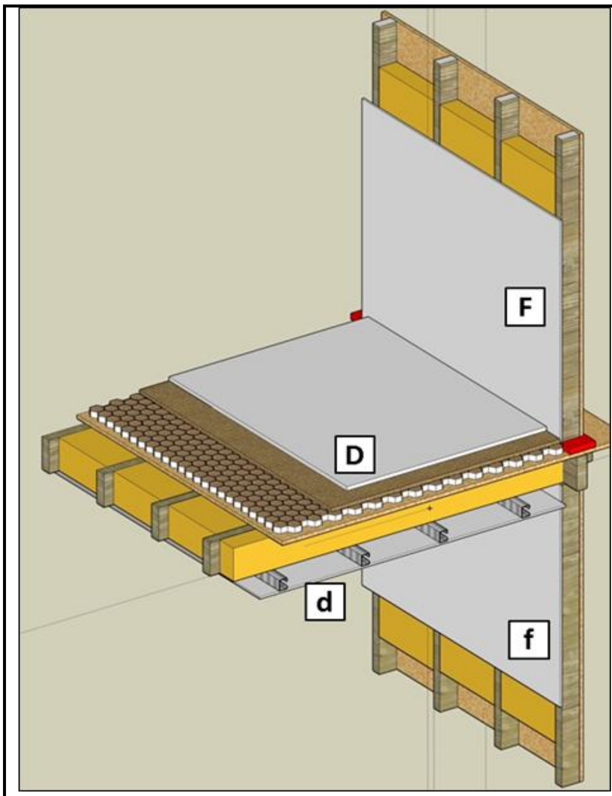

Figure f: similar as in figure 'e' but with an elastic junction: T-junction with the stud wall rigidly fixed below the floor. The stud wall on top of the floor stands on an elastic interlayer (CDM 41010, see red strip in drawing). A screw fixes the top wall every 60 cm through the elastic interlayer to the floor, resulting in a punctual rigid connection. The effect of the resilient interlayer appears to be negligible.
</td>
<td>
<u>Floor</u> 3750 x 2400 mm²:
OSB 22 mm (11.7 kg/m²) *** joists 165x65 mm², 40 cm o.c
<u>Topping 'D':</u> honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board)
<u>Ceiling 'd':</u> totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³)
<u>Wall 'F' and 'f':</u> 12.5 mm gypsum board, studs 90x40 mm² 60 cm o.c., MW 90 mm, OSB 18 mm

$R_{w,Dd}$ = R_w ($C;C_{tr}$)=68 (-3;-9) dB
(direct sound transmission, measured in the situation corresponding with figure 'c', BBRI – OSSABOIS TEST2)
$R_{w,Fd}$> 78 dB (flanking insulation for the flanking transmission from the flanking wall F to the ceiling d, value obtained by the energetic subtraction of the value determined by the intensity measurement result on the ceiling minus $R_{w,Dd}$. Ref. BBRI –OSSABOIS TEST06)
$R_{w,Ff}$ > 71 dB (flanking insulation for the transmission from the flanking wall 'F' to the flanking wall 'f', value obtained by the intensity measurement result on the wall 'f', we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path 'Df'. Ref. BBRI – OSSABOIS TEST06)
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Figure 44 : junction f

(2) Example 2: quantifying the flanking insulation of some lightweight timber frame junctions in an experimental mock-up (Beringen, MBS).

A major lightweight timber frame manufacturer wants to expand its activities to apartment constructions. They agreed to cooperate in a research project aiming to generate building guidelines for lightweight timber frame apartment constructions. A mock-up has been built that complies with the setup instructions as stipulated by EOTA (see figure a). One of the experiments was to study the flanking sound transmission in a simple 3-cell timber frame mock-up and to confront the measurements with the prediction methods as developed by WG1 (results are discussed in a research report)

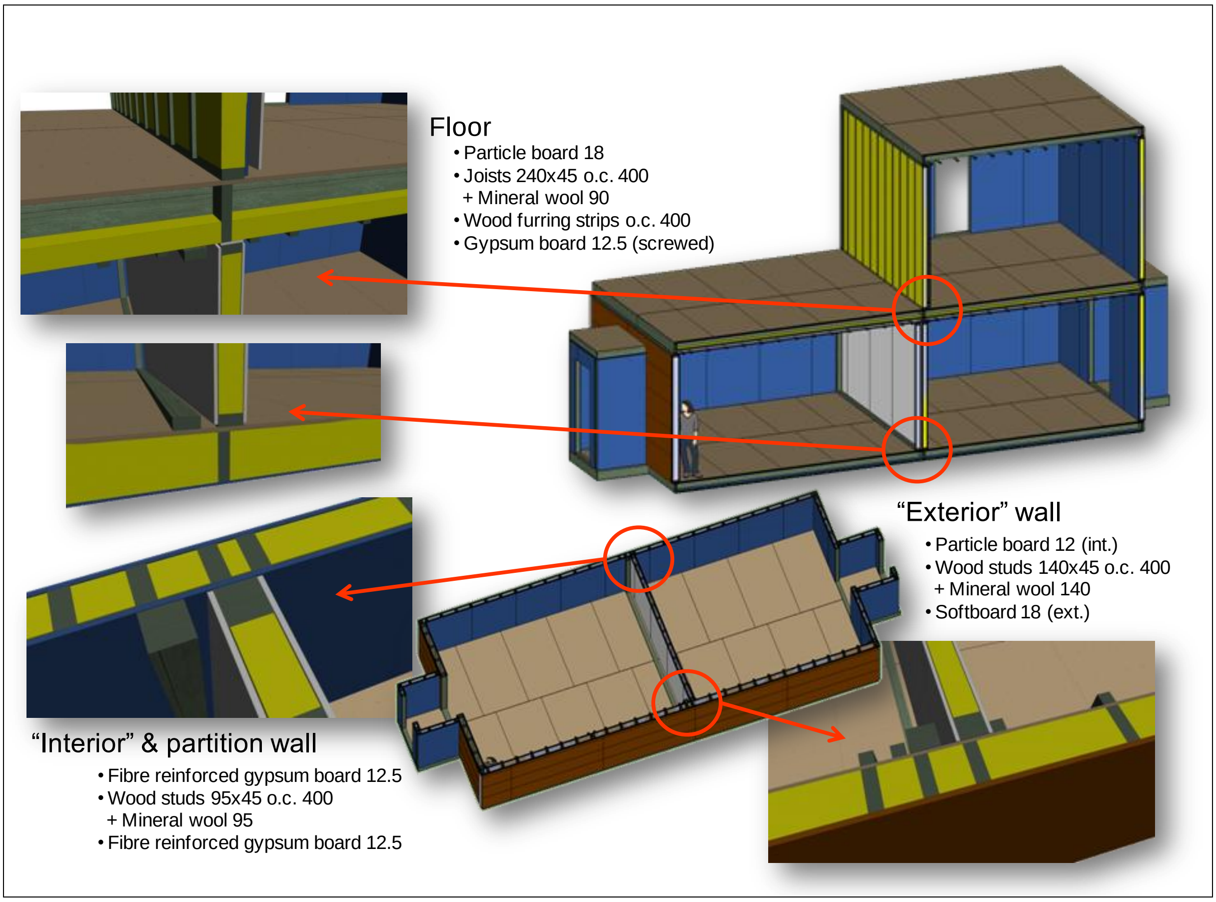


Figure 45 a: Timber frame mock-up at Machiels Building Solutions at Beringen (Belgium) (all dimensions in mm)

Both vibration reduction indices $D_{v,ij,n}$ using structural excitation and flanking sound reduction indices R_{ij} using airborne excitation have been measured. In the further analysis, we will focus only on the flanking sound reduction indices. These have been measured using the sound intensity technique (using both 50 mm and 12 mm microphone spacers) with appropriate shielding (see figure b). Only the vertical sound transmission is studied along 2 junctions: the cross junction and the T-junction involving the "exterior" wall. The measurement results are displayed in figures c and d. Since the direct sound reduction index - estimated at $R_w(C;C_{tr};C_{50-5000};C_{tr,50-5000})$ = 40(-1;-3;0;-6) dB - is much lower than all the flanking sound reduction indices measured(see figure e), it is clear that, in this case (very basic floor construction), flanking is not important. However, when the floor construction is improved considerably, flanking sound transmission may become important.

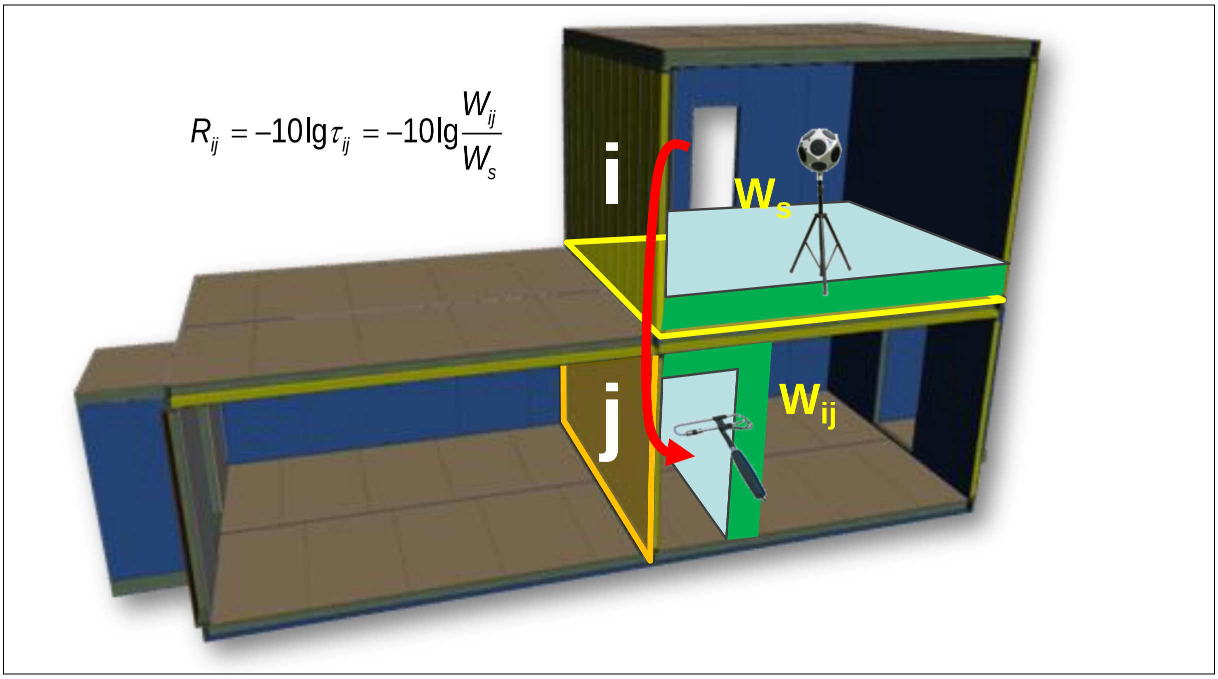


Figure 45 b: Test setup example for measuring the flanking sound reduction index

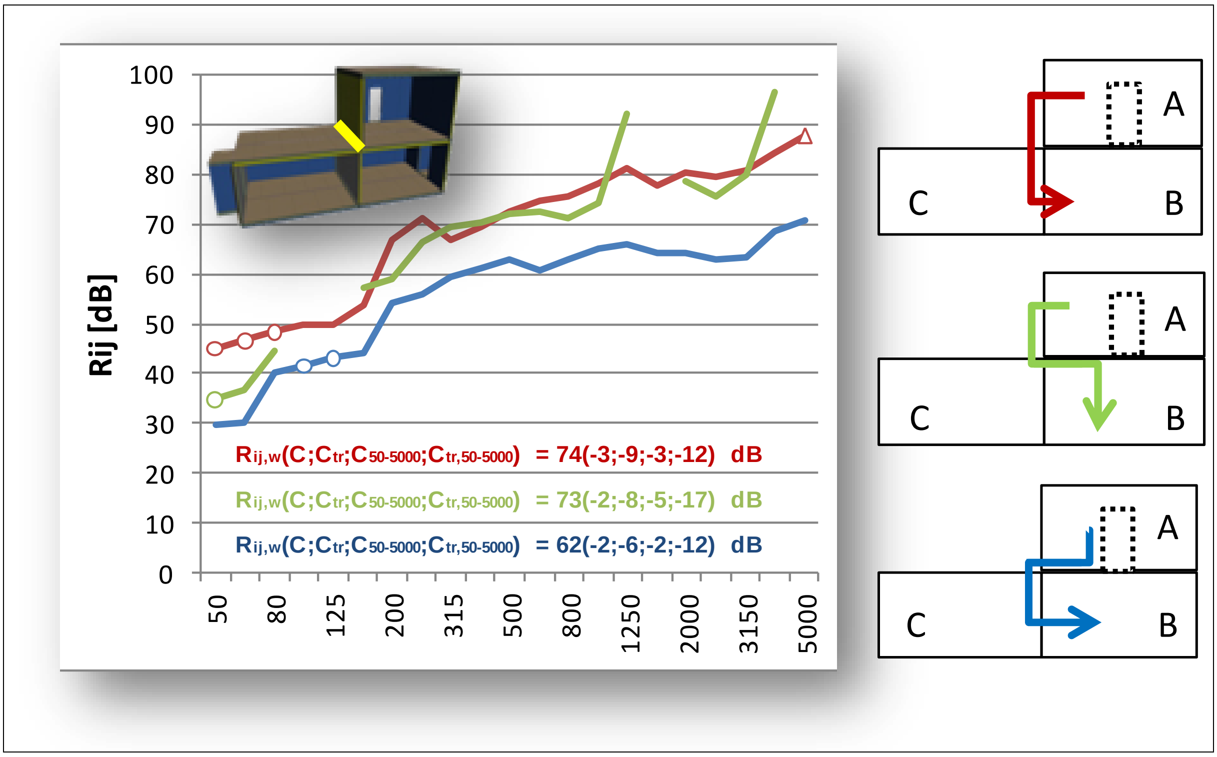


Figure 45 c: Measured flanking sound reduction indices on the cross junction for the 3 paths Ff, Fd and Df. Values indicated with a triangle are minimal values, whereas values indicated with a circle are interpolated or extrapolated values (-5 dB/octave going down at low frequencies).

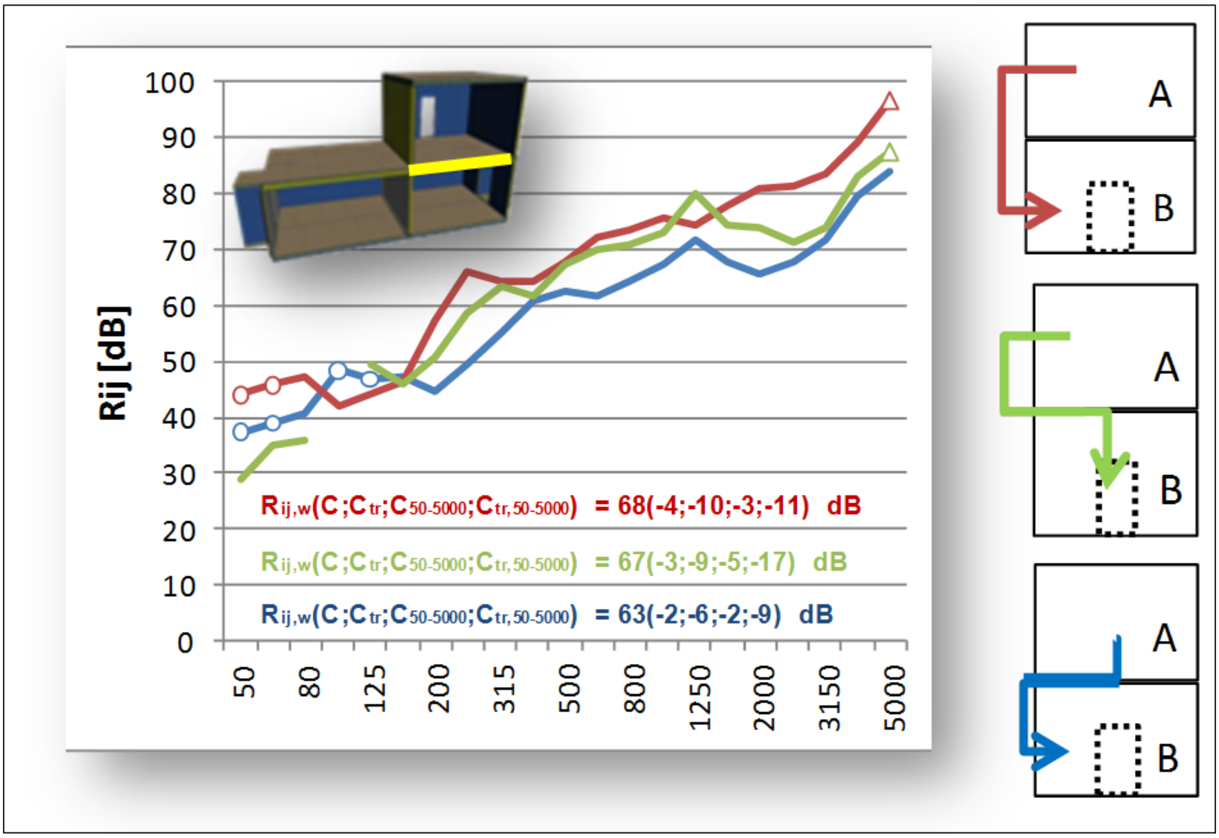


Figure 45 d: Measured flanking sound reduction indices on the T junction for the 3 paths Ff, Fd and Df. Values indicated with a triangle are minimal values, whereas values indicated with a circle are interpolated or extrapolated values (-5 dB/octave going down at low frequencies).

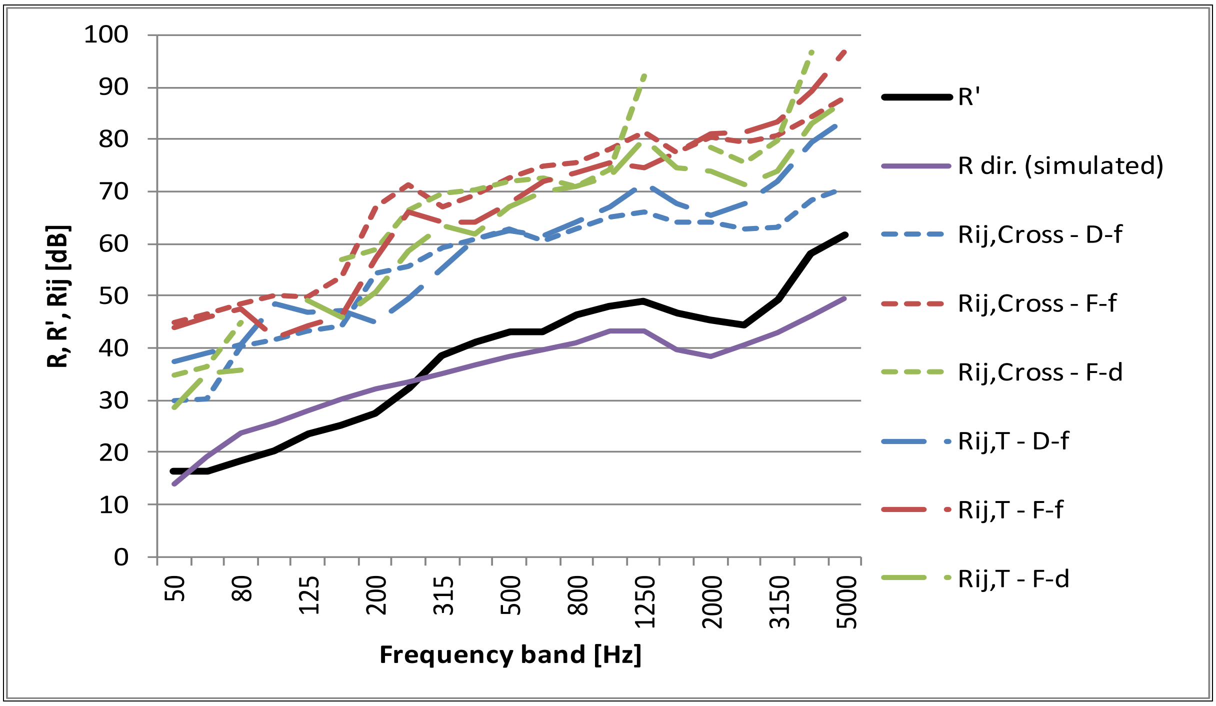


Figure e: Comparison of the (simulated) direct sound reduction index R, the measured overall sound reduction index R′ and the measured flanking sound reduction indices R_{ij}.

(3) Example 3: Quantifying the flanking insulation of some cross laminated timber junctions with and without elastic joints in a laboratory setup

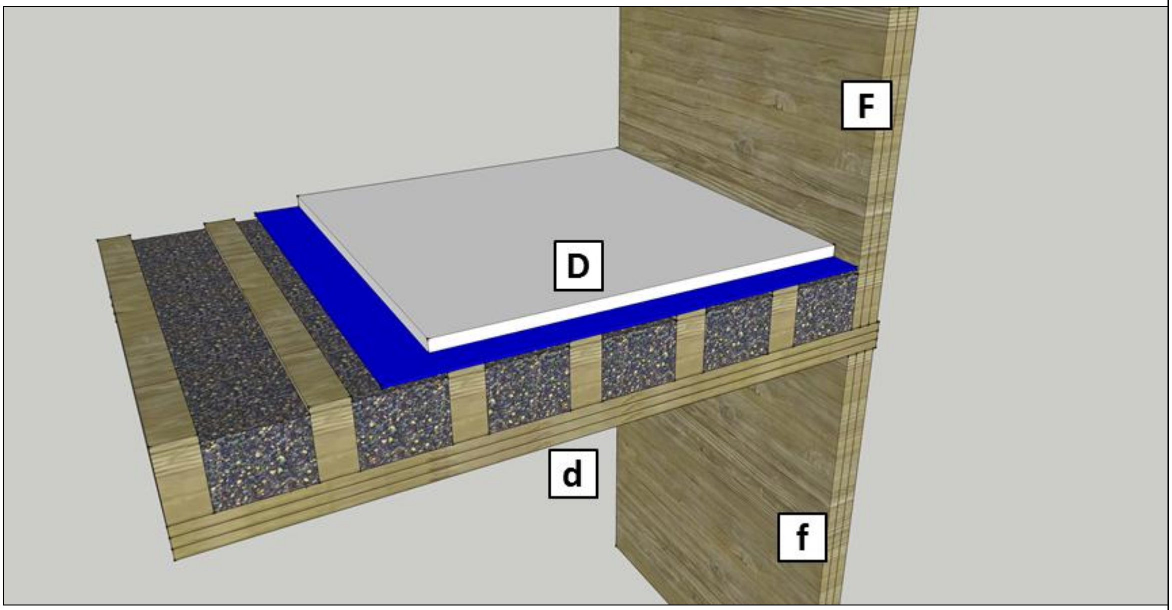


Figure a: T-junction with cross laminated timber (RE GT Wal)

Floor 'd' *cross laminated timber 9.4 cm thick, with wooden 'ribs' (see drawing) of 9.5x20 cm², interdistance 25 cm. The space between the 'ribs' is filled with gravel (1400 kg/m³).*

Topping 'D': *9 mm thick elastic latex lining Isopack, with a Fermacell dryfloor (fibre gypsum) system 'Maxifloor' of 38 mm thickness (1100 kg/m³ or 41.8 kg/m²)*

Wall 'F' and 'f': *9.4 cm cross laminated timber 9.4 cm thick, connected with 3 steel connecting hooks (see picture left) for each wall.*

Floor element alone

$\boldsymbol{R_{w,Dd} = R_w\ (C;C_{tr}) = 65\ (-3;-9)\ dB}$

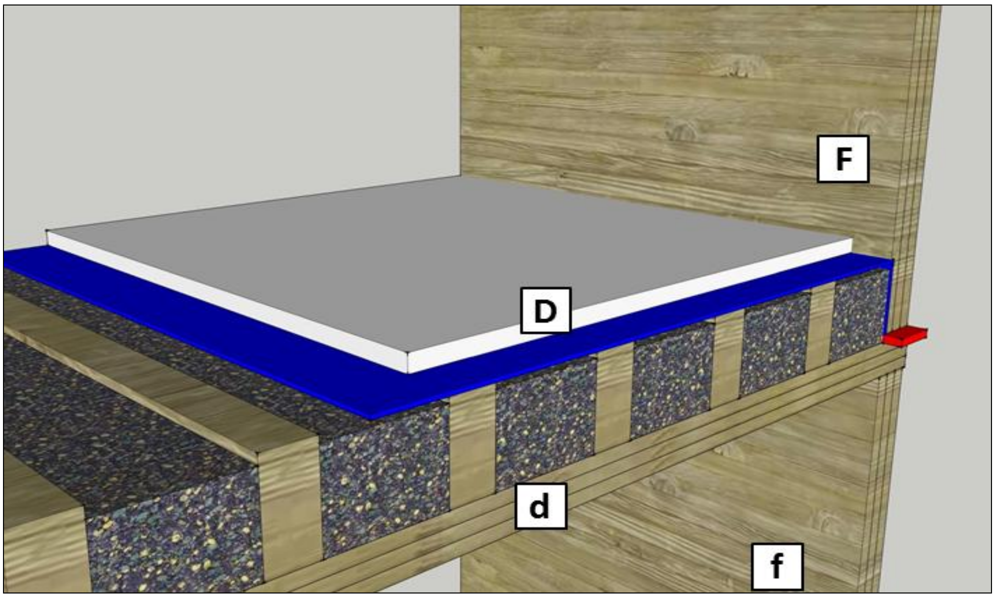
(direct sound transmission through the floor alone, BBRI –AC5126)

$\boldsymbol{L_{n,w}\ (C_I) = 50\ (-1)\ dB}$ *(BBRI-AC5068)*

Flanking sound insulation

$\boldsymbol{R_{w,\ Dd\oplus Fd} = 61(-2;-8)\ dB}$ *(total insulation for the transmission paths Dd and Fd determined by intensity measurement result on the ceiling minus* $R_{w,Fd}$*. Ref. BBRI –AC5127)*

$\boldsymbol{R_{w,Ff} = 61\ dB}$ *(determined by intensity measurement on f, we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path Df. Ref. BBRI –AC5127)*



Floor 'd' *cross laminated timber 9.4 cm thick, with wooden 'ribs' (see drawing) of 9.5x20 cm², interdistance 25 cm. The space between the 'ribs' is filled with gravel (1400 kg/m³).*

Topping 'D': *9 mm thick elastic latex lining Isopack, with a Fermacell dryfloor (fibre gypsum) system 'Maxifloor' of 38 mm thickness (1100 kg/m³ or 41.8 kg/m²)*

Wall 'F' and 'f': *9.4 cm cross laminated timber 9.4 cm thick, connected with 3 steel connecting hooks (see picture left) for each wall.*

Floor element alone

$R_{w,Dd} = R_w\ (C;C_{tr}) = 65\ (-3;-9)$ **dB**

(direct sound transmission through the floor alone, BBRI –AC5126)

$L_{n,w}\ (C_I) = 50\ (-1)$ **dB** *(BBRI-AC5068)*

Flanking sound insulation

$R_{w,\ Dd\oplus Fd} = 60(-3;-8)$ **dB** *(total insulation for the transmission paths Dd and Fd determined by intensity measurement result on the ceiling minus $R_{w,Fd}$. Ref. BBRI –AC5128)*

$R_{w,Ff} = 60$ **dB** *(determined by intensity measurement on f, we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path Df. Ref. BBRI –AC5128)*

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