IMPACT SOUND INSULATION IN TIMBER FRAME FLATS: INTERNATIONAL EXPERIENCE AND OPPORTUNITIES FOR APPLICATION IN THE UK

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1 ABSTRACT

Problems with the assessment of impact sound in timber frame flats have been investigated in other countries, some of which are taking positive steps to address the issues, while in the UK the issues are neither widely known nor understood. The programme for the harmonization of sound insulation descriptors, COST TU0901, adopted two parallel parameters for the assessment of impact sound: both $L'_{nT,w}$ and $L'_{nT,w} + C_{I50-2500}$, with the same values to be achieved for both in each performance class. This acoustic classification system is being developed into ISO 19488, and so will have considerable status in the UK when published. There is also increasing evidence that assessment down to and including 20 Hz is essential to enable better correlation between measured values and occupant satisfaction with impact sound transmission; however, the validity of measurements in rooms at these frequencies does not attract universal acceptance in the acoustics community.

This paper reviews the available data from the UK and abroad, and compares performance parameters that correlate with annoyance in timber frame buildings. The potential performance of common UK construction details is considered in terms of the new metrics, and survey data is presented. Three case studies of multi-storey timber frame details that offer better performance in terms of the new metrics, compared with common construction details, are presented, and the potential performance evaluated.

2 INTRODUCTION

The various building regulations in the UK require impact sound insulation to be measured in accordance with ISO 140-7 [1], and assessed in terms of the standardised impact sound pressure level, $L'_{nT,w}$ according to ISO 717-2 [2]. This assessment is carried out for frequencies between 100 Hz and 3150 Hz in third octave bands. However, recent research has demonstrated that there is a significant lack of correlation between occupants' satisfaction with impact sound levels and this metric, $L'_{nT,w}$ in timber frame flats. This paper sets out to gather and present evidence around this issue from the UK and other countries, to discuss how impact sound may be more suitably assessed, and to identify some potential construction details for timber frame buildings that may perform more favourably than the more commonly adopted typical designs.

As timber frame construction offers so many advantages in terms of cost, speed and sustainability, it would be a tragedy for the construction industry as a whole if it attracted a negative reputation that may blight its sustainable credentials. It is therefore considered essential that the potential future assessment parameters are adopted without delay to prevent a negative reputation for timber frame flats.

2.1 BRE survey

BRE undertook a limited opportunity survey in 2014 which was circulated to around 300 RSLs / Housing Associations seeking opinions in relation to sound insulation and construction types; the results have not been published to date. Amongst the questions and responses from housing associations was the following question:

Have you noticed any relationship between the construction method and the type of complaints about noise you receive from residents?

In response, 60% agreed (12 out of 20 respondents), and all the relevant comments noted an association with timber framed buildings. Of the respondents, 82% (9 out of 11 respondents) noted that this has had an influence on their choice of construction method for future projects. Where complaints about noise disturbance were considered to be justified (in the respondent's opinion) testing had often demonstrated compliance with Approved Document E of the Building Regulations.

2.2 Apex Acoustics anecdotal evidence

As consultants, we often hear from Housing Associations / RSLs that they wish to avoid timber frame construction, and prefer load bearing masonry walls and concrete floors, typically beam and block or pre-cast concrete (PCC) planks. A major UK hotel operator also informed us they find one of the most reported acoustic problems to be associated with impact sound transmission in timber frame buildings.

2.3 European research

Researchers in other European countries have been more proactive in conducting systematic research to identify the problems with the current assessment of impact sound transmission. This research has helped to shape the assessment of impact sound that is proposed to be adopted for ISO 19488: Acoustic Classification of Dwellings [3]; however, the research findings are not fully adopted as it involves measurement and assessment down to 20 Hz. The meaning of measurements at such low frequencies does not attract international consensus of validity, but is discussed further below.

3 BACKGROUND

3.1 Harmonised sound insulation descriptors from COST TU0901

COST Action TU0901 "Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions" [4] was a European project involving 32 countries that developed an acoustic classification scheme for dwellings based on harmonised sound insulation descriptors. As well as identifying the most appropriate performance parameters, this project has also proposed a classification system with performance values assigned to each Class, ranging from A – the highest – the F - the lowest. The systems covers airborne and impact sound, as well as sound from service equipment within the building and façade sound insulation. The classification system has been approved for development by the International Standards Organisation into ISO 19488 under ISO/TC43/SC2. The background and future perspectives for this work item are described most recently by Birgit Rasmussen [5], where there are many references to other acoustic classification systems.

The preferred descriptor for impact sound insulation is $L'_{nT,w} + C_{I50\text{-}2500}$, according to ISO 717-2, which is described in shorthand as $L'_{nT,50}$. There is an option to declare the performance above 100 Hz, denoted $L'_{nT,100} = L'_{nT,w} + C_I$, but it is noted that this is not safe method for assessing lightweight building constructions. Indeed, in Chapter 3 of COST TU0901 it is noted that:

The performance between 50 and 100 Hz is essential for lightweight constructions

It is also noted that the parameter $L'_{nT,50}$ does not adequately deal with higher frequency noise transmission, and therefore the proposed classification system suggests the same performance value for the parameter $L'_{nT,w}$ as well as for $L'_{nT,50}$.

3.2 Acoustic classification performance and meaning

The values currently assigned to each class are shown in Table 5.2 of the COST TU0901 final report, an extract of which is reproduced in Figure 1 below.

Type of space	Class A $L'_{nT,50}$ (dB)	Class B $L'_{nT,50}$ (dB)	Class C $L'_{nT,50}$ (dB)	Class D $L'_{nT,50}$ (dB)	Class E $L'_{nT,50}$ (dB)	Class F $L'_{nT,50}$ (dB)
In dwellings from other dwellings	≤ 44	≤ 48	≤ 52	≤ 56	≤ 60	≤ 64

Figure 1: Proposed impact sound Classes; extract from Table 5.2 of COST TU0901 report

The meaning of the different Classes is described in Table 5.6 of COST TU0901, reproduced in Figure 2.

Class	General	Sound insulation judged poor
A	A quiet atmosphere with a high level of protection against sound	less than 5%
B	Under normal circumstances a good protection without too much restriction to the behaviour of the occupants	around 5%
C	Protection against unbearable disturbance under normal behaviour of the occupants, bearing in mind their neighbours	around 10%
D	Regularly disturbance by noise, even in case of comparable behaviour of occupants, adjusted to neighbours	around 20%
E	Hardly any protection is offered against intruding sounds	around 35%
F	No protection is offered against intruding sounds	50% or more

Figure 2: Description in general terms of the Class quality according to COST TU0901

This description is augmented by a description of activities associated with impact sound generation as described in Table 5.7 of COST TU0901, reproduced in part in Figure 3.

Sources:	A	B	C	D	E	F
walking	not audible	hardly audible	just audible	audible	clearly audible	very clearly audible
kids playing	hardly audible	Just audible	audible	clearly audible	very clearly audible	
dropping & moving objects	not audible	hardly audible	just audible	audible	clearly audible	very clearly audible

Figure 3: Extract from Table 5.7 of COST TU0901 for a global indication of expectation for impact sound sources

Currently in Europe by far the most common descriptors for impact sound are $L'_{n,w}$ and $L'_{nT,w}$.

3.3 Research by Iain Critchley

The problems with impact sound in timber frame buildings have been most thoroughly explored in Europe following research by Iain Critchley and through the AkuLite project in Sweden (see below). This research has also informed the newly adopted performance parameters under the COST project. Work by Iain Critchley began in the period between 2011 and 2012, investigating the “fitness for purpose” of timber frame buildings where there was significant transmission at low frequencies, but the constructions met English Building Regulations requirements. He found a very good correlation between the impact sound pressure level at 20 Hz, using a standard tapping machine, with occupant dissatisfaction. He used the unweighted value of the 20 Hz third octave band, with no reverberation time or other correction applied, just ‘as measured’. He notes that this isn’t necessarily a problem at 20 Hz in the floor but is just the floor reacting to the 2nd harmonic of the driven frequency of the tapping machine. A ‘big’ reaction, up to 90 dB, simply correlates with a ‘big’ adverse response to impact noise from footfall.

The measured parameters and subjective response are shown in Table 1, in rank order for the value of impact sound at 20 Hz. It can be seen in this small sample that neither of the parameters $L'_{nT,w}$ nor $L'_{nT,50}$ would appear to correlate with the subjective response, which is aligned with the performance at 20 Hz. The curves of measured impact sound are shown in
Figure 4. It is interesting to note that the parameter $L'_{nT,50}$ may have a value that would be considered to be in Class A according to the proposed classification system, such as in the dressing room, but the subjective response is still “very bad”. This data illustrates how even though the performance between 50 Hz and 100 Hz may be essential for assessing lightweight constructions, it may not be sufficient; disregarding measured performance below 50 Hz can mean that objective parameters do not represent subjective response. It is understood that this research helped form the direction taken by the AkuLite project.

Table 1: Subjective responses and measured criteria in one property with different floor finishes above

Room	Floor finish above	$L'_{nT,w}$ / dB	$L'_{nT,50}$ / dB	L_n / dB, 20 Hz	Subjective response
Living room	Carpet	28	43	63	Not bad
Bedroom 2 (study)	Solid oak	57	68	65	Good
Dining room	Marble tile	41	49	66	Good
Kitchen	Solid oak	55	58	69	Not bad
Bedroom 1	Carpet	25	38	74	Poor
Dressing room	Carpet	31	41	84	Very bad
Ensuite	Hard vinyl	52	59	86	Intolerable
Bedroom 3	Carpet	59	55	90	Intolerable

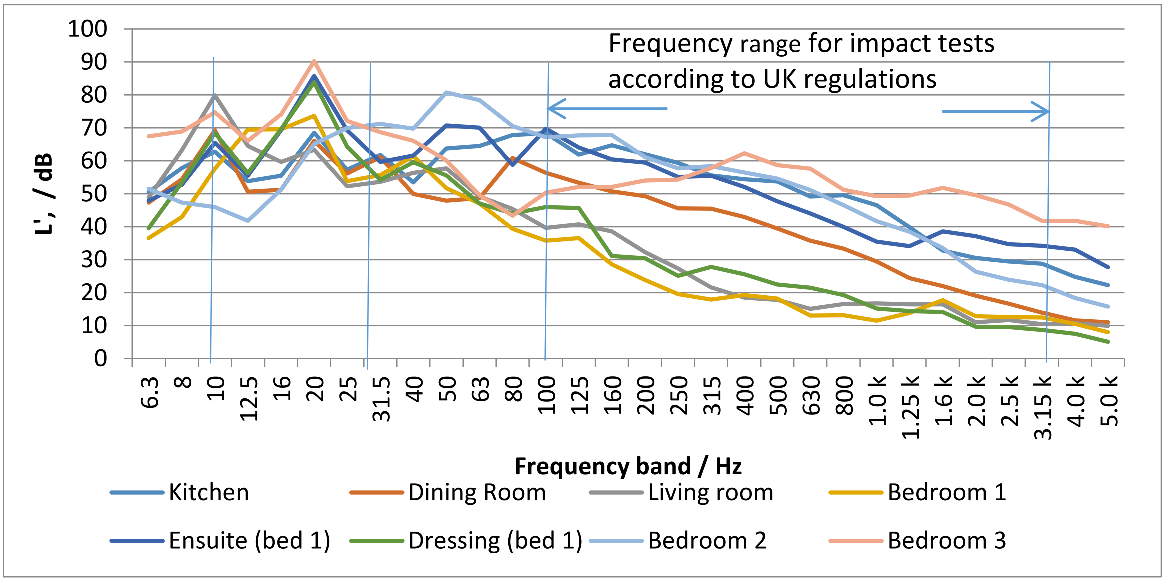

Figure 4: Measured values of impact sound from which the single figure parameters in Table 1 are derived after standardising.

3.4 AkuLite and AkuWood projects, Sweden

The research carried out for the AkuLite and AkuWood projects is described in various conference proceedings, and a newsletter [6]; Hagberg [7, 8] describes the research that demonstrates how measurements below 50 Hz enable much better correlation with subjective responses, but how the industry at large is not ready for measurements and assessment at such low frequencies. This research developed a new weighting curve for impact sound between 20 Hz and 2500 Hz that accounts for both the low frequency and high frequency impact, as shown in Figure 5. Despite not being adopted as proposed, this research was instrumental in informing the performance parameter adopted under COST TU0901. Hagberg et al demonstrate that ***only*** using measurements between 20 and 50 Hz, in timber frame buildings, can provide much better correlation with subjective response compared with using measurements from 50 to 2500 Hz – such that it could almost be argued that we are using the wrong frequency range altogether! Hagberg also describes the development of prediction tools for the calculation of impact sound down to the relevant lower frequencies; this is a complex area as described by Bard et al [9].

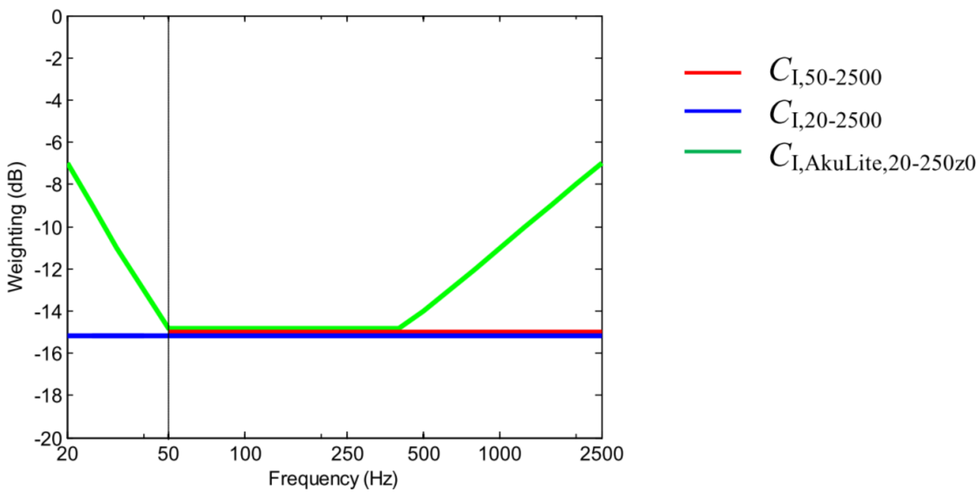

Figure 5: Weighting curves for different parameters from Ljunggren et al [10, 11]

3.5 Belgian Building Research Institute

Researchers at the Belgian Building Research Institute (BBRI), Lieven De Geetere and Bart Ingelaere, have adopted the new performance parameters and undertaken a significant programme of research to determine suitable construction solutions for timber frame buildings [12]. Their consideration and development of lightweight structures and measurements of the impact sound insulation achieved are described, and their proposed solution for the Belgian timber frame industry is detailed. The design goal they adopt is for impact sound equivalent to heavyweight concrete floors.

They illustrate how it is not possible to achieve equivalent performance to concrete floors using lightweight elements alone, as the degree of isolation required entails a floor that is too springy – suffering the “trampoline effect”. This leaves them the only choice of adopting heavier elements – a screed on the walking surface and gravel over the ceiling - within a structural timber frame design. Performance equivalent to a heavy concrete floor may not be the design goal for any particular application, but it is a useful benchmark.

3.6 Swiss research

A project to develop a timber floor with better impact sound insulation for the Swiss market is described [13]. The design involves a dowelled joist floor and incorporates Swiss hardwoods; thus while interesting, it is not directly applicable to the UK.

3.7 American research

According to Loverde and Dong [14], there have been publications documenting the poor correlation between current US rating metrics and subjective reaction since 1967. Their paper proposes a new metric to quantify and evaluate low frequency impact noise, based on extensive measurements and evaluations, and compares the correlation between a range of performance parameters with subjective response. They illustrate how equal loudness contours in the low frequencies are much closer together than in the mid-frequency range, such that a smaller variation in measured levels is more significant than at higher frequencies. They compare the coefficients of correlation and determination between various metrics and subjective reaction, which is reproduced in Figure 6. This figure illustrates how the second-best metric is $L'_{n,w} + C_{I50-2500}$ (i.e. closely related to $L'_{nT,50}$), but this is still not as effective as the measure of Low Frequency Impact Sound Pressure Level (LFISPL). They found that the best correlation for low frequency sound and complaints was for the sum of the non-normalised sound level in the 50, 63 and 80 Hz third octave bands – which is also the 63 Hz octave band level.

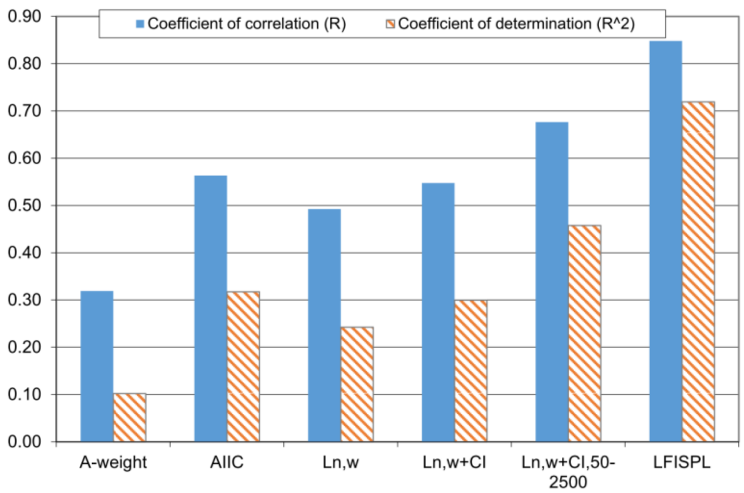

Figure 6: Comparing the coefficients of correlation and determination for various metrics and subjective reaction, reproduced by kind permission from LoVerde et al [14]

3.8 Other test methods

The laboratory test procedure for impact sound transmission, ISO 10140-3 [15] includes the opportunity to measure the sound generated from dropping a soft heavy ball onto the floor, intended to better represent the effect of footsteps with bare feet, or a child jumping. The ball is described in Annex F of ISO 10140-5 [16]. Classification schemes for ball impact sound levels have been proposed, such as by Sato et al [17]. However, it appears that a single number index for a common metric such as $L_{AF,max}$ may not provide better correlation with low frequency impact sounds. It appears that a tapping machine has sufficient energy to excite the frequencies of interest; the difficulty is how to evaluate the levels in different frequency bands. Therefore this alternative test method is not discussed further.

4 UNDERSTANDING THE SINGLE FIGURE INDEX

The parameter $L'_{nT,50}$ (i.e. $L'_{nT,w}$ + $C_{I50\text{-}2500}$) is derived directly from the third octave band data without the need to first calculate the value of $L'_{nT,w}$. Hence no curve fitting is required as for the calculation of $L'_{nT,w}$; rather, each value of L'_{nT} is weighted with the appropriate frequency band weighting for the parameter sought. For the parameter $C_{I,50\text{-}2500}$, the weighting is equal in all frequency bands, at a value of 15 dB, as illustrated in Figure 5. That figure also illustrates the greater weighting ascribed to both the lower and higher frequency bands in the weighting factor proposed in the AkuLite project.

Jack Harvie-Clark has previously described a method for interpreting the effect of any single frequency band on the global result [18]. In the case of the parameter $L'_{nT,50}$, as the weighting for all frequency bands is the same, the graph of values of L'_{nT} reveals the frequency bands that are most significant in contributing to the global parameter. It is interesting to note that as the weighting value of 15 dB is the same whether the rating is taken from 50 Hz or 100 Hz, the effect of extending the range down to 50 Hz is simply to add more contributions to the global result. Where the most significant contributions to the global result come from the end of the assessed frequency range and are continuing to increase towards that end of the range, as is almost always the case with impact sound on lightweight timber floors, it can be seen immediately that something is lost in the assessment by the choice of limiting the frequency range.

5 BENCHMARKING THE UK

5.1 Typical UK timber floor performance

The COST TU0901 programme developed a method to convert existing performance parameters into the new ones, described in its Chapter 4. However, the procedure may not be reliable for light weight constructions assessed from 50 Hz. BS 8233 [19] indicates that the mean value for impact sound for both E-FT-1 and E-FT-2 constructions as 52 dB $L'_{nT,w}$. The results from a range of tests on typical timber frame constructions built to Robust Detail undertaken by Apex Acoustics have been reviewed, and the typical performance is shown in Table 2.

Table 2: Benchmarking timber floor performance in the UK

Floor type	$L'_{nT,w}$ / dB	$L'_{nT,50}$ / dB	COST TU0901 Class	Source
E-FT-1 and E-FT-2	Mean 52	n/a	-	BS 8233
E-FT-1	Mean 55	Mean 59 Range 56 - 62	D – F	Apex measurements
Timber floor with shallow overlay FFT	Mean 53	Mean 58 Range 54 - 61	D – F	

The above suggests that typical Robust Detail or other proprietary timber floors in the UK may be regularly achieving an impact sound insulation performance up to 62 dB $L'_{nT,50}$. Comparison with the Class limits, meaning and interpretation in Figure 1, Figure 2, and Figure 3 indicate that this means that typical constructions may be at the upper end of Class D, but more generally in Class E or even Class F. It is suggested that walking may be “audible” or “clearly audible”, and that between 20 % and 50 % of people may judge the sound insulation to be “poor”. Robust Details Ltd are likely to have a large database of performance that may cover this frequency range, and therefore would be able to provide much better informed statistical values than those illustrated in Table 2.

This begs the question - is there a significant problem with impact sound in our current timber frame residential buildings that is unacknowledged? Or are the proposed Classes and associated descriptions unduly pessimistic for occupant satisfaction? The extensive research undertaken in the UK and other European countries would certainly suggest that the problems are simply not widely acknowledged in this country.

6 DESIRABLE PERFORMANCE & CASE STUDIES

It would appear from the description of the proposed Classes that the minimum desirable performance may be Class C for residential buildings, i.e. a performance limit of 52 dB $L'_{nT,50}$; to be able to offer higher performance in timber frame would also be a significant benefit. The significant testing programme carried out by the BBRI [12] demonstrates that this level of performance is not practically achievable with light weight elements alone. It is therefore necessary to include heavier elements within the overall build up, typically achieved with the use of a screed.

6.1 Case study 1: BBRI solution adapted for UK construction methods, Class B / C

The solution adopted by the BBRI for field trials has a laboratory performance of 48 dB $L_{nw,50}$, and is anticipated to achieve similar performance in terms of $L'_{nT,50}$.; if it achieves a similar value in terms of $L'_{nT,50}$ and $L'_{nT,w}$ it would be on the boundary between Class B and C according to the proposed classification system. The floor comprises:

- 60 mm screed cast on 18 mm moisture resistant particle board
- Resilient pads on solid timber joists with mineral wool between
- 12 mm fibre-cement sheet to the underside, holding 35 mm gravel, min 1700 kg/m^3
- 18 mm plasterboard ceiling finish

Although the mass of the screed is not explicitly identified, it is likely to be at least 100 kg/m^2; the gravel layer would be 60 kg/m^2. A significant feature is that typically in UK timber frame design, the sub-floor base acts as a structural diaphragm for lateral restraint across the building; in the above design, this element is switched to the underside of the joists. It is understood that this is also possible for the UK timber frame industry, but only where floors are installed as cassettes rather than the joists installed separately from the floor base. Clearly, this is because it would not be possible to install the (typically OSB board) to the underside of the joists before the joists are in place to hold it up – as this board needs to tie in with the walls, with the joists resting on it. A typical detail of how this type of approach could be adopted for UK construction is shown in Figure 7.

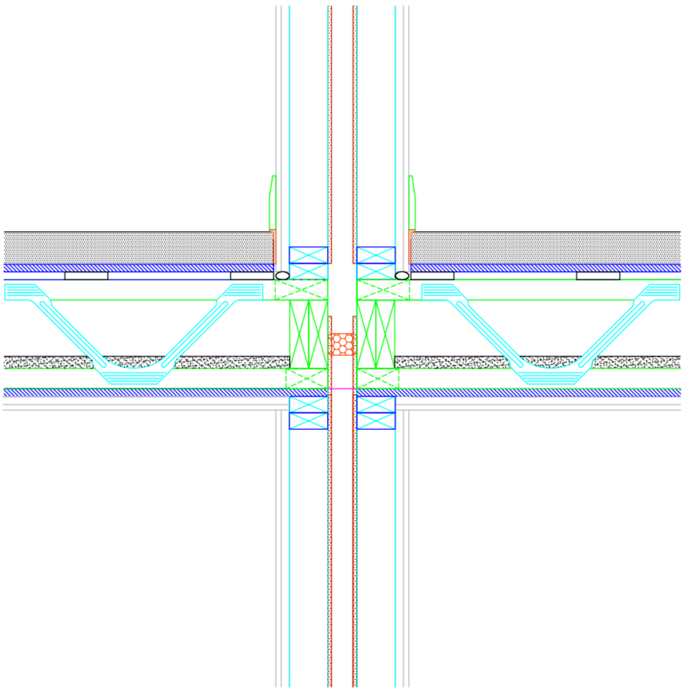

Figure 7: Implementation of BBRI design with UK construction detailing, © Datum Ltd

6.2 Case study 2: screed on low profile steel decking on resilient strips, typically Class C

An alternative approach, that requires less deviation from more typical structures and elements, is to use a cast screed on low profile Lewis decking, floating on resilient strips on a more conventional timber floor base. In this particular example there is also a sacrificial ceiling void for services.

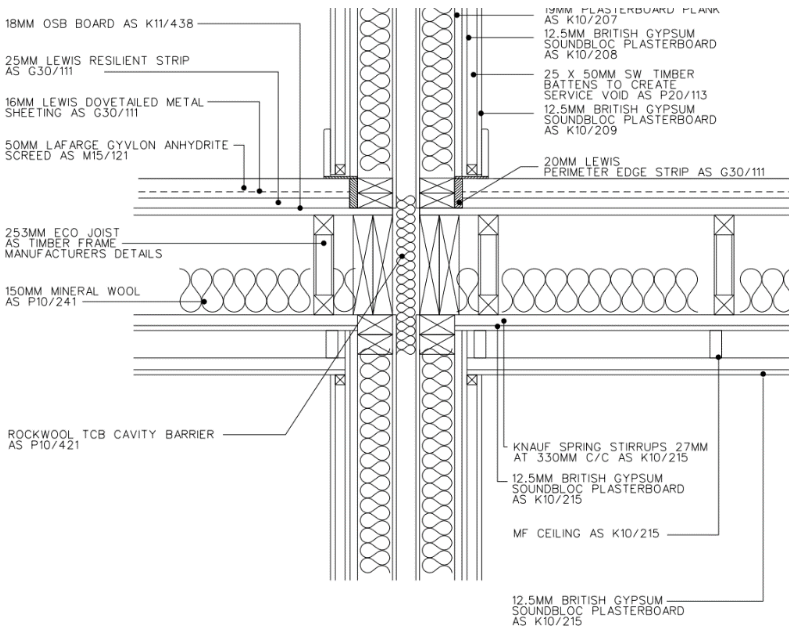

Figure 8: Detail of floating screed on Lewis decking on resilient strips on timber floor

The four floors tested achieved 51 – 53 dB $L'_{nT,w}$. The data between 50 and 100 Hz is not available, but the performance is estimated by extrapolating based on a log trendline, as this represents similar constructions well; on this basis it is estimated that the performance of between 49 – 53 dB $L'_{nT,50}$ is achieved. It is notable that the tests data shows, Figure 9, that the value of $L'_{nT,w}$ is limited by the high frequency performance, not the low frequency. This detail generally achieves Class C for impact sound, although it is understood that better performance can be achieved with higher performance Sylomer resilient material, rather than the mineral wool resilient strips used here. This build up is one option from a range of floor details incorporating a low profile steel deck with in-situ concrete as promoted by CDI [20], with a range of performances and associated test data.

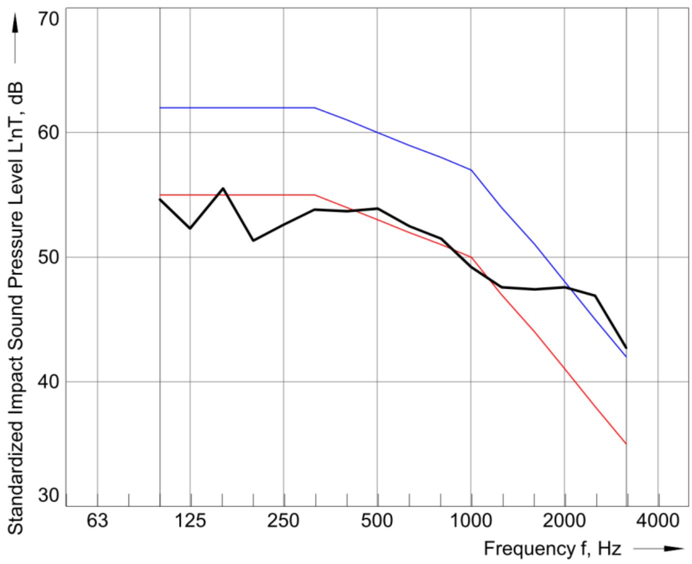

Figure 9: Typical result for construction detail shown in Figure 5

6.3 Case study 3: screed on continuous resilient layer on existing timber floor, Class A

For a recent refurbishment project to form an Aparthotel, a screed was specified on a resilient layer directly onto the existing timber floor. Due to the floor to floor heights, a sacrifical ceiling was installed with a large void to the underside of the timber floor. The build up comprised:

- 65 mm sand / cement screed containing underfloor heating pipes on Monarfloor Tranquilt
- Existing 20 mm timber flooring boards on existing solid timber joists with quilt between
- Underdraw of 2 x fire rated 12.5 mm plasterboard fixed directly to joists
- Approx 600 mm void with 1 x 12.5 mm plasterboard on MF suspension

The joist depth and spacing is not known, but they are likely to be at 16 inches (approx 400 mm) centres, due to the age of the building. The walls are thick masonry, which control flanking sound very.

With a hard (ie non-cushion) vinyl floor finish, the above floor achieved 41 dB $L'_{nT,50}$ and 42 dB $L'_{nT,w}$, as shown in Figure 10. With an underlay and carpet, it achieved 22 dB $L'_{nT,50}$ and 25 dB $L'_{nT,w}$., but was severely limited by background sound. Hence with a vinyl floor finish this floor achieves Class A for impact sound; it is not known how the classification system will include floor finishes.

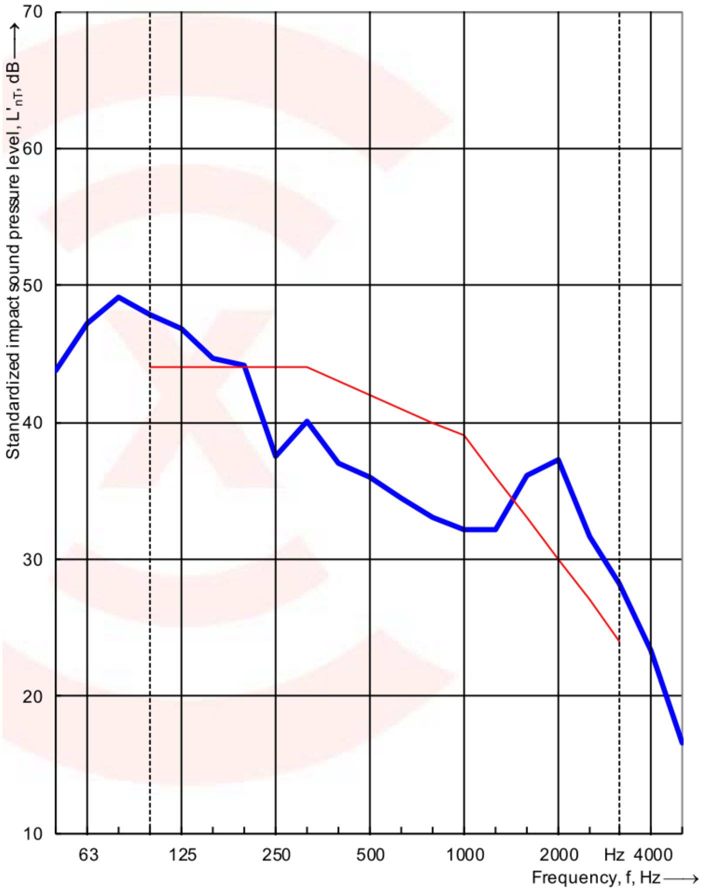

Figure 10: Impact sound pressure tested on vinyl

7 CONCLUSION

It is considered likely that many timber frame flats have and are being constructed that have an impact sound performance that is safely compliant with current Building Regulations, but may fall short of adequacy for occupant satisfaction. Although there is multiple anecdotal and limited survey evidence of this in the UK, it is suggested that the results and conclusions of the European research should be applied without delay, to avoid the potential for a negative reputation to be wrongly simply associated with timber frame construction.

The application of the performance parameter $L'_{nT,50}$ may generally improve correlation with occupant satisfaction, but it may also still leave the opportunity for significantly adverse conditions to be classed as satisfactory or even good. Some researchers have found that the best correlation with occupant satisfaction is based only on measurements between 50 and 100 Hz. As universal agreement within the acoustics community on measurements below 50 Hz would appear unlikely in the near future, assessment down to 20 Hz may remain a tool for those investigating complaints rather than general application. The difficulty of what recourse the occupants may have in those cases, however, remains.

As Hagberg dramatically comments [7]:

It is proved that the low frequencies have to be part of the evaluation procedure or the entire wooden building industry will have no success at all for the future!

8 REFERENCES

1. ISO 140-7:1998, Acoustics - Measurement of sound insulation in buildings and of building elements - Part 7: Field measurements of impact sound insulation of floors.
2. ISO 717-2: 2013, Acoustics - Rating of sound insulation in buildings and of building elements -- Part 2: Impact sound insulation. (NB Approved Document E refers to a previous version).
3. ISO/NP 19488, Acoustics - Acoustic classification scheme for dwellings
4. COST TU0901, downloaded from http://www.costtu0901.eu/tu0901-e-books/volume-1.html
5. B Rasmussen, International proposal for an acoustic classification scheme for dwellings – Background and perspectives, Proc. Internoise 2014, Melbourne, Australia.
6. AkuLite & AcuWood newsletter 2013, available at http://www.wspgroup.com/Documentsn/pdf/pdf-%C3%B6vrigt/Newsletter-akulite-acuwood.pdf
7. K Hagberg, D Bard; Low frequency sound transmission in multifamily wooden houses, Proc. Internoise 2014, Melbourne, Australia http://www.acoustics.asn.au/conference_proceedings/INTERNOISE2014/papers/p935.pdf
8. K Hagberg, New research create basis for future competitive wooden structures, 21st ICSV Beijing, China, 2014. Available from: http://www.icsv21.org/content/papers/papers/full_paper_438_20140315151022249.pdf
9. D Bard, G Borello, C Guigou, J Negreira, J-L Kouyoumji; Challenges for acoustic calculation models in "silent timber build, 21st ICSV Beijing, China, 2014. Available from: http://www.icsv21.org/content/papers/papers/full_paper_493_20140315150044600.pdf
10. F Ljunggren, C Simmons, K Hagberg, Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound, Applied Acoustics Vol 85, Nov 2014, Pages 57–68, http://dx.doi.org/10.1016/j.apacoust.2014.04.003
11. F Ljunggren, Is it necessary to measure impact sound insulation from 20 Hz in lightweight multi-storey buildings? Proc. Forum Acusticum, Krakow, September 2014, available from: www.fa2014.agh.edu.pl/fa2014_cd/article/SS/SS04_1.pdf
12. L De Geetere, B Ingelaere; A new building acoustical concept for lightweight timber frame constructions, Proc Internoise 2014, Melbourne, Australia, and also at:

http://www.fa2014.agh.edu.pl/fa2014_cd/article/SS/SS02_9.pdf
13. J Mahn, C Hopkins, M Filippoupolitis, U Schanda, R Völtl, L Krajči; The Optimization of a Wooden Floor Design Based on Validated Finite Element Models, Proc. Internoise 2014, Melbourne, Australia.
http://www.acoustics.asn.au/conference_proceedings/INTERNOISE2014/papers/p998.pdf
14. J. LoVerde; W Dong, A new metric to quantify and evaluate low frequency impact noise, Proc. Internoise 2014, Melbourne, Australia available at:
www.acoustics.asn.au/conference_proceedings/INTERNOISE2014/papers/p887.pdf
15. ISO 10140-3:2010, Acoustics - Laboratory measurement of sound insulation of building elements - Part 3: Measurement of impact sound insulation.
16. ISO 10140-5:2010, Acoustics -- Laboratory measurement of sound insulation of building elements -- Part 5: Requirements for test facilities and equipment.
17. H Sato, J Yoshimura, Classification scheme of floor impact sounds with the standard rubber ball in dwellings, Proc Internoise 2014, Melbourne, Australia, available at:
www.acoustics.asn.au/conference_proceedings/INTERNOISE2014/papers/p978.pdf
18. J Harvie-Clark, Practical Acoustic Design – The Apex Method, Proc. Institute of Acoustics, Vol 36 Pt 3 2014, pages 561 – 569.
19. BS 8233: 2014, Guidance on sound insulation and noise reduction for buildings.
20. http://cdi-icm.co.uk/, contact Chris Holt, Chris@CDI-ICM.co.uk