Structural Insulated Panels (SIP) and Rain noise

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Abstract

In this paper we discuss the requirements of the generic international standard (ISO, BS EN ISO 10140) for testing of sound transmission through sample roofs exposed to simulated rainfall and of lessons learned during a recent test program. The test data forms the basis for calculating in-situ sound levels in rooms beneath the roof and we discuss the differences in sound produced by simulated rain to that of natural rain. The differences in impact velocity and raindrop distribution between simulated and natural rain are key factors that are not addressed by the Standard. In addition, an optional normalization test using a pane of glass is included, for the explicit comparison of products tested and as quality control for test laboratories, and its results have been incorrectly shown in some manufacturer's publicity material as the basis for calculating room sound levels. The Standard does not specify whether the normalization test should be carried out as a skylight or as glazing but the two tests have different requirements. Being optional and intended for inter-lab comparison suggests that the normalization data should not be released to clients as it is misleading and thus should be excluded from reporting.

Keywords: rain noise, roof systems

Introduction

Depending upon the listener's contextual situation, noise generated by rainfall can be soothing or annoying. Lengthy *You Tube* videos and *mp3* audio are available [1] for playing rain noise to support relaxation, yet in other circumstances the same sound masks communications and becomes a nuisance. It is in this latter context that we report on the incidence of rainfall on metal roofs supported by structural insulated panels (SIPs) – these panels are composites consisting of stiff facing panels adhered to a soft core, usually foamed expanded polystyrene or polyurethane. The intrinsic mass and acoustic insulation properties of the panels are low, which may lead to high levels of rain induced noise in the building's interior rooms. The rooms in question could be classrooms or open learning spaces where good conditions for communication for teaching are paramount.

Figure 1 shows the typical form of response curve for the sound transmission loss characteristic of foam cored SIPs. The dips at frequencies around 630 Hz and 3150 Hz basically control the STC rating for the panel.

The response in the range of 630 Hz is a bounce mode of the masses of the facing panels on the springy foam core. Adding mass layers to improve the transmission loss rating (as in the broken line curve in Figure 1), also stiffens the panel yet the upper and lower modal frequencies remain unchanged. The effect on the NC rating, as determined for a room where SIPs are used in a roofing application, can be seen in Figure 2.

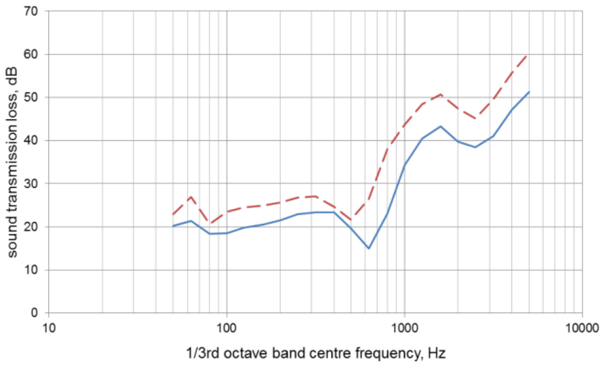

Figure 1 Typical sound transmission loss response for SIPs

Clearly, the resonance mode in the 630 Hz region is limiting the rating for the room. The broken line curve represents a SIP with additional face treatments and the full line curve is the effect of adding insulation (with a suspended ceiling).

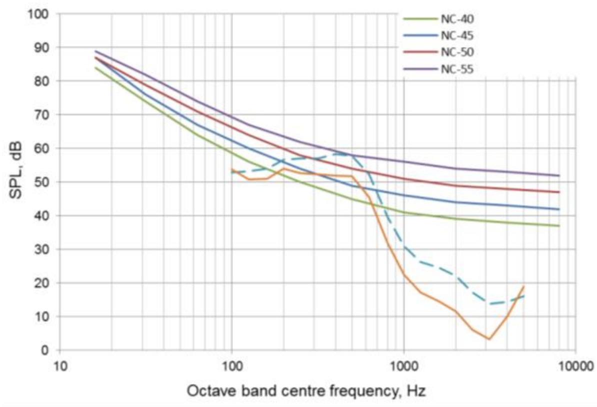

Figure 2 Sound level in a room bounded by SIPs exposed to rain noise

Rain

Rain is a form of impact loading, generating noise by the excitation of vibration of roof panels by the dynamic force exerted by the falling droplets. The size of raindrops varies in natural rain and is related to the intensity or rainfall rate. Rain is classified as light, moderate, heavy or intense. In the laboratory, simulated rain as defined in Standards is classified as moderate, intense, heavy or cloudburst, and is generated in the laboratory as a means to make observations under reproducible and standard conditions. It does not correlate well with natural rain but the spectral character of the noise is consistent, whilst the sound level is at variance. The impacting raindrops excite the natural modes of vibration of the exposed roof panel and the resulting motion is radiated as sound. The modal frequencies of the roof structure are determined by the mass, boundary conditions (screw or nail fixing and their spacing), the spacing and material of the purlins, and system damping (overlap joints, membranes, material). For a given installation then, as would be expected, an increase in rainfall rate leads to higher noise being generated. Lower frequency modes require higher input energy to excite and so may not be present in low intensity rain.

Design

For acoustic design and evaluation purposes, international standards [2] use 'heavy' rainfall for simulated testing. This is defined as rainfall up to 40mm/h. This rate may or may not be suitable for designs for specific locations and results would need to be tailored accordingly. For Greymouth and Auckland in New Zealand for example, the average rainfall rates (from https://www.weather-atlas.com/en/new-zealand/auckland-climate (accessed 26th Feb 2019)), are as shown in Figure 3

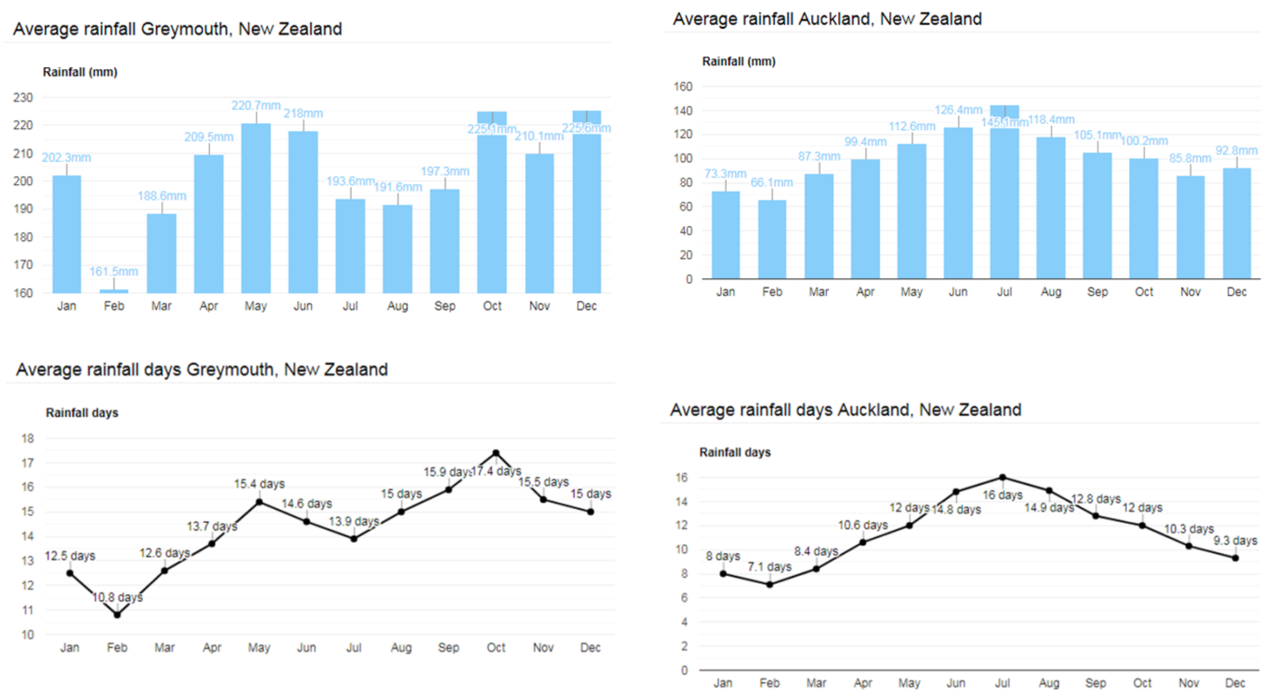

Figure 3 Rainfall data for two sites in New Zealand [*data from NIWA and NZ Met Office*]

Auckland has 60 to 140 mm of rain in a month, falling over 8 to 16 days. Greymouth has160 to 260 mm of rain per month, falling over 10 to 16 days; On average, Greymouth receives twice as much rain annually than Auckland – but neither record says anything about intensity of rainfall, or how often one can expect a rainfall rate of 40 mm/h and for how long it may last. In New Zealand, the Ministry of Education design guidance document [3] specifies a sound level performance of NC 45 or less as the rain noise criterion for all open learning spaces, irrespective of rainfall rate. Thus for areas of high rainfall, such as Greymouth, the solutions for the roofing system will be more onerous than for an area with lower or much lower rainfall. In the UK, the comparable education sector document [4] specifies background noise levels to be achieved in various rooms of a school and these must not rise by more than 25 dB as a result of the contribution from rainfall. The document also differentiates between new buildings and refurbished ones and the difference mostly amounts to -5 dBA, i.e. indicative of a trend to improved (higher standard) acoustic environments. Taking the open learning spaces as an example, [4] specifies an upper limit of $L_{Aeq,30mins}$ 40 dBA (new builds) and 45 dBA (refurbished buildings). This then gives rain noise limits of 65 and 70 dBA respectively. In comparison, the New Zealand document [3] specifies NC45, and taking the octave band values for that criterion between 125 Hz to 8000 Hz, this equates to 51.3 dBA – substantially lower than the UK case but a lot higher than the specification for ambient background, L_{Aeq} 30 to 45 dB, depending upon the use definition of the space. The challenge is to determine the make-up of the roof system to ensure that these noise criteria are met for a given design rainfall rate and recognising that European case studies will be different than for application in New Zealand.

Some rainfall rate guides are available, such as shown in Figure 4 for the Waitakere district of Auckland, and these are mainly used for prediction of flooding and sizing of drains and guttering. An interactive high intensity rainfall prediction tool is available at NIWA:

(https://www.niwa.co.nz/information-services/hirds).

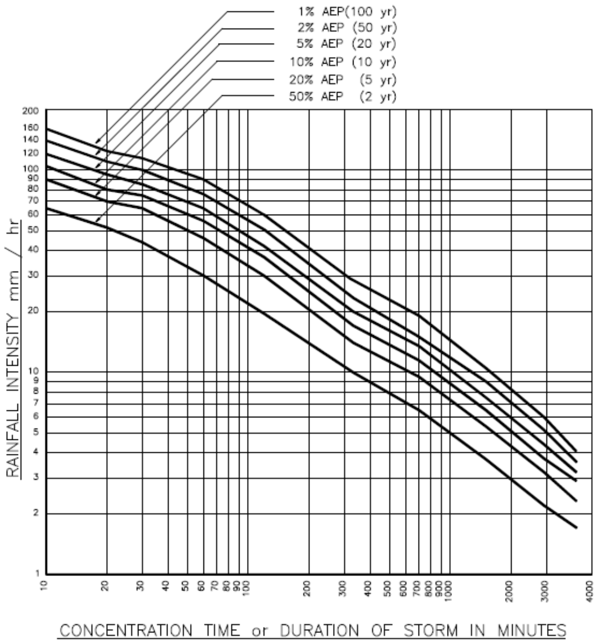

Figure 4 Waitakere Council Engineering Standards graph for rainfall intensity

(Plotted from NZ Meteorological Service data 2002 for Whenuapai)

These tools include a temporal component that is not present in the design guides [3, 4], although [4] does use the $L_{Aeq,30mins}$ metric. Figure 4 indicates that there is a high probability that there will be at least one event in two years where rain with an intensity of 40 mm/h will fall for 30 minutes duration – in Auckland. Factor in that the rain event would have to fall during a normal school day and that there are only 190 school days in a year and the probability of being in a classroom during the event is quite low – but never-the-less we are required to design for it.

Predicting rain noise levels

Three methodologies are in use:

1. Use test data for the specified roof profile to determine the noise level generated and then use airborne sound transmission loss data to estimate the attenuation through the constructed roof system and into the room below.
2. Use data for a similar roofing system, making adjustments deemed necessary to account for the differences in the structure.
3. Use empirical formulations to estimate the rain noise received in the room below.

The prediction of expected noise levels from rainfall appears to be a "black art". It is based on many assumptions and cannot be viewed as sufficiently accurate as to be able to state with any certainty that any given roof/ceiling structure will meet a specified criterion [5]. The possible exception is where a roof structure has been tested and data is available to support calculation of an in-situ case. Even so, one has to make assumptions about the in-situ case regarding flanking noise, room absorption, deviations in construction methodology for installing the sample compared with the real world, and the differences between test conditions using simulated rainfall and natural rain for the target building site.

The international test standard for testing roof systems for rain noise requires a sample size between 10 m^2 and 20 m^2 and the transmitted sound is reported as sound intensity in dB re 10^{-12} W/m^2. The sound intensity may be determined from the measurement of sound pressure levels within the test room below the roof sample or by measuring it directly using a sound intensity probe. The sound power developed by the roof system is determined by the product of the sound intensity and the area of the test sample. Once the sound power is known it can be used to find the sound intensity for an in-situ case by taking the quotient using the in-situ space's ceiling area. The calculations are carried out for each of the one-third octave bands between 100 Hz and 5000 Hz [6].

Testing

Simulated rain is different from natural rain as it seeks to standardise a testing method. Simulated rain must comprise 50% of the volume flow of droplets of the same size and have a specified impact velocity where in natural rain the drop size distribution is related to rainfall rate and therefore each event will have a different impact velocity distribution [6].

Rain noise testing is carried out to the international standard BS EN 10140-Part 1, Appendix-K. Parts 3 and 5 of the older version of the standard (ISO 10140) are referenced in the test methodology, and details of the drip tray for generating water droplets is detailed in Amendment 1 to Part 5. This amendment includes a table where the hole size and number of holes per unit area is given, but surprisingly there is no detail on hole entry and exit conditions. The holes are 1 mm diameter so small enough for surface tension to play a significant role in drop formation and capillary flow.

The Standard states a preference for randomly distributed holes yet the diagram - Figure H.1 as shown in Figure 5, associated with the text is not random, one example of which is shown in Figure 6.

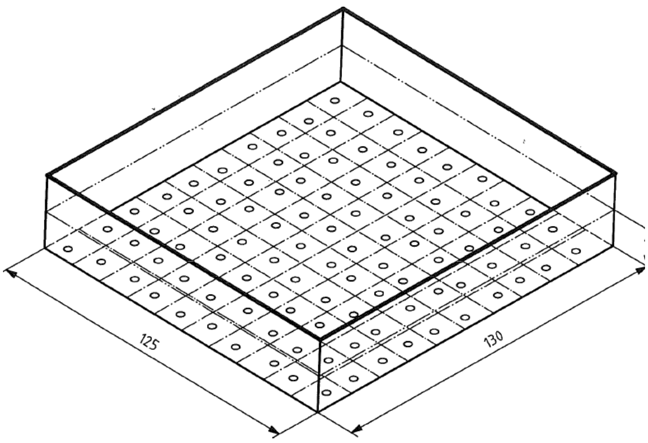

Figure 5 Schematic Figure H.1 from [7]

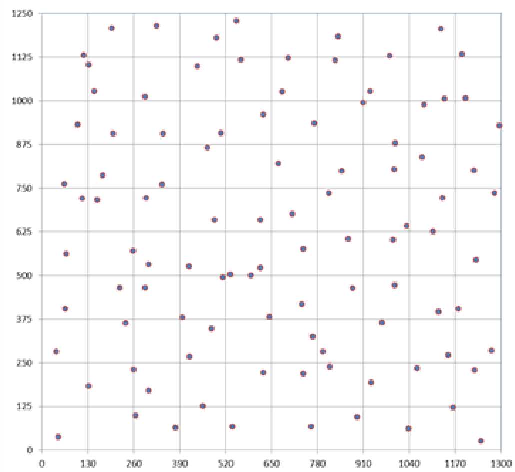

Figure 6 Random pattern of holes

The formation of droplets giving the required intensity (rainfall rate) requires a head in the tray of only a few millimetres of water. Small increases in depth will lead to higher intensities with the specified droplet size. An appreciable increase in the head of water would lead to stream flow and rely on this breaking up before impact on the sample to give individual droplets of a random size. The depth of water required is around 3 mm and so a 1mm change is significant – this means that levelling the tray must be carefully carried out and maintained during the test cycle.

The laboratory test uses a drip tray whose area is only a fraction of the test sample to avoid symmetry. Thus, between 23% and 47% of the sample is exposed to simulated rain depending on the sample size (20 m^2 to 10m^2 respectively). The resulting sound intensity is found from area and three test positions are required – not overlapping and offset from the centre

measuring sound pressure and using equation K.1 or measured directly with a sound intensity probe and using equation K.4 [2]:

$$L_I = L_{pr} - 10\text{Log}\left(\frac{T}{T_0}\right) + 10\text{Log}\left(\frac{V}{V_0}\right) - 14 - 10\text{Log}\left(\frac{S_e}{S_0}\right)\ \text{dB} \qquad \text{Equation K.1}$$

$$L_I = L_{Im} + 10Log\left(\frac{S_m}{S_e}\right)\ \text{dB} \qquad \text{Equation K.4}$$

where:

- L_{pr} is the energy averaged sound pressure (for the three test positions of the drip tray) in the test room, dB;
- T is the reverberation time of the test room in seconds;
- T_0 is the reference time (=1 sec);
- V is the volume of the test room in cubic metres (m^3);
- V_0 is the reference volume (=1 m^3);
- S_e is the total of the areas of the sample excited by the rainfall in square metres, (m^2, corresponds to three times the perforated area of the drip tray;
- S_0 is the reference area(= 1 m^2)
- L_{Im} is the sound intensity directly measured, dB
- S_m is the area of the measuring surface, m^2.

Note that the laboratory is only required to report the intensity value L_I - unless a reference glass pane test was carried out, in which case its results are applied to the roof system data and are reported as L_{Inorm} or L_{Imnorm},. The results are subsequently A-weighted and a single descriptor included. The Standard is quite explicit in stating that the glass pane test is for quality control and inter-laboratory comparisons only, that provide information for the test laboratory [7, Annex I] - and is not mandatory. The normalised values are obtained by applying 'correction' factors to the results for the sample test yet there is no logic to this procedure. Firstly it is not mandatory, and secondly there is no specified way in which the glass pane is to be tested. That is, there is no specification as to the angle it presents to the rainfall. The pane is not mounted in the sample roof structure that has been tested but in a supporting system that has sufficient sound blocking capacity to ensure that the main transmission path is through the glass. Thus, neither geometry nor construction are the same as used for the roof system tested.

Data is published by suppliers as L_I and L_{IA} and whilst the Standard does not say that the sample size should be reported it is necessary to have it as further calculations cannot proceed without it. Some roof system suppliers' publicity brochures were found to have erroneously listed only L_{Inorm} values.

Making Predictions

The sound intensity radiated by the test roof sample is used to find the sound pressure in another space of known dimensions and reverberation time. Hopkins [5] demonstrates this process for skylights, giving two examples for the application to classrooms.

As mentioned in the previous section, the sound intensity reported from the test laboratory is for a partially excited roof sample and so must be modified as if the sound pressure was increased for the whole sample being exposed to rainfall. This is done using the expression:

$$L_{I(s)} = L_I + 10Log\left(\frac{S_s}{S_0}\right) \qquad \text{Equation 1}$$

where

$L_{I(s)}$ is the sound intensity if the whole sample was subjected to rainfall, dB

S_s is the area of the test sample, m^2

S_0 is the reference area for the rainfall rate (=1 m^2)

This assumes a linear relationship between the area excited by the rain and the sound generated – which may not be true, since the dynamic response of the roof sample will not be the same at every point.

If sound intensity was directly measured then providing that the measurement surface (S_m) is the whole roof sample area then that intensity (from equation K.4) has been adjusted for the difference between exposure and measurement areas, but if the sample area is greater than the measurement surface area then a further adjustment is necessary as:

$$L_{I(s)} = L_I + 10Log\left(\frac{S_s}{S_m}\right) \quad \text{Equation 2}$$

The process is carried out for each of the one-third or octave bands as required by contractual requirements and requires detail of the reverberation times and absorption characteristics of the space(s) - [4] gives target values for RT based on room size, see Figure 3 together with target values for specific learning spaces as shown in Table 1.

Table 1 Design reverberation times in different learning spaces

Learning space	Reverberation time (s) – mid frequency average (RT_{MF})
breakout spaces/meeting spaces/teacher work spaces	0.4 – 0.5
flexible learning spaces	0.5 – 0.8
cellular classrooms	0.4 – 0.5
music learning spaces	0.6 – 0.8
halls/multipurpose spaces	0.6 – 0.8
gymnasiums	0.8 – 1.5
technology and science spaces	0.6 – 0.8
libraries	0.5 – 0.8

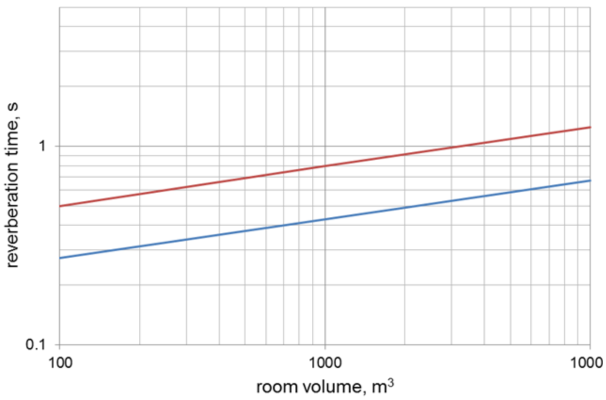

Figure 7 Reverberation times RT_{MF} recommended in [4] as a function of room size

A recent example for a school had multiple open learning spaces where the room volumes were around 850 m^3 with floor areas each around 200 m^2 The value of RT_{MF} recommended in Figure 7 and Table 1 is 0.4 to 0.75 sec. The less absorption supplied the lower the cost of the room and so it is likely that designers would opt for the longer RT values and so 0.6 secs was used in the analysis for the frequency range 100 to 500 Hz and 0.4sec for the 630 Hz to 5 kHz frequency range.

It should be noted that the Standard does not require the area of the sample to be stated in the report, only its description (Clause 6, ISO 10140-3:2010 and BS EN ISO10140-1 2016: Appendix K). The effect is obvious, since the sample area can vary between 10 m^2 and 20 m^2, then the difference in converting the reported intensities for sample size will be up to 3 dB. If the sample area is not given in manufacturers' data then one cannot do the conversion or even know that there is one to be made and so predictions will err.

Table 2 and Figure 8 show an example for a metal roof over a SIP with a comparison between correcting or not correcting the intensities reported.

Table 2 Application of test results for metal tray roof over a structural insulated panel roof, all values in dB

1/3rd Octave band freq, Hz	L_i	$L_{i(s)}$	L_w	$L_{p(in\text{-}situ)}$[1]	$L_{p(in\text{-}situ)}$[2] corrected	$L_{p(in\text{-}situ)}$[3] not corrected
	From the test sample					
100	40.5	50.6	73.6	55.6	58.0	46.2
125	40.9	51.0	74.0	56.0	58.4	46.6
160	41.7	51.8	74.8	56.8	59.2	47.4
200	44.4	54.5	77.5	59.5	61.9	50.1
250	44.7	54.8	77.8	59.8	62.2	50.4
315	44.7	54.8	77.8	59.8	62.2	50.4
400	46.1	56.2	79.2	61.2	63.6	51.8
500	45.4	55.5	78.5	60.5	62.9	51.1
630	40.0	50.1	73.1	55.1	55.8	44.0
800	27.4	37.5	60.5	42.5	43.2	31.4
1000	18.6	28.7	51.7	33.7	34.4	22.6
1250	14.0	24.1	47.1	29.1	29.8	18.0
1600	12.2	22.3	45.3	27.3	28.0	16.2
2000	9.8	19.9	42.9	24.9	25.6	13.8
2500	4.9	15.0	38.0	20.0	20.7	8.9
3150	1.5	11.6	34.6	16.6	17.3	5.5
4000	2.1	12.2	35.2	17.2	17.9	6.1
5000	3.8	13.9	36.9	18.9	19.6	7.8
			overall dBA =	62.1	70.7	58.9

Notes:
1. Calculated for the in-situ exposed roof area.
2. Calculated for in-situ exposed roof area and for natural rainfall.
3. Calculated from laboratory sound intensity with no correction for sample size.

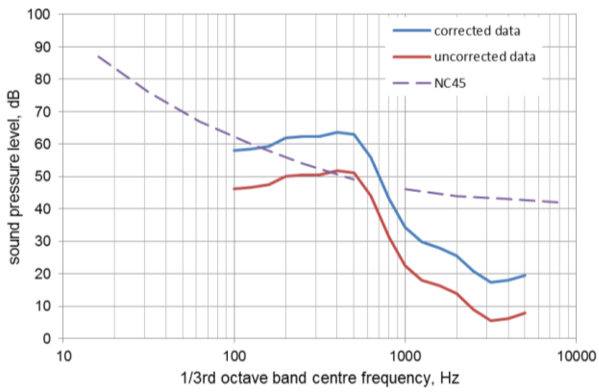

Figure 8 Data from Table 2 plotted with NC45 curve

From Figure 8 it is clear that if corrections are not made for either sample size and natural rain versus simulated rain then the prediction is that the roof system will almost meet the NC 45 criteria. In contrast, the corrected data prediction is some10 dB outside the requirements and additional treatments, such as suspended ceiling, ceiling insulation, damping paints etc. are necessary.

Discussion and Conclusions

The consolidated theory for predicting rain noise, as presented by Griffin and Ballagh in 2012 [11], under-predicts for steel roofing by a considerable margin (7 dB for corrugated steel and 16 dB for metal tray.) Griffin presented a paper at a 2016 conference [12] in which he concluded "*In this context, the ability to evaluate the accuracy of rain noise predictions is currently limited as are the benefits of such prediction methods for evaluating a wide variety of construction types*". The context of which he spoke relates to the dearth of supporting data from laboratory tests. In other words, prediction methods have been developed but the results are poor and unable to be improved until more test data and laboratory inter-comparisons are available. Thus, to improve models we need to test, but the standards to which we test lack reproducibility due to loose prescription of the method, hardware and reporting requirements. Most of the issues raised in this paper have already been discussed by Chené et al [] in 2010, before the addendum to Part 5 of !SO 10140 was released (in 2014) and yet none have since been addressed. One imagines that the rain noise testing community is small so perhaps the way forward is to encourage it to cooperate. It is incumbent upon architects, consultants and others who specify roofing systems to ensure that the data supplied by roofing manufacturers is appropriate and is used in the correct manner.

References

[1] https://www.youtube.com/watch?v=IdGUunu7pVI for example (accessed 20th Sept 2018)

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