QUANTITATIVE MEASUREMENTS OF LIGHTWEIGHT TIMBER FLOORS USING LOW-FREQUENCY IMPACT SOURCE; ANALYSIS OF THE ACCURACY OF 1/3 OCTAVE BAND HEAVY-HARD IMPACT PREDICTION MODELLING IN LIGHTWEIGHT STRUCTURES.

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1 INTRODUCTION

In recent years lightweight structures became more popular with a particular rise of CLT buildings. Most of new developments are mixed-use buildings, including retail, commercial, residential and gyms units. Especially gyms are vibration-sensitive areas and can excite the structure which may lead to complaints in the adjacencies. Hence, a particular detailed focus must lay on the design of the gym floor to ensure a quiet habitat for the residents. Whereas new developments have the flexibility to include robust systems with build-up thicknesses up to 300 mm, existing lightweight structures require a slim solution to mitigate the vibration sufficiently. In many cases, mixed-use lightweight structures were designed for offices or similar use with less stringent acoustic requirements and are not suited for the use as a gym. This change of use is in most cases considered as permitted development without being subject to planning conditions [10]. Therefore, this paper analyses different strategies, looking at various lightweight structures such as timber joists, posi joists, steel frames and CLT, to outline how to provide sufficient vibration mitigation.

2 GYM AIRBORNE AND IMPACT TESTING

When assessing the building's capabilities to house a gym, both airborne and structure-borne noise and vibration must be measured. The airborne noise is generated by the music and people within the premises. More critical is the structure-borne noise and vibration caused by exercises like treadmills, pin-loaded machines, rhythmic exercises, and weight drops. Especially the latter one is typically the worst-case scenario, resulting in the highest energy input into the slab. Hence, when obtaining the acoustic performance of the gym flooring, special interest lies in the heavy-hard impact. Generally, acoustic issues can be summarised in the following categories [10]:

- Heavy-Hard Impacts (HHI): Weight drops etc.
- Synchronised Repetitive Excitation (SRE): Treadmill, pin-loaded machines, dance classes etc.
- Airborne Noise (AN): Spinning class music etc.

Based on these categories, gym activities can be subcategorised into the following risk ratings [12]:

Table 1: Gym activity risk rating according to [12]

Gym activity risk rating	Activity description
High	Olympic-style weights, heavy free weights, CrossFit training
Moderate	Kettlebell free weights, rope rolls, static weight machines
Low	Circuit training, resistive training with free weights, running, resistive machine such as rowing and spin

The common testing method in the UK is partly based on the guidance of EN ISO 10140 Part 5, which describes dropping a heavy-hard object directly onto the bare slab, followed by various gym flooring solutions to measure the frequency response of the building structure in the most sensitive adjacency. The energy input of the drop must be sufficient to excite the building to determine the structure-borne noise in the noise-sensitive area [12].
Measuring the impact performance of lightweight structures comes with greater uncertainty than conducting on-site testing on a classic concrete slab. Therefore, the ANC ProPG Gym Acoustics Guidance recommends selecting the drop weight and drop height individually for each project. Nevertheless, to ensure repeatability of the impulsive force a kettlebell with a rounded base should be utilised [10]. To allow a comparison across different projects/structures 23.4 kg from a height of 0.5 m has been used in this paper which is in line with the ANC ProPG Gym Acoustics Guidance.
A common acoustic requirement for gyms in the UK is NR20 which represents inaudibility when compared against the threshold of hearing for ontologically normal persons in the age range of 18 to 20 years according to ISO226:2003 [10]. Furthermore, BS6841 recommends a weighted vibration with a peak magnitude of 15 mm/s2 is 'just detectable' for half of the population. Important to consider, BS6472 suggests that occupants are tolerant to a peak magnitude of 30 mm/s2 in non-residential arrangements like offices or retail.

3 FLOOR STRUCTURES

Lightweight structures are more sensitive to vibrations and energy input from heavy-hard impacts than concrete floors due to the lack of mass and stiffness, respectively. Whereas the latter is the main driver for the acoustic performance of lightweight structures. Therefore, locally reactive and resonantly reactive acoustic flooring are required to achieve sufficient noise and vibration mitigation, comparable to heavy structures such as concrete slabs.

3.1 Cross Laminated Timber

Cross Laminated Timber (CLT) is a popular building material, and numerous new developments are designed to be either a full CLT structure or a hybrid design with a concrete/steel frame. The main benefit is the sustainability aspect, namely lower embodied carbon, faster building time, and fewer deliveries required to the site. However, the bare CLT slab lacks stiffness which results in poor acoustic performance. Thus, it requires a special focus on the acoustic design of the project to provide sufficient sound mitigation. To achieve sufficient stiffness for the CLT floor, a concrete topping can be directly poured onto the bare slab. This increases the overall stiffness and adds mass to the system. As demonstrated in Figure 1, the impact performance using a tapping machine is better by 2 dB than for the bare concrete slab. However, the concrete topping increases the embodied carbon of the overall build-up by around 61 kg/m2. Therefore, pouring concrete should be limited to very sensitive areas like a gym. To date, more data must be gathered using heavy-hard impact sources such as a kettlebell on gym flooring. The data presented are obtained by using a tapping machine in accordance with ASTM E492 in a third-party laboratory that is IAS accredited.

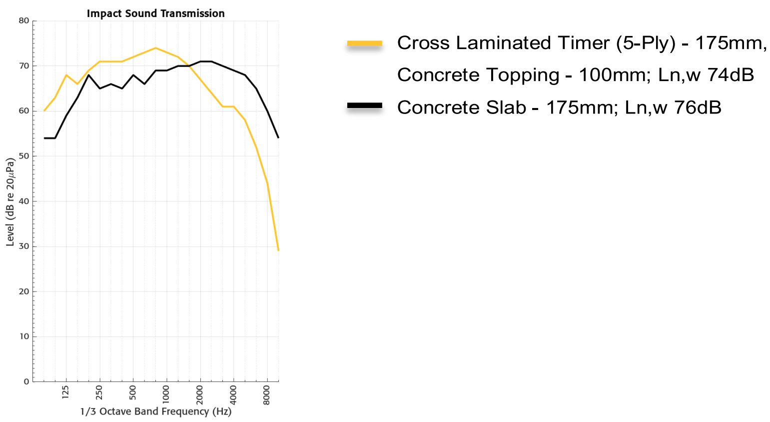

Figure 1: Impact Sound Transmission concrete slab vs CLT with concrete topping.

Comparing the impact performance of the bare CLT slab vs CLT slab with 100 mm concrete topping, the normalised impact sound transmission is reduced by 12 dB. With a great improvement in the mid-frequency range from 160 Hz to 4000 Hz, up to 15 dB at 400 Hz. A further reduction can be achieved by adding Pliteq GenieMat® FF50 between the slab and the topping. This results in an additional gain of 18 dB, see Figure 2.

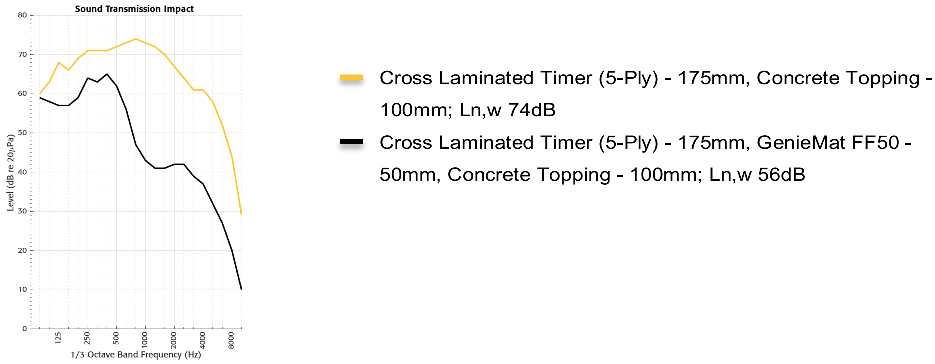

Figure 2: Impact Sound Transmission CLT with concrete topping with/without a floating floor.

The impact sound pressure level depends on the input power and the impact transmission loss of the floor structure. Further, the input power is dependent on the impedance of the floor, which is influenced by the material change between layers. Matching or miss-matching the impedance results in a higher or lower impact sound pressure level. The larger the miss-match in impedance, the greater the change in impact sound pressure level [1].
The amount of power of a wave entering and reflecting from a sub-system is determined by the impedance match of the materials [1]. A floating floor is a resonantly reactive system, that has an impact on the impact transmission loss, by enhancing or attenuating the energy input as well as the wave propagation. This is the reason why adding a floating floor system (Pliteq GenieMat® FF), especially with a low natural frequency, is beneficial for the overall performance.

3.2 Posi Joist

Another typical lightweight structure in the UK is the posi joist. Compared to the CLT slab, posi joist structures provide a lower overall mass as well as less stiffness. Nevertheless, the normalised impact sound pressure levels of the bare posi joist structure are 12 dB better than of the bare CLT slab presented in the previous section. For the purpose of this research, heavy-hard impact data were collected at an ISO-accredited third-party laboratory dropping 23.4 kg from 0.5 m onto Pliteq GenieMat® FIT70, a 70 mm locally reactive fitness flooring. As Figure 3 shows, the sound pressure level in the receiver room below is high. Further improvements to the floor build-up, namely adding Pliteq GenieMat® FF10 and Pliteq GenieBoard® on top as well as a installing a Pliteq GenieClip® RST ceiling, improve the performance from 63 Hz onwards. The effects and additional actions to enhance the performance further will be described in section 4.

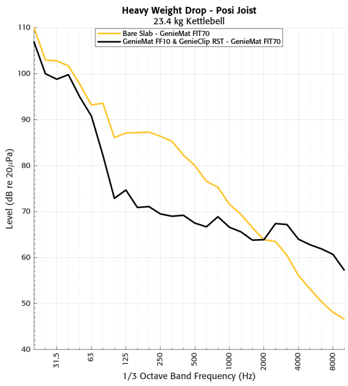

Figure 3: Noise Levels Heavy Weight Drop – Posi Joist.

3.3 Steel Frame

Steel structures are sensitive towards vibration input from high-risk gym activities and require localized isolation treatments. To increase the stiffness a 5 tonne steel 'ingot' was embedded at the Imperial Sport Complex in London [4]. No further details about the build-up are known to the author. Evaluating the structure highlights a peak at 115 Hz where the steel frame resonates due to the weight drop, see Figure 4. In this scenario, a 20 kg dumbbell has been dropped from 1 m height.

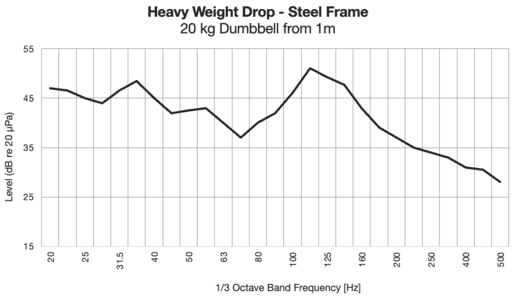

Figure 4: Noise Levels Heavy Weight Drop – Steel Frame [12].

3.4 Comparison

A further comparison of lightweight and non-lightweight structures is carried out, focusing on the spectrum shape and mass of the systems. All data were gathered at a third-party laboratory utilising a tapping machine for consistent energy input. It can be observed that the lightweight and non-lightweight structures follow different trends, see Figure 5. The spectrum shape of the lightweight structures starts at a relatively high level, increasing in the low to mid-frequency range before decreasing rapidly. Interesting to highlight is that in the high-frequency range, these systems perform better than the non-lightweight structures. However, especially in the low-frequency range the higher mass and the higher stiffness are beneficial for the impact performance. In this case, the steel frame structure has a 76 mm concrete topping and hence is considered to be a non-lightweight structure due to its mass of 220 kg/m2. This is supported by its spectrum shape following the non-lightweight structure trend up to the mid-frequency range. Nevertheless, it can be seen as a hybrid as it follows the trend of lightweight structures in the higher frequency range from 2500 Hz. Comparing the Ln,w figures against the mass, it can be stated that no correlation is observed and therefore proven that the stiffness has a bigger influence on the performance than just the mass.

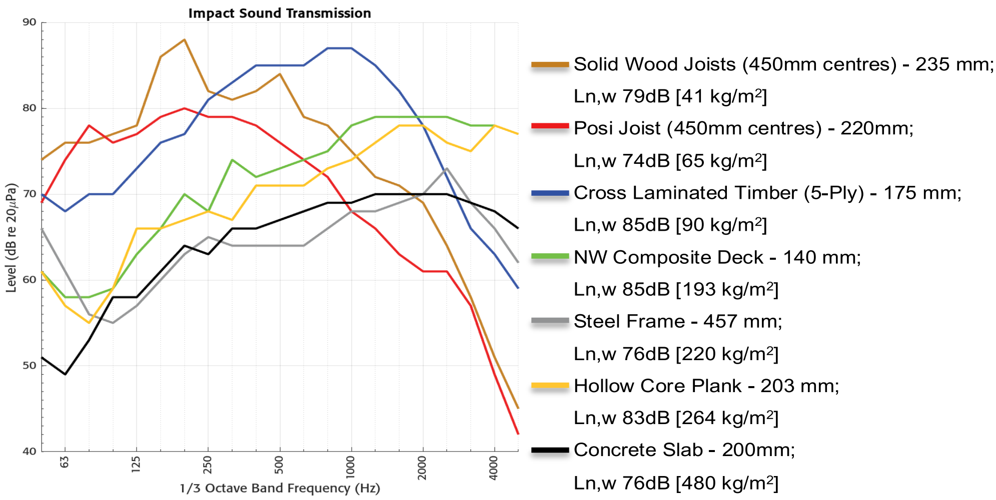

Figure 5: Noise Levels Heavy Weight Drop – Steel Frame.

4 WAYS TO IMPROVE

Studies have shown that there are various ways to improve the impact performance of lightweight structures by stiffening the floor, adding mass, implementing a floating floor, the combination of all three, and decoupling the ceiling [3]. Section 3.2 already discussed the effect of stiffening the floor by pouring a concrete topping and the effects of decoupling the concrete from the base structure with a floating floor. In this chapter, the author elaborates following possibilities to achieve an improved acoustic performance based on previous research by B. Zeitler et al. [3]:

1. Stiffening perpendicular to the joists through blocking and strapping (B&S)
2. Stiffening parallel to the joists by adding scabbed joists
3. Implementing a resilient ceiling
4. Adding mass to the ceiling by adding a second layer of plasterboard

4.1 Structure Stiffness

As described earlier, lightweight structures' acoustic performance is mainly driven by its stiffness. Particularly, joist structures such as timber joist and posi joist systems lack stiffness, which is not only important for the acoustic performance but also for the load capacity and hence its suitability for gym areas. There are various ways to increase the stiffness of the system. A common solution is halving the spacing between the joists which is beneficial in the direction parallel to the joists. Studies have shown that the greatest improvement is between 80 Hz and 200 Hz with a gain of 3 dB overall [2]. Stiffening the floor by halving the spacing is a great way to increase the impact performance, however, it must be recognised that it may cause an increased structure-borne transmission.
Furthermore, it offers little improvement in the perpendicular direction to the joists. To increase the perpendicular stiffness, solid blocking and strapping can be added. The improvement due to this measurement starts above 80 Hz and varies around a 3 dB gain until dropping again into negative values between 315 Hz and 2 kHz, before offering a benefit in the very high-frequency range [3].
Another solution is implementing scabbed joists parallel to the original joists, offering an average improvement of 2 dB over most frequency bands. More importantly, the system offers an improvement in the lower frequency range, starting at 50 Hz and a greater improvement in the mid-frequencies up to 4 dB [3]. Overall, the provided improvement is greater than for the blocking and strapping method.

4.2 Implementing Resilient Ceiling

Implementing a resilient ceiling to a lightweight structure is beneficial in the low frequencies due to the additional mass on the underside of the build-up. A second layer of plasterboard adds mass to the build-up resulting in a higher stiffness. Particularly joist structures benefit from the increase in stiffness. Depending on the properties of the resilient hanger, higher improvements can be achieved when the product has a low natural frequency. Figure 6 highlights the increase in performance by implementing a resilient hanger vs direct fix.

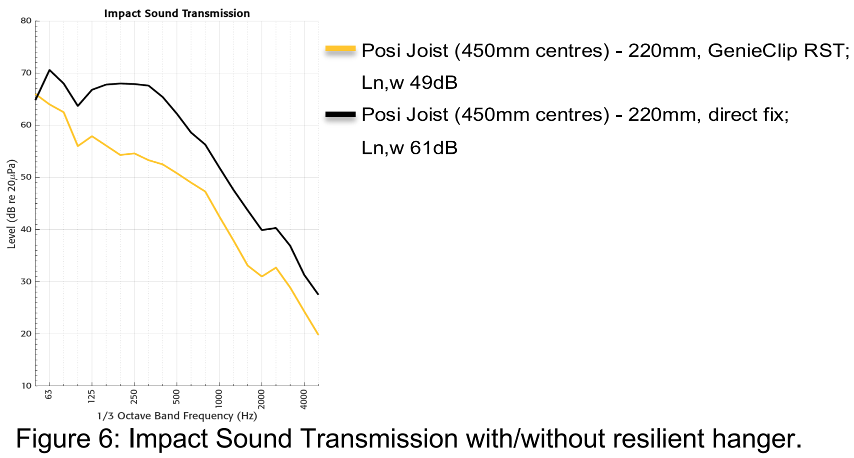

Figure 6: Impact Sound Transmission with/without resilient hanger.

It is beneficial that the used resilient hanger has a rubber component decoupling the plasterboard from the posi joist. This rubber component eliminates micro-movements caused by the heavy-hard impact to reduce noise intrusion. This micro-movement may cause noise disturbance, likely to happen when using a resilient channel when the vibration is larger than the maximum expansion of the channel (clipping). At the limit, an abrupt change in displacement causes a large increase in velocity squared, which is proportional to the radiated power [3]. This shifts some of the low-frequency energy content to the higher frequencies, limiting the improvement in that range. The non-linear effect of resilient channels can be reduced by stiffening the floor and adding mass to the ceiling. [3] Research has shown that adding a second layer of plasterboard gains about 3 dB in all frequency ranges. This is based on the mass-law and agrees well with previous studies [3].

4.3 Final Concept

It can be summarised that there are various ways to improve the low-frequency performance of lightweight structures for heavy-hard impacts. Ranked from least to most effective in the low-frequency range are [3]: resilient channels tied with blocking and strapping, scabbed joists, added plasterboard layer, implementing resilient hangers, concrete topping, and finally the concrete topping with a floating floor. Additionally, the lower the natural frequency of the floating, the greater the vibration mitigation and isolation efficiency.
It is emphasised that havening the joist centres in conjunction with scabbed joists is the most effective solution for joist structures due to the increase in stiffness. Furthermore, it adds structural integrity to the system which is an important aspect due to the anticipated high dead load of a gym.

5 1/3 OCTAVE BAND HEAVY-HARD IMPACT PREDICTION MODELLING

The author along with other co-authors have presented papers at conferences on measuring the noise and vibration in laboratories in accordance with ASTM E492, measuring the actual impact force with drop towers, creating a prediction methodology based on the actual impact force and an in-situ measured transfer function, and finally predicting the one-third octave band sound and vibration levels using data obtained with a reference drop of a 7.26 kg (16 lb) spherical mass dropped from 1 m (39.4 in) onto Pliteq's reference sheet [5, 6, 7, 8, 9, 11].

5.1 Background

In the year 2022, Golden and the author [5] showed that data from the drop tower can be used along with in-situ measurements of lower mass impacts, a steel shot of 7.26 kg, onto a pretested sheet of Pliteq GenieMat® FIT08 used as a reference floor sheet. The method is summarised in Equation 1.

$$L'_{I,F,max,DU} = L'_{I,F,max,Ref} - (L_{dt,Ref} - L_{dt,DUT}) \qquad (1)$$

Where L'I,F,max,DUT is the in-situ measured fast-time-weighted maximum vibration level of the device under test, L'I,F,max,Ref is the in-situ measured fast-time-weighted maximum vibration level of a reference sheet, Ldt,DUT is the overall impact force levels of the device under test via Pliteq's drop tower, and Ldt,Ref is the overall impact force levels of the same reference sheet via Pliteq's drop tower. This prediction method was very successful at predicting the sound and vibration that would be created by dropping 22.7 kg mass onto Pliteq GenieMat® FIT70. Note that the predictions are accurate up to approximately 200 Hz. Above that the prediction method overpredicted the resulting sound and vibration.

5.2 Case Study

In this section two case studies are presented, one shows the predicted results of a non-lightweight structure (left graph), and one shows the prediction for a lightweight structure (right graph), respectively. The non-lightweight structure is a proposed gym on the 1st floor with an existing

construction being 250 mm precast hollow core slab and metal grid suspended ceiling with mineral fibre tiles in the office below. The external facade is rendered masonry with double-glazed windows. The lightweight structure is a posi joist slab, tested in a laboratory facility.
An all-quiet background noise has been targeted when obtaining the transfer function. A positive correlation between the prediction and the in-situ measurements for the Pliteq GenieMat® FIT70 tile can be observed with better accuracy for the non-lightweight structure, as demonstrated in Figure 7. The signal-to-noise ratio when obtaining the transfer function was excellent, as can be seen from the low background noise level. Note, this background noise level does not represent normal activities occurring in the receiving room.

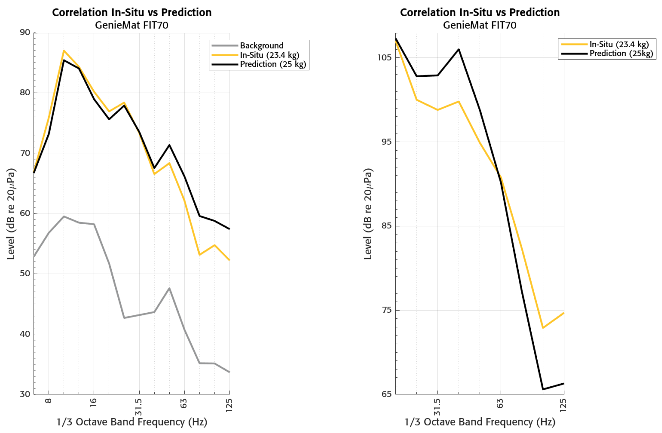

Figure 7: Case Study 1/3 Octave Band Heavy-Hard Impact Prediction Modelling.

6 DISCUSSION

It can be summarised that there are various ways to improve the low-frequency performance of lightweight structures for heavy-hard weight impacts. Ranked from least to most effective in the low-frequency range are [3]: resilient channels tied with blocking and strapping, scabbed joists, added plasterboard layer, implementing resilient hangers, concrete topping, and finally the concrete topping with a floating floor.
It is recommended to limit the activities within the gym of lightweight structures to SRE and AN to reduce the risk of complaints. Nevertheless, if a free weight area is unavoidable, robust measurements such as stiffening the structure and implementing a resilient ceiling are needed to mitigate the vibration input sufficiently. The lower the natural frequency of the sound mitigation systems, the better the overall performance.
Finally, it can be said that the 1/3 octave band heavy-hard impact prediction modelling also works for lightweight structures, however, it does show a lower accuracy than for the non-lightweight structure.

7 REFERENCES

1. B. Zeitler, T. R. T. Nightingale, S. Schoenwald. Effect of floor treatments on direct impact sound pressure level. In Proceedings of EURONOISE 2009, pages 1-9. Edinburgh, Scotland, October 26-28, 2009.
2. B. Zeitler, T. Nightingale, F. King. Methods to control low frequency impact noise in wood frame construction. In Proceedings of EURONOISE 08 Paris. Paris, France, June 29 – July 04, 2008.
3. B. Zeitler, T. R. T. Nightingale, S. Schoenwald. Parametric study of sound transmission through lightweight floors. In Proceedings of InterNoise 2010. Lisbon, Portugal, June 13 – 16, 2010.
4. H. Hartman: The Aerobics Studio Had To Be Isolated From The Flats. The Architects Journal, p. 43-45, 2006.
5. M. Golden, T. Patzke. Improvements to the 1/3 octave band heavy-hard impact prediction method. In Proceedings of InterNoise 2022. August 21 – 24, Glasgow, Scotland. 2022.
6. M. Golden. Drop Tower Testing—The next step in heavy weight impact testing. The Journal of the Acoustical Society of America 143, p. 1726, 2018.
7. M. Golden, P. Gartenburg. Prediction of Heavy Weight Drops on Resilient Sports Floors in Existing Buildings. In Proceedings of INTER-NOISE 2018. Chicago, IL, US, August 26 – 28, 2018.
8. M. Golden, F. Musafere. Continuing Prediction of Heavy/Hard Impacts on Resilient Sports Floors in Existing Buildings. In Proceedings of International Commission for Acoustics 2019. Aachen, Germany, September 9 – 13, 2019.
9. M. Golden, J. LoVerde, R. Silva, W. Dong, S. Rawlings. Prediction of one-third octave band sound and vibration levels from heavy-hard impacts. In Proceedings of INTER-NOISE 2021, Washington, DC, US, August 1 – 5, 2021.
10. P. Rogers, J. Bligh, D. Chapman, A. Fox, W. Highton, C. Hurst, M. McNulty, A. Robinson, J. Stokes, M. Sugden, S. Woodhams, ProPG : Gym Acoustics Guidance (GAG), March, 2023.
11. P. Gartenburg, M. Golden. Comparing force impulses for various fitness flooring assemblies. In Proceedings of NOISE-CON 2017. Grand Rapids, MI US, June 12 – 14, 2017.
12. S. Woodhams, P. Rogers, C. Matheson, S. Rubio. Standardising structure-borne noise assessments with heavy impacts for potential gyms in lightweight mixed use structures. In Proceedings of EURONOISE 2018. Crete, Greece, May 27 – 31, 2018.**]**