SOUND ABSORPTION OF SLAT STRUCTURES FOR PRACTICAL APPLICATIONS

J Riionheimo   Aalto University, Akukon Ltd. Helsinki, Finland
N Näveri   Akukon Ltd. Helsinki, Finland
T Lokki   Aalto University, Espoo, Finland
H Möller   Akukon Ltd. Helsinki, Finland

1   INTRODUCTION

This paper presents a study of sound absorption of slat structures. The paper stems from a need for a tool to predict the absorption coefficient for slat structures used in spaces for critical listening. For an acoustic designer, the accurate knowledge of absorption coefficient is vital in successful planning and predicting the behaviour of sound in, say a sound studio or instrument rehearsal room.

Theoretical models can be used to predict the absorption of slat structures, but in our experience, only with regular structures and moderate thicknesses. Even in these cases, the results leave much room for experience-based approximation. For thicker absorbers and irregular slat sequences measurements are needed. However, not many published measurement results can be found.

A study, with measurements of sound absorption in a reverberation room was concluded, to provide acoustic designers with more reliable and comprehensive understanding about the behaviour of slat absorbers. Four different slat sequences were used in the measurements, with complementary additions to provide different slot percentages. Each sequence was measured with multiple absorber thicknesses, varying from 600 mm to 100 mm. The results are presented at one-third-octave bands from 63 Hz to 8000 Hz. The room modes were not addressed in the measurements, and therefore it seems, that the results are only applicable from 200 Hz upwards.

2   PREVIOUS RESEARCH

Theoretical models, such as proposed by J.F.Allard[1] and equations for design purposes proposed by K.U.Ingård[2] can be used to predict the absorption of Helmholtz-resonators with porous absorbers. As T.J. Cox and P. D'Antonio point out, the transfer matrix approach to modelling sound propagation is also a very powerful technique, which could be applied to porous absorption with and without perforated facings[3]. Some online calculators as well as commercial software are also available for absorption calculation. They are usable with perforated boards and regular slat structures and moderate thicknesses. However, according to our experience, they do not predict reliably the behaviour of irregular slat structures or more extreme material thicknesses. With these cases, which are also of interest in this study, the measurements are needed.

Published measurement results are scarce and not particularly systematic. Some published slat absorber measurement results can be found in Finnish, e.g., from Rakennustekniikan käsikirja[4] and in Norwegian from Romakustisk prosjektering[5] but these are both from the 1970's. Some individual measurements can also be found in textbooks and in numerous studies, but a comprehensive data library cannot be found. One can assume that many acoustical consultancies have created their own data bases, but none of these seem to be published.

Some common statements exist for perforated panels, such as that if the open area of a perforated panel is greater than circa 20 %, the absorption of the structure is entirely controlled by the properties

of the porous liner[6]. This does not apply for slat absorbers, and unfortunately no rule of thumb for them can be found in the literature.

3   MEASUREMENTS

The sound absorption coefficient measurements of the slat structures were performed in the acoustic laboratory of Aalto University, in reverberation room, according to the ISO-354 standard.

3.1   Standard ISO 354

The standard ISO 354 specifies a method of measuring the sound absorption coefficient of acoustical material in a reverberation room. The standard does not address the modal behaviour of sound in the low frequencies, and the limitations of this can clearly be seen in the low frequency results. D'Antonio and Rife[7] have proposed a modified method for frequencies where the modal density is very low, but it was not used in this study.

The relative humidity in the room varied from 37 % to 44,6 % and temperature was between 21,4-21,9 °C during the measurements, while the minimum defined in the standard is 30 % for humidity and 15 °C for the temperature.

The equivalent sound absorption area of the room exceeds the requirement of the standard in especially in 125 Hz (+39 %) and 400 Hz (+45 %) as can be seen in *figure 1*. The reason could be the modal behaviour of the room in 125 Hz band and at 400 Hz band the narrow slots between structural wall concrete elements.
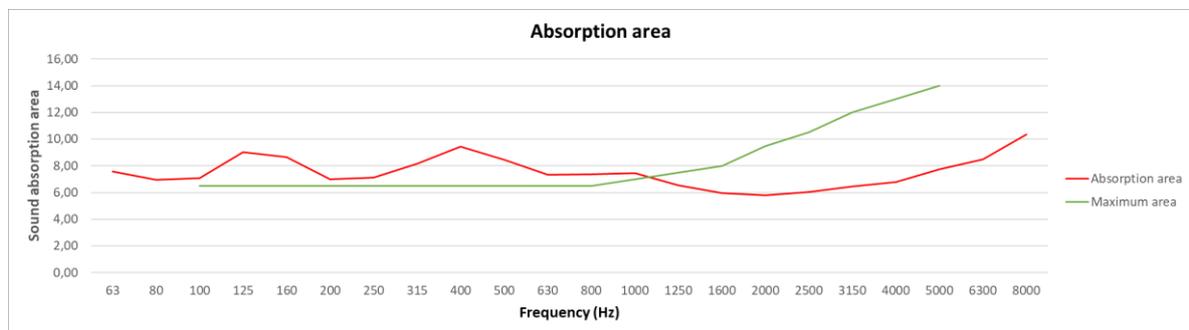

Figure 1 The equivalent sound absorption area of the used reverberation room.

3.2   Measurement setup

The absorption coefficient measurements were performed in a reverberation room. The volume and properties of the reverberation room used were according to Standard ISO 354. The humidity as well as the temperature in the room were recorded for each measurement and used in calculating the absorption coefficient according to the standard. To ascertain a diffuse sound field, concave diffusers were distributed in the room. *Figure 2* gives a view of the reverberation room and the diffusers as well as an overall view of the measurement set up. The detailed information about the reverberation room as well as the equipment used is shown in *table 1*.
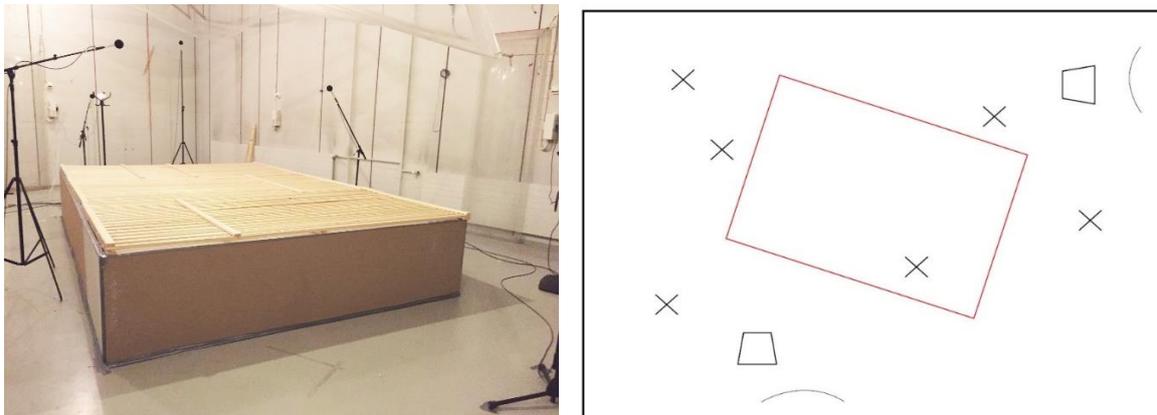
Figure 2. On the left, an image from the reverberation room showing the measurement setup. On the right, the measurement setup. Microphone positions are marked with x and loudspeaker positions with trapezoid, whose wider side shows the facing direction of the loudspeaker. Curved lines present the convex surfaces used to diffuse the sound from loudspeakers. The sample area is shown with red line.

The impulse responses were recorded with logarithmic sine sweeps that were reproduced with two active loudspeakers directed towards diffusers on the walls, to simulate omnidirectional sound source.

The recordings were captured using six omnidirectional GRAS microphones, GRAS pre-amplifier and a laptop computer with Roland Octa-capture soundcard. The recordings were processed, and reverberation times were calculated with Matlab script in accordance with ISO-3382 standard.

The measured sample was erected away from the room surfaces and non-parallel to any but the floor. The sample was set in a rectangular box built out of two gypsum board layers and supporting structures from timber.

The absorption data was calculated in accordance with the Standard ISO 354, but the volume of the sample "bed" was diminished from the room volume when calculating the equivalent sound absorption area of the reverberation room containing a test specimen. This was done due to the significant change in room volume especially with the highest bed (-3,5%). Similar method was used by A.A.G. Torres, in her diploma work.[8]

Table 1. The measurement setup details

MEASUREMENT SETUP		
Reverberation room	Volume Length Width Hight	193,6 m^3 8,7 m 6,18 m 3,6 m
Sample	Area Length Width	10,1 m^2 3,9 m 2,6 m
Side covers and supporting structure	Material Surface mass	1 x Normal gypsum board + 1 x Extra hard gypsum board 18,3 kg/m^2
Loudspeakers	Amount Type	2 Genelec 8260A
Microphones	Amount Type	6 GRAS 46BF
Pre-amplifier	Type	GRAS 12AG

3.3 Measured structures

Four different slat sequences were used in the measurements. The sequences are presented in *figures 3-5*. Two of these sequences were supplemented with extra slats, that were set on top of the

fixed sequences to provide more coverage and smaller open area, shown in figure 6. This rises the number of slat sequences to eight all together.
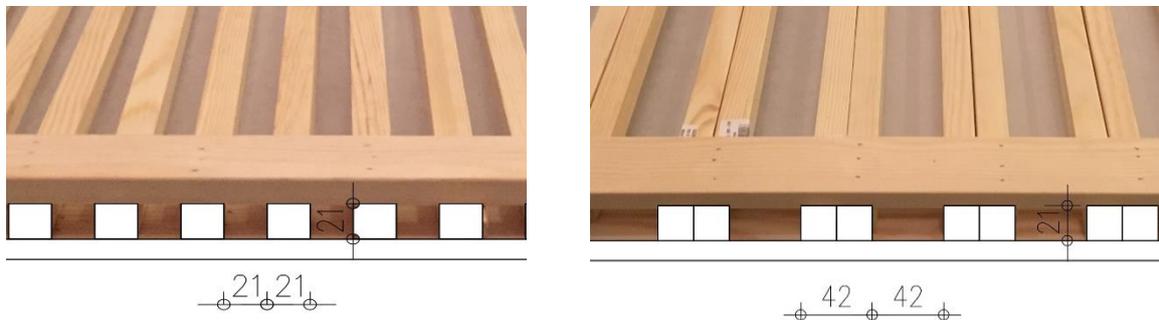

Figure 3. Slat sequence with uniform slats and slots with 50 % open area. On the left 21 mm slats and slots, on the right 42 mm slats and slots.
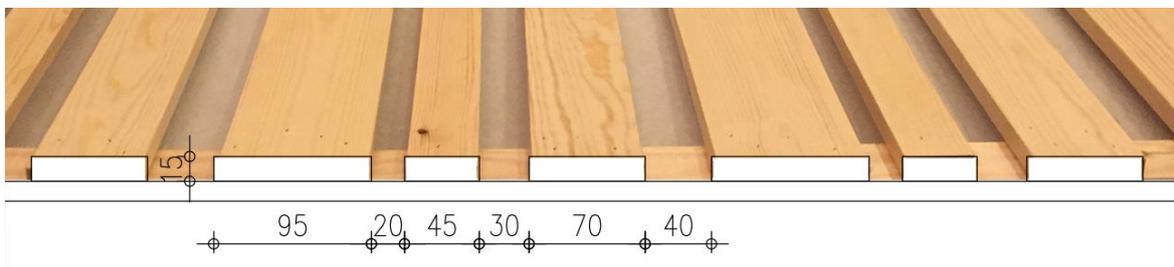

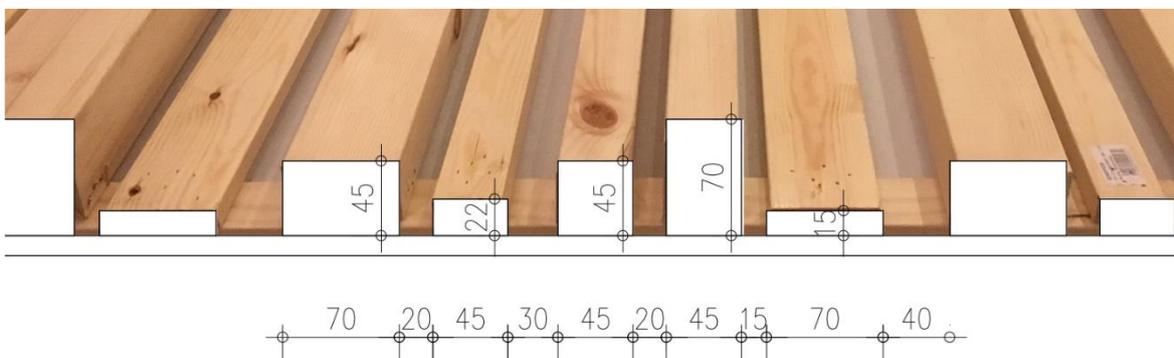*Figure 4. Slat sequence with 15mm thick slats and 30 % open area.*

Figure 5. Slat sequence with diffusive slats and 30 % open area.

Figure 6. Slat sequence with diffusive slats and 23 % open area, with extra slats for higher coverage.

Each sequence was measured with 4 different absorber and air gap thicknesses. For each thickness, also the structure without the slats was measured. Added to this, two sequences were measured with additional absorber thickness (50 mm). The different construction thicknesses are shown in *figure 7.*
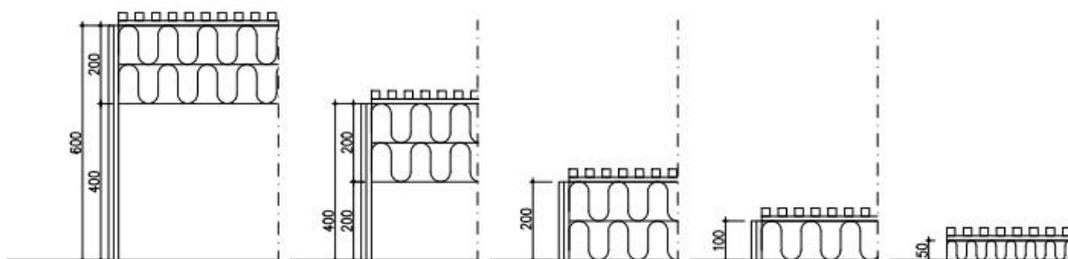

Figure 7. *Absorber thicknesses measured with the slat sequences. The absorbent layer consisted of 100 mm polyester fiber wool (Ewona, 20 kg/m2) and 100 mm mineral wool (30 kg/m2), polyester being on the top. 50 mm measurement was performed with mineral wool.*

4   RESULTS AND DISCUSSION

The results of the measurements are presented in *figures 8-17*. In *figure 8* the absorption of only the absorbent is shown. In *figures 9-14* the effect of all slat structures in front of varying absorbent depth is presented whereas in *figures 15-17* the effect of individual slat structure in front of different absorbent depth is presented. Finally, *figure 18* presents the averaged absorption of different slat sequences.

4.1   The absorbent only

According to the well-known theory, the absorption of the porous absorbent depends on the thickness of the material. The thicker the material, the better the absorption in the low frequencies while the best absorption can be obtained when the material thickness is equal or more than one quarter of the wave length[3]. This phenomenon can be seen clearly in *figure 7* when the absorbent thickness is 50-200 mm. However, an unexpected absorption drop is noticed in 100-200 Hz bands when the thickness of absorbent is increased to 400-600 mm with an air gap. The reason could be the before mentioned problems in the reverberation room method: the lack of diffusion and modal behavior of the room in low frequencies. In addition, the equivalent sound absorption area of the reverberation room exceeds the standard maximum especially in 125 Hz as can be seen in *figure* 1.

However, the absorption is increased when the "bed" structure walls are cut from 600 mm to 200 mm. This indicates that the sound is getting trapped between the high walls of the bed and constructional walls of the room. The surfaces were not exactly parallel (see *figure* 2), and the gap between the "bed" and walls of the room vary between 1,5 – 2,6 m that coincides with 125-200 Hz. Another explanation could be a room mode, which is excited at 110 Hz. If the mode was horizontal, for instance fourth widthwise mode, the absorbent placed on the floor facing up longitudinally to the mode would have only minor effect to the mode. This could be supported by *figure 9* where a low frequency waterfall graph from one microphone is presented. The modal behavior of the empty room is shown in blue and the room with 600 mm absorbent is shown in yellow. As can be seen the 110 Hz mode is hardly attenuated.
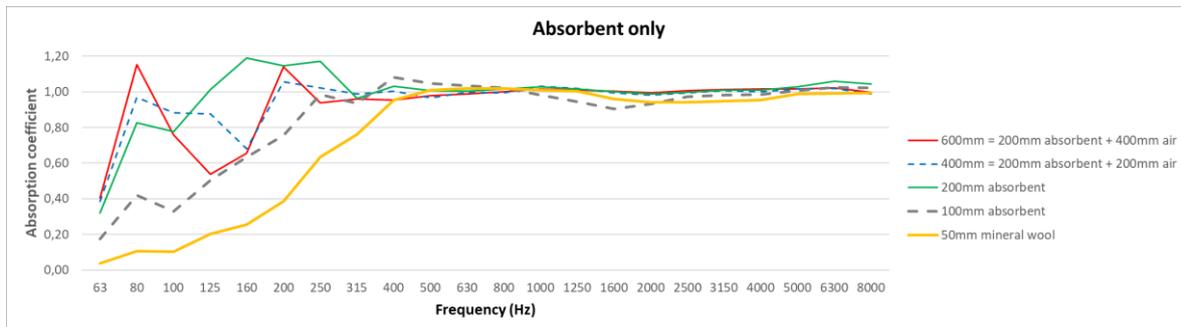
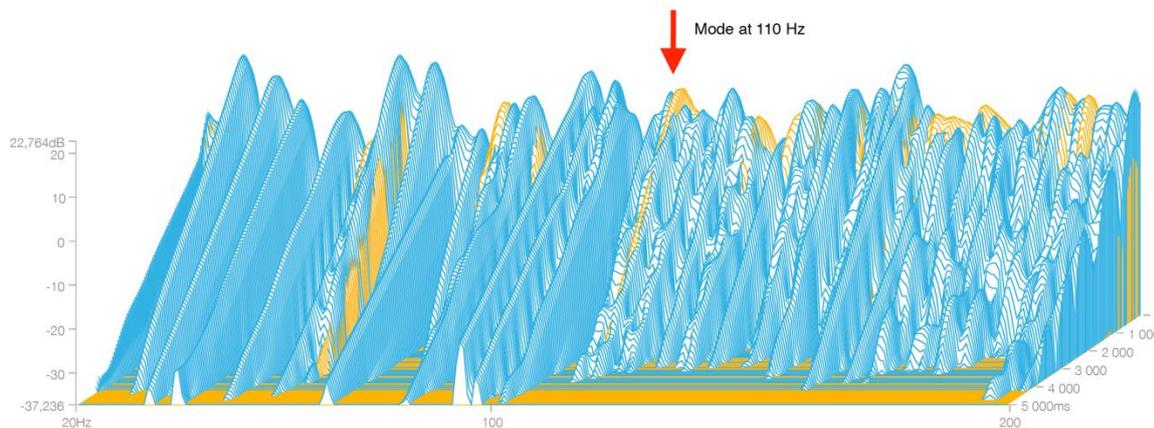*Figure 8. The absorption of only the absorbent with different material thicknesses.*

Figure 9. The FFT waterfall of the reverberation room between 20-200 Hz from one microphone position. The empty room is shown in blue and the room with 600 mm absorbent on the floor is shown in yellow.

4.2   The slat structures

As can be seen in *figures 10-12,* the slat structure does not have any major effect on the absorption below 200 Hz when the thickness of the structure is 600-200 mm. When the thickness is 100 mm (*figure 13*), there is a mild improvement in the absorption at 100-250 Hertz, but the tendency is that the absorption of the whole structure is defined only by the absorbent below 500 Hz with the 50 mm absorbent (*figure 14*). Above these frequencies the absorption depends on the slat structure.
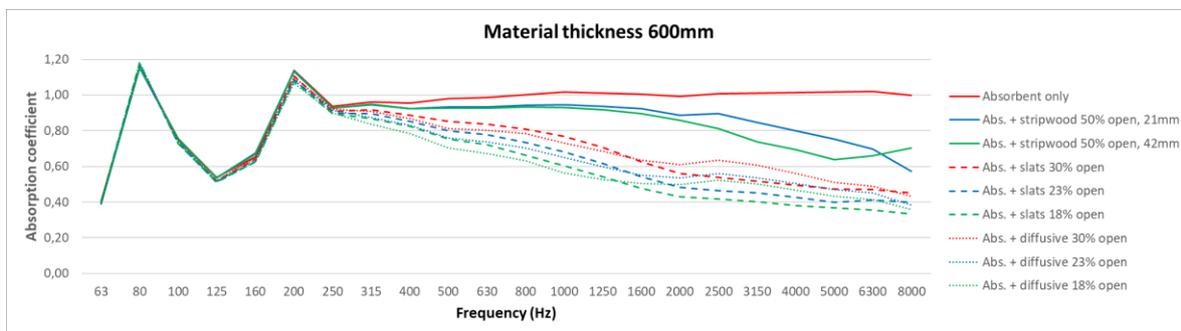

Figure 10. The absorption of absorbent only and different slat structures with 600 mm material thickness.
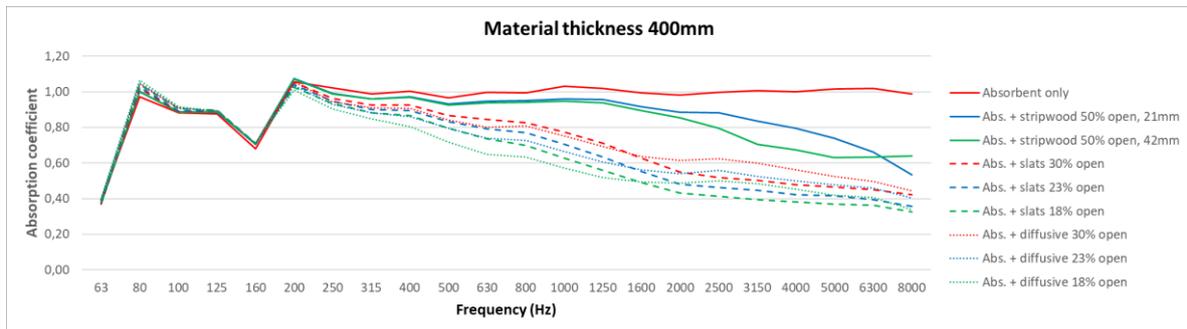
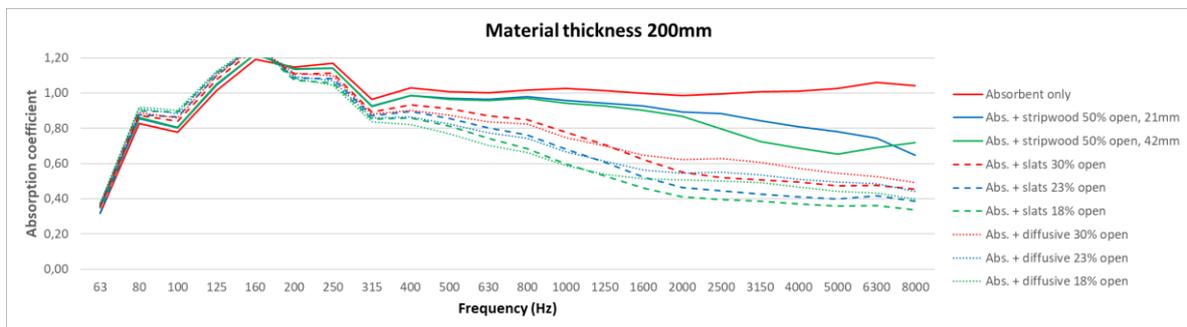*Figure 11. The absorption of absorbent only and different slat structures with 400 mm material thickness.*

Figure 12. The absorption of absorbent only and different slat structures with 200 mm material thickness.
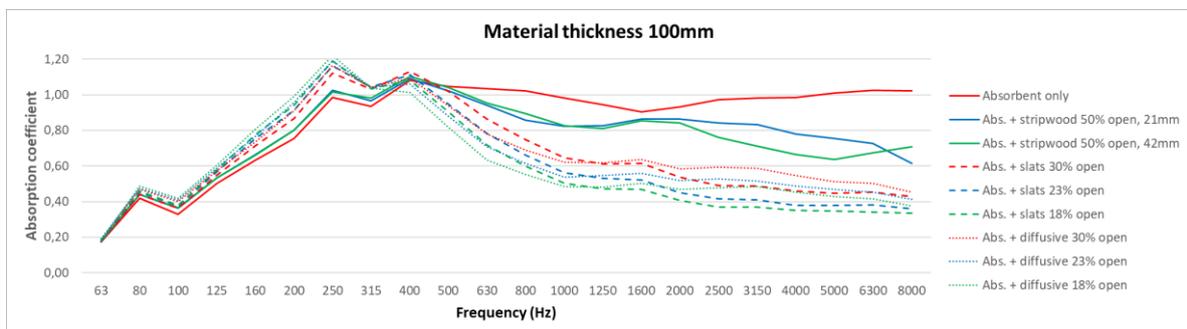

Figure 13. The absorption of absorbent only and different slat structures with 100 mm material thickness.
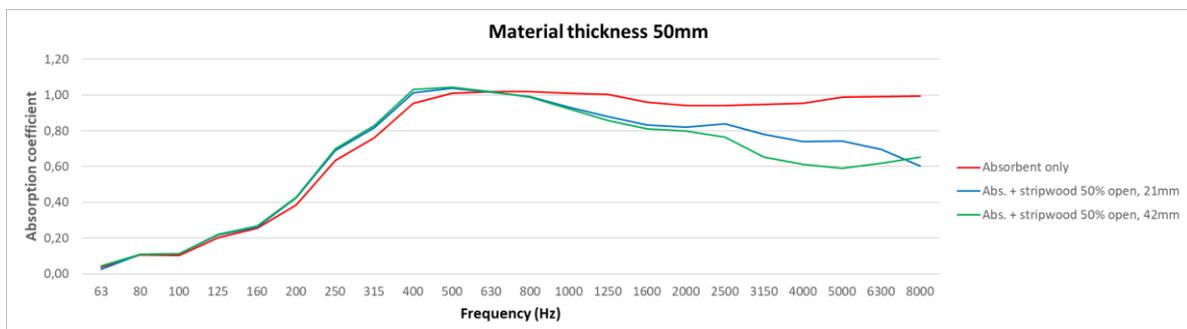

Figure 14. The absorption of absorbent only and different slat structures with 50 mm material thickness.

4.3   Uniform slats with 50 % open area

The uniform slats with 50 % open area was measured with two versions where the width of the slat and the slots were uniform. The first version had 21x21 mm slats with 21 mm slots and the second version had 42x21 mm slats with 42 mm slots. The results of the two versions presented in *figure 15* are similar below 2,5 kHz, but the narrower version has slightly better absorption between 2,5-6,3 kHz, whereas the wider version absorbs better at 8 kHz. In the wider version a dip can be seen in the

absorption at 4000 Hz where the half wavelength coincides with the width of the 42 mm slat. Similarly, the width of the narrower slat 21 mm coincides with the half wavelength of the 8000 Hz where the absorption drops in the narrower version.

The results suggest that even though both versions have 50% open area, the size of the closed area is important. The larger the closed area is, the more it reflects high frequencies. Here, with 42mm slats, the absorption drops above 2 kHz, corresponding the quarter wave length at 2 kHz.
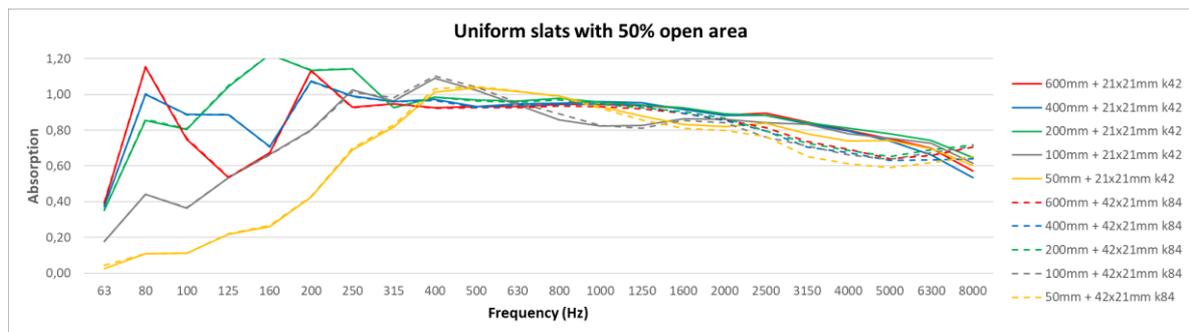

Figure 15. The absorption of uniform slats with 50 % open area.

4.4 15 mm thick variable slats

Slat sequence with 15mm thick slats was measured with three open area percentage. 30 %, 23 % and 18 %. As can be seen in *figure 16,* the absorption drops as the open area diminishes, however, the change is very small. It can be also noticed, that the absorption of the structure is somewhat independent of the thickness of the absorbent above 250 Hz, while the absorption below that frequency is defined only by the absorbent.

Figure 16. The absorption of 15 mm variable slats with 30 %, 23 % and 18 % open area.

4.5 Diffusive slats

Diffusive slats were measured with three open area percentage: 30 %, 23 % and 18 %. Similar dropping of absorption as with 15 mm slats can be seen in *figure 17* as the open area diminishes. Again, the change is not significant. The absorption of the structure is somewhat independent of the thickness of the absorbent above 250 Hz while the absorption below that frequency is defined only by the absorbent.
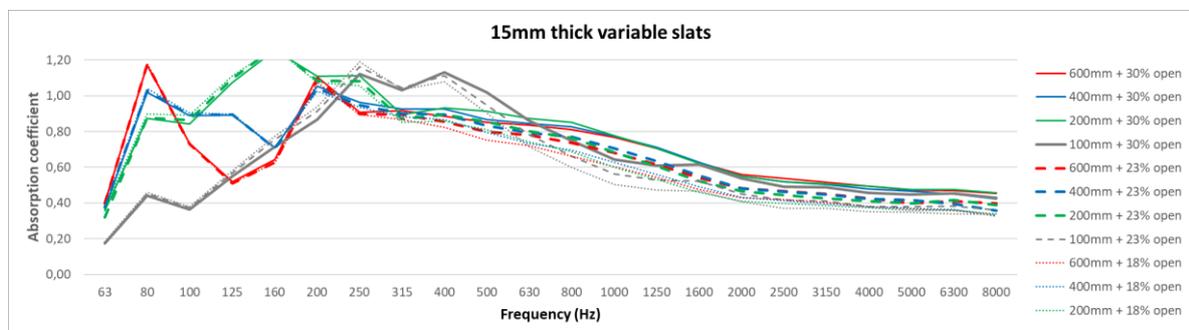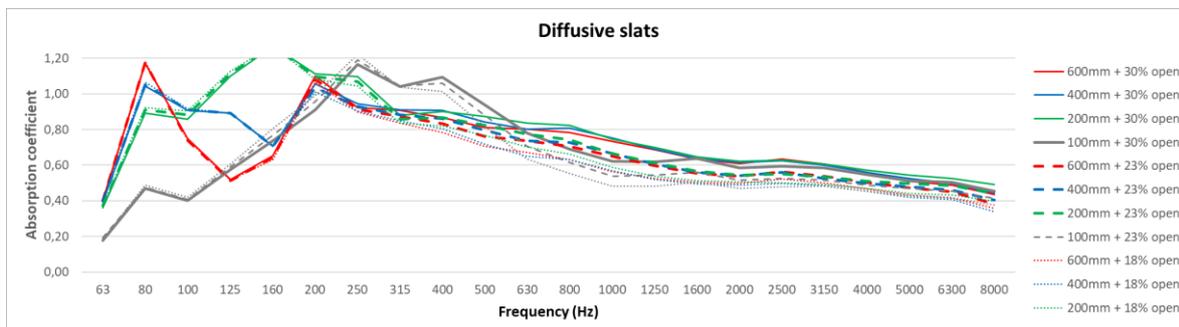
Figure 17. The absorption of diffusive slats with 30 %, 23 % and 18 % opening area.

4.6   Discussion

The absorption of the different structures is defined only by the thickness of the absorbent below 250 Hz. Above that frequency, the absorption is defined by the slat structure while the thickness has only minor effect.

Taking this into account, the results are averaged between 400-8000 Hz across all thicknesses and presented in *figure 18*. As can be seen the absorption decreases as the open area percentage decreases. It could also be seen that the absorption is somewhat higher with similar open area percentage when the slat structure is diffusive, although the openings are not visibly as open to the oblique angle sound waves as with 15 mm slats, with even thickness.
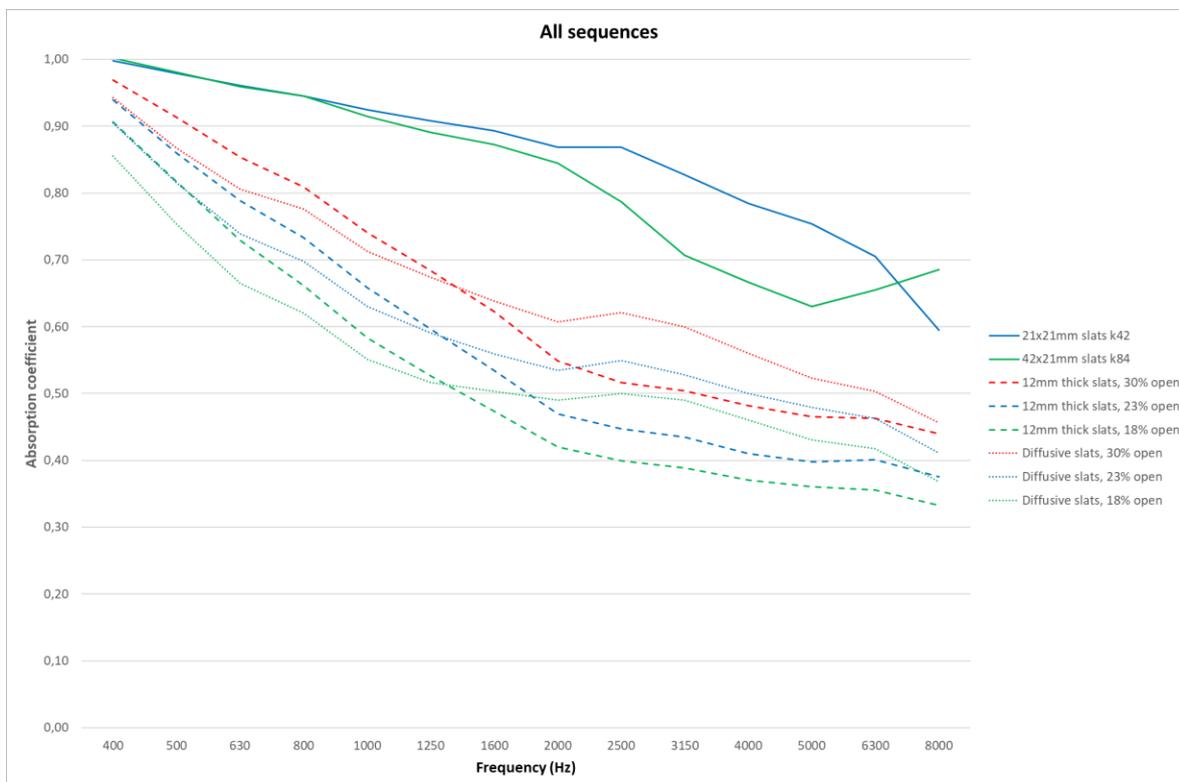

Figure 18. The absorption of all sequences between 400-8000 Hertz, averaged across all thicknesses.

5   CONCLUSIONS AND FUTURE RESEARCH

The motivation for this study has been the need for a tool to estimate the absorption coefficient for different kinds of slat structures, for everyday design purposes. The models available today only provide predictions for slat absorbers with uniform structure and do not work well when the structure is thicker than 200 mm. The result of this study can be concluded as follows:

- Slat structures with 18 - 50 % open area have negligible effect to the absorption below 250 Hz. In low frequencies the absorption is defined only by the absorbent.
- in frequency bands above 250 Hz, the absorption increases as the open area increases.
- The absorption has a minimum at the frequency where the slat width coincides with the half wavelength, but the absorption diminishes already at the quarter wavelength. The effect is mild but can cause problems, when uniform width slats are used.
- If the slats are varying in height and thereby somewhat diffusive, the absorption is higher than with uniform height slats.

The next steps towards the design tool are complementing these measurements with measurements of corresponding structures in impedance tube, and expanding the range with different slat sequences. The use of impedance tube would allow measuring a wider range of slat sequences in a much shorter time and with smaller effort. With these results it would hopefully be possible to construct a tool to predict absorption also for those structures that have not been measured. The feasibility of the tool can be tested with a design project, where the slat absorbers would be chosen with the tool, implemented in the design and modelled in this phase, and measured in the actual room when the project is finished.

The low end of the spectrum is also of interest. In the future, it would be beneficial to measure at least one of the sequences used in this study with the previously mentioned modified method proposed by D'Antonio and Rife[7], to get an understanding of the absorptive qualities of the thicker structures in low frequencies.

Even more critical question for the development of this slat absorber prediction tool is how the results from reverberation room measurements can be translated into prediction modelling. The problem lies in that the measurement of absorption coefficient with the standard ISO 354 produces absorption coefficient values over 1. The values over 1 indicate that the result in not directly applicable to modelling or predictions. However, it does not tell us, weather the problem lies only with the results for certain frequency ranges or in the whole spectrum. For a slat absorber prediction tool to perform reliably, an answer to this question should be found. Since even a very small inaccuracy in the absorptive qualities of a material used in calculations or modelling can produce a significant error in the resulting reverberation time, it is of utmost importance, that this question is tackled.

6   REFERENCES

1. J.F.Allard, N. Atalla; Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials 2nd ed, John Wiley & Sons, Ltd, United Kingdom. (2009).
2. U. Ingård, R. H. Bolt; Absorption characteristics of acoustic material with perforated facings, The Journal of the Acoustical Society of America 23.5 (1951): 533-540.
3. T.J. Cox, P. D'Antonio; Acoustic Absorbers and Diffusers, Theory, design and application, 2nd ed Taylor & Francis Group. (2009).
4. E. Koiso-Kanttila, P, Palmqvist; Rakennustekniikan käsikirja: [5], Pääjakso 4 $b talonrakennustekniikka : 1. osa. Helsinki: Tammi. (1974).
5. S. Strøm; Romakustisk prosjektering. Norges byggforsknings institut, Norway. (1979)
6. D.A. Bies, C. Hansen, C. Howard; Engineering noise control, 4th edition, CRC press. (2009).
7. P. D'Antonio, B. Rife; The state of the art in the measurement of acoustical coefficients, Proceedings of Meetings on Acoustics 161ASA. Vol. 12. No. 1. ASA. (2011).
8. A. A. G. Torres: Effects of specimen mounting and diffuser configurations of the sound absorption measurements in reverberation chambers. (2015).