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Structural reverberation time measurements on WOODSOL prototype

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ABSTRACT

The WOODSOL research project aims at developing urban timber buildings based on moment resisting frames. One of the key aspects when dealing with the sound insulation in the building system is the flanking sound transmission across the floor elements and through the special connecting elements of the floor to the columns. We build a system prototype to be able to investigate experimentally the vibroacoustic behavior of the floor elements and the vibration transmission to the columns considering in particular impact excitation. In this paper, we focus on the structural reverberation time, which is a key parameter to determine calculation quantities such as e.g. K_{ij} required by the ISO12354. The K_{ij}-index is necessary to estimate flanking sound transmission and therefore a key input to SEA based calculation models. We present the measurement setup used at the Woodsol prototype. We present the measurement procedure designed following the ISO 10848-1 and discuss the measurement program, excitation type and sensor placement. We present the challenges we encountered and discuss the obtained result with particular focus on the comparison of impact hammer excitation and shaker excitation with swept sine.

Keywords: timber, reverberation, measurements

1. INTRODUCTION

As part of the research work within the WOODSOL project, we are investigating experimentally the vibroacoustic behavior of the WOODSOL floor element and the special moment resisting connection between the floor elements and the load bearing columns.

The experimental activities shall deliver the impact noise level for the floor element and an evaluation of the flanking transmission both in vertical and horizontal direction. Both aspects are to be studied considering the principle of the ISO12354 (1). Herein, a key parameter that needs to be investigated is the structural reverberation time. The reference standard for the structural reverberation time is the ISO10848-1 (2). Although the standard refers for the signal processing to the ISO3382 (3), the measurement of the structural reverberation time is more challenging than the room reverberation time. Moreover the standard was mainly developed looking at heavy homogeneous monolithic walls such as masonry or concrete walls (2, 4) and there have been discussions regarding the challenges related to applying the standard to lightweight walls (5) and to inhomogeneous objects (6, 7).

In our specific case, we are dealing with a strongly inhomogeneous lightweight structure, with low damping at low frequencies and highly damped above approximately 60 Hz (8). This calls for a critical approach to the measurement setup and the measurement procedure. In the following we describe our approach, the challenges we encountered and draft some preliminary conclusions.

2. TEST OBJECT

The measurements were performed on the WOODSOL prototype, shown in Figure 1. The prototype consists of two floor elements, mounted on six columns. At each corner of the floor element, one

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WOODSOL connector is used to establish a moment resisting connection between the floor itself and the column. The current version of the connector is shown in Figure 3 along with a schematic of the principle. It is based on metal brackets connected by friction bolts. The brackets are mounted to the timber by means of threaded metal rods (9).

The material for the columns is glulam and they have dimensions of 400 mm x 450 mm x 5200 mm. Their size is given by the structural and fire safety requirement for an eight to ten story building, which is the target building of the WOODSOL project. The floor is mounted with the bottom flange at 2 m above the floor of the lab.

The floor element has dimensions of 4.7 m x 2.4 m x 0.5 m and is of type hollow box. The cross section is shown in Figure 2 and is designed for a 9 m to 10 m span. The top and bottom plates are KERTO-Q plates with thickness of 43 mm and 61 mm respectively. The thickness of the bottom flange was designed to fulfill fire safety requirements when the floor is installed without additional ceiling. The outermost stringers are glulam GL30c, while the inner ones are glulam GL28c (10). The total weight of the floor element is 2.6 tons including the filling of gravel.

Figure 1 – Woodsol prototype installed at Charlottenlund Videregående Skole, Trondheim (Norway)

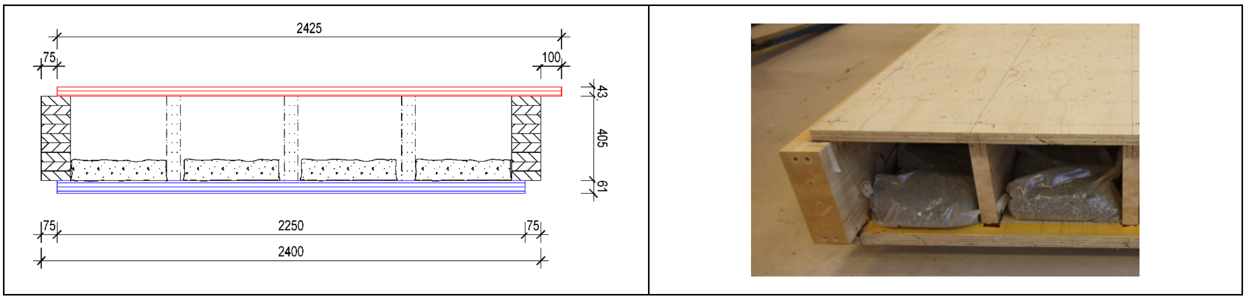

Figure 2 – Floor element cross section (left) and picture showing the gravel bags positioned in the element cavity (right).

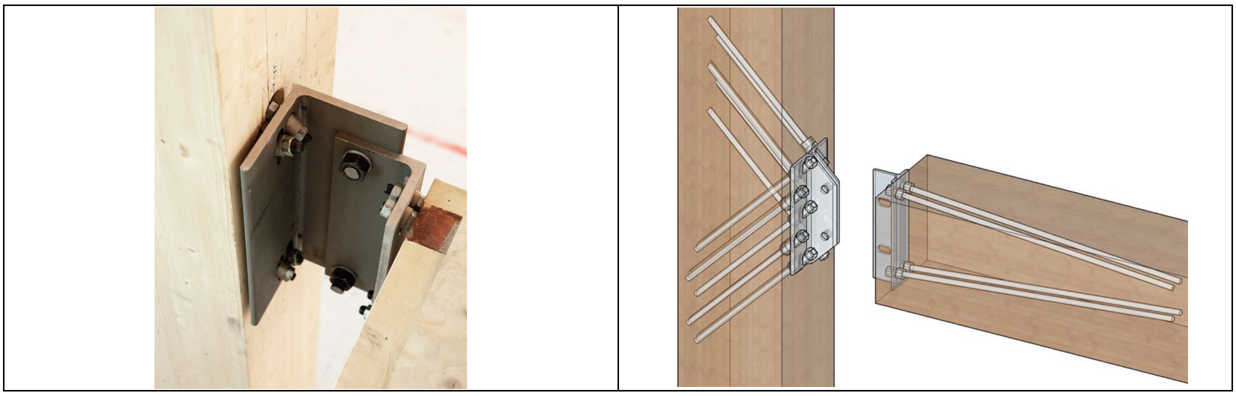

Figure 3 – Picture of the connector installed between the floor element and the column (left) and principle of the connector showing the threaded rods (right).

3. MEASUREMENT SETUP AND ANALYSIS PROCEDURE

3.1 General

The ISO10848 suggests as preferred method to measure the structural reverberation time the one that uses an electrodynamic shaker with an MLS or swept sine signal (2). This method seems to be less prone to excite nonlinearities (11-13), but is more complicated and time consuming compared to the very straightforward excitation with an impact hammer. The ISO10848 also does not exclude the impact excitation provided that the linearity of the system is checked. Other works on timber lightweight structure suggest that impact excitation might provide linear excitation on these type of structures (7). Moreover Hopkins in (14) suggest that it might be more appropriate to use hammer excitation when focusing on impact noise level, since this is usually measured using the ISO standard tapping machine. Considering these different arguments we decided to use both impact and shaker excitation in our investigations. In the measurement program we included preliminary measurements of transfer functions to compare impact with shaker excitation as suggested in the ISO10848 and observe their dependency on the amplitude of the excitation. During these preliminary measurements, we also verified the effect of the sweep length. The test setup for these preliminary measurements is shown in Figure 4.

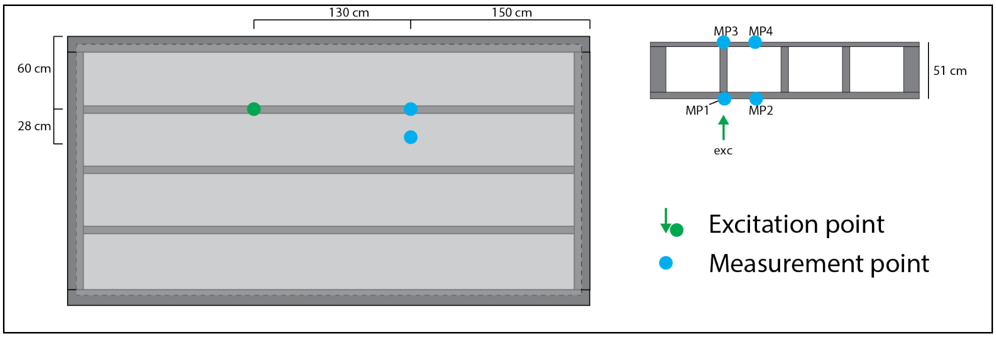

Figure 4 - Test setup for the preliminary measurements

3.2 Measurement program

The measurement program included: a) preliminary measurements: shaker excitation with varying amplitude, shaker excitation with varying sweep length, impact excitation with varying amplitude; b) measurements with impact excitation both on top and bottom of the element with sensors placed on both sides; c) measurements with shaker excitation both on top and bottom of the element with sensors placed on both sides.

3.3 Excitation

We used a B&K impact hammer type 8208 with medium tip (green) for the impact excitation.

The shaker used was a B&K 4808 with approx. 20 kg additional mass. We mounted the shaker on a separate structure by means of metal springs and connected to the excitation point by means of a stinger. Between the stinger and the excitation point we inserted an impedance head to measure force and vibration. The impedance head was fixed to a timber screw inserted in the Kerto plate. The driving signal was a linear sweep from 20 Hz to 1250 Hz. Three different sweep lengths were tested during the preliminary measurements: 12.5 s, 25 s, and 50 s and no differences were observed in the obtained transfer functions. For all further measurements the sweep length was set to 25 s.

Four excitation positions were used on the bottom flange both with shaker and impact excitation. Three excitation position were also placed on the top flange, but used only for the impact excitation.

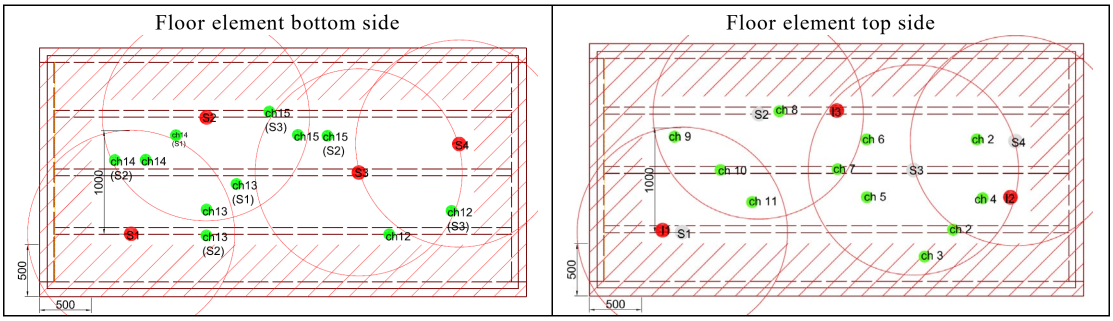

Figure 5 - Measurement and excitation positions on the floor element: S1..S4 shaker and impact positions (only bottom side); I1… I3 impact positions (only top side); ch2… ch15 accelerometer positions; the red hatch and circles mark the ISO requirement on minimum distance from the object boundaries and between source and measurement position.

3.4 Response acquisition

The acceleration was recorded with a multichannel signal analyzer at 10 positions on the top flange of the floor element and 4 on the bottom flange using accelerometers as shown in Figure 5. This corresponds to a total of 56 measurement position for shaker excitation and 98 measurement positions for impact excitation. This largely exceed the requirement from the standard (9 measurement positions). Thick washers were mounted by means of timber screw to the Kerto plates and the accelerometers were applied on the washers by magnetic mounting.

3.5 Impulse response analysis

The measurement with impact excitation delivers directly the impulse response of the system. The transfer function was calculated dividing the acceleration spectrum by the force spectrum.

When using the shaker excitation, the impulse response of the system was calculated from the transfer function in the frequency domain using the inverse fourier transformation. To calculate the transfer function we used the acceleration signal from the accelerometer and the force signal from the impedance head. In this way, we could exclude the effects of the amplifier, the shaker and the stinger.

The impulse responses were processed using the commercial software m|reverb (Müller-BBM GmbH). The software fullfills the requirements of ISO3382 and was mainly designed for room acoustic purposes. We highlight following steps of the processing of the impulse response: 1) the first step in the procedure is the filtering of the impulse responses. The 1/3 octave filters are implemented as reverse filters. They have a shorter inherent reverberation time and allow for analyses of shorter times. The lower limit is given by $BT > 4$, where B is the bandwidth of the filter and T the reverberation time at the frequency of interest (2). 2) The filtered and squared impulse responses are then backwards integrated to compute the Schroeder plots. 3) On the basis of the Schroeder plot the reverberation times are calculated by fitting a regression line and calculating the energy decay over a specific range. Different options were available here: T5 (-5 dB to -10 dB), T10 (-5 dB to -15 dB) and T20 (-5 dB to -25 dB). The reverberation times are calculated for each measurement positions and the aritmetically averaged. When averaging, the reverberation times shorter than $T < 4/B * 0.8$ were excluded. The arbitrary choice of “softening” the $BT > 4$ criteria was made considering the very low reverberation time measured and the discussions presented in (14) and in (7).

4. MEASUREMENT RESULTS AND DISCUSSION

4.1 Linearity of the excitation

During the preliminary measurements, the amplitude of the excitation was varied in three steps denominated “strong”, “normal” and “soft” both for impact and shaker excitation. The results are shown in Figure 6. The left part of the diagram shows the results for impact excitation and the right part for shaker excitation. On both sides, the top diagram shows the force spectrum. The two lower diagrams show the transfer functions recorded at two different measurement positions (MP). MP1 was on the bottom plate of the floor element, in correspondence of a joist. MP2 was on the bottom plate as well, but in between two joists.

The results show a strong dependency of the transfer function amplitude on the excitation amplitude for the impact excitation. Surprisingly two different trends are observed below 80 Hz..100Hz and above: below this frequency the amplitude of the transfer function decreases with increasing amplitude of the excitation. Above this frequency the trend is inverted. The effect is more pronounced for the measurement point between the joists. In the case of shaker excitation the amplitude of the transfer function remains constant changing the amplitude of the excitation. Similar behavior was observed by other authors, e.g. (13) and might be an indication of nonlinearities.

General differences are observed between the transfer functions recorded with impact excitation and shaker excitation, in particular above 100 Hz, but clearly evident also between 50 Hz and 100 Hz. A possible reason is the slightly different excitation position between the shaker position – fixed by a screw – and the hammer hits, which impact a few centimeters (ca. 5 cm) next to it. We assume an effect from this on the differences between the excitation methods. A further explanation could be a more dominant reverberant field with impact excitation compared to shaker excitation.

Both aspects described above need further investigations for better clarification.

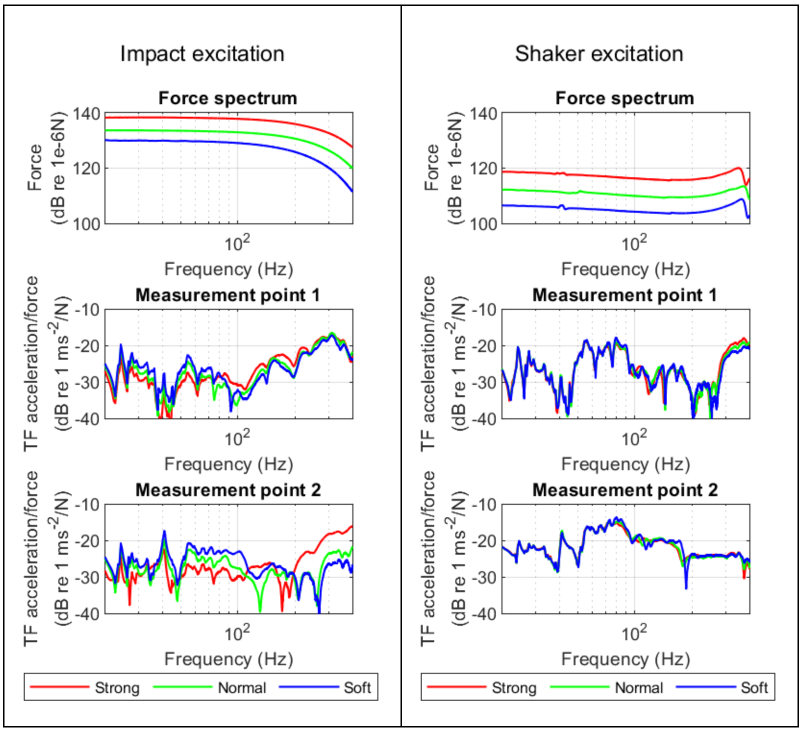

Figure 6 - Results from the preliminary measurements to determine linearity of the system; Left: impact excitation; Right: shaker excitation

4.2 Schroeder plots

Figure 7 shows the Schroeder plots obtained for all channels on the top flange of the floor element by shaker excitation on the bottom side, for the 1/3 octave bands 100 Hz, 250 Hz and 500 Hz. They are representative for all results obtained and show following features: a) there is a strong variability between measurement points. The variability has a maximum at about 250 Hz; b) the decay range with a linear trend is between -4 dB… -5 dB and -10 dB. At -10 dB some of the curves already deviate strongly from a linear decay; c) the number of points in the curves decreases with the frequency due to the increase of the wavelength and makes the fitting process at low frequencies over short decay ranges particularly challenging.

Based on the evaluation of the Schroeder plots, we decided to use T5 (reverberation time calculated on the decay between -5dB and -10dB) for the further analysis.

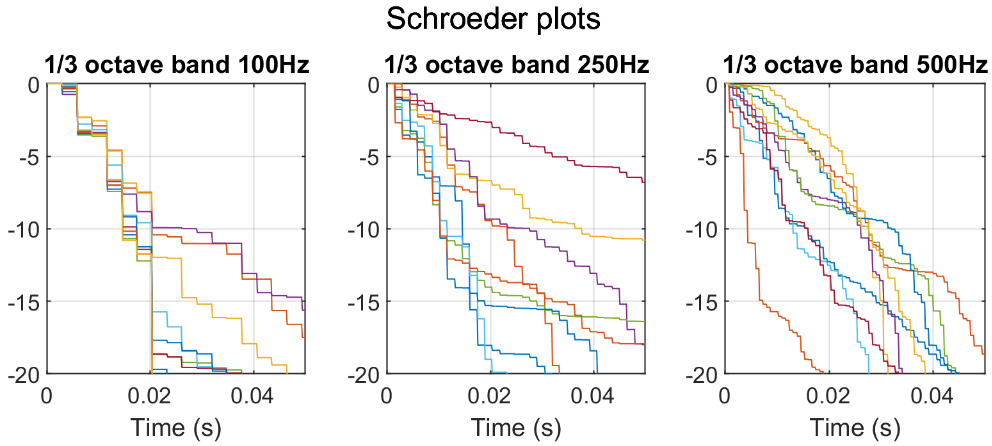

Figure 7 - Schroder plot for one of the shaker measurements. Displayed are several accelerometer positions and three 1/3 octave bands.

4.3 Excitation and response position

In Figure 8, we show the average reverberation times (T5) obtained for different excitation and receiver positions. The different combinations are shown in Table 1, where we also indicate which excitation type was used. These results investigate the variability of the reverberation time based on the spatial choice of the excitation and the receiver positions.

Table 1 – Combinations of excitation and receiver position

	Receiver: top	Receiver: bottom
Excitation: top	impact	impact
Excitation: bottom	shaker, impact	shaker, impact

The results obtained show a clear dependency between the reverberation time and the excitation / receiver locations. Similar results are obtained for both shaker and impact excitation. Shorter reverberation times are recorded on the highly damped bottom flange of the element, which is covered with gravel. Longer reverberation times are recorded on the top flange, which is not damped by the gravel. The longest reverberation time is recorded when both excitation and response are on the top flange. It should be pointed out that the evaluation of the reverberation times from acceleration on the bottom plate was particularly challenging due to the very short reverberation times, falling often below the lower limit (BT>4). For this reason the respective line in the diagram with the data from impact excitation is dotted and the line in the diagram with the data from shaker excitation is not continuous.

The standard deviation is not shown in these diagrams for practical reasons. Nevertheless it should be noted that the order of magnitude of the standard deviation is similar to the one shown in Figure 9.

4.4 Floor element reverberation time

In Figure 9, we show the reverberation time (T5) calculated as an average over all available measurement positions. To make the results comparable, for the impact excitation only the bottom excitation positions are considered.

The recorded reverberation times are very short above 100 Hz quicly decreasing from about 0.3 s at 100 Hz to less than 0.1 s at about 800 Hz. Below 100 Hz the dynamic of the undamped modes dominates the reverberation time that becomes much longer exceeding 1 s at 50 Hz. This trend meet the expectations from the experimental modal analysis previously performed on the same setup (8).

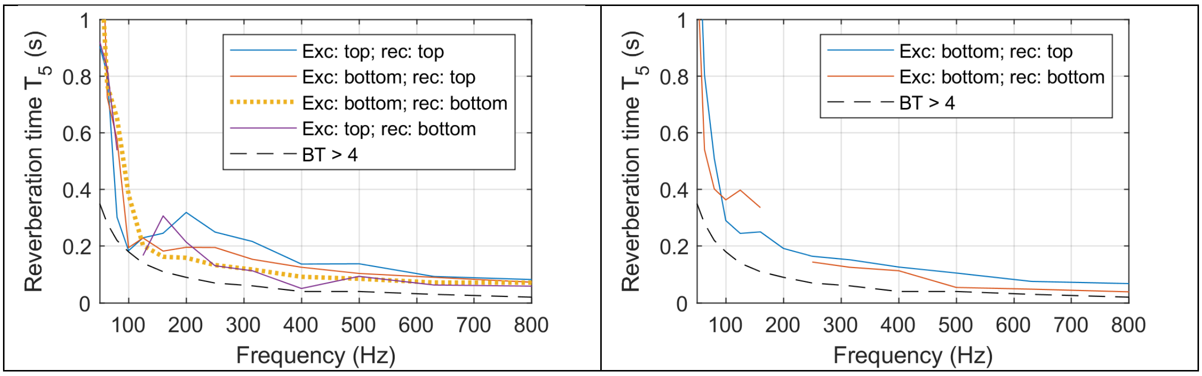

Figure 8 - Reverberation times obtained with impact (left) and shaker (right) excitation for different combinations of excitation (Exc) and sensor position (rec).

Impact and shaker excitation deliver results that are comparable and well within one standard deviation. This confirms the thesis from (6) that both methods are suitable for measurements on lightweight structures. The trend that impact excitation would deliver higher reverberation times than shaker observed by other authors (11, 13) on heavier structures was not observed here.

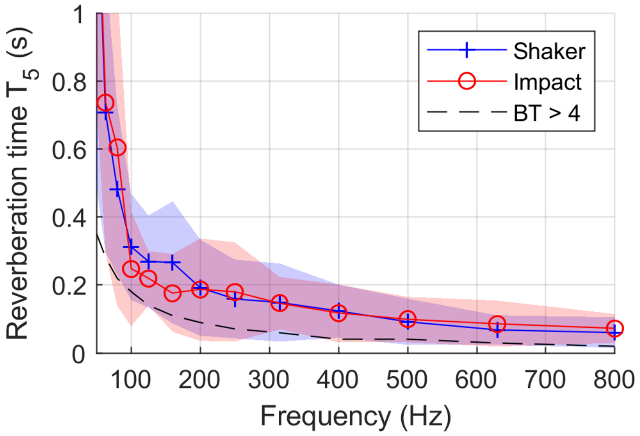

Figure 9 Reverberation time (T5) measured with impact excitation and shaker excitation. The average over all available receiver positions for bottom excitation is shown along with the standard deviation.

5. CONCLUSION

We performed reverberation times measurements on a strongly inhomogeneous lightweight structure, built with several different orthotropic materials. We followed the procedures suggested be the ISO10848-1 and encountered several challenges, which we highlight below: a) the spreading of the measurement results is high and b) a dependency of the results on both the excitation and sensors position was observed. Higher reverberation times were recorded on the upper lightly damped part of the structure and lower reverberation times were recorded on the lower highly damped flange. This raises the question of which position should be considered and if the in the standard suggested minimum 9 positions are enough for this kind of structures. c) The analysis of the data with commercial room acoustic software turned out to be very challenging, requiring enhance features (T5) evaluate very short linear decays. More flexibility (e.g. regression line starting at -3dB, evaluation range -3 dB to -8 dB as suggested in (4)) in the analysis would have been an advantage but makes the results rather used dependent. The evaluation at low frequencies was particularly difficult, since very few points are available to fit the regression line for the evaluation of the reverberation time from the Schroeder plot. d) Shaker and impact excitation delivered comparable results. Impact excitation had the clear advantage of being faster and more flexible but the frequency range is of course limited. e) The results found were nevertheless in agreement with the findings of other authors and the expectations from a previously performed experimental analysis. f) We observed differences in the measured transfer function between shaker and impact excitation that are not fully understood yet. Further investigations are needed here.

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