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A SIMULATION BASED STUDY OF LOW FREQUENCY TRANSIENT SOUND RADIATION FROM FLOORS – A CONCRETE VS. A HYBRID FLOOR

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Timber is a renewable and human friendly construction material and thereby a potential solution to achieve life cycle sustainable buildings. However, it is clear that impact sound and vibrations within the low frequency range still are challenges for wooden joist floors. Another challenge is the, mostly, larger building heights of wooden or hybrid floors compared to the heights of concrete floors. Using timber as the structural joist floor material could imply fewer stories due to maximum allowed building heights, which renders in less income in a building project. Accurate simulations of impact sound may decrease the need for prototypes; thus saving money and time in the timber building industry. Here, a hybrid joist floor consisting of wood, sand and steel is compared to a concrete floor in terms of radiated impact sound into a rectangular cavity. The hybrid floor is designed such that its mass distribution and global stiffness are close to the same properties of the concrete floor. Finite element models are used for simulations of the radiated transient sound induced by impact forces having the characteristics of human walking. The simulations indicate that similar surface mass and bending stiffness of a floor intersection give similar impact sound transmission properties around the first bending mode, while it is not necessary so at higher frequencies.
Keywords: timber buildings, impact sound, simulation

1. Introduction

Timber is a renewable material which has good recyclable properties. It is light and is thus generally less labour and equipment demanding in mechanical manufacturing processes and it is generally human-friendly. In addition, the material´s strength and stiffness is high, along its fibres, in comparison to its weight. Thereby, an increased share of multi-storey buildings made of timber is an opportunity to obtain more sustainable apartment buildings, seen over their life cycles.

Constructions of lightweight building components, like timber joist floors, are normally designed based on serviceability criteria rather than strength. For instance, a minimum fundamental frequency of 8 Hz is required in order to avoid discomfort of vibrations from other people walking [1]. Another challenge for light weight joist floors is to limit low frequency impact sound [2]. In order to achieve satisfactory properties in terms of sound insulation, wooden floors tend to be significant thicker than corresponding concrete floors. Hence, constructing multi-storey buildings in areas with limited allowed heights due to city planning, may imply loss of storeys. Development of thin, well performing joist floors is important in order for multi-storey timber based buildings to be competitive. Like in other industries, a strive for an increased share of simulations enabling a decrease of prototype tests may give benefits in decreased costs in a development stage.

Traditionally, the possible disturbing impact sound of concrete floors has been in the range well above 100 Hz. Measuring this kind of sound with a tapping machine is done with well established and well performing methods based on the diffuse field theory [3].

When it comes to simulations, a lot of research have been done, but that has not really made the building acousticians and engineers, who work with development of new building systems, adapt numerical simulations of the acoustic properties of joist floors as a standard procedure. One reason is that the tapping machine [4] is difficult to simulate accurately [5, 6].

By applying a transfer function approach, the need to simulate the interaction of the hammers of a tapping machine and the floor can be avoided. Transfer function calculations using the Finite Element Method (FEM) is a well established procedure in structural analysis although damping data is difficult to estimate in a pure theoretical stage. In order to correlate such a finite element (FE) model with test data, the force at the point of excitation on the structure during the measurements is needed. If accelerometers are added; the structural eigenmodes, including damping values, can be extracted from test data and the transmission paths can be better understood and visualized [7].

In the simulations of impact sound here, besides the joist floor structure, the air geometry bounded by the walls that enclosure the room below is included. The purpose is to simulate the sound propagation down through the room properly. By simulating the propagations using continued cavity in a transient analysis, the sound transmission into the room can be studied without having to take the reverberation time into consideration [8]. If the simulations are accurate, a comparison with a measurement of a joist floor as a reference would enable an estimate of the sound level in a room similar to the reference room. Another benefit is the possibility to use the same model as the FRFs are calculated with, to simulate the real sound and the sound insulation between neighbouring rooms.

2. Aim and objective

This study is a continuation from a semi-analytical comparison, within the frequency domain, between the sound transmission from a hollow core concrete floor and a hybrid floor made of timber with additions of steel and sand [8]. The purpose is to compare sound transmission of impact sound for different joist floor designs. Concrete floors normally have less transmission of low frequency impact sounds compared to timber based floors. Timber based floors have, on the other hand, characteristic of low transmission in the higher frequency range where concrete floors traditionally have their highest transmission of impact sound. The question concerned here is whether or not it is possible to achieve timber based floors with the same section bending stiffness (EI), similar thickness and the same weight per surface area as a concrete counterpart. If so, would such a floor have similar impact sound transmission properties as the concrete floor? Timber is too light and has too low Young's modulus in order to enable such a joist floor. Since thickness is an important parameter, here we allow us to include a small portion of sand and steel in order to achieve the similar weight, thickness and global bending stiffness as a modern hollow core concrete floor.

Here, the transient sound response to a human footstep is also calculated. The principle used in this study and these of the semi analytical calculation are shown in Figure 1.

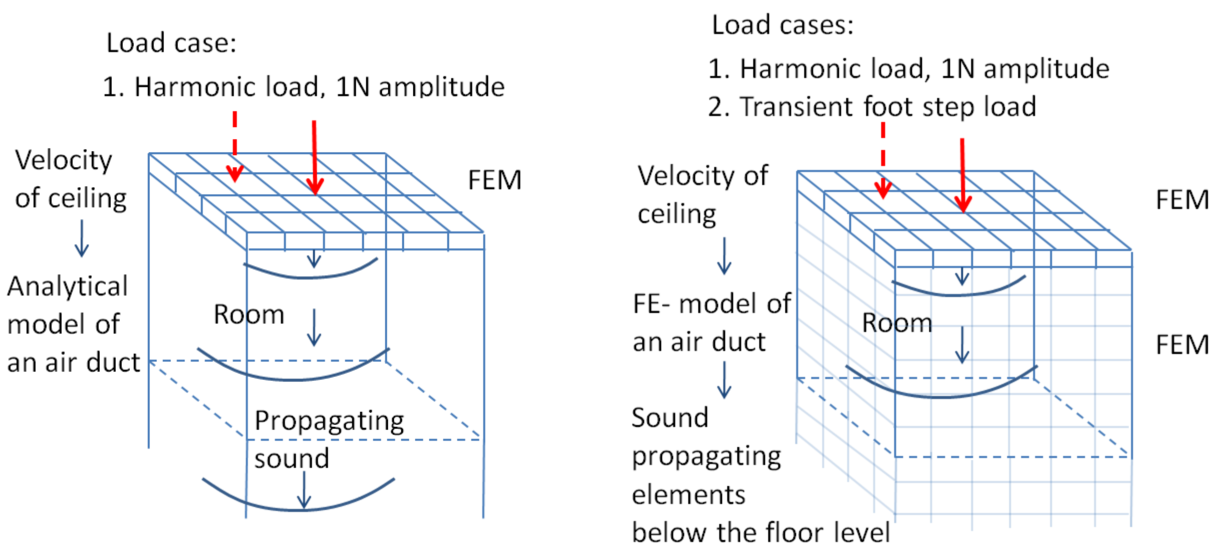

Figure 1: The left figure shows the procedure of the previous semi-analytical calculations [8]. It consists of an FE model of the floor together with an analytical model of an air duct. The right figure shows the calculation methodology used here with the air represented by an FE model with fluid elements also below the floor level.

3. Method and analysis objects

The simulations of the impact sound transmissions are made using FE-models of both the floor structure and the fluid in the room. The focus is on the sound radiation and the sound propagation into the room. The solver used is the modal transient solver (SOL 112) in MSC Nastran.

The concrete floor that is analysed is a modern pre-stressed, pre-manufactured concrete hollow core floor. The intersection modelled is replicated from an intersection provided on the market, see Figure 2. In Figure 3 the cross section of the hybrid joist floor used in this study is shown.

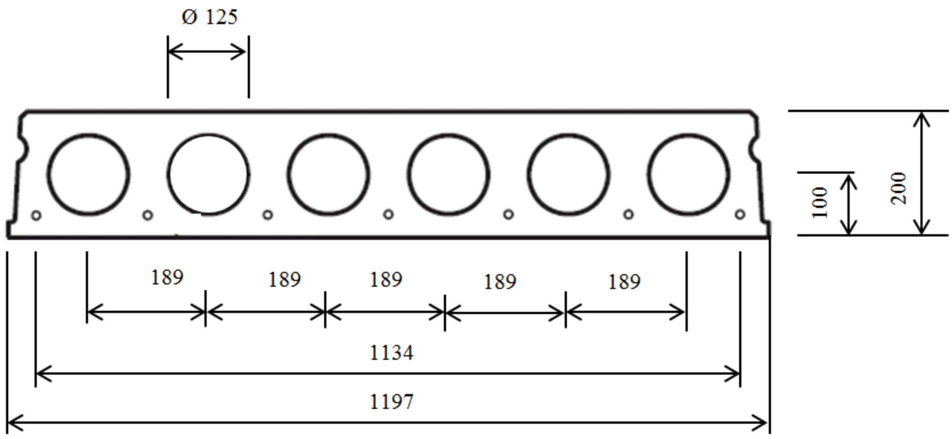

Figure 2: The cross section of the concrete floor [mm].

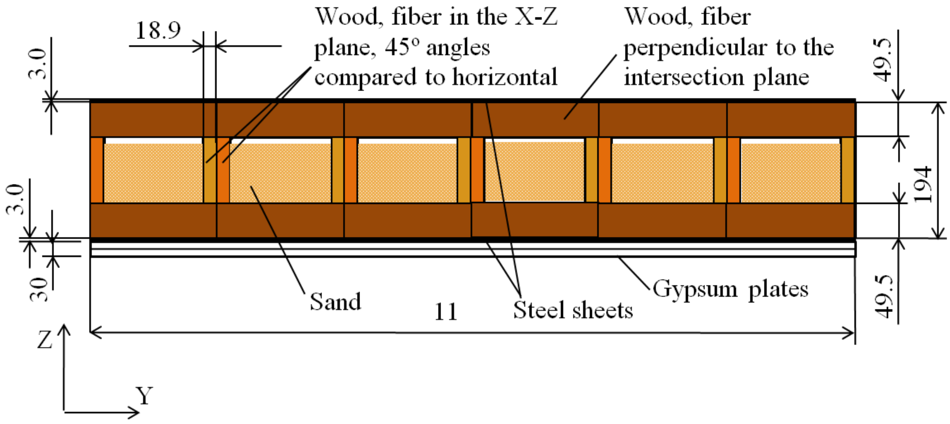

Figure 3: The cross section of the hybrid joist floor [mm].

The material data used in the FE-models are presented in Table 1 and Table 2. The sand is modelled as a distributed mass on the lower surface of the hollow part of the hybrid floor. The surface mass of the sand is set to 129.4 kg/m^2. The gypsum plates are also represented by a surface weight on the lower surface of the hybrid joist floor; the density 88.8 kg/m^2 is used for them. The models of both floors are 5.0 m long and 1.134 m wide.

Table 1: Homogeneous, isotropic material / medium data.

Material	Concrete	Steel, wire	Steel sheet	Sand	Air
Young's Modulus [GPa]	30	210	210	-	-
Density [kg/m^3]	2320	7850	7800	1650	1.204
Poisson's ratio [-]	0.21	0.30	0.30	-	-
Speed of sound [m/s]	-	-	-	-	343

Table 2: Orthotropic material data for the wood parts.

Density	[kg/m^3]	430
Young's Modulus	E1 [GPa]	11.0
	E2 [GPa]	0.57
	E3 [GPa]	0.57
Shear Modulus	G12 [GPa]	0.56
	G13 [GPa]	0.56
	G23 [GPa]	0.023

The real concrete joist floor is pre-stressed whereas the model of it is not. The pre-stress gives some effect on the natural frequencies, especially on the first bending mode. According to Zhang et. al. [9]; for a bonded pre-stressed concrete beam (PSC) with an intersection of 242 x 121 mm and a length of 3.6 m, the first bending frequency increases from 28.3 Hz for a 60 kN pre-stress to 29.4 Hz for 100 kN and the 2nd bending frequency increases from 97.2 Hz to 100.1 Hz. The increase in percent for the first mode is 3.7 % and for the second mode it is 2.8 %. Due to the relatively small deviation, ignoring the pre-stress was judged to be a reasonable simplification. The wires are modelled as circular beams with the diameter 4.43 mm. The constraints used in the models correspond to the ones for simply supported beams. The air cavity is modelled with fluid elements (MSC Nastran MAT 10 material properties). The air space is projected perpendicular out from the floors' ceiling surfaces (the same width and length as the floors). The average spacing for the fluid elements is 175 mm (the maximum element size is 200 mm) for the first 5.1 m from the ceiling. The elements below the room have the same projection and spacing in the horizontal plane but a coarser spacing in its vertical direction (a spacing of 500 mm). The vertical distance of this air model, below the room, is 350 m. Here, the low frequency range of interest is up to 100 Hz in the analyses. Relative viscous modal dampings of 2% are applied to all modes of both the hybrid and the concrete FE-models. Two excitation cases are studied; a mono sinusoidal loading and a load representing a human foot step. Two locations for the excitations are used. The first is the mid-point of the upper side of the floors. The second point is one fourth from the edges (the nodes closest to 1.25 m in x, and at 0.85 m in the y-direction). The mono sinusoidal loadings have a 1 N amplitude. The foot step force is an authentic load reproduced from Ohlsson [10], see Figure 4. The floors are fixed in all translational directions (x, y, z) at the short side at x = 0. At the edge at x = 5.0 the translation constraints are in the vertical and transverse directions (y, z).

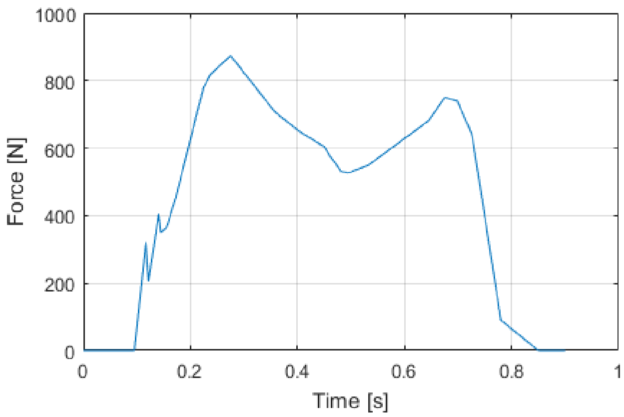

Figure 4: Load, as function of time, representing the human foot step used in the analyses.

The sound level results from the sine loadings are taken from the last 0.2 seconds of the time signal, where the signals have, more or less, settled to steady state conditions. For this part a mono harmonic is fitted with the least squares method. The magnitudes of these harmonics are presented. The evaluated points form a grid 35 cm from the corners, walls, ceiling and in the middle of the room. The evaluation points are presented in Table 3.

Table 3: Numbering of points in the air cavity. Zero in vertical direction is the ceiling surface.

Point	X [m]	Y [m]	Z [m]	Point	X [m]	Y [m]	Z [m]
101	0.35	0.35	-0.35	114	0.35	0.784	-1.35
102	4.65	0.35	-0.35	115	2.5	0.567	-1.35
103	4.65	0.784	-0.35	121	0.35	0.35	-2.35
104	0.35	0.784	-0.35	122	4.65	0.35	-2.35
105	2.5	0.567	-0.35	123	4.65	0.784	-2.35
111	0.35	0.35	-1.35	124	0.35	0.784	-2.35
112	4.65	0.35	-1.35	125	2.5	0.567	-2.35
113	4.65	0.784	-1.35				

4. Results

4.1 Average values

The average results for all grid points together with their standard deviations are presented in Figure 5. At the 63 Hz and 80 Hz excitations, the beat phenomenon is observed in points 115 and 121. That gives an increased uncertainty in the estimated sound pressure levels here.

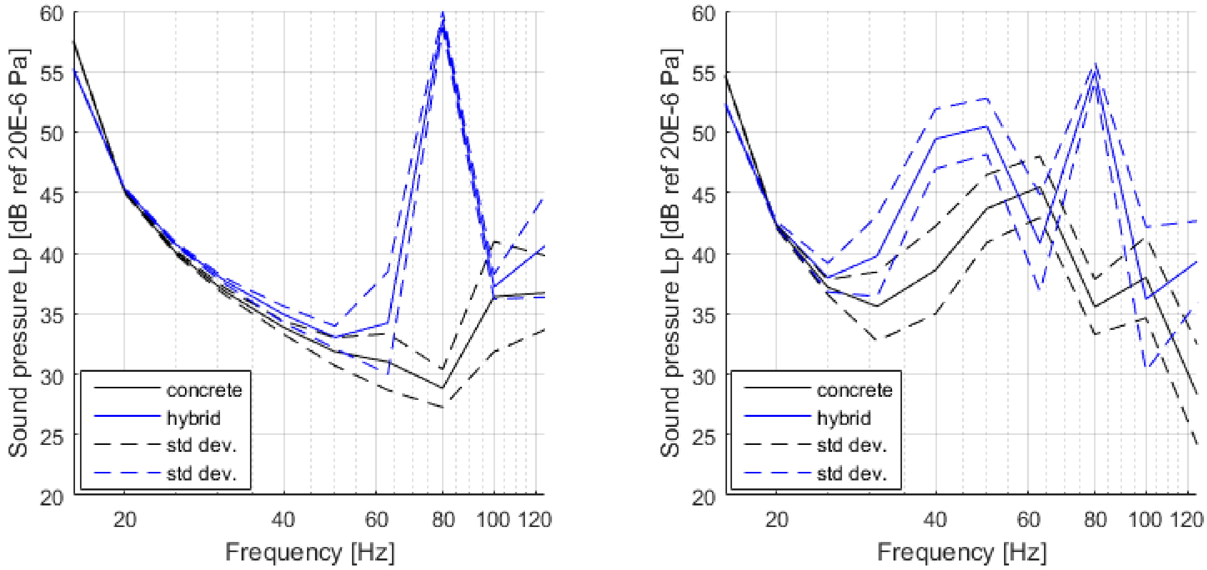

Figure 5: Average results for all grid points together with the standard deviations for both floors. The left figure shows the results for the excitations at the middle of the floors. The right figure shows the results due to the excitations 1/4th from the corners of the floors.

The resulting sound pressure levels at the grid points are presented in Table 4 and Table 5.

Table 4: The sound level results due to the excitations at the mid floor. Left; the results for the concrete floor. Right; for the hybrid floor. Sound pressure levels L_p [dB ref. $20 \cdot 10^{-6}$ Pa].

Left (concrete floor) — Frequency [Hz]

	16	20	25	31	40	50	63	80	100	125
101	57.6	45.2	40.2	37.0	34.6	33.2	30.2	29.1	39.1	39.9
102	57.6	45.2	40.2	37.1	33.9	31.3	33.1	31.1	35.5	37.8
103	57.6	45.2	40.2	37.1	33.9	31.4	33.3	30.1	35.1	38.2
104	57.6	45.2	40.2	37.0	34.6	33.3	30.5	27.7	39.0	40.2
105	57.4	44.9	39.8	36.4	33.1	30.6	28.3	26.1	26.2	33.7
111	57.6	45.1	40.1	36.9	34.5	33.3	30.5	28.6	36.6	37.8
112	57.6	45.2	40.2	37.1	33.8	31.4	33.4	30.5	38.1	33.7
113	57.6	45.2	40.2	37.1	33.8	31.4	33.4	30.5	38.1	33.9
114	57.6	45.1	40.1	36.9	34.5	33.3	30.5	28.5	36.6	37.9
115	57.4	44.9	39.8	36.4	33.0	30.2	25.6	26.2	27.1	37.2
121	57.5	45.0	40.0	36.6	34.0	32.4	28.2	27.2	30.3	32.4
122	57.5	45.0	40.0	36.8	33.4	30.5	31.6	29.2	39.1	31.9
123	57.5	45.0	40.0	36.8	33.4	30.5	31.6	29.2	39.1	31.8
124	57.5	45.0	40.0	36.6	34.0	32.4	28.2	27.3	30.3	32.3
125	57.4	44.8	39.7	36.3	33.0	30.5	28.8	27.2	30.9	38.3

Right (hybrid floor) — Frequency [Hz]

	16	20	25	31	40	50	63	80	100	125
101	55.3	45.4	40.8	37.8	35.8	31.9	35.6	59.7	37.8	40.6
102	55.3	45.4	40.9	37.9	34.5	34.2	35.9	59.9	35.0	40.5
103	55.3	45.4	40.9	37.9	34.5	34.1	35.9	59.9	35.0	40.4
104	55.3	45.4	40.8	37.8	35.8	31.9	35.6	59.7	37.8	40.7
105	55.1	45.2	40.5	37.3	34.4	32.6	39.4	57.7	37.6	46.7
111	55.2	45.4	40.8	37.8	35.8	32.2	16.5	59.7	37.7	36.0
112	55.2	45.4	40.8	37.9	34.5	34.1	21.0	59.9	36.7	36.3
113	55.2	45.4	40.8	37.9	34.5	34.1	20.9	59.9	36.7	36.2
114	55.2	45.4	40.8	37.8	35.8	32.2	16.6	59.7	37.7	36.1
115	55.1	45.2	40.5	37.3	34.5	33.0	38.4	58.6	38.5	43.6
121	55.2	45.3	40.7	37.5	35.3	32.0	30.9	58.6	35.9	40.1
122	55.2	45.3	40.7	37.7	34.2	33.6	31.4	58.7	37.9	40.0
123	55.2	45.3	40.7	37.7	34.2	33.6	31.4	58.7	37.9	40.0
124	55.2	45.3	40.7	37.5	35.3	32.0	30.9	58.6	35.9	40.1
125	55.1	45.1	40.4	37.2	34.4	32.8	35.6	59.1	38.0	18.4

Table 5: The sound level results due to the excitation at 1/4th from the edges. Left; the results for the concrete floor. Right; for the hybrid floor. Sound pressure levels L_p [dB ref. $20 \cdot 10^{-6}$ Pa].

Left (concrete floor) — Frequency [Hz]

	16	20	25	31	40	50	63	80	100	125
101	42.4	54.7	37.8	38.1	34.4	42.8	47.4	35.5	36.4	32.1
102	42.2	54.7	37.0	35.2	41.8	46.1	45.7	37.0	29.7	28.4
103	42.2	54.7	37.0	35.1	41.8	46.1	45.7	39.0	32.7	29.9
104	42.4	54.7	37.9	38.1	34.4	42.8	47.4	31.8	36.6	33.6
105	42.0	54.5	36.9	33.5	30.2	28.7	30.0	32.2	31.7	24.8
111	42.4	54.7	37.9	38.1	35.0	42.8	47.7	34.3	38.4	28.9
112	42.1	54.7	36.6	31.3	41.7	46.0	45.2	37.5	39.9	24.4
113	42.1	54.7	36.6	31.3	41.7	46.0	45.2	37.5	40.0	19.1
114	42.4	54.7	37.9	38.1	35.0	42.8	47.7	34.3	38.4	29.6
115	42.0	54.5	36.8	33.3	29.5	25.6	10.2	32.2	32.7	14.6
121	42.3	54.6	37.7	37.7	36.3	42.8	46.9	35.6	37.8	30.0
122	42.0	54.6	36.3	27.0	41.1	45.6	44.9	35.7	42.0	11.8
123	42.0	54.6	36.3	27.0	41.1	45.6	44.9	35.7	42.0	12.6
124	42.3	54.6	37.7	37.7	36.3	42.8	46.9	35.7	37.9	29.6
125	41.9	54.5	36.7	33.2	29.6	26.7	23.9	30.2	32.5	25.1

Right (hybrid floor) — Frequency [Hz]

	16	20	25	31	40	50	63	80	100	125
101	52.4	42.6	38.9	43.1	49.2	52.0	45.8	55.6	42.8	35.3
102	52.4	42.4	38.7	40.3	51.4	51.0	40.8	56.0	28.8	38.5
103	52.4	42.4	36.8	41.0	51.3	50.9	40.3	55.6	30.0	39.8
104	52.4	42.7	39.4	42.7	49.2	52.0	41.2	55.6	40.2	42.0
105	52.2	42.2	37.4	34.1	31.2	29.4	39.8	53.6	19.7	44.2
111	52.4	42.7	39.1	42.3	49.3	52.1	44.0	55.1	40.4	37.9
112	52.4	42.2	36.6	36.2	51.3	50.9	31.7	55.7	26.2	31.7
113	52.4	42.2	36.7	36.1	51.3	50.9	32.0	55.7	26.8	33.5
114	52.4	42.7	39.1	42.3	49.3	52.1	44.1	55.1	40.1	39.7
115	52.2	42.2	37.3	33.9	30.1	23.6	33.0	54.7	26.5	40.4
121	52.3	42.6	38.9	41.5	49.5	51.7	42.4	53.3	34.0	40.6
122	52.3	42.1	36.2	27.5	51.1	50.8	34.3	54.6	31.8	36.6
123	52.3	42.1	36.2	27.5	51.1	50.8	34.4	54.5	31.4	36.5
124	52.3	42.6	38.9	41.5	49.5	51.7	42.4	53.2	33.6	41.0
125	52.2	42.1	37.2	33.8	30.2	25.4	30.9	55.4	29.5	33.5

4.2 Simulation of a human step

The response in the point in the middle of the room (point 115) and in a corner close to the floor (point 121) are presented in Figure 6 and Figure 7 below. The response is dominated by the first bending mode of the joist floors; at 14.4 Hz for the hybrid floor and at 14.9 Hz for the concrete floor.

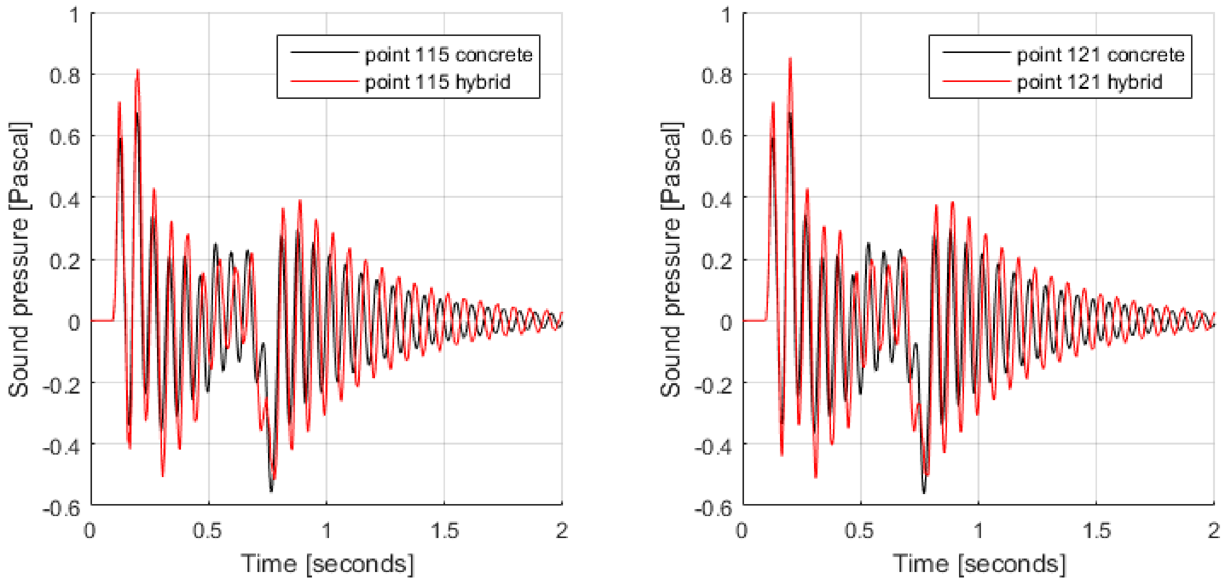

Figure 6: The figure to the left shows the pressure time signals at the mid room points (115) for the human step excitation at the mid-point of the floor above. The right shows the corresponding signals for the corner point 121.

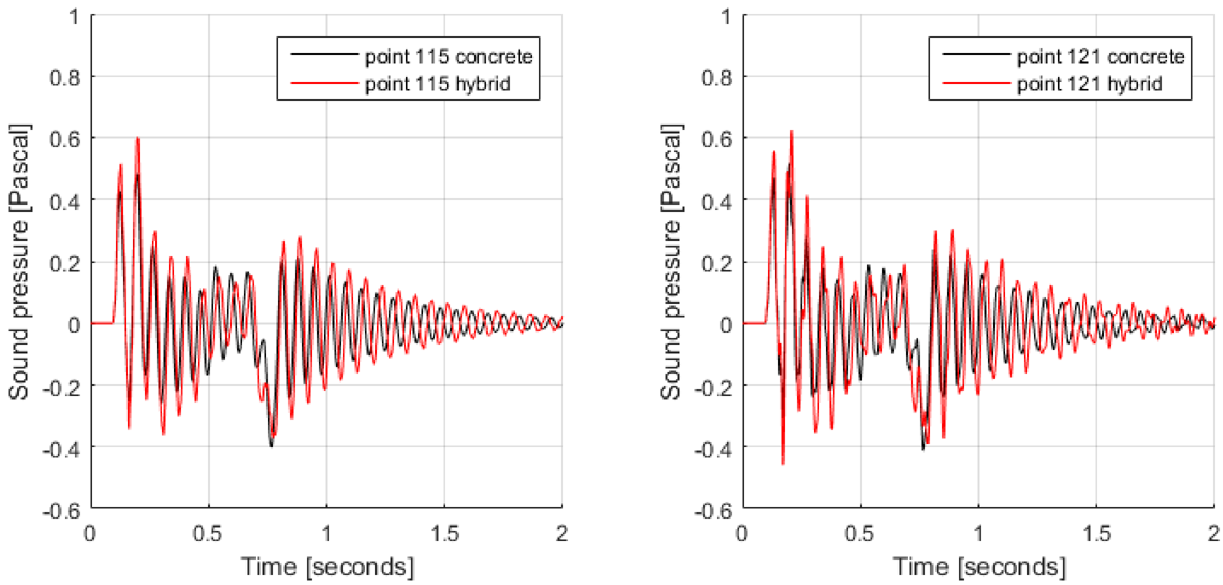

Figure 7: The figure to the left shows the pressure time signal at the mid room points (115) for the human step excitation at 1/4th from the edges of the floor above. The right shows the corresponding signals for the corner point 121.

5. Conclusions

The global bending stiffness and mass per surface area are close to identical for the concrete and hybrid joist floors. Similar to the previous study with semi-analytical calculations, it is seen here that the timber-hybrid floor has similar sound transmission as the concrete floor in the lower frequency range, close to the first bending mode. However, as the frequency increases, the difference increases. For the excitation 1/4th from the edges, the pressure differences start lower in frequency and the standard deviation becomes larger than the situation with the excitation on the middle of the floor. The reason is believed to be that the second mode shape is effectively excited in this point. This second and other higher mode shapes are asymmetric and may contribute to different levels in the room and thus an increased standard deviation.

The conclusion is that although the global stiffnesses and mass distributions are the same for the two different floors, it is not a guarantee that the sound transmission will be the same. Mainly the first bending mode is the same, after that the deviation increases. Due to lower local stiffness, the hybrid joist floor has significantly higher modal density already after the first global bending mode. It is likely that as the frequency increases, the local properties through the thickness also have to be more similar in order to achieve similar sound transmission results.

The transient results from the foot step excitations are better for listening and for potential subjective listening tests of sound quality rather than being presented in graphs. These kind of simulations may help at decisions and understanding, before construction of building projects, of the expected sound quality.

6. Acknowledgements

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