Vibration Transmission Across Junctions of Walls and Floors in an Apartment Building – A Case Study

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Résumé

La perception du son rayonné par le sol d'un bâtiment est fortement influencé par les pièces dans lesquelles il est immergé, par les positions de l'auditeur et de la source. La principale question qui reste sans réponse est liée à l'influence de la position de la source sur la puissance sonore rayonnée par un système complexe mur-plancher dans les bâtiments. Cette recherche concerne l'investigation de la transmission des vibrations à travers les murs et les planchers dans les bâtiments. Elle est principalement basée sur la détermination de l'indice de réduction des vibrations par des tests expérimentaux. La connaissance de ce paramètre peut aider à prédire la propagation du bruit et des vibrations dans les éléments de construction. Tout d'abord, les mécanismes physiques impliquant la transmission des vibrations à travers les jonctions structurelles sont décrits. Un montage expérimental est réalisé pour faciliter cette étude. Les tests expérimentaux ont montré que la génération de vibrations dans les murs et les planchers est directement liée à leur taille et aux conditions aux limites. Il est également démontré que la position de la source de vibration peut affecter de manière significative le spectre de vibration global. Ensuite, les caractéristiques des spectres de bruit à l'intérieur des pièces dues à une source d'impact (machine à tarauder) sont également présentées. Des conclusions sont tirées pour la tendance générale du spectre de vibration et de bruit des composants structurels et des pièces respectivement. En résumé, l'objectif de cet article est d'étudier le comportement vibro-acoustique des sols et des murs d'un bâtiment sous l'effet d'une excitation par impact. Les impacts ont été réalisés à des positions distinctes sur la dalle. L'analyse a mis en évidence les principales caractéristiques physiques du mécanisme de transmission des vibrations.

Mots-clés : Transmission des vibrations, indice de réduction des vibrations, excitation par impact

Abstract

The perception of sound radiated from a building floor is greatly influenced by the rooms in which it is immersed and by the position of both listener and source. The main question that remains unanswered is related to the influence of the source position on the sound power radiated by a complex wall-floor system in buildings. This research is concerned with the investigation of vibration transmission across walls and floors in buildings. It is primarily based on the determination of vibration reduction index via experimental tests. Knowledge of this parameter may help in predicting noise and vibration propagation in building components. First, the physical mechanisms involving vibration transmission across structural junctions is described. An experimental set-up is performed to aid this investigation. The experimental tests have showed that the vibration generation in the walls and floors are directed related to their size and boundary conditions. It is also shown that the vibration source position can affect the overall vibration spectrum significantly. Second, the characteristics of the noise spectra inside the rooms due to an impact source (tapping machine) are also presented. Conclusions are drawn for the general trend of vibration and noise spectrum of the structural components and rooms respectively. In summary, the aim of this paper is to investigate the vibro-acoustical behavior of building floors and walls under floor impact excitation. The impact excitation was at distinct positions on the slab. The analysis has highlighted the main physical characteristics of the vibration transmission mechanism.

Keywords: Vibration transmission, Vibration Reduction Index, Impact excitation

1 Introduction

The literature survey has revealed that a significant amount of work has concentrated on analyzing structural response to a dynamic loading using uncoupled structural modes for the building components. In this case the boundary condition at the interface between walls and floors, which is due to the velocity of the corresponding structure, cannot be replicated. Hence, the aim of this paper is to develop alternative 'in-situ' tests for the measurement of vibration transmission. It is performed here initially to structural coupled components to verify the accuracy and applicability of the approach.

Recently, various researchers have concentrated their work on presenting the main advantages of floating floors in terms of their sound isolation effectiveness. The use of floating floors on building construction is well-known among civil engineers, architects, and acoustic space designers. They are popular not only for their ability to decrease the transmission of structure-borne sound throughout the building structural components but also for their slender

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dimension which may be relevant on the calculation of the building total cost price.

Although the physical understanding of floating floor mechanisms is well established, the assessment of the sound power radiated by the structural floor has not been fully considered in terms of its boundary conditions. For example, it is important to know the relationship between the vibration transmission across wall-floor junctions and the sound pressure inside the adjacent rooms. Recently some researchers have concentrated their investigation on optimizing the dynamic models of floating floor systems to improve their effectiveness, i.e., to minimize the transmitted vibrational energy to the structural floor.

The effects of panel boundaries on sound radiation, including a comparison with an infinite panel have been discussed by several researchers [1-3]. A simple two-dimensional model has been used for evaluating the sound radiation characteristics of finite panels [3]. The analysis of the radiation, through a baffled plate of finite width and infinite length was rigorously. The effects of panel size have been studied in frequency regions below, above and at the critical frequency. In addition, estimates of averaged response over a given frequency range have also been investigated. The literature survey has revealed that a significant amount of work has concentrated on analyzing sound radiation of simply supported panels [4-8].

This research was first undertaken as a result of the need to develop an easy and reliable methodology for measuring the floor-wall vibration transmission in order to obtain a better comprehension of the structure-borne vibration transmission across an apartment slab.

2 Experimental tests

The vibration transmission experiments were performed in a particular unreinforced masonry building. The building is composed of four floors. Each structural floor and load bearing wall has a thickness equal to 10cm and 15 cm respectively. The tests were made on the 2nd floor of a particular apartment. The external noise influences were well below the vibration level measurements in the walls and floors, i.e., the signal-to-noise ratio was high enough to assure good quality measurements. The experimental set-up and floor characteristics are shown in Figures 1 and 2 below. First, a tapping machine and accelerometers were positioned on different positions on the floors and walls. The acceleration measurements were made using ICP accelerometers (50 g range, 100 mV/g general purpose accelerometer with 10-32 top connector and 10-32 mounting hole). Before each measurement, the entire arrangement was checked and calibrated.

Next, the total loss factor of each floor and wall was measured indirectly using the structural reverberation time. Impulse responses were obtained using the impact testing procedure described as follows. On impacting the 'panel' by an instrumented hammer, the analyzer was triggered and started recording the response signal at the receiving point, where accelerometers were attached and connected to the acquisition equipment (National Instruments data acquisition module type NI-9234). The input signal was filtered by conveniently configuring the channel parameters. The acceleration levels were obtained via Fourier transforms of the measured quantities.

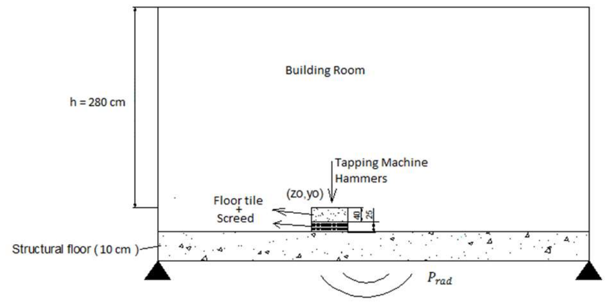


Figure 1: Set-up of the experimental tests.

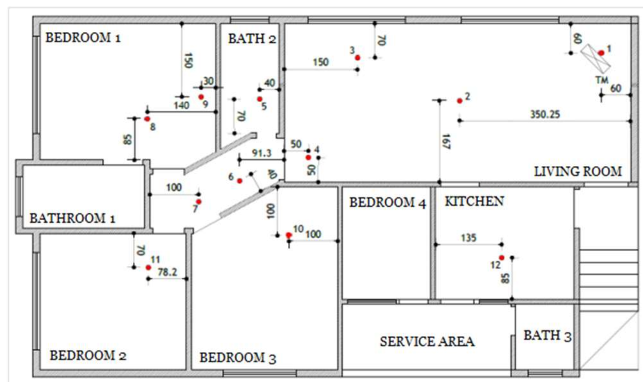


Figure 2: Accelerometer positions on the apartment floor and tapping machine at position TM-1.

A frequency range of 100–4000 Hz was considered on measuring the acceleration levels due to the tapping machine. For the structural reverberation time, decay curves were measured in the frequency range 100-630 Hz, where the signal/noise ratio was high enough and the results were validated. The vibration source was a plastic headed hammer. It was used to hit the concrete panel at different locations (in order to obtain spatial averaged values) over a period of 6 seconds. The velocities were determined by integrating the accelerations at every frequency line

3 Structural Reverberation Time

The structural reverberation time T_s was evaluated from the decay curves from a range of 5 dB to 25 dB below the steady-state level. Within the evaluation range a least-squares fit line was computed for the curve. The slope of the straight line gives the decay rate, d, in decibels per second, from which the structural reverberation time was calculated as $T_s = 60/d$. The commercial software named 'WinMLS' used the impulse responses for the calculation of the reverberation time.

The damping η, known as total loss factor, can be obtained using the following equation

$$\eta = \frac{2.2}{f\,T_s} \tag{1}$$

where T_s is the structural reverberation time in seconds and f is the frequency in Hertz.

The values of damping η are sometimes termed structural damping, to identify that the damping is dependent on both the damping inherent in the material and that which comes from other mechanisms including dissipation losses at the boundary which might be significant. In other words, the total loss factor is equal to the sum of the internal loss factor of the material, the coupling loss factor to the adjacent structures and the radiation loss factor to the surrounding media [1].

An acquisition time of five seconds was adopted. Figure 3 shows the accelerometer positions on the floors and walls for the reverberation time measurements. At very low frequencies, T_s depends to a large extent on the position of the source and the receiving accelerometer. It is recommended that an ensemble averaging procedure based on a combination of accelerometer positions be adopted for each one-third octave band result.

4 Evaluation of the Vibration Reduction Index K_{ij}

In this section the methodology used for the measurement of vibration reduction index $\boldsymbol{K_{ij}}$ of the cross-junction type is described. The vibration reduction index was obtained using the following expression [4]:

$$\boldsymbol{K_{ij}} = \overline{\boldsymbol{D_{v,ij}}} + 10log_{10}\left(\frac{\boldsymbol{L_{ij}}}{\sqrt{\boldsymbol{a_i a_j}}}\right) \quad (2)$$

$$\overline{\boldsymbol{D_{v,ij}}} = \frac{\boldsymbol{D_{v,ij}} - \boldsymbol{D_{v,ji}}}{2} \quad (3)$$

$$a = \frac{2.2\pi^2 S}{c_0 T_s}\sqrt{\frac{f_{ref}}{f}} = \frac{\pi^2 S\eta}{c_0}\sqrt{f_{ref} f} \quad (4)$$

where $\overline{\boldsymbol{D_{v,ij}}}$ is the average vibration level difference between the source element i and the receiving element j (walls, ceiling or floor); $\boldsymbol{L_{ij}}$ is the junction length between the source and the receiver; a is the equivalent absorption length; S is the area; f_{ref} is the reference frequency which is equal to 1,000 Hz; f is the centre frequency; c_0 is the sound phase speed in air and η is the total loss factor.

The vibration source (tapping machine) was placed at particular positions in the building 2nd floor. The corresponding distances between the source and the receivers (accelerometers) are presented in Table 1. The average vibration velocity level was then measured at points shown in Figure 1. The first parameter to be measured was the vibration level in each 'subsystem' (floor and/or wall) which were the source or receiver plate (see Figure 4 below). After that, the structural reverberation time was also measured.

5 Results and discussions

Figure 5 presents the time and space average acceleration levels of the floors. It is seen the variation of floor acceleration levels measured at different points (see Table 1) considering three distinct locations for the tapping machine: living room, bathroom, and bedroom *1*. The values were obtained due to tapping machine generating impact vibrations and the corresponding accelerations being measured at

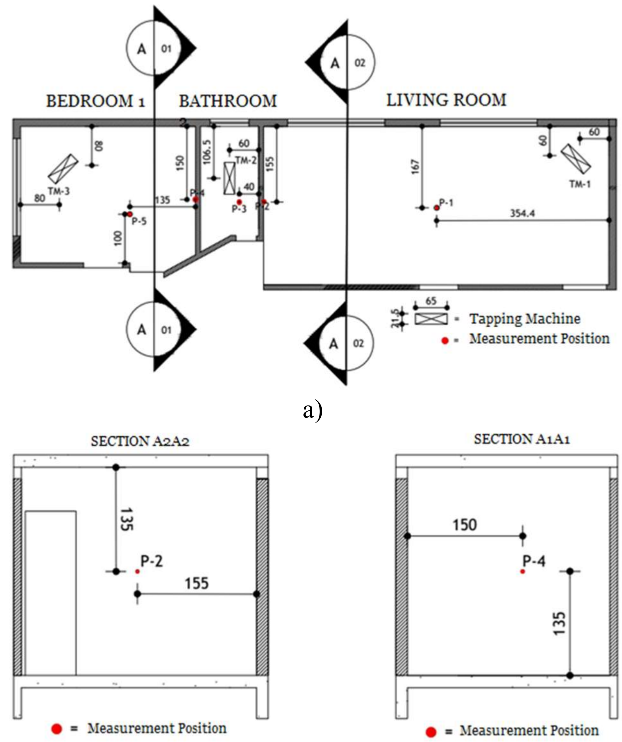


Figure 3: Accelerometer and tapping machine positions on the apartment floor (P-1, P-3 and P-5) and walls (P-2 and P-4). a) Floor plan; b) Floor plan cuts (A_1 and A_2).

Table 1: Distances between the sources (tapping machine at position TM-1, TM-2 and TM-3) and the receivers (accelerometers at positions P-1 – P-5).

Distance Source/Receiver	P-1 cm	P-2 cm	P-3 cm	P-4 cm	P-5 cm
TM-1	313	656	706	795	938
TM-2	430	85	52	82	218
TM-3	780	426	358	288	176

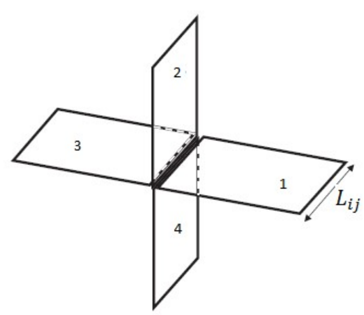
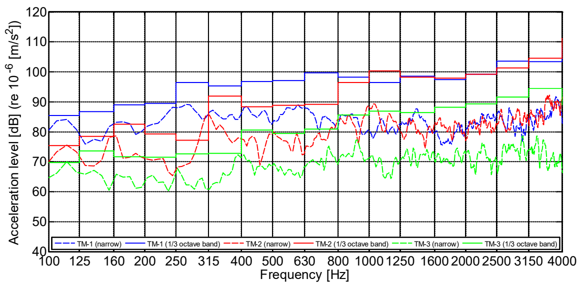


Figure 4: Cross-junction type considered for the determination of the vibration reduction index $\boldsymbol{K_{ij}}$ between floors and walls. The subscripts i, j represent the source and receiver plate respectively.

points P-1, P-3, and P-5 (see Figure 3a). It is seen that the vibration level at point P-5 has the greatest values in the frequency range considered as the tapping machine was on the living room floor (Figure 5a). Likewise, the highest levels of acceleration at points P-3 and P-5 were for the tapping machine located on the bathroom floor and bedroom *1* respectively (see Figures 5b and 5c). It is also observed that the acceleration levels at distinct positions decrease as the distance from the tapping machine increases, as expected.



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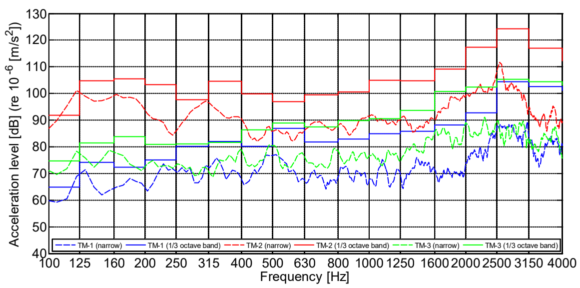

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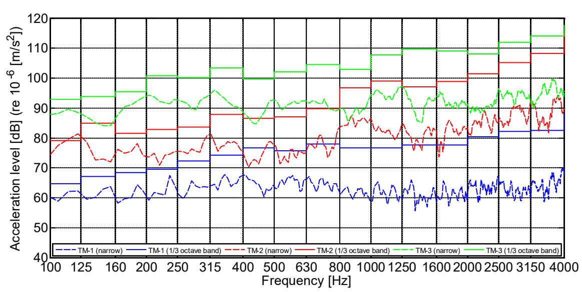
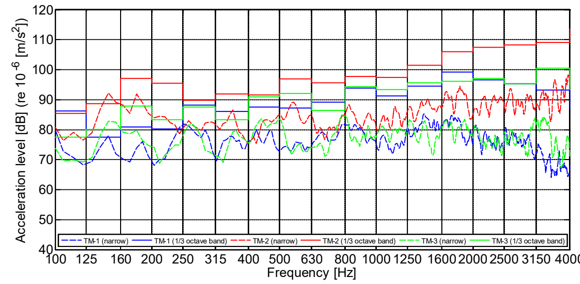


c)

Figure 5: Variation of floor acceleration level measured at distinct points considering the tapping machine location. a) point P-1 (living room ceiling); b) point P-3 (bathroom ceiling); c) point P-5 (bedroom ceiling).

Figure 6 presents the time average acceleration levels of two walls (points P-2 and P-4). It can be observed that the acceleration level varies according to the relative position between source (tapping machine) and receivers (accelerometers), as expected. It is seen that the highest vibration levels are found as the tapping machine was located on the bathroom floor which is supported on two of its edges by the corresponding walls.

In Figure 7 it is seen that the vibrational level is dependent upon frequency and the distance between the source and receiver, as expected. In this case, the tapping machine is fixed at a particular position on the living room floor (see



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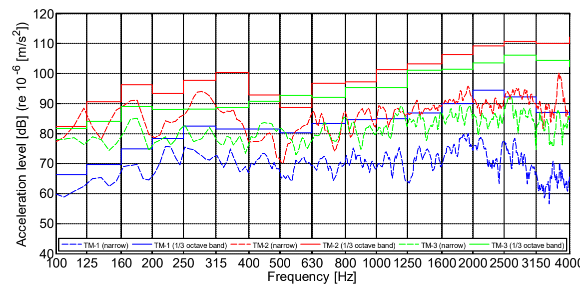

b)

Figure 6: Variation of wall acceleration level measured at distinct points considering the tapping machine location. a) accelerometer on point P-2 (living room wall); b) accelerometer on point P-4 (bedroom wall).

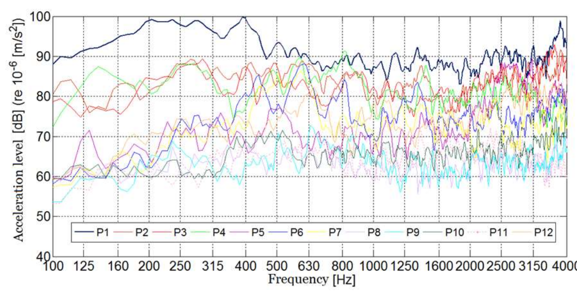

Figure 7: Variation of floor acceleration level measured at distinct positions located in the apartment. The tapping machine location was fixed on the living room floor.

Figure 2). There is a direct correlation between the distance between source-receiver and the acceleration level of the floors in most frequency range. Below 500 Hz, the acceleration levels vary as much as 40 dB. In general, structure-borne vibrational modes are predominant at frequencies below the critical frequencies of the floors. In this case, the critical frequency of the floors was approximately 185 Hz.

Table 3 below shows the acceleration levels in 1/3 octave band centre frequencies (dB re 10^{-6} m/s^2) measured at points P-1 – P-5 illustrated in Figure 3. The level values are presented in the frequency range 100-630 Hz. These values were used in equations (2) and (3) for the determination of the vibration reduction index which are shown in Figure 8.

Figure 8 shows the variation of $\boldsymbol{K_{ij}}$ with frequency. As expected, $\boldsymbol{K_{15}}$ and $\boldsymbol{K_{12}}$ shows the top and bottom values in the whole frequency range. The difference between them reaches 15 dB in the frequency range. On. the other hand, $\boldsymbol{K_{13}}$ and $\boldsymbol{K_{14}}$ present a difference of less than 5 dB between each other.

Table 2: Structural reverberation time of floors (accelerometers at positions P-1, P-3, and P-5) and walls (accelerometers at positions P-2 and P-4).

1/3 octave band (Hz)	T_s(s) P-1	T_s(s) P-2	T_s(s) P-3	T_s(s) P-4	T_s(s) P-5
100	0.53	1.49	0.50	0.46	0.66
125	0.34	0.79	0.41	0.37	0.85
160	0.38	0.38	0.30	0.40	1.28
200	0.33	0.46	0.27	0.27	0.63
250	0.18	0.41	0.15	0.57	0.29
315	0.15	0.28	0.11	0.21	0.15
400	0.21	0.26	0.13	0.16	0.11
500	0.14	0.14	0.10	0.13	0.11
630	0.09	0.14	0.12	0.11	0.10

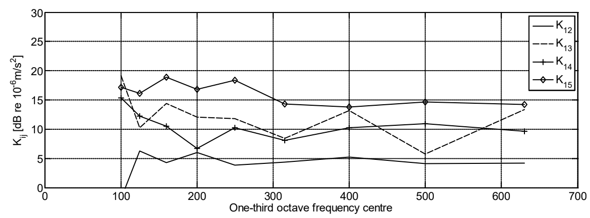

Figure 8: Variation of the Vibration Reduction Index (K_{ij}) with frequency and accelerometer positions P-1 – P-5. Four different situations were considered: $\boldsymbol{K_{12}}$ (TM1 – P-2), K_{13} (TM1 – P-3), K_{14} (TM1 – P-4) and K_{15} (TM1 – P-5).

6 Conclusions

The study presented herein is an alternative for understanding the structure-borne transmission across junctions in dwellings. Flanking transmission via flanked building floors and walls have been investigated using the concept of the parameter named vibration reduction index. This concept is a reliable approach which provides a rapid and practical measurement of the total sound power transmitted into structural panels. The method of measuring vibration acceleration levels, outlined in this study, is a cost-effective technique that can be used in place of traditional techniques which considers the structure sound radiation. In addition, experimental tests can be made in a noisier environment where background noise levels (in one octave band) can be tolerated. The acoustic-based technique may be alternatively applied to mechanical vibration techniques. The influence of vibration level exposure on the physiological and psychological behavior of humans inside residential buildings is already under investigation as part of future work.

Acknowledgments

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Table 3: Acceleration levels in 1/3 octave band centre frequencies (dB re 10^{-6} m/s^2) measured at points P-1 – P-5 (see Figure 3) as the tapping machine change positions in the apartment rooms (living room, bathroom, and bedroom 1).

Acceleration level [dB re 10^{-6} m/s^2]	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz
AL (TM-1, P-1)	85	86	89	90	96	95	97	97	99
AL (TM-2, P-1)	75	78	83	79	77	92	88	88	89
AL (TM-3, P-1)	69	73	72	72	73	73	81	79	81
AL (TM-1, P-2)	86	77	81	80	88	86	88	87	89
AL (TM-2, P-2)	85	89	97	95	89	92	92	97	96
AL (TM-3, P-2)	78	80	88	8	88	8	91	92	87
AL (TM-1, P-3)	65	74	72	75	80	82	80	87	81
AL (TM-2, P-3)	92	105	106	103	98	105	99	97	99
AL (TM-3, P-3)	75	81	84	81	81	82	86	89	87
AL (TM-1, P-4)	66	69	75	78	83	82	82	80	83
AL (TM-2, P-4)	82	91	96	93	98	100	93	89	96
AL (TM-3, P-4)	82	84	89	88	88	89	91	93	92
AL (TM-1, P-5)	65	67	68	70	72	74	77	76	78
AL (TM-2, P-5)	79	85	82	82	84	88	87	87	90
AL (TM-3, P-5)	93	94	95	101	100	104	99	102	105
Max	93	105.7	105.5	103.2	1002	104.7	99.9	102.2	104.5
Min	64,8	67,2	68.4	69.6	72.4	72.8	76.7	75.7	78.0
Avg	78,5	82,4	85,1	84,8	86,4	88,4	88,7	89,4	90,3
Var	84,9	96,1	114.1	101.9	80.7	93.9	49.3	52.8	59.3
Stdn	9.2	9.8	10.7	10.1	9.0	9.7	7.0	7.3	7.7

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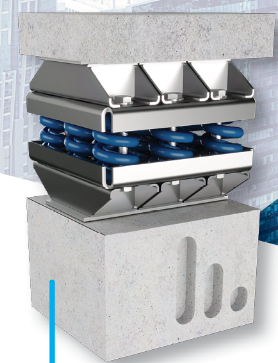

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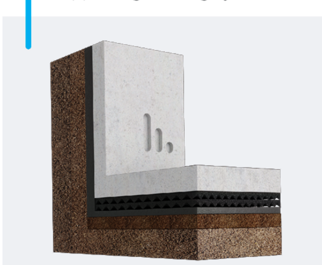

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