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FINITE ELEMENT ANALYSIS OF THE VIBRATION REDUCTION INDEX BETWEEN PRECAST HOLLOW CORE FLOORS AND A LIGHTWEIGHT WALL

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ABSTRACT

In Finland, the lightweight partitioning wall between dwellings or rooms is in some cases built within the span of a continuous, precast hollow core slab floor. This type of construction is most common in hotels, care homes, and apartment buildings. However, this solution has been found to result in insufficient airborne sound insulation between adjacent rooms. It has been suggested that the low sound insulation is caused by flanking transmission via the continuous precast concrete floor. A concrete core fill of the hollow core slabs in the junction of the partitioning wall has been suggested as a solution to improve the apparent sound insulation. The finite element method was used to study the vibration reduction index of the junction between the lightweight wall and the precast concrete floor, as well as the total loss factors of the precast floors. The analysis was carried out for floors of different thicknesses, with and without the core fill. The results of the FE-analyses were used to calculate the apparent sound insulation between rooms. It was found that while the core fill does have an effect on the vibration reduction index, its effect on the apparent sound insulation was negligible.

Keywords: *finite element method, apparent sound insulation, vibration reduction index, precast hollow core floor*

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1. INTRODUCTION

In Finland, buildings are often built using precast concrete elements. The exterior walls in such buildings are usually concrete sandwich elements, and the interior partitioning walls are either precast concrete or lightweight gypsum board walls. The load bearing floor structure is usually made of hollow core slabs, which are precast concrete elements with hollow air cavities along the length of the slab.

In certain types of buildings, e.g. hotels, care homes or apartment buildings, a lightweight partitioning wall between rooms is sometimes built within the span of a hollow core floor. This means that the floor structure is continuous between the two rooms. Previously, it had been found that this solution led to insufficient airborne sound insulation between rooms in the horizontal direction. It was suggested that the reason for the low sound insulation was flanking transmission via the continuous floor structure.

A concrete core fill of the hollow core slabs in the junction with the partitioning wall was proposed to improve the sound insulation between dwellings. This kind of technique has been used in Finland since 2013. [1] A concrete core fill means locally filling the cores of the hollow core slab with concrete, see Fig. 1. The length of the core fill should be at least 600 mm [1]. According to the knowledge of the authors, no similar practice is used elsewhere in Europe.

In more recent measurements of sound insulation, it has been noted, however, that in similar situations the sound insulation requirements between dwellings could be fulfilled without the concrete core fill. This has led to the necessity of the core fill being questioned.

To examine the necessity of the core fill, its effect on both the floor-floor flanking path and the airborne sound insulation between rooms was studied.

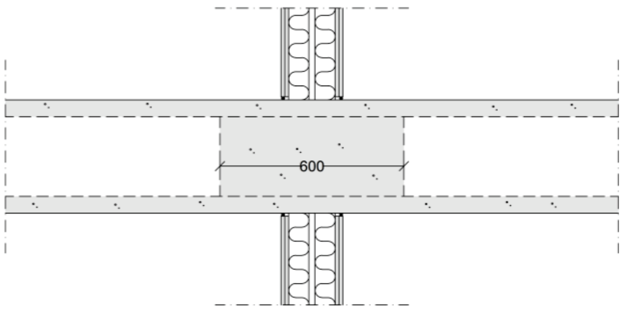

Figure 1. Sketch of a concrete core fill in the junction of a hollow core slab and a lightweight, double leaf partitioning wall.

To examine the effect of the concrete core fill on the floor-floor flanking path, the vibration reduction index of the path in question was examined with and without the core fill using the finite element method (FEM). FEM can predict vibration transmission between concrete structures with sufficient accuracy [2], and it has been previously used for investigating the vibration reduction index of building junctions [2–6]. Additionally, FEM allows the complex geometry of the hollow core slabs and the core fill to be taken into account accurately.

The effect of the core fill on airborne sound insulation between rooms was examined with the ISO 12354-1 [7] prediction method, using the previously determined vibration reduction indices for the floor-floor and ceiling-ceiling flanking paths.

This article is based on the study carried out by Talus in his master's thesis [8].

2. MATERIALS AND METHODS

2.1 Rationale for the concrete core fill

The idea of a core fill is sound in theory; structural discontinuities and so-called blocking masses do increase the attenuation of vibrations propagating along a plate or beam. The attenuation is, however, dependent on the geometry of the blocking mass as well as frequency [9].

2.2 Prediction of sound insulation between rooms

The apparent airborne sound insulation between rooms can be predicted using the ISO 12354-1 [7] calculation model. The model presented in the standard is based on work by Gerretsen [10]. The ISO 12354-1 prediction method considers first order flanking paths, where the vibration attenuation in structural junctions is described using the vibration reduction index K_{ij} (dB). The standard ISO 12354-1 [7] presents K_{ij} values for certain types of structural junctions based on empirical and calculated data. The vibration reduction index of a structural junction can also be measured according to the standard ISO 10848-1 [11].

The vibration reduction index between structural elements i and j is defined as [11]:

$$K_{ij} = D_{v,avg} + 10\log\left(\frac{l_{ij}}{\sqrt{a_i a_j}}\right) \quad (1)$$

where $D_{v,avg}$ (dB) is the direction averaged velocity level difference between the two structural elements and l_{ij} (m) is the width of the junction. The equivalent absorption lengths a_i (m) and a_j (m) of elements i and j can be determined from

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

where T_s (s) is the structural reverberation time of the element, f (Hz) is frequency, f_{ref} (1000 Hz) is the reference frequency, c_0 (m/s) is the speed of sound in air and S (m^2) is the area of the element. [11]

Various calculation methods have been used for investigating the vibration reduction index of junctions. The finite element method (FEM) [2–6], the spectral finite element method (SFEM) [6], as well as wave theory [3] have all been previously used with good results.

2.3 Partitioning structures and junctions

Three different floor-wall cross junctions were investigated. Each junction consisted of a continuous hollow core floor structure and a lightweight double leaf partitioning wall. The partitioning wall structure was the same in each case, but the thickness of the hollow core floor structure was varied. The three different thicknesses were 265 mm (O27 approx. 380 kg/m^2), 320 mm (O32, approx. 400 kg/m^2) and 370 mm (O37, approx. 510 kg/m^2) (see Fig. 2). These thicknesses were chosen because they are the most common in Finnish precast concrete buildings.

The partitioning wall was a typical lightweight wall structure used between dwellings, and it had the following structural layers:

- 13 mm Plasterboard, extra hard
- 13 mm Plasterboard
- 66 mm wooden stud / 50 mm mineral wool
- 16 mm Air gap
- 66 mm wooden stud / 50 mm mineral wool
- 13 mm Plasterboard
- 13 mm Plasterboard, extra hard

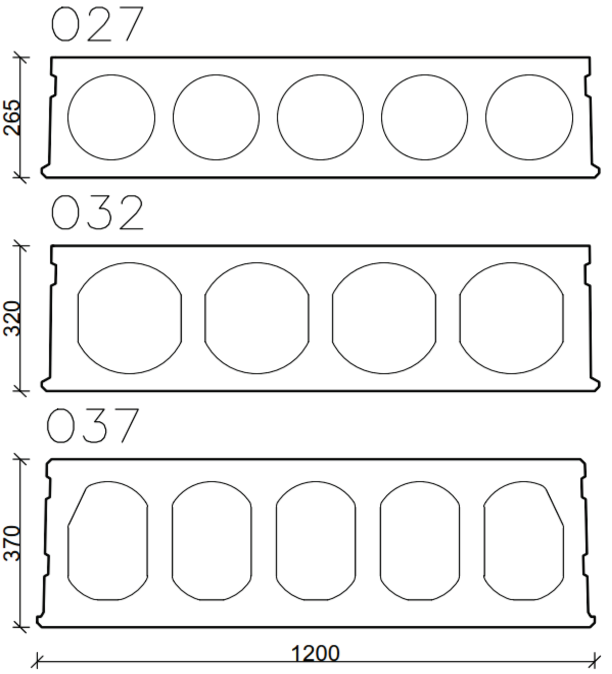

Figure 2. The cross-sections of the hollow core slabs examined in this study.

The vibration reduction index K_{ij} was determined using FEM for the following six cross junctions:

- O27 + Partitioning wall, no core fill
- O27 + Partitioning wall, core fill included
- O32 + Partitioning wall, no core fill
- O32 + Partitioning wall, core fill included
- O37 + Partitioning wall, no core fill
- O37 + Partitioning wall, core fill included

2.4 Finite element analysis

The vibration reduction index K_{ij} of the floor-floor flanking path of the junction was investigated using a 3D finite element model of the junction. The FE-analysis was carried out using ANSYS® Mechanical. The FE-model was built according to the measurement setup of the vibration reduction index K_{ij} as presented in the standards ISO 10848-1 [11] and ISO 10848-4 [12].

2.4.1 Material properties

The material properties used in the calculations are presented in Tab. 1.

Table 1. Material properties used in the calculations.

Material	ρ [kg/m^3]	E [MPa]	ν [-]	η_{int} [-]
Precast concrete (C40/45)	2500	35 000	0,2	0,005
Cast in-situ concrete (C20/25)	2500	30 000	0,2	0,005
Load-bearing concrete walls (C30/37)	2500	33 000	0,2	0,005
Gypsum board, extra hard	~820	3500	0,28	0,003
Gypsum board	~650	2600	0,28	0,003
Wood	500	10 000	0,28	0,01

2.4.2 Geometry

The hollow core slabs and the studs of the partitioning wall were modeled as 3D structural solids. The gypsum boards were modelled as 2D shells. The air domains in the voids of the hollow core slabs were also included in the FE-model as acoustical fluids. The air domains were coupled to the structural elements of the hollow core slabs using fluid-structure interaction (FSI) in ANSYS. The air and mineral wool domains within the partitioning wall were not taken into account when simulating the vibration reduction index. A part of the geometry of the model is shown in Fig. 3.

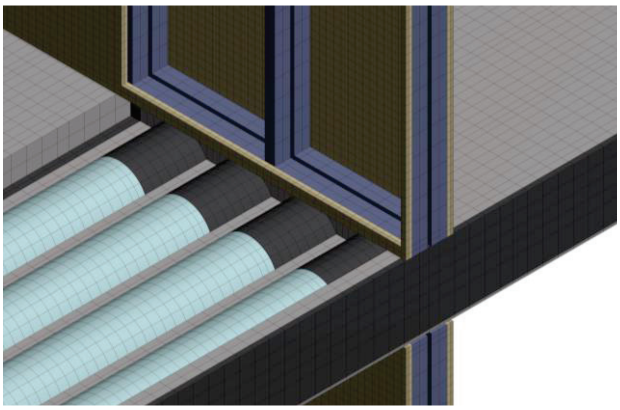

Figure 3. A section of the junction model's geometry. Parts of the top section of the hollow core slab and the gypsum walls have been hidden.

According to ISO 10848-1 [11], the measured velocity level difference $D_{v,ij}$ should fulfill the condition:

$$D_{v,ij} \geq 3\,dB - 10\log\left(\frac{m_i f_{c,j}}{m_j f_{c,i}}\right) \quad (3)$$

where m_i and m_j (kg/m^2) are the surface masses of elements i and j, and $f_{c,i}$ and $f_{c,j}$ are the critical frequencies of the elements. If the condition can't be met, additional structural elements can be added to increase the total losses of the measurement setup. [11] Based on preliminary simulations, the total loss factor of the floor structure was increased by adding structural shell elements on the free edges of the floor structure. The shells represent a continuation of the hollow core slabs, as well as load bearing walls at the ends of the floor span. The additional elements were modeled in such a way, that no unwanted flanking paths were created.

The shells representing the load bearing walls were 200 mm thick, and they were given isotropic elastic properties as shown in Tab. 1. For the shells representing the continuations of the floor structure, isotropic elastic material properties equivalent to the orthotropic material properties of the corresponding hollow core slabs were calculated.

The junction geometry was simply supported on all free edges of the partitioning wall, as well as the free edges of the shell elements. The junction line itself was left unsupported to allow for generation of in-plane waves in the junction [2]. In-plane waves were included since they are important for vibration propagation [13].

2.4.3 Mesh

The model was meshed using hexahedral, quadratic elements. For the air cavities, the mesh size was 1/6 of the wavelength of sound in air λ (m) according to [14]. The mesh size for the structural parts of the model was 1/6 of the bending wavelength λ_B (m) according to [2].

2.4.4 Velocity level difference

To determine the vibration reduction index K_{ij}, the direction averaged velocity level difference $D_{v,avg}$ must first be determined (see Eqn. 1). The simulation of $D_{v,avg}$ of the junctions was carried out using a steady-state, harmonic acoustics analysis. The finite element model was built based on the ISO 10848-1 [11] measurement method. However, in Gerretsen's [10] original work, an assumption of diffuse vibration fields was made. To account for this requirement, a rain-on-the-roof (ROR) excitation was used instead of multiple point excitations as described in ISO 10848-1. A rain-on-the-roof excitation means that a unit magnitude, random phase force is applied to each free node on the element surface [13]. A ROR-excitation has also been previously used for investigating a junctions velocity level difference in [2] and [4]. The area in which the ROR-excitation was applied was selected according to the ISO 10848-1 [11] measurement setup criteria.

To determine the velocity level difference for the floor-floor path, the junction is excited from element i using the ROR-excitation. Then the velocity level L_v (dB) is determined for each element according to [11]. From the velocity levels the velocity level difference from plate i to plate j $D_{v,ij}$ can be determined from:

$$D_{v,ij} = L_{v,i} - L_{v,j} \tag{4}$$

Then the process is repeated by exciting element j to determine the velocity level difference in the opposite direction $D_{v,ji}$. The direction averaged velocity level difference $D_{v,avg}$ is simply the arithmetic average of $D_{v,ij}$ and $D_{v,ji}$:

$$D_{v,avg} = \frac{D_{v,ij} - D_{v,ji}}{2} \tag{5}$$

2.4.5 Structural reverberation time

To determine the vibration reduction index K_{ij}, the direction averaged velocity level difference $D_{v,avg}$ is normalized using the structural reverberation times of the elements i and j according to Eqn. 1 and 2. The structural reverberation time T_s for each hollow core slab element was determined from the FE-model of the junction by applying the half-power bandwidth method [15].

2.4.6 Validation

To ensure that the FE-model works as intended, the model was validated using measured vibration reduction index data by Mahn [16]. The measured K_{ij} data was for a junction of a hollow core slab floor and a concrete masonry wall.

2.5 Airborne sound insulation between rooms

The significance of the core fill on airborne sound insulation between rooms was examined using the ISO 12354-1 [7] prediction method. For the floor-floor and ceiling-ceiling paths, the K_{ij} values acquired from the FE-model described in section 2.4 were used.

In the calculations, the following flanking structures were used:

- Four thicknesses of exterior concrete sandwich walls and one lightweight exterior wall.
- Three thicknesses (O27, O32, O37) of hollow core slab floor/ceiling structures.
- Two different interior flanking walls (one heavy and one lightweight wall).

In each case the floor and ceiling were both hollow core slab structures of the same thickness. The partitioning wall was a lightweight double leaf wall as described in section 2.1. The standardized level difference $D_{nT,w}$ (dB) was calculated for each combination of flanking structures, with and without the core fill in the junction. In total, the airborne sound insulation was investigated in 60 cases.

3. RESULTS AND DISCUSSION

3.1 Validation of the FE-model

The measured and calculated vibration reduction index for the cross junction of a concrete masonry wall and a hollow core slab floor as shown in [16] is presented in Fig. 4.

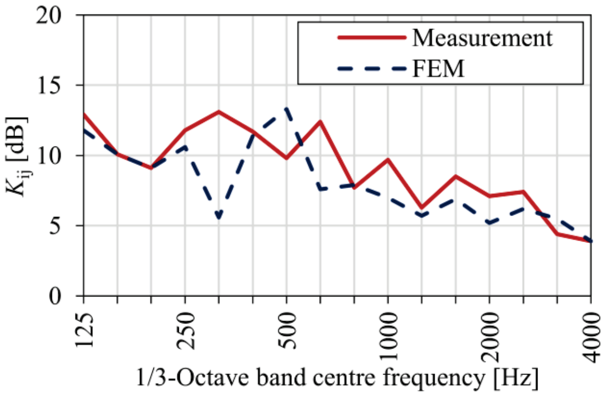

Figure 4. Measured [16] vs. simulated vibration reduction index.

The calculated vibration reduction index corresponds well with the measured values, with a larger deviation in the 315 Hz and 630 Hz 1/3-octave bands. The deviations can be attributed to the lack of accurate geometrical data on the hollow core slab used, as well as the lack of information on the material properties of the measured products.

3.2 Vibration reduction index

The calculated vibration reduction indices for each size of hollow core slab, with and without the core fill, are presented in Fig. 5–7.

From Fig. 5–7 it is apparent that the core fill improves the vibration attenuation in the high frequencies, while the effect is lesser in the mid frequencies and negligible in the low frequencies. In Fig. 8 are shown plots of the acoustic pressure in the 320 mm hollow core slab's voids and the total displacement of the junction, with and without the core fill. The results in Fig. 8 are plotted at ~1000 Hz, where the effect of the core fill is most noticeable.

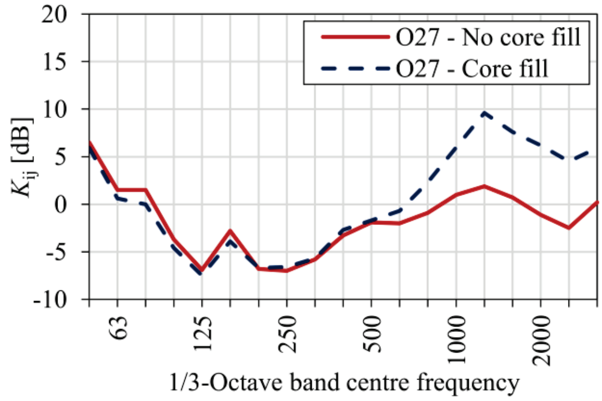

Figure 5. The simulated vibration reduction index K_{ij} for the 265 mm hollow core slab.

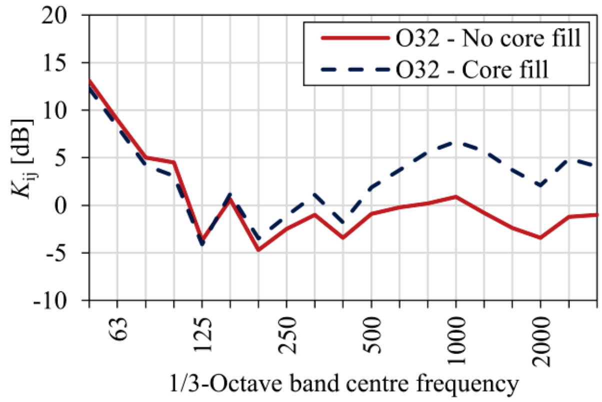

Figure 6. The simulated vibration reduction index K_{ij} for the 320 mm hollow core slab.

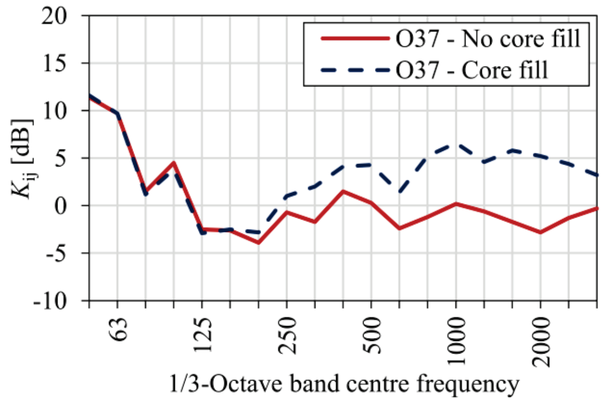

Figure 7. The simulated vibration reduction index K_{ij} for the 370 mm hollow core slab.

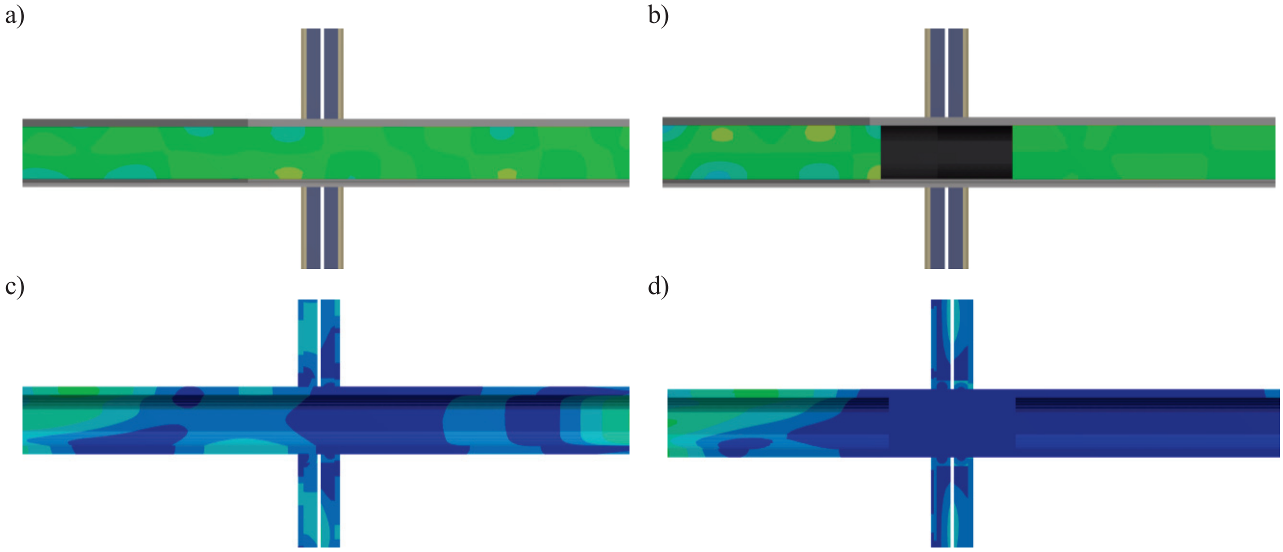

Figure 8. The calculated response in the junction of the 320 mm hollow core slab (O32) and a lightweight double leaf wall at ~1000 Hz. a) acoustic pressure, no core fill. b) acoustic pressure, core fill included. c) total displacement, no core fill. d) total displacement, core fill included. In a) and b), dark green represents an acoustic pressure of 0 Pa. In c) and d), dark blue represents a total displacement of 0 mm.

3.3 Airborne sound insulation between rooms

The standardized level difference $D_{nT,w}$ was calculated according to ISO 12354-1 [7] and ISO 717-1 [17] for several combinations of flanking structures. The effect of the core fill on the single number quantity $D_{nT,w}$ between rooms is presented in Fig. 9.

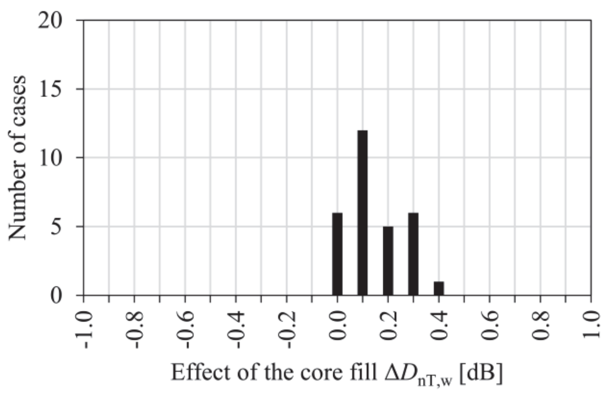

Figure 9. The effect of the concrete core fill on the standardized level difference $D_{nT,w}$ between rooms.

The calculation results in Fig. 9 show that the core fill does not have a significant effect on the standardized level difference $D_{nT,w}$, with the largest improvement of the single number quantity being 0,4 dB.

From the results it was found that the floor-floor path along the hollow core slabs was not the dominant flanking path. Instead, it was usually flanking sound along the exterior concrete wall that was the factor limiting the horizontal airborne sound insulation. When the flanking walls were lightweight, the effect of the floor-floor path became more noticeable.

4. CONCLUSIONS

The effect of a concrete core fill on the vibration reduction index K_{ij} of a junction between a hollow core slab structure and a double leaf partitioning wall was investigated using the finite element method. The FE-model was validated using measured K_{ij} data by Mahn [16]. Simulations of K_{ij} were carried out with three different thicknesses of hollow core slabs, with and without the core fill.

The simulation results show that the core fill improves the vibration attenuation in the floor-floor path in the high frequencies. In the mid frequencies the improvement is less significant, and in the low frequencies it is negligible.

To investigate the significance of the core fill on airborne sound insulation between rooms, calculations were carried out using the ISO 12354-1 [7] prediction method. From the calculation results, it was apparent that despite the core fill improving the vibration attenuation in the floor-floor path, there was no significant improvement in the airborne sound insulation.

The floor-floor path along the continuous hollow core slabs was not the dominant flanking path in most of the investigated cases. When the airborne sound insulation was limited by the floor-floor path, it was in the mid-frequencies, whereas the core fill's effect on the vibration reduction index is significant only in the high frequencies. Therefore, according to the calculation results, the core fill does not appear to improve the apparent airborne sound insulation between rooms despite improving the vibration attenuation in the junction.

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