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FLANKING TRANSMISSION IN STEEL-CONCRETE COMPOSITE FLOORS

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This paper describes measurements and predictions of wall airborne sound insulation tests in buildings with a continuous steel-concrete composite floor beneath a plasterboard separating partition. Although this is a common building typology with many applications including residential (flats and hotels), offices and schools, there is a marked absence of specific data in the literature that can be used to calculate flanking transmission between rooms through the floor. As such, empirical data must be relied upon for such calculations. However, calculations based on empirical data are demonstrated to under-estimate the sound insulation achieved in practice.

This paper presents field measurements of both direct floor sound insulation, for the profiled steel-concrete composite slab alone, and velocity level differences for flanking transmission. This new input data for flanking calculations with the EN 12354-1 model gives a more reliable prediction of sound transmission between adjacent rooms. This data overcomes the need to rely on previous in-situ measurements with different floor and wall details. Floating floors may be omitted in many instances of this building typology based on the new data presented in this paper. Control of flanking sound can be more suitably specified with appropriate floating floors where it is required for particular performance requirements.

Keywords: Flanking sound, steel concrete composite floors

1. Introduction

Continuous steel-concrete composite floor decks are a popular choice in steel framed buildings due to their structural efficiency and speed of construction. Acoustic advice on the use of continuous steel-concrete composite floors has frequently been to install a floating floor or screed in order to prevent flanking transmission through the floor from undermining the performance of the partition, involving significant costs associated with construction materials and worker hours. This construction type is frequently used in large developments with rooms for residential purposes, such as student accommodation blocks and hotels. These rooms are typically around 2.8 m by 4.5 m, including a bathroom pod. The experience of Apex Acoustics suggested that the desired level of sound insulation between two adjacent rooms may be achieved with no floating floor construction. On the basis of calculations, however, this would not appear to be the case. Despite continuous steel-concrete composite floors with plasterboard partitions being a common building typology, there is surprisingly little information on either the direct or flanking sound performance of these floors in the literature.

Airborne sound insulation wall tests were carried out between rooms for residential purposes at a development (Site A) with a steel-concrete composite floor construction and no floating floors. Bastian software [1], which implements the calculation model for sound transmission described in EN 12354-1 [2] was used to model the performance expected from such a construction. The floor construction chosen in the model was a homogeneous concrete floor with equivalent surface mass to that of the profiled composite floor used at Site A. Since only the direct transmission through the partition and flanking path through the floor were considered, the Bastian results were expected to underestimate the overall room to room transmission (and therefore overestimate the sound insulation), since contributions from other paths were neglected. Measured sound test data from 13 pairs of rooms with identical dimensions and separating partitions were averaged and compared with the Bastian prediction. The results are shown in Fig. 1. Significantly, the sound insulation performance in the lower frequency range, between 125 and 400 Hz was better in practice than predicted; as the performance for English Building Regulations is evaluated in terms of $D_{nT,w} + C_{tr}$, this means that the overall single figure value can be better in practice than that predicted.

The relative contributions of the direct transmission path and floor flanking path in Fig 1 show that the sound insulation performance is calculated to be limited across most of the frequency range by flanking transmission through the floor. The separating wall at Site A was a twin stud wall so that the steel columns were entirely enclosed within the wall.

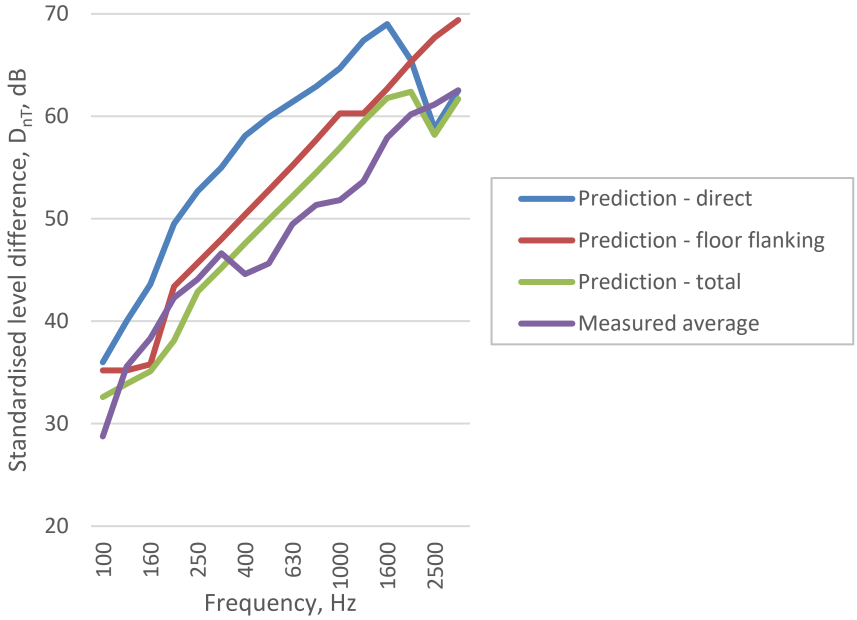

Figure 1: Comparison of Bastian sound insulation predictions with measured data

2. EN 12354-1 model and assumptions

The EN 12354-1 standard uses a simplified version of Statistical Energy Analysis (SEA) adapted for the use of measured data, with each building element assigned as an SEA subsystem. In the EN 12354-1 calculation method, sound transmission is simplified into a direct path and individual flanking paths involving a single source room element, receiving room element and junction between the two. The contribution of each of these paths is calculated separately and the transmission paths are then combined outside the framework of SEA.

Since EN 12354-1 is based on an SEA model, the limitations on prediction accuracy that apply to the results of SEA also apply to the calculation method described in the standard. Most subsystems in buildings only approximate an ideal SEA subsystem and the accuracy of predictions therefore largely depends on how closely the subsystems approximate these conditions.

Building elements are assumed to be homogeneous and isotropic, with relatively diffuse vibration fields. The vibration field should be dominated by the reverberant field rather than the direct field, therefore building elements should not be highly damped with a strong gradient in energy density [3]. The number and grouping of modes across the relevant frequency range is key to the accuracy of an SEA model. Ideally, modal density should be even across the frequency range of interest, modes should be well spread and of sufficient number that the statistical averages used are meaningful. In masonry elements, the mode count and modal overlap factor are frequently insufficient at low frequency, leading to greater prediction uncertainty in this range.

Steel-concrete composite floors may be considered to be orthotropic – the physical properties of the plate are different in orthogonal directions due to the repeating profile of the steel floor deck. Orthotropic behaviour in a building element may impact on its modal behaviour and the diffuseness of the vibration field it supports.

The SEA model is based on the assumption that individual subsystems are 'weakly coupled', where the 'coupling' is between modes in separate subsystems. This is to ensure that there are separate modes in each subsystem and that an energy level difference between the two exists. If two elements are strongly coupled then they will behave as one subsystem, with no net energy transfer between the two. Nightingale and Bosmans warn that in the case of a continuous concrete slab under a lightweight partition wall, "it is quite likely that the vibration response of the floor slab will be unaffected by the presence of the wall" [3]. In a traditional SEA model, the continuous floor should be modelled as a single subsystem; the simplified EN 12354-1 model does not allow this. This may not be overly detrimental to measurement accuracy; theoretical and experimental studies have demonstrated good predictions even where strong coupling occurs, especially where the coupled plates have similar wavenumbers and a long junction length [3].

3. Measurements

In the EN 12354-1 model, the sound reduction index of a flanking element is used to characterise the coupling between the vibration field in the element and the sound field in the source or receiving room. Inaccuracy in this input parameter could therefore substantially affect the modelling results. Since laboratory test data for composite concrete floors without a suspended ceiling below is not widely available, the sound reduction properties of homogeneous concrete with equivalent surface mass had previously been assumed for composite floors.

To obtain more accurate data for the sound reduction properties of profiled concrete floors, seven in-situ airborne sound insulation tests were carried out at another development with rooms for residential purposes (Site B) with Metfloor 60 floors (overall slab depth 150 mm) [4] and plasterboard ceilings not yet installed to the rooms tested. The measured $D_{nT,\mathrm{w}}$ +C_{tr} had a range of 5 dB, which was attributed to varying amounts of flanking transmission. At the time of testing, room doors had not yet been installed and airborne flanking transmission up stairwells and incomplete risers was observed in some tests. The average apparent sound reduction index R' for four tests with the least notable flanking transmission is compared in Table 1 with calculations in Insul [5] of the sound reduction index of a homogeneous concrete floor with equivalent surface mass.

The composite floor sound insulation performance is noted to be measured up to 6 dB higher in the mid-frequency range than predicted by Insul. It may be possible to attribute the lower than predicted sound insulation performance at high-frequency to noise flanking through the building façade and other paths. In further EN 12354-1 prediction model calculations presented below, the effect of flanking transmission is neglected and the apparent sound reduction index R' is taken as the in-situ sound reduction index R for input data.

Another key input parameter for the EN 12354-1 model is the vibration reduction index K_{ij} of the 'junction' between floor plates. The ISO 10848 series of standards describes methods for measuring the vibration reduction index of a junction in the laboratory. The measurement method is described in the frame document ISO 10848-1 [6] with additional guidance on the application of this to junctions comprised of at least one heavy element provided in ISO 10848-4 [7]. The methodology of these standards was adapted to measure the vibration reduction index of a 'junction' between floor plates in adjacent rooms at Site B. Since the measurements, draft international standards (ISO/DIS 10848-1:2016 [8] and ISO/DIS 10848-4:2016 [9]) with an extended scope have been published which cover measurements of flanking transmission in the field and contain more explicit guidance on the applicability of measured parameters. These draft standards were not available at the time of the measurements, and therefore the guidance has not been used.

Table 1: Floor sound reduction index: comparison of measured R' with Insul calculated R

Source	Third-octave band centre frequency, Hz Sound reduction index R, R', dB							
	100	125	160	200	250	315	400	500
Measured	38	43	42	44	45	47	49	50
Insul	42	42	41	42	39	41	43	46

Source	Third-octave band centre frequency, Hz Sound reduction index R, R', dB							
	630	800	1000	1250	1600	2000	2500	3150
Measured	52	52	54	55	54	55	56	57
Insul	49	51	54	56	59	62	63	65

Calculation of the situation invariant quantity K_{ij} as defined in EN 12354-1 requires the measurement of two parameters: the direction-averaged velocity level difference $\overline{D_{v,ij}}$ and the structural reverberation time T_s of the elements under test. The direction-averaged velocity level difference between two pairs of rooms was measured using a standard ISO tapping machine as vibration source.

Due to the sizes of the rooms tested, it was not possible to adhere to the minimum separation distances required by ISO 10848-1 between the vibration source and test element boundaries. Where the tapping machine was placed closer to the junction under test than permissible in the standard, an underestimation of the velocity level difference would be expected. Third octave band results for the two tests are arithmetically averaged.

According to ISO/DIS 10848-1, results for the measured velocity level difference should be "expressed as a single number for each of the low-, mid-, and high-frequency ranges, and these average values shall be used for all one-third octave bands in each of the low-, mid-, and high-frequency ranges respectively". Both these frequency-range averages and the individual third octave band values are shown in Table 2.

The measured velocity level difference was considerably higher than both Bastian predictions for a similar junction and guidance based on empirical measurements presented in Annex E of EN 12354-1, as shown in Table 2. In the case of data from Annex E of EN 12354-1, the direction-averaged velocity level difference is calculated from the junction reduction index by subtracting 5 dB, following guidance from a recently published draft version of EN 12354-1 [10].

The low values for velocity level difference taken from Bastian and Annex E of EN 12354-1 reflect the assumption that the effect of the separating partition is not sufficient to significantly interrupt the bending wave field in the floor plate. This assumption is consistent with the low internal losses expected in homogeneous concrete and the SEA assumption of a diffuse vibration field in each building element, regardless of room geometry. Annex E of EN 12354-1 requires $\overline{D_{v,ij,situ}}$ to have a minimum value of 0 dB to ensure an energy gradient between source and receiving elements.

ISO 10848-1 gives $D_{v,ij} \geq 3$ dB (simplified to reflect the equal masses and critical frequencies of the source and receiving elements of the rooms tested) as an objective criterion for 'weak coupling' between elements. The standard states that "the measured value of K_{ij} may not be relevant due to strong coupling" if this is not satisfied. The measured values of the direction-averaged velocity level difference satisfy this criterion in all but the 315 Hz third octave band.

Table 2: Comparison of measured velocity level difference with modelled and empirical data

Source	Third-octave band centre frequency, Hz Velocity level difference $D_{v,ij,\,situ}$, dB							
	100	125	160	200	250	315	400	500
Measured	3.7	6.5	6.6	4.3	3.5	2.5	4.7	5.0
Measured (low-, mid-, high-frequency averages)	5.5				5.2			
Bastian	1.0	1.0	0.9	0.9	0.9	0.9	1.0	1.0
EN 12354-1 Annex E	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Source	Third-octave band centre frequency, Hz Velocity level difference $D_{v,ij,\,situ}$, dB							
	630	800	1000	1250	1600	2000	2500	3150
Measured	4.9	7.9	7.6	6.7	8.0	6.9	7.2	9.3
Measured (low-, mid-, high-frequency averages)	5.2			7.6				
Bastian	1.0	1.1	1.1	1.2	1.2	1.3	1.4	1.5
EN 12354-1 Annex E	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

A strong decay of vibration with distance may cause the measured velocity level difference to be greater than expected. Annex A of ISO/DIS 10848-1 details a measurement procedure to assess the decrease in vibration level with distance. Measurements in accordance with this procedure both perpendicular and parallel to the floor profile in composite floors are suggested as further work to determine whether the decrease in vibration with distance is large enough to invalidate the assumptions behind the model. A decrease in vibration level 6 dB across an element in the direction perpendicular to the junction line is considered in ISO 10848-1 as the maximum allowable for K_{ij} to be a relevant parameter. Previous measurements of vibration decay with distance using a tapping machine as vibration source have indicated that this criterion may not be satisfied in room sizes typical of rooms for residential purposes.

In order to correct the measured direction-averaged velocity level difference to the situation invariant quantity K_{ij}, the structural reverberation time of the floor was also measured in two rooms. Taking accurate measurements of structural reverberation time has proved problematic due to the characteristics of vibration decay in a solid plate. The minimum reverberation time measurable is mainly determined by the transient decay of the third octave band filters, leading to frequency dependent lower limits for a valid reverberation time measurement. The structural reverberation times measured for the floor, as is typical of reverberation times in masonry structures, were much shorter than those usually measured in rooms and were typically lower than the limit for validity in the third octave bands up to 250 Hz. Another feature of vibration decay curves in masonry structures is a "distinctive curvature due to energy returning from other parts of the building structure" [11]. Hopkins and Robinson [11] propose suitable evaluation procedures for structural reverberation times on heavyweight walls and floors with shorter evaluation ranges than the standard T_{20} used in rooms and altered initial decay values.

It is proposed that pending accurate in-situ measurements of structural reverberation time, the $D_{v,ij,situ}$ is applied directly in predictions made for other buildings with a similar construction and similar plate and junction geometry.

ISO 10848-4 requires that the mode count in each frequency band and modal overlap factor are estimated for measurement accuracy. Calculations of the predicted mode count and modal overlap factor are not presented here due to uncertainty about the plate critical frequency and structural reverberation time. ISO/DIS 10848-4 notes that "K_{ij} is generally overestimated when measured for a transmission path that includes an element with a modal overlap factor of less than unity".

Four preliminary sound insulation wall tests have been completed at Site B. The measured parameters have been inputted into equation (25a) from EN 12354-1 to calculate the flanking sound reduction index of the floor plate. Laboratory test data for the separating partition between rooms is taken from Knauf [12]; in this case the separating wall is a single stud with resilient bar, and the structural steel columns protrude into the rooms. Following guidance of EN 12354-1 for lightweight, double leaf elements, $T_{s,situ}$ is taken as equal to $T_{s,lab}$.

The overall sound transmission between rooms is calculated for different combinations of source data using the EN 12354-1 model, considering only the direct path and floor-floor flanking path, with other flanking pathways neglected, and is shown in Fig 2.

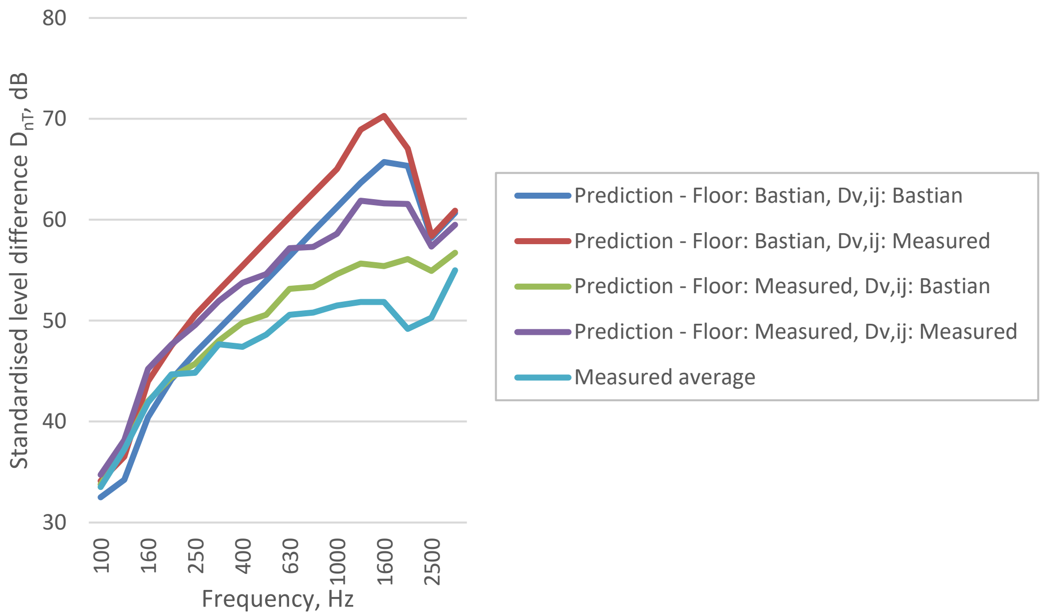

Figure 2: Site B – comparison of EN 12354-1 predictions with various combinations of input data

The best prediction is achieved using a combination of measured apparent sound reduction data for the floor and Bastian velocity level difference, and is a clear improvement on the prediction made using input data from Bastian only. The relative contributions of the direct transmission and floor-floor flanking path to the EN 12354-1 prediction are compared with the measured results in Fig. 3.

The predicted overestimation of performance compared with the measured values is consistent with the sound insulation performance of the separating wall being degraded in practice compared with laboratory test data and contributions from other flanking paths, notably, transmission associated with the steel columns forming part of the separating partition in the rooms tested. This effect would be expected at high frequency in particular. Other more significant flanking paths in these particular rooms are noted from the sound insulation tests to be associated with the protruding column detail, and flanking through the doors to the corridor. The prediction indicates that the floor flanking transmission limits the overall performance over the majority of the relevant frequency range, though the direct path is likely to provide a greater contribution to the sound transmission in practice due to on-site defects.

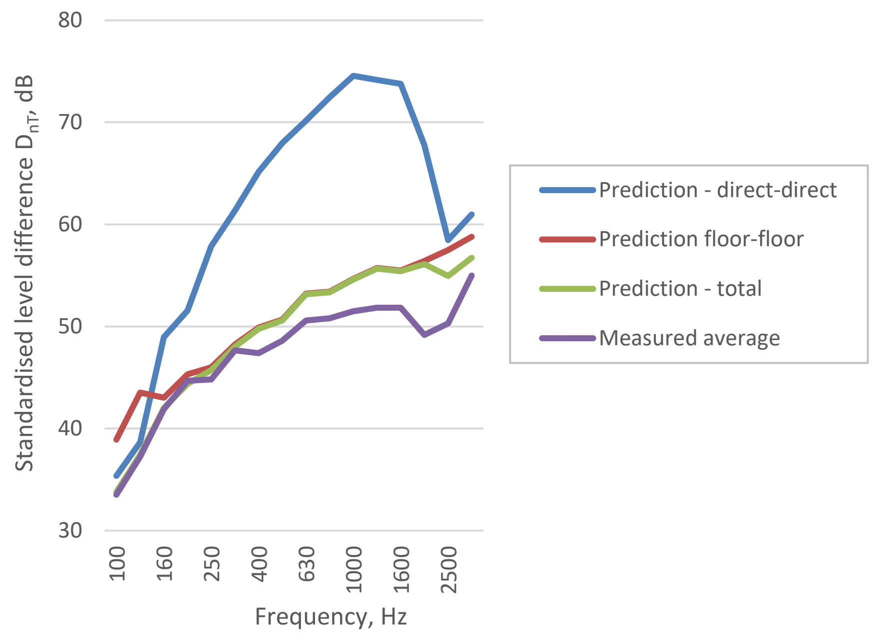

Figure 3: Site B – comparison of predicted sound insulation with measured data

In order to evaluate the transferability of this prediction method to other sites, sound transmission has been predicted for a typical pair of rooms at Site A using velocity level difference data from Bastian and measured floor data, corrected to reflect the different floor surface mass at this site. Figure 4 shows the relative contributions of the direct and floor paths to the prediction, averaged measured sound test results, and the initial Bastian prediction. The new prediction is an improvement on the initial Bastian prediction, other than in the high-frequency range, where it is noted that the measured test results show better performance at high frequency even than the prediction of direct sound insulation alone.

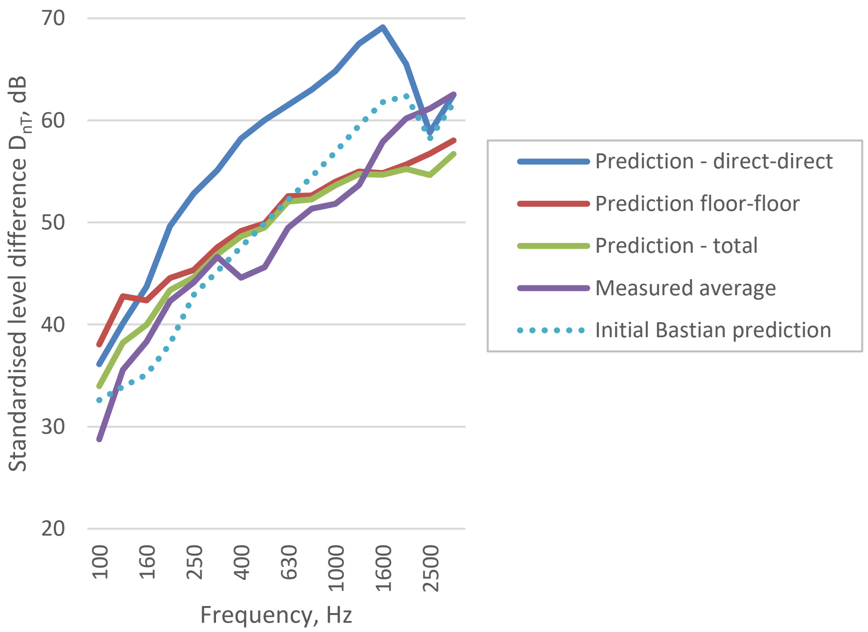

Figure 4: Site A – comparison of updated prediction with measured data and initial prediction

4. Uncertainty

Many sources of uncertainty remain in the predictions. While some uncertainty is an unavoidable consequence of differences between the theoretical and practical behaviour of building elements, measurement uncertainty and variation in workmanship between nominally identical constructions, among other things, uncertainty in the model input parameters may be reduced by further measurements in similar constructions and access to more accurate data for the floor sound insulation performance. The decay of vibration with distance should be measured in accordance with the procedure described in ISO/DIS 10848-1 to better understand potential non-compliance with modelling assumptions.

5. Conclusion

Measurements of both direct floor sound insulation and velocity level difference in the field has produced input data for flanking calculations with the EN 12354-1 model; this gives a more reliable prediction of sound transmission between adjacent rooms with profiled concrete floors and a plasterboard separating partition. This data overcomes the need to rely on previous in-situ measurements. The new data indicates that flanking transmission is considerably lower in some frequency ranges than was calculated using previous empirical data. Floating floors may be omitted in many instances of this building typology based on the new data presented in this paper. Control of flanking sound can be more suitably specified with appropriate floating floors where it is required for particular performance requirements.

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