Empirical relationships between single number quantities for impact sound insulation

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Summary
In the Belgian building acoustical standards, two different descriptors are currently used in the requirements for the impact sound insulation, depending on the building type. On the one hand, the weighted standardised impact sound pressure level $L'_{\mathrm{n}T,\mathrm{w}}$ is used, on the other hand the descriptor $L'_{\mathrm{I}} = L'_{\mathrm{n}T,\mathrm{w}} + C_{\mathrm{I}}$. To simplify the standards, one is considering to express all requirements using the descriptor L'_{I}. For this reason, the translation between the two single number quantities was investigated for different types of floor constructions. Empirical relationships were derived from a statistical analysis performed on a large database of laboratory measurements extended with simulations for heavyweight reference floors. A strong correlation is found between the descriptors $L_{\mathrm{n,w}}$ and L_{I} when the floor constructions are subdivided in the following three categories: I) heavyweight reference floors, II) lightweight reference floors, and III) heavyweight or lightweight floors with floor coverings and/or suspended ceilings. For each category, the correlation coefficient between the two descriptors is larger than 0.97. Furthermore, the L_{I}-value of heavyweight reference floors can be accurately estimated from the floor mass per unit area. A clear correlation is also revealed between the single number quantities describing the reduction in impact sound level, e.g. by floor coverings or suspended ceilings, depending on the type of reference floor.

PACS no. 43.55.Rg, 43.55.Ti

1. Introduction

The standard ISO 717-2 [1] defines the single-number quantities for the impact sound insulation of floors and for the impact sound reduction of e.g. floating floors. The single-number quantities are derived from one-third-octave band measurements of the normalized impact sound pressure level, L_{n}, or the standardized impact sound pressure level $L_{\mathrm{n}T}$. Two rating methods are described. The weighted normalized and standardized impact sound pressure levels, $L_{\mathrm{n,w}}$ and $L_{\mathrm{n}T,\mathrm{w}}$, are determined by comparing the impact sound pressure level spectrum with a reference curve, while the spectrum adaptation term C_{I} is based on the unweighted linear impact sound level. Similarly, the improvement of impact sound insulation can be described by the weighted reduction in impact sound pressure level, ΔL_{w}, or by the single-number reduction ΔL_{lin} based on the unweighted linear impact sound pressure level. The descriptor ΔL_{w} characterizes the reduction of $L_{\mathrm{n}(T),\mathrm{w}}$, while ΔL_{lin} characterizes the reduction of $L_{\mathrm{I}} = L_{\mathrm{n}(T),\mathrm{w}} + C_{\mathrm{I}}$.

In the current Belgian standard for dwellings [2], the weighted standardized impact sound pressure level, $L'_{\mathrm{n}T,\mathrm{w}}$, is used in the requirements for impact sound insulation. On the other hand, the Belgian standard for schools [3] uses the descriptor $L'_{\mathrm{I}} = L'_{\mathrm{n}T,\mathrm{w}} + C_{\mathrm{I}}$ in the requirements. The primed symbols are used to denote a value obtained *in situ*, i.e. with flanking transmission.

To simplify the standards and also in view of a European harmonization [4], one is considering to express all requirements using the descriptor L'_{I}. For this reason, the translation between the two single number quantities was investigated for different types of floor constructions. Because the Belgian standard does not consider the enlarged frequency range (including the frequency bands 50 Hz, 63 Hz and 80 Hz), the present study concerns single number quantities calculated for frequencies $100 - 2500$ Hz.

Similar studies [4, 5] have been performed but considered the spectrum adaptation term $C_{\mathrm{I},50-2500}$ in the enlarged frequency range. The most extensive study into relationships between rating systems has been reported by Scholl *et al.* [5]. The floor constructions were divided in two categories: heavy floors and lightweight wooden floors. The heavy floors incorporated different types of bare concrete floors with different types of floor coverings (soft floor coverings, float-

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ing floors). In [4], a data set of 51 floors (including homogeneous, heavy floors with and without floor coverings, cement based floating floors, lightweight floating floors and two lightweight floor constructions) was analyzed.

2. Methodology

2.1. Database of measurements

Statistical relationships were reduced from a database of measurements performed in the Laboratory of Acoustics of the Belgian Building Research Institute (BBRI). The database for Cross-Laminated Timber (CLT) floor constructions was further extended with measurement results found in literature [6, 7, 8]. The extended database included:

- 85 heavy homogeneous floors;
- 137 heavy homogeneous floors with floating floor;
- 6 lightweight wooden reference floors (without floating floor and without ceiling plate);
- 4 lightweight wooden reference floors with fixed ceiling plate (without floating floor);
- 151 lightweight wooden floor constructions with floating floor and/or suspended ceiling;
- 19 CLT reference floors (without floating floor and suspended ceiling);
- 61 CLT floor constructions with floating floor and/or suspended ceiling.

The database for the heavy homogeneous floors consist of 81 measurements of the reference floor (140 mm or 160 mm concrete) used to measure the improvement of impact sound insulation by floor coverings. Four additional measurements on lighter floors - consisting of a $4 - 5\,\mathrm{cm}$ concrete layer or screed on top of a lightweight wooden or steel structure, have been included because the L_n-spectrum follows that of homogeneous floors. The lightweight wooden reference floors consist of wooden joists with subfloor sheeting, with or without rigidly connected ceiling.

2.2. Simulations for heavy homogeneous floors

Because the variation in heavy homogeneous floors as measured in the laboratory was very limited, the database was extended with calculation results for homogeneous concrete floors with thickness varying between 40 mm and 280 mm (surface mass $100\,\mathrm{kg/m^2}$ - $700\,\mathrm{kg/m^2}$). The calculations were performed with following formula (annex B of ISO 12354-2 [9]):

$$L_\mathrm{n} \simeq 155 - 30\lg\frac{m'}{1\,\mathrm{kg/m^2}} + 10\lg\frac{T_\mathrm{s}}{1\,\mathrm{s}} + 10\lg\sigma + 10\lg\frac{f}{f_\mathrm{ref}}\ \mathrm{dB}, \qquad (1)$$

with $f_\mathrm{ref} = 1000\,\mathrm{Hz}$, m' the mass per unit area, T_s the structural reverberation time and σ the radiation factor for free bending waves of the floor. The radiation factor for free bending waves σ and the structural reverberation time T_s was calculated in accordance with annex B and C of ISO 12354-1:2017 [10], assuming a floor area of $3\,\mathrm{m} \times 3\,\mathrm{m}$. The material properties used for the concrete are: density $\rho = 2500\,\mathrm{kg/m^3}$, Young's modulus $E = 33\,\mathrm{MPa}$, longitudinal wave velocity $c_\mathrm{L} = 3700\,\mathrm{m/s}$, and internal loss factor $\eta = 0.005$.

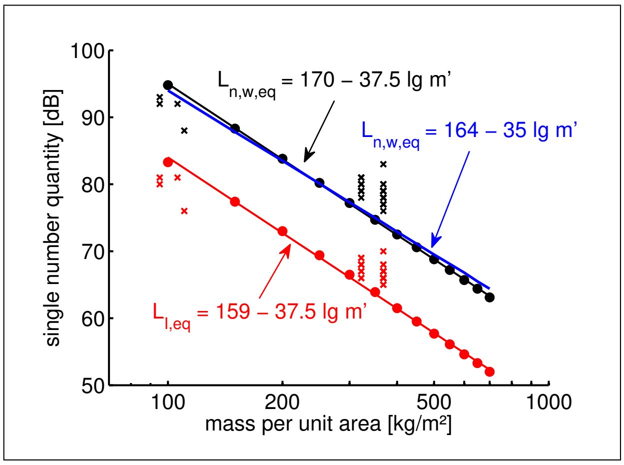

Figure 1. Equivalent single number quantities $L_\mathrm{n,w,eq}$ and $L_\mathrm{I,eq}$ for homogeneous floor constructions. ● simulations, × measurements

3. Results

3.1. Single number quantities $L_\mathrm{n,w,eq}$ and $L_\mathrm{I,eq}$ for heavy homogeneous floors

Figure 1 shows the calculated values of $L_\mathrm{n,w}$ and L_I (bullets) for the homogeneous floor constructions. ISO 12354-2 [9] gives following formula to calculate the weighted normalized impact sound pressure level for homogeneous floor constructions with mass per unit area between $100\,\mathrm{kg/m^2}$ and $600\,\mathrm{kg/m^2}$:

$$L_\mathrm{n,w,eq} \simeq 164 - 35\lg\frac{m'}{1\,\mathrm{kg/m^2}}\ \mathrm{dB}. \qquad (2)$$

The simulations for the bare concrete floors with mass per unit area between $100\,\mathrm{kg/m^2}$ and $700\,\mathrm{kg/m^2}$ give a slightly different correlation:

$$L_\mathrm{n,w,eq} \simeq 170 - 37.5\lg\frac{m'}{1\,\mathrm{kg/m^2}}\ \mathrm{dB}. \qquad (3)$$

Equation (3) corresponds better with the simulations for the heaviest concrete floors with $m' > 500\,\mathrm{kg/m^2}$ compared to equation (2). A new relation can be deduced for the single number quantity $L_\mathrm{I} = L_{\mathrm{n}T,\mathrm{w}} + C_\mathrm{I}$ for homogeneous floors in function of the mass per unit area:

$$L_\mathrm{I,eq} \simeq 159 - 37.5\lg\frac{m'}{1\,\mathrm{kg/m^2}}\ \mathrm{dB}. \qquad (4)$$

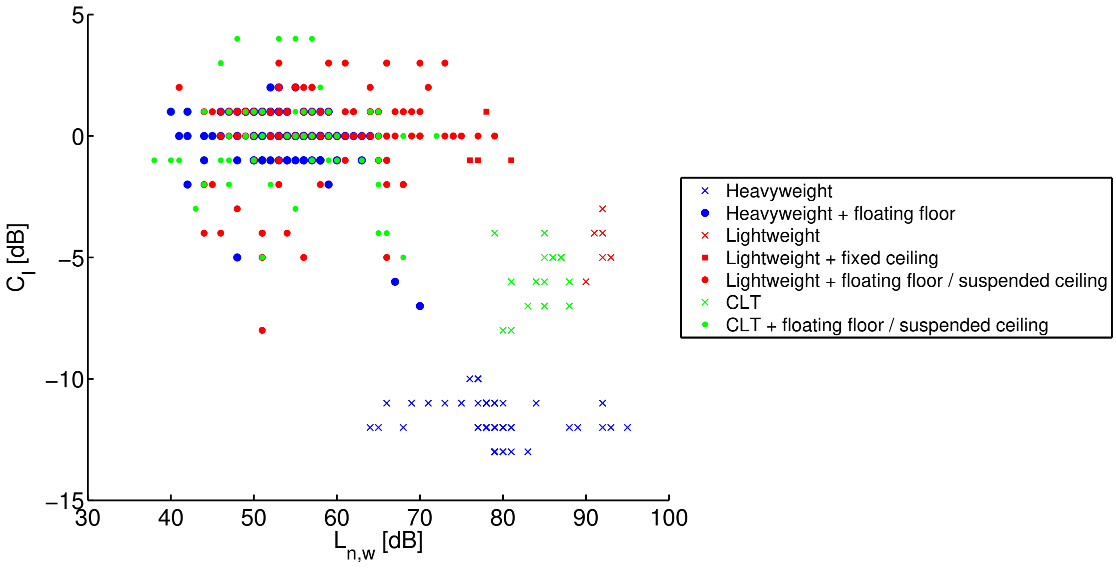

Figure 2. Relation between C_{I} and $L_{\mathrm{n,w}}$

By comparing equations (3) and (4), it follows that the spectrum adaptation term C_{I} is independent of the mass per unit area and equals -11 dB.

Figure 1 also compares the ISO 12354 simulations with measurement results for homogeneous floor constructions. The measurement results for $L_{\mathrm{n,w}}$ and L_{I} of the reference concrete floors (with mass per unit area of approximately 320 kg/m^2 and 370 kg/m^2) show a spread of approximately 5 dB. The spread may be caused by the variation in structural damping of the homogeneous floor constructions. The ISO 12354 simulations underestimate the impact sound level of all these tested floors. On the other hand, the single number rating of the four lighter hybrid floor constructions (wood/steel + screed/concrete with mass per unit area of approximately 100 kg/m^2) is overestimated by the simulations.

3.2. Statistical relations between $L_{\mathrm{n,w}}$, C_{I} and L_{I}

There is no clear correlation between the spectrum adaptation term C_{I} and the single number quantity $L_{\mathrm{n,w}}$ (figure 2). The spread for the reference floor constructions is limited. For the heavy homogeneous floors without floating floor, the spectrum adaptation term C_{I} varies between -10 and -13 dB. For the CLT reference floors, C_{I} varies between -4 and -8 dB, for the wooden reference floors without ceiling plate, C_{I} lies between -3 and -6 dB and for the wooden reference floors with fixed ceiling plate, C_{I} lies between $+1$ en -1 dB. The spread is however larger for the floors with floating floor and/or suspended ceiling, with C_{I}-values between $+4$ and -8 dB.

The correlation between the single number quantities L_{I} and $L_{\mathrm{n,w}}$ is more clear (figure 3). The data can be subdivided in three groups:

I) heavy homogeneous floors,
II) lightweight reference floors, i.e. CLT floors and wooden floor constructions without floating floor and ceiling
III) floor constructions (heavyweight, lightweight, CLT) with floating floor and/or (suspended) ceiling.

Following linear statistical relations are found between L_{I} en $L_{\mathrm{n,w}}$, with a correlation coefficient R larger than 0.97 (figure 3).

$$\mathrm{I}: \quad L_{\mathrm{I}} = 0.96\, L_{\mathrm{n,w}} - 8.3\,\mathrm{dB} \tag{5}$$

$$\mathrm{II}: \quad L_{\mathrm{I}} = 1.16\, L_{\mathrm{n,w}} - 19.6\,\mathrm{dB} \tag{6}$$

$$\mathrm{III}: \quad L_{\mathrm{I}} = 1.00\, L_{\mathrm{n,w}} + 0.2\,\mathrm{dB} \tag{7}$$

The floor constructions from group III (constructions with floating floor and/or suspended ceiling) are the only ones that may meet the requirements for impact sound insulation between dwellings in Belgium. On average, L_{I} equals $L_{\mathrm{n,w}}$ (i.e. $C_{\mathrm{I}} = 0$ dB) for group III.

Figure 4 compares the relations (5), (6) and (7) with statistical relations from literature [4, 5]. It must be noted that the relations from [4] and [5] apply to the single number quantity $L_{\mathrm{I},50-2500} = L_{\mathrm{n,w}} + C_{\mathrm{I},50-2500}$, i.e. including the lowest frequency bands $50-80$ Hz. These frequency bands especially influence the overall performance of lightweight floor constructions and floor constructions with floating floor for which $L_{\mathrm{n,w}} < 60-65$ dB [4]. The relations from literature clearly show a different trend. Apart from the difference in C_{I} and $C_{\mathrm{I},50-2500}$ for the constructions with higher performance, the dissimilarity is mainly

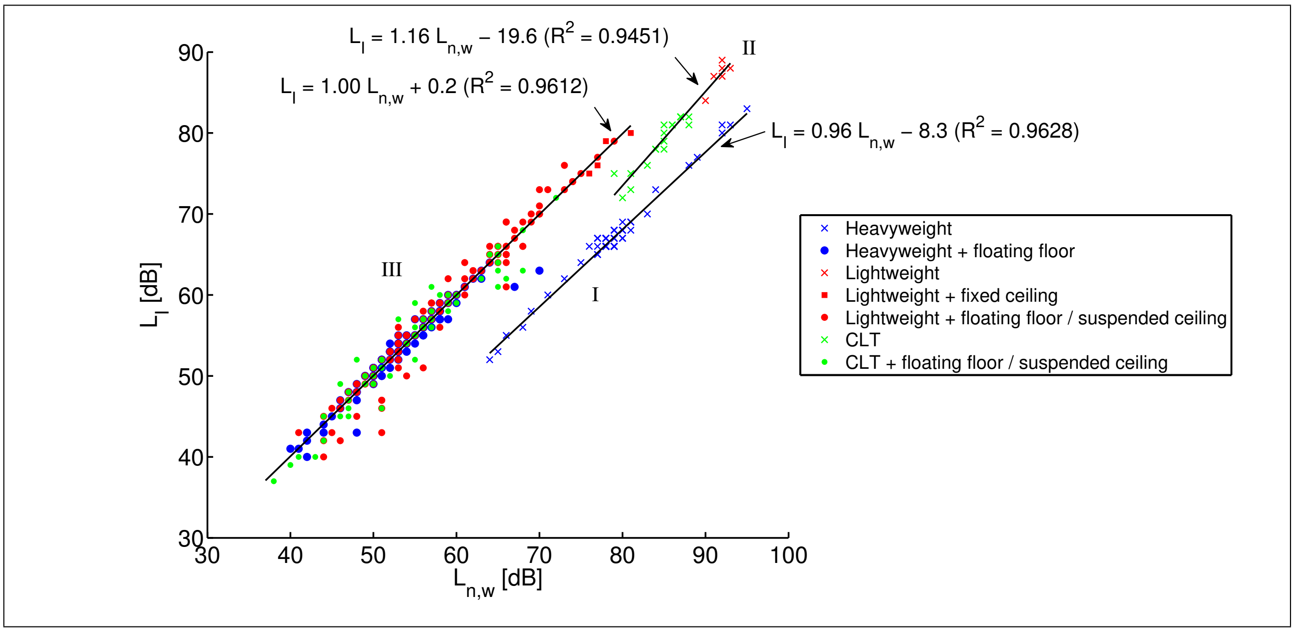

Figure 3. Statistical relations between $L_{\mathrm{I}} = L_{\mathrm{n,w}} + C_{\mathrm{I}}$ and $L_{\mathrm{n,w}}$

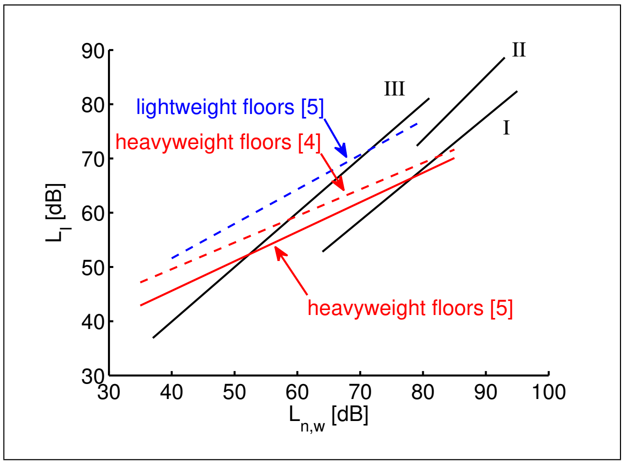

Figure 4. Statistical relations between $L_{\mathrm{I}} = L_{\mathrm{n,w}} + C_{\mathrm{I}}$ and $L_{\mathrm{n,w}}$ derived from BBRI measurements versus relations from literature [4, 5].

caused by the different classification used. The traditional division into heavyweight constructions (with or without floating floor) and lightweight constructions, as used in [4] and [5], seems however less appropriate because the heavyweight floors with floating floor clearly show a different trend than the heavyweight reference floors (figure 3).

For group III, figure 3 shows outliers up to +3 dB and −8 dB compared to the statistical relation. However, the spread of values in the figure appears to be worse than it actually is. An analysis of the tests with $L_{\mathrm{n,w}}$-values between 50 dB and 57 dB shows the distribution pattern of figure 5.

3.3. Statistical relations between ΔL_{w} and ΔL_{lin}

A floating floor or suspended ceiling will improve the impact sound insulation. The improvement of ΔL_{lin} for the single number quantity L_{I} can be deduced from the improvement of ΔL_{w} for the single number quantity $L_{\mathrm{n,w}}$ with good correlation (figure 6). The measurement results can be divided into three groups:

I) improvements of heavy homogeneous floors (floating floors)
II) improvements of wooden, lightweight floors (floating floors and/or suspended ceilings)
III) improvements of CLT floors (floating floors and/or suspended ceilings)

The following statistical relations between ΔL_{lin} and ΔL_{w} can be deduced with a correlation coefficient R larger than 0.96.

$$\mathrm{I}: \quad \Delta L_{\mathrm{lin}} = 0.80\,\Delta L_{\mathrm{w}} - 7.2\,\mathrm{dB} \tag{8}$$

$$\mathrm{II}: \quad \Delta L_{\mathrm{lin}} = 0.91\,\Delta L_{\mathrm{w}} - 0.7\,\mathrm{dB} \tag{9}$$

$$\mathrm{III}: \quad \Delta L_{\mathrm{lin}} = 0.93\,\Delta L_{\mathrm{w}} - 3.1\,\mathrm{dB} \tag{10}$$

For heavy homogeneous floors the improvement of $L_{\mathrm{n,w}}$ is on average 10 − 15 dB larger than the improvement of L_{I}. It must be noted that relation (8) is only valid for a standard screed thickness of 50 − 80 mm. The three measurements results for a screed of 200 mm show that the additional mass of a thicker screed results in a larger improvement for ΔL_{lin}.

For lightweight floors the improvement of $L_{\mathrm{n,w}}$ is on average 1 to 5 dB larger than the improvement of L_{I}. The measurement results for CLT follow a similar trend, but for a certain ΔL_{w}-value, the improvement ΔL_{lin} is on average 1.5 − 2 dB smaller for CLT floors

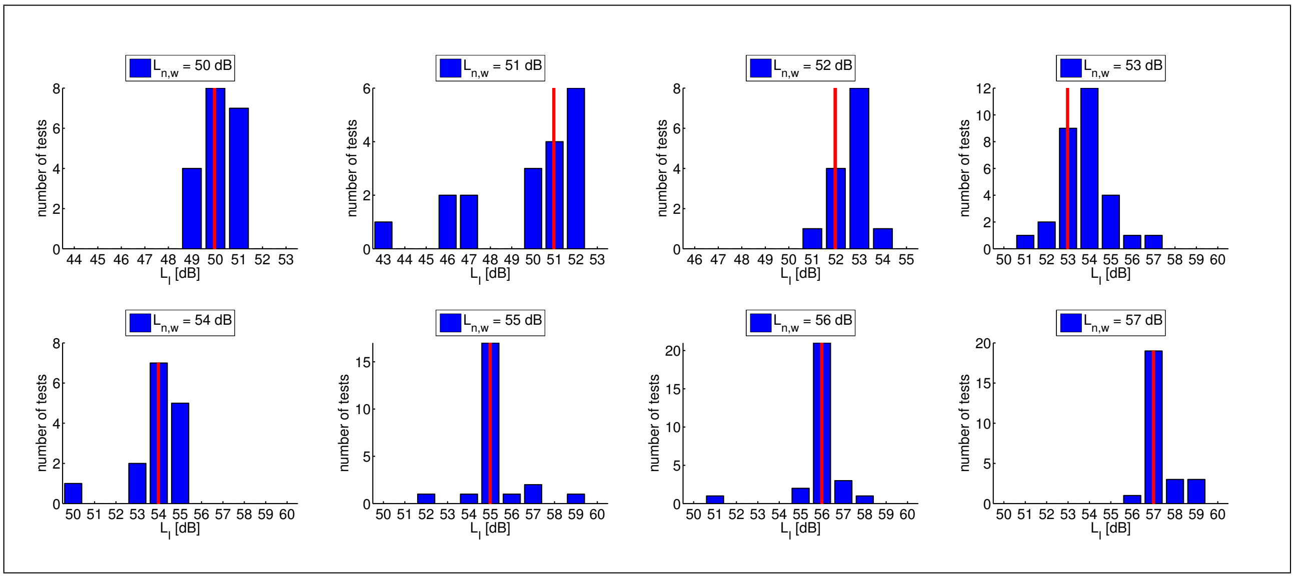

Figure 5. Statistical distribution of all available tests for specific $L_{\mathrm{n,w}}$-values for group III. The red lines indicate the values calculated with the empirical relation (7).

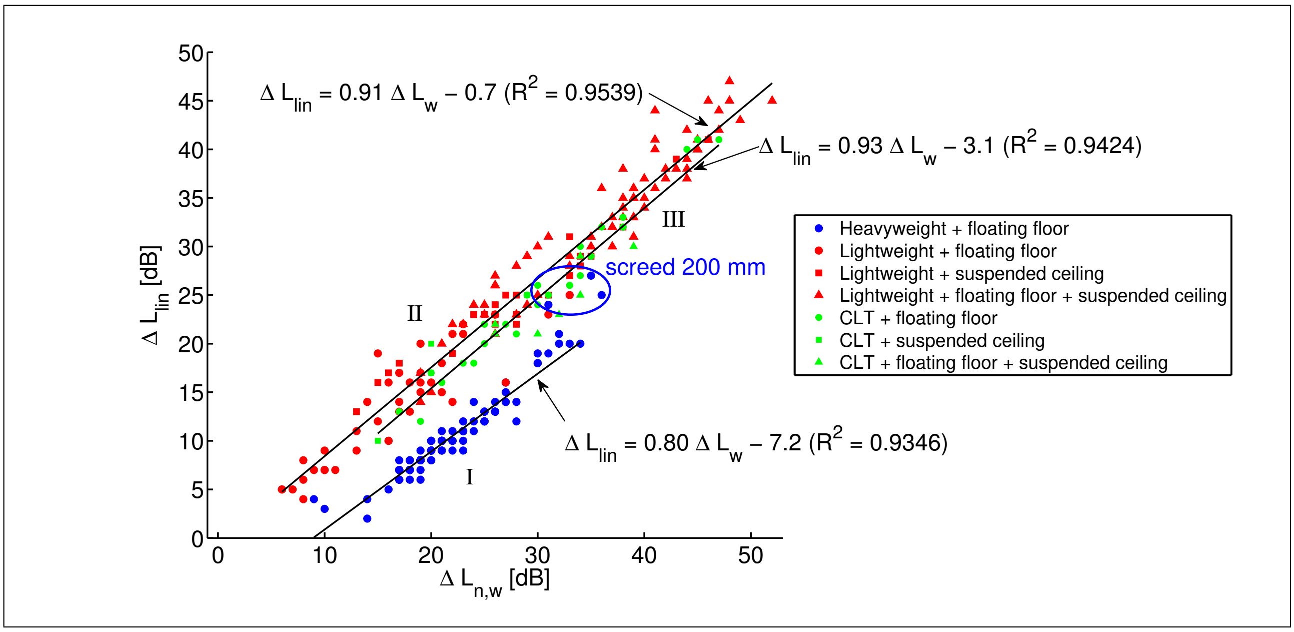

Figure 6. Statistical relations between ΔL_{lin} en ΔL_{w}.

(equation (10)) than for lightweight reference floors (equation (9)).

For a specific value for ΔL_{w}, the spread in ΔL_{lin}-values is limited for the heavy homogeneous floors of group I (figure 7). Due to the larger variation in ΔL_{w}-values for the lightweight and CLT reference floors, the number of tests for a specific ΔL_{w}-value in the database is limited. As a result, there is no clear bell-shaped distribution visible (see figure 8 for results for group II). In general, the spread seems however larger for group II (lightweight floors) and group III (CLT floors) compared to group I (heavyweight floors).

4. Conclusions

New empirical formula have been proposed for the single number quantities $L_{\mathrm{n,w}}$ and L_{I} of heavyweight homogeneous floors in function of the mass per unit area of the floor.

The statistical investigation of an extended database of laboratory measurements shows that there is a strong correlation between the single number quantities $L_{\mathrm{n,w}}$ and L_{I}, provided that the floor constructions are divided in following three categories: I) heavyweight reference floors, II) lightweight reference floors, and III) heavyweight or lightweight floors with floor coverings and/or suspended ceilings. Simi-

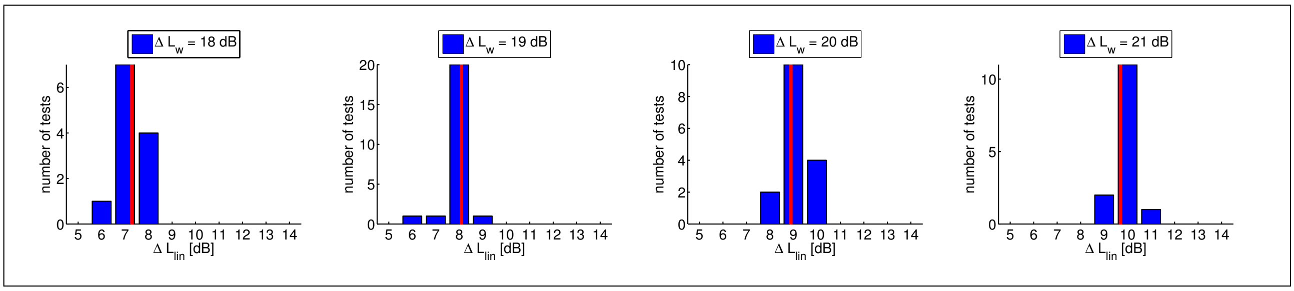

Figure 7. Statistical distribution of all available tests for specific ΔL_w-values for group I. The red lines indicate the values calculated with the empirical relation (8).

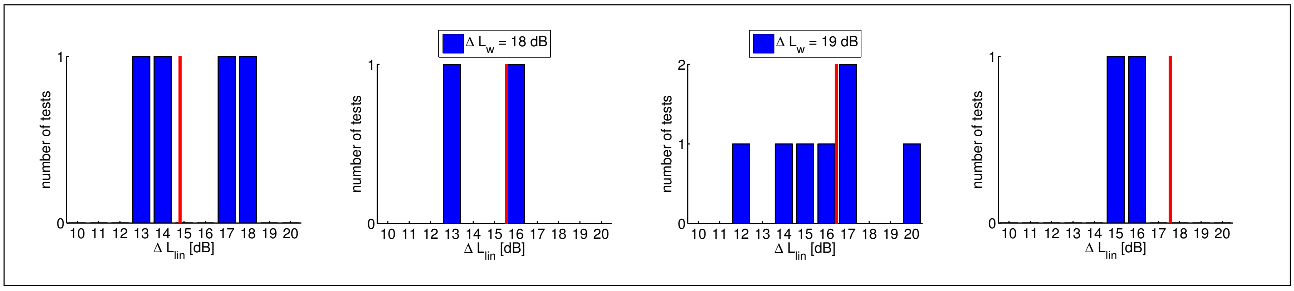

Figure 8. Statistical distribution of all available tests for specific ΔL_w-values for group II. The red lines indicate the values calculated with the empirical relation (9).

larly, there is a clear correlation between the quantities ΔL_w and ΔL_lin which characterize the impact sound insulation improvement of a floating floor or a suspended ceiling. The relation between ΔL_w and ΔL_lin depends on the type of reference floor (lightweight/CLT/heavyweight).

Acknowledgement

The authors are grateful for the financial support from the Federal Public Service Economy of Belgium.

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