UNCERTAINTY OF MEASURED AND CALCULATED SOUND INSULATION IN BUILDINGS - RESULTS OF A ROUND ROBIN TEST

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A NORDTEST inter-laboratory comparison has been made \textit{in situ} with the participation of 8 laboratories. The operators measured airborne and impact sound insulation of 7 partitions according to the ISO 140 standards and some additional guidelines. Variations of sound insulation, and their components, have been analyzed. In addition, field measurements of sound insulations in 40 building cases were compared to calculations according to EN 12354 (-1, -2). Safety margins for predictions of 3 dB are now recommended for calculation of heavy building partitions, with respect to an estimated risk of 5\% being disapproved by a sample measurement \textit{in situ} because of accumulated uncertainties. If some averaging of measured data is allowed, and the constructions used are well known, 1-2 dB margins may be sufficient.

1 Introduction

The uncertainties of measurement and prediction of the sound insulation in a building put increased expenses on all actors of the building process, because they have to keep safety margins to prescribed requirements. Knowledge of these uncertainties and the appropriate safety margins may therefore be a critical competence for these actors. This paper deals with estimates of both types of uncertainty, and some recommendations on suitable safety margins for predictions are suggested.

Requirements on sound insulation are defined by the Swedish sound classification standards SS 25267 [1] and SS 25268, as well as the ISO 140- and ISO 717 series of standards. New standards for the measurement and the prediction (by calculation) of sound insulation, EN 12354 (ISO 15712) are now incorporated as a means of verification. The frequency range of interest was expanded in 1999 to include low frequencies (50-100 Hz). This project was initiated 2001 to examine how the new methods apply to typical building cases with respect to the new requirements on sound insulation (within the expanded frequency range).

In the first part of this study, an inter-laboratory comparison (round robin) has been conducted in Mölndal, Sweden with the support from the Nordic Innovation Center (formerly NORDTEST) and the eight participating laboratories. The operators made sound insulation measurements on 7 partitions located in the same building. The operators were instructed to follow the procedures of ISO 140 parts 4, 7 and 14, as well as the guidelines in the informative annex H of the standard SS 25267. The differences of the measured sound insulation and its components (sound pressure level difference, normalized impact sound pressure level, reverberation time, partition area and receiving room volume) are analysed in the first part of this paper.

In the second part of the study, about 40 calculations of sound insulation between rooms in real buildings were made according to EN 12354 (ISO 15712). The calculated values were compared to field measurements obtained from consultants from the Nordic countries. The resulting differences (calculated-measured results) include all kind of variations that may be expected and therefore yield a reliable estimate of the uncertainty that may be expected in practical design work. This uncertainty estimate could even be expected to be conservative, because several details on the building construction measured were not properly documented, and default values had to be chosen for the calculation, with respect to traditional constructions in houses of the same age and style. In the individual case, when all details are known, a more precise calculation could be made. However, there are still several uncertainties to consider, and there will always remain a difference between calculated and measured sound insulations \textit{in situ}. The task is to characterize the mean deviation (and correct for this) and the random variations (and to apply a safety margin for these).

2 Summary of results

The main results from the comparisons are tabulated below. Detailed results are given in the next section. The project report [2] contains some advice on possible improvements of the measurement procedure, a detailed description of the study and all results.

From the measurements, the sample standard deviation of the weighted airborne and impact sound insulations and the spectrum adaptation terms $R'_{W}(C;C_{50,3150})$ and $L_{n_{1,2}} + C_{1,50,3500}$ are presented in table 1.

Special attention was paid to variations of sound insulation related to the choice of the area $S$ of the common partition and the volume $V$ of the receiving room. From the measurements, the sample standard deviation of the factor $10 \log (S7/0,16V)$ was determined to 0,6-0,8 dB, including the variation of...
Table 1. Variation of measured airborne and impact sound insulation and spectrum adaptation terms

<table>
<thead>
<tr>
<th>Estimated uncertainties, in decibels, dB:</th>
<th>Standard deviation, 7 (all) cases</th>
<th>90% confidence (1,6*Standard-deviation), 7 (all) cases</th>
<th>Standard deviation, 5 regular spaces</th>
<th>90% confidence (1,6*Standard-deviation), 5 regular spaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R'_w )</td>
<td>1,0</td>
<td>1,7</td>
<td>0,7</td>
<td>1,1</td>
</tr>
<tr>
<td>( R'_w + C )</td>
<td>1,2</td>
<td>1,9</td>
<td>0,8</td>
<td>1,3</td>
</tr>
<tr>
<td>( R'<em>w + C</em>{tr} )</td>
<td>1,3</td>
<td>2,2</td>
<td>0,9</td>
<td>1,5</td>
</tr>
<tr>
<td>( R'<em>w + C</em>{50-3150} )</td>
<td>1,3</td>
<td>2,1</td>
<td>0,7</td>
<td>1,1</td>
</tr>
<tr>
<td>( R'<em>w + C</em>{tr,50-3150} )</td>
<td>1,7</td>
<td>2,7</td>
<td>0,8</td>
<td>1,3</td>
</tr>
<tr>
<td>( L'_{n,w} ) (4 cases)</td>
<td>0,7</td>
<td>1,1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( L'_{n,w} + C_I )</td>
<td>0,7</td>
<td>1,2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( L'_{n,w} + C_I,50-2500 )</td>
<td>0,8</td>
<td>1,3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Comparison between measured and calculated sound insulation, 40 building cases

<table>
<thead>
<tr>
<th>Difference calculated-measured insulation:</th>
<th>( R'_w )</th>
<th>( R'<em>w + C</em>{50-3150} )</th>
<th>( L'_{n,w} )</th>
<th>( L'_{n,w} + C_I,50-2500 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>…between the averages (systematic variations)</td>
<td>-0,17</td>
<td>0,42</td>
<td>1,87</td>
<td>1,91</td>
</tr>
<tr>
<td>…standard deviation (random variations)</td>
<td>2,3</td>
<td>1,6</td>
<td>4,4</td>
<td>2,9</td>
</tr>
<tr>
<td>…90%-confidence limits (5% risk of disapproval)</td>
<td>3,5</td>
<td>3,0</td>
<td>5,1</td>
<td>2,7</td>
</tr>
</tbody>
</table>

Table 3. Recommended safety margins for calculations on heavy building constructions

<table>
<thead>
<tr>
<th>Practical safety margin to a requirement in an individual case, as verified by a sample measurement</th>
<th>( R'_w )</th>
<th>( R'<em>w + C</em>{50-3150} )</th>
<th>( L'_{n,w} )</th>
<th>( L'_{n,w} + C_I,50-2500 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

reverberation time \( T \). A brief survey was made among the operators on the choice of \( S \) and \( V \) for 5 additional (schematic) cases (with a fixed value of \( T \) ). The cases comprised dwellings with open plan constructions, or regular spaces with several wardrobes or a toilet room covering parts of the partition and receiving room. The sample standard deviation was then 0,7 dB (one outlier was removed from the set of data, 1,2 dB including this special case). It can be concluded, that work could be made to improve the instructions of the measurement standard to make the choice of \( S \) and \( V \) less ambiguous. Another strategy would be to express sound insulation requirements as \( D_{nT,w} \) instead of \( R'_w \). Then, the choice of \( S \) and \( V \) does not have any influence on the result. A compromise, adopted in SS 25267, was to restrict the ratio \( V/S \geq 3,1 \) in which case \( R'_w \) equals \( D_{nT,w} \). For impact sound, \( L'_{n,w} \) is equal to \( L'_{nT,w} \) when \( V \geq 31 \) m\(^3\), and this limitation was also added to SS 25267.

In order to compare calculated and measured sound insulation, about 40 field measurements were collected from consultants in the Nordic countries and analyzed. Estimates of the sound insulation between the rooms were made with calculations according to EN 12354 (ISO 15712). All measurements had been made vertically in buildings with concrete slab floors, with various floorings, where a mix of heavy and light walls defined the measurement spaces. The resulting
differences between calculated and measured values yield a more reliable estimate of the practical uncertainty that may be expected in practical planning work, because all kind of uncertainties are included in the comparison.

The software used for the comparison was BASTIAN version 2.1 and the input data for concrete slabs, floorings and walls were taken from the Nordic database for this software, used by several consultants in the Nordic countries. The number of comparisons is given in [2] for each type of weighted value.

The values correspond to practical experience and approximately to the results of a previous Nordtest study by Pedersen [3], except for $L'_{A,W}$ that is higher than expected, but reasons for this has not been examined further.

From the results presented, the safety margins of table 3 are recommended for practical planning work, applicable when sound data of building elements have been tested and documented properly, and the quality of workmanship is high. Under these conditions, the uncertainty may be assumed less than given in table 2. The margins in table 3 do not guarantee that non-conformance with requirements may never occur, in fact it must even be expected that measured sound insulation may occasionally be less satisfactory than predicted, by say 1-2 dB.

The measurement uncertainty can be reduced to some extent by a careful measurement work and an extended averaging procedure. The uncertainty of calculations of the performance in a building with specified products may be reduced by a continuous comparison between predicted and measured sound insulation. Input data for the calculations may initially be taken from laboratory values or theoretical calculations, and adjusted after some time if empirical experience proves there are systematic differences that need to be compensated for. The manufacturers should take on the responsibility for maintenance of their data, but all actors of the building industry could contribute, with an open mind to exchange of experience.

### 3 Results - details

The main parameters studied are variations about the ensemble average of the sound pressure level difference, impact sound pressure level, reverberation time, partition area and the receiving room volume. Results are shown in the figures below as third octave band data 50-3150 Hz, followed by the weighted airborne sound insulation including four spectrum adaptation terms, in decibels (dB):

$$ R'_{W} \quad R'_{W}+C \quad R'_{W}+C_{I,50-3150} \quad R'_{W}+C_{I,50-3150} $n,w \quad L'_{n,w} \quad L'_{n,w}+C_{I} \quad L'_{n,w}+C_{I,50-2500} \quad \text{(dB)}$$

The overall results, including all (7) cases, for the airborne sound insulation, are shown in figure 1. The solid (red) line with triangular marks shows the standard deviation about the ensemble average. The solid (blue) line with squared marks shows the standard deviation of the sound pressure level difference between the source and receiving rooms. The solid (green) line with circular marks shows the standard deviation of the sound absorption term 10 log($S/A$), or rather 10 log($S/0.16V$). The dashed (red) line with triangular marks shows the standard deviation of sound insulation reproducibility according to ISO 140-2:1991.

In the figure 2, the standard deviations are plotted as in figure 1, but two measurement cases have been considered statistical outliers and removed from the data series. This is discussed to some detail in the project report [2].

The figure 2 shows some interesting changes as compared to figure 1. The uncertainty of $R$ is still explained mainly by the variations of $\Delta L$, but there is a significant improvement. The uncertainty of the weighted sound insulation $R'_{W}$ is now only 0.7 dB. Even more interesting, the uncertainty does not increase much when the low frequency spectrum adaptation term $C_{I,50-3150}$ is added, in spite of the fact that some microphone positions were much closer to the room boundaries than recommended in ISO 140-4 annex B. This conclusion is concordant with the opinion among some building acoustic consultants in the Nordic countries, who have had a positive experience of the extension of the frequency range from 100-3150 Hz to 50-3150 Hz made to the Swedish building code (BBR) in 1999. Most consultants were by then already using this extended frequency range and supported the changes of code, even though some were very sceptical. It is not clear however, if the consultants also changed the measurement procedure accordingly, so this comparison with practical experience should merely be considered as an indication, not an empirical evidence.

**Impact sound:**

The normalized impact sound pressure levels $L_{n}$, in decibels (dB), were determined by 4 of the operators in 4 cases. The operators were not the same in all building cases. The overall variation of result (standard deviation) are demonstrated by figures 3 and 4 below, where the standard deviation of reproducibility in ISO 140-2 are included for comparison.
Figure 1. Standard deviation of sound pressure level differences (dL), the receiving room absorption term 10log(S/A) and the resulting sound reduction index (dR). All measurement cases included.

Figure 2. Standard deviation of sound pressure level differences (dL), the receiving room absorption term 10log(S/A) and the resulting sound reduction index (dR). Dashed thin lines replicate Figure 1 and the solid lines show the same quantities as in Figure 1 but only results from 5 regular spaces are included. Legend, see figure 1.
Figure 3. Standard deviation of normalized impact sound pressure levels, all cases

Figure 4. Illustration of the variation of normalized impact sound pressure levels, all cases, with the standard deviation according to ISO 140-2 plotted for comparison (dashed lines).
4 Agreement between measurements and calculations in situ

When a calculation model of a building is established according to EN 12354 (ISO 15712), several decisions must be taken by the operator.

- Appropriate input data for each building element that enclose the transmission rooms
- The size of partitions and room dimensions. The size of the model may differ from the actual physical dimensions, particularly where the geometry of the building is complicated, e.g. staggered rooms, open-plan spaces etc.
- Junctions between the building elements
- The actual performance of elements in the building depends on how elements are connected to each other and the quality of workmanship (air leakages, structural sound bridges etc.). Another important issue is the choice of loss factor, that relates to the structural vibration energy transmission through external building elements (i.e., elements that are connected firmly to the partition and flanking structure and therefore extract energy from the “system”, but do not increase the flanking transmission to the receiving room). This loss factor is particularly important to heavy building systems. Large concrete slabs, with room partitions built by light weight plasterboard walls, will give substantially higher sound insulation vertically than buildings with heavy partition walls. This is sometimes referred to as the “area factor” and it is mentioned in EN 12354

One may assume that calculation results may vary depending on the operators experience and which building element data in the database is considered most appropriate to model the real building construction.

When comparisons are made with respect to the conformance to field measurements, measurement uncertainty has to be taken into account

When EN 12354 was issued in 2000, there was a need to compare measurements and calculations of real buildings, to see whether there are systematic or random errors that need to be taken into account. The sound insulations in a variety of building cases (mainly residential buildings) have been analysed by the project leader, using the BASTIAN software and a propriety database of building elements. The comparison between measured and calculated sound insulation, in the tables 2 and 3, refers to vertical sound transmission through concrete slabs with different floorings.

The measured building cases were not documented with respect to all building products used for the respective building. When the calculations were made, data for constructions typical for the age and type of building were used when no other information was available. Naturally, such assumptions increase uncertainty of the calculations. In spite of these uncertainties, the table above shows that the 90% confidence limits agree reasonably well with a common experience, that a 3 dB margin is sufficient for most practical applications. The risk of a field measurement (performed according to all relevant standards) being non-conformant to the requirement is then less than 5%. This confidence limit corresponds to a coverage factor of $k=1.6$, assuming the random variations being normally distributed and the influence of systematic errors being negligible. If well documented building products are used, and the quality of workmanship is high, the margins should be possible to reduce, according to the recommendation in table 3.

No comparison has been made in this project of data for light weight slabs, but the practical experience is that the margin must be increased compared to the uncertainty values given above. This depends on the type of product and the quality of workmanship. Some indications are given by Pedersen [3].

5 References


[4] Simmons, C. - Reliable building element sound insulation data for EN 12354 calculations facilitates analysis of Swedish dwelling houses. Inter-noise proceedings, 2004 Prague