Sound Insulation of a Wall in a Panel House with Demountable Joints

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Abstract. Classical technologies used in civil engineering are characterized by limited adaptability. Easy disassembling and relocation to another location are practically eliminated. Flexible building systems, that make this possible, are not only favourable in terms of sustainable buildings. These structures are an alternative to traditional prefabricated or monolithic systems implemented in previous years. This solution is more sophisticated in term of sustainability than solutions with rigid non-demountable joints. Problems associated with it arise with regard to guaranteeing the desired properties of such a structure. Many requirements are placed on partition wall structures. The paper deals with the verification of the sound insulation of a partition wall made of reinforced concrete panels with dismountable joints. The principle of the solution of the demountable joints in the vertical heading joint between the panels is described. The heading joint is designed in two variations, which are described in detail. The aim of the structural solution is to ensure meeting sound insulation for use between flats. Furthermore, the fire resistance of the whole structure is necessary to ensure, too. The sound reduction index of the wall depending on the frequency is first calculated using three different methods of computation. Parameters of the used material, namely bulk density, longitudinal wave speed density and loss factor, were measured to ensure reliability of calculations. The results from measurement of the sound reduction index of the two variants of the solutions of demountable joints in acoustic chamber are presented at the end of the paper.

1. Introduction

Many requirements are placed on the dividing structure. The ability of the partition structure to protect sound propagate from one space to another (from the sound source room to the sound reception room) is one of them. The sound insulation is represented by two quantities:

- weighted apparent sound reduction index $R'_{w}$ (dB), which expresses the ability of structures to protect against airborne sound;
- weighted normalized impact sound pressure level $L'_{n,w}$ (dB), which expresses the ability of structures to protect against sound that spreads through the structure.
The requirement for airborne sound insulation relates the investigated party-wall. The requirement placed on the wall structure between flats ($R'_w \geq 53$ dB by the Czech standards CTN 73 0532 [3]) was required. The structure was designed with regard to the satisfaction of appropriate fire resistance.

2. Description of the dismountable wall system

A unique demountable prefabricated system was developed within the project TA02010837 [7] in the years 2012-2015. Final modifications of demountable contacts and joints and completion by peripheral elements and by structures of finishing cycle are the subject of the project TH02020309 [8]. Besides other things, two variants of energy and material efficiency peripheral structures for demountable prefabricated building systems with the possibility of reuse were designed as part of the project solution. A detailed description of the structural solution of the dismountable system is not given here due the limited length of this paper. More detailed information can be found in the article Construction systems of the new generation – part 2: A dismountable prefabricated wall system [9].

3. Description of the examined wall structure

Measurement of sound insulation was performed on 2 mock-up model. The wall was assembled from two identical panels with a width of 1.77 m. The solution differed only in the solution of the central heading joint between panels and in the solution of the pockets with bolts, which are used to interconnect the panels.

Overall width of joints is $3,600 - 2 \times 1,770 = 60$ mm taking into account the size of the test hole. The lateral vertical joints in a width of 25 mm were sealed expanded rubber and textile cord. The panels were placed to the mortar bed. The heading joint between the panels was considered at a thickness of 10 mm and a height equal to the height of the test hole, i.e. 2,875 mm.

Soft mineral fibres with a thickness of 40 mm were attached to the joint of the first panel and they were compressed to the thickness of 10 mm subsequently (required joint thickness). The panels were connected by a threaded rod at two points (in kits) thereafter. The bolts were tightened so as to ensure the joint 10 mm thick over the entire height of the researched wall.

The both variants have been designed with respect to acoustic requirements and fire resistance requirements. In the first variant, a soft fireproof stopping material was used in the heading joint and for surface treatment (detailed on the Figure 2), too.

The second variant addresses differently both the heading joint and the kit with bolts. The fill from flexible stone fibres was left, but only at the thickness of 160 mm (compared to the original 180 mm after pressing the fibres). A solid (after drying) anti-fire sealant at the thickness of ca. 15 mm was used as a fireproof material. The requirement for a solid surface has been taken into account. The kit was solved using an anti-fire board wall in the view. It was filled with flexible stone fibres in side. The board was cut off along the periphery of the kit and was sealed with the anti-fire sealant of the same type as in the solution of the central heading joint (see Figure 3).
4. Determination of sound insulation by calculation

Methods used to determine of weighted sound reduction index of structures on a silicate basis are commonly used in practice. The assessed wall structure meets the definition of a single structure in a common section. Three methods were used to calculate for the calculation of sound insulation. They are briefly described below.

4.1. Modified Watters method

The Watters method, which was adapted by associate professor Čechura (described e.g. in [4]) is the most used method in the Czech Republic. The computational model considers with several simplifications, for example, it neglects resonance over the entire frequency band. The calculation principle is summarized in Tables 1 and 2. Bulk density $\rho$ (kgm$^{-3}$), speed of sound in the longitudinal direction $c_L$ (m$\cdot$s$^{-1}$), loss factor $\eta$ (-) and thickness of structure $h$ (m) is important to know.
Table 1. Computation of airborne sound insulation values of a single structure

| Interval | Definition the interval | The slope of the course line | Computation $R$ |
|----------|-------------------------|-----------------------------|----------------|
| I.       | $f \leq f_A$            | 6 dB per octave             | $R = R_A + 20 \log_{20} \frac{f}{f_A}$ |
| II.      | $f_A \leq f \leq f_B$   | 0 dB per octave             | $R = R_A$ |
| III.     | $f_B \leq f \leq f_C$   | 10 dB per octave            | $R = R_A + \frac{100}{3} \log_{20} \frac{f}{f_B}$ |
| IV.      | $f_C \leq f$            | 6 dB per octave             | $R = R_A + 10 + 20 \log_{20} \frac{f}{f_C}$ |

(A, B, C denote points of turn in the model of sound insulation)

Table 2. Specification of parameters for determination of airborne sound insulation values

| Parameter | Parameter name | Computation of parameter |
|-----------|----------------|--------------------------|
| $f_A$ (Hz) | frequency in the point A | $f_A = 0.4 f_{cr} \eta^{0.1}$ |
| $f_B$ (Hz) | frequency in the point B | $f_B = 2 f_A$ |
| $f_C$ (Hz) | frequency in the point C | $f_C = 2 f_B$ |
| $f_{cr}$ (Hz) | critical frequency of wave coincidence | $f_{cr} = \frac{63734}{c \times h}$ |
| $x$ (-) | the number of octaves between $f_A$ and $f_B$ | $x = 1.33 \eta^{-0.157}$ |
| $R_A$ (dB) | value of sound reduction index in point A | $R_A = 20 \log_{20}(m' \times f_A) - 47.5$ |
| $\eta$ (-) | loss factor | $\eta \geq \eta_{int} + \frac{m'}{485 \sqrt{f_{cr}}}$ |
| $m'$ (kg/m$^2$) | surface density | $m' = \rho \times h$ |

4.2. The VÚPS method
This method was derived in CSI a.s. in Prague (in VÚPS Prague at that time) on the basis of laboratory-measured values of sound reduction index. This methodology already takes into account the effect of resonance by decreasing sound insulation in II. interval (minus 7 dB per octave). Partial frequency $f_A$ (Hz) and $f_B$ (Hz) must be determined first:

\[
 f_{a} = f_{cr} - f_{cr} \times K1 \times \log \frac{c}{m'} 
\]

\[
 f_{b} = f_{cr} + K2 
\]

The diagrams in [6] must be used to determine the auxiliary quantities $K1$ and $K2$. Detailed calculation procedure is listed in [6], too.

4.3. Method according EN ISO 12354-1
This method (description in [5]) is another method used and is the most complicated of these methods.

4.4. Determination of weighted apparent sound reduction index
The apparent sound insulation includes indirect transmission, too. Simplified approach was chosen in this case, a one digit correction is deducted from weighted sound reduction index:
\[ R'_{w} = R_{w} - k_{1} \]  

where \( R_{w} \) (dB) indicates weighted apparent sound reduction index; \( R_{w} \) (dB) indicates weighted (laboratory) sound reduction index and \( k_{1} \) (dB) indicates relevant correction. The value of the correction \( k_{1} = 2 \) dB applies by the CTN 73 0532 [3] for concrete and masonry structures in massive buildings. It was required that the researched structure had weighted sound reduction index (using equation (3) and information in Chapter 1): \( R_{w} = R'_{w, \text{required}} + k_{1} = 53 + 2 = 55 \) dB.

4.5. Sound reduction index of built-up structure

The effect of the central heading joint at a thickness of 10 mm was examined in the grant, too. It shall proceed in the computation as in the evaluation of built-up structure, because the structure is consisted of the panels and of the joint filling with different material characteristics. The following computational relationship has been used:

\[ R = 10 \log S - 10 \log \left( \sum_{i=1}^{n} \left( S_{i} \times 10^{-0.16} \right) \right) \]  

where:
- \( R \) (dB) sound reduction index of built-up structure at a given frequency;
- \( R_{i} \) (dB) sound reduction index of partial structure at a given frequency;
- \( S \) (m²) surface of built-up structure;
- \( S_{i} \) (m²) surface of partial structure;
- \( i \) (-) partial structure (e.g.: 1 means a part from the panels and 2 means joint etc.).

5. Computation of sound reduction index of the panel wall

The sound reduction index of the partition wall was computed in a variant without the influence of the joint first. The minimum thickness of the wall was determined by 200 mm with a view to meeting the requirement for structure between flats. The acoustic parameters were first estimated from tables for preliminary computation. Subsequently, they were determined on the basis of measurement on samples with dimensions 50 × 100 × 700 mm, see Table 3.

### Table 3. The considered acoustic parameter

| Parameter | Parameter name | Estimated values | Values determined based on measurement [1] |
|-----------|----------------|-----------------|-------------------------------------------|
| \( \rho \) (kg·m\(^{-3} \)) | 2400 | 2408 |
| \( m' \) (kg·m\(^{-2} \)) | 2400 × 0.2 = 480 | 2408 × 0.2 = 481.6 |
| \( c_{L} \) (m·s\(^{-1} \)) | 3228 | 2558 |
| \( \eta \) (-) | 0.08 | \( \eta \approx 0.015 + \frac{481.6}{485 \sqrt{98.72}} = 0.115 \) |

Partial results using the modified Watters method are: \( f_{A} = 30.67 \) Hz; \( f_{B} = 120.78 \) Hz; \( f_{C} = 241.56 \) Hz; \( x = 1.98 \) octaves; \( R_{A} = 35.9 \) dB. The calculated values of sound reduction index depending on the frequency and the method used are stated in the following tables for clarity. Sound reduction index of the heading joint was calculated by the modified Watters method for double structures.

Material of the central heading joint was considered as follows (see the text for variant 2): double-sided synthetic resin with inorganic fillers (\( h = 15 \) mm; \( \rho = 1,500 \) kg·m\(^{-3} \); \( c = 2,010 \) m·s\(^{-1} \); \( \eta = 0.07 \)) and a gap is filled with mineral felt in the entire thickness of 160 mm.

Notes to the next Table 4: The values of sound insulation according to estimated input data (\( R_{\text{estim}} \) in the left part) and according to measured data (\( R_{\text{accur}} \) in the right part) are given for each method.
Table 4. Summary of the calculated values of sound insulation a) of the full part of the panel in relation to the frequency and the used method and b) of joint in the second variant (double structure)

| Method: | Modified Watters | VÚPS | CTN EN 12354-1 | Mod. Watters |
|---------|------------------|------|----------------|--------------|
| $f$ (Hz) | $R_{\text{estim}}$ (dB) | $R_{\text{accur}}$ (dB) | $R_{\text{estim}}$ (dB) | $R_{\text{accur}}$ (dB) | $R_{\text{estim}}$ (dB) | $R_{\text{accur}}$ (dB) | $R_{\text{joint}}$ (dB) |
| 100     | 35.9             | 38.2 | 36.6           | 40.7          | 39.3          | 39.2          | 19.5          |
| 125     | 36.4             | 38.2 | 38.7           | 38.5          | 42.1          | 40.3          | 21.5          |
| 160     | 39.9             | 39.5 | 41.0           | 40.8          | 43.7          | 43.1          | 23.6          |
| 200     | 43.2             | 42.7 | 43.1           | 42.9          | 45.1          | 44.6          | 25.6          |
| 250     | 46.2             | 46.0 | 45.2           | 45.0          | 46.8          | 46.1          | 27.5          |
| 315     | 48.2             | 48.9 | 47.4           | 47.2          | 49.9          | 48.7          | 29.5          |
| 400     | 50.2             | 50.9 | 49.6           | 49.4          | 52.9          | 51.9          | 31.6          |
| 500     | 52.2             | 52.9 | 51.7           | 51.5          | 55.5          | 54.7          | 33.5          |
| 630     | 54.2             | 54.9 | 53.9           | 53.7          | 58.2          | 57.5          | 35.5          |
| 800     | 56.3             | 56.9 | 56.1           | 55.9          | 60.8          | 60.2          | 35.8          |
| 1000    | 58.2             | 58.9 | 58.2           | 58.0          | 63.2          | 62.7          | 35.8          |
| 1250    | 60.1             | 60.8 | 60.3           | 60.1          | 65.6          | 65.1          | 35.8          |
| 1600    | 62.3             | 63.0 | 62.6           | 62.4          | 68.1          | 67.6          | 35.8          |
| 2000    | 64.2             | 64.9 | 64.7           | 64.5          | 70.3          | 69.8          | 35.8          |
| 2500    | 66.2             | 66.8 | 66.8           | 66.6          | 72.4          | 72.0          | 35.8          |
| 3150    | 68.2             | 68.9 | 68.5           | 68.3          | 74.4          | 72.4          | 38.4          |

$R_w$ (dB)  $56$ (-2; -6)  $56$ (-1; -6)  $56$ (-2; -6)  $56$ (-2; -5)  $59$ (-2; -6)  $58$ (-1; -6)  $36$

Table 5. Summary of the calculated values of sound insulation depending on the frequency and the method used – variant with the influence of the central heading joint, see equation (4)

| Method: | Modified Watters | VÚPS | CTN EN 12354-1 |
|---------|------------------|------|---------------|
| $f$ (Hz) | $R$ (dB) | $\Delta_i$ (dB) | $R$ (dB) | $\Delta_i$ (dB) | $R$ (dB) | $\Delta_i$ (dB) |
| 100     | 37.4          | ---          | 39.4        | ---          | 38.2        | ---          |
| 125     | 37.7          | 1.3          | 38.0        | 1.0          | 39.5        | 0.5          |
| 160     | 39.1          | 2.9          | 40.3        | 1.7          | 42.1        | 0.9          |
| 200     | 42.1          | 2.9          | 42.3        | 2.7          | 43.7        | 2.3          |
| 250     | 45.2          | 2.8          | 44.4        | 3.6          | 45.3        | 3.7          |
| 315     | 47.9          | 3.1          | 46.5        | 4.5          | 47.8        | 4.2          |
| 400     | 50.0          | 4.0          | 48.8        | 5.2          | 50.8        | 4.2          |
| 500     | 51.9          | 3.1          | 50.8        | 4.2          | 53.3        | 2.7          |
| 630     | 53.9          | 2.1          | 53.0        | 3.0          | 55.9        | 1.1          |
| 800     | 55.6          | 1.4          | 54.8        | 2.2          | 57.7        | 0.3          |
| 1000    | 56.9          | 1.1          | 56.4        | 1.6          | 58.9        | 0.1          |
| 1250    | 58.0          | 1.0          | 57.7        | 1.3          | 59.8        | 0.2          |
| 1600    | 59.0          | ---          | 58.8        | 0.2          | 60.4        | ---          |
| 2000    | 59.7          | ---          | 59.6        | ---          | 60.7        | ---          |
| 2500    | 60.2          | ---          | 60.2        | ---          | 60.9        | ---          |
| 3150    | 62.7          | ---          | 62.6        | ---          | 63.3        | ---          |

$\Sigma \Delta_i$  25.6  31.3  20.1

$R_w$  $55$ (-1; -5) dB  $55$ (-2; -5) dB  $56$ (-1; -5) dB
The average value of the weighted sound reduction index $R_{w,\text{comp}} = 55$ dB was calculated. This value was expected when measured in a laboratory. However, it is necessary to realize that the precise acoustic parameters of fire-resistant materials are not known. The results of measurements may differ from those calculated.

6. Measurement of the sound reduction index of the panel wall
The sound reduction index of the wall was determined by measurements in an accredited test laboratory, too. The laboratory with the chance to mount the panels from above using a crane was selected. The test hole with dimensions of ca. 3,600 × 2,875 mm was appropriated for measurement of sound insulation of wall structures. Sample dimensions were 3.56 × 2.85 m. The measured wall structure has a thickness of 200 mm.

6.1. Evaluation of measurements results
The weighted sound reduction index 55 dB came out in both variants. This is the same result as the computation. The values of sound reduction index depending on the frequency are similar, see Figure 4. The values differ maximum of 1.3 dB at frequency 100 Hz.

The largest decline is at the frequency 250 Hz against expectations. The lowest resonance frequency $f_0$ (Hz) at which the structure oscillates with the highest displacement in the middle is calculated according to:

$$f_{11} = 0.45 \times c_L \times h \times \left( \frac{1}{l_x^2} + \frac{1}{l_y^2} \right)$$

in which (outside the previously mentioned) $l_x$ (m) and $l_y$ (m) denote length and height of the structure.

The basis resonance frequency $f_{11}$ (Hz) of each panel about dimensions 1.77 m × 2.85 m is by (5):

$$f_{11} = 0.45 \times 2.558 \times 0.2 \times \left( \frac{1}{1.77^2} + \frac{1}{2.85^2} \right) = 101.83 \text{ Hz}$$
Unfavourable effect of resonance can be affected by choosing the dimensions of the structure and the used material. The dimensions of the assessed wall structure were affected by the size of the test hole and it was not possible to change it.

7. Conclusion
The ability of the demountable wall structure to prevent airborne sound was assessed under the terms of the grant, besides other things. The heading joint connection is a critical location for airborne sound insulation. The joint was solved and assessed in two material variants. They were designed for satisfaction of acoustic requirements and fire protection. The sound reduction index was calculated using 3 methods first. Besides other things, the selected acoustic parameters were measured in the laboratory for these purposes. The weighted sound reduction index $R_{w} = 55\, \text{dB}$ was determined in both variants of the solution of the central heading joint between panels based on measurement in the accredited acoustic laboratory. The evaluated wall structure meets the requirements for weighted apparent sound reduction index of the walls between flats, because $R'_{w} = 53\, \text{dB}$ (requirement of the CTN 73 0532 [3]). It should be remembered that the quality of making of the whole wall including joints is necessary to verify by measurement the $R'_{w}$ after the realization of a building.

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References
[1] CSI, a.s., Prague 2018 Measurement of flexural rigidity of concrete SX01 (Prague) p 3
[2] CSI, a.s., division in Zlín 2017 Test report No. 391/17. Laboratory measurement of sound reduction index of reinforced concrete wall 200 mm thick with assembling joint according EN ISO 10140-2 (Zlín) 2017 p 4–5
[3] CTN 73 0532 Acoustics – Protection against noise in buildings and evaluation of acoustic properties of building elements – Requirements. Prague: ÚNMZ, 2010 p 7-8
[4] Čechura J. 1997 Building physics 10, Acoustics of building structures (in the Czech original: Stavební fyzika 10, Akustika stavebních konstrukcí) (Prague, CTU in Prague) ISBN 80-01-01593-9 pp 59–60
[5] EN ISO 12354-1 Building acoustics – Estimation of acoustical performance of buildings from the performance of elements – Part 1: Airborne sound insulation between rooms. Prague: ÚNMZ, 2018 p 20–2, 29–35
[6] Mrlík F at al. 1981 Principles for designing and assessing of structures and spaces of residential and civil buildings. Building thermal protection and building acoustics, Part 1: Criteria. Design principles. Computational methods. (in the Czech original: Zásady pro navrhování a posuzování konstrukcí a prostorů bytových a občanských staveb, Stavební tepelná technika a stavební akustika, Díl 1: Kritéria. Principy navrhování. Výpočtové metody). Publication 34/81 (Prague: VÚPS Prague, Ministry of Building Industry ČSR pp 170–1
[7] TAČR TA02010837 Multipurpose dismantle able prefabricated reinforced concrete building system with controlled joint properties and the possibility of repeated use. 2012-2015, main solver: prof. Jiří Witzany.
[8] TAČR TH02020309 Structures of finishing cycle for multi-purpose demountable prefabricated material and energy-saving building system. 2016-2020, main solver: prof. Jiří Witzany.
[9] Witzany J, Zigler R, Čejka T and Polák A 2018 Construction systems of the new generation, part 2: A dismountable prefabricated wall system (in the Czech original: Stavební systémy nové generace, 2. díl: Demontovatelný stěnový systém) Stavebnictví magazine Year 12, Issue 05, ISSN 1802-2030 pp 44–50