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Effect of resilient joints on the airborne sound insulation of single-leaf heavyweight constructions

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ABSTRACT

The joint between a heavyweight construction and the surrounding building frame can be rigid or resilient. It is often believed that a resilient joint improves sound insulation. The purpose of this study was to investigate how the joint resiliency of a single-leaf heavyweight construction affects the sound reduction index and the total loss factor. A masonry wall of 10 m^2 (220 kg/m^2 calcium silicate block wall) was built three times (A–C) in laboratory using three different joint types between the wall perimeter and the test opening frame: A - All four joints rigid; B - Three joints resilient and one rigid; C - All four joints resilient. The sound reduction index was determined using both pressure and intensity method. The total loss factor was determined by measuring the structural reverberation time using hammer impacts. The sound reduction index reduced significantly with increasing level of resiliency. For joint type A, the weighted sound reduction index, R_w, was 50 dB while it was 45 dB for B and 43 dB for C. Correspondingly, the total loss factor reduced from A to C, i.e., with increasing joint resiliency. The effect of joint type was evident above the coincidence frequency (250 Hz) of the block wall. Resilient joint prevented the energy transmission from the wall to the building frame, which increased the sound radiation to the air, which was reflected as reduced sound reduction index. The results imply that the joints of a heavyweight construction shall be rigid if high sound reduction index is desired above the coincidence frequency. On the other hand, the increased joint resiliency improved the sound reduction index at most frequency bands below the coincidence frequency. Resilient joints around heavyweight construction can be beneficial in situations where the reduction of low-frequency noise is of primary concern.

1. Introduction

Heavyweight single-leaf constructions are frequently used in residential and occupational apartments to provide sound insulation against noises from neighbors and environment [1]. Materials that are used in heavyweight constructions are, e.g., concrete, calcium silicate (sand-lime), clay, autoclaved aerated concrete, and aggregate concrete. The frequency-dependent sound reduction index (SRI, the physical quantity describing the airborne sound insulation) of a single-leaf wall or intermediate floor construction mostly depends on four physical parameters: surface mass (i.e., density times thickness), Young's modulus, plate dimensions, and the total loss factor (TLF) [2]. While the first three parameters are simple and relatively easy to achieve from the manufacturers or the building plans, the fourth is not. Furthermore, TLF depends on the frequency of sound. TLF depends on internal losses, radiation losses, and coupling losses in the joints. The coupling losses have the strongest effect on TLF [2]. They depend on the type (resilient vs. rigid) of the joints

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(also known as connection, coupling, junction) to the surrounding constructions as well as the properties of the surrounding constructions. TLF can be experimentally measured, but there is very little data available about the frequency-dependence of TLFs of different materials used in single-leaf constructions since joints are case-dependent and TLF measurements are seldom conducted when the SRI is measured in laboratory or in building site. Therefore, SRI predictions are often made assuming a constant TLF [3]. However, this choice may lead to major prediction errors at and above the coincidence frequency, where the TLF significantly affects the SRI [2]. (At coincidence frequency, the wavelength of bending wave in the construction equals with the wavelength of longitudinal wave in air.) There is a general need to better know how the frequency-dependent TLF depends on the joint properties.

Load-bearing heavyweight constructions are usually rigidly attached to the surrounding constructions using mortar and/or metal ties (tension straps) in the joints. Heavyweight constructions are also used in partition walls which are not load bearing. In such situations, masonry units are often applied. Rigid joints to surrounding constructions are not necessary in such cases.

Resilient joints between building constructions reduce vibration transmission from one element to another [4]. Because of that, it is a frequent impression among building engineers that resilient joints in any position close to the joint positively affect the sound insulation between two rooms. Therefore, some masonry building instructions presume that the joints of the masonry wall against surrounding floor, ceiling, and walls, should be resilient when higher sound insulation is desired.

Meier & Schmitz [5] studied the effect of resilient joints around the wall perimeter on the direct SRI through a single-leaf heavyweight wall in laboratory conditions. They tested a gypsum brick wall (thickness 100 mm, surface mass 120 kg/m^2) using two mounting conditions: three edges of the wall (ceiling edge and vertical edges) were connected to the test facility with a layer of bitumen (rigid joint), and three edges were filled with cork and sealed with silicon (resilient or elastic joint). The floor joint was rigid in both mounting conditions. Both SRI and TLF were measured for both mounting conditions. Rigid joint resulted in a higher TLF and a higher SRI above the coincidence frequency. However, since the floor joint was rigid for both mounting conditions, the effect of joint resiliency was only partially investigated. Overall, there is very little experimental data about the effect of resilient floor joint on SRI directly through the construction.

The brick wall of **Meier & Schmitz** [5] had a reasonably low surface mass. This leads to a relatively high coincidence frequency (250–400 Hz) and a relatively small weighted SRI, R_w (39 or 44 dB depending on the joint resiliency). Such walls are not accepted between residential apartments in any European country since the typical requirements in European countries are within 50–55 dB for the weighted standardized level difference, $D_{nT,w}$, or the weighted apparent SRI, R'_w [6]. Heavyweight walls used between residential apartments, hospital rooms, and classrooms must usually be heavier (>200 kg/m^2) to achieve the above-mentioned requirements. It is, therefore, justified to conduct an experimental study exploring the effect of joint resiliency using a construction with greater surface mass than 120 kg/m^2 to see how the findings of **Meier & Schmitz** [5] apply for heavier constructions. Furthermore, it is justified to test the condition where all four joints (including the floor joint) are resilient.

Reliable sound insulation test of a heavy construction in laboratory conditions requires that the body of the test opening frame (and adjoining building mass) is significantly heavier than the mass of the tested construction. Otherwise, the vibration transmission from the tested construction to the test opening frame would be excessively high. Furthermore, it is necessary to reduce flanking sound transmission from the source room (or from the body of the test opening frame) to the receiving room using resilient materials or springs under the receiving room.

Meier et al. [7] conducted a major accuracy experiment (also known as Round Robin test or interlaboratory comparison) where the same heavyweight single-leaf wall construction (440 kg/m^2) was built by the same installation team to 12 different test laboratories. The SRI was determined according to ISO 140 [8] which was the predecessor of ISO 10140-2 [9]. Furthermore, the TLF was determined. The interlaboratory differences of SRI were much larger than expected: the R_w values ranged between 54–61 dB. For comparison, a Nordic accuracy experiment where a window was tested in five laboratories resulted in significantly smaller and feasible variation: R_w ranged between 40–42 dB [10,11]. Large interlaboratory differences of **Meier et al.** [7] were apparently caused by several reasons: differences in laboratory constructions and vibration isolations between the test rooms, test opening, and surrounding building (as clarified in a parallel paper of [12]), laboratory room dimensions (room modes were different), test opening dimensions, and the TLF of the wall. **Meier et al.** [7] analyzed that the interlaboratory variations in TLFs could not alone explain the observed interlaboratory differences. Despite of this, they proposed that when single-leaf heavyweight walls are tested in laboratory conditions, the TLF should be measured together with SRI measurements to be able to correct the obtained SRI values to another desirable TLF value. Adoption of such correction could improve the comparability between the test results obtained in different laboratories differing in the TLF. Such a procedure has been adopted in the revised standard ISO 10140-5 [13]. However, there is very little research about the effect of TLF on SRI even in a simple situation where the TLF is manipulated within a single test laboratory.

SRI is usually measured in laboratory conditions using *pressure method* described in ISO 10140-2 standard [9]. The uncertainty of the method is very large below 200 Hz mainly because of different room sizes, test opening sizes, and test opening geometries. They influence the modal coupling between the source and receiving room and lead to major interlaboratory variations [10,11]. Furthermore, when heavyweight constructions are tested in laboratory, flanking sound transmission can be strong and reduces the highest measurable SRI [14]. Flanking transmission is a serious problem for the pressure method, especially, for heavyweight constructions at low frequencies. Therefore, *intensity method* of ISO 15186-3 [15] is generally recommended to measure the SRI below 200 Hz reliably. An accuracy experiment involving five countries [11,16] showed that the interlaboratory differences within 50–160 Hz were significantly smaller for the intensity method than for the pressure method. Although the intensity method is evidently the most precise method to determine the SRI at low frequencies, it has been quite seldom applied in scientific research. The probable reasons are the time-consuming measurement procedure, complexity of measurement, analysis, calibration, and expensive measurement apparatus (2-channel analyzer, dual microphone probe, calibrator). Despite of that, all attempts to measure the SRI at low frequencies reliably are extremely important to avoid the distribution of biased measurement data. This is, especially, important for heavyweight constructions since they are seldom tested due to the large workmanship required.

The purpose of our study was to investigate how the joint resiliency around a single-leaf heavyweight wall affects the SRI within frequency band 50–5000 Hz. Three different joint types between the perimeters of the wall and adjoining constructions were investigated. SRI was measured using both pressure and intensity methods to avoid false conclusions at low frequencies. Another purpose was to find out if the change in SRI caused by resilient joints could be explained by the difference between the measured TLFs of the constructions.

2. Materials and methods

2.1. Description of the laboratory

All measurements were conducted in the acoustics laboratory of Turku University of Applied Sciences (Turku, Finland) in 2020. The walls were installed to a test opening (10.2 m^2) between adjacent reverberation rooms 1 and 2. The test opening was 2774 mm high, 3610 mm wide, and 720 mm deep. The depth refers to the middle part of the test opening which is connected to the building frame and mechanically isolated from the constructions of reverberation rooms 1 and 2. The rooms are isolated from the building using resilient vibration isolators having a resonance frequency of 8 Hz (Fig. 1). This kind of acoustic design is necessary in laboratories where sound insulation of heavyweight constructions is tested to minimize the flanking transmission via adjoining constructions.

Before the current study, the laboratory part used in this study (two rooms and the test opening between them) had to be validated according to ISO 10140-5 [13] to verify that the laboratory is suitable for testing single-leaf heavyweight constructions. Two basic properties were determined: the TLF for a heavy wall construction with rigid joints (400 ± 40 kg/m^2) and the maximum measurable SRI. A brick wall was built to the test opening using rigid joints against the test opening. The wall thickness was 210 mm, and the surface mass was 360 kg/m^2. More details about the brick wall are given in Supplementary data.

According to ISO 10140-5, the TLF should exceed a lower boundary $0.01 + 0.3/f^{1/2}$ for single-leaf walls heavier than 150 kg/m^2, when rigid joints are used. Such a large TLF should guarantee that the between-laboratory differences are minimized [7]. TLF smaller than the lower boundary indicates that the test opening frame is not sufficiently rigid and too much vibration energy is reflected from the test opening frame back to the tested wall. The measured TLF is shown in Fig. S2 in Supplementary data. The TLF exceeded the lower boundary within 50–3150 Hz. The deviation from the lower boundary was only marginal within 4000–5000 Hz.

The maximum measurable sound reduction index, R_{max}, of the test opening needs to be known to avoid a situation where the test results obtained for a wall are contaminated by flanking transmission. Because the block wall of the primary investigation (see **Sec. 2.2**) was relatively heavy (216 kg/m^2), possible bias due to flanking transmission had to be ruled out in advance. According to ISO 10140-2 [9], such results shall be denoted, where R and R_{max} differ less than 6 dB, since such results are underestimates of the true SRI. R_{max} was determined by adding a thick, lightweight lining to the above-mentioned 210 mm brick wall. The lining comprised of a 475 mm cavity with 250 mm mineral wool filling, and two layers of 13 mm gypsum board supported by a timber stud frame that had no mechanical connection to the brick wall. The construction is shown in Fig. S1 in Supplementary data.

2.2. Constructions and joint types

Heavyweight constructions are available, e.g., in prefabricated elements, masonry units (blocks or bricks), and cast material (shape is defined by molds). Heavyweight constructions are also available as double constructions, where the two layers are separated by a cavity (frequently filled with insulator) and mechanical ties.

The heavyweight wall in the primary investigation was made from calcium silicate masonry units (block wall). Masonry units are available both as bricks and blocks. The block wall was built into the test opening three times using three different joint types A–C

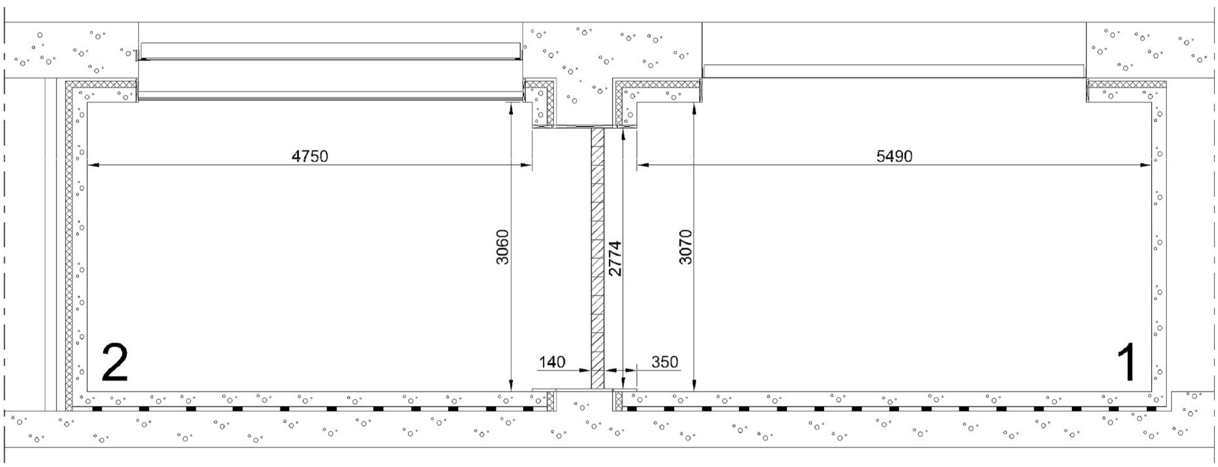

Fig. 1. Section of the laboratory showing the source room 1 (76 m^3) and the receiving room 2 (64 m^3). The position of the block wall in the test opening (thickness 140 mm) is shown.

(Fig. 2). The thickness of the block wall was approximately 140 mm (including plastering mortar on both faces), coincidence frequency was approximately 250 Hz, and surface mass was approximately 216 kg/m^2.

Fig. 2 clarifies the single-leaf block wall used in the investigation of the resilient joints. The layers 1–3 were the following:

1. Paint and plastering.
2. Blocks and thin layer masonry mortar in horizontal joints.
3. Plastering and paint.

Further information about the exact materials is given in Supplementary data.

The joint types used in the perimeters are elucidated in Fig. 3 and they are explained below.

A. **Four joints rigid.** The seams were filled with mortar and the block wall was mechanically tied to the test opening frame with a steel band every 500 mm on vertical sides.
B. **Floor joint rigid, other joints resilient.** Floor joint was filled with mortar. The other three joints were resilient (without steel bands), and the seams were filled manually with flexible solution.
C. **All joints resilient.** The block wall was built on top of a vibration isolation strip. The resonance frequency of the wall-spring-system was 14 Hz. The other three joints were similar as in B.

Each construction dried 4–7 days before the measurements were conducted. Each wall was built by the same experienced mason who was informed about the importance of careful workmanship. Figs. S3−S6 in Supplementary data involves some photographs of the walls and the joints.

2.3. Airborne sound insulation measurements

2.3.1. Pressure method

SRI using pressure method, R [dB], was measured within 1/3-octave bands 50–5000 Hz according to ISO 10140-2 [9]. Loud pink noise was produced in the source room using four independent sound sources (signal generator, power amplifier, and loudspeaker). The sound pressure levels (SPL) were measured simultaneously in the source room, $L_{p,1}$ [dB *re* 20 μPa], and in the receiving room, $L_{p,2}$ [dB], using condenser microphones (Brüel & Kjaer 4165, Denmark). The microphones were installed on rotating microphone booms (Brüel & Kjaer 3923, Denmark). The radius of rotation was 1.00 m and the time of one complete rotation was 64 s. The SPL of background noise in the receiving room, $L_{p,2,B}$, was measured immediately after the measurement of $L_{p,2}$. The measurement equipment was checked before and after the measurements using a sound level calibrator (Brüel & Kjaer 4231, Denmark). All analyses were made using the same real-time analyzer (Norsonic Nor121, Norway). The SRI was determined by equation [9].

$$R = L_{p,1} - L_{p,2} + 10 \cdot \log_{10}\left(\frac{S}{A_2}\right) \quad (1)$$

where $L_{p,2}$ [dB] is the background noise corrected SPL in the receiving room, S [m^2] was the area of the tested wall, and A_2 [m^2] was the equivalent absorption area in the receiving room determined by [9].

$$A_2 = \frac{0.16 \cdot V_2}{T_2} \quad (2)$$

where V_2 [m^3] was the volume of the receiving room. The reverberation time, T_2 [s], was determined in the receiving room according

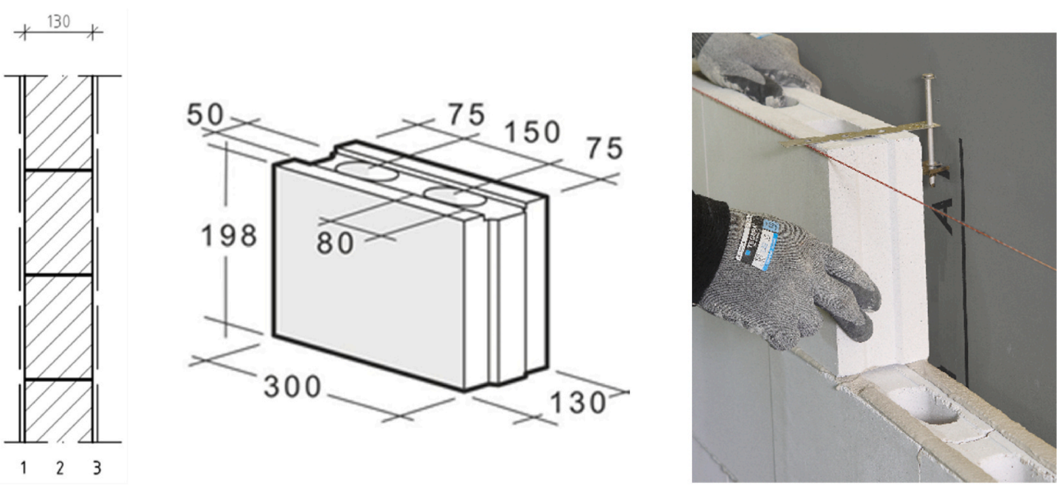

Fig. 2. Left) The section drawing of the calcium-silicate (sand-lime) block wall. Middle) The dimensions of a single block. Right) Installation of the block wall showing the mortar that is used in horizontal seams. The permission for the drawings was given by Saint-Gobain Finland Oy/Weber. (two columns, color online).

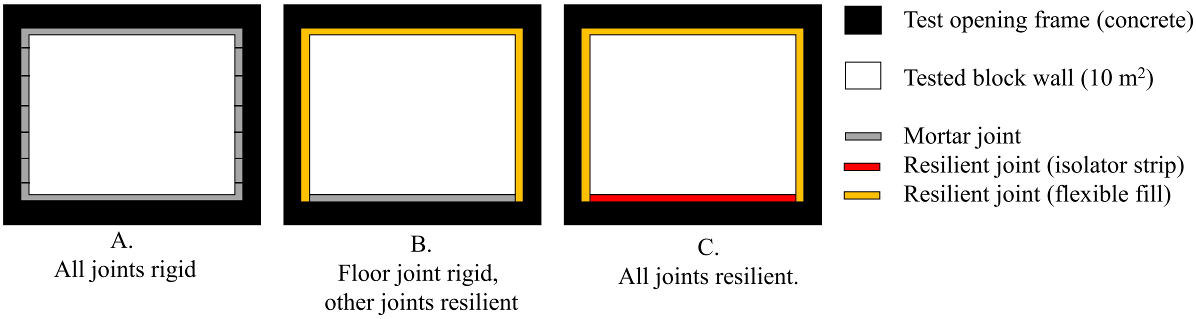

Fig. 3. Joint types A–C. The thicknesses of the joints are exaggerated (two columns, color online).

to engineering method of ISO 3382-2 [17].

The laboratory is accredited by FINAS for SRI measurements according to ISO/IEC 17025 [18].

2.3.2. *Intensity method*

Intensity SRI, R_I [dB], was measured within 1/3-octave bands 100–5000 Hz according to ISO 15186-2 [19] by

$$R_I = L_{p,1} - 6 - L_{I,2} + K_c \tag{3}$$

where $L_{I,2}$ [dB *re* 1 pW/m^2] is the sound intensity level radiated by the specimen to the receiving room, and K_c [dB] is the adaptation term determined by

$$K_c = 10 \cdot \log_{10}\left(1 + \frac{S_b \cdot \lambda}{8 \cdot V_2}\right) \tag{4}$$

where S_b [m^2] was the area of all the boundary surfaces in the receiving room, and λ [m] is the wavelength of sound in air. The adaptation term provides a correction after which the R_I value is better comparable with the R obtained with the pressure method of **Eq. (1)**.

Intensity SRI within 1/3-octave bands 50–80 Hz was determined according to ISO 15186-3 [15] by

$$R_I = L_{pS,1} - 9 - L_{I,2} \tag{5}$$

where $L_{pS,1}$ [dB] is the SPL in the vicinity of the wall in the source room.

$L_{p,1}$ was measured in the middle zone of the source room within 100–5000 Hz. Middle zone measurements were conducted as in **Sec. 2.3.1**. $L_{pS,1}$ was measured in the vicinity of the wall surface (closer than 10 mm) within 50–80 Hz. Wall surface measurements involved nine measurement positions using 20 s averaging time in each of them. Sound intensity levels were measured at 10–15 cm distance from the wall surface in the receiving room using a sound intensity probe comprising two phase-matched measurement microphones (Brüel & Kjaer 4197, Denmark). Scanning method was applied so that the total measurement time was 360 s. The spacer between the microphones in the sound intensity probe (Brüel & Kjaer 3595, Denmark) was 50 mm in measurements within 50–80 Hz and 12 mm in measurements within 100–5000 Hz. The measurement equipment was checked before and after the measurements using a sound intensity calibrator (Brüel & Kjaer 4297, Denmark). All analyses were made using the same real-time analyzer (Brüel & Kjaer 2260 Investigator, Denmark).

The intensity method [15] has been shown to provide lower interlaboratory differences below 200 Hz than the pressure method [11].

2.3.3. *Single-number values*

Sound insulation performance is expressed in trade and regulations using single-number quantities, which give specific frequency weights for the measured R values within 50–5000 Hz. In this study, three single-number values R_w (weighted SRI), $R_w + C_{50\text{-}5000}$ (weighted SRI using pink noise spectrum), and $R_w + C_{tr,50\text{-}5000}$ (weighted SRI using urban traffic noise spectrum) determined by ISO 717-1 [20] are reported. In addition, the sound transmission class (STC) determined according to ASTM E413 [21] is reported. The single-number values are based on the results obtained with the pressure method.

2.4. *Total loss factor measurements*

TLF was measured applying impulse excitation as described in ISO 10848-1 [22]. The excitation impulse towards the construction was produced using a hammer of total weight 1.2 kg. The head was made of hard elastic material (Finbullet, China). Vibration velocity was measured with an accelerometer (Brüel & Kjaer 4297, Denmark). The analyses were made using a real-time analyzer (Norsonic Nor840, Norway).

Three excitation positions and three measurement positions were selected according to ISO 10848-1 [22]. The decay curves were analyzed, and the structural reverberation time, T_s [s], was determined based on the vibration level decay from −5 dB to −25 dB. The

TLF was determined by

$$\eta = \frac{2.2}{f \cdot T_s} \tag{6}$$

where f [Hz] was the center frequency of the 1/3-octave band. The TLF level was determined by [23].

$$L_\eta = 10 \cdot \log_{10}\left(\frac{\eta}{\eta_0}\right) \tag{7}$$

where the reference value is $\eta_0 = 10^{-12}$. Backwards integration method was applied in the analyzer (Norsonic Nor840, Norway).

2.5. Prediction of change in SRI due to joint resiliency

If the rigid joints (X) of a heavyweight wall are changed to resilient (Y), SRI reduces in frequencies above the coincidence frequency of the wall [5]. The reduction of SRI, D_R [dB], is determined using equation

$$D_R = 10 \cdot \log_{10}\left(\frac{\eta_Y}{\eta_X}\right) \tag{8}$$

where η_X and η_Y are the TLFs with rigid and resilient joints, respectively. The value D_R is added to the measured SRI of the wall with rigid joints (X). This method was applied for the SRIs obtained using pressure method and only at and above the coincidence frequency.

3. Results

The measured intensity SRIs for the block wall with the three joint types A–C are presented in Fig. 4 using both pressure and intensity methods. The single-number values are presented in Table 1. The comparison of intensity SRIs with joint types A−C is shown in Fig. 5. SRI reduces with increasing resiliency of the joints above the coincidence frequency (250 Hz) while an opposite behavior is observed below it.

The maximum measurable SRI, R_{max}, was always at least 13.5 dB larger than any of the SRI values of Fig. 5 (see Fig. S7 in supplementary data). Therefore, the results obtained for joint types A−C were not biased by flanking transmission.

The measured TLF and TLF level for the block wall with the three joint types A–C are presented in Fig. 6. The TLF above the coincidence frequency is greater with rigid joint type (A) than with resilient joint types (B or C). Opposite behavior is observed within 50-80 Hz.

The predicted SRI for joint types B and C is presented in Fig. 7. The measured SRI using the pressure method is presented for comparison. The data is only shown above the coincidence frequency, where **Eq. (8)** is valid.

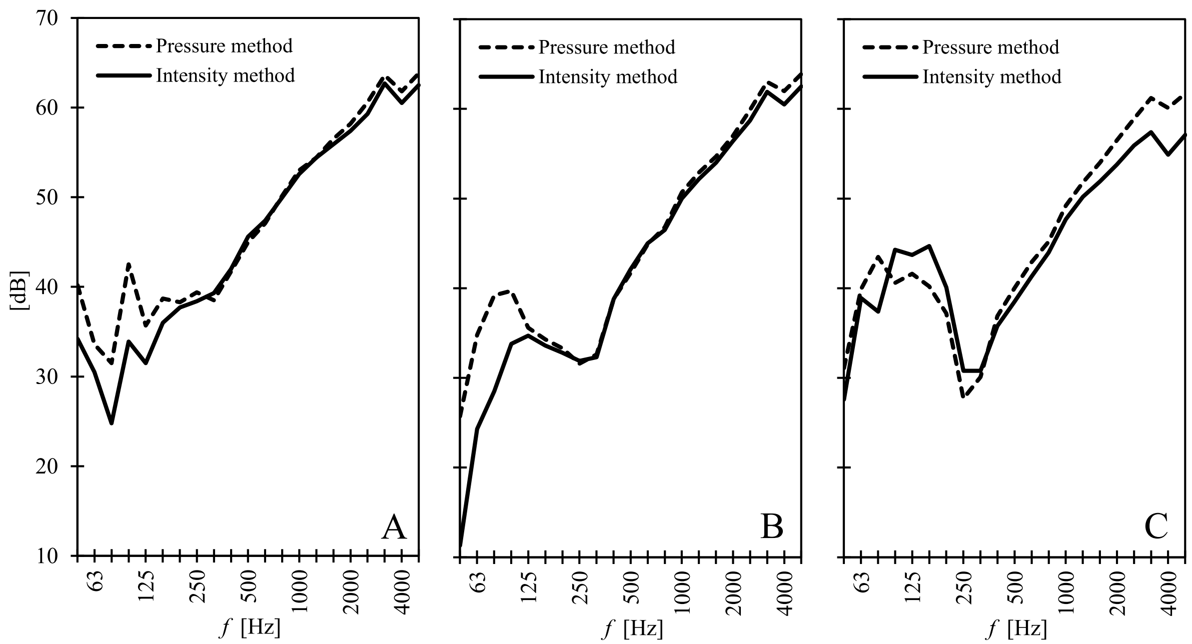

Fig. 4. Measured sound reduction index [dB] of the block wall for joint types A−C using both pressure and intensity method. (two columns).

Table 1
The single-number values of the SRI for the block walls with different joint types A–C. The values are based on the SRIs obtained with pressure method. (two columns).

Joint type	R_w [dB]	$R_w + C_{50\text{-}5000}$ [dB]	$R_w + C_{tr,50\text{-}5000}$ [dB]	STC [dB]
A (All joints rigid)	50	49	44	50
B (Floor joint rigid, other joints resilient)	45	45	40	44
C (All joints resilient)	43	43	39	42

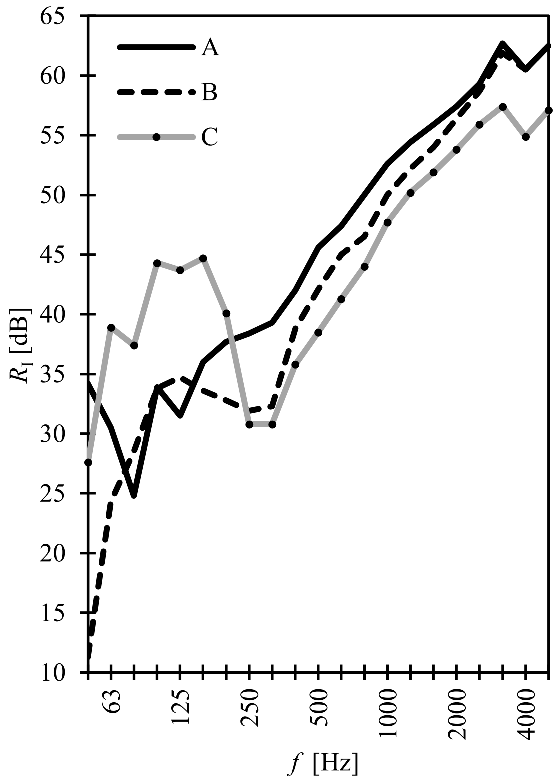

Fig. 5. Intensity SRI, R_I, as a function of frequency, f, for the block wall with joint types A–C. (one column).

4. Discussion

4.1. Findings above coincidence frequency

The novelty of this work deals with the careful and multifaceted experimental analysis of the effect of joint resiliency around heavyweight walls. The SRI depended strongly on the joint type (Fig. 5) but the effect of joint resiliency changed at the coincidence frequency (250 Hz). Therefore, the discussion is divided in these two frequency ranges.

Above coincidence frequency, the more resilient is the joint, the lower is the TLF, and the lower is the SRI. In other words, the SRI directly through the wall was higher with rigid joints than with resilient joints. The reason for this behavior is that the vibration energy easily transmits to the test opening frame via rigid joints and more energy dissipates to the surrounding building structures. When the joint is resilient, energy cannot transmit to the surrounding building structures and remains in the wall, which increases structural reverberation time, decreases TLF, and decreases the SRI.

Our findings agree with **Meier & Schmitz** [5], who studied a single-leaf wall (120 kg/m^2) using two kinds of joints: all joints rigid (44 dB R_w) and three joints resilient and floor joint rigid (39 dB R_w). Our study is more extensive since it involved three different levels of joint resiliency: rigid (50 dB R_w), partially resilient (45 dB R_w), and fully resilient (43 dB R_w). Furthermore, our single-leaf wall was significantly heavier (216 kg/m^2) which is closer to heavyweight single-leaf partitions used between apartments in Europe [1].

Our study provides important scientific contribution to the field, because partially resilient joints have been very little studied before in detail as now. It was shown that joint resiliency affects R_w even by 7 dB, i.e., 2 dB more than reported by **Meier & Schmitz** [5]. It should be noted that a 7-dB-decrement in SRI means a 7-dB-increment in SPL transmitted through the wall. A 7-dB-increment in SPL means 400% increment in absolute sound energy. A 7-dB change also means a significant increment in subjective annoyance sensation (e.g., Refs. [24,25]. Furthermore, a 7-dB-increment of R_w for a single-leaf heavyweight wall requires more than 100% increment in surface mass based on the prediction model of **Rindel** [2]. Therefore, our study highlights the importance of joint design

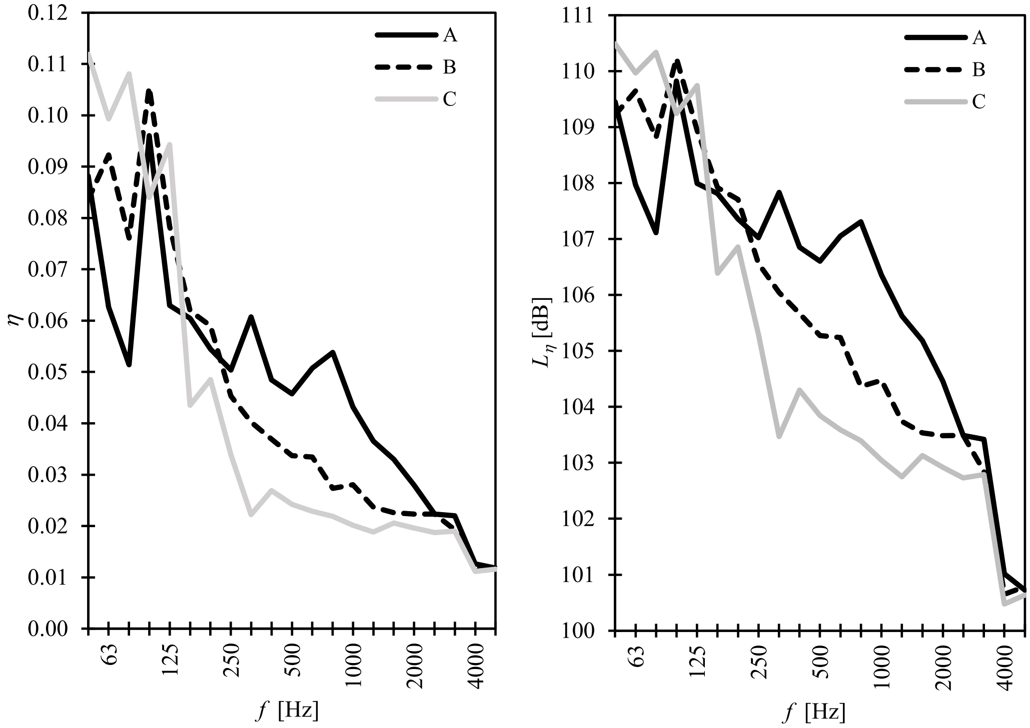

Fig. 6. The measured total loss factor, η, and the corresponding total loss factor level, L_η, of the block wall with joint types A–C. (two columns).

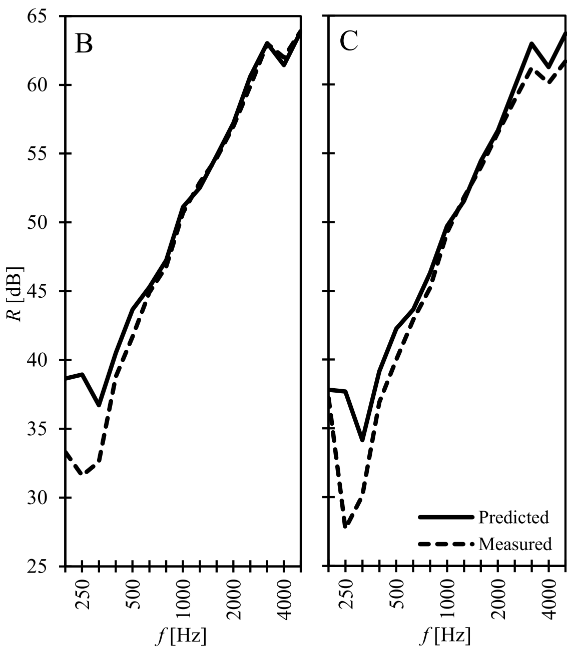

Fig. 7. The comparison of the predicted SRI using Eq. (8) to the measured SRI for the block wall with joint type B (left) and C (right). (one column).

in practical building instructions for single-leaf heavyweight walls.

The results suggest that resilient joints around a heavyweight construction should be avoided if highest possible direct SRI is desired above the coincidence frequency. On the other hand, it is well-known that resilient joints (as well as mobile joints) are beneficial to prevent flanking transmission from the source room via adjoining constructions to the receiving room [26,27]. In such case, the resilient joint should be located along the adjoining constructions (see Fig. 8) and not around the heavyweight construction as we experimented (Fig. 3). The application of resilient joints in the prevention of flanking transmission may explain the false understanding among the construction sector that resilient joints surrounding a heavyweight construction is believed to enhance the SRI through the construction.

4.2. Findings below coincidence frequency

Below coincidence frequency, the experimental findings of both TLF and SRI were, unexpectedly, opposite to that observed above the coincidence frequency. Fully resilient joints (joint type C) significantly improved the SRI compared to other two joint types A and B. However, this behavior did not affect the single-number values R_w, $R_w + C_{50\text{-}5000}$, $R_w + C_{tr,50\text{-}5000}$, and STC, since they are mainly depending on the dip at 315 Hz. The finding cannot be explained by simple analytic theories, which expect that the SRI is primarily dependent on surface mass at low frequencies due to non-resonant vibration [2]. The experimental findings of SRI cannot be explained by measurement errors since both pressure and intensity methods supported this finding and these two methods involved totally independent measurement positions and apparatus. Our finding related to SRI agrees with the experimental work of **Meier & Schmitz** [5]. They suggested that the resilient joint changes the edge conditions and, thus, the bending wave modes of the construction. With rigid joints, the edge modes radiate sound efficiently below the coincidence frequency, which reduces the SRI. With resilient joints, such radiation could be absent. Further research is needed to explain and validate this finding because the positive effect of resilient joints on SRI was drastic, 2–12 dB within 63–200 Hz (C compared to A). For example, simple analytic theories presume that doubling of surface mass leads to a 6-dB increment in SRI. Thus, resilient joints can provide significant advantages in situations where the reduction of low-frequency noise is of primary concern.

4.3. Predictions

The predicted SRI of joint types B and C in Fig. 7 was based on the SRI measurement result with joint type A and the reduction D_R due to the change in the TLF according to **Eq. (8)**. The predicted SRI values for joint type B agreed very well with the measured values within 400–5000 Hz. However, the drop in measured SRI between 200 and 315 Hz could not be accurately predicted. **Meier & Schmitz** [5] also reported a good agreement between the prediction and measurement using **Eq. (8)**. Because the TLF evidently explains the variations in SRI, it is important to conduct more research using extreme alternatives of joint resiliencies as our joint types A and C. However, the research should cover also other heavyweight building materials: both we and **Meier & Schmitz** [5] studied sand-lime block walls.

4.4. Uncertainty evaluations

It is important to evaluate the measurement uncertainty to conclude that the observed differences in SRI (Fig. 5) were caused by the physical difference in the joint type and not by random variations between two repeated installations of the wall and repeated measurements. There is relatively little information about the difference between repeated installations of heavy constructions. This is obvious since the required workmanship is significant. **Schmitz et al.** [12]**; p. 163)** reported the SRI of a masonry wall identically installed to the same laboratory three times using rigid joints. The maximum difference between repeatedly installed walls was less than 1.4 dB within 160–5000 Hz and less than 3.0 dB within 50–125 Hz. Within 160−5000 Hz, the difference was systematic for the whole frequency range (one wall was always worse than the others) while the differences were random within 50–125 Hz. In our study, the SRI differences between the joint types A−C were significantly larger than 3.0 dB in a large frequency range (Fig. 5). Therefore, it seems to be improbable that our experimental findings were biased by unavoidable variations between repeated installations and measurements.

Schmitz et al. [12]**; p. 164)** also reported the TLF level measured for the three abovementioned repeatedly installed walls. The differences between the walls were 0.1–1.1 dB within 160–5000 Hz and 0.2–2.5 dB within 50–125 Hz. In our study, the TLF level differences between the joint types A−C were usually larger than 1.0 dB in a large part of studied frequency range (Fig. 6). Therefore, it is improbable that the TLF values were significantly biased by errors caused by improper installation.

In general, the uncertainty of TLF can increase when the structural reverberation time is very short and the loss factor becomes high [5,23]. Standard filters involve inherent short reverberation, and this property can contaminate the reverberation time measurement in a construction, when the TLF is sufficiently high (TLF = 0.032 for standard analog filters). Above that, the measured reverberation time can be meaningless [5]. The limit can be increased up to TLF = 0.12 by using time-reversed filtering method [28,29]. Therefore, our TLF results below coincidence frequency may contain larger uncertainties and should be interpreted with reservations.

Both **Meier & Schmitz** [5] and **Bietz et al.** [23] found that the excitation force of the hammer or shaker affects the measured structural reverberation time of a sand-lime wall. **Bietz et al.** [23] specified that a similar effect was not found with a monolithic concrete wall. It was suggested that the strong force caused by hammer may cause nonlinear vibration behavior in sand-lime wall, which is not a monolithic construction. This effect may affect the decay process and result in meaningless reverberation times. Another explanation was that the hammer could excite the free bending modes while the shaker could excite only the forced vibration. These vibrational fields may have different reverberation times.

Because of that, we tested the use of vibration exciter and MLS method, because shorter reverberation times could be measured using the MLS method. However, we did not report these results, because sufficient stimulus levels could not be produced with our vibration exciter weighing 40 kg (B&K 4805 & 4813 shaker, B&K 2707 amplifier). The application of MLS method and a shaker would have been an option if the shaker were significantly heavier (e.g., 250 kg used by Ref. [23]. This requires a robust installation to the wall which is very time-consuming. Requirement of such installations together with standard SRI measurement of every heavyweight construction is very challenging in the long term. Future research is warranted related to the reliable structural reverberation time

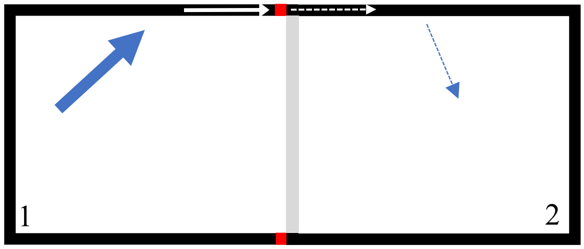

Fig. 8. Structural flanking transmission of airborne sound reduces by using resilient joints along the primary flanking paths. (color online, one column).

measurements of heavyweight constructions using hammer impacts since hammer is often the only realistic option to conduct the TLF measurements both in laboratory and, especially, in field conditions.

5. Conclusions

The airborne sound insulation of a single-leaf heavyweight construction was experimentally studied using three different perimeter joint types against the surrounding massive building constructions. The joint types had different resiliencies which affected the acoustic coupling between the wall and the surrounding constructions. The novelty of this work deals with the careful and multifaceted experimental analysis of the effect of joint resiliency around the heavyweight construction. Increased resiliency of the joints significantly decreased the airborne sound insulation. The weighted sound reduction index, R_w, was 50 dB with rigid joints, and decreased to 45 dB and 43 dB when the joints were resilient on three or four edges of the construction, respectively. Our study shows that the construction joints play a significant role in sound insulation. The joints of the single-leaf heavyweight construction to the surrounding building should be rigid when highest possible sound insulation directly through the construction is desired above the coincidence frequency. The conclusions are not limited to airborne sound insulation, but they are valid also for impact sound insulation. The reduction in sound reduction index due to increased joint resiliency could be reasonably predicted by the measured total loss factor of the construction above the coincidence frequency. Thus, the knowledge of the total loss factor is critical when sound insulation of heavyweight constructions is measured or predicted. Furthermore, we found that the increased joint resiliency improved the sound reduction index at most frequency bands below the coincidence frequency. This unexpected finding may be caused by the changes in the edge conditions and modal behavior of the construction. Resilient joints around heavyweight construction can provide significant advantages in situations where the reduction of low-frequency noise is of primary concern.

Author statement

Conceptualization: VH & JK; Data curation; JK. Formal analysis: JK. Funding acquisition; Investigation: JK. Methodology: JK. Project administration: VH. Resources: VH. Software: JK. Supervision: VH. Validation: JK. Visualization: JK & VH. Writing - original draft; JK&VH. Writing - review & editing: To be reported later.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jobe.2022.104711.

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