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Original scientific paper

SOUND INSULATION PARADOX OF MASSIVE CAVITY WALLS IN BUILDINGS

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Abstract. *In literature, the "box-in-box" system is described as a solution for achieving the highest possible sound insulation in a room. The system involves double walls separating a room from the surroundings in all directions, without any lateral pass for sound. This approach doubles the number of discontinuities in the material through which sound energy travels, thus providing higher sound insulation. Based on such an idea, some dwelling houses were designed with massive cavity walls between apartments with the expectation of better sound insulation. The concept was further motivated by the need to achieve adequate thermal insulation between apartments using insulation material in the cavity. However, in buildings where this was implemented, residents complained about inadequate sound insulation. Measurements showed that the sound reduction index of the double brick wall was lower than expected, even less than that of a wall where the two thinner layers were combined into a single thicker brick wall without an internal cavity. This was surprising, leading to research aimed at finding an explanation. It was concluded that in buildings there is the influence of sound paths through the wall's lateral junctions, which is more pronounced with two thinner layers. With a cavity wall, the transmission of sound energy through lateral junctions and further by flanking transmission is more pronounced than with a single wall of the same surface mass. Additionally, the high seismic zone in Serbia requires certain adjustments in construction, invisible in architectural drawings, that further diminish the effect of the increased number of discontinuities in the wall. All of this makes the massive cavity wall in the building, contrary to expectations, less effective than a single wall made of the same quantity of material, making it acoustically and financially unreasonable. Research also revealed that material in the cavity has no influence on the sound reduction index value of the wall.*

Key words: *flanking transmission, massive cavity wall, sound insulation, sound reduction index, vibration reduction index*

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1. Introduction

The concept of sound insulation between rooms in buildings is based on the appropriate application of partitions with different physical properties. Partitions differ from each other in the mechanisms of sound transmission, and their combinations are used to adjust the processes for stopping sound propagation. In design practice, this involves using elements of the building's concrete structure, massive walls made of various construction materials, typically brick or different types of blocks, and lightweight flexible partitions in the form of drywall and lining, usually made of gypsum boards of different densities.

In literature addressing sound insulation in buildings, the concept referred to as the "box within a box" or "room within a room" is highlighted as a solution for achieving the highest level of insulation. Many studio spaces, where the goal is always to maximize sound isolation from the surroundings, are constructed with this concept. The image of two massive walls at a certain distance from each other, surrounding a room on all sides, can be seen in manuals for designing studio spaces for sound recording. The partition made of two massive walls positioned at a small distance apart is described in DIN 4109 [1]. It is noted that this construction provides an improvement of approximately 12 dB compared to a single wall of the same mass.

What happens when the concept of sound insulation with double massive walls is applied in the construction of typical residential buildings? This idea appeared in Serbia during the last 10 years. It involves dividing a thicker massive wall into two slightly spaced thinner walls and placing them between concrete ceilings, as illustrated in Figure 1. It is not entirely clear, but it seems that the idea of splitting a massive wall into two parts arose from the demands for energy efficiency and the need to achieve adequate thermal insulation between apartments. The aim was to meet the minimum thermal insulation requirements with a material inserted between the two massive layers. The thermal behaviour of such partitions has been thoroughly analysed in various literature (e.g., [2]). It is likely assumed that this approach also improved sound insulation between apartments.

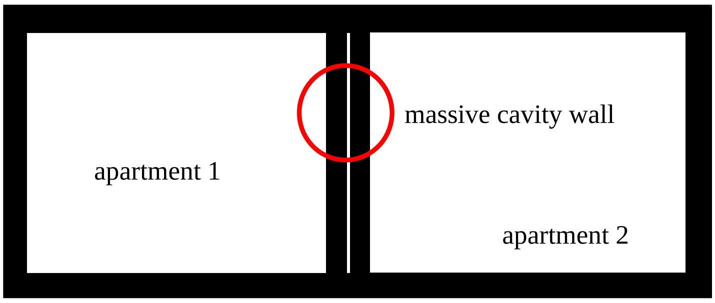

Fig. 1 Concept of a double massive wall (“cavity wall”) between rooms in a building

However, in the buildings where this was implemented, residents began to complain about the inadequate sound insulation. It is well known that sound insulation problems in buildings can be quickly identified, immediately upon moving in, unlike thermal insulation issues, which require time and suitable conditions to reveal potential problems. The residents' complaints, followed by the confusion of architects due to the unexpected results, initiated research that included laboratory measurements of the sound insulation capabilities of certain configurations of massive cavity walls, along with theoretical analysis and simulations based on known calculation algorithms. This paper attempts to synthesize the results of that research and draw conclusions that can assist architects in making decisions regarding wall selection in the future.

2. Experimental Analysis of Massive Cavity Walls in Buildings

The concept of a double massive wall is illustrated in Fig. 2. A single partition made of a massive material is "split" into two parts and spaced apart to create room for thermal insulation material, typically mineral wool. It is reasonable to assume that there was also an intention for the wool to contribute to the sound insulation of such a wall. The size of the gap between the two layers of the wall is dictated by the minimum required thickness of the thermal insulation material to meet energy efficiency requirements, as well as various practical considerations (minimizing wall thickness to avoid losing space in the rooms, the practical feasibility of the partition structure under given conditions, and so on).

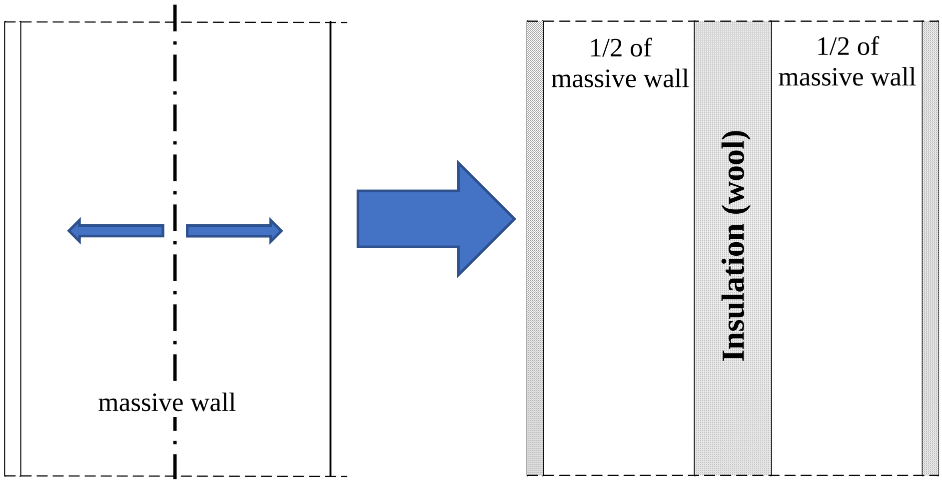

Fig. 2 Concept of idea about massive cavity wall

To explain the unexpected sound insulation measurement results achieved with cavity walls in several buildings, an investigation was initiated. Some of the results have been previously published [3,4]. The research included laboratory measurements of a cavity wall and a single wall made of nearly the same mass of material. Silicate brick as the material was selected for the tested wall, which has a density of about 1,800 kg/m³. This material was chosen because it has been used in buildings where unsatisfactory sound insulation was measured.

The results of the laboratory measurements are shown in Fig. 3 [3]. The diagram presents the measured sound reduction index values of a cavity wall with a width of 2x115 mm and a single wall with a width of 175 mm, both made of the same material (silicate bricks). Although these walls do not have equal surface masses to correspond to the situation in Fig. 2, they are close enough to qualitatively illustrate the principle of the processes occurring when a massive wall is split into two thinner layers. Both walls were plastered on both sides with the same type of mortar. Glass wool was installed in the cavity of the wall.

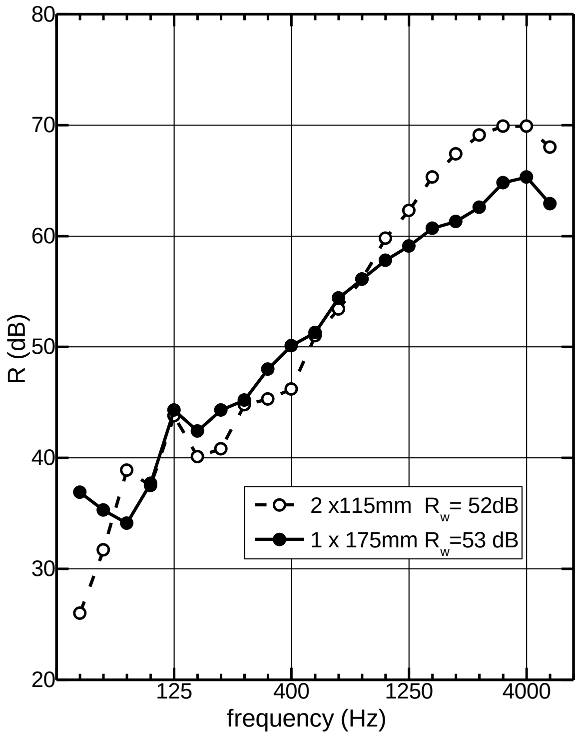

Fig. 3 Comparison of the sound reduction index of a single and double wall made of the same material**:** 1 **–** Double wall made of solid silicate bricks, 2x115 mm, with a 50 mm gap filled with wool, plastered on both sides**;** 2 **–** Single wall made of solid silicate bricks, 175 mm wide, plastered on both sides [3]

In this experimental analysis, the single wall is slightly thinner in terms of the total thickness of the massive material, measuring 175 mm compared to 225 mm of the double wall. That fact actually provided a slight advantage to the double wall in terms of total surface mass. Nevertheless, the measured sound reduction index *R* for the single wall was 1 dB higher. Only at the highest frequencies, the sound reduction index of the double wall exceeds that of the single wall, but due to the shape of the standard curve, this did not affect the single-number, apparent value of the sound reduction index.

In an effort to discover the reason behind the result achieved by the cavity wall, various modifications were tested by changing the material, its thickness, and density, in the cavity. The idea was to reveal the possible influence of cavity content on the sound reduction index. The result of those measurements is shown in Fig. 4 [3]. The most drastic option was the addition of gypsum board in the cavity along with the glass wool. The idea behind this modification was the potential contribution of the gypsum board, by analogy with the contribution it provides by typical wall lining in rooms. It can be seen that with all the described changes, the sound reduction index value varied by only 1 dB. That is negligible considering measurement uncertainty and the fact that minor details in the wall construction might have such an effect.

Therefore, the conclusions obtained from laboratory tests of various configurations are:

- A massive cavity wall applied in buildings between two rooms does not provide an improvement in sound insulation compared to a single wall made of the same quantity of massive material;
- The material in the cavity of the double wall has no practical effect on the wall's sound reduction index.

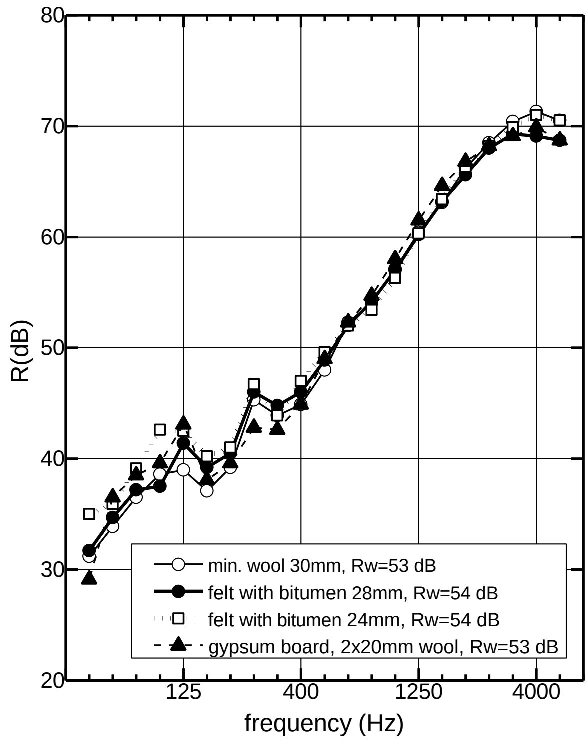

Fig. 4 The laboratory measurement of the massive cavity wall sound reduction index with various materials applied in the cavity [3]

3. Further Analysis of the Massive Cavity Wall

The measurement results in the laboratory showed that the double massive wall does not exhibit the expected improvement in sound insulation compared to a single wall, even though some additional discontinuities appear inside the partition affecting the sound energy propagation. After the experimental analysis performed in the laboratory, the reasons for the phenomenon that negates the theoretically expected improvement remained unclear. Therefore, explanations were sought in the theory of sound propagation through the complex structure of the buildings and in constructive details of the cavity wall.

Factors influencing the sound propagation between two adjacent rooms in a building separated by a partition are marked in Fig. 5 [5]. It is well known that there is flanking sound transmission between neighbouring rooms involving all lateral partitions, walls, and ceilings. Flanking transmission makes the difference between laboratory results and apparent sound reduction index in buildings. The transmission paths are indicated in the figure with red arrows. The drawing presented in Fig. 5 is simplified to a two-dimensional representation of the rooms, where lateral transmission is shown within the four represented partitions. However, in three-dimensional reality, eight lateral partitions are involved in sound energy traffic between rooms.

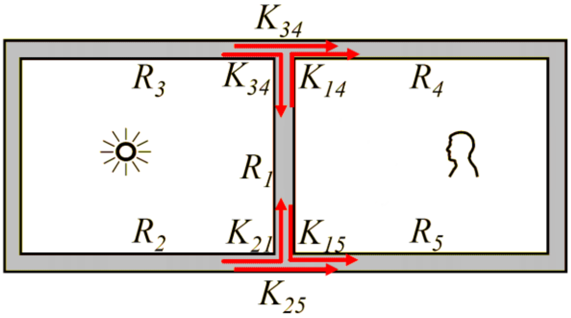

Fig. 5 Paths of sound energy transmission between rooms with identified factors affecting its attenuation [5].

Figure 5 reveals that the sound insulation is determined not only by the sound reduction index of the partition directly separating the rooms, marked as R_1, but also by the sound reduction index of the sideways partitions along which sound energy also travels between the rooms. Their sound reduction index marked from R_2 to R_5 is indicated in the figure (but the total of eight in three-dimensional space).

When propagating through a partition, wall or ceiling, the attenuation of sound energy with distance is relatively small compared to that in free space. This is because there is no wavefront spreading out inside the partitions, unlike in three-dimensional open space where a phenomenon of energy density, known as the "6 dB law", occurs. Significant attenuation of sound energy appears only at the partition’s junctions. At those points, attenuation occurs due to material discontinuities at junctions, as well as because at junctions, energy is splitting into multiple paths. The attenuation at junctions is described by a parameter called the vibration reduction index K_{ij}.

The value of the vibration reduction index K_{ij} is expressed in decibels and depends on two factors: the ratio of the surface masses of the partitions connected at a junction and the type of their joint (rigid or flexible). In the case of massive cavity walls, the connection of the wall falls into the category of rigid joints, meaning that the energy transfer processes are determined by the masses of the connected partitions. The values of the index K_{ij} for rigid joints of massive partitions are defined by a diagram shown in standard EN 12354-1, which is also presented here in Fig. 6 [5]. The diagram illustrates the parameter’s changes as a function of the surface mass ratio of the connecting partitions. Splitting a single massive partition into two lighter ones, affects the reduction of sound energy that passes through the joints. This means that such changes alter the conditions on the paths of lateral transmission. The diagram presented in Fig. 6 should be understood as an illustration of the trends in these changes.

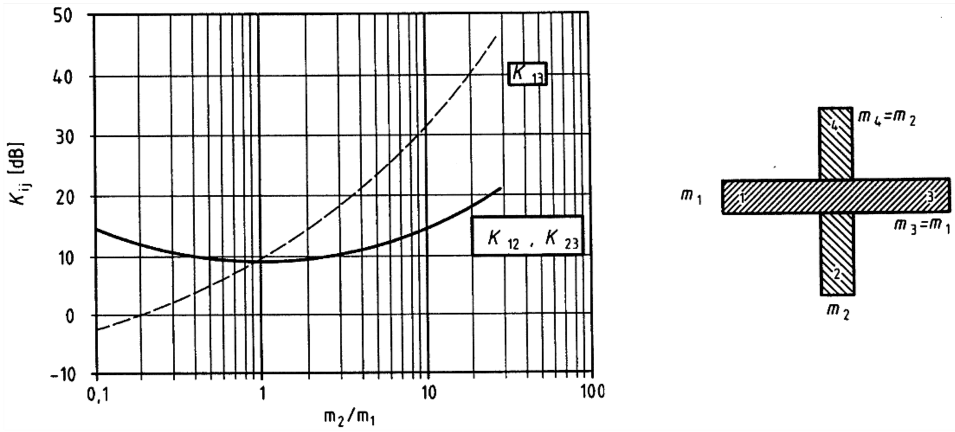

Fig. 6 Vibration reduction index K_{ij} at the joints of partitions as a function of their mass per unit area (according to document EN 12354-1) [5]

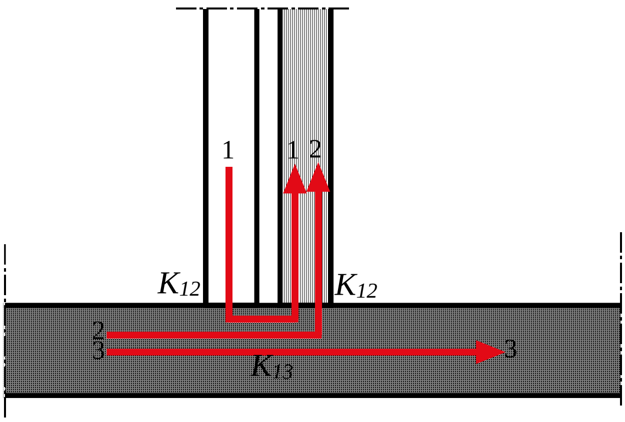

Fig. 7 Sound energy flow along a flanking path with the cavity wall; numbers in the index of vibration reduction index K_{ij} correspond to those in Fig. 6

At the joint of a massive cavity wall with lateral partitions, there are sound energy pathways illustrated in Fig. 7. When the layers' mass is reduced in a double partition, the values of the vibration reduction index at all joints change when compared to a single massive wall (diagram K_{12} in Fig. 6). There is now an additional pathway between two partitions, marked as 1 in Fig. 7. This is a parallel pathway introducing a by-pass for the transmission of sound energy through the cavity. Such a pathway is formed around the entire perimeter of the wall, which means its impact is certainly not negligible in a quantitative sense for the sound isolation between rooms. That path is present in the laboratory, too.

In laboratory environments, the measurement of the sound reduction index, by definition, does not include flanking transmission paths between the transmitting and receiving rooms. However, in the case of cavity walls, there are important additional paths illustrated in Fig. 7 and marked as 2. That is an indirect path for the transmission of sound energy between flanking partitions in the source room and the cavity wall thin layer on the receiving room side. The diagram in Fig. 6 illustrates that with reduced wall mass connected with very massive ceilings, the value of vibration reduction index K_{12} is lower. Furthermore, in buildings, there is a flanking path marked as 3. Due to the change in wall mass ratio when the cavity wall is between rooms, there will be increased transmission of sound energy through the flanking paths [6,7].

Alongside all the changes that occur in the transmission of sound energy between adjacent rooms when a massive cavity wall is installed instead of a single wall, there are also some effects that are not visible in architectural drawings but contribute to the reduction of the apparent sound reduction index in buildings. Specifically, when cavity partitions are organized as a 'box within a box' system, the statics of such a construction are also somehow addressed. The inner 'box' is designed as a rigid form resting on specific supports, which means that the contact between the layers is limited to the supports of the inner 'box.' However, when a standalone double massive wall is placed between two concrete ceilings, as shown in Figure 1, new issues arise independent of acoustics, such as the statics of the wall and its seismic stability. Thus, massive cavity walls require secure connections between layers, meaning there needs to be a certain number of solid connections between them. Some manufacturers of clay and similar blocks have even provided accessories for such purposes. This means that additional paths will appear between the two wall layers due to the inserted solid connections, making it so that the partition no longer consists of two completely separate layers with insulation material in between, but rather two point-connected masses.

4. CONCLUSION

Double massive walls, typically made of clay blocks or bricks, with thermal insulation material in the cavity did not exhibit the expected sound insulation properties in residential buildings. Moreover, the results in some buildings were below the established minimum criteria for acoustic comfort. All expectations regarding massive cavity walls are based on the elementary theory of sound propagation. In these walls, the discontinuities of the medium that cause attenuation of transparent sound energy are effectively doubled, which would imply an increased value of the sound reduction index. Such expectations are further supported by literature that contains statements about the double walls applied in various music studios, as by information generated in some European countries regarding insulation in residential buildings constructed in a row.

None of this is incorrect; however, the physical conditions in buildings built in a conventional manner, with reinforced concrete structures, in general, do not provide the necessary conditions for massive cavity walls to demonstrate their theoretically expected properties. The physical explanation for the somewhat unexpected outcome lies in the complexity of sound paths between adjacent rooms with lighter partitions that are rigidly connected to the surroundings. In the case of massive cavity walls, the mass of the layers connected to the side partitions is smaller than a single monolithic wall made from the same amount of building material. As the surface mass of the wall layers decreases, the value of the vibration transmission reduction index K_{ij} at the junctions changes when compared to the state with a single massive wall at the same position. As a result, in massive cavity walls, the influence of sound energy paths through their lateral connections is amplified.

In short, the sound insulation effectiveness of double massive walls in buildings will significantly depend on the physical context in which they are placed. To reach a theoretical limit of their sound reduction index value it is necessary to place them along a dilation in construction. In standard residential buildings, it is hardly possible to provide such conditions, or can be unreasonable. Such walls have increased thickness, but slightly lower or, at best, the same insulation effectiveness as single walls made with the same quantity of massive material. When examples from the literature concerned with the application of massive cavity walls are presented, it becomes evident that they are always placed at the dilation in the structure [1]. Thus, any connection for lateral sound transmission is destroyed. In literature was shown that a single wall with a gypsum board lining provides higher sound insulation effectiveness than a wall with a doubled massive layer and some infill in the cavity [8].

What is particularly significant in the topic addressed in this paper regarding massive cavity walls is the demonstration of complexity in sound insulation issues inside buildings. The case of cavity walls shows that details, such as changes in physical processes at the partitions junctions can affect the sound insulation. This further implies that for a quality design of buildings, it is essential to systematically consider the physical characteristics of building constructions, rather than just selecting walls based on their data from a catalogue or database.

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