Article citation info:
Xu R., Wang Z., Zhou Y., Xu Q., Wu X., Xu B., Zhang D. 2026. Research on Sound Insulation Performance of Lightweight Wooden Partition Walls Based on Constrained Damping Technology. *Drewno. Prace naukowe. Doniesienia. Komunikaty* 69 (218): 00096. https://doi.org/10.53502/wood-209237

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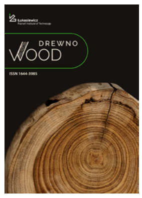
Journal website: https://drewno-wood.pl



Research on Sound Insulation Performance of Lightweight Wooden Partition Walls Based on Constrained Damping Technology

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Article info
Received: 28 March 2025
Accepted: 11 August 2025
Published: 29 May 2026

Keywords
lightweight wooden partition wall
constrained damping
COMSOL
impedance tube method
reverberation chamber method

This study introduces damping vibration and noise reduction technology to improve the sound insulation performance of lightweight wooden partition walls, aiming to alleviate indoor environmental noise and enhance living comfort. By applying this technology, a constrained damping structure was developed and its sound insulation capabilities were modelled using COMSOL finite element analysis. The model's accuracy was confirmed through impedance tube testing, leading to an optimization of structural parameters that identified stiffness and area density as key to sound insulation performance. Reverberation chamber tests validated the proposed design optimizations, showing that the test group's walls achieved superior sound insulation, with an 11.2 dB greater reduction in sound transmission loss at 80 Hz compared to the control group. The constrained damping technology not only improves insulation across a broad frequency spectrum but also specifically targets and mitigates sound insulation deficiencies, steering clear of problematic architectural acoustic ranges and improving overall soundproofing effectiveness. This research contributes to advancements in architectural acoustics by providing a solution that enhances the sound insulation performance of wooden partition walls.

DOI: 10.53502/wood-209237

Introduction

Light timber structure is one of the forms in the modern timber structure building system. It has the advantages of economy and environmental protection, and has broad application prospects. Lightweight partition walls are a building component that came into being with the emergence of a large number of high-rise buildings and the improvement of building energy-saving requirements. It has the advantages of light weight, being filled with thermal insulation materials and being prefabricated, and It has found extensive application across diverse building types, like light timber structures. Nevertheless, due to the poor sound insulation performance of this wall, it is not favourable for its further market promotion and

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application. Lightweight wooden partition walls are prone to sound insulation troughs caused by structural resonance effect and coincidence effect in the low frequency and high frequency areas concerned by architectural acoustics research, which impacts the overall appraisal of the sound insulation performance of the wall. Therefore, adopting appropriate noise reduction technology to improve the sound insulation performance of walls has a positive effect on popularizing light wooden partition walls and improving the comfort level of buildings. In view of this, it becomes essential to conduct new research to improve the sound insulation abilities of lightweight partition walls in edifices.

With the development of science and technology, computer simulation of sound insulation characteristics of walls has been realized, such as finite element method, boundary element method, statistics energy analysis, and modal analysis approach. In addition to numerical simulation, scholars have conducted relevant research in many aspects, such as theoretical analysis, experimental methods, and wall structure optimization. In 2017, Garg et al. (2017) developed an artificial neural network model to predict the sound insulation performance of multi-layer sandwich gypsum board partition walls using a multi-layer forward feedback method involving 13 construction parameters. In 2020, Tamas-Gavrea et al. (2020) proposed a three-layer plywood with wool as the core material, which was found to have good sound absorption and sound insulation performance by experiments and was suitable for the wallboard of light partition wall. In 2020, Lyu (2020) studied the sound insulation performance of 13 prefabricated lightweight partition walls with different materials and structures. The results show that the sound insulation performance can be effectively improved by hanging or sticking glass-magnesium plates on both sides of the wall, but simply hanging the plates easily produces low-frequency resonance, which leads to the decrease of low-frequency sound insulation.

Most of the research on constrained damping technology is carried out around the vibration control and noise suppression of mechanical structures (Lu et al. 2021; Qin et al. 2022; Wang et al. 2023) , involving a variety of industrial fields such as aerospace, shipbuilding, and railway transportation (Gao et al. 2018; Rouleau et al. 2022). It has become a common and effective method to control structural vibration and noise radiation (Rao 2003). The three-plywood laminated form of constrained damping structure is feasible in light partition walls with wallboard as the main structure. This structure can be applied to partition walls to explore its repair effect on sound insulation performance. In 2017, Liang (2017) carried out an investigation into the sound insulation performance of a double-layer board. The double-layer board had damping layers added to it, thus creating a constrained damping structure. The results show that the introduction of damping layer not only weakens the resonance of damping control region but also shifts the frequency domain of coincidence effect to high frequency, and as the thickness of the damping layer increases, the enhancement in sound insulation performance is more significant than that brought about by the quality factors. In 2018, Xiang et al. (2018) applied a porous layered three-dimensional polymer material based on organic nanoparticles: Polymer-crosslinked aerogel to gypsum sandwich wallboard. The experiment showed that using light X- aerogel with a thickness of less than 10 mm could significantly increase the structural sound transmission loss. In 2020, Ehrig et al. (2020) proposed a compressible constrained damping structure consisting of a base layer, a constrained layer and a compressible open-cell foam core layer in the middle. The vibration behaviour of the structure can be adjusted by changing the compression of the core layer with different driving pressures, thus improving the acoustic performance of the structure.

To sum up, lightweight wooden partition wall is a commonly used partition product in the market at present, which has been applied in many types of buildings represented by light timber structures. By changing the number of layers and materials of the wallboard and adding flexible cushion, the sound insulation performance of partition wall is improved. At the same time, the construction cost is increased, and the effect of improving acoustic insulation performance is not significant enough, especially since it isn't easy to repair the sound insulation trough at resonance and coincidence frequency. This paper aims to research the acoustic insulation performance of lightweight wooden separating walls using constraint damping technology. The goal is to apply damping noise reduction technology to building walls to optimize the design of light wood partition walls and improve their sound insulation performance. This will promote the application of lightweight wooden partition walls in different types of buildings.

The addition of damping materials of appropriate thickness can boost the acoustic insulation performance of the wall without excessively increasing its thickness and quality, and its construction is simple, which meets the development needs of the times for lightweight and prefabricated partition walls. This work also provides a reference for the application research of other damping composite structures in building components to broaden the application scope of damping materials and increase their market demand.

Simulation

1. Material parameters used for simulation

In the finite element modelling process, the precise definition of different material properties is the basic premise to ensure reliable simulation results. The constrained damping structure consists of upper and lower elastic layers (constrained layer, base layer) along with an intermediate damping layer. As shown in Figure 1.

The gypsum board specimen utilised as the constraining layer dimensions 420 × 60 × 12 mm, with an average density of 560 kg/m^3, and a moisture content of 8%. Using the transient excitation method, the measured first - order bending frequency and first - order torsion frequency of the gypsum board specimens were 143 Hz and 538 Hz respectively. (Wang et al. 2018; Wang et al. 2016; Wang et al. 2015; Wang et al. 2014) respectively, and Young's modulus E was 2380 MPa, and the shear modulus G was 900 MPa through calculation. The Poisson's ratio measured from the cantilever plate vibration test is 0.26.

The oriented strand board used as the base layer is an orthotropic material with nine independent elastic constants. In order to improve the reliability of the test results, multiple test pieces were cut from different parts of the entire board. OSB-X, OSB-Y, and OSB-Z respectively represent the length of the test piece along the x, y, and z directions. Their dimensions are 340 × 15 × 15 mm, 340 × 15 × 15 mm, and 50 × 50 × 15 mm. The average density is 693.3 kg/m^3, and the moisture content is 10.4%. By using the symmetrical four-point bending test method (Wang et al. 2023a, Wang et al. 2023b, Wang et al. 2019) based on electrical measurement, the Young's modulus and of the OSB specimen are 8200MPa and 3940MPa, respectively, and Poisson's ratio ,and are 0.38, 0.26, and 0.23, respectively. The shear modulus , , and of the specimen measured by the asymmetric four-point bending test method are 1240 MPa, 360 MPa, and 500 MPa, respectively. The Young's modulus measured by the tensile test method based on the determination of the internal bonding strength of wood-based panels, which is 470 MPa.

The densities of viscoelastic materials 3M rubber, butyl rubber, and chloroprene rubber (CR) used as damping layer are 950 kg/m^3, 1500 kg/m^3, and 1350 kg/m^3, respectively. Dynamic mechanical thermal analysis (DMA) test based on the forced non-resonance method was carried out. The complex Young's modulus E* was measured by DMA tensile deformation mode, and the complex shear modulus G* was measured by shear deformation mode. In order to obtain the dynamic mechanical parameters of materials in a wide frequency range, the multi-frequency temperature scanning mode is adopted in the test, and the spectrum is expanded and changed according to the "temperature-frequency equivalent theory" (Williams et al. 1995, Jin et al. 1997, ISO 1991). After obtaining parameter data in a wide frequency range at room temperature, the corresponding parameters are fitted into frequency-dependent expressions based on the K-V fractional derivative model of viscoelastic materials, which is suitable for numerical simulation research (Enelund et al. 1999, Hosseinkhani et al. 2021, Lewandowski et al. 2010, Podlubny 2000).

2. Model optimization research

In this study, COMSOL Multiphysics is used to establish the COMSOL model of constrained perform a simulation analysis for the damping structure, which is illustrated in Figure 2. According to the above test results in "material parameters used for simulation", the acoustic transmission loss is obtained while damping layer is 3M rubber, butyl rubber, and chloroprene rubber. To verify the effectiveness of constrained damping structure in noise reduction and explore the sound insulation mechanism of constrained damping structure, a double-layer board control group consisting of gypsum board and OSB is set, and the corresponding parameters are the same as those of constrained damping structure.

The physical and mechanical parameters of unit components greatly influence the structure's overall performance, which is the focus of structural optimization design. Based on the COMSOL acoustic model, the structural parameters are changed, and the corresponding sound transmission losses are calculated to explore the impact of parameter changes on the structural sound insulation performance. The selected optimization parameters are: the thickness of every unit layer, the density of each individual unit layer, the Young's modulus of the elastic - layer material, the storage shear modulus, and the shear loss factor of the

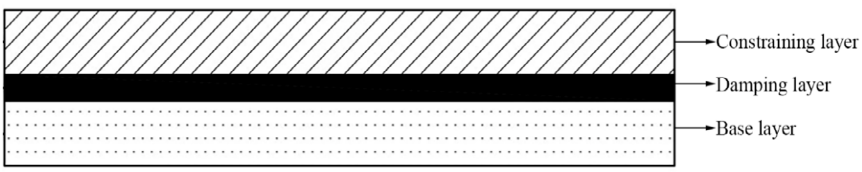


Fig. 1. Schematic diagram of constrained damping structure

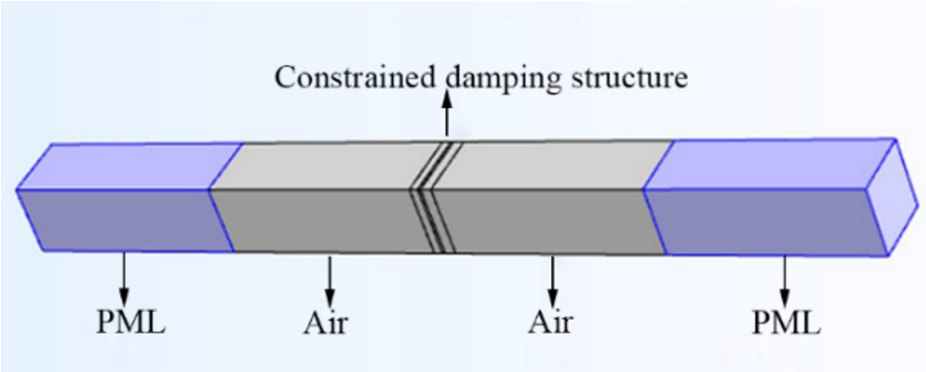


Fig. 2. Schematic diagram of COMSOL model

damping - layer material(Ma 2020). The common thicknesses of gypsum board and OSB in the market are 9 mm, 12 mm, and 15 mm. This paper uses these three thicknesses to explore the change in the attenuation of acoustic transmission. Considering the density range of commonly used materials in walls, the variables take values , 2, and 3. Regarding the Young's modulus of the elastic layer, considering the orthotropic anisotropy of OSB, in order to control the variables and simplify the analysis, the isotropic gypsum board is used as an example to study. The Young's modulus of the gypsum board is recorded as E, and the values of variables are 0.5E, E, 5E, and 10E based on the Young's modulus range of elastic materials (except metal materials) commonly used in actual walls. Note that the shear storage modulus of butyl rubber is G', and the values of variables are 0.1G', G', and 10G'. When the constrained damping structure undergoes vibration and deformation, the damping layer is subjected to shear forces. In this context, the shear loss factor of the material serves as a crucial indicator for characterizing its damping capabilities. Record the shear loss of butyl rubber as tgδG. Considering the shear loss factor range of most viscoelastic materials, the values of the variable are 0.2tgδG, 0.5tgδG, tgδG, and 2tgδG.

Materials and methods

1. Sound insulation performance test of impedance tube

1.1. Test object

Constrained damping structure composed of gypsum board, viscoelastic material and OSB, control group consisting of gypsum board and OSB only. The test materials and material parameters were measured from the same batch of materials. Butyl rubber and 3M rubber have high viscosity, and gypsum board and OSB are directly attached on both sides. Chloroprene rubber is bonded to gypsum board and OSB

Table 1. Fundamental parameters of the constrained damping structural sample

Specimen	Compose	Size /mm × mm × mm	Density /(kg/m^3)	Quantity/block
Constraint-3M	Gypsum board	100 × 100 × 12	550	3
	3M rubber	100 × 100 × 1	950	
	OSB	100 × 100 ×1 5	700	
Constraint-Butyl	Gypsum board	100 × 100 × 12	550	3
	Butyl rubber	100 × 100× 1	1500	
	OSB	100 × 100 × 15	700	
Restraint - Chloroprene	Gypsum board	100 × 100× 12	550	3
	Chloroprene rubber	100 × 100 × 1	1350	
	OSB	100 × 100 × 15	700	
Control group	Gypsum board	100 × 100 × 12	550	3
	OSB	100 × 100 × 15	700	

by applying single-component polyurethane adhesive on the surface, and the sizing amount is 64 g/m^2 (Liu 2018). After the bonding is completed, the combined specimen is placed under a heavy object and pressed for 24 hours. The specimen parameters are shown in Table 1.

1.2. Test instruments

One set of rectangular cross-section sound insulation measurement system based on the Pulse system from Danish B&K company, along with one piece of sound-absorbing sponge; 2716C power amplifier; 3560D multi-channel signal acquisition and real-time analysis system; HiVi-M3S speaker; 4 Type26CA microphones; 7700FFT Analysis data analysis software.

3.1.3 Test methods

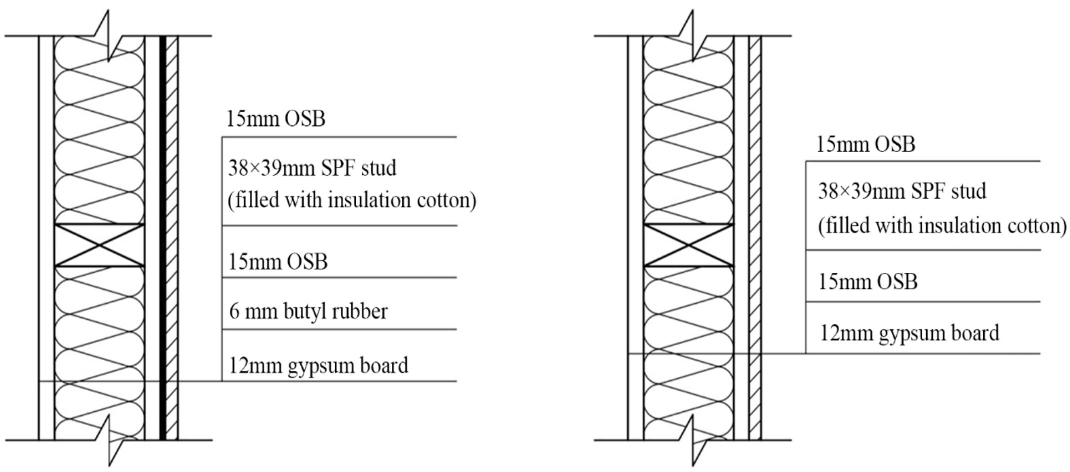
Referring to standards ASTM E 2611-19 (ASTM 2019) and ISO 10534-2:2023 (ISO 2023), this study uses the four-microphone method to measure sound insulation. The fundamental principle is to acquire the sound insulation performance (instead of the traditional expression of sound transmission loss) of the components within the impedance tube by means of the transfer matrix approach.

2. Sound insulation performance test of reverberation room

The impedance tube technique is only capable of measuring the sound isolation property of small-sized components when the sound waves are incident vertically. In practical engineering projects, the partition wall usually has a large dimension, and the incident direction of the sound waves frequently turns out to be random. Based on the theory of room acoustics, in contrast to the impedance tube method, the reverberation chamber method has the ability to more accurately represent the real sound insulation features of the wall. Therefore, in this study, two sets of light wood structure partition walls were designed and manufactured with reference to the design atlas of relevant national building standards, sound insulation test standards and research results, and the reverberation room method test was carried out. By comparing the test results, the improvement effect of constrained damping structure on the acoustic insulation ability of the wall was explored.

2.1. Test object

On the basis of the outcomes of the COMSOL simulation and the sound isolation property test of the impedance tube, a constrained damping structure consisting of 12 mm thick gypsum board, 6 mm thick butyl rubber, and 15 mm thick OSB is selected to be applied to the solid partition wall. In order to explore the applicability of constrained damping technology in sound insulation design of large-scale wall structures, the control group without damping materials and the experimental group with constrained damping structures were designed. The practices of two kinds of partition wall structures refer to China National Building Standard Design Atlas 14J924 "Wood Structure", the structural schematic diagram is shown in Figure 3. The partition wall size of the experimental group shown in Figure 3 (a) is 1.95 m × 1.2 m × 0.137 m, and that of the control group shown in Figure 3 (b) is 1.95 m ×1.2 m × 0.131 m. The primary component parameters of the partition wall are presented in Table 2.



(a)Test group (b) Control group

Fig. 3. Partition structure diagram

Table 2. Parameters of the main component of the partition as the test group

Component	Size/mm × mm × mm	Density /(kg/m^3)	Quantity/block
SPF stud a	1134 × 38 × 89	480	4
SPF stud b	1950 × 38 × 89	480	2
OSB	1950 × 1200 ×15	700	2
Butyl rubber	1950 × 1200 × 6	1500	1
Gypsum board	1950 × 1200 × 12	560	1
Insulation	-	12	-

2.2. Test instruments

Model 4292-L omnidirectional dodecahedron loudspeaker, manufactured by Danish B&K company; 01dB FUSION 3G sound level meter with analysis function; Some balloons.

3.2.3 Test methods

Referring to the standard ISO 140-3:1995+A1:2004 (ISO 2023), the laboratory required by the reverberation chamber method consists of two connected reverberation rooms: the room with the sound source and the room for receiving sound There is an opening between the reverberation chambers to install the components to be tested.

Results and analysis

1. COMSOL simulation results and analysis

The simulation results of the three groups of constrained damping structures and the control group are shown in Figure 4.

1.1. Analysis of the attenuation of sound transmission at medium and low frequencies

In the simulation results for the mid - low frequency range, the soundproofing performance of the control group is roughly 5 dB superior to that of the three constrained - damping - structure groups. The thicknesses of the three constrained - damping - structure groups are a bit larger than that of the control group. Nevertheless, the Young's storage modulus of the damping - layer material, ranging from 10^6 to 10^7 Pa, is substantially smaller than the 10^9 Pa Young's modulus of the elastic - layer material. Combined with the simulation results, it is known that the existence of the damping layer reduces the equivalent stiffness of the overall structure. This is essentially caused by the low Young's modulus of the damping layer material, which results in the sound insulation of the constrained damping structure being inferior to that of the control group. In fact, adding damping layer increases the area density of the structure, which is helpful to improve the sound insulation from the perspective of quality law, but the change of structural stiffness brought by the damping layer plays a significant role in this frequency band.

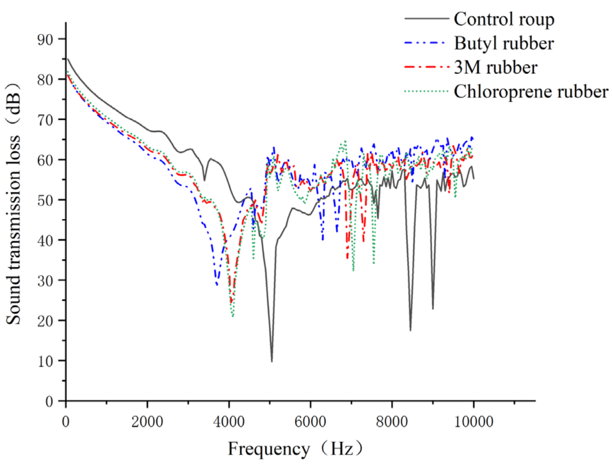


Fig. 4. Simulation results of sound transmission loss of COMSOL model

In addition, although the acoustic insulation abilities of the three groups of constrained damping structures is not much different, their order of magnitude also corresponds to Young's storage modulus of the materials in the middle damping layer, from large to small: chloroprene rubber, 3M rubber, and butyl rubber (Ma 2002).

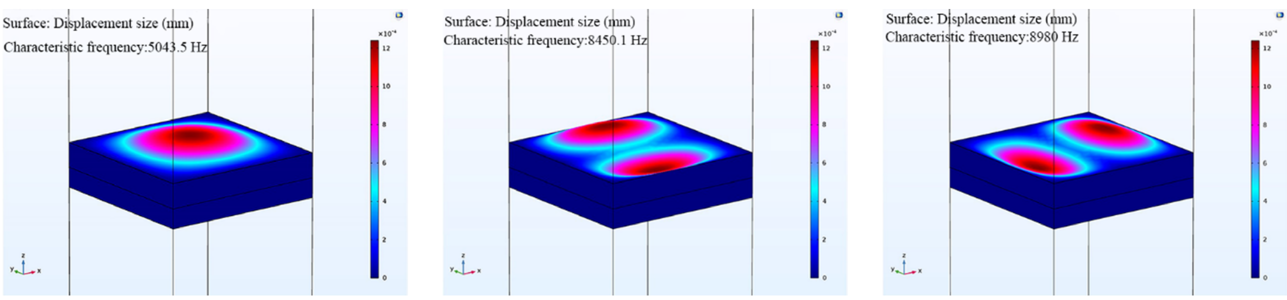
1.2. Analysis of high-frequency sound insulation trough

In the frequency range where the sound insulation dip emerges in the simulation outcomes, the resonance frequencies of diverse structures vary, and the respective sound insulation dip values are distinct as well. Firstly, the characteristic frequency calculation verifies whether the sound insulation trough is caused by resonance frequency, and the structural modal order represented by the frequency at each trough is obtained. Taking the control group as an example, the first three resonant modes of the structure within 10000Hz are shown in Figure 5.

As is observable from Figure 5, the initial three modal frequencies of the control group match the three frequencies of the sound - insulation troughs in Figure 5. This demonstrates that structural resonance is the cause of sound - insulation deficiencies in certain frequency bands. It also reveals that the nature of structural sound propagation lies in the transmission of the vibration state, and sound insulation requires the suppression of structural vibration. The resonant frequencies and the corresponding sound - transmission loss values of the four groups of structures are presented in Table 3. When compared with the control group, the resonant frequencies of the three groups of constrained damping structures shift towards lower frequencies, and the sound - insulation troughs at the resonant frequencies are notably improved.

From Figure 4 and Table 3, it can be seen that the minimum sound insulation of the four groups of structures in the whole frequency band appears at the (1,1) order resonance mode frequency, so it can be seen that the overall vibration amplitude of the structure is the largest at the first order resonance frequency, which causes a large amount of transmission of acoustic energy and has the most significant impact on the overall sound insulation performance evaluation. For each order of resonance frequency, the order of four groups of structural frequency values from large to small is: control group, constrained-chloroprene, constrained -3M, constrained-butyl, which exactly corresponds to the order of four groups of structural stiffness, which confirms the relationship between structural resonance frequency and stiffness. In addition, the resonance frequencies of the structures with 3M rubber and chloroprene rubber as damping materials are similar because although the Young's/shear modulus of chloroprene rubber is higher than that of 3M rubber, resulting in high structural stiffness and high resonance frequency, its material density is also higher than that of 3M rubber, resulting in high structural area density and reduced resonance frequency. Under the comprehensive effect of stiffness and area density, the resonant frequencies of the two structures tend to be the same. When we make a comparison of the sound transmission loss at each resonance frequency, we find that the three groups of constrained damping structures have a value that is 10 dB - 20 dB higher than that of the control group. This is because the viscoelastic materials in the middle layer possess high - damping characteristics, which are capable of efficiently dissipating vibration energy.

With the exception of the sound insulation trough that is induced by the resonance frequency, the sound transmission loss of the four groups of structures in high frequency band increases with the increase of frequency, which accords with the sound insulation quality law. The sound - insulation performance of the three groups of constrained damping structures is approximately 5 dB greater than that of the control group. This is mainly attributed to the loss of vibration energy in the damping - layer material. Among the three groups of structures, the structure with butyl rubber as damping layer material has the highest overall



(a) (1,1) resonant mode (b) (1,2) resonant mode (c) (2,1) resonant mode

Fig. 5. Structural mode

Table 3. Resonance frequency and corresponding sound transmission loss of four structures

Structure	(1,1) resonant mode		(1,2) resonant mode		(2,1) resonant mode	
	/Hz	/dB	/Hz	/dB	/Hz	/dB
Constraint - Butyl	3716	27.23	6308	39.67	6651	41.02
Constraint -3M	4069	23.54	6892	34.19	7322	37.30
Constraint - Chloroprene	4087	18.55	7055	30.01	7547	31.86
Contrast	5044	8.79	8450	17.42	8980	18.78

sound transmission loss in high frequency band, which is because butyl rubber has the highest shear loss factor and the highest area density among the three materials, that is, The overall sound insulation performance within the high-frequency band is likewise influenced by the energy dissipation of the damping materials and adheres to the mass law.

It should be noted that although the sample size used in this study is smaller than the recommended value in ISO 10140-2, based on existing studies (del Rey et al. 2019; del Rey et al. 2017; Wang et al. 2022), the relatively small sample size adopted in this study has a limited impact on the results of sound insulation measurements. Meanwhile, the consistency of test conditions between the experimental group and the control group was strictly controlled in this study to ensure the reliability of the comparison results. Future studies will consider using standard-sized samples for verification.

In summary, constrained damping structures with viscoelastic materials have certain application prospects in wall sound insulation. After viscoelastic materials with high area density and large shear loss factor are applied to full-scale walls in the form of constrained damping, it is anticipated that the soundproofing capability within the frequency band that is of interest in architectural acoustics will be enhanced. Among the three viscoelastic materials used in this study, butyl rubber has the best damping performance and is suitable for use as a sandwich material for constrained damping structures in subsequent studies.

1.3. Optimization of research results and analysis

According to the above simulation results, butyl rubber with the best energy consumption effect is selected as the damping layer material of the structure to be optimized, the influence of different structural parameters on sound transmission loss and its reasons are studied, and the optimization design suggestions of the acoustic insulation performance of the constrained damping structure is presented, which can provide a reference for the design and manufacture of partition walls.

The standard thicknesses of gypsum board and OSB used as elastic layer materials on the market are 9 mm, 12 mm, and 15 mm. The research results show that the sound transmission loss has a similar trend with the thickness of the two materials. Therefore, the gypsum board is used as an example to explain. The OSB thickness is fixed to 15 mm while controlling a single variable. The corresponding curve is shown in Figure 6(a). The sound transmission loss curves of constrained damping structures with different damping layer thicknesses are shown in Figure 6(b). Changing the density of distinct unit layers yields a comparable effect on sound transmission loss. Hence, a gypsum board with a density of ρ is taken as an illustration for the discussion. The corresponding curve is shown in Figure 6(c). For the Young's modulus of the elastic layer, the relevant results are shown in Figure 6(d). The influences of the change of shear energy storage modulus of the damping layer and the shear loss factor on the sound transmission loss of the constrained damping structure are shown in Figures 6(e) and 6(f), respectively.

Based on the aforementioned simulation research, when the structural parameters within the impedance tube-based acoustic model increase, the corresponding alterations of the key parameters that represent the sound insulation performance of the structure are summarized, as presented in Table 4.

From Figure 6(a), it is evident that in the mid - low frequency band, for each 3 mm increment in thickness, the overall sound transmission loss value grows by roughly 2 dB. On one hand, this frequency band is the region where the structure's stiffness is the dominant factor. When the thickness of the elastic layer goes up, the structure's stiffness is enhanced, thereby increasing the sound transmission loss. On the other hand, as the elastic - layer thickness increases, the structure's area density rises, and according to the mass law, the sound insulation performance improves. In the overall resonance region of the subsequent frequency band, as the elastic - layer thickness increases, the

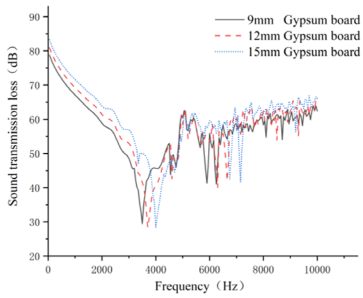
Table 4. Effects of various parameters on sound insulation performance of the structure

Structural parameters (increase)	Resonance effect	Sound transmission loss (except insulation trough)
Elastic layer thickness	The frequency moves to higher frequencies Sound insulation low value unchanged	Full band enhancement
Damping layer thickness	The frequency moves to lower frequencies The value of the acoustic trough has increased	The high frequency band increases after the first resonance trough
Density of cell layer	The frequency moves to lower frequencies The value of the sound insulation trough is unchanged	The high frequency band increases after the first resonance trough
Young's modulus of elastic layer	The frequency moves to higher frequencies The value of the sound insulation trough is unchanged	The middle and low frequency bands are increased before the first resonance trough
Shear energy storage modulus of damping layer	The frequency moves to higher frequencies The value of the sound insulation trough is unchanged	The middle and low frequency bands are increased before the first resonance trough
Damping layer shear loss factor	Frequency immobility The value of the acoustic trough has increased	Full band enhancement

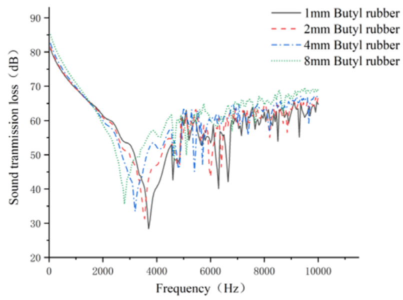
resonance frequency shifts to a higher frequency. This is also caused by changes in structural stiffness and area density. The former has a positive correlation with the resonance frequency value, while the latter has a negative correlation. Under the combined effect of the two, the resonance frequency increases. It is clear that the change in stiffness caused by the thickness has a greater influence on the resonance frequency than the change in area density.

Furthermore, thickness variation has a negligible effect on the sound insulation trough at the structural resonance frequency. Within the high - frequency band, with each 3 - mm increment in thickness, the overall sound transmission loss value increases by approximately 1 dB. This trend is consistent with the quality law.

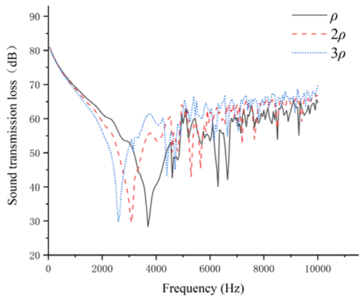
It can be seen from Figure 6(b) that the sound transmission loss of the structure is positively correlated with the thickness of butyl rubber in a low frequency band, but with the increase of frequency, the sound transmission loss decreases with the increase of thickness with 1500 Hz as the turning point. The increase in damping layer thickness reduces the stiffness of the structure and increases the area density of the structure. The former will reduce the sound transmission loss in the structural stiffness control area, while the latter will increase the sound transmission loss according to the quality law.



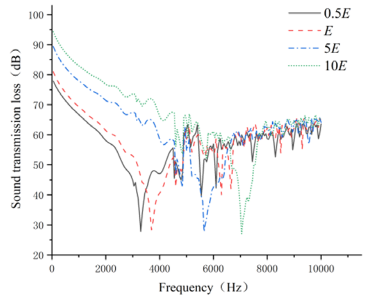
(a) Variation of structural sound transmission loss with thickness of gypsum board



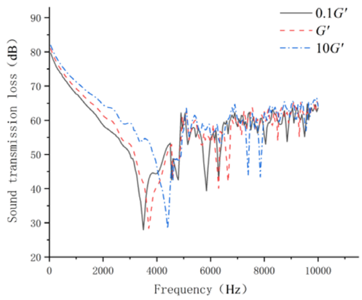
(b) Variation of structural sound transmission loss with thickness of butyl rubber



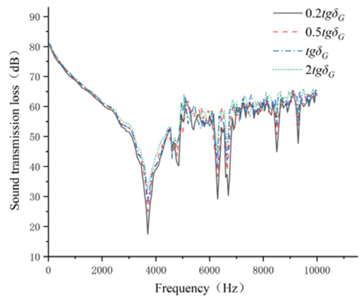
(c) Variation of structural sound transmission loss with density of gypsum board



(d) Variation of structural sound transmission loss with Young's modulus of butyl rubber



(e) Variation of sound transmission loss with shear storage modulus of butyl rubber



(f) Variation of structural sound transmission loss with shear loss factor of butyl rubber

Fig. 6. The Effect of Various Parameters on the Acoustic Insulation Performance of the Structure

Taking into account the above - mentioned trend, it is evident that in the low - frequency band, the area density influenced by thickness exerts a more dominant influence than the stiffness. That is, the sound transmission loss is controlled by quality; with the increase of frequency, the effect of stiffness is gradually improved, and the sound transmission loss is controlled by stiffness. The turning point in the middle frequency band is obviously influenced by the change of resonance frequency, which is also related to stiffness and area density. In the structural resonance region, there is a negative correlation between the resonance frequency and the thickness of the damping layer. Owing to the energy dissipation of the viscoelastic material, the sound insulation trough at the resonance frequency grows as the thickness of the damping layer increases. This is something that is not easily accomplished by increasing the thickness of the elastic layer. In the high - frequency region, the overall sound insulation complies with the mass law. Specifically, for every 2 - mm increase in thickness, the overall sound transmission loss rises by roughly 1.5 dB.

As can be seen from Figure 6(c), in the low frequency band, the sound transmission loss is mainly affected by stiffness, so the role of the quality law in this frequency band needs to be further explored. In this frequency band, the structure is influenced by stiffness, so the effect of the mass law in this frequency band requires further exploration. As the frequency rises, due to the shift of the resonance - frequency trough, the sound transmission loss of panels with varying densities differs. Since the stiffness and size of the three groups of structures are identical, the resonance - frequency value is solely affected by the area density and decreases as the area density increases. Moreover, the trough value at the resonant frequency is hardly affected by the area density. In the high - frequency band, except for the resonance frequency, the sound transmission loss increases as the area density grows. When the density of the gypsum board is 2, the sound transmission loss is approximately 2 dB higher than when it is . When the density of the gypsum board is 3, it is about 3 dB higher than . Considering the mass of the gypsum board itself within the overall structure, it can be seen that this change adheres to the mass law.

As can be observed from Figure 6(d), in the middle and low - frequency bands, the sound transmission loss rises as the Young's modulus of the gypsum board increases. Fundamentally, this is the outcome of the change in structural stiffness with the Young's modulus. As the Young's modulus of the elastic layer grows, the resonance frequency shifts to a higher frequency. This is because the resonance frequency value has a positive correlation with the structural stiffness. The trough value at the resonance frequency barely changes with the variation of the Young's modulus of the elastic layer. In the high - frequency band, the sound transmission loss of the overall structure is minimally affected by the Young's modulus. This indicates that in this frequency band, the sound insulation performance of the structure is mainly influenced by the area density.

By comparing Figure 6(e) and Figure 6(d), it can be seen that the influence exerted by the shear storage modulus of the damping layer on the sound - transmission loss of the structure is similar to that of the Young's modulus of the elastic layer. This similarity exists because both the shear storage modulus of the damping layer and the Young's modulus of the elastic layer play a role in affecting the stiffness of the structure. The difference between the two parameters is that when the modulus changes in the same proportion, the Young's modulus of the elastic layer influences the sound - transmission loss and resonance frequency in the middle and low frequencies more greatly. because the influence weight of the Young's modulus of the elastic layer on the structural stiffness is higher than that of the shear storage modulus of the damping layer, that is, the latter is a small value relative to the former. In addition, in the definition of COMSOL model, Poisson's ratio of damping layer material can be approximately constant (Martinez-Agirre et al. 2010;Ren et al. 2019), and on this basis, it can be considered that Young's storage modulus of damping layer changes with shear storage modulus.

As can be observed from Figure 6(f), except for the sound - insulation trough, throughout the entire frequency band, the sound - transmission loss of the structure increases slightly as the shear loss factor of butyl rubber rises. The area density that impacts the sound - insulation performance of the structure remains unchanged. The resonant frequency value of the structure, which is affected by stiffness and area density, shows almost no change, indicating limited changes in stiffness. Consequently, it is inferred that the increase in sound - transmission loss across the whole frequency range is caused by the enhancement of the material's ability to dissipate vibration energy. This also leads to an improvement in the sound - insulation trough at the resonance frequency as the shear loss factor of the damping layer increases. It should be noted that increasing the shear loss factor of the damping layer to repair the sound - insulation trough cannot be achieved by adjusting most of the parameters mentioned above (except for the thickness of the damping layer).

From Figure 6 and Table 4, it can be known that the change in the thickness of elastic layer and damping layer will affect the area density and stiffness of the structure, thus changing the position of resonance frequency and the size of sound transmission loss in the whole frequency band. The change in the density of each unit layer will affect the area density of the structure, thus changing the position of the resonance frequency and the size of the high-frequency sound transmission loss in this research model. Young's modulus of elastic layer and shear storage modulus of damping layer will affect the stiffness of the structure, thus changing the position of resonance frequency and the size of low-frequency sound transmission loss in this research model. At the same time, the shear loss factor of damping layer material has an important influence on the improvement effect of sound insulation trough at resonance frequency. Therefore, in engineering practice, on the premise that the overall thickness of the structure is certain, priority should be given to increasing the thickness of the damping layer, but the thickness of the damping layer has its appropriate upper limit value for the specific structure. When the thickness of the damping layer exceeds a certain value, the increase of damping effect is not significant, and the thickness ratio of constraint layer and damping layer can be 2~3 (Liu 2018). While considering wallboard materials for building functions, emphasize those with high areal density. In order to meet the stiffness requirements of the wall, the corresponding modulus of wallboard materials should not be too large, and viscoelastic materials with high shear loss factor should be selected as damping layer as far as possible.

4.2. Impedance tube test results and analysis

Four groups of specimens are tested by impedance tube, and the average value of the test results is taken. In order to verify the validity of the above simulation, the proposed COMSOL model is used to calculate its sound transmission loss in the same frequency range. The sound transmission loss curve of the test and simulation results is shown in Figure 7, and its abscissa scale is in the form of logarithmic function.

As is observable from Figure 7, within the test frequency range, the simulated values of the sound - transmission loss for four groups of structures are 5 dB - 20 dB higher than the experimental values. The perfect matching layer set in COMSOL model is the ideal sound propagation end condition. Although the non-ideal end is compensated by changing the boundary condition in the actual test, it will still be affected by the reflected sound wave, resulting in the reduction of sound transmission loss. The relationship between sound transmission loss and boundary conditions can also refer to the structural stress distribution shown in Figure 8. At all frequency calculation points in the simulation, the maximum stress occurs at the boundary of the structure. The whole deformation of the structure is related to the stress distribution, so it can be seen that the setting of boundary conditions influences the sound transmission loss of the structure. When the logarithmic function (octave) is used as the abscissa scale, the analogue values of the four groups of structures decrease linearly with the increase of frequency, and the slope is about 6 dB/oct. The experimental values of the four groups of structures are linear with frequency, and the descending slope is about 5 dB/oct. The slope difference between the simulated and experimental values with frequency is influenced by different stiffness and boundary conditions in the simulation and test. In the middle and low frequency bands simulated and tested by the impedance tube method, both shows similar sound insulation rules. In addition, the sound transmission losses of the three groups of constrained damping structures are similar, and the sound insulation of the three groups of constrained damping structures also has a similar corresponding relationship with the modulus of the respective damping layer materials.

The impedance tube test verified the reliability of the aforementioned COMSOL structural - acoustic model. The simulation results and test results demonstrate similar sound - insulation patterns. Nevertheless, the impedance tube test has certain drawbacks. The size of the tube restricts its testable frequency range, and it's impossible to investigate the sound - insulation characteristics of the structure beyond the upper - limit frequency. By combining Figures 4 and 7, it's evident that relying solely on the impedance tube test makes it challenging to characterize the sound - insulation effect of the constrained - damping structure in the resonance zone. If only the test values in the range of 50Hz - 1600Hz are used to assess the sound - insulation performance of the structure, the composite form of constrained damping will result in a decrease in the structure's sound - transmission loss. This implies that it's unsuitable for vibration and noise reduction, which goes against the common understanding in related fields. Consequently, in terms of exploring the sound - insulation characteristics of actual structures, this model has a certain application value and can be applied in related analysis and research.

3. Reverberation room test results and analysis

Perform sound - transmission loss tests in the sound source room and the receiving room, with the measurement duration for each measuring point being 30 seconds. The sound - transmission loss of the specimen is calculated based on the sound pressure obtained

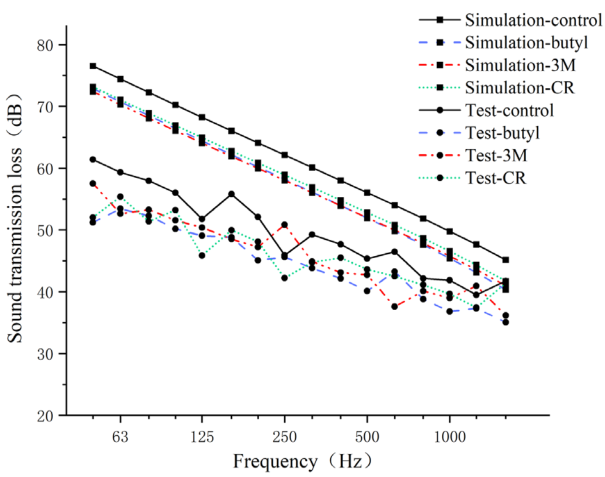


Fig. 7. Test and simulated sound attenuation curve of four groups at 50 Hz - 1600 Hz

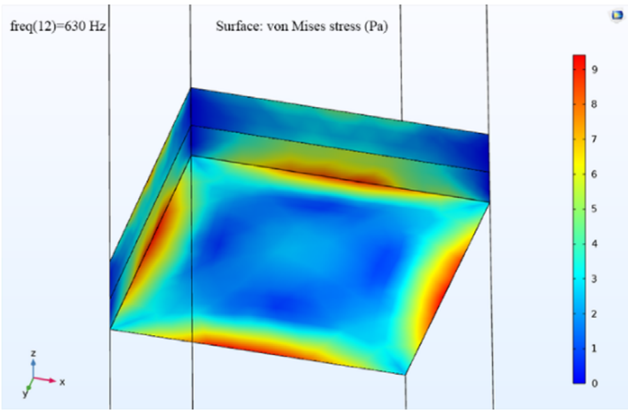


Fig. 8. Stress distribution of structure at 630 Hz

at each measuring point and the reverberation time at the corresponding frequency, as depicted in Figure 9.

As is evident from Figure 9, within the 50 Hz - 5000 Hz measurement frequency range, the overall sound - insulation performance of the test - group partition wall outperforms that of the control - group partition wall. Its superiority is mainly demonstrated in the low - frequency and high - frequency bands. In the 63 Hz to 160 Hz low - frequency range, the test group's arithmetic average sound insulation is 5.6 dB greater than the control group's. At 80 Hz, this difference even reaches 11.2 dB. In the 2000 Hz to 5000 Hz high - frequency band, the test group's arithmetic average sound insulation exceeds the control group's by 6.4 dB. At 2500 Hz, the difference between them amounts to 8 dB. In the 160 - 1250 Hz frequency range, except for the small sound - insulation dip near 250 Hz in the control group, the test group's arithmetic average sound - insulation ability is approximately 1 dB higher than the control group's. The sound - transmission loss curves of the two partition groups exemplify the sound - insulation quality law: doubling the frequency increases the sound insulation by about 3 dB. The constrained - damping structure in partition walls functions to shift the resonance frequency to a lower value and correct the sound - insulation flaws at resonance and coincidence frequencies, thereby enhancing the overall sound - insulation performance.

Conclusion

1. On the premise of accurately characterizing the material parameters, comparing the results of COMSOL simulation and impedance tube test, it is known that they have similar sound insulation laws in the middle and low frequency band (50-2000 Hz), and the acoustic numerical model is effective and reliable. In terms of sound transmission loss values, the simulated values in the middle and low frequency bands are higher than the experimental values. From the simulation results of controlling the variation of parameters under the condition of a single variable, it can be known that the stiffness and area density of constrained damping structure are the main factors affecting its sound insulation performance.

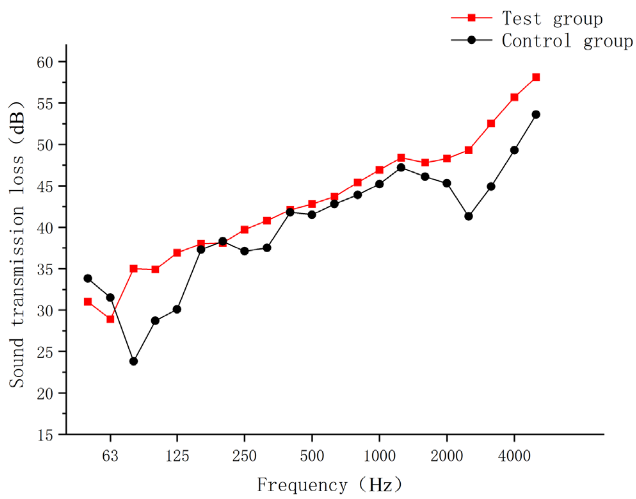


Fig. 9. Sound transmission loss of two partition structures using reverberation chamber method

2. According to the reverberation chamber method test results, the sound insulation performance of lightweight wooden partition walls based on constrained damping technology is better than that of the control partition wall without damping layer. This advantage lies in the fact that the overall sound insulation capacity of the former is higher than that of the latter at 50 Hz-5000 Hz, especially in the low frequency band of 63 Hz-160 Hz affected by structural resonance and the high frequency band above 2000 Hz affected by coincidence effect. The maximum difference in sound transmission loss between the two is 11.2 dB at 80 Hz.
3. The implementation of constrained damping technology in partition walls can not only enhance sound insulation across most frequency bands and rectify a series of sound - insulation troughs, including the resonance - related sound - insulation trough in the low - frequency range and the coincidence - related sound - insulation trough in the high - frequency range. It can also keep these drawbacks away from the frequency bands of concern in architectural acoustics. Consequently, the overall sound - insulation performance is improved.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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