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ACOUSTICS OF MODERN THERMAL INSULATION GLAZING

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Due to the increasing proportion of glass surface in modern architecture, as well as their lower sound transmission loss compared to outer walls, environmental noise is transmitted into buildings mostly via windows. Nevertheless, the development of modern insulation glass panes mostly focuses on their energy efficiency and thermal insulation. Especially different kinds of spacers made of plastic, so called "warm edges" are becoming more and more common. However, its effect on the acoustic performance was not studied. The acoustic performance of glass panes is usually estimated by the glass and air layer thickness disregarding the edge bond, and is proven by a test certificate, which refers to the ISO standard measurement of the sound reduction index in a laboratory. Since windows in real construction generally have different dimensions, edge connections and mounting conditions, the acoustic performance of the window in construction often differs from the value specified in the test certificate. This project aims to develop a method to predict the sound transmission loss of glass panes by measuring only certain parameters of the edge bond. A total of 20 glass panes with 5 different formats and 4 pane configurations were tested according to ISO 10140 in third octave and narrow band frequencies. In addition, modulus of elasticity and loss factors of window putty, insulating glass sealant and spacers made of different materials were measured. The measurement data served as input parameters for a finite element simulation model. Finally, the results of the ISO standard measurements and simulations were compared with each other. This paper focuses on the influence of the spacer stiffness on the sound transmission loss and the extent, to which the simulation can accurately predict a standard measurement of the sound reduction index.

Keywords: insulation glass, window pane, sound transmission loss, warm edge

1. Introduction

In building planning, the sound transmission from the given external noise level into the building interior can be analytically determined, provided the sound insulation of the individual building elements is known. The sound insulation of glazing is usually determined according to DIN EN ISO 10140 [1] with a standardized installation area of W x H = 1.23 m x 1.48 m. A lot of older measurement data relate to glasses with metal butyl edge seals. But the windows in buildings usually have different dimensions, edge connections, and the gas composition in the space between the panes due to thermal reasons (e.g. adaptation to GEG, LTECV, etc.) [2-4], as they are part of the thermal protection certificate. Although these changes also affect the acoustic performance, there is only little reliable information available concerning the dependence on format and layer thickness [5], as well as the dynamic properties of the spacers [6, 7]. Finally, the sound insulation in buildings deviates from the values specified in the test certificate, and accordingly considerable deficiencies in the structural noise protection planning are to be expected.

In the period from 2021 to 2023, a research project funded by the "Bundesinstitut für Bau-, Stadt, und Raumforschung BBSR" was carried out at the "Fraunhofer Institute for Building Physics IBP" to investigate these problems. The aim of the project was to develop suitable corrections to the sound reduction indices of modern thermal insulations glass and to take the uncertainties into account. First, the sound transmission loss of 20 triple glazing was measured according to ISO 10140. In the next step, a numerical simulation model was created to calculate the sound insulation and verified using the measurement results. With the help of the simulations, parameter studies were then be carried out in order to assess the various window parameters on the STL. This paper presents the influence of the edge bond on the sound transmission loss, and the extent, to which the simulation can accurately predict a standard measurement of the sound reduction index.

2. Physical Arrangement

2.1 Experiments

An Insulating Glass Unit (IGU) consists of two or more glass panes mechanically connected by an edge spacer, and further sealed by the sealing agent to seal the gas filling in the space between the panes. For the Sound Transmission Loss (STL) measurement, the glazing is aligned in the opening according to ISO 10140 using strips of hardwood and specific window putty. Figure 1-(a) illustrates the overview of a double layer glass pane with an edge spacer and edge sealant mounted on the testing facility.

During the project, in total 20 triple glazing were tested. To provide a representative overview, measurements were carried out on 5 combinations of pane dimensions and 4 combination of the layer thickness. The space between the panes was kept being 14 mm using a polymer spacer and filled with Argon for all glazing. Table 1 summarises the dimensions of the measured triple glazing. All measurements were taken in the frequency range from 50 - 5000 Hz in 1/3rd and 1/24th octave bands in an accredited window testing facility with an installation opening of 1.25 m × 1.50 m (the former three dimensions in Table 1), or in another building acoustics test facility with an installation opening from 3.20 m x 1.25 m (the latter two dimensions in Table 1). For adjustment of the opening to the respective pane format was served by one double-shell installation mask in lightweight construction with a maximum STL ($R_{w,max}$) ≥ 64 dB. See Figure 1-(b).

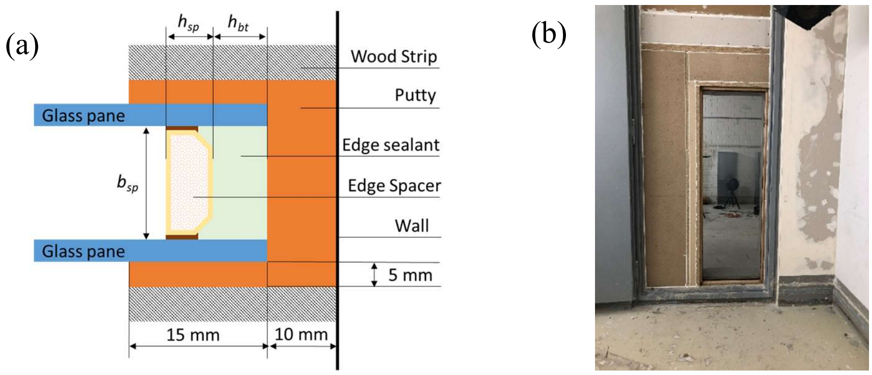


Figure 1: (a) A double layer glass pane with an edge spacer and edge sealant aligned in the opening. (b) A double-shell installation mask in lightweight construction.

Table 1: Triple glazing dimensions

	variance	Parameters
Window Dimensions, L×W [m]	5	0,87×1,05; 0,97×1,17; 1,23×1,48 0,67×2,05; 0,77×2,37;
Glass thickness [mm]	4	3-2-3; 3-3-3; 4-2-3; 4-3-3

2.2 Numerical Model

In order to achieve high accuracy, a detailed numerical model of multi glazing was built by the commercial FE software COMSOL (version 6.1) for the prediction of the STL under diffuse field excitation. The purpose of the numerical model is to replace the experiments at least partly by this numerical tool. However, it is computationally extremely complex to model all the details of the test facility, particularly the sending and receiving rooms [9]. Although the acoustic modes of the chamber largely affect the measured results particularly at low frequency, they are essentially not related to the acoustic performance of the glazing. On the other hand, it is important to model the boundary condition of the glazing precisely. Particularly at low frequencies, the response of the structure is characterized by well-separated low order modes.

The following simplifications were applied to the model to keep a balance between simulation accuracy and computational efficiency: (1) The acoustic field on the sending side is eliminated. The structure is excited by the numerically calculated blocked force of the summation of 500 incident plane waves with random phases and angles. (2) The structure is modelled by thin shell elements and is installed in the infinite baffle. (3) The structure transmits the sound toward the free field with the anechoic termination. (4) The window putty is modelled by solid elements. The surface covered by the wall and the wooden strips are modelled as the fixed boundary condition. The material properties were experimentally determined during the project. (5) In case of multiple glazing, the spacer and the secondary sealant were combined and modelled by using flexible "boundary to boundary" connection. Figure 2 visualizes the the numerical model to predict the STL. The simplification (1)-(3) are visualized in the left-hand side, while (4) and (5) are shown in the right-hand side.

The STL of a triple glazing was simulated in 1/48th octave band frequency resolution between 44 Hz and 1,4 kHz, which are respectively the lower and the upper frequency limits of the octave band, centered at 62,5 Hz and 1 kHz. As the tested triple glazing have high STL at higher frequenzcies, the frequency up to 1,4 kHz is sufficient to predict the weighted sound reduction index, R_w, according to DIN EN IS0 717 [2].

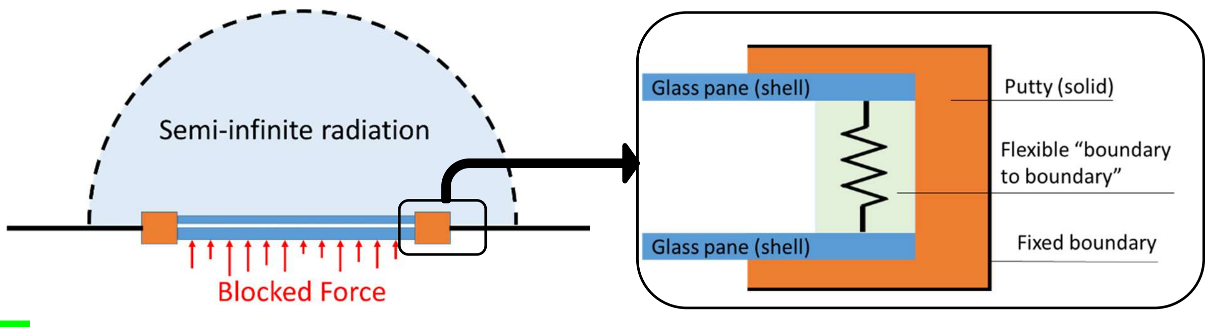


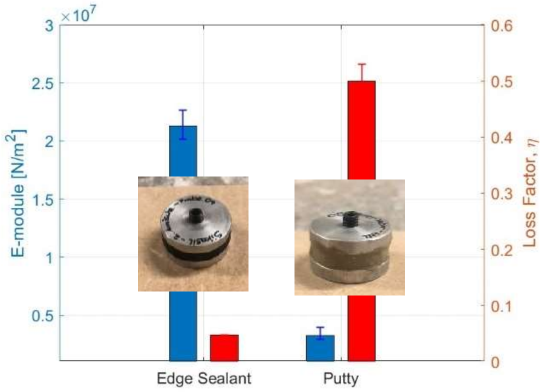
Figure 2: Schematic of the numerical model to predict the sound transmission loss (left), and the magnified view around the edge spacers (right).

2.3 Determination of the Structural Parameter

The simulation can provide reliable and realistic results only with accurate input parameter values. Therefore, it is essential to precisely estimate the structural parameters of the components of glazing and its boundary sealant. The non-resonance testing method in DIN EN ISO 6721-4 [9] was used to measure the mechanical properties of the window putty, the edge sealant, and the edge spacers. In this paper, stainless steel, polymer (SAN mit 35% GF), and hybrid (stainless steel and polypropylene) spacers were tested. Spacers made of polymer and of the hybrid materials are called warm edge, due to its high thermal insulation.

The sample was placed between 25 mm diameter circular aluminium discs of 4 mm thickness. The spacer profile was cut into pieces measuring 10 mm in length. To ensure a uniform distribution of the applied force, two of the cut spacer pieces were glued symmetrically with approximately 5 mm distance on the base disc. The measured dynamic stiffness and the loss factor were approximated using the linear function in double logarithmic scale. Finally, the frequency constant stiffness and the loss factor were evaluated using the approximated curve at 500 Hz. As a spacer has its own structure, only the equivalent stiffness per unit length, N/m^3, can be derived from the measured dynamic response.

The measured stiffness (blue bars) and the loss factor (red bars) are summarized in Figure 3 with the picture of a sample for each test object. The putty is much softer and far more dissipative than the edge sealant. Considering the fact that a glass is in general very low dissipative material, incoming sound power can mostly be dissipated by the resilient boundaries covered by the putty. Regarding the edge system, the edge sealant and the spacers have comparable loss factor. The hybrid spacer shows the lowest stiffness and considerably higher loss factor than the others. The steel spacer has a higher stiffness than the others by the factor of approximately 4-8.



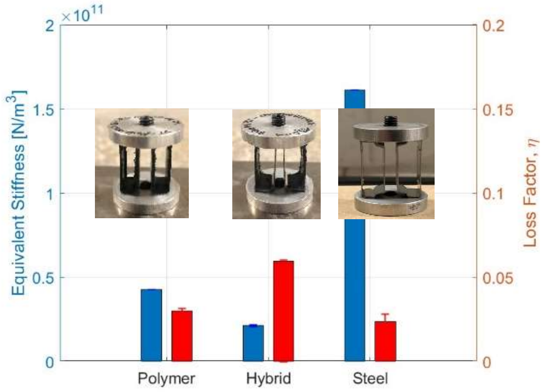


Figure 3: Measured stiffness (blue bars) and the loss factor (red bars) of the edge sealant and the window putty (left), and the spacer with various materials (right).

The equivalent stiffness of the spacer-sealant combined edge system is expressed by the parallel connection of the spacer and the edge sealant:

$$k_{eq} = \frac{h_{sp}}{h_{sp}+h_{bt}} k_{sp} + \frac{h_{bt}}{h_{sp}+h_{bt}} \frac{E_{s2}}{b_{sp}} \quad (1)$$

where h_{sp} and h_{bt} respectively denote the thickness of the spacer and the sealant, and b_{sp} is the cavity thickness (See Figure 1-a). k_{sp} is the equivalent stiffness of the spacer, and E_{s2} denotes the modulus of elasticity of the sealant. The equivalent stiffness of the polymer edge system per unit length of the tested triple glazing is estimated to be 40 x 10^9 N/m^3. See Table 2.

3. Sound Transmission Loss

3.1 Comparison between the measurements and simulations

Figure 4 compares the measured (black) and the simulated (red) STL of the triple glazing 3-14(Ar)-2-14(Ar)-3 mm with the dimensions of 1230 mm x 1480 mm (left) and 770 mm x 2370 (right). These two cases were selected, because the surface area of the two models is identical. The geometry and material parameters are summarized in Table 2.

Table 2: Geometry and material parameters used in the simulation.

Parameter		Unit	Value
Glass	Elastic modulus	N/m^2	72 x 10^9
	Poisson Ratio	--	0,3
	Loss factor	--	0,005
	Density	kg/m^3	2500
Window putty	Elastic modulus	N/m^2	30 x 10^6
	Poisson Ratio	--	0,3
	Loss factor	--	0,5
	Density	kg/m^3	2150
Edge system (Spacer and Sealant)	Width, b_{sp}	mm	14
	Thickness ($h_{sp} + h_{bt}$)	mm	10 (6,5 + 3,5)
	Stiffness	N/m^3	40 x 10^9 N/m^3
	Loss factor	--	0,05
Dry Air /Argon	Speed of sound	m/sec	343/319
	Density	kg/m^3	1,21/1,65

In the left-hand side plot, the measured STL shows higher value than the simulated one at frequencies below 100 Hz. The discrepancy might be attributed to the room acoustic mode. The measured STL shows a dip between 200 Hz and 250 Hz, while the dip of simulated STL occurs at a lower 1/3rd octave frequency band, between 160 and 200 Hz. The frequency band and the sharpness of the peak and dip in the band averaged spectra is strongly influenced by the resonant and anti-resonances included in the distinct frequency band. When the resonance or anti-resonance is slightly shifted in frequency, and is moved into the adjacent frequency band, the band averaged STL in these distinct bands sharply decreases or increase. As the resonant frequency is easily influenced by a minor change in the boundary condition, it is difficult to reach excellent agreement in this frequency range.

In the right-hand side plot, the agreement between the measurement and the simulation is significantly improved at low frequency. The difference is that the measurement was taken in another test facility because the glass pane did not fit in the ISO test opening. This might confirm that the measured STL at low frequency is controlled by the acoustic mode of the testing facility.

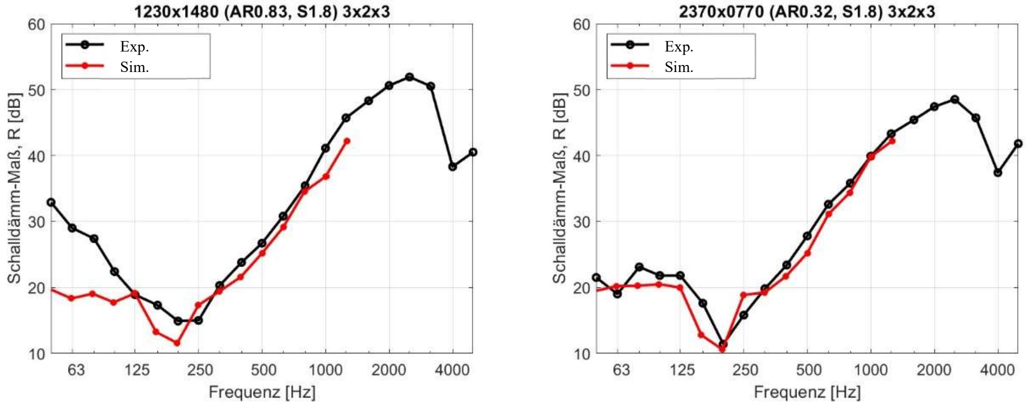


Figure 4: STL of the triple glazing with the dimensions of 1230 x 1480 x 3-2-3 mm (left) and of 2370 x 770 x 3-2-3 mm (right), measured (black) and predicted by the numerical model (red).

Above 250 Hz, both plots show the similar tendency. The agreement between the simulation and the measurements is fairly good, but the simulated STL is in general slightly lower than the measured one. One reason could be loss in a cavity. In the simulation, the cavity is filled with the ideal loss-less fluid, and the spacer surface is modelled as a sound hard impervious wall. However, the spacer has small holes for the air circulation, and is filled with the desiccant, which is a porous material. Finally, the structure of the spacer can be considered as a micro perforated plate backed by the porous sound absorber. Although the absorption is not high due to low perforation rate of the spacer surface and the low porosity of the desiccants, the effect can be visible compared with zero-absorption system, particularly at high frequency.

Figure 5 compares the measured (left) and simulated (right) weighted sound reduction indices of triple glazing with plastic spacers. These plots indicate that the simulated R_w is in general lower than the measured one, except for four cases with small dimensions of 870 x 1050 mm and 970 x 1170 mm.

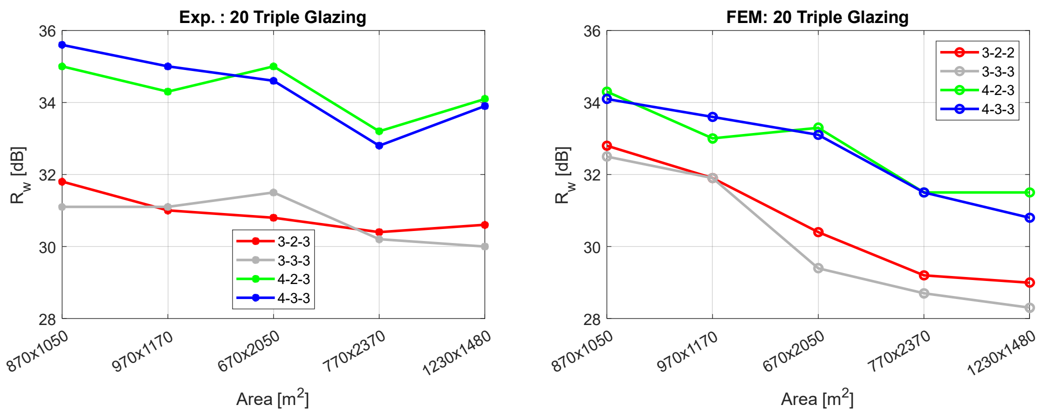


Figure 5: Measured (left) and simulated (right) weighted Sound Reduction Index of the triple glazing with the dimensions of 1230 x 1480 x 3-2-3 mm (red), 3-3-3 mm (grey), 4-2-3 mm (green), and 4-3-3 mm (blue).

In addition to the no cavity dissipation modelled in the simulation, another reason of overall discrepancy is the imperfection of the test objects. In the simulation, the plates are ideally spaced with the equal distance, and the cavity pressure is always ideally set to be the atmospheric pressure. In reality, there is an acceptable range of variance of the cavity thickness without being considered faulty. Furthermore, the air pressure in the cavity can change due to various factors, such as temperature fluctuations, and variations in atmospheric pressure. These factors can cause the air inside the cavity to expand or contract, resulting in changes in pressure. The glass plate can be prestressed due to the pressure exerted by the air inside the cavity between the glass panels, and the material stiffness of each plate can slightly differ. As a result, the resonance frequencies of the glass plates as well as that of two cavities of the same thickness can be slightly differ in measurements, while they are perfectly identical in simulation. It is difficult to implement these imperfections in the numerical model. As a conclusion, the agreement between the simulation and the measurements is sufficiently high for the parametric study to highlight the effect of one parameter on the STL.

3.2 Effect of the stiffness

Figure 6-(a) compares the STL of the triple glazing with the edge system stiffness $k_{eq} = 1\times10^9$ N/m^3 (black solid line), $k_{eq} = 10\times10^9$ N/m^3 (red line), and $k_{eq} = 100\times10^9$ N/m^3 (blue line). At low frequency below 125 Hz, there is no clear difference among all three cases. Between 125 Hz and 500 Hz, the spectra are characterized by sharp dips, which are related to mass-spring-mass resonance of the glass panels and the spacer. Above 500 Hz, the triple glazing with a stiff spacer clearly shows lower acoustic performance.

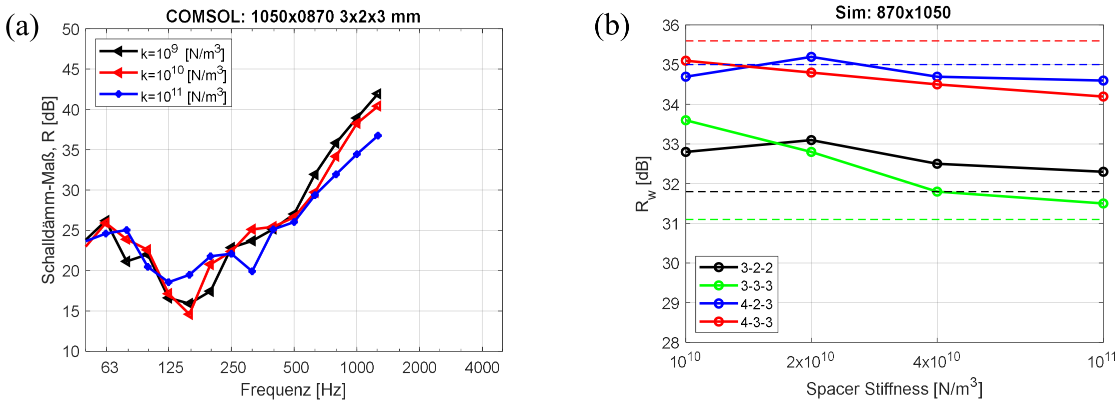


Figure 6: (a) Simulated STL of the triple glazing with the dimensions of 870 × 1050 × 4-2-3 mm with the different spacer stiffness: $k_{eq} = 1\times10^9$ N/m^3 (black), $k_{eq} = 10\times10^9$ N/m^3 (red), $k_{eq} = 100\times10^9$ N/m^3 (blue). (b) Simulated weighted sound reduction index of the triple glazing with the dimensions of 870 x 1050 x 3-2-3 mm (red), 3-3-3 mm (grey), 4-2-3 mm (green), and 4-3-3 mm (blue) with reference to the spacer stiffness.

Figure 6-(b) summarises the effect of the spacer stiffness on the acoustic performance of the triple glazing using the weighted sound reduction index R_w. The horizontal dotted line indicates the measured R_w of the corresponding triple glazing, plotted in the same color. As the stiffness increases, the simulated R_w keeps decreases with minor oscillations. Furthermore, the distance between upper two curves in blue and red color and the lower two curved in green and black slightly increases and getting closer to the distance between two groups of the measured R_w. It indicates that (1) the quality of the simulation model can be improved by using properly selected stiffness of the edge system, and (2) the softer spacer has advantage in terms of acoustic performance, as the adjacent glass panels are more loosely connected, and thus sound power is less transmitted to the receiving side. However, the measured equivalent stiffness of the edge spacers ranges between 20 x 10^9 N/m^3 and 160 x 10^9 N/m^3 (See Figure 3). According to Figure 6-(b), the effect of the edge system depends on the glass thickness. The maximum of about 2 dB deterioration of the acoustic performance R_w was observed by increasing the stiffness of the edge system by the factor of 10. This effect might be further reduced in case of bigger glazing, as the edge effect is more prominent for a small glazing. It is reasonable to assume, that the influence of the stiffness of the

spacer on the STL is higher in real windows since the high dissipation factor of the putty cushions the edges during the ISO measurement.

4. Conclusion

In the research project "Acoustically optimized thermal insulation glazing", the acoustic performance of modern triple glazed insulating glass was investigated. One of the challenges at hand is the development of the suitable correction factors to the sound reduction index of modern thermal insulation glass in terms of the glazing geometry and material changes. In particular, this paper discusses the influence of the edge seal on the STL in the context of spacer material and its structural parameters. In order to reduce the experimental effort, a numerical model for virtual window testing and modification of materials was developed. The non-resonance testing method in DIN EN ISO 6721-4 was used to characterise the internal material loss factor and the stiffness of the carious edge spacers, edge sealant, and the window putty. The experimental results are used in a numerical multiscale simulation in order to determine the sound transmission loss and to provide the base for the correction factor. The simulation model was examined in detail in comparison with the measurements of 20 triple glazing. A comparison reveals that determining the spacer stiffness is crucial to improve the agreement. After implementing the measured stiffness of the edge spacer system, the simulated STL shows demonstrate sufficient result quality. Based on measurement and simulation results, it was found the reduction of the spacer stiffness improves the acoustic performance, but the effect is not significant in the rage of the measured stiffness of tested spacers. Both simulation model and validation efforts should be expanded in the future to further improve the prediction quality.

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