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# *S*-Shaped Glass also stands for *Soundless*
# Sound Insulation measurements and implication for building practice

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**ABSTRACT**

This paper brings to discussion the sound insulation of a special type of glazing by studying a S(inusoidal)-shaped curved glass. This has been used in a concert hall (under construction) in Portugal with a forward-thinking Rem Koolhaas's architecture requiring non-standard solutions: glazing with very large dimensions (22 m by 15 m) and each "S-glass panel" with a wavelength of about 1.0 m and an amplitude of about 0.35 m will be applied as a double facade. The restrictions in ISO 104-3 laboratory measurements (standard test opening for glazings 1.25 m by 1.50 m and niche depth of 0.45 m) were not appropriate and not completely fulfilled due to differences in dimensions between the small standard test sample and the real required ones used on site as well as the silicone joints that connect the glass elements in their frame. For these reasons, the standard laboratory test opening of 10 $m^2$ was used. These aspects are described and analyzed. The tests results (showing satisfactory sound insulation) were essential to understand the effect of the shape and the efficiency of the glass. This study aspires to be helpful to building designers who can, in this way, lose dependency on production process constraints and bring into being all kind of shapes.

## 1 – INTRODUCTION

The architect's main aspiration, starting a new project, especially in large concert halls, is to create a unique building. This happened in a new concert hall (under construction) the "Casa da Música" (House of Music) in Porto, Portugal with a forward-thinking Rem Koolhaas's architecture requiring non-standard solutions. That ambition, together with the need for a sound diffusing shape for the concert hall in study, without loosing transparency, resulted in a window solution with very large curved glass.

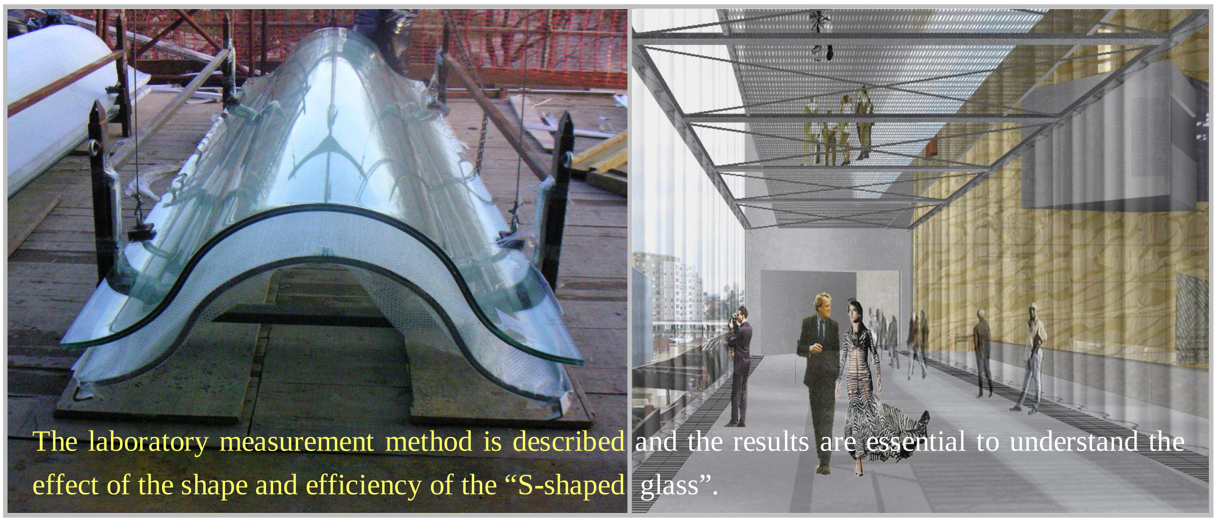
Buildings with high acoustic requirements often coincide with the ones with the most atypical architecture, and windows, as visual openings, are an important point of attention as they influence the architecture of the design project.

In addition to their main function, windows also transmit sound. This counts not only for the facades, but also for the interior partitions that divide spaces with different use.

Sound insulation of glass relates to mass law, coincidence frequency and resonance effects as some of the focal study points. These three physical principles are the main aspects that rule the behavior of the distinct types of glazing. The performance of a single glazing can be very different from a laminated one (two or more layers of glass bonded together by a thin interlayer). These two options can be applied as a single solution (one pane), double or triple, varying thickness, dimensions and shape and, in case of double or triple constructions, air cavity dimensions.

The influence of the shape in the glass acoustical performance is highlighted in view of the fact that the sound insulation of a special type of glazing: *S(inusoidal)-shaped curved glass*, is the central subject of this work. What can be expected, introducing this shape? No coincidence frequency, two times the coincidence frequency (orthotropic shape) or a value in a shifted frequency range? Lower or higher $R_w$ values?

In essence, analyzing the main physical principles, is it possible to predict the glass performance taking into account the variables and making some interpretations on what can be behind that? As well, how reliable are airborne sound insulation measurements done with a specimen in the laboratory and which effects should be taken into account? What about translation of the results to real practice?




## 2 – METHODOLOGY

### 2.1 – Sample

In order to be tested, three samples (S-shaped laminated glass) were submitted to the Laboratory of Acoustics, Department of Civil Engineering, Faculty of Engineering, University of Porto, Portugal, according to EN-ISO-140-3, and analyzed, to determine the airborne sound insulation of the glass panels.

| SAMPLES | DESCRIPTION | REMARKS |
|---|---|---|
| Glass sample 1 | Curved glass, laminated, 10.10-2, with 2 vertical joints filled with silicone (14x21x3092 mm) | Aluminium frame, filled with mineral wool, elastometer material: simple glass, laminated, rolled, with 10+10 mm thickness; silicone joints DOW CORNING 791 |
| Glass sample 2 | Curved glass, laminated, 10.10 -2, with 2 vertical joints, one open (14x21x3092 mm) | Aluminium frame, filled with mineral wool, elastometer material: simple glass, laminated, rolled, with 10+10 mm thickness; silicone joints DOW CORNING 791, however, one of the vertical joints was with no silicone with an open area of 15 x 3092 mm |
| Glass sample 3 | Curved glass, laminated, 6.6 -2, with 2 vertical joints filled with silicone (14x13x3092 mm) | Aluminium frame, filled with mineral wool, elastometer material: simple glass, laminated, rolled, with 6+6 mm thickness; silicone joints DOW CORNING 791 |

Table 1 – Main description of the glass samples.

The glazing that was applied in the building has very large dimensions (about 22 to 15 m). To be able to mount these, small glass panels, each one 1.22 m wide, are coupled by 0.014 m silicone joints.

This principle is also used in the laboratory. However, here the height of the panels was limited to 3.092 m.

Each S-glass panel has a wavelength of 1.22 m and amplitude of 0.39 m. For this reason, a different standard test opening from the one mentioned in the ISO 140-3 (for glass) was used. The restrictions in this standard (standard test opening for glazing 1.25 m by 1.50 m and niche depth of 0.45 m) were not suitable and not completely fulfilled since it would mean enormous differences in dimensions between small test sample and the real ones used on site as well as the silicone joints that connect the glass elements, without whose it would not be possible to mount the S-Shaped glass. Therefore, the standard test opening for vertical elements (walls, etc.) of 10 $m^2$, also mentioned in the EN ISO 140-3, was used.

The samples were positioned in a 3.298 m by 3.092 m frame, meant for testing vertical partitions. The sample is placed between the receiving room (R1) and the source room (E1). The mounting on a special aluminum frame has been used to seal the perimeter.


Figure 1 – Sample detail in the test opening

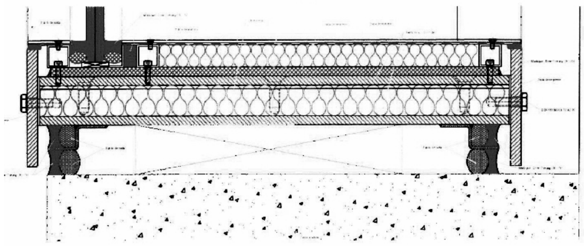


Figure 2 – Schematic drawing of the glass sample and frame (cross section)

In an earlier phase, the same type of glass, in a smooth shape has been tested in the Acoustics Laboratory of Eindhoven University of Technology. These measurements were carried out according to EN-ISO-140-3. The dimensions of the test opening for glazings were 1.25 by 1.50 $m^2$ and differ substantially from the ones used to measure the curved glass.

## 2.2 – Test Rooms

Reverberant receiving room (R1) has the following dimensions:

| | |
|---|---|
| Average length | L = 7.25 m |
| Average width | W = 5.88 m |
| Height | H = 4.65 m |
| Volume | V = 217.7 $m^3$ |

Figure 3 – Sample between chamber rooms

Reverberant emission room (E1) has the following dimensions:

| | |
|---|---|
| Average length | L = 5.99 m |
| Average width | W = 3.69 m |
| Height | H = 4.63 m |
| Volume | V = 106.4 $m^3$ |

The atmospheric conditions inside the rooms, during the measurements, were:
- Air temperature – 23 ˚C
- Relative Humidity – 55 % (on Sept. 15 and 16, 2003) and 70% (on Sept. 22, 2003)

## 2.3 – Equipment

The mounting of the samples and the equipment used for these measurements was chosen according to the internal specifications or normalization constants applicable. It included an Integrating Sound Level Meter (B&K 2260), Calibrator (B&K 4231), Microphone 13 mm (B&K 4189), Sound source (B&K 4224), Statistic modules, Movable Fixation support and Thermal-Hygrometric apparatus.

## 2.4 – Method

The determination of the acoustic parameter R, sound reduction index, was possible due to sound pressure levels measurements in both chambers, according to the EN ISO 140-3 and required corrections made after measuring the reverberation times in the receiving room (R1).

The sound reduction index (airborne sound) – $R_w$ and the spectrum adaptation terms were calculated according to the standard EN ISO 717-1.

$$R = L_1 - L_2 + 10 \lg \frac{S}{A} \qquad (dB)$$

$L_1$ – Source room averaged sound pressure level (dB);
$L_2$ - Receiving room averaged sound pressure level (dB);
S – Tested element surface area ($m^2$) = test opening;
A – Equivalent sound absorption area of the receiving room ($m^2$);

R = TL (Transmission Loss) (dB).

The sound pressure levels in both chambers were calculated measuring the levels in different positions in each room.

$$L = 10 \log \frac{1}{n} \sum_{i=1}^{n} 10^{\frac{L_i}{10}} \quad (dB)$$

$L_i$ to $L_n$ is the sound pressure level for the different *n* positions in the chamber rooms.

Ninety measurements took place in the chambers and the method chosen was the following:

- Three positions of the sound source with a 60˚ angle, in the emission chamber (E1) chosen according to the annex C of EN ISO 140-3;
- Five positions of the microphone in each room (E1 and R1);
- Three measurements in each position of the microphone.

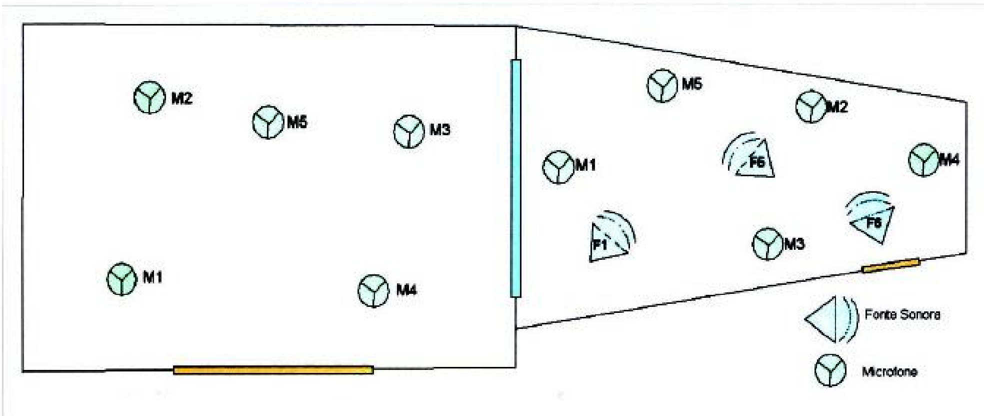



Figure 4 – Sound source and measuring points positions in the sound transmission rooms (no scale)

## 3 - RESULTS

The measurements on the three S-shaped (laminated) glass samples submitted to the laboratory tests, according to the EN ISO 140-3, lead to the values of noise reduction (airborne sound) shown in Table 2.

| Glass type \ Freq. (Hz) | 50 | 63 | 80 | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | $R_w$(dB) | $R_{wtr}$(dB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.10.2 (silicone joints closed) | 32,2 | 33,1 | 27,1 | 23,3 | 28,0 | 28,6 | 30,4 | 32,0 | 33,7 | 35,7 | 36,8 | 39,1 | 39,2 | 39,9 | 41,4 | 43,2 | 45,7 | 47,8 | 50,8 | 54,2 | 55,8 | **41** | **36** |
| 10.10.2 (one silicone joint open) | 25,5 | 26,1 | 17,3 | 12,3 | 21,8 | 22,1 | 20,6 | 21,3 | 22,0 | 22,6 | 23,0 | 22,8 | 22,9 | 23,6 | 24,4 | 24,5 | 24,7 | 25,0 | 24,4 | 23,1 | 21,8 | **24** | **23** |
| 6.6.2 (joints closed) | 30,3 | 28,8 | 23,9 | 21,6 | 25,4 | 24,0 | 27,3 | 29,5 | 28,9 | 31,6 | 32,1 | 32,9 | 33,6 | 33,5 | 33,6 | 34,7 | 37,8 | 39,8 | 43,0 | 47,3 | 50,9 | **35** | **32** |

Table 2 – R values (dB) for the S-Shaped glass.

The measurement with the open joint (between glass panels) is important to get indications of the influence and importance of the silicone joint and moreover to allow a comparison between this tested glass and a similar (in thickness) smooth glass.

The third sample, thinner glass panes, was measured to understand the influence of varying thicknesses.

The same type of glass, in a plane smooth shape, tested earlier in the Acoustics Laboratory of Eindhoven University of Technology, according to EN-ISO-140-3, resulted in the values of noise reduction (airborne sound) presented on Table 3.

| Glass type \ Freq. (Hz) | 50 | 63 | 80 | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | $R_w$ (dB) | $R_{w\,tr}$ (dB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.10.2 | 22,9 | 35,9 | 33,0 | 34,7 | 35,3 | 30,4 | 34,1 | 34,3 | 36,4 | 39,2 | 38,6 | 35,3 | 33,8 | 36,6 | 40,6 | 45,0 | 47,6 | 50,9 | 53,9 | 57,5 | 58,2 | **41** | **37** |
| 6.6.2 | 20,7 | 31,2 | 32,8 | 27,1 | 30,4 | 26,5 | 28,7 | 30,0 | 30,6 | 33,6 | 36,3 | 38,0 | 39,6 | 40,4 | 40,7 | 40,2 | 41,1 | 44,1 | 47,9 | 51,1 | 53,8 | **39** | **36** |

Table 3 – R values (dB) for the Smooth glass

### 3.4 – Analysis

Analyzing the results for the three glass samples with the S-Shaped outline, R or TL values for each frequency can be displayed as in Figure 3.

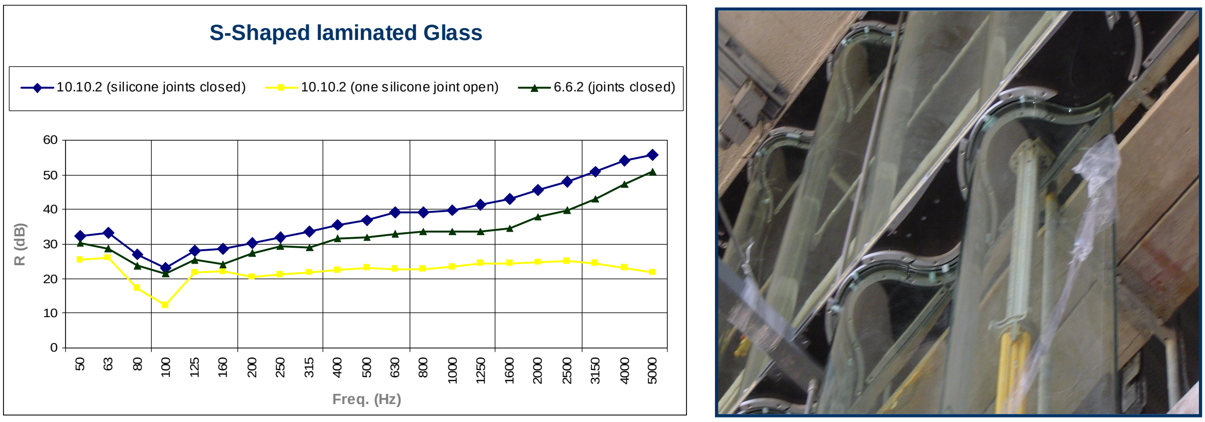



Figure 5 – S-Shaped laminated glass TL values (dB)

Looking at the two distinct samples, it is obvious that increasing the panel thickness the sound insulation, in global terms, improves. In addition, the behavior of both panels, along frequencies, leads to a pattern in sound effectiveness. A similar efficiency is understandable in every frequency range (even though, the thicker one is slightly more efficient in the higher frequencies). However, the re-mounting in the laboratory tests may influence these results.

One of the most important ranges, when studying an element that is part of a façade (outside noise) of a concert hall, is the low frequency range. An abrupt decay occurs around 80–125 Hz and to understand this effect was also one goal of this study. Does it have to do with the shape of the glass, showing that this kind of form is not appropriate? Can it be a consequence of the silicone applied to couple the large single panels or is it a result of the mounting of the test opening and restrictions/conditions in the laboratory tests?

Believing that the S-Shape is not responsible for this effect, the analysis of the other two possibilities, understanding if one of them can be the origin of such a negative response in the low frequencies, is made.

Another important step is to compare to the smooth similar glass but with all the restrictions and special considerations due to differences in samples, the comparison is presented in the end of this section and concludes with the interpretations on the results found and related interpretations.
The silicone applied in the joints seems vital to the global sound insulation provided by this element, since we are speaking of several panels putted together and a lack of this material immediately results on noise reduction or transmission loss decreasing. This material could be to blame for the abrupt decay that occurs around 80-125 Hz but in fact the *10.10.2 with one silicone joint open curve* shows that the decay remains, which means that the silicone is not the cause and the critical frequency with such a strong prominence is not explained by this material existence.

The laboratory tests include some of possible causes that can be described and brought into discussion. Still, it is very difficult to prove that one of these pointed possibilities is the only responsible of the negative effect in study.

The mounting of the test opening and all the measurements were carried out according to the EN ISO 140-3 and as everything followed the rules, the critical frequency with such a strong prominence on the critical range 80-125 Hz could be explained by possible *standing waves* in rooms, that will not occur in reality (diffuse room) and that could just become visible because of lack of diffusion in the receiving room. Nevertheless, the receiving chamber has tilted walls to minimize this effect and is reasonably large (volume about 220 $m^3$). Very high reverberation times and significant abrupt RT difference (decay) on that frequency range were detected. Even though, if this was the main cause, the decay would be shifted, changing the sample, and we would not have such a strong prominence just on the particular range 80-125 Hz. This leads us to the possibility of a standing wave close to the glass itself because of a possible niche effect. The amplitude of a curve is 0.39 m, together with the edge of the frame a total depth of approximately 0.60 m has to be taken into account. The height of the test opening is 3.092 m, which corresponds to a wavelength of 112 Hz. This wavelength matches with the area where the effect occurs.

This probable cause, together with the sum of small other causes, makes the S-Shaped glass behavior satisfactory in terms of global sound insulation for the application meant and leaves us optimistic, believing that, in practice, this effect will not occur.

To be sure, it seems important to compare to the smooth similar glass. This means that putting side to side the results of 10.10.2 and 6.6.2 laminated non curved glass samples, more interpretations and conclusions, reliable for the study in focus, can be achieved.

First, and to understand the characteristic performance of the smooth laminated glass, the results are separated from the global comparative final graphic.
Analyzing the two glass samples with the smooth shape, R (or TL) values for each frequency can be displayed as in the Figure 6.

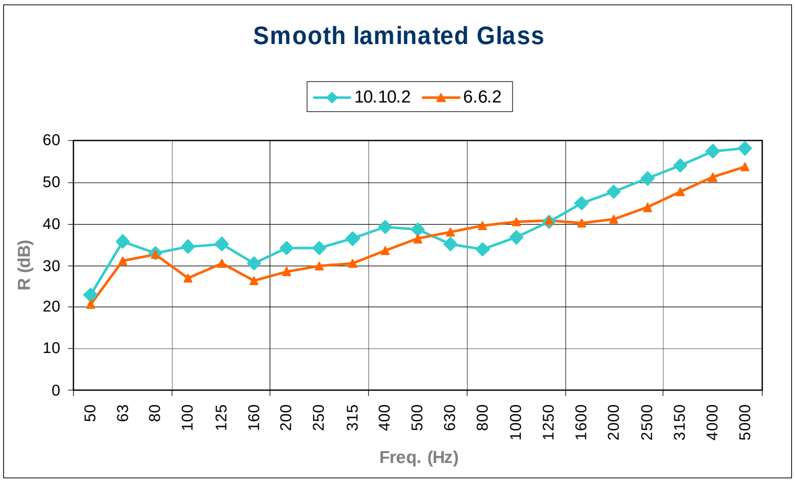



Figure 6 – Smooth laminated glass TL values (dB)

The decrease, in some frequencies (the higher ones), of the Transmission Loss (TL) values is noticeable. It is clear that the different performance in the lower frequencies (higher values than the ones predicted by mass law or other theoretically formulas, in both cases), strange unexpected distinct efficiency in mid frequencies inverse to the varying thickness and a good effectiveness in the higher frequencies.

The two distinct samples (in thickness) present a similar behavior in R values variation, though shifted in terms of frequency range. The sound insulation, in global terms, improves with thickness.

At the lower frequencies, a high efficiency is clear in both cases and there is no abrupt decay, existing, though, a critical frequency around 1000 Hz (10.10.2 sample) and 1600 Hz (6.6.2 sample).

At first glance, the smooth glass seems to be more adequate but such an interpretation is very risky. A careful comparison between the two types of glass, showing the smooth and the curved glass side to side raises some questions and makes clearer the acoustic efficiency along the frequency bands.

Comparing the smooth laminated glass with the S-Shaped laminated glass, with all the restrictions and special considerations due to differences in samples, the R or TL values for each frequency can be together displayed as in the Table 4 and Figure 7.

| Glass type \ Freq. (Hz) | 50 | 63 | 80 | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2150 | 3150 | 4000 | 5000 | $R_w$ | $R_{w\,tr}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.10.2 (silicone joints closed) | 32,2 | 33,1 | 27,1 | 23,3 | 28,0 | 28,6 | 30,4 | 32,0 | 33,7 | 35,7 | 36,8 | 39,1 | 39,2 | 39,9 | 41,4 | 43,2 | 45,7 | 47,8 | 50,8 | 54,2 | 55,8 | **41** | **36** |
| 6.6.2 (joints closed) | 30,3 | 28,8 | 23,9 | 21,6 | 25,4 | 24,0 | 27,3 | 29,5 | 28,9 | 31,6 | 32,1 | 32,9 | 33,6 | 33,5 | 33,6 | 34,7 | 37,8 | 39,8 | 43,0 | 47,3 | 50,9 | **35** | **32** |
| 10.10.2 smooth | 22,9 | 35,9 | 33,0 | 34,7 | 35,3 | 30,4 | 34,1 | 34,3 | 36,4 | 39,2 | 38,6 | 35,3 | 33,8 | 36,6 | 40,6 | 45,0 | 47,6 | 50,9 | 53,9 | 57,5 | 58,2 | **41** | **37** |
| 6.6.2 smooth | 20,7 | 31,2 | 32,8 | 27,1 | 30,4 | 26,5 | 28,7 | 30,0 | 30,6 | 33,6 | 36,3 | 38,0 | 39,6 | 40,4 | 40,7 | 40,2 | 41,1 | 44,1 | 47,9 | 51,1 | 53,8 | **39** | **36** |

Table 4 – R values (dB) for the S-Shaped laminated glass vs. Smooth laminated glass.

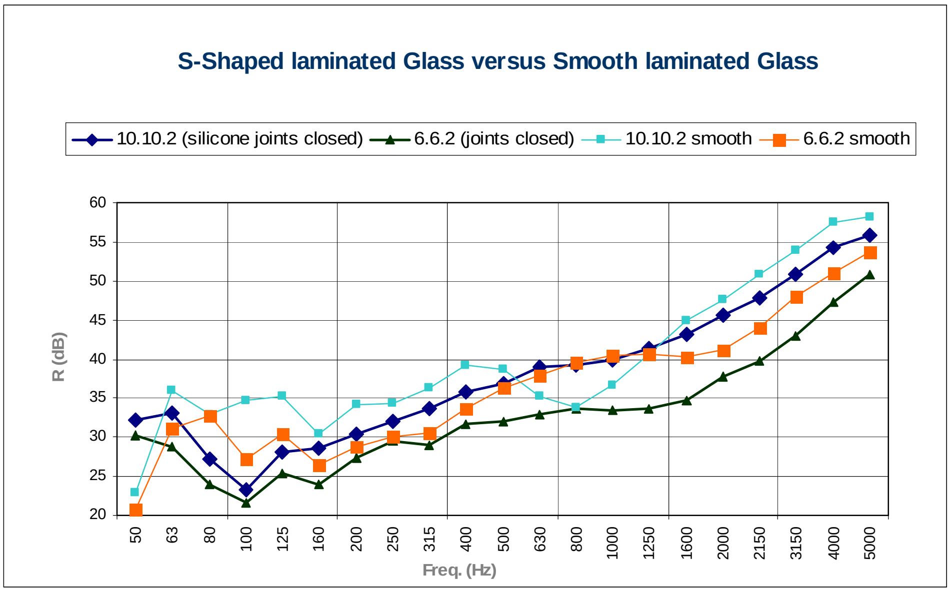



Figure 7 – S-Shaped glass TL values (dB) versus Smooth glass TL values (dB) (both laminated).

As mentioned, there are restrictions and special considerations due to differences in samples, test opening and laboratory characteristics. In fact, the smooth glass results come from small samples and must be carefully compared with large panels, which is the case of the studied S-Shaped Glass.  However, although dimensions can influence the plate's resonance, in this case, rough calculations have shown that the resonance frequency for the elements in study, with this type of dimensions, is always under the 50 Hz. This means that it is not critical and, in addition, we cannot base ourselves on values obtained under 50 Hz because they are not reliable.  This makes the comparison of the two types of glass more consistent, even with different samples dimensions.

When we look at the four samples in focus and assuming the decay on the 100 Hz as a result of the causes described before, we dare to state that the S-shaped glass seems to eliminate the critical frequency between 800 Hz and 1600 Hz experienced by the smooth glass samples, which would mean an improvement in insulation behaviour when choosing this shape to isolate speech.

## 5 – CONCLUSIONS

Applying new constructions' systems or unusual shapes asks for basic theoretical study and, if possible, measurements carried out under controlled conditions. Unexpected or unknown effects can occur and have to be studied before taking final decisions to approve the material or construction's system for the proposed application.

In this specific case, the authors were confronted with a precise dip in the sound insulation curve between 80 and 125 Hz. Analyzing this effect, taking into account repeatability and reproducibility, leads to the conclusion that we probably have to deal with niche effect that in this specific situation is manifest.

It is more than likely that this effect will not occur in the building on site. Moreover, the study is a nice example of a new acoustic phenomenon to be compared with because architects designs ask for.

## ACKNOWLEDGMENTS

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