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Laboratory testing of different window design cases for noise transmission

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Abstract. We investigated the effect of different window designs employed in Abu Dhabi Emirate- UAE on the level of noise transmission. For that, 21 window cases were tested in the laboratory. Several factors were considered, including window glass thickness, glazing, lamination, opening style, area, frame type, frame style, and use of shutters. Results showed that sound transmission loss is improved significantly with the use of shutters and the use of hinged, not sliding, windows. The instalment of glass thicker than 6 mm did not cause any improvement. As for the double glazed windows, no noticeable improvement was detected with an air gap of 12 mm or less, but increasing the air gap to 20 mm causes a moderate improvement. Slight improvement was found when a lamination layer or uPVC frame (instead of aluminum) was used. It was further found that box umbrella and curtain wall frames did not seal as well as half umbrella frames, and thus resulted in a lower acoustic performance of the windows.

1. Introduction
Noise is a threat to human health and well-being. Prolonged exposure to high levels of noise causes impaired hearing, and increases stress and blood pressure, causing gastric problems as well as headaches, migraines, and anxiety or depression [1]. Although noise problems have been well recognized in many countries, the problem continues to grow, accompanied by an increasing number of complaints from affected individuals. From a global perspective, the growth in urban noise pollution is considered unsustainable, because not only it has adverse effects on health but it also affects future generations by degrading residential, social and learning environments [2]. With the realization that noise is a global issue [3, 4], precautionary actions are needed for noise protection in any environmental planning situation.

Windows play a significant role in achieving a good acoustic environment. In fact, windows provide an acoustic weakness to the facade of a building as noise is transferred more easily through glazing than through external walls [5]. Thus, improving the sound insulation of windows helps reduce the ingress of external noise. Several factors could affect noise transmission through windows, such as glass thickness, sealant type, type of glazing (single, double or triple), air gap thickness in multiple glazing, frame type, frame material, external shutters, use of secondary windows, window area, opening style, lamination, etc. Therefore, particular attention to the construction detail of windows is
needed to effectively lower the level of external noise breach into a building. Such details should be incorporated into building codes to assure optimal window design.

The objective of this study was to assess sound transmission loss of different window designs currently used in the Emirate of Abu Dhabi, UAE. The motivation to carry on the study was driven by the desire of Abu Dhabi City Municipality (the funding agency) to develop specifications to control noise propagation through windows. Findings of this study are considered an essential component towards meeting such a goal. Once developed, the specification could be incorporated in the Abu Dhabi International Building Code [6] to guide and assist designers to achieve the required drop in the noise level between the two sides of the window.

2. Methodology

2.1. Tested cases

The used window sizes in Abu Dhabi Emirate vary widely. Some windows could be as small as 1 m², while others could be as large as 9 m² or larger, with the majority of windows fall in the range between 2 and 4.5 m². These figures are approximate and are based on a visual survey of windows on Al Salam Street in Abu Dhabi City. Furthermore, variation occurs in window configurations, but the most commonly used ones are rectangular. Based on that, three window sizes were selected for laboratory testing for noise transmission loss. All tested windows had a fixed part on the top (60 cm high). The windows could be sliding or hinged. The hinged windows had a similar configuration as that of the sliding windows with the exception that the sliding panes were fixed from the top and open to the outside. For all windows, the glass was float, except one case where tempered glass was used.

Given that the window glass thickness used in Abu Dhabi Emirate varies from 6 to 19 mm and the air gap thickness in double glazing ranges from 12 to 20 mm, many different alternatives could be envisioned. Testing for all possible alternatives would be costly and time-consuming. As a result, the acoustic performance of only some glazing systems and window design alternatives was obtained. In total, 21 window cases were tested for noise transmission loss in the laboratory. These cases are listed in table 1. Factors that were considered include window size, glass thickness, glazing type (single versus double), air gap thickness between glazing, use of external shutters, type of window (sliding vs hinged), type of frame (half umbrella, full umbrella, or curtain wall), frame material (aluminum vs uPVC), glass type (float vs tempered), and glass lamination.

2.2. Window fabrication and installation

Window fabrication was carried out by Zoltic Aluminum and Glass Company as per the specifications listed in table 1. Window frames and glass panes were transported to the laboratory for installation. For each case, the frame was fixed first in the provided opening and the sides were sealed with silicone (Dow Corning 813c). The bottom part of the frame was installed near the floor for all cases. Glass panes were then fixed to the frame and were sealed with rubber (Premium Quality Seal, UAE). For each case, the window panes were checked to make sure they are completely closed before testing. For all cases (except case 18), float, transparent glass was used (Emirates Float Glass LLC, UAE). For case 18, tempered glass was used (City Land Glass Factory, UAE). Laminated glass of case 4 was obtained from Emirates Float Glass LLC. For the tested double glazed cases, aluminum spacer bars were used (Gulf Extrusions Company). Wood shutters used in case 11 and 14 cover the whole window length. The shutter is made of solid timber, with pieces (5 cm x 1 cm thick) that overlay each other. Aluminum shutters used in case 12 and 15 were made of hollow aluminum pieces, each 11 cm wide. The shutters have been entirely closed during testing and were placed at the outer edge of the opening of the window holder (i.e., adjacent to the source room side), with a 5-cm distance from the window frame.

2.3. Window testing

Laboratory testing of noise transmission through the various window cases was carried out at Al Futtaim Exova in Dubai, UAE. The tests were intended to determine the acoustic performance of the
different window samples. The test methods were conducted in accordance with the ASTM methods. At the laboratory, the test chamber has been constructed according to specifications detailed in ISO 140-1:1998. The acoustic test facility comprises an adjacent pair of acoustically sealed semi-reverberant chambers. Both chambers have been installed on separate, isolated acoustic floor systems to limit sound and vibrational energy transference (flanking) between the chambers and from the immediate surroundings. The walls of the test facility are formed from sound absorbent acoustic paneling that has been specially designed to provide a high sound transmission loss capability while producing the desired reverberant levels for the semi-reverberant acoustic test chamber. The test specimen is mounted into the opening between the test chambers, provided by the separate, isolated sample holder. The dimensions of the noise source room are 7.08 m long, 5.753 m wide and 4.425 m high. The receiving room is 7.36 m long, 5.98 m wide and 4.6 m high. As for the opening of the testing chamber, the dimensions are 3.7 m long, 0.35 m wide and 2.7 m high.

| Case | L (m) | H (m) | Glazing | Frame style | Opening style | Shutter type | Frame type |
|------|-------|-------|---------|-------------|---------------|--------------|------------|
| 1    | 1.8   | 1.8   | Single 6mm | HU          | Hinge         | No           | LA         |
| 2    | 1.8   | 1.8   | Single 6mm | HU          | Sliding       | No           | LA         |
| 3    | 1.8   | 1.8   | Single 8mm | FU          | Sliding       | No           | MA         |
| 4    | 1.8   | 1.8   | Single 12mm | HU          | Sliding       | No           | LA         |
| 5    | 1.8   | 1.8   | Double 6mm-12mm-6mm | FU          | Sliding       | No           | MA         |
| 6    | 1.8   | 1.8   | Double 6mm-12mm-12mm-12mm | CW          | Hinge         | No           | HA         |
| 7    | 1.8   | 1.8   | Double 6mm-20mm-6mm-6mm | CW          | Hinge         | No           | HA         |
| 8    | 1.8   | 1.8   | Double 12mm-12mm-12mm-12mm | CW          | Hinge         | No           | HA         |
| 9    | 1.8   | 1.8   | Single 6mm | HU          | Hinge         | No           | uPVC       |
| 10   | 1.8   | 1.8   | Single 6mm | HU          | Sliding       | Wood         | LA         |
| 11   | 1.8   | 1.8   | Single 6mm | HU          | Sliding       | Aluminum     | LA         |
| 12   | 1.8   | 1.8   | Double 6mm-12mm-6mm-6mm | CW          | Hinge         | No           | HA         |
| 13   | 1.8   | 1.8   | Double 6mm-12mm-6mm-6mm | FU          | Sliding       | Wood         | MA         |
| 14   | 1.8   | 1.8   | Double 6mm-12mm-6mm-6mm | FU          | Sliding       | Aluminum     | MA         |
| 15   | 2.4   | 1.8   | Single 6mm | HU          | Sliding       | No           | LA         |
| 16   | 1.2   | 1.8   | Single 6mm | HU          | Sliding       | No           | LA         |
| 17   | 1.8   | 1.8   | Single 6mm (tempered) | HU          | Hinge         | No           | LA         |
| 18   | 1.8   | 1.8   | Double 6mm-12mm-6mm-6mm | HU          | Hinge         | No           | LA         |
| 19   | 1.8   | 1.8   | Single 8mm | HU          | Sliding       | No           | LA         |
| 20   | 1.8   | 1.8   | Single 12mm | HU          | Sliding       | No           | LA         |
| 21   | 1.8   | 1.8   | Single 12mm | HU          | Sliding       | No           | LA         |

Table 1. List of tested cases 4.

4 HU is for half umbrella, FU is for full umbrella, CW is for curtain wall, LA is for light-weight aluminum, MA is for medium-weight aluminum, HA is for heavy-weight aluminum, and uPVC is for unplasticized polyvinyl chloride.

The sample holder at Exova’s laboratory comprises of 350 mm wide steel channel which is directly connected to a concrete slab which is isolated from the ground by a high-density mineral wool matt. The infill lining of the steel channel section is high-density hardwood. Both the source and receiving rooms are separate constructions, isolated by high-density mineral wool blankets from the concrete.
slab. Reduction of the size of the opening to accommodate the tested window cases was carried out using four layers of gypsum board sheets (2 cm thick each, filled with fiber glass).

The source and receiving rooms are covered by a secondary external enclosure which is only connected at doorways by heavy density flexible loaded vinyl sheeting. Similarly, the gaps between the sample holder frame and the source and receiving rooms are sealed by flexible mastic. The entry to both the source and receiving rooms is protected by two sets of isolated doorways. Calibration of the acoustic laboratory of Exova was conducted by PKA Acoustic Consulting [7].

The instruments used for measurement of sound transmission were all made by Brul & Kjaer and include a sound level meter (Model 2250), a pre-amplifier (Model ZC-0032), a microphone (Model 4189), a calibrator (Model 4231), an omnidirectional loudspeaker (Model 4292), a loudspeaker amplifier (Model 2716), and a pink noise source (Model 2250). Measuring instruments and related test equipment were all calibrated.

Sound transmission testing was carried out as per the ASTM E90-09 [8] requirements. The test was performed to ascertain the airborne sound insulation capabilities of the sample windows under laboratory conditions, from the source room to the receiving room. The sound transmission test sample was installed and sealed in the available aperture test opening between the acoustic rooms. To restrict the passage of any flanking noise between the chambers, all instances of bridging between the acoustic chambers were investigated and cleared following the installation of the sample. The reverberant levels of the chamber were retested for each new test arrangement or set up.

During testing, the sound generator was set up in the corner of the sound source chamber at two different locations. The sound source was generated in the form of an impulse sound energy, which is a signal produced internally from the sound level meter and fed into the loudspeaker. The level of the impulse signal was sufficiently above the background ambient noise level to permit evaluation of the decay curves (at least 30 dB above ambient).

Sound levels in the 1/3 octave bands from 100 to 5,000 Hz were measured, in both the source and receiving rooms using a rotating microphone boom. The rotating microphone was positioned at two points in the source room and two points in the receiving room. The arm of the rotating boom holding the microphone was 1.2 m and was held at an elevation of 1.4 m above the ground. The arm was set to rotate one full revolution in 64 seconds with an angle of inclination within 10 degrees from a horizontal plane. The microphone was set at a minimum distance of 1.5 m from the source to ensure that measurements were not taken in the direct field. Also, in all measurements, the microphone was moved to a minimum distance of 1 m from walls and extended objects. The test for each sample was taken at six microphone receiver positions, with at least 1.5 m between each position. For each microphone position, a minimum of 15-second recording period was done. The distance between room boundaries, diffusers, and the microphone was at least 1 m. Figure 1 shows the setup for one of the tested cases.

![Figure 1. Testing setup of case 5.](image-url)
Background noise measurement was also measured in the receiving room. The average background noise level in the receiving room ranged between 7.07 to 13.66 dB, with generally higher background noise occurred at the border of the 1/3 octave bands as compared to values at intermediate frequencies. The background noise level in the receiving room, even at low frequency, was considered negligible and hardly detected by human ears. Therefore, correction for background noise was not necessary since the background level was more than 10 dB below the combination of signal and background [8].

Reverberation time was measured according to the ASTM method C423-09a [9] by setting up the sound generator in the corner of the receiving room at two different locations, while the rotating microphone was positioned at two points. In all cases, initiation of the sound generator was controlled by a wireless transmission meter (AKG, Model WMS450). Variation in the reverberation time was small among the tested frequencies, albeit there was a drop in the reverberation time with the increase in frequency. The overall average reverberation time for the tested cases ranged between 2.30 and 2.39 sec.

2.4. Calculation of sound reduction
The results for each tested case were reported as the sound transmission class (STC) according to the ASTM method E413-10 [10]. STC is a single-number rating used to compare the sound transmission loss of a material with the subjective notion of sound insulation from sources. The calculation of the sound transmission loss follows the correction of the receiver side readings for the ambient and reverberation time factors. Sound transmission loss (STL) is defined as:

$$STL = L_1 - L_2 + 10 \log \left( \frac{S}{A} \right)$$

where \(L_1\) and \(L_2\) are the sound levels in the source and receiving rooms (dB), respectively, \(S\) is the area of the test specimen that is exposed in the receiving room (m²), and \(A\) is the sound absorption of the receiving room with the test specimen in place (m²). The sound absorption of the receiving room is given by the Sabine equation:

$$A = 0.921 \frac{Vd}{c}$$

where \(V\) is the volume of the reverberation room (202 m³ in our case), \(c\) is the speed of sound (340 m/s), and \(d\) is the sound decay rate (dB/s). The sound decay rate is estimated as:

$$d = \frac{60}{T_2}$$

where \(T_2\) is the reverberation time (i.e., the time that corresponds to a drop of 60 dB in the receiving room). STC is derived by fitting a reference rating curve to the STL values measured for the 16 contiguous 1/3 octave frequency bands with nominal mid-band frequencies of 125 Hz to 4,000 Hz inclusive. A reference rating curve is fitted to the corresponding 16 measured STL values. Comparison with the reference curve results in a set of positive and negative deviations for each frequency band. The reference curve is increased or decreased in 1 dB intervals to achieve the maximum sum of deficiencies (STL values less than the reference rating curve), less than or equal to 32 dB, and no single deficiency is greater than 8 dB. Then, the STC value is determined as the numerical value of the reference contour at 500 Hz.

3. Results and discussion
STL curves were generated for all tested cases. An example of an STL curve is shown in figure 2. The curve for each case was generated by subtracting the average sound level at a given frequency in the receiving room from the mean sound level at the same frequency in the source room using the collected raw data. The STC value for each case was then determined as listed in table 2. The effect of changes in window design on the STC value is presented below. Factors that were considered are glass thickness, glass lamination, glazing, air gap between glass panes, frame material, frame type, window area, use of shutters, and glass type.
The impact of glass thickness was evaluated by considering case 2, 20 and 21 are considered. These cases were identical except for the glass thickness (6 mm for case 2, 8 mm for case 20, and 12 mm for case 21). All these cases resulted in equal STC values of 23 dB, indicating no impact on sound transmission for the tested range of glass thickness. However, from the STL values for these cases (not shown here), there appeared to be a small improvement in sound transmission loss in selecting a thicker glass. The effect of glass thickness on sound transmission could also be evaluated by considering case 3 and 5. These two cases were similar with the exception of glass thickness (8 mm for case 3 and 12 mm for case 5). The STC value for case 3 was 21 dB and that for case 5 was 20 dB. Similar results were also obtained in the experiments of Tadeu and Mateus [11] for the glass thickness of 4 and 8 mm. These results, once again, indicate no impact on sound transmission due to changes in glass thickness, and thus the selection of a thicker glass for sound reduction would not be justified.

![Figure 2. STL at the 1/3 octave bands of case 1.](image)

The effect of glass lamination could be evaluated by considering case 4 and 21. The two cases were similar with the exception of lamination (case 4 was laminated by a 0.76 polyvinyl butyral (PVB) layer sandwiched between two 6-mm glass sheets while in case 21 single glazing of 12 mm glass panes was used). The STC value for the case with laminated glass was 24 dB, while that for the non-laminated glass was 23 dB. Thus, the use of a 0.76 mm lamination resulted in only 1 dB reduction in sound transmission as compared to a non-laminated case. It has been reported that laminated glass has an advantage of addressing specific noise reduction efficiency [12]. The plastic interlayers change the frequency response of the composite sheet in comparison with the same weight of ordinary glass and also absorb some of the sound energy [13]. Although not investigated in this study, it is possible that a thicker laminated layer could lead to higher STC values.

The effect of glazing could be evaluated by considering case 5 and 6. Both cases are similar with the exception that case 5 included a single glazed window using 12 mm glass, while the window in case 6 was double glazed using 6 mm glass panes with an air gap of 12 mm in between. For both cases, the STC value was the same (20 dB), indicating that a slight air gap would not improve the performance of windows from a sound reduction point-of-view. The low STC value of the two cases as compared to those of the other tested cases could be mainly attributed to the use of a box umbrella frame, which did not provide a good seal with the glass panes as will be discussed later.

The impact of the air gap thickness between glass panes in double glazed windows could be evaluated by considering case 8 and case 13. In both cases, double glazed curtain wall windows of 6
mm glass were used. The difference between the two cases was in the thickness of the air gap. In case 8 an air gap of 20 mm was used, while in case 13 the air gap was 12 mm. The STC value for case 8 was 29 dB while that for case 13 was 25 dB. As noted by Pilkington [14], a standard double glazed unit does not reduce sound transmission much more than a monolithic glass. What matters is the thickness of the air space between glass panes, but only for really wide cavities. Tadeu and Mateus [11] found that the sound reduction index improves, if the air space between glass panes is close to or greater than 50 mm. However, beyond a spacing of about 200 mm, it becomes uneconomical to install such windows because the incremental acoustic improvement is small.

### Table 2. STC values of the tested cases.

| Case | STC (dB) | Case | STC (dB) | Case | STC (dB) |
|------|----------|------|----------|------|----------|
| 1    | 29       | 8    | 29       | 15   | 32       |
| 2    | 23       | 9    | 26       | 16   | 23       |
| 3    | 21       | 10   | 31       | 17   | 23       |
| 4    | 24       | 11   | 32       | 18   | 29       |
| 5    | 20       | 12   | 34       | 19   | 29       |
| 6    | 20       | 13   | 25       | 20   | 23       |
| 7    | 25       | 14   | 29       | 21   | 23       |

The effect of changing the glass thickness in double glazed windows could be evaluated by considering case 7, 9 and 13. In the three cases, hinged, double glazed curtain wall windows were used. The difference between these cases was that case 7 consisted of 6 mm and 12 mm glass panes with 12 mm air gap, while case 9 consisted of two 12 mm glass panes with 12 mm air gap, and case 13 was made of 6 mm glass sheets with 12 mm air gap. The STC value for case 7, 9 and 13 were 25, 26, and 25 dB, respectively. Apparently, changes in the glass thickness within the same window do not cause a noticeable improvement in the STC value.

The two types of frame materials used in this study were aluminum and uPVC. The impact of frame material could be evaluated by considering case 1 and 10. Both cases were similar except in the material of the frame (the frame in case 1 was made of aluminum while that in case 10 was made of uPVC). For case 1, an STC value of 29 dB was obtained, while for case 10 an STC value of 31 dB was obtained. Thus, uPVC frames result in 2 dB increase in the STC value compared to aluminum frames. The improvement in the performance of the uPVC frame was mainly due to a higher sound transmission loss at low and intermediate frequencies (not shown here).

Evaluation of the effect of frame type on sound transmission through windows could be made by considering case 3 and 20. Both cases were similar except that in case 3 a full (box) umbrella frame was used, while in case 20 a half umbrella frame was used. Results revealed that a half umbrella frame results in a better performance regarding STL, with the STC value for case 20 being a 2-dB higher than that of case 3. A similar conclusion would be obtained if one compared the STC values of case 5 and 21. The difference between these cases was in the type of umbrella frame used (in case 5 a box umbrella frame was used while in case 21 half umbrella frame was used). The STC value for case 21 was 3 dB higher than that of case 5. In conclusion, half umbrella frames result in a 2-3 dB increase in the STC value compared to full umbrella frames.

Additional comparison of the effect of frame type could be made considering case 13 and 19. The difference between these cases was that in case 13 a curtain wall frame was used while in case 19 a half umbrella frame was used. The STC for case 13 was 25 dB while that for case 19 was 29 dB. Thus, a half umbrella hinged frame would result in a 5 dB increase in the STC value compared to similar windows made of curtain walls. In general, the effect of frame type depends on the sealing mechanism (air leaks/tightness). Tadeu and Mateus [11] studied the sealing effect on window considering the sound reduction index. They found that the sound reduction index is 18 dB for a window with a small gap of 2 mm, and it is 20 dB for a window with poorly sealed frame. However, the same well-sealed window has a sound reduction index of 29 dB which is almost similar to the same window without a
Moreover, Park and Kim [15] found that windows with the highest performance grade airtightness had better sound insulation that those with poor or unmeasurable airtightness.

The effect of shutters could be evaluated by considering case 2, 11 and 12. These cases were identical had the types and presence of shutters varied (case 2 was tested without a shutter, while case 11 and 12 were tested with wood and aluminum shutters, respectively). The STC values for case 11 and 12 were 9-11 dB higher than that of case 2. Comparison between cases 11 and 12 showed that windows with aluminum shutters had a slightly better sound insulation (about 2 dB) than those with wood shutters. A similar conclusion would be reached if one compared the STC values for case 6, 14, and 15. The difference between these cases is that case 6 was tested without a shutter, while case 14 and 15 were tested with wood and aluminum shutters, respectively. The STC values for case 14 and 15 were 9-12 dB higher than that of case 6, with the windows with aluminum shutters showing a slightly better sound insulation (about 2 dB) than that of the wood ones. A possible reason for the slightly better performance of aluminum shutters as compared to wood shutters that are used in this study is that in the former hollow aluminum was used while in the latter solid wood was used. The air gap in the aluminum shutter could have resulted in an improvement over solid wood shutters. Another possible reason could be due to the presence of more openings in the wood shutter than in the aluminum shutter due to variations in the width of the pieces making the two shutters (the width of wood pieces was 5 cm and of aluminum pieces was 11 cm).

Evaluation of the effect of window area on the sound transmission loss revealed that the STC value is independent of the window area because the results are corrected for window size in obtaining the STC value. This is evident by comparing the STC values for case 2, 16 and 17. These windows differed only in their areas, but the STC values were the same for all of them.

The two types of window opening styles that were tested in this study were sliding and hinged. The effect of window opening style could be demonstrated by comparing the results of case 1 (sliding window) and case 2 (hinged window). The STC value for case 1 was 29 dB while that of case 2 was 23 dB. Thus, the use of hinged windows results in a significant increase of about 6 dB in the STC value as compared to sliding windows, assuming other factors remain the same. A similar conclusion could be reached if the assessment is made by considering case 6 and 19. These cases differ in two aspects: (1) in case 6 a sliding window was used while in case 19 a hinged window was used, and (2) in case 6 a box umbrella frame was used while for case 19 a half umbrella frame was used. The STC value for case 6 was 20 dB and that for case 19 was 29 dB. Given that half umbrella frames gave STC values of 2-3 dB higher than those of box umbrella frames (as explained previously), hinged windows would then have STC values that are 6 to 7 dB higher than those of sliding windows. The outperformance of hinged windows compared to sliding windows, as noticed here, is consistent with the findings reported in the literature. Milgard [16], for example, reported that hinge style windows provide a tighter seal against the frame as compared to sliding windows, therefore reducing noise transmission.

Two types of glass were tested in this study: float and tempered. The effect of glass type could be demonstrated by considering case 1 (float glass) and case 18 (tempered glass). The STC values for both cases were 29 dB. Thus, the use of tempered glass over float one does not add value to sound transmission loss.

4. Conclusion
Based on laboratory testing of 21 window cases, it was concluded that sound transmission loss through windows is improved significantly with the use of shutters (when completely closed) and the use of hinged, not sliding, windows. However, using glass thicker than 6 mm or using tempered glass instead of float glass does not cause any improvement. Meanwhile, use of double glazed windows with an air gap of 12 mm or less does not result in any tangible effect. However, increasing the air gap from 12 to 20 mm causes a moderate improvement. The use 0.76 mm PVB lamination layer and the use of uPVC frames (instead of aluminum frames) resulted in a slight improvement. It was also concluded that the
current design of box umbrella and curtain wall frames do not seal well as compared to those of half umbrella frames, and thus result in lower STC values.

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