Pertanika J. Sci. & Technol. 30 (4): 2983 - 2997 (2022)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Evaluation of Acoustical Performance for Atrium Design with Respect to Skylight Geometry and Material in the Tropics

Nazli Che Din*, Tio Seng Zhi and Chia Keng Soon

The Centre for Building, Construction and Tropical Architecture (BuCTA), Faculty of Built Environment, Universiti Malaya, 50603 UM, Kuala Lumpur, Malaysia

ABSTRACT

Atriums, in most conditions, are considered the heart of buildings, the main spaces where different functions and activities are held. Nowadays, various atrium designs are incorporated in the building, varying from pyramidal to barrel vault. Therefore, it is of great importance to study the basic characteristics of sound fields in such spaces and their related materials. This research aims to determine the effect of various skylight geometry configurations on the atrium's acoustical performance. Next, an acoustical performance evaluation of the effect of skylight materials was performed by using computer simulation. Four selected atriums with different types of skylight geometries modeling and respective materials, i.e., glass, polycarbonate, and acrylic, have been used in this acoustical simulation. From the results, it can be concluded that an atrium with a pyramidal skylight provides a better reverberation time for music purposes. In contrast, all atriums' models' speech transmission index values were almost identical. However, no significant acoustical performance can be found in different used materials. The result also indicates that the shape of the atrium has a higher effect on the acoustical performance than the different materials used.

Keywords: Acoustical performance, atrium, geometry, ODEON, simulation, skylight

ARTICLE INFO

Article history:
Received: 16 December 2021
Accepted: 3 February 2022
Published: 19 September 2022

DOI: https://doi.org/10.47836/pjst.30.4.35

E-mail addresess:
nazlichedin@um.edu.my (Nazli Che Din)
z.tio@hotmail.com (Tio Seng Zhi)
soon_chia91@hotmail.com (Chia Keng Soon)
*Corresponding author

INTRODUCTION

A large open or covered space that continues through several levels of a building is an atrium in architecture. A courtyard house in

ISSN: 0128-7680
e-ISSN: 2231-8526

© Universiti Putra Malaysia Press

Ur, Mesopotamia, was identified as one of the traditional atrium forms in archaeological remains dating back to 3000 BC (Bednar, 1986). It was discovered as a central courtyard in ancient Roman and Greek architecture. The form of the atrium has gradually developed from a common traditional impression into high complexity methods to the difficulty in providing a sheltered courtyard (Saxon, 1983).

According to De Ruiter (1988), an atrium is a space with a large and high volume covered by glass-roofed. The atrium is also usually involved in large open spaces linking several floors, and it offers potential advantages as a building form over a typical building configuration (Gritch & Eason, 2016). Generally located at the center of the building, the atrium can be acted as a key circulation and transition space to proceed to other spaces (Wood & Salib, 2013; Pitts, 2013; Passe & Battaglia, 2015). It also gives an impression of large volume and has the potential to provide good air circulation and light penetration towards indoor comfort within the space (Jalil et al., 2014; Bai et al., 2015; Moosavi et al., 2014; Moosavi et al., 2015). Nowadays, the atrium is widely used in residential, commercial, and institutional buildings and not only acts as protection from the climate conditions but also creates a significant visual effect on the existing space.

Apart from serving as a transition zone between two spaces within the building, the atrium now hosts a variety of functions and activities, such as musical dance performances and exhibitions (Lee, 2019). Therefore, acoustic design or treatment should take into consideration its function. Normally, a larger volume and having too many reflecting materials installed in the space will result in higher reverberation time; thus, the reverberation time in the atrium should be lower and shorter if used for the reception or gathering space to allow acceptable speech intelligibility (Tio, 2016).

These days, the construction of public spaces with large atriums or high volumes, such as shopping malls and mixed-use developments, has increased. The acoustics in such a space is difficult to control and can contribute to poor acoustic comfort in the atrium (Nowicka, 2020). Also, the changes to meet the acoustic parameter may be highly extensive in cost afterward, so the early stage of acoustic design for the atrium should consider. Furthermore, acoustically reflecting construction materials and finishes, such as glass, concrete, and brick, are commonly utilized in the atrium and have lower sound absorption characteristics in overall frequency ranges, but it depends on the thickness of the materials (Fediuk et al., 2021). As a result, the acoustic performances in such places are poor since the reverberation time is longer. Subsequently, acoustic comfort in the space will become uncomfortable for the users. However, with recent rapid technologies and material studies, some solutions have become available to control the problem (Fuchs, 2001; Urban et al., 2016; Rychtarikova et al., 2017a; Rychtarikova et al., 2017b).

Based on Valtonen's (2014) observation, a shopping mall nowadays is not only a place to quickly do their routine shopping, but the time spent in the centers of the building or atrium becomes favored by an individual or group of users. Long reverberation time in the atrium reduces the intelligibility of speech and human comfort (Šimek & Chmelík, 2021; Alnuman & Altaweel, 2020; Lavasani et al., 2021; Dökmeci, 2009), may even prevent people from hearing the announcement from the public address (PA) system. Until now, fewer or fewer acoustical studies have been conducted compared to the daylighting and thermal comfort studies for the atrium space.

Fundamental of Atrium Shape and Relationship with Sound

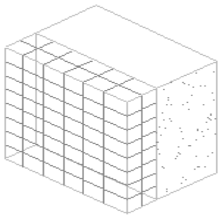
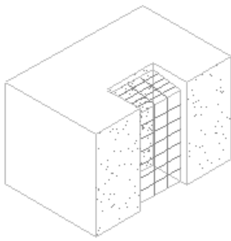
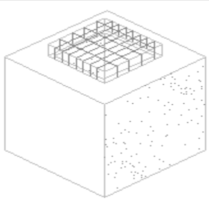
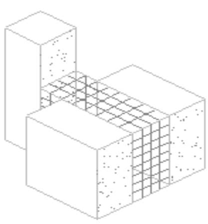
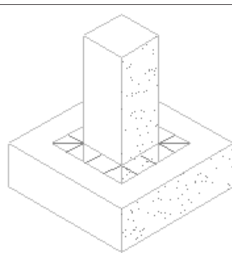
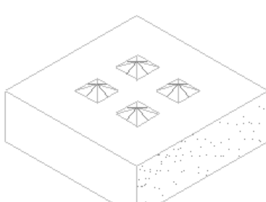
According to Gritch and Eason (2016), the shape and geometry of an atrium are largely determined by the product and rationale for the adjacent inhabited areas of the structure. Therefore, the arrangement or configuration of the atrium area has a significant impact on these places. As illustrated in Table 1, a few fundamental configurations of the atrium space are simple and complex. The simple types are Single Sided Atrium, Two Sided Atrium, Three Sided Atrium, Four Sided Atrium, and Linear Atrium. Furthermore, the complex types of the atrium can be divided into Bridging Atrium, Podium Atrium, Multiple Lateral Atrium, and Multiple Vertical Atrium. The minimalist atrium design is appropriate for modest single structures, while the complex atrium style is appropriate for massive complex buildings.

One of the key elements deciding the reverberation period in acoustics is the volume, shape, and size of space (Long, 2014). The reverberation time in a large volume of spaces will be longer, resulting in poor speech intelligibility (Jalil et al., 2016). When a sound source is applied in a room, sound waves can propagate from the source of sound until they hit the room's boundary. When a sound source is used in a room, sound waves scatter from the source until they reach the room's perimeter. Sound energy is reflected into the room space during propagation; some are absorbed and transmitted throughout the barrier. As a result, a room's volume, shape, and size changes may impact its acoustics (Maekawa et al., 2010). Sound rays from the sound source will focus the sound waves by reflecting the focal point in geometric shapes, such as a concave surface, as seen in Figure 1(a). Meanwhile, the surface in a convex shape will disperse the sound wave, as depicted in Figure 1(b). When compared to high-frequency sounds of short wavelength, the effect of sound ray diffraction is more obvious during long wavelength for low frequency (Ginn, 1978).

This study is divided into two objectives: i) to identify the acoustical condition of selected atrium design by using computer simulation, and ii) to evaluate the effectiveness of selected skylight materials on the acoustical performance of selected atrium space. In order to study and evaluate the acoustical performance in the atrium space, a series of acoustical simulations and analyses in different types of the atrium will be carried out using specialized room-acoustic software. The result of the acoustical performance of the selected atrium with different materials on the skylight will be generated and compared.

Table 1

Example of simple and complex basic configurations of atrium space (Gritch & Eason, 2016)

	**Simple Type** **Single-Sided Atrium:** The atrium borders one side of the structure's occupied area
	**Simple Type** **Three-Sided Atrium:** The atrium borders three sides of the structure's occupied area
	**Simple Type** **Four-sided Atrium:** The atrium runs along four sides of the structure's occupied area
	**Complex Type** **Bridging Atrium**: The atrium connects several occupied areas of the structure.
	**Complex Type** **Podium Atrium**: The atrium sits at the bottom or below an occupied area of the structure
	**Complex Type** **Multiple Lateral Atrium:** Atrium areas spread throughout the layout on single or several stories.

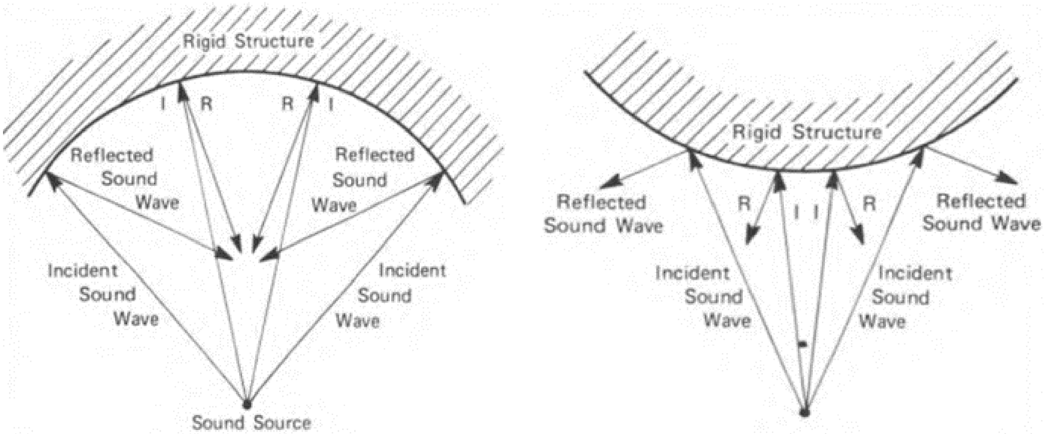


Figure 1. Reflections of sound rays on the curved surface; a) concave b) convex (Ginn, 1978)
Source. https://www.bksv.com/media/doc/bn1329.pdf

METHODS

Simulation Set-Up

Geometric Proportion of Atrium Space. The relationship between the length, width, and height of the atrium defines the differing degree of its light levels. The geometrical proportions of the atrium are similar to the well index ratio. Therefore, the shorter and broader atrium space will have improved daylight visibility because the height of the atrium defines the degree of the visible sky component. The Section Aspect Ratio (SAR), Plan Aspect Ratio (PAR), and Well Index Ratio (WI) can all be used to portray atrium geometry (Bednar, 1986; Saxon, 1983).

The height-to-width ratio determines the sectional proportion of the atrium. The lower SAR value suggests a lower atrium. For example, a shallow atrium has a SAR of less than 1.0, while a tall or narrow atrium has a SAR of larger than 2.0. (Atif, 1994). The PAR is the width-to-length ratio that defines whether the atrium is linear or square in plan proportion. A linear atrium is defined as one with a PAR of less than 0.4. (Bednar, 1986; Atif, 1994). Both the PAR and the SAR are included in the WI. It is also the best way to figure out how geometry affects the distribution of daylight illumination in the atrium. It is often the logarithmic scale index used to produce preliminary daylight predictions for various amounts of atrium volume (Atif, 1994; Boyer & Oh, 1988; Kim, 1987). The geometrical correlations are summarized as Equations 1, 2, and 3:

$$SAR = h / w \quad (1)$$

$$PAR = w / l \quad (2)$$

$$WI = h\,(l + w) / 2\,(l)\,(w) \quad (3)$$

where, h = atrium height, w = atrium width, l = atrium length

Aside from the atrium's geometric proportions, the surface reflectivity of the well influences the quality and amount of sunshine inside the atrium, including the walls and floor. It is mostly determined by the type of materials utilized and the colors, textures, and finishes. When the surface is matte-finished with dispersed reflections, the polished and bright surface causes reflections. The ratio of the concrete wall to the glass surface determines the intensity of daylight created between the upper and lower floors of the atrium (Saxon, 1983; Navvab, 1990; Quek, 1989). Clear glass windows are less reflecting than solid walls. Because direct light is acquired mostly on the higher levels, a larger solid wall area is necessary to reflect the sun. The window area and ceiling height rise steadily towards the lower floors to obtain reflected light.

Skylight Glazing. Skylight glazing is a type of light-transmitting fenestration (elements that fill building envelope apertures) that forms all or a portion of a structure's roof for daylighting purposes. Several types of skylights are available in a wide range of sizes and shapes. It can improve the building's interior aesthetic by harmonizing the design form and characteristics of light penetration from the skylight. It is usually worked by properly selecting the skylights that enhance the ceiling grid and room proportions. A range of glass and plastic glazing materials, such as acrylics, polycarbonates, and fiberglass, are regularly available on the market for skylights. These materials are also available in various thicknesses and combination structure materials. Therefore, all these variables may affect the acoustical performance of the atrium.

Simulation 1. The major goal of this study was to determine the acoustical performance of various types of atriums. Therefore, choosing the sort of atrium was the first step. Generally, the atrium's basic model is based on the literature research "Design Principles of Atriums Buildings for the Tropic" (Ahmad & Rasdi, 2000), which identified the characteristics of a typical Malaysian atrium.

According to a review of the literature, the four-sided rectangular atrium with top-lit is the most prevalent atrium design in Malaysia; Plan-Aspect-Ratio (PAR) of 1:3; Section-Aspect-Ratio (SAR) of 1:1; The atrium void height should be four levels, and the floor to floor height should be 12 feet (about 4 m); The corridor floor to ceiling height should be 9 feet (about 3 meters), and the corridor width should be 12 feet (roughly 4 meters), with 1.2 meters of transparent glass balustrade or railing. Table 2 shows the details of the description of each room model created in Simulation 1 and has a similar size with approximately 643 m^2 of floor area in all models.

Four types of the atrium were selected in this research. The atrium is a model with different skylight geometry with the same materials used, as shown in Table 3. The four different types of atrium skylight are the Single Pitched (F1), Double Pitched (F2), Barrel

Vault (F3), and Pyramid (F4). For the computational study of computer modeling, the architectural characteristics of these atrium models have been streamlined. This simulation purposely identifies the effectiveness of the skylight geometry so that the materials assigned in this study are not identical with any existing atrium and are to be used similarly for all models.

Table 2
Description of each room model in Simulation 1 & 2 (sound source in red dots and receiver in blue dots)

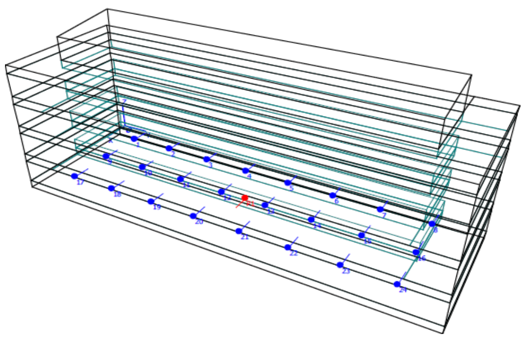
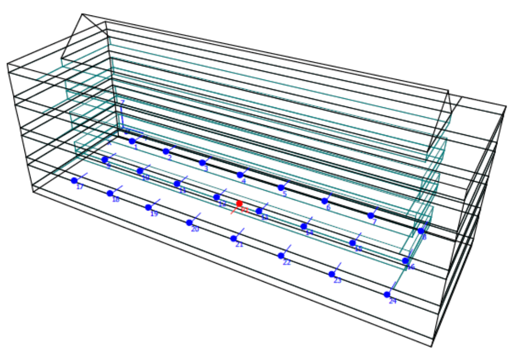
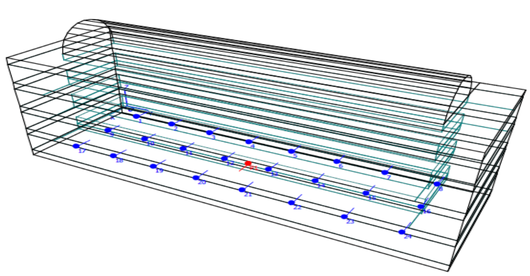
Model	Volume, m^3	Max Height, m
 F1: Single Pitch Shape	10566.3	18.22
 F2: Double Pitch Shape	10331.8	20.74
 F3: Barrel Vault Shape	10470.2	19.87

Table 2 *(Continue)*

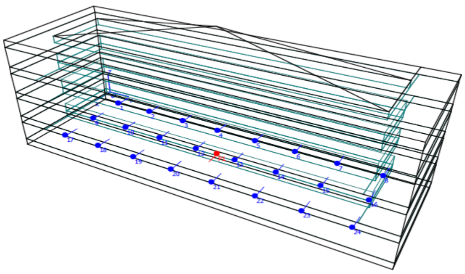
Model	Volume, m^3	Max Height, m
 F4: Pyramid Shape	10651.5	22.29

Table 3

Absorption coefficients of materials applied for Simulation 1 (Ref. from ODEON material library)

	Frequency (Hz)			
Materials	**250**	**500**	**1000**	**2000**
Floor: Ceramic tiles. Perforation = 12%. Mineral wool in a cavity (Stroem, 1979)	0.44	0.68	0.79	0.56
Walls: Smooth brickwork, 10mm dep pointing, pit sand mortar (Kristensen, 1984)	0.09	0.12	0.16	0.22
Ceiling: Perf. 27 mm gypsumboard (16%), d= 4.5mm 300mm from ceiling (Dalenback, CATT)	0.55	0.60	0.90	0.86
Skylight Glazing: 6mm Single pane glass (Ref. Multiconsult, Norway)	0.06	0.04	0.03	0.02
Railing: Solid Glass block (Ref. Multiconsult, Norway)	0.02	0.02	0.02	0.02

Table 4

Absorption coefficients of materials applied for Simulation 2 (Ref. from ODEON material library)

	Frequency (Hz)			
Materials	**250**	**500**	**1000**	**2000**
Glass: 6 mm Single pane glass (Ref. Multiconsult, Norway)	0.06	0.04	0.03	0.02
Polycarbonate: 6 mm polycarbonate sheet (Ref. Panelite, 2016)	0.20	0.16	0.15	0.10
Acrylic: 6 mm acrylic sheet (Ref. Deamp, Norway)	0.25	0.20	0.18	0.10

Table 5

Sound power of an omnidirectional speaker was used in both simulations (Omni.SO8)

Frequency, Hz	250	500	1000	2000
Sound power, dB	69.6	74.8	71.8	63.8

Simulation 2. Using the inadequate acoustical performance of skylight geometry derived from Simulation 1, the next goal of this study was to assess the effectiveness of selected skylight materials on the acoustical performance of a specified atrium space.

A selected atrium model with similar materials is used except for the skylight glazing. Furthermore, two additional materials have been assigned (Table 4), i.e., polycarbonate and acrylic, to compare the impact of the acoustical performance in the atrium spaces. The motivation for materials used in this simulation is based on the observation that common materials used for atrium skylights in Malaysia include glass, polycarbonate, and acrylic.

Simulation Procedure. In the beginning, the four types of the selected atriums with different skylight geometries were modeled using Google Sketchup®, and then models were exported into ODEON Room Acoustic Software 13.0 Industrial (Cristensen & Koutsouris, 2015). A new room's validity was verified when assigned in ODEON to ascertain the simulation's accuracy. The verification process involves checking whether data is coherent and in the proper format. In addition, it involves a water tightness test of the room through tracing rays in the 3D Investigate Rays or 3D Billiard window, as depicted in Figure 2, to ensure that the room model is entirely enclosed. All architectural details such as an ornament, cornice, and framing were not included in the room modeling because such details do not produce any strong early reflections to the receiver (Jalil et al., 2019).

The sound source and receiver were defined systematically. First, a single point of natural raised sound (Table 5) was used as a sound source. The sound source was located in the center of the atrium and lifted 1.7 m from the floor level (stage height) to provide an even sound distribution in the atrium space. The receiver positions were then spread consistently across the entire floor space. Table 2 depicts the distribution of sound sources (red dots) and receiver sites (blue dots) for each room model. All simulation results from Simulations 1 and 2 were compared in two key parameters: reverberation time (RT) and speech transmission index (STI).

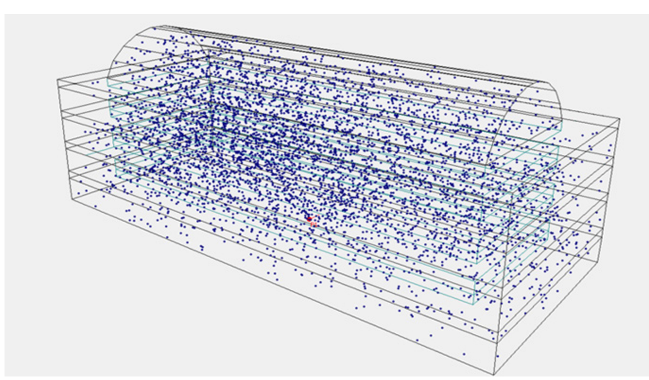


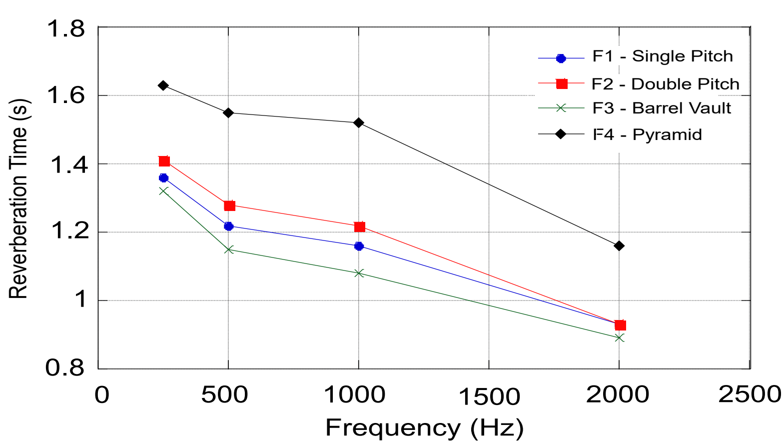
Figure 2. Example of the validation process using water tightness test by 3D billiard in the model room of F3 rectangular atrium with barrel vault-shaped skylight

RESULTS & DISCUSSIONS

Simulation 1: Acoustical Performance vs Skylight Geometry

Figure 3 shows the comparison of RT between all simulated models. A similar tendency of RT can be found in all models from 250 Hz until 2000 Hz. F4 exhibits higher RT values than the other atriums, followed by F2, F1, and F3. The Pyramid Skylight F4 may be better suited for a musical event due to its longer reverberation period, producing a warmer sound for musical activity. An atrium space considered good for a musical event has an RT value between 1.5 s to 1.8 s or a 'fair' value of 1.3 s to 1.5 s and 1.8 s to 1.9 s at 500 Hz and 1000 Hz, respectively (Egan, 2007). Based on the data obtained in Figure 3, all RT values decreased as the frequency increased. It was probably attributed to the fact that most materials do not absorb low frequencies well, so room reverberation is shorter at higher frequencies and longer at lower frequencies. This phenomenon is also supported by Ginn (1978) that the effect is more noticeable at low frequencies region.

Table 6 shows that all room models achieved a good STI and have an almost identical average STI, around 0.7. In general, all room models have attained outstanding agreement and provided speech intelligibility at the surrounding middle location of the atrium. However, a lower STI value can be observed where the distance between the sound source and the receiver exceeds around 5 m. There is a clear correlation between the STI mean value and the distance between the sound source and the receiver point, where the STI value decreases with the increased distance from the sound source. Generally, it can be inferred that F4 has a better STI value for a strong subjective perception of speech intelligibility.



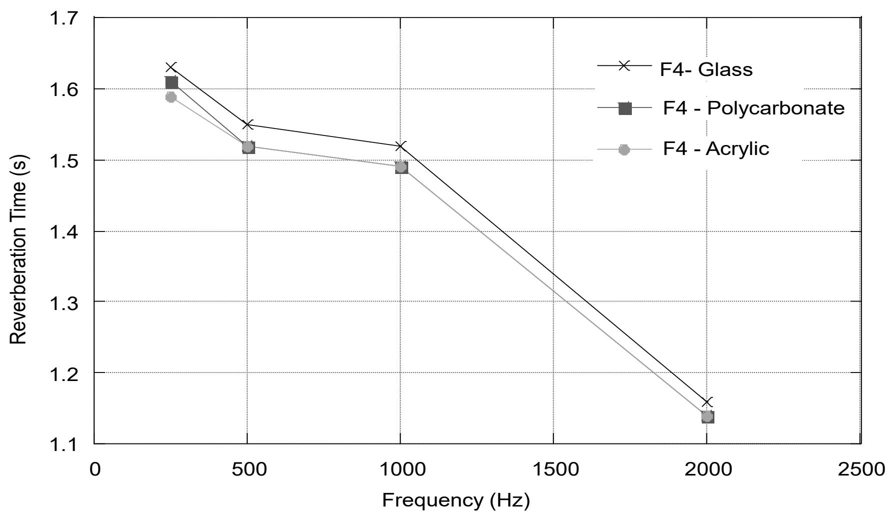
	T30 (s)			
Atrium Type	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**
Single Pitch - F1	1.36	1.22	1.16	0.93
Double Pitch - F2	1.41	1.28	1.22	0.93
Barrel Vault - F3	1.32	1.15	1.08	0.89
Pyramid - F4	1.63	1.55	1.52	1.16

Figure 3. Comparison of reverberation time, T30 for each room model in Simulation 1

Table 6

Comparison of sound transmission index, STI for each model in Simulation 1

	Atrium Type			
Parameter	**F1**	**F2**	**F3**	**F4**
STI Max	0.86	**0.87**	**0.87**	0.85
STI Min	0.63	0.63	0.63	**0.64**
STI Ave	0.69	**0.70**	**0.70**	**0.70**
Distance (m) @STI-0.75	4.68	5.87	5.87	**5.96**



	T30 (s)			
Materials	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**
Glass	1.63	1.55	1.52	1.16
Polycarbonate	1.61	1.52	1.49	1.14
Acrylic	1.59	1.52	1.49	1.14

Figure 4. Comparison of reverberation time, T30 for each room model in Simulation 2

Table 7

Comparison of sound transmission index, STI for each model in Simulation 2

	Atrium pyramid skylight with material type		
Parameter	**F4-Glass**	**F4-Polycarbonate**	**F4-Aryclic**
STI Max	0.85	**0.86**	**0.86**
STI Min	0.64	**0.65**	**0.65**
STI Ave	0.70	**0.71**	**0.71**
Distance (m) @STI-0.75	5.96	**6.62**	**6.62**

Simulation 2: Acoustical Performance vs Skylight Material

For Simulation 2, the F4 model was chosen and compared the two additional different types of materials used in the atrium skylight. A similar methodology was applied in this simulation, except the materials were assigned differently to evaluate their effectiveness in acoustical performance.

In this simulation, an atrium with similar skylight geometry and volume was used; the difference in RT value is caused by the difference in the absorption coefficient of materials used at the atrium skylight. However, there is no distinct agreement for all simulated RT observed in Figure 4, whereby the maximum dispersion is only 0.04 s.

Furthermore, no substantial difference in STI value can be found in Table 7 except for the distance of STI at 0.75 when a comparison of different materials has been performed. The distance of STI at 0.75 with polycarbonate and acrylic was slightly increased compared to the glass type of material. However, it can be concluded that the additional two types of materials gave a less significant performance on STI even though higher absorptive materials were used compared to the material glass.

CONCLUSION

This study is a series of investigations on different type of atrium skylights and their impact of skylight materials on acoustical performance using a computer simulation. From the simulation result, it can be concluded that the atrium with a pyramid skylight provides a better and longer reverberation time for music function. However, a less significant acoustical performance can be observed in simulated results when different materials for atrium skylights are used. It can also be concluded that the shape of the atrium has a higher impact on the acoustical performance than the materials used in this study. This study contributes to further investigation, such as on-site psychological and physical measurements, for evaluating human acoustic comfort in different atriums.

ACKNOWLEDGEMENT

The authors declared no conflicts of interest concerning this article's research, authorship, and/or publication. This work was conducted as part of completing the Master of Architecture degree requirements and supported by the Department of Architecture, Faculty of Built Environment, Universiti Malaya.

REFERENCES

Ahmad, M. H., & Rasdi, M. T. H. M. (2000). *Design principles of atrium buildings for the tropics*. Penerbit UTM.

Alnuman, N., & Altaweel, M. Z. (2020). Investigation of the acoustical environment in a shopping mall and its correlation to the acoustic comfort of the workers. *Applied Sciences, 10*(3), Article 1170. https://doi.org/10.3390/app10031170

Atif, M. R. (1994). *Daylighting and cooling of atrium buildings in warm climates: Impact of the top-fenestration and wall mass area*. Texas A&M University.

Bai, G., Gong, G., Yu, C. W., & Zhen, O. (2015). A combined, large, multi-faceted bulbous façade glazed curtain with open atrium as a natural ventilation solution for an energy efficient sustainable office building in Southern China. *Indoor and Built Environment*, *24*(6), 813-832. https://doi.org/10.1177/1420326X15602048

Bednar, M. J. (1986). *The New Atrium*. McGraw-hill book company.

Boyer, L. L., & Oh, M. S. (1988). Computer prediction and measurement comparison of daylighting performance in selected atrium buildings using SERI algorithms. *ASHRAE Transactions*, *94*(1), 799-811.

Cristensen, C. L., & Koutsouris, G. (2015). *Odeon room acoustics software version 13* (User's Manual). Odeon A/S.

De Ruiter, E. P. J. (1988). Atria in shopping centres, office buildings and hospitals. In *Proceedings of the Institute of Acoustics* (Vol. 10, No. Part 8, pp. 299-307). Institute of Acoustics.

Dökmeci, P. N. (2009). *Acoustical comfort evaluation in enclosed public spaces with a central atrium: a case study in food court of cepa shopping center, Ankara* (Doctoral dissertation). Bilkent Universitesi, Turkey.

Egan, M. D. (2007). *Architectural acoustics*. J. Ross Publishing.

Fediuk, R., Amran, M., Vatin, N., Vasilev, Y., Lesovik, V., & Ozbakkaloglu, T. (2021). Acoustic Properties of Innovative Concretes: A Review. *Materials, 14*(2), Article 398. https://doi.org/10.3390/ma14020398

Fuchs, H. V. (2001). Alternative fibreless absorbers - New tools and materials for noise control and acoustic comfort. *Acta Acustica United with Acustica*, *87*(3), 414-422.

Ginn, K. B. (1978). *Architectural acoustics*. Brüel & Kjaer. https://www.bksv.com/media/doc/bn1329.pdf.

Gritch, T., & Eason, B. (2016). *Building envelope design guide - Atria systems*. Whole Building Design Guide. http://www. wbdg. org/design/env_atria. php.

Jalil, N. A. A., Din, N. C., & Daud, N. I. M. K. (2014). A literature analysis on acoustical environment in green building design strategies. In *Applied Mechanics and Materials* (Vol. 471, pp. 138-142). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/AMM.471.138.

Jalil, N. A. A., Din, N. C., & Keumala, N. (2016). Assessment on acoustical performance of green office buildings in Malaysia. *Indoor and Built Environment, 25*(4), 589-602. https://doi.org/10.1177/1420326X14559855

Jalil, N. A. A., Din, N. C., Keumala, N., & Razak, A. S. (2019). Effect of model simplification through manual reduction in number of surfaces on room acoustics simulation. *Journal of Design and Built Environment*, *19*(3), 31-41. https://doi.org/10.22452/jdbe.vol19no3.4.

Kim, K. S. (1987). *Development of daylighting prediction algorithms for atrium design*. Texas A&M University.

Lavasani, M., Sluyts, Y., Urbán, D., & Rychtarikova, M. (2021, October 25-27). Acoustic comfort evaluation based on architectural aspects in atria. In *Proceedings of Euronoise 2021* (pp. 1-9). Madera, Portugal. http://ftp.sea-acustica.es/fileadmin/Madeira21/ID269.pdf

Lee, J. H. (2019). Identifying spatial meanings of atria in built environment and how they work. *Journal of Asian Architecture and Building Engineering, 18*(3), 247-261. https://doi.org/10.1080/13467581.2019.1627216

Long, M. (2014). *Architectural Acoustics*. Elsevier.

Maekawa, Z., Rindel, J., & Lord, P. (2010). *Environmental and architectural acoustics*. CRC Press. https://doi.org/10.4324/9780203931356

Moosavi, L., Mahyuddin, N., & Ghafar, N. A. (2015). Atrium cooling performance in a low energy office building in the Tropics, a field study. *Building and Environment*, *94*, 384-394. https://doi.org/10.1016/j.buildenv.2015.06.020

Moosavi, L., Mahyuddin, N., Ghafar, N. A., & Ismail, M. A. (2014). Thermal performance of atria: An overview of natural ventilation effective designs. *Renewable and Sustainable Energy Reviews*, *34*, 654-670. https://doi.org/10.1016/j.rser.2014.02.035

Navvab, M. (1990). Outdoors indoors. *Daylighting within atrium spaces, LD+ A, 20*(5), 6-31.

Nowicka, E. (2020). The acoustical assessment of the commercial spaces and buildings. *Applied Acoustics, 169*, Article 107491. https://doi.org/10.1016/j.apacoust.2020.107491

Passe, U., & Battaglia, F. (2015). *Designing Spaces for Natural Ventilation: An architect's guide*. Routledge.

Pitts, A. (2013). Thermal comfort in transition spaces. *Buildings*, *3*(1), 122-142. https://doi.org/10.3390/buildings3010122

Quek, C. K. (1989). *Design of atrium. Building in the warm humid tropics* (Unpublished M. Phil. dissertation). Darwin College Cambridge, France.

Rychtarikova, M., Urban, D., Kassakova, M., Maywald, C., & Glorieux, C. (2017b). Perception of acoustic comfort in large halls covered by transparent structural skins. In *Proceedings of Meetings on Acoustics 173EAA* (Vol. 30, No. 1, p. 015005). Acoustical Society of America.

Rychtarikova, M., Urban, D., Maywald, C., Zelem, L., & Kassakova, M. (2017a). Advantages of ETFE in terms of acoustic comfort in atria and large halls. In *Proceedings of Advanced Building Skins* (pp. 646-654). Advanced Building Skins GmbH.

Saxon, R. (1983). *Atrium buildings: Development and design*. Architectural Press.

Šimek, R., & Chmelík, V. (2021, October 25-27). Investigation of acoustical phenomenon in atria covered by structural glass roof. In *Proceedings of Euronoise 2021* (pp. 1-6). Madera, Portugal. http://ftp.sea-acustica.es/fileadmin/Madeira21/ID232.pdf

Tio, S. Z. (2016). *Evalutation of acoustical performance for atrium design by using computer simulation model* (Master dissertation). Universiti Malaya, Malaysia.

Urban, D., Zrneková, J., Zat'ko, P., Maywald, C., & Rychtáriková, M. (2016). Acoustic comfort in atria covered by novel structural skins. *Procedia Engineering*, *155*, 361-368.

Valtonen, M. (2014). *Acoustic design of a public space using perforated panel resonators* (Master Thesis). Aalto University, Finland.

Wood, A., & Salib, R. (2013). *Guide to natural ventilation in high rise office buildings.* Routledge.