The Negative Impact of Solar Reflections Caused by Reflective Buildings' Facades: Case Study of the Nasher Museum in Texas

Sahar Abdelwahab[1]**, Mariam Elhussainy**[1]**, Rania Labib**[2,3]

[1] Faculty of Engineering, Architecture department, Al Azhar University, Cairo, Egypt
[2] Department of Architecture, Texas A&M University, College Station, Texas, USA
[3] Department of Architecture, Prairie View A&M University, Prairie View, Texas, USA

Abstract. Large reflective facades in buildings can cause severe visual discomfort due to the reflection of sunlight falling on buildings' surfaces. These intense reflections can cause a intolerable glare and contribute to overheating the interior of surrounding buildings.
An example of reflective building materials causing glare is experienced in Dallas, Texas, where a residential tower, which was fitted with a fully glazed façade, has caused intense specular reflections into the Nasher sculpture museum. The problem has caused glare and overheating of the interior spaces in the museum, thus leading to the damage and deterioration of the sculptures on display.

In order to examine the negative impact of the Museum Tower's reflective façade on the visual comfort inside the Nasher museum, glare simulations are carried out at different times of the year. Additionally, to examine a possible solution to the glare problem, a proposed solution of using a less reflective material on the tower's facade is examined via glare simulations. The initial set of simulations confirmed that tower skin contributed to blinding glare particularly at 12:00 and 15:00 on the summer and winter solstice, and the spring equinox. Use of less reflective material on the tower façade concluded that the tower façade still contributed to glare and that is due to its convex geometry.

1- Introduction

Reflective façade is a popular architectural feature that is widely used in buildings, especially tall buildings in condensed urban settlements. In the last few decades, architects have been inspired by the contemporary architectural style, which utilizes full glazed building façades despite the noticeable differences in thermal requirements across diverse climatic regions. The increased preferences to use glazed façades in buildings contributes to severe visual discomfort due to the excessive sunlight internally received and, equally important, external reflection of sunlight falling on buildings' surfaces. The intense external sunlight reflections on buildings can cause an intolerable glare, which can impair the vision of surrounding buildings' occupants thus hindering them from performing their daily tasks. Figure 1 shows various examples of sunlight bounced off glazed façades causing blinding glare.

A 2014 research study that investigated the probability of disability glare in a residential building caused by sun reflections off a nearby tall building façade that is fitted with photovoltaic (PV) panels,

confirmed that solar reflections are causing severe glare, that is known as disabling glare for 30 minutes up to 72 days a year and for over an hour for up to 34 days a year [1].

In order to mitigate the problem of glare, building occupants tend to abandon the use of daylighting by permanently closing their blinds and depend on the use of artificial lighting, therefore, increasing the lighting loads which leads to a significant increase in energy consumption that is estimated to account for 25 to 40% of commercial buildings' total energy consumption [2].

Figure 1. Examples of intense solar reflections in urban settings causing severe visual discomfort[1]

Solar reflections caused by high reflective façade materials, such as dark solar glazing, not only cause glare but can also contribute to other undesirable issues; such as the overheating of the areas in the vicinity of the building and negatively impacting the thermal comfort of both outdoors pedestrians and the indoor occupants of surrounding buildings. In turn, this leads to a significant increase in building cooling capacity. This is necessary to overcome the problem of overheated indoor spaces caused by intense sunlight reflections [3–5].

An example of reflective building materials causing disabling glare is an installation of a PV array at a Massachusetts airport. The installation of this array has caused specular solar reflections, leading to intolerable glare, resulting in difficulties viewing computer screens inside the airport control tower [6].

Similarly, when a 42-story high-rise building in Dallas, Texas (the Museum Tower) was fitted with a fully glazed façade, this led to the intense solar reflections that caused visual and thermal discomfort to the Nasher sculpture museum across the street. The problem has caused disabling glare and overheating inside the museum that results in damaging the sculptures in the display. In order to mitigate these problems, museum officials spent over one million, yet, no viable solution has yet been found [4,7,8].

2-The Nasher Sculpture Museum Description

The museum building is nearly 5,000 square meters. It is made up of five identical and parallel rectangular pavilions, whose volumes are delineated by walls that are covered with Italian travertine, which is a type of stone that is used in wall finishing. The stone has been polished inside the pavilions,

giving the walls some reflectivity features. The façades of the museum at each end are made up of large transparent windows.

The museum was constructed on two levels. The three central arcades on the ground floor house the sculptures and paintings that are most sensitive to atmospheric agents, while the two arcades (one on each side of the building) contain the cafeteria, the shop, and the offices. On the lower level, there's a small gallery for light-sensitive works, such as prints and drawings; as well as preservation laboratories, research and teaching areas; and even an auditorium that overlooks a portion of the garden that descends toward the hall in a terraced fashion, thus creating an outdoor theatre.

The ceiling of the museum is comprised of five glass vaults nestled between the seven travertine walls, which are extended above the pavilions. A shielding system, made up of aluminum panels, is positioned above the glass ceiling. These three-dimensional elements, whose design has been patented, are repeated 223,020 times and only allow for the passage of direct light from the north. The Nasher museum is across the street from the Museum Tower. The façade causing glare is facing the south-west direction. (see Figure 2)
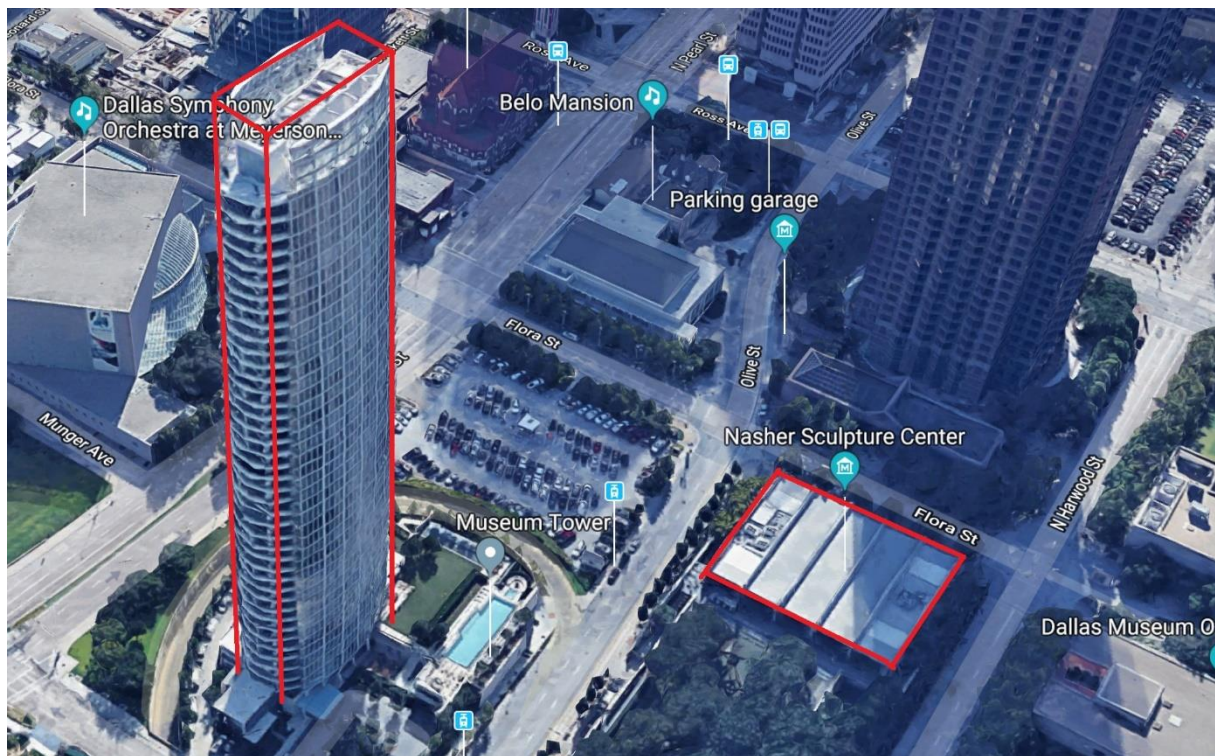

Figure 2. Nasher Sculpture museum and the Museum Tower highlighted in red. The tower's façade faces the south-west direction.

To be able to understand how and when the sun reflections that are caused by the museum tower façade impact the visual and thermal conditions inside the Nasher sculpture museum, glare simulations were carried out during different times of the year. To find out if replacing tower façade with a less reflective material can offer a solution to the problem of the intense specular reflections, another set of glare simulations were preformed using a less reflective material.

3-Methodology

3.1. Simulation Tools and Analysis Type

Point-in-time glare analyses were carried out under Texas climate, US. The analyses were conducted on the 21st of March, June, September, and December at 9 am, 12 pm, and 3 pm. The simulations were performed using the graphical algorithm editor Grasshopper, linked to the daylight simulation engine RADIANCE through the DIVA V.4 tool [9]. DIVA calculates glare using RGB-format picture that contains the full luminance distribution of a half hemisphere in the viewing direction using a fish-eye angular lens [10–12]. Each pixel with a luminance value four times higher than the average task-zone luminance is treated as a glare source [13].

Daylight Glare Probability DGP [13] was used as an indicator for the received glare. The evaluation of DGP was based on the DGP rating proposed by Wienold [14]: imperceptible glare= DGP≤0.35; perceptible glare= 0.35<DGP≤0.40; disturbing glare= 0.40<DGP≤0.45; intolerable glare= DGP>0.45. DGP was measured from a perspective of two subjects: visitor 1, and visitor 2 (shown in Figure 3) standing in front of a sculpture (0.6x0.6m cabinet) at a distance of 1.5m. The Museum Tower is in the field of view of visitor 1, while visitor 2 faces the opposite direction. (see Figure 3).
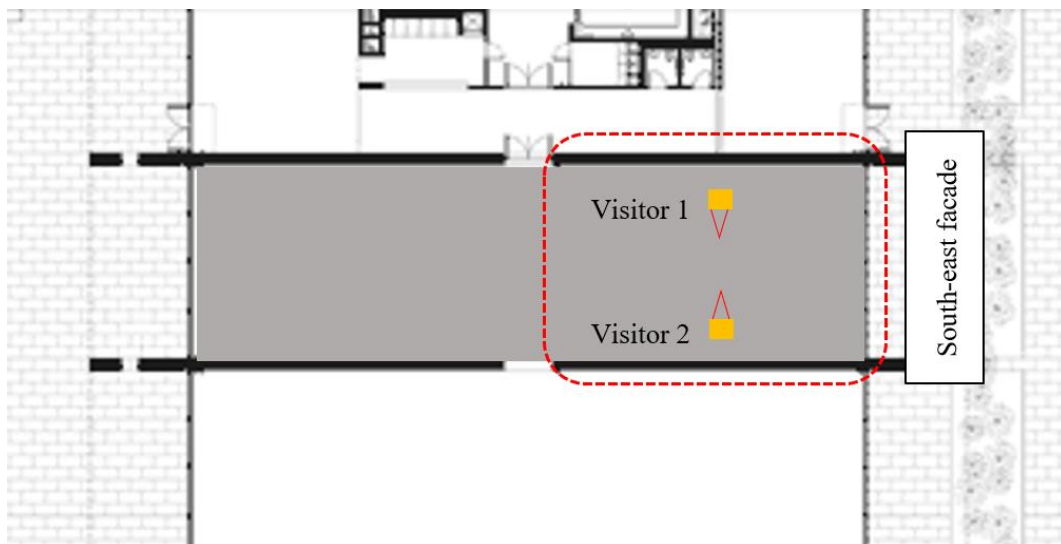

Figure 3. The simulated pavilion and visitor locations.

The two view positions were chosen close to the south-east façade, so the probability of severe glare occurrence from the ceiling and the facade can be clearly tackled (preliminary analysis showed that this particular façade receives excessive direct light compared to the north-west façade).

3.2. Model Parameters

A model of the five-pavilion museum, in addition to the museum tower, was modeled. The pavilion, shown in Figure 3, was tested for glare performance as one of the three middle pavilions that house the sculpture and, more importantly, it is the closest pavilion to the museum tower where severe light reflection from tower's skin is more likely to occur. Figure 4 shows detailed Rhino scenes for the model built for the Museum and the museum tower.

Material characteristics of the museum and the museum tower were mainly based on the described materials in the museum description section, solar control glazing with low-e coating was used for museum facades, while the interior walls finished with Italian travertine were assumed with a 70% reflectance. The ceiling was modeled with aluminum roof structure (so as façade mullions) and shielding system made of aluminum panels on top of clear glazing. Floor tiles were assumed with 40% reflectance. The external ground was modeled with 20% reflectance. The analysis considered no external abstractions except for the museum tower.
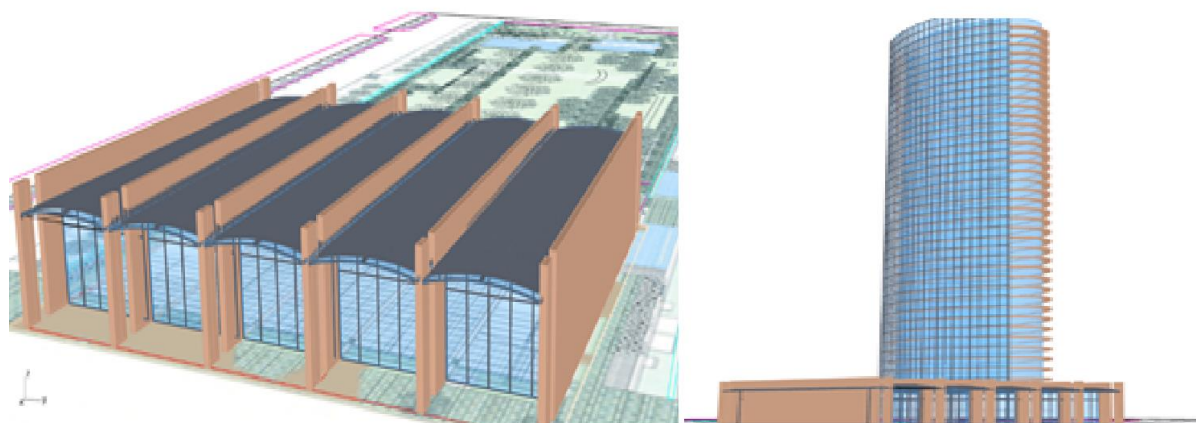

Figure 4. Rhino scene for the modeled Nasher Museum and the museum tower.

3.3 Simulation settings

Compliant with the findings from work by Abdelwahab, S. et al. [15], it suggested using ambient bounces of -ab2 for glare analysis in order to improve simulation accuracy. Simulation settings are illustrated in detail in Table 1. On the other hand, Perez sky model [16] was used for the simulation, as it showed to give the best agreement with interior measured values, particularly when performing discomfort glare analysis [17].

Table 1 Radiance settings used for discomfort glare simulations.

RADIANCE parameters	DGP simulation parameters				
	Ambient bounce -ab	Ambient division -ad	Ambient sampling -as	Ambient resolution -ar	Ambient accuracy -aa
	2	2024	1024	256	0.2

4- Results (Point-in-time glare analysis)

Point-in-time DGP analysis was carried out through DIVA for each time of day and year from the perspective of visitor 1 and 2, separately. DIVA automatically calculates DGP and generates a luminance map for the fish-eye lens scene. It also produces a JPG image that highlights sources of glare within the scene.

The luminance maps generated from the perspective of visitor 1 and 2 showed a high potential of glare occurrence due to excessive light received from the window and, obviously, the ceiling through the shielding system. Table 2 shows a summary of glare analysis conducted at different times of day and year. DGP rating was consistently intolerable (DGP >0.45) particularly at 12 pm and 3 pm on the 21st

of March, June, and September. The probability of glare occurrence was low on the 21st of December as DGP was imperceptible (DGP <0.35).

Table 2. Point-in-time glare analysis: DGP received from the perspective of visitor 1 (cam1) and 2 (cam2) at different times of day and year.

	Time of year	Time of day	DGP		Time of year	Time of day	DGP
Camera 1	21st December	9:00 AM	0.21	**Camera 2**	21st December	9:00 AM	0.26
		12:00 PM	0.32			12:00 PM	0.32
		3:00 PM	0.28			3:00 PM	0.28
	21st March	9:00 AM	0.45		21st March	9:00 AM	0.32
		12:00 PM	0.88			12:00 PM	0.43
		3:00 PM	0.71			3:00 PM	0.38
	21st June	9:00 AM	0.34		21st June	9:00 AM	0.62
		12:00 PM	0.51			12:00 PM	0.68
		3:00 PM	0.55			3:00 PM	1
	21st September	9:00 AM	0.60		21st September	9:00 AM	0.33
		12:00 PM	0.47			12:00 PM	1
		3:00 PM	0.37			3:00 PM	0.33

The examples of luminance maps in Figure 5 show that the museum tower does not provide any shading for the museum's roof. Rather, high reflective envelope reflects excessive sunlight, except for some parts in the tower's south-east-elevation, where low luminance levels from the non-reflective slabs were detected. However, it should be noted that, in general, both light sources (i.e. sun, sky) and the reflected light from the tower may contribute in receiving high DGP at 12 pm because, as expected, the sun has a high angle and therefore sunlight is excessively received through the glazed roof. On the other hand, the tower skin was detected as a potential source of glare (see circular red marks in 4), particularly with low sun angle at 3 pm.

These results, however, were expected since the literature and the observations have a referred glare issue inside the museum to the reflected light from the museum tower's skin. Therefore, it was suggested examining the potential of glare when using less reflective material. The simulations hence were repeated, assuming low-e glazing with Tvis 65% assigned to the Museum Tower's façade, in order to examine its impact on the reflected amount of light and the likely effect on the received glare (from the perspective of visitor 1 who looks at a sculpture facing tower direction). Table 3 shows a comparison between DGP received with the current high reflective tower skin and when using less reflective material
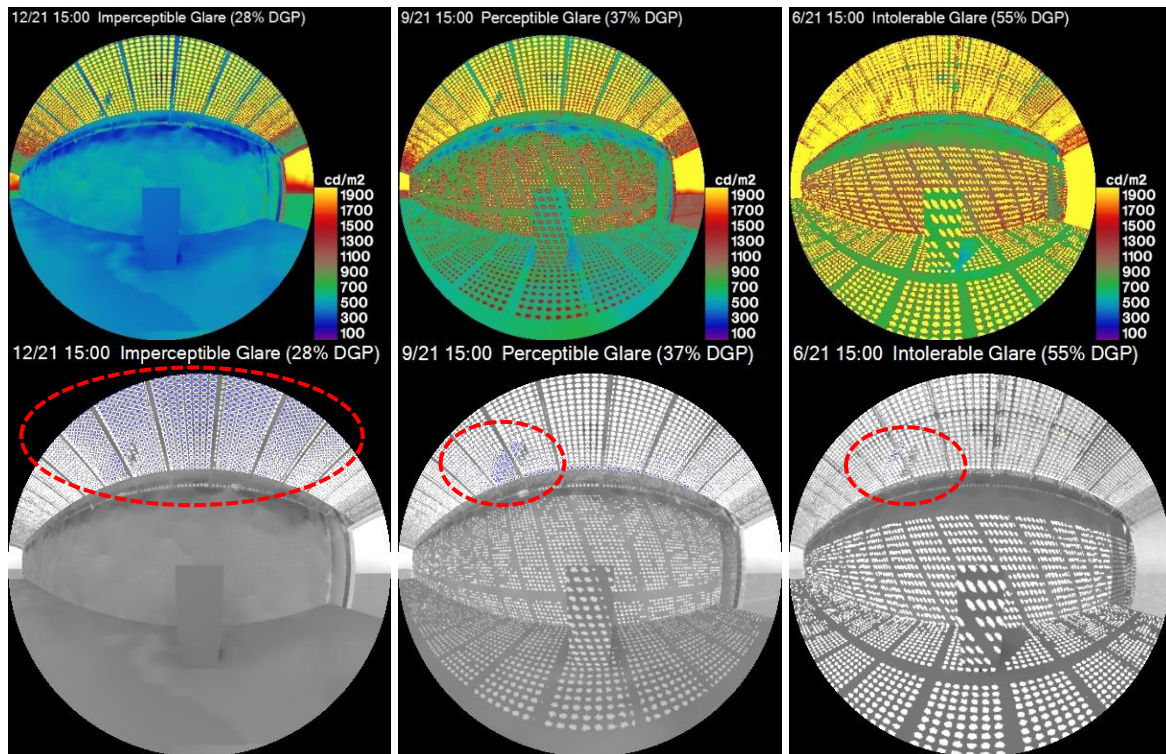
Figure 5 Example for luminance maps generated from the perspective of visitor 1 (facing tower's direction) on the top, and the potential sources of glare detected (blue patches) on the bottom.

.

Table 3 A comparison between DGP received from the perspective of visitor 1 with the current high reflective tower skin and when using less reflective material

	Time of year	Time of day	DGP (High reflective glazing)	DGP (Glazing with low-e coating, T_{vis}= 65%)
Camera 1	21st December	9:00 AM	0.21	0.21
		12:00 PM	0.32	0.32
		3:00 PM	0.28	0.28
	21st March	9:00 AM	0.45	0.43
		12:00 PM	0.88	0.50
		3:00 PM	0.71	0.71
	21st June	9:00 AM	0.34	0.34
		12:00 PM	0.50	0.50
		3:00 PM	0.55	0.52
	21st September	9:00 AM	0.60	0.30
		12:00 PM	0.47	0.47
		3:00 PM	0.37	0.36

As seen from the results, DGP values almost remained the same for most of the comparisons. In some cases, however, the estimated DGP slightly decreased when using less-reflective material for the tower's skin, although, this didn't lead to further improvement in the level of DGP received (i.e. DGP rating).

The examples in Figure 6 show lower luminance levels detected on the tower when using less-reflective material compared to the current high reflective glazing (see magenta marks). Nevertheless, the reduction in DGP values resulted only in very few cases and didn't prevent glare. This essentially means that replacing the tower's skin, using less reflective material, may not solve the Museum Tower's negative impacts experienced inside the museum.

In fact, these results speculate that glare probability inside the museum increases, not only because of the material reflection, but it could be the elliptical geometry of the museum tower with multi surfaces that reflect the light. This brings some examples that have similar issues because of its convex outside geometry (e.g. Fenchurch tower in London). Even with low-reflective material, the estimated DGP was generally high. Additionally, in some cases, the analysis showed that not only the tower skin was detected as a potential source of glare, but also direct light from the sun and sky received from the ceiling through the shielding system contributed to glare occurrence (see Figure **5** 6 left-bottom).
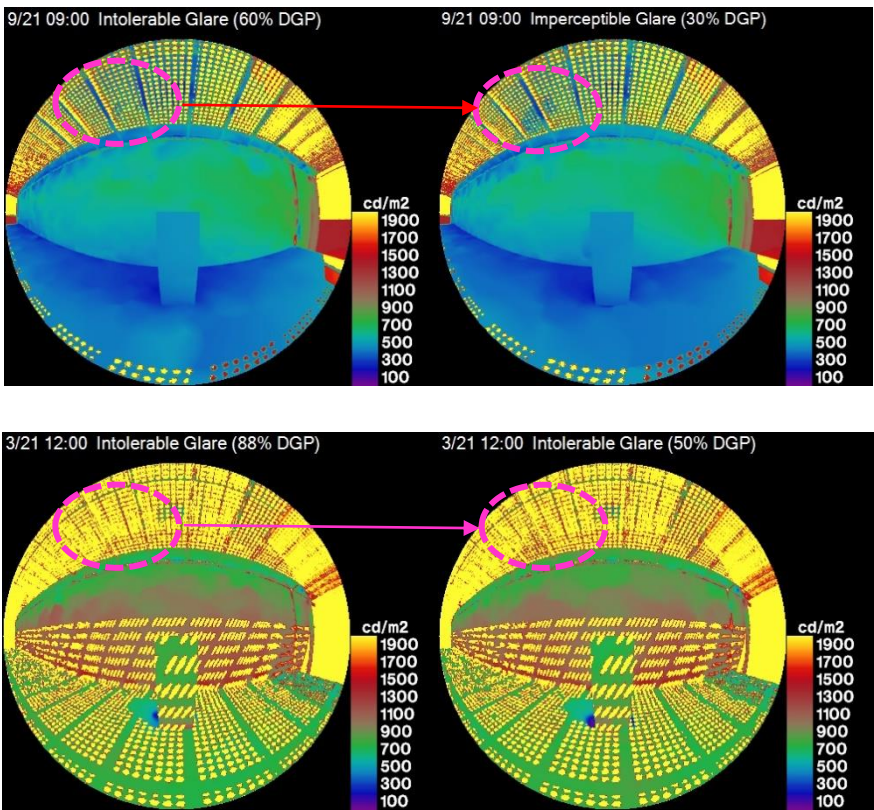

Figure 6 luminance maps generated from the perspective of visitor 1 with the current materials (left) and less reflective glazing assigned on the tower's skin (right)

Since replacing tower's skin didn't lead in further improvements in limiting glare, it is suggested that the solution hence could be through using low Tvis glazing in the museum ceiling, or through adding shading elements on the museum tower facade. Research by Singh et al. [18] showed that glazing with a high visible transmittance can result in higher glare. Other studies in the literature showed that some façade parameters (e.g., shading devices, window size, etc.) have an impact on limiting received glare[19,20]. This can be thoroughly examined in future research.

5- Limitations

Due to the computational limitations associated with modeling the light through complex geometries, the shielding system was simplified, and the number of openings was reduced, keeping the same opening ratio, in order to enable RADIANCE to perform the simulations in a reasonable timeframe.

6- Conclusion

Large glazed facades in urban settings contribute to undesirable issues, such as glare and overheating. To examine the glare problem inside the Nasher museum, which is caused by the Museum Tower's reflective façade, a computer simulation-based approach was carried out. The simulation-based approach examined glare from the point-of-view of two museum visitors; The Museum Tower is in the field of view of visitor 1, while visitor 2 faces the opposite direction. Glare simulations showed a high potential of glare occurrence due to excessive light received from the window, and the perforated ceiling in both views, additionally, the HDR images confirmed that the tower reflective skin is recognized as a potential glare source, especially when the sun is at a low angle at 15:00 in the summer and winter solstice, and the spring equinox. In an effort to examine a solution to the glare problem, a less reflective material was used to carry out another set of glare simulations. Use of less reflective material on the tower façade concluded that the tower façade still contributes to glare and that is due to its convex geometry.

References

[1]   W.J. Brotas Luisa, Solar reflected glare affecting visual performance, in: Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World Cumberland Lodge, 2014: pp. 10–13.

[2]   J.D. Kelso, Buildings Energy Databook, Department of Energy, 2011.

[3]   M. Schiler, E. Valmont, Microclimatic Impact: Glare around the Walt Disney Concert Hall, in: Proceedings of the International Solar Energy Society Conference, 2005: pp. 6–12.

[4]   Council on Tall Buildings and Urban Habitat, "Oculi Solution" to Museum Tower Glare Rejected, (2012). http://www.ctbuh.org/News/GlobalTallNews/tabid/4810/Article/165/language/en-US/view.aspx (accessed December 10, 2017).

[5]   T. Tsoutsos, N. Frantzeskaki, V. Gekas, Environmental Impacts from the Solar Energy Technologies, Energy Policy. 33 (2005) 289–296. doi:10.1016/S0301-4215(03)00241-6.

[6]   J.A. Jakubiec, C.F. Reinhart, Assessing Disability Glare Potential Due to Reflections from New Constructions : A Case Study Analysis and Recommendations for the Future, Transportation Research Record. (2014) 1–12. doi:10.3141/2449-13.

[7]   M. Granberry, S. Thompson, G. Jacobson, Museum Tower hires technical firm to help solve glare dispute | News | Dallas News, (2014). https://www.dallasnews.com/news/news/2014/04/02/museum-tower-hires-technical-firm-to-help-solve-glare-dispute (accessed December 10, 2017).

[8]   R. Stott, Search Ends for Solution to Museum Tower's Glare Problems at Nasher Sculpture Center, (2015). https://www.archdaily.com/773066/search-ends-for-solution-to-museum-towers-glare-problems-at-nasher-sculpture-center (accessed December 10, 2017).

[9]   J.A. Jakubiec, C.F. Reinhart, DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, DAYSIM and EnergyPlus, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association. (2011) 2202–2209.

[10] M. Hirning, G. Isoardi, S. Coyne, I. Cowling, Applying the use of high dynamic range imaging pipelines to discomfort glare research, in: Proceedings of CIE, 2010: p. 767e75.

[11] J.A. Jakubiec, The use of visual comfort metrics in the design of daylit spaces, (2014).

[12] I. Konstantzos, A. Tzempelikos, Daylight Glare Probability Measurements And Correlation With Indoor Illuminances In A Full-Scale Office With Dynamic Shading Controls, (2014).

[13] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy and Buildings. 38 (2006) 743–757.

[14] J. Wienold, Dynamic daylight glare evaluation, in: Proceedings of Building Simulation, 2009.

[15] S. Abdelwahab, M. Kent, S. Altomonte, Sensitivity Analysis for the Daylight Simulation of Complex Façades, in: 2017 Advanced Building Facade, Bern, Switzerland, 2017.

[16] R. Perez, R. Seals, J. Michalsky, All-weather model for sky luminance distribution—preliminary configuration and validation, Solar Energy. 50 (1993) 235–245.

[17] N.L. Jones, C.F. Reinhart, Experimental validation of ray tracing as a means of image-based visual discomfort prediction, Building and Environment. 113 (2017) 131–150.

[18] R. Singh, I.J. Lazarus, V. Kishore, Uncertainty and sensitivity analyses of energy and visual performances of office building with external venetian blind shading in hot-dry climate, Applied Energy. 184 (2016) 155–170.

[19] J. Wienold, F. Frontini, S. Herkel, S. Mende, Climate based simulation of different shading device systems for comfort and energy demand, in: 12th Conference of International Building Performance Simulation Association, 2011: pp. 14–16.

[20] L. Brotas, D. Rusovan, Parametric daylight envelope, PLEA, in: 2013.