SOLAR AND DAYLIGHT PERFORMANCE OF A BUILDING WITH GLASS ROOF AND MULTILATERAL GLASS SHADING SYSTEM

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ABSTRACT

The skylight geometry and its glazing affect thermal comfort, occupant visual filed and energy consumption of the building. Multilateral glass shading systems are designed to protect against direct sun and transmit and reflect the sky component to the space below; however, the performance of these unique systems are not widely tested. To contribute to the design decision process, this paper aims to examine their performance and specifically, their impact on the spaces due to the incoming solar and visible energy. The main variable is the tilted angle of glass blades, which generates complex solar incident angles and multi-reflection, multi-transmission through various layers of glass. To solve this complex problem, solar geometry calculations and computer simulation have been utilized. The results show that the horizontal glass blade (low tilted angle) is the most effective choice. The heat is easily reflected out to the environment or filtered by the layers of glass blades; thus, the cooling load and energy are minimized.

1. INTRODUCTION

Unlike typical opaque shading device, the multilateral glass shading system uses glass as a shading material. Recently, the application of this system was proposed as part of a building roof system designed by Renzo Piano. This building will be constructed as a new addition to the Law School building at the University of Michigan [1].The thermal and lighting performance of this system is evaluated as part of the study for this paper. There are three parts to this analysis:

- Energy performance and computer simulation.
- Solar geometry and radiation transmittance.
- Visualization of the interior space.

The solar geometry or hand calculations are used when the current computer software could not handle the complexity of the desired input and the environmental factors. This paper is focusing on the various aspect of design variables used as part of the decision process and the final selection of the blade angles for these multilateral glass-shading systems.

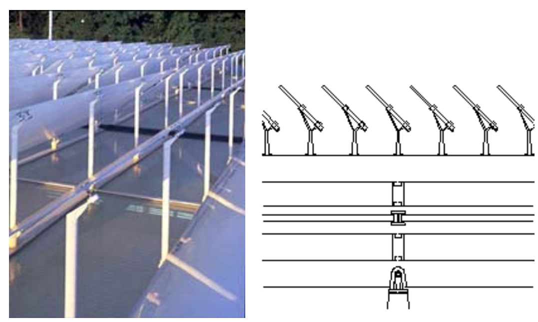

Fig. 1: The design of multilateral glass shading system

2. ENERGY ANALYSIS BY USING COMPUTER SIMULATION

The eQUEST energy simulation software based on original DOE-2 algorithm is used to obtain accurate building energy consumption [2]. This program allows the users to simulate the building performance and predict energy consumption using hourly local weather data. The impact of the multilateral glass shading system on the energy performance of the building was simulated. Although in some cases, the complexity of geometry is beyond the capability of the software, results show appropriate input on glass properties (e.g., solar, visible transmittance and reflectance characteristics) of the glazing system for the skylights reduces the energy consumption.

2.1 Effective Aperture (EA)

The effective aperture is a common index used to estimate the lighting performance of any opening. The equation (1) shows the effective aperture (EA.) as a relationship between Visual Transmission (VT), skylight-to-floor ratio (SFR), and Well Index (WI). The equation allows users to create a constant EA while changing the glass VT or surface geometry and its reflectance as part of the well index.

$$EA = VT \times SFR \times WI \qquad (1)$$

As part of the parametric studies using eQUEST, EAs ranging from 0 to 0.72 (SFR from 0.0 to 0.9) were used. The SFR is multiplied by VT for a clear glass with VT of 0.81 and WI of 1. This covers a broad range of no glass to almost the entire roof covered by glass. Fig. 2 shows the variation of SFR and the geometry of the skylights simulated using the eQUEST program modeling capabilities.

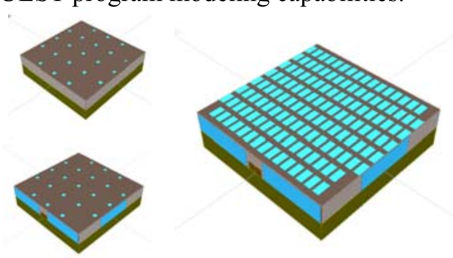

Fig. 2: Skylight modeling output by eQUEST Program

2.2 Computer Energy Consumption Analysis

The space within this newly design building that is covered by the glass roof is a rectangular shape with an area of 13000 sq-ft and a ceiling height of 14 feet. As part of the energy simulation modeling requirements, the building geometry, HVAC system, and all the opaque materials were input as constant variables. The building type was selected as an office building with an atrium and sun space being operated from 7AM to 11PM on a typical institutional building schedule.

The various report output options by eQUEST program provide information on heating, cooling as well as lighting and electrical energy usage of the building. The variations of the EA as it relates to the skylight size and glazing characteristics provides a closer view of the electrical energy use of the building. The results show the skylight with an EA of 0.08 will consume annually 23 kWh/sq. ft., and the maximum size of skylight with the EA of 0.72 will use 33.5 kWh/sq. ft. Fig. 3 shows the energy consumption as a function of EA as it relates to selected skylight options. The HVAC load and building energy use increase proportional to the EA.

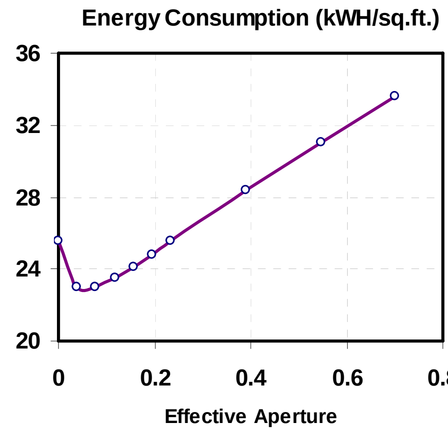

Fig. 3 The energy consumption as a function of EA

3. GEOMETRICAL FACTOR AND SOLAR RADIATION IMPACT

Although energy consumption or EA is a good index to examine the selection of skylight size and its design, the complexity of this type of shading system in not accurately modeled or systematically calculated within this energy program. The lighting program "LightScape" is used to demonstrate the complexity of the multi-transmission, reflection and absorption due to the variations in solar geometry, incident angle and the glass blade angles within this roof shading system. Fig. 4 shows the variation of the illuminance/irradiance and the inter-reflection within the blade and the shade and shadows falling on the roof due other building obstructions.

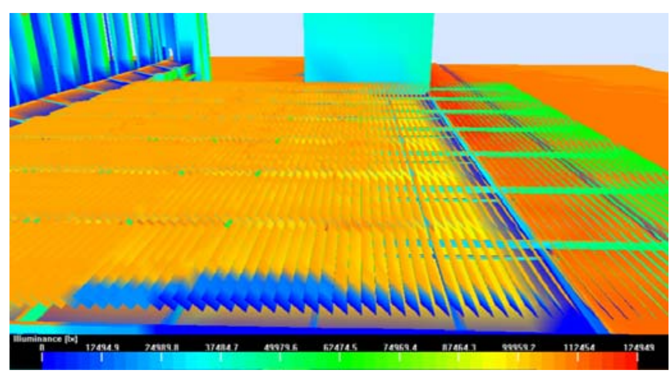

Fig. 4: LightScape simulation of the roof shading system.

The major variable that contributes to this complexity is the tilted blade angle. The variation of blade angle from horizontal to vertical is the main variable in these calculations. The number of the blades per area has to stay constant in all cases by using 45-degrees as a base case. As a result, when the glass is laid horizontally, the amount of glass overlapping has to be determined. The five variations of the tilt of blade angles are shown in Fig. 5.

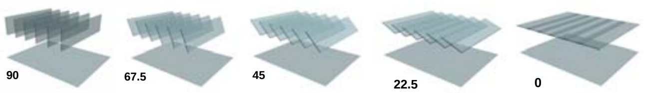

Fig. 5: The roof variations of the tilt of blade angles.

To study the effects of these components including multi-transmission, multi-reflection and solar incident angle variation in Solar Heat Gain Coefficient (SHGC) is calculated [4.] The SHGC allows one to examine the impact of solar geometry and its dynamic through out the time of day. Many attempts have been made to predict the SHGC of multiple glazing systems. [5] However, the research on tilted multiple blades is still limited. The current model that precisely predicts SHGC is based on tilted translucent shading devices (blinds) [6] Thus, this new approach is introduced. This evaluation method estimates the SHGC and the roof shading system performance, only for the direct irradiation component. The diffuse component is neglected.

3.1 Multi-Transmission

The multi-transmission effect occurs by the overlapping of the glass layers and depends on the direct solar incident angle. In Fig. 6, the 22.5-degree tilted glass generates the different multi-transmission effects. The variation of blade angle and the solar angle produces the different overlapping patterns. These patterns can affect the SHGC of overall glass layers. The calculation of SHGC is shown in equation (2).

$$SHGC = \left(\frac{\tau_i \tau_o}{1-\rho_i \rho_o}\right) + N_i \alpha_i + N_o \alpha_o \qquad (2)$$

This equation is base on the concept of insulated glass made of two parallel glass layers [7]. This equation includes all the effects comprising multi-transmission ($\tau_o \tau_i$), multi-reflection ($1-\rho_o \rho_i$), and absorption ($N_i\alpha_i+N_o\alpha_o$.). However, the concept of multi-reflection is based on the infinite bouncing of solar ray between the parallel glass layers. Also, the absorption of the glass fully impacts the heat transfers when the glass is attached to the interior space. The anatomy of the multilateral shading system performs differently as compared to the double glazing system. The former is shading devices and the latter is building envelop. Therefore, the effect of multi-refection effect is considered separately, while the absorption of glass is assumed to be very small. In this paper, the $SHGC_t$ is based only on the multi-transmission effect as shown in equation (3).

$$SHGC_t = \tau_1 \tau_2 ......\tau_n \qquad (3)$$

To calculate the SHGC for the overlapping areas of the blade angles, the sun profile angles from 20 to 60 degrees of altitude for this location are estimated. In Fig. 7, the effect of multi-transmission produces the different $SHGC_t$ depending on the pattern of each profile angle. The variation of $SHGC_t$ tends to increase when the tilted angle increase, while the flat glass blade shows almost no variation when the profile angle changes. In general, every tilted angle shows the tendency of reducing $SHGC_t$ if the profile angle decreases.

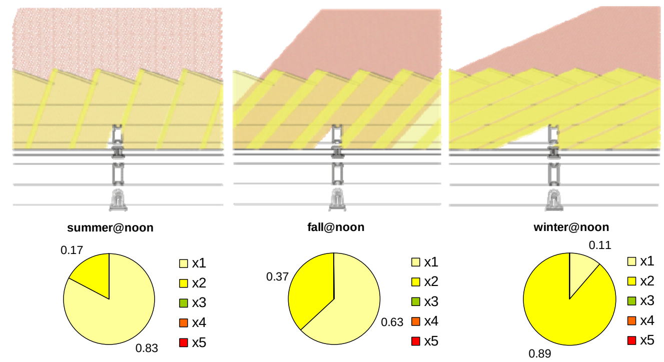

Fig. 6: the multi-transmission effect produced by overlapping layer of glass blade.

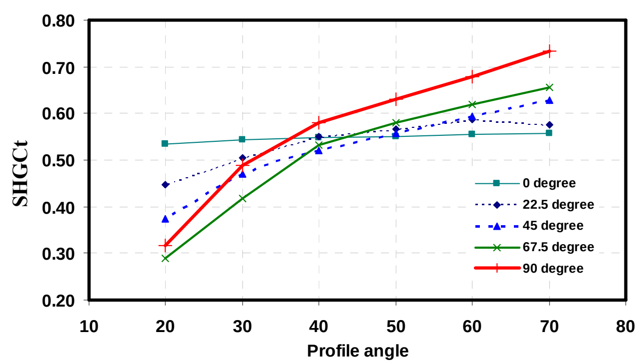

Fig. 7: The $SHGC_t$ depending on profile angle.

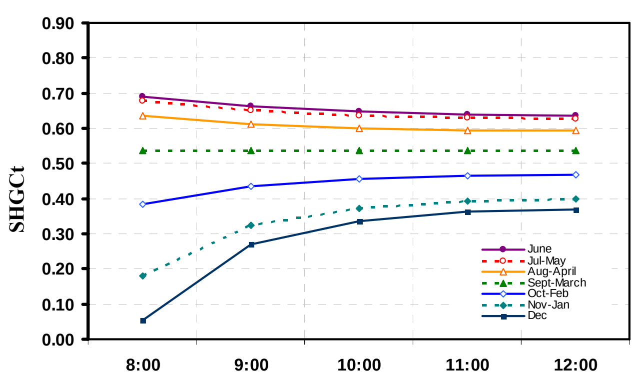

Fig. 8: the $SHGC_t$ depending on time of 45-degree blade.

The results on blade angle and solar geometry variations are converted to hourly data for various months of the year. Fig.8 shows the $SHGC_t$ of a 45 degree angle. Each line represents $SHGC_t$ of each month. In summer, $SHGC_t$ is higher and uniform, while, in winter, $SHGC_t$ is on the average lower and fluctuates. Based on only the multi-transmission effect, the glass shading device does not block the sun in summer, while protecting only the sun in winter which may require passive heating.

3.2 Effect of Solar Incident angle

Obviously, the solar incident angle varies as a function of time. The higher incident angle is, the lower will be the transmission through the glass, known as Rivero's function [7]. These dynamic variations make the estimation of cooling load and energy more difficult. The Shading Coefficient (SC) is used as a simple index to calculate the ratio of SHGC of the investigated glass to the SHGC of clear glass for the same incident angle; this (SC) seems to be constant. However, SC seems to be close to SHGC when the incident angle is low, but will be less representative of SHGC when the incident angle is high. [8] To estimate the performance of multilateral glass shading systems properly, the glass transmission should be determined on an hourly basis, and instead of using SC; the angular SHGC should be applied.

To estimate the angular SHGC, the hourly solar incident angle is required. Equation (4) shows that, to calculated solar incident angel (S_normal), the surface azimuth (azm), profile angle, the tilted angle (α= profile-tilted angle.) are required.

$$\cos(S\_normal) = \cos(\alpha) \times \cos(\tan^{-1}(\tan(azm) \times \cos(profile))) \quad (4)$$

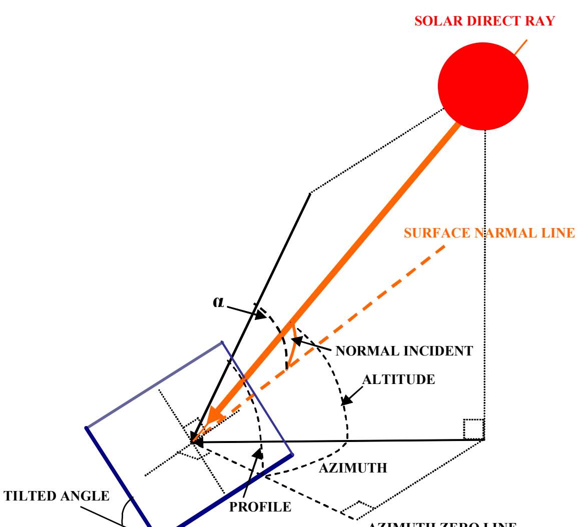

Fig. 9: The solar incident angle calculation diagram.

Fig. 10 shows the hourly incident angle of 45-dergrees. This overall pattern shows that the incident angle will close to zero at noon time, and the variation is high in summer but low in winter. The reverse of this effect is the glass transmission in Fig. 11. The rough estimate of solar incident angle is applied to compute the fraction of glass transmission based on clear glass pattern [8]. Considering only geometrical factor, the solar incident angle of clear glass is applied.

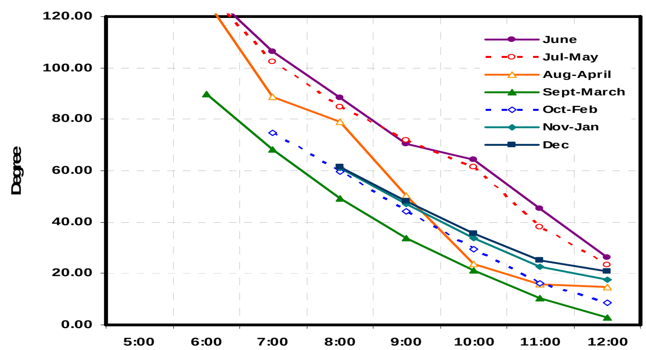

Fig. 10: The hourly solar incident angle of 45-degree blade.

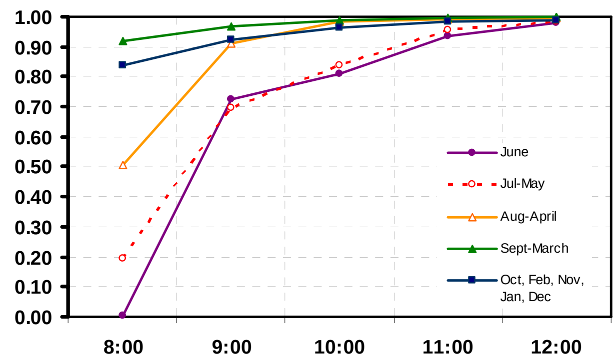

Fig. 11: the hourly fraction of glass transmission of 45-degree blade due to Solar Incident Angle effect.

The fraction of transmission in Fig. 11 represents the proportion of SHGC. In Equation (5), SHGC is the result of $SHGC_t$ and transmission fraction (Fr) of the solar incident angle. For example, if $SHGC_t$ =0.81 (clear class with no overlap) and if the incident angle is 0, the SHGC is equal to 0.81 (0.81 x 1).

$$SHGC = SHGC_t * Fr \quad (5)$$

3.3 Energy and AC Load

After analyzing both multi-transmission and solar incident angle effect, the HVAC energy consumption and peak load are calculated. Equation (6) shows that the heating load (q_i) is equal to SHGC multiplied by the incident energy (E_i). [8] The incident energy is the direct normal solar irradiance from the Ann Arbor, MI weather file data file [9].

$$q_i = SHGC * E_i \quad (6)$$

Fig. 12 shows the result on cooling load of the 45-degree tilted blade. The multi-transmission effect helps to reduce the peak load in the summer time from 290 Btu/h sq. ft. to 160 Btu/h sq. ft. This reduction occurs also within other months of the year. In summer, the cooling load is low in the morning and evening time because of the low sun altitude.

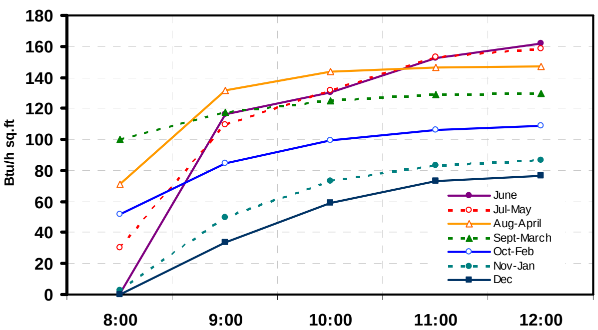

Fig. 12: The hourly cooling load for the 45-degree blade

The multi-reflection is the last variable. To calculate the total multi-reflection effect by hand is almost impossible because the inter-reflection depends on profile angle and tilted angle of glass blade. However, this effect should not be ignored. The results show that its impact is significant on both cooling load and energy consumption.

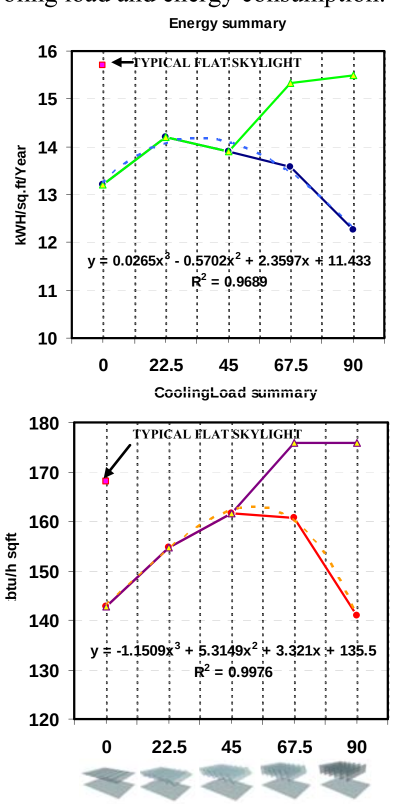

Fig. 13: the cooling energy (top) and the cooling load (bottom) of every tilted angle blade.

Results based on calculating the profile angle for every tilted glass blade angle show the glass blade at 67.5 and 90 degrees have the same condition as they reflect the direct solar ray to the same area below within the space. The reflected irradiance needs to be included in the cooling load and energy. Therefore, equation (7) is developed by adding the first reflected component (ρE_i).

$$q_i = SHGC * E_i + \rho * E_i \qquad (7)$$

Fig. 13 shows the cooling load and air conditioning energy summary. These results demonstrate that the vertical glass blade is the main variable that reduces both cooling load and energy not taking into account the inter-reflection. The glass with low reflectance may be more appropriate if using this angle. However, if the multi-transmission effect is included then the horizontal glass blades with low transmission with fritted pattern might provide the best performance in both cases.

4. LIGHTING AND VISUALIZATION

The performance of the multilateral glass shading system was shown in section 3. Each blade angle blocks the direct solar radiation differently due to its angle with respect to the sun position. Since there is a high correlation between the global irradiance and illuminance, the glass roof shading system allows large amount of heat to penetrate while admitting daylight in to the space.

The space under the glass roof is modeled using LightScape. This program is fairly accurate for analysis of lighting and visualization of architectural space with complex geometry [10]. The result in Fig. 14 shows the illuminance distribution patterns within the space using the various glass blades. The largest amount of light penetrates by the use of 90-degree blades and the smallest amount illumination comes from the 0-degree blades. These results are the same or close to the results based on hand calculation as shown in Fig. 13.

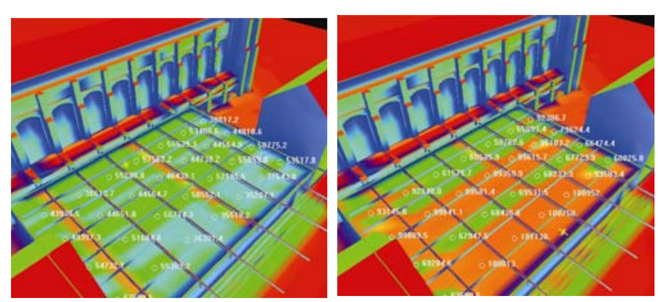

Fig. 14: the illumination (at June, 21th, 2PM) of lower glass at both 0-degrees (left) and 90-degrees (right).

The amount of light that falls on the glass also affects the lighting condition and visualization of the space below. Fig. 15 shows the illumination in the space with the use of the 90-dergee blade. This option allows more of light to illuminate the space compared with that of the 0-degree blade. This includes multi-reflection within the blades as well as within the space below.

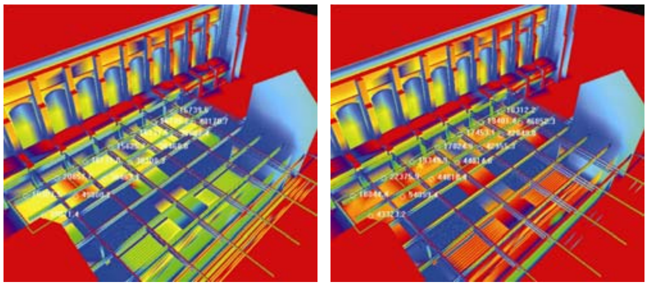

Fig. 15: the illumination (at June, 21th, 2PM) of interior space of both 0-degree (left) and 90-degree (right).

The illumination level is more than adequate even during the winter overcast sky in both cases, and complies with EA requirement for energy use. The design criteria should include the optimization of glass area, glass visible transmittance, angular SHGC and the appropriate tilted angle of glass blades.

The more illumination in this space means the more brightness. In both cases, if the interior material is not selected properly, the average brightness in the space will be extremely high and very difficult to obtain visual comfort and uniformity if needed. The high levels of luminance from the glazing system would equate to major glare problem within the visual filed. [11] In the case of the 90-degree blade angle, the illumination is higher than that of the 0-degree and the uniformity is significantly lower. This means that the 90-degree blades have potential to produce more glare problem within the space, and reduce the visual comfort probability (VCP).

Although clear glass (VT 0.81) is used as a base case in this simulation of the glass roof, the blade angle and the overlapping of the glass layers contribute to the reduction of light or lowering the total roof transmittance and a lower illumination in the space. This condition has contributed to the reduction of the glare condition. The use of lower VT and lower material reflectance may also help, but we have to pay attention to the overall space interior lighting condition. VCP and glare studies under extreme daylighting conditions given the application of this type of roof glazing system will be presented in an upcoming publication by the authors.

5. CONCLUSION

Obviously, the field experiment is required for verification of some of these results, and will be tested in the future. However, by application of various design tools and their integration at different stages of design we can influence positively and contribute to the final design. The multilateral glass shading device reduces the lighting energy use, and provides ample use of natural light.

The eQUEST simulation reveals that the EA of 0.08 is suitable for designing the skylight based on given conditions within the atrium. The multi-transmission, reflection and the 0 degree blade angle minimized both cooling loads and energy consumption. The lighting and visualization analysis shows similar results. The 0-degree angle has less potential to create glare compared with that of 90-degree.

The use of a fritted pattern of translucent glass without any complicated shading structure may be one solution. However, this solution will change if considering the use of glass photovoltaic system and automatic or adjustable shading systems.

6. REFERENCES

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