The Performance of Daylighting with Shading Device in Architecture Design

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ABSTRACT

This paper presents the relationship between daylighting performance and shading device design in the perimeter area of buildings. In the area of tropic and sub-tropic, designers always face with the contradiction between solar heat gain and daylighting using. Factors such as different type of shading device, material reflectance, fenestration design, opening ratio, and daylight distribution will be considered in this study. Models study will base on horizontal, vertical, and eggcrate types of shading device and tested under an artificial sky in the hemisphere daylight skydome. This paper discusses and analyzes certain aspects critical to develop regression models to predict the daylight distribution of a room with different shading device design.

Key Words: Daylighting, Shading Device, Energy Conservation, Solar Radiation

1. Introduction

1.1. Energy Context

Fenestration is a significant factor affecting architecture, whether from the viewpoint of aesthetics, function, or economy. Most building designers are well trained in aesthetics and building function in architectural design. International events and the resultant energy crisis in the 70’s and 90’s forced a reexamination of energy use patterns in building design. Consequently, the concerns of energy consciousness also apply to the design profession. The building design professions need to examine their current curriculums and available resources to determine the extent of the need for adaptation of energy-related training for assisting in their decision making on energy related design.

Buildings accounts for 16 percent of the total energy consumption in Taiwan, or 8.16 million Kiloliters of oil equivalent [1]. Taiwan is not endowed with indigenous energy in total energy supply, the ratio of imported energy to the total energy supply in Taiwan is 93 percent. Based on the statistical information of Taiwan Power Company [2], lighting accounts for 30.3% consumption in total electricity sales. Which means lighting take about 22.5 billion KWH per year. Besides lighting, air-conditioning also take about 40% electricity in the season of summer. Therefore, effective use of fenestration design is considered one of most promising energy conservation strategies in building design.

1.2. Perimeter Concern

The climate of a given region, such as Taiwan, which critically affects the energy related performance of buildings. Taiwan is located in the hot-humid zone. Humidity is fairly high constant during most of the year. Relative humidity above 80% for most of the time, but may vary from 75 to 90%. Cooling degree hours base 22 degree centigrade in this island is vary from 28,000 to 40,000 CDH. Most part of this area is greater than 32,000 CDH. The climatic condition, mainly the humidity and cooling
degree hours, give an index for outlining hot periods that need air-conditioning. The energy consumed for air-conditioning is mainly for the perimeter area of buildings. Therefore, shading devices are needed to prevent solar radiation penetrate through the openings directly and to save energy consumption in air-conditioning.

Building designers should pay attention to available daylighting use in perimeter area for compensating lighting and its electricity saving. Designers always face with the contradiction between solar heat gain and perimeter daylighting. This paper will analyze the solar heat prevent by shading device and their effect to the daylighting performance in the perimeter area. The perimeter zone, which may defined vary from 3.5 to 6.0 meters away from window wall. Daylighting study shows that five-meter zone is significant area for daylighting use [3]. This studies will base on the five-meter zone to represent the perimeter area of buildings. Factors such as different type of shading device, material reflectance, fenestration type, opening ratio, and daylighting distribution will be considered in this study.

1.3. Daylighting and Shading Devices

Daylight, like other natural resources, is free. Many reasons have been offered for admitting daylight into buildings such as energy conservation, the promotion of health, the psychological response, and the belief that daylight is inexhaustible. Many researchers have contributed results to the definition and measurement or prediction of both quantity and quality of the daylighting conditions in architecture. Existing methods for prediction of daylight can be analytic or computational or graphic; they can be in the form of graphic tables and computer programs or protractors and physical models. Fifty-eight recognized daylight design methods are listed in the CIE publication [4]. Most were originated in European countries where cloudy skies are the typical minimum brightness condition, and few are well suited to tropical area where clear skies prevail and strong direct sunlight is involved. This means that daylight design is impractical for tropical area with no shading devices concern to resist the penetration of direct solar radiation. In other words, the influence of shading devices in daylighting performance of buildings’ perimeter area is very important for fenestration design.

Design is not a one-way, linear problem defining, decision-making, and solution-finding process. Building designers move back and forth between defining problems, making decisions, finding solutions, and some other elements of this iterative design process until an acceptable configuration has been reached. It is also probable that the criteria and conditions of design problems change constantly and cannot be well defined. The design process requires an analytical tool has the ability to interact with the designers at different levels of specificity. Therefore, there is a need for a mathematical model with a microcomputer appropriate for the process of designing. The mathematical model, developed in theoretical from the viewpoint of the physics of light and processed with mathematical relations, should provide the reliability, accuracy, and generalization in daylight analysis that will sufficiently assist designers in their dynamic design process.

2. Methods

2.1. Physical Scale Models Studies

Of all methods used for studying daylight performance, the use of physical models studies is probably the most reliable evaluation tool. The most difficult problem in studying daylight with the use of models is simulating the sky. This study is made with the model under an artificial sky. The studies of scale models, include model building, measuring positions, and data collecting under the hemispherical artificial sky in the Daylight Simulator Laboratory at Tamkang University. Figure 1 shows the vault, which is a grid hemisphere, 7 meters in diameter. Several instrument have been employed for scale model experiments. These include 16 Minolta NT–1 luminance meter, a gloss-meter and reflectance meter, and two TEAC DR–F1 digital recorders. Figures 2 and 3 illustrated the section diagram of the simulator and the experimental condition under the simulator.

In theory, the scale of model intended for photometric measurements is of no significance. In practice, scale is limited by the size of the photocell that is to be used for measurements. This determines the scale of the physical model. A designed model was built for stability of experiments in the scale of 1 to 20. This model is designed by the moveable right wall, back wall and expanded ceiling area. It will ensures the dimension of testing room changeable via those moving parts of model. This model has the advantage of fixing experimental variables such as reflectance of interior wall, stabilizing the photocell
position and model building. The only testing part of scale model is the window wall with the changing of shading device and its material reflectance, fenestration design, opening ratio. Figure 4 illustrated the scale model testing and the 15 points of photocell.

For the purpose of analysis for the influence of shading device in daylighting performance of buildings’ perimeter area. 278 scale models have been tested with the variables changing in this study. Figures 5 and 6 shows the concept of testing models. There are three prototypes of shading device being divided for experiments. They are horizontal, vertical, and eggcrate shapes. The opening ratio for scale model is ranging from 15% to 45%. Fenestration design is tested via one, two, and three openings with the base of same opening ratio and shading devices. Material reflectance of shading device is divided into seven levels of reflectance by painting the shading device from dark to white color. Testing variable are sys-

Figure 1. General view of the skydome at Tamkang University.

Figure 2. Section diagram of the simulator.

Figure 3. Experiment studies in the sky simulator.

Figure 4. Physical scale model under testing condition.

Figure 5. Horizontal shading device models testing.

Figure 6. All 3-type shading device models.
tematic multi-combined to reform the testing condition. The testing data acquisition procedure employs a computer interface system to collect data simultaneously from the 16 photocells. Sixty observations were collected and recorded for each photocell in each case. Figure 7 presents the original data plotting of physical scale model experiment in one case. All the data were convert from illuminance to daylight factor for representing consistency. The multivariate analysis test under the Statistical Analysis System (SAS) were executed. The regression models are well established for comparing and validating the theoretical development.

2.2. Theoretical Development

The only and the original source of daylight is the Sun. The relative contributions of direct daylight and of diffuse daylight in interior lighting depend on, the latitude and longitude of the place, and on the local climate with respect to the distributed sky. These two natural factors determine the building tradition in relation to windows and fenestration design in architecture. Hence, the theoretical development can be divided into three parts. One is the relationship between the Sun’s rhythm and the geometry of a room. The theory and the mathematical formula in this part is very popular. Most studies are well developed to compute these relationships for any specific time and day between Sun’s ray and window. There is no need to repeat explanation herein. The second is the relationship between diffuse daylight and distribution of interior illuminance. The third is the relationship between the penetration of direct sunlight and the performance of shading device. These three sections of the theoretical development then be combined for calculating the total quantity of daylight distribution and performance in a room. It is the purpose of this study to deal with.

The window is the only opening to let daylight come in and to light the interior space. It is the bas assumption that no window means no daylight available in the room. The major concern is the diffuse daylight coming from the sky vault and the exterior ground; other factors, Basically, the diffuse daylight received via the window at any measuring points can be divided into two parts: light directly from sky vault, and light indirectly and reflectively from the exterior ground. Both kinds of diffuse daylight coming from exterior to interior can be termed the first order of diffuse daylight. This first order of diffuse daylight must transit through the window to the interior reference points or surfaces. Once the surfaces receive the diffuse daylight from the exterior, a certain amount of diffuse light will be reflected to the other surfaces or reference points which depend on the reflectance of the surfaces. Therefore, this illuminance passing through the window is the key point for discussing the distribution of diffuse daylight in a room. In other words, the window is the only source of diffuse daylight for interior space as the sky vault is the only source of diffuse daylight for the earth. Hence, the intensity of illuminance for an interior point depends on solid angle [5], the source of diffuse daylight outside the window, and how the diffuse daylight is transferred among surfaces and between surfaces and reference points inside a room. The solid angle can be defined as the area intercepted on the surface of a unit sphere by a conical angle originating at the sphere center.

3. Results and Discussion

278 physical scale models have been tested under the sky simulator for understanding the influence of shading device in daylighting performance of perimeter area. There are five variables were been concerned, they are shading device type, depth of the shading device, reflectance of material, opening ratio, and fenestration design. Shading device types include horizontal (86 cases), vertical (94 cases), and eggcrate (98 cases) shape. The depth of shading device is tested under 0, 15, 30, 45, 60, 75, and 90 centimeter conditions. The reflectance of
shading material is tested with six levels. Opening ratio are tested from 15% to 40%. Fenestration design test are divide the opening into 1, 2, 3, and 4 windows with the same opening ratio. Figure 8 shows the points inside the 3 meters perimeter area are higher than 3.0% daylight factor mostly. It appears that 3 meters perimeter zone can use the daylight normally. Points between 3 to 5 meters perimeter zone should use the artificial lighting for supplement.

3.1. Opening Ratio

Opening ratio stand for the area of opening to the area of the window wall. The larger opening will get the higher daylight factor is understandable. But larger opening ratio do not ensures the better daylight penetration. Figure 8 illustrates the daylighting distribution from the ratio of 15% to 40% with the step of 5% increased. The opening ratio of fenestration does affect the daylight distribution in the perimeter area. The points close to the window wall influenced by the opening ratio fewer than the points away from window wall. Both the daylight factor and opening ratio will increase together, but not proportionally. Especially, the points located at 4 and 5-meter-depth. This means that the opening ratio increased will not make the daylight penetration deeper.

3.2. Shading Device Type

Solar control devices may affect the daylight distribution positively or negatively. This section intends to use the experiment data to compare different type of shading device in the aspect of daylighting. The effect of horizontal devices on daylighting has been well documented. Usually, A horizontal device in effect reduces the amount of daylight in a room by acting as a larger room and changing the light levels by interpolation. This predicting method can give designers a very rough idea of the influence of daylighting. The better method still is using the physical scale models to examine and compare the difference of effect.

Figure 9 illustrate the comparison of daylight distribution for different shading device type. Experiments are conducted under the same opening ratio (30%), modeling material, fenestration design, and depth of shading (30 cm). For the 1-meter-depth points, daylight factor decreased from 19.5% (without shading device) to 10% (eggcrate shading). For the 3-meter-depth points, daylight factor decreased from 4% to 3%. If taking the 3.0% as the reference daylight factor, 3-meter perimeter area still available for using daylight. This presents that the shading device will decrease the daylighting performance with the range from 75% to 50%. In the perimeter area of buildings, 3-meter-zone is still available for daylighting use. The results of testing data should encourage designer to use shading control devices for preventing of extra solar radiation. The eggcrate shading make the biggest influence to daylighting performance, the vertical shading is the second, the horizontal shading is the lowest. Designer can choose appropriate shading form for fitting local climate condition and building’s orientation, and still have the daylight.

Figure 8  Comparison of daylight factor with opening ratio.

Figure 9. Comparison of shading device type.
3.3. Depth of Shading Devices

Besides the influence of shading device type to daylighting performance, testing data of the different depth of shadings in different types also prove that the influence does exist. The different depth of shading was represent with the shading ratio in Figure 10 (Shading Ratio = D/H). All the physical models were designed with the height of window is 150 cm. Thus, the depth of shading devices which under tested is ranging from 15 cm to 90 cm. With the concept of shading ratio, the shading ratio under tested is ranging form 0.1 to 0.6 with the step of 0.1.

The same phenomenon in influence level, like the shading types, has been observed. Figure 11 shows the deeper of the shadings, the lower of daylight factor inside the room. This decrease phenomenon with the depth of shadings is especially obvious in eggrate shading form. Experimental results suggest that the depth of shading devices have the influence to the distribution of daylight. In the horizontal (Figure 12) and vertical (Figure 13) shading form, the influence level is not very serious. But in the eggrate shading form, the influence level changed very rapid with depth increased. For the purpose of using daylight, designer design the eggrate shading device

![Figure 10. The concept of shading ratio.](image)

![Figure 11. Comparison of depth in eggrate form shading device.](image)

![Figure 12. Comparison of depth in horizontal form shading device.](image)

![Figure 13. Comparison of depth in vertical form shading device.](image)
should avoid the depth of shading more than 45 centimeter.

3.4. Fenestration Design

Fenestration design might be changed with the preference of the designer. Since design is a very hard control variable, the scale model study only test the number of window under the same opening ratio. Figure 14 shows the result of testing data plotting. It is clear that the number of window will influence the daylight distribution. Especially in the 4 and 5-meter-perimeter, the number of window increased will make the higher daylight factor. This result will give better daylighting design for its distribution.

3.5 Multivariable Analysis and Validation

The statistical multivariable model has been established for predicting daylight distribution. The scale model study was selected because it represents the simplest, most acceptable, and most reliable technique for simulating daylight distribution, as mentioned earlier. This statistical model will also employed for validating the theoretical model in the future. The major concern in validation of the multivariable model was how accurately the daylighting distribution might be predicted as compared to the scale model studies. Statistics analysis includes four major variables. These variables are opening ratio (OR, %), depth of predicting point (DP, meter), depth of shading devices (SR, shading ratio), and number of windows (NW, number). The shading ratio is the depth of shading device divided by the height of window. The multi-variable regression models were established under the Statistical Analysis System (SAS) computer program. Table 1 shows the regression model. Table 2 illustrates the correlation coefficients of these models.

Most designer predicts daylight distribution using methods such as the Lumen method, the Daylight Factor method, and charts and tables in IES handbook. Others use scale model studies under a daylight simulator and real sky. Still others use sophisticated computer programs based on correlation coefficient functions generated mainly via scale model studies. The multi-variable regression model proposed in this study is intended to provide a more convenient design methods for designers and to encourage them to consider daylight in their designs. Figures 15 and 16 are examples to show the comparison of the physical scale models experimental study and the regression models from SAS program. Both the Figures 15 and 16 were under the conditions of the eggcrate shading device with the 30% opening ratio and two-window opening. The comparisons were made the shading

![Model Testing Scatter](image)

Figure 14. Comparison of fenestration design in windows.

| Table 1. The multivariable regression models of different shading types |
|-----------------------------|-------------------|-------------------|
| Shading Devices Type        | DF (daylight factor/%); DP (depth of predicting point/m); NW (number of windows); OR (opening ratio %); SR (shading ratio %) |
| No Shading                  | $DF = 3.06 \times 10^{-3} + 2.38 \times 10^{-3}DP + 1.44 \times 10^{-3}OR$ |
| Horizontal                  | $DF = 3.51 \times 10^{-3} + 1.8667 \times 10^{-3}DP + 1.1683 \times 10^{-3}OR - 0.0119 SR$ |
| Vertical                    | $DF = 6.7913 \times 10^{-3} + 2.6438 \times 10^{-3}DP + 8.7036 \times 10^{-3}NW + 1.1173 \times 10^{-3}OR - 8.5548 \times 10^{-3}SR$ |
| Eggcrate                    | $DF = 0.0126 + 1.925 \times 10^{-3}DP - 1.1438 \times 10^{-3}NW + 1.0211 \times 10^{-3}OR - 7.2902 \times 10^{-3}SR$ |

| Table 2. Correlation coefficients of multivariate analysis for shading devices |
|-----------------------------|-------------------|-------------------|
| Devices Type                | Opening 20%       | Ratio 25%         |
| Horizontal                  | 0.989             | 0.971             |
| Vertical                    | 0.947             | 0.925             |
| Eggcrate                    | 0.968             | 0.964             |

Shading Opening Ratio

| Devices Type                | 30% 40%           |
| Horizontal                  | 0.912 0.978       |
| Vertical                    | 0.958 0.943       |
| Eggcrate                    | 0.969 0.972       |

| Shading Overview            | 30% 40%           |
| Horizontal                  | 0.978 0.987       |
| Vertical                    | 0.943 0.968       |
| Eggcrate                    | 0.972 0.978       |
ration changing from 0.1 (15 cm) to 0.6 (90 cm). It is clear that these curves of data are quite similar. This will more encourage designers use daylight as one of the issues in their design for energy conservation.

4. Conclusion

This paper presents the idea of physical scale models studies under the Skydome for daylighting performance measurements. Many affecting variable of fenestration design had been tested, such as opening ratio, type of shading device, and the number of opening. Those experiments data validate within the statistics program and show the results are very reliable for daylight predicting. Architecture designers in their schematic design process can use the results. The regression model is very helpful for the purpose of daylight prediction.

References