

Characteristics of Daylight Distributions in Different Shading Systems for Daylight Responsive Dimming System Performance

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ABSTRACT: Daylight responsive dimming system, which utilizes available daylight, can save more than 30% of lighting energy in Buildings. Such a system, however, has a weakness that causes uncomfortable direct sunlight to the human vision. Automated shading systems can solve such unpleasant problems, and lead only useful light of skylight and diffused or reflected sunlight into indoor space. Both systems are possibly applied in the skyscrapers comprised of high technical systems and the glass facades. In this research, measurement tests are performed to analyze the daylight distributions in three different types of rooms, which are a roller shade room, a venetian blind room, and a non-shading system room. In addition, other daylight distributions are also analyzed for different heights of roller shade compared to the cases of closed roller shade room and non-shading system room.

Keywords: integrated system, daylight responsive dimming system, shading system, energy saving

1. INTRODUCTION

In these days, global oil prices are constantly going up, and energy

consumption of fossil fuels is an enormous problem through the world. About 40% of the total energy consumption in OECD countries is related to buildings.

G8 readers issued a declaration which includes recommendations to save huge energy and to reduce 5,700 t-CO₂/yr by 2030[1]. EU has approved Energy Performance of Buildings Directive (EPBD) which is a regulatory initiative to reduce the energy use in buildings. EPBD is also to reduce CO₂ emissions, and it will be fully applied in 2009 [2]. A lot of researcher, countries, and institutes have tried to reduce CO emissions and energy consumption.

A number of high-rise buildings have been constructed through the world, and high technology systems have been developed and applied for energy savings and indoor environment. The facades of recent high-rise buildings consist of glasses, and height of these buildings is competitively becoming higher and higher.

Lightings have significant portions more than 20% of the total energy consumption in a high-rise building [3]. Therefore, control of the lighting is an important factor for energy savings. Recently, various lighting control systems have been developed, and purpose of these lighting systems is to save lighting energy consumption from the total building energy consumption and to make more comfortable lighting environment.

One of the lighting control systems is daylight responsive dimming system which is continuously to adjust lighting output with an algorithm of the correlation of photo-sensor signal and workplane illuminance for maintaining target illuminance levels at the workplane for saving lighting energy consumption and using available daylight [4].

Daylight is an important factor of indoor lighting environment and lighting energy saving, particularly in a high-rise building with tall height and glass facades, because it has more opportunities for utilizing daylight than other buildings. In addition, provision of daylight has been shown by a number of researchers on the occupant satisfaction and positive influence of work efficiency [5].

Daylight responsive dimming system has not been widely installed, despite the

usefulness of the system. One of the major problems is relate to control shading devices by occupant. In case of passive shading system, particularly in office buildings, occupants do not care to open shades after closing then to block sunlight and glare. Active shading systems, therefore, are required in office buildings for using useful daylight. Active shading system is to automatically control shade height and blind angle against variable sky conditions and sun altitudes.

Daylight responsive dimming system is to use daylight for energy saving and comfortable visual environment. Daylight is always not available thing because daylight, such as direct sunlight, can lead to uncomfortable glare and thermal load. Shading systems is to screen out direct sunlight and to lead to diffuse daylight. Therefore, integration of daylight responsive dimming system and automated shading system is needed for best performance and application of daylight responsive dimming system.

In this study, as a fundamental study for integrated system of daylight responsive dimming system and automated shading system, the characteristics of daylight distributions in different shading systems are analyzed because different distributions of each shading systems can affect control algorithm of daylight responsive dimming system. This study demonstrates different shade type, heights and angles in two places: Lawrence Berkeley National Laboratory (LBNL) in the United States and Sejong University in Korea.

2. METHOD

Field tests provide valuable information that can not be gotten from computer simulations. This study demonstrates in two testbeds for analyzing daylight distributions of each shade condition. First test is performed in three test rooms of full-scale at LBNL. One room has roller shade and

another room has venetian blind. The other room, which is a reference room, has no shading system. Second test is performed in three test rooms on 1:2 scale at Sejong University. The same roller shades are installed in two rooms. One roller shade is fully downed and the other is controlled by outside conditions. The other room has no shading system as a reference room.

2.1 Facility Description

In case of LBNL testbed (Latitude 37°4'N, Longitude 122°1'W), the testbed consists of identical side-by-side test rooms (Fig. 1). In this study, analyzed data was monitored from on July 3, 2007 to July 24, 2007.

Each test room is 3.05 m (W) × 4.57 m (D) × 3.35 m (H) and has a 2.7 m (W) × 2.4 m (H) window facing the south. The windows consist of an array of five rows and three columns each window, and its size is a 0.85 m (W) × 0.43 m (H). Window transmittances of each room are 0.42 (Room A), 0.60 (Room B), and 0.60 (Room C), respectively. Data of Room A is corrected based on reference room data because of different transmittance. Interior surface reflectances of the floor, walls and ceiling are 0.18, 0.85 and 0.86, respectively. Roller shade is installed in Room A and venetian blind is installed in Room B. Room C, as a reference room, has not any shading systems.



Figure 1: Exterior and interior view of the testbed in LBNL. In the exterior view, Room C is the left side and Room A is the right side.

In case of Sejong University testbed (Latitude 37°3'N, Longitude 127°4'E), the

testbed also consists of identical side-by-side test rooms (Fig. 2). This testbed is constructed as in half scale. In this study, analyzed data was monitored on March 20 and 21, 2008.

Each test room is 1.51 m (W) × 2.87 m (D) × 1.64 m (H) or 1.57 m (H), and has a 1.29 m (W) × 1.22 m (H) window facing the south. Ceiling is inclined from window side (1.64 m) to other side (1.57 m). Window transmittance of each room is 0.86. Interior surface reflectances of the floor, walls and ceiling are 0.26, 0.84, and 0.84, respectively, and the rooms are unfurnished. Roller shade is fully downed and fixed in Room A as a reference room. And movable roller shade is installed in Room B. Room C, also as a reference room, has not any shading systems.



Figure 2: Exterior and interior view of the testbed in Sejong University. In the exterior view, Room C is the left side, and Room A is the right side. In contradiction to exterior view, Room C is the right side and Room A is the left side in the interior view.

2.2 Test Configuration

In case of LBNL testbed, each room has seven illuminance sensors (LS-210SA, ±1.5% to 7500 lx, ±0.15%/°C) which are six illuminance sensors (0.78 m) facing to ceiling on the workplane and one illuminance sensor (2.44 m) facing to floor on the ceiling (Fig. 3). Illuminance data were sampled in every second and then averaged for 1 min.-interval.

Heights of roller shade (Room A) and venetian blind (Room B) are changed by five levels which are 0% (fully down), 40%, 60%, 80%, and 100% (fully up) of window height. 20% of window height is not tested because of desk position. The desk is close to window in each room. Slat angle of venetian blind in Room B is at 0°.

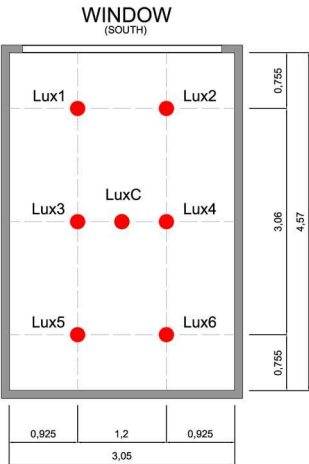


Figure 3: Sensor position of the testbed in LBNL. Lux 1-6 are at 0.78 m and Lux C is at 2.44 m height.

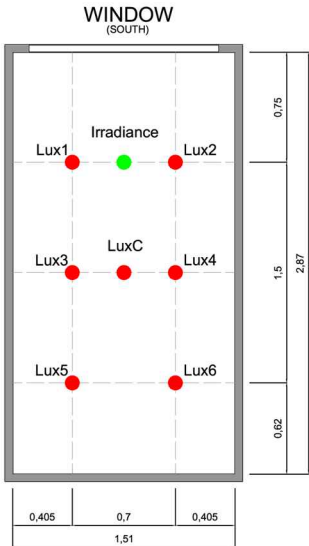


Figure 4: Sensor position of the testbed (1:2 scale) in Sejong University. Lux 1-6 and Irradiance are at 0.375 m and Lux C is at 1.6 m height.

In case of Sejong University testbed, each room has seven illuminance sensors (LS-210SA, $\pm 1.0\%$ to 100 klx, $\pm 0.15\%/^{\circ}\text{C}$) which are six illuminance sensors (0.375 m) facing to ceiling on the workplane and one illuminance sensor (1.6 m) facing to floor on the ceiling (Fig. 4). Illuminance data were measured by the same way in LBNL

Height of roller shade in Room B is controlled by calculated levels based on profile angle. In the Lighting Handbook [6], “The profile angle is the apparent altitude of the sun relative to a vertical surface of interest. It is used primarily to determine shadow and to plot direct beam penetration on building sections.” Hourly profile angles of Sejong University testbed on each equinox (Mar/Sep 21) and each solstice (Jun/Dec 21) are calculated (see Table I).

Table I: Hourly profile angles of Sejong University testbed.

Hour	Mar/Sep 21	Jun 21	Dec 21
09:00	27.26	42.33	11.35
10:00	37.48	54.21	19.34
11:00	46.20	65.31	25.26
12:00	51.43	74.09	28.35
13:00	52.30	74.47	28.36
14:00	48.25	66.45	25.26
15:00	40.40	55.45	19.32
16:00	30.45	43.60	11.32
17:00	19.39	32.07	2.02

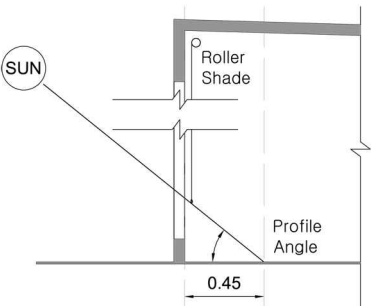


Figure 5: To calculate height of roller shade based on profile angle and boundary length of direct sunlight penetration.

In this test, penetration of direct sunlight was allowed from window to 0.45 m of real length for preventing glare. 0.45 m means 0.9 m because of 1:2 scale in this test. Hourly heights of roller shade in Room B were calculated based on profile angles and 0.45 m on Mar/Jun/Sep/Dec 21 (see Fig. and Table II).

Table II: Derived roller shade height using profile angle in Room B of Sejong University testbed.

Hour	Mar/Sep 21 (cm)	Jun 21 (cm)	Dec 21 (cm)
09:00	23.19	40.99	<u>9.04</u>
10:00	34.51	62.42	15.81
11:00	46.93	97.89	21.26
12:00	56.43	<u>157.91</u>	24.31
13:00	58.23	<u>161.97</u>	24.30
14:00	50.42	103.26	21.24
15:00	38.31	65.36	15.78
16:00	26.46	42.86	<u>9.01</u>
17:00	15.84	28.20	<u>1.59</u>

Window height is from 0.13 m to 1.35 m above the floor. In Table II, roller shade can be fully up at 12:00 and 13:00 on June 21 and also fully downed at 09:00, 16:00 and 17:00 on December 21. In this test, roller shade of Room B is controlled based on results of Table II on March 21 (see Table III). Roller shade height is controlled at one hour interval except 12:00-15:00.

Table III: Controlled roller shade height in Room B of Sejong University testbed on March 21.

Time	Mar 21(cm)
09:00-10:00	23
10:00-11:00	33
11:00-12:00	43
12:00-13:00	53
13:00-14:00	53
14:00-15:00	53

15:00-16:00	43
16:00-17:00	33
17:00-18:00	23

2.3 Data Correction

Room A data of LBNL testbed is corrected because of different transmittance. On July 16, 2008, roller shade in Room A is fully up for comparing with Room C. Correction values of each sensor are hourly derived (see Table IV).

Table IV: Correction values of Room A data. These values are calculated by Room C data/Room A data.

Hour	Lx1 (lx)	Lx2 (lx)	Lx3 (lx)	Lx4 (lx)	Lx5 (lx)	Lx6 (lx)	LxC (lx)
09:30	1.42	1.40	1.47	1.51	1.50	1.38	1.51
10:30	1.43	1.41	1.48	1.52	1.52	1.39	1.52
11:30	1.44	1.43	1.48	1.53	1.52	1.40	1.53
12:30	1.48	1.45	1.53	1.55	1.55	1.43	1.53
13:30	1.58	1.54	1.58	1.60	1.58	1.46	1.52
14:30	1.53	1.50	1.54	1.57	1.54	1.43	1.48
15:30	1.46	1.42	1.47	1.50	1.49	1.37	1.46
16:30	1.44	1.39	1.47	1.50	1.50	1.37	1.49
17:30	1.43	1.39	1.46	1.50	1.48	1.36	1.47

3. TEST RESULTS

3.1 Vertical Daylight Distribution by Shading Type

The illuminance ratio of each shade height by space depth from window on the workplane is compared (Fig. 6). The average illuminance ratio is calculated in every minute, and then averaged from 9:00 to 18:00 in Fig. 6 and 7. 'Lx1,2/5,6' means average illuminance of Lux 1 and Lux 2 divided by average illuminance of Lux 5 and Lux 6 in each room of LBNL testbed. When heights of shades are controlled as 0%, downward curves of each shade room are steadier than those of reference room. Especially, downward curve of roller shade

room is unsteady because of large illuminance difference between Lux 1, 2 and Lux 3, 4.

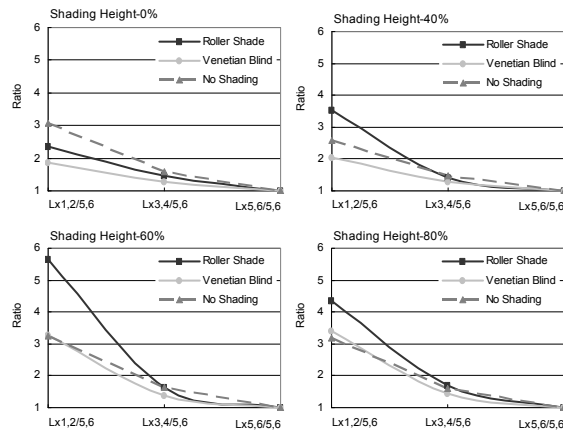


Figure 6: The comparison of illuminance ratio of each shade height by a space depth from window.

The comparison of illuminance ratio of each shade height by space depth from window on the workplane is analyzed (Fig. 7). The curves on the graphs can be regarded as sectional daylight distribution in a space. In case of roller shade, curve of lower shade height is steady. The curve of 60% of shade height, however, is much unsteady than that of 80%. It means that the ratio of large variation is figured between 40% and 60% of shade height. In the venetian blind plot, ratio of large variation is figured from 40% to 60% of shade height. The curves of under the 40% and over the 60% of shade height are similar.

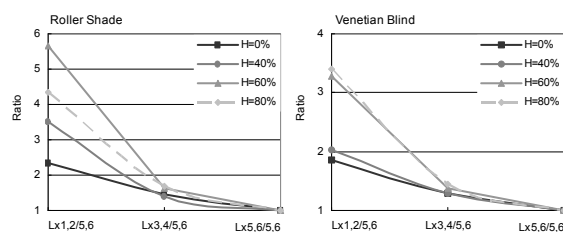


Figure 7: The comparison of illuminance ratio of each shade type by a space depth from window. Slat angle of venetian blind is at 0°.

Correlation of ceiling illuminance (Lux C) and average illuminance (Lux 11-16) on the workplane is figured as a linear fit, and this linear fit is evaluated using coefficient of determination (see Table V). Correlation of photosensor and workplane illuminance can be assumed by this analyzed correlation.

The coefficient of determination (R^2) is widely used to determine how well a regression fits. R^2 represents the fraction of variability in y that can be explained by the variability in x . In this study, R^2 of correlation of ceiling illuminance (Lux C) and average illuminance (Lux 11-16) can be used how much percent of prediction can be predicted with derived linear fits in the correlation of ceiling illuminance (Lux C) and average illuminance (Lux 11-16).

Table V: R^2 and coefficient of slop in derived linear fit of 'Lux C' and average 'Lux11-16'. Lux C is y , and average Lux11-16 is x . Intercept of x and y is '0'.

Shade / Height	Slop Coefficient	R^2
R.Shade /H=0%	0.4214	0.9569
V.Blind /H=0%	0.4616	0.6895
Ref.Room	0.3690	0.8715
R.Shade /H=40%	0.6070	0.8497
V.Blind /H=40%	0.4760	0.9163
Ref.Room	0.4166	0.8883
R.Shade /H=60%	0.3270	0.9803
V.Blind /H=60%	0.3102	0.9857
Ref.Room	0.3169	0.9957
R.Shade /H=80%	0.3228	0.9714
V.Blind /H=80%	0.3069	0.9758
Ref.Room	0.3266	0.9873

In the Table V, especially, the values of R^2 are different at 0% of shade height among the values which are 0.9569, 0.6895 and 0.8715, respectively. It can be analyzed that roller shade is much stable and simple in the situation of shade fully downed for

controlling of the daylight responsive dimming system. In case of slop coefficient, although the values of a reference room are relatively stable, the values of installed shading system are unstable by different shade height. It can be concluded that different control algorithms shall be needed for integration of daylight responsive dimming system and automated shading system.

3.2 Daylight Distribution by controlled height of roller shade on spring equinox

The data of controlled roller shade height in Room B of Sejong University testbed is compared with the data of two reference rooms which are Room A data of roller shade height fully downed and Room C data of no shading.

The average illuminance on the workplane is figured on March 20 and 21(Fig 8). Some data, which is error and '0' of value, between 14 and 15 on March 21 was not measured. The hourly sky conditions were estimated by the sky cover method. In the Lighting Handbook [6], the amount of sky concealed in the sky cover method is expressed as "on a scale from 0.0 for no clouds to 1.0 for complete sky cover." Clear sky is 0.0-0.3, and partly cloudy is 0.4-0.7. And cloudy is 0.8-1.0. The amount of sky covered on March 20 and 21 was measured by the Meteorological Office in Korea[7] (see Table VI).

Table VI: The amount of sky covered on March 20 and 21.

Date	9	10	11	12	13	14	15	16	17h
Mar 20	0	0	0	0	0	0	0	0	0
Mar 21	0	3	3	2	3	6	7	6	6

The illuminance ratio by space depth from window on the workplane is compared on March 20 and 21(Fig 9). 'Lx1,2/5,6' means average illuminance of Lux 1 and Lux 2 divided by average illuminance of

Lux 5 and Lux 6 in each room of Sejong University testbed.

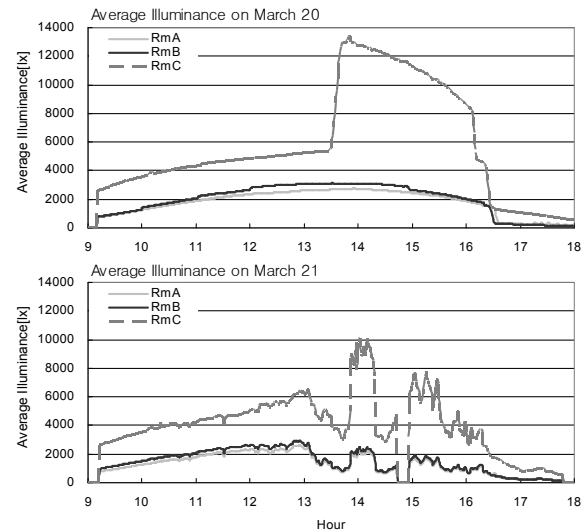


Figure 8: The average illuminance on the workplane on March 20 and 21.

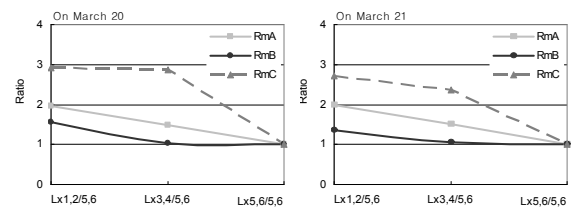


Figure 9: The comparison of illuminance ratio by a space depth from window on March 20 and 21.

The illuminance ratio and daylight distribution of Room B are much useful than the others, because Room B adopts more stable daylight. In other words, controlled height of roller shade, which is calculated by profile angle (see Table II), leads available daylight into a deep space.

Correlation of ceiling illuminance (Lux C) and average illuminance(Lux 11-16) on the workplane is figured as a linear fit and this linear fit is evaluated using coefficient of determination (see Table VII). The values R^2 of Room A and Room B are very similar near to '1'. It means that fixed algorithm is adoptable such like in these conditions which are small space, facing south, unfurnished space and roller shade height controlled by profile angle.

Table VII: R^2 and coefficient of slop in derived linear fit of 'Lux C' and average 'Lux 11-16'. Lux C is y , and average Lux11-16 is x . Intercept of x and y is '0' on March 20 and 21.

Date	Room	Slop Coefficient	R^2
Mar 20	Room A	0.8458	0.9991
	Room B	0.9646	0.9984
	Room C	0.5012	0.1626
Mar 21	Room A	0.8475	0.9995
	Room B	0.9562	0.9994
	Room C	0.6262	0.6567

4. CONCLUSION

This paper analyzes the daylight distribution of different shading conditions, and evaluates the daylight distribution of roller shade height controlled by profile angle for daylight responsive dimming system performance.

The first test results of LBNL testbed show correlations related to the different shade types and shade heights. In case of roller shade, a gap between window side and middle illuminance of a space increases between 40% and 60% of height. Correlation of ceiling and workplane illuminance is much stable than that of a reference room at 0% of shade height. In case of venetian blind, the ratio of illuminance on the workplane related to depth of space is similar at 0% and 40% of shade height, and it is also similar at 60% and 80% of shade height.

The second test results of Sejong University testbed show correlations related to controlling of roller shade height. In this test, roller shade height was controlled (Room B) on March 20, 21 by profile angle for controlling (depth 0.45 m from window on 1:2 scale) the penetrated direct sunlight. Controlled roller shade height of Room B

leads available daylight into a deep space and makes much uniform daylight distribution on the workplane. In case of correlation of ceiling and workplane illuminance, both slop coefficients of linear fits on March 20 and 21 are similar. The linear fits of the correlation is much stable as R^2 of nearly '1'. The second test, however, is performed for limited period. Further test for annual relationships is needed for a general conclusion.

ACKNOWLEDGEMENT

This research was funded by Samsung C&T Corporation. Some of authors are funded by 2nd Brain Korea 21 project.

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