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Laboratory testing of a high efficiency light redirection system

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Abstract. Automated daylight redirecting slat technologies are designed to divert sunlight into the living space. They have a distinct advantage in that they can be retracted and extended, and slat angles can be adjusted according to the solar geometry and sky conditions. This study aimed to explore the geometric and photometric properties of a novel high-efficiency light redirection system (LRS). The LRS prototypes were installed in the clerestory window in the south-facing window testbed office and monitored under real sun and sky conditions. Workplane illuminance, daylight delivery efficiency (DDE) and visual comfort were evaluated. A number of simulation studies were conducted to evaluate the LRS and compare the results to the laboratory tests. The study shows that the specular properties of the slats provided significantly higher work plane illuminance and DDE. All systems showed an acceptable discomfort glare, or daylight glare probability (DGP) lower than 0.35. The comparison of the laboratory test and computer simulation was conducted using a Radiance tool. The results show that, for specular slats, the mkillum method with plastic material provided accurate work plane illuminance compared to the measurement. All simulated DGP shows accurate results compared to the laboratory test.

1. Introduction

Daylight redirecting technologies are used to increase illuminance from vertical windows further into a space by redirecting sunlight toward the ceiling plane [1] They are typically deployed in the upper clerestory to avoid redirecting light into the eyes of the occupants seated near the window. The lower window can give occupants access to outdoor views and bring daylight to the area near the window. Automated daylight redirecting venetian blinds have been long used to redirect light from the clerestory window to the ceiling plane. Their distinct advantage is that they can be retracted and extended, and slat angles can be adjusted according to the solar geometry and sky conditions. This study focused on a novel high-efficiency light redirecting system (LRS) based on automated light redirecting blinds. For a primary investigation of the LRS performance, a static LRS prototype was used for laboratory testing; this prototype consisted of slats that were manually replaced throughout the day according to the sun's position in the sky. The LRS slats were installed in the clerestory window in the south-facing test bed offices. The measurement data were collected under predominantly clear sky conditions, so the findings are illustrative of south-facing perimeter zones in a sunny climate. This analysis provides an assessment of the impact of the slat design and finish on the performance of slat-based daylight redirecting systems and the potential for this approach to achieve significant lighting energy savings. Additionally, a comparison of the virtual model and laboratory testing was performed for an exploratory investigation of the applicability of the computer simulation for LRS simulation. The Radiance lighting simulation software was used to determine work plane illuminance and visual comfort. The specular property of the light redirecting system is known to be challenging to simulate with Radiance. The radiance simulation



often results in an undersampled specular component and excessive noise [2],[4]. A forward ray-tracing module has been developed that uses a rendering technique called *photon mapping* [3]. In this study, both mkillum and photon map (pmap) methods were used for simulation.

2. Methodology

2.1. Test room

The test room used in this study is the Advanced Windows Test Bed Facility at Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. Figure 1 and Figure 2 illustrate the test room's geometrical and photometrical properties, including the testing instrumentation. The test room is oriented due south with minimal obstruction. The virtual test room replicated the experimental conditions assumed when using the Radiance lighting simulation software. For simplicity, lighting fixtures, furniture and other scientific devices and cables that could have a minor impact on the results were not modeled, to reduce the calculation time.

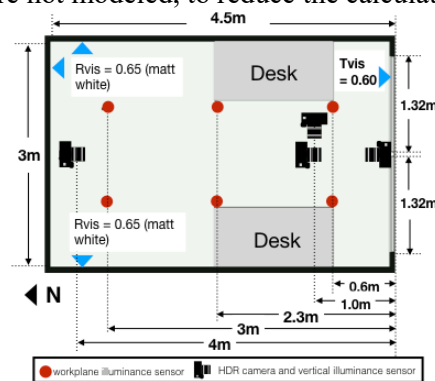


Figure 1. Test room instrumentation layout and geometry, high dynamic range (HDR) camera and illuminance sensor position.

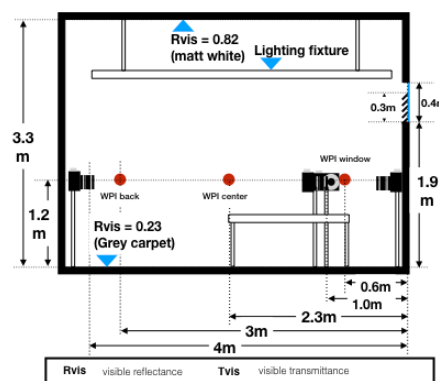


Figure 2. Test room section and geometry, high dynamic range (HDR) camera and illuminance sensor position.



Figure 3. Close-up view from the interior of (left) curved specular slats, (center) curved prismatic slats (right) and flat specular slats.

2.2. LRS prototype

This study focused on comparing the performance of static LRS prototypes with different slat properties. A reference condition, i.e., conventional venetian blind, was out of scope for this study.¹ To be able to perform testing before a dynamic prototype was finalized, a series of static prototypes was used, each with a unique combination of slat tilt angle and spacing. The LRS slat angles were designed to deliver the maximal light redirection toward the rear of the room (3.95 m from the window), and the angles were designed for a few exact times of the day. The prototypes were then manually replaced throughout the day according to the solar position in the sky. Three types of slats were used in this test (Figure 3): (1) curved specular slats, (2) curved prismatic slats and (3) flat specular slats. The *curved*

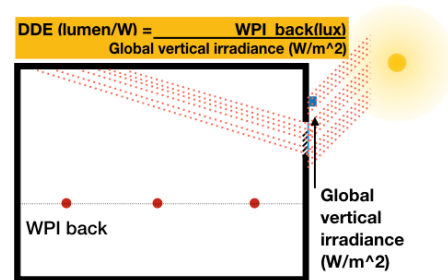


Figure 4. Daylight delivery efficacy (DDE) calculation.

¹ A prior evaluation of a static venetian blind [9] provides limited benchmark data; discomfort glare was insufficiently controlled so rear zone illuminance levels were correspondingly high."

specular slats were the mirrored slats from conventional, light-redirecting blinds (Warema E80L). This type of slat has a specularly reflective coating upper (concave) surface with a visible reflectance (R_{vis}) of 0.91, and a gray semi-matte lower (convex) surface with a R_{vis} of 0.27. The slat width is 7.72 cm and sag is 6.4 mm. The *curved prismatic slats* were the prismatic-surface slats from an existing blind (Koster). The slat width is 2.54 cm and sag is about 3.2 mm. The *flat specular slats* were custom made for this study using 3.2 mm clear acrylic sheets. A specular reflective film was laminated on the upper surface, with a R_{vis} change of 0.99. The opaque paper backing was left on the lower surface of the slat. The slat width is 7.6 cm. This slat was used to assess visual performance of redirection and diffusion.

In the simulation, the flat specular slat was evaluated with different angles throughout the day. The window configuration tested in the simulation had the same geometrical and photometrical properties as the test condition in the window test bed facility. Optical properties of surfaces were derived from the measurements. The upper slats have a R_{vis} of 0.99 and specularity of 1. The lower slats have a R_{vis} of 0.375 and specularity of 0.

2.3. Measurements

2.3.1. Workplane illuminance (WPI) and daylight delivery efficacy (DDE)

Workplane illuminance across a 123.2 cm height surface was used to evaluate the level of the brightness within the test room, for evaluation of how well the LRS performed and distributed light within a deep space. In this study, the slat systems were tested on different dates, therefore the work plane illuminance is not by itself adequate for comparison of the different LRS systems. DDE across the room – at window, center and rear – was plotted to illustrate the profile of the light level from window side to the rear. The DDE (lumens/W) (Figure 4) provides a method of evaluating the efficacy of delivered daylight in the test room, based on the ratio of average workplane illuminance (lux) and global vertical irradiance at the south orientation (W/m^2). The DDE shows how well the LRS performs relative to the solar irradiance at the vertical window.

2.3.2. Discomfort glare

In this study, evaluation of discomfort glare was conducted using HDR images from the commercial grade digital cameras (Canon 5D) equipped with an equidistant fisheye lens and the evalglare software tool [7]. This command line based tool identifies glare sources within a fisheye HDR image, then computes the daylight glare probability (DGP).

2.4. Simulation

The Radiance program was used to model the LRS in the test room and to calculate the workplane illuminance. Radiance [6] is a powerful tool for daylighting simulation; however, to simulate the light redirecting system with the specular property materials, it can be very challenging and may need other methods to support the simulation. In this study, a comparison of the Radiance, mkillum [5] and pmap [3] methods for LRS simulation were preliminarily tested to find the results best fit to reality. The DGP calculation was done using evalglare to detect glare sources and calculate glare indices. The glare sources were determined within a 180-degree fisheye image.

Table 1. Simulation parameters

	mkillum	pmap
Ambient bounces (-ab)	2	5
Ambient divisions (-ad)	256	4096
Ambient super-samplers (-as)	128	1024
Secondary source presampling density (-dp)	1024	8192
Specular sampling (-ss)	64	1024
Caustic photons (-apc)	–	5M
Global photons (-apg)	–	2M
View setting	-vta (-vv 180 -vh 180)	-vta (-vv 180 -vh 180)

3. Results and Discussion

3.1. Work plane illuminance (WPI) and DDE from the rear of the test room

In this study, we were particularly interested in increased daylight levels at the rear area of the room. Figure 5 illustrates the average WPI at the rear (3.95 m from the window) for all three systems on five clear and sunny days from May to August, 2017. The flat specular slats were tested at a lower solar angle than the other systems, and results showed a higher WPI than the others. The curved prismatic slats showed a very low WPI, under 150 lux, at all the times tested (10:45–12:15). Figure 6 presents the DDE values for the tests conducted at the rear of the room. The DDE values show that the curved specular slats provided a higher DDE on May 9 (max solar altitude angle = 69.7 deg) from 11:00–13:00 compared to the tests on other days and compared to the flat specular slats. However, for the tests on June 21 (max solar altitude angle = 75.4 deg) and July 12 (max solar altitude angle = 73.7 deg), DDE values of the curved specular slats were lower than those of the flat specular slats all day long.

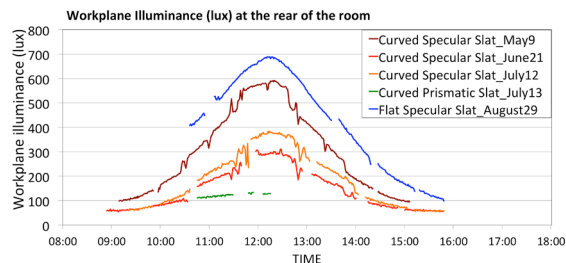


Figure 5. Work plane illuminance at the rear of the room

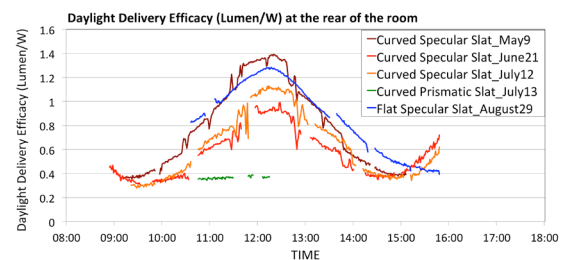
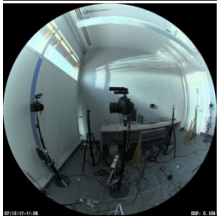
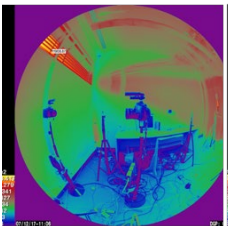
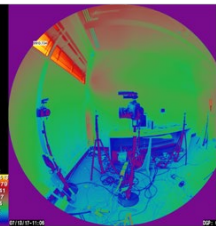
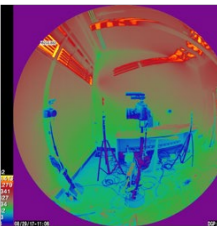


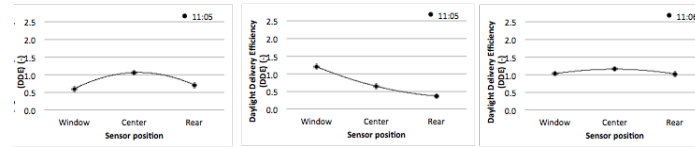
Figure 6. DDE at the rear of the room

For a more detailed study, the three systems at about the same time of day (11:05–11:06) were compared. Table 2 presents DDE due to daylight versus distance from the window and HDR and false-color images for the camera facing the west wall for three types of slats. At this time, the solar altitude angles were 57.9° for the curved specular slats, 57.8° for the curved prismatic slats and 49.8° for the flat specular slats. In terms of DDE, which controls for the variety of solar angles that were encountered during testing, the levels encountered at the rear of the room showed that the flat specular slats had the most consistent daylight delivery, with DDE reaching up to 1.2 at the center and 1 at the rear. The curved specular slats provided, at times, even more daylight, but their performance was not even over time, showing DDE below 1 at the rear of the room. The curved prismatic slats did not deliver a significant amount of light to the rear of the room.

Table 2. Comparison of HDR images, false-color images and DDE charts for the three systems

	Curved specular slat (July 12, 11:05)	Curved prismatic slat (July 13, 11:05)	Flat specular slat (Aug 29, 11:06)
HDR image			
False color image			

DDE



3.2. Visual comfort

Most of the DGP levels recorded using four HDR cameras at different positions and orientations (Figure 1 and Figure 2) during this study were under 0.350, which is the limit that discomfort glare is noticeable. DGP over 0.350 was found only from the camera looking toward the window at 3.95 m from the window for the curved specular slats on June 21, 2017, between 12:00 and 13:00, when the reflection of the whole sun orb was visible on the slats. From Table 1, the curved specular slats effectively redirected sunlight up toward the ceiling plane and the rear wall on all the test dates. However, the light was reflected in a way that caused very noticeable glare to occupants when they entered the room, even though the measurements only detected slightly perceptible glare on one occasion. The curved prismatic slats were tested briefly for one day in July. These slats redirected sunlight up toward the ceiling plane and rear wall. However, the light was not concentrated enough to effectively act like a secondary light source for the rear of the room. The flat specular slats were the only slats tested on one day in August. These slats effectively redirected sunlight up toward the ceiling and rear wall, and acted as a light source for the rear part of the room. The light was focused and, in comparison to the other slats, showed sharply delimited bright patches on the ceiling and walls.

3.3. Comparing laboratory testing and Radiance simulation.

The test room with flat specular slats was modeled and simulated using two methods: mkillum and pmap. Slat materials were assigned with a plastic modifier and mirror modifier. The plots in Figure 7 illustrate the work plane illuminance at the rear of the room. mkillum with a plastic modifier has the best correspondence to the measurements, even though it is likely to underestimate light level in the morning and early afternoon, and overestimate the light level in the late afternoon.

The scattering plots of measured DGP (Y-axis) and simulated DGP (X-axis) in Figure 8 compare the mkillum and pmap methods of all four cameras. Both methods act very similarly and overestimate the measured DGP. DGP using mkillum had a slightly better fit to the measurement. HDR images, Radiance mkillum pictures and Radiance pmap pictures (for the flat specular slats, showing a sideways view of the room) are compared side-by-side to identify the differences of the outcome of redirected light from the slats on the walls and ceiling and how light diffused on the interior surfaces of the test room and simulations. In Figure 9, the HDR image shows the light redirected toward the ceiling, side and rear wall. A lower luminance level was found at the other part of the ceiling and side wall. The pmap picture shows the light from the clerestory window redirected toward the ceiling and all walls, but it was more diffused than the HDR image. The mkillum picture shows light from the clerestory window redirected toward all walls and the ceiling, very similar to the HDR image, however the redirected light patch on the wall and ceiling was not found in the mkillum with plastic material picture, only in the mkillum with mirror material picture.

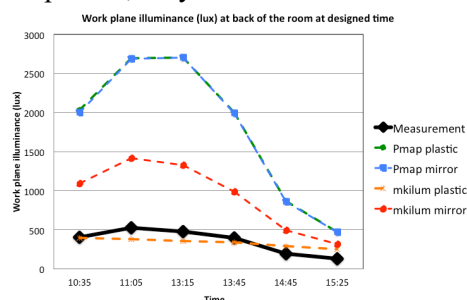


Figure 7. Measured and simulated workplane illuminance (lux).

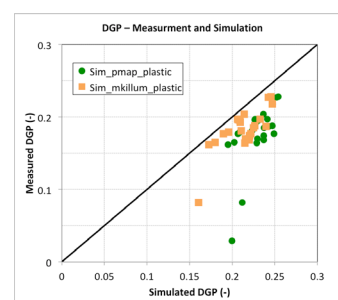


Figure 8. Comparison between measured and simulated DGP using the mkillum method.

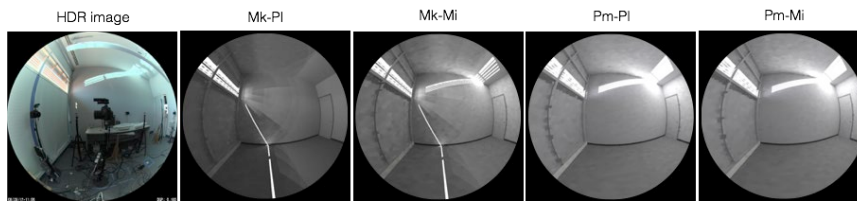


Figure 9. Comparison of HDR images and simulated images using the Pmap and mkillum methods on July 12, 2017, at 12:00 (Mk = mkillum, Pm = pmap, Pl = plastic, Mi = mirror)

4. Conclusion

The primary value of laboratory measurement is that the prototype technologies can be directly investigated under real conditions. This is particularly true for visual comfort, which is subjective and can be difficult to model when the technologies may have peaky light output distribution (such as some daylight redirecting technologies). In this primary study, three different slat types were investigated in a full-scale testbed. The flat specular slats, which demonstrated their ability to redirect sunlight to the ceiling and back wall plane greater than the others, were modeled in the Radiance tool. The results are summarized as follows:

- The specular properties of the flat specular slats redirected daylight further at the rear of the room than the curved specular and curved prismatic slats did. The DDE was the highest within the deep space.
- Most of the DGP levels recorded during this study were under 0.350, which is the limit that discomfort glare is noticeable. DGP over 0.350 was found only from the camera looking toward the window at 3.95 m from the window for the curved specular slats. This camera position demonstrated the far view of the LRS and sought to evaluate the DGP of the occupant seated far from the window.
- Two different Radiance simulation techniques (mkillum and pmap) were used, and two different materials – plastic and mirror – were used to model the reflective flat slats. The results show that the mkillum method with the plastic material provided the most accurate work plane illuminance compared to the measurement; however, when simulated images were compared among all methods, this simulation method did not appear to provide an accurate match for the appearance of redirected light at the rear of the room, especially with regard to the patches of reflected sunlight. All the methods showed reasonably accurate DGP results when compared to the HDR images.

It is conclusive that, for the clear sky condition, the higher reflective surface material slats with the angles that carefully adjusted could carry the maximum daylight to the rear part of the room in higher and lower solar angles while still maintaining acceptable discomfort glare. The simulation used accurate inputs and appropriate methods, and agreed well with the laboratory testing. Further research is required to determine the energy performance for the development of the novel high-efficiency light redirecting system (LRS) in different climates.

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