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Measured daylighting potential of a static optical louver system under real sun and sky conditions

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A B S T R A C T

By utilizing highly specular surfaces and engineered profile geometry, optical sunlight redirecting systems integrated into the overhead “clerestory” zone of the building facade present the potential to enlarge the daylighting zone by redirecting the luminous flux incident on the window deeper into the space than conventional shading systems. In addition, by developing system geometry to redirect daylight to specific zones within the space, optical light redirecting systems have the potential to avoid the glare conditions commonly produced by conventional facade shading systems that direct significant amounts of daylight below head height into the occupant's field of view. In this case study, side-by-side comparisons were made over solstice-to-solstice changes in sun and sky conditions between an optical louver system (OLS) and a conventional Venetian blind set at a horizontal slat angle and located inboard of a south-facing, small-area, clerestory window in a full-scale office testbed. Daylight autonomy (DA), window luminance, and ceiling luminance uniformity were used to assess performance. The performance of both systems was found to have significant seasonal variation, where performance under clear sky conditions improved as maximum solar altitude angles transitioned from solstice to equinox. Although the OLS produced fewer hours per day of DA on average than the Venetian blind, the OLS never exceeded the designated 2000 cd/m^2 threshold for window glare. In contrast, the Venetian blind was found to exceed the visual discomfort threshold over a large fraction of the day during equinox conditions (from 40 to 64% of the test day between August 22 and October 12). Notably, these peak periods of visual discomfort occurred during the best periods of daylighting performance. Luminance uniformity was analyzed using calibrated high dynamic range luminance images. Under clear sky conditions, the OLS was found to increase the luminance of the ceiling as well as produce a more uniform distribution of luminance over the ceiling. Compared to conventional venetian blinds, the static optical sunlight redirecting system studied has the potential to significantly reduce the annual electrical lighting energy demand of a daylit space and improve the quality from the perspective of building occupants by consistently transmitting useful daylight while eliminating window glare.

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1. Introduction

Electrical lighting energy consumption in U.S. commercial buildings accounts for 3.69 quad annually [1]. Of this, a recent estimate by Shehabi et al. found that 2.21 quad (60%) is consumed by electrical lighting in perimeter zones located 0–12.2 m from the facade during typical daytime work hours (8:00–18:00) [2]. Consequently, the delivery of sufficient daylight from windows has the potential to reduce annual electrical lighting energy demand by minimizing the need for electrical lighting in the perimeter zone during daylight hours. However, as a general rule of thumb, conventional windows cannot provide useful daylight beyond approximately 1.0–1.5 times the head height of the window [3], leading to useful daylight for areas within a distance of 0–4.5 m from the facade. Subdivision of the window wall into a lower “view” zone and an upper “clerestory” zone for daylight transmission is a common strategy to extend the daylight zone beyond this distance. Because occupants often reduce the daylight transmission of the view zone with shading devices to maintain visual comfort, the clerestory zone is designed to serve as the primary means of daylight delivery into the space. For single-occupancy

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offices, this strategy can be effective. Due to the relatively shallow office depth, typically 3.05 m–6.1 m, the occupant is located relatively close to the window wall and the clerestory is not within the occupant's primary field of view. Because many occupants working in open plan offices are located at a greater distance from the facade, the relatively lower ambient light levels combined with a more direct view of the bright clerestory can cause uncomfortable luminance contrasts, leading to the deployment of shading devices to maintain visual comfort. As an example, in a number of case study evaluations conducted in the UK, Bordass et al. [4] noted that tall windows intended to enable greater daylight penetration to open plan workspaces were often found with the shades closed and the electric lights turned on. Bordass reported that the cause of the default state of "shades down, lights on" was the need to resolve the visual discomfort experienced by those who worked the farthest distance from the facade and did not have control over the shades. In addition to the unnecessary use of electrical lighting that can result from the shading of clerestory windows, electric lights may be switched on by occupants in daylit spaces even when sufficient daylight is provided by windows because the contrast in luminance between interior surfaces adjacent to the facade and surfaces away from the facade causes the space to appear dark or "cave-like" to occupants.

Many systems have been developed for the clerestory zone with the goal of increasing the daylit area of the floor plate. A comprehensive description of existing systems can be found in Ref. [5] (see chapter 4). These include light shelves, anidolic daylighting systems, translucent panels, prismatic structures, and Optical Louver Systems (OLS). By reflecting daylight to the ceiling, light shelves have been shown to deliver useful daylight at slightly greater depths from the facade than conventional windows [6]. However, at low sun angles, conventional light shelves fail to block direct sun, which can lead to glare from direct view of the solar disc and, in turn, deployment of interior shading devices. Further, external light shelves of sufficient depth as to be effective in daylight redirection and perimeter shading are rarely implemented in commercial building facades due to additional structuring required for wind loads and to support the system itself. More advanced light shelve designs, such as those developed by Beltran et al. [7], as well anidolic daylighting systems [8], use an arrangement of optical components to redirect daylight and effectively control glare. However, these more advanced designs have failed to be broadly adopted by architects due in part to their large size, complexity, and challenges with integration into otherwise two-dimensional (flat) facade systems popular among architects. Translucent panels with near-lamberitan diffusing properties, such as those characterized by Reinhart and Andersen [9], redirect incident daylight towards the ceiling but also downward into the view zone of occupants. Although these panels can be easily incorporated into a façade system, the downward-redirected light, as well as the relatively high luminance of the panel itself, can become a source of glare. Prismatic structures have been in use for over a century for lighting applications [10] and work (in sidelighting applications) by refracting light to the ceiling plane for a range of incident angles. Recent developments in the application of prismatic structures for sidelighting have led to the development of prismatic window films which can be adhered to both new and existing glazing systems, creating the possibility of broad application at low cost. However empirical assessment has shown than the current film technology produces perceptible levels of glare under clear sky conditions [11]. Optical louver systems utilize reflective mirrored coatings to reflect daylight to the ceiling while blocking direct view of the window and can be incorporated into the clerestory zone as static louvers (e.g. Refs. [12,13]) or as adjustable lamellas (see systems evaluated in Ref. [14]). Static optical louver systems offer the benefit of not requiring daily or seasonal adjustments in tilt angle, which makes them a potentially more practical and reliable technology for broad application in clerestory zones. However, as a consequence, the profile geometry of static systems must be designed to function effectively over the full seasonal range in incident sun angles.

With the increasing trend of open plan workspaces designed to comply with the daylight illuminance criteria specified in green building rating systems (e.g., Leadership in Energy and Environmental Design (LEED) [15], Building Research Establishment Environmental Assessment Method (BREEAM) [16]), it is important for daylighting strategies to consider human factors issues of visual comfort and luminance uniformity in addition to providing sufficient illumination for performance of visual tasks. When located in the clerestory zone, OLS have the potential to meet daylight illuminance requirements while providing improved visual comfort and light distribution relative to conventional shading systems. Recent developments in computer-based lighting simulation tools, namely the simulation of complex fenestration systems using bidirectional scattering distribution functions [17] and the development of the three-phase simulation method [18] have made it possible to accurately solve for high flux light transport through optically complex daylight redirecting devices such as OLS to produce annual assessments of daylighting performance. These new capabilities are making it easier to assess the application of optically complex fenestration in the design of low-energy buildings. However, the Architecture, Engineering and Construction (AEC) industry is extremely risk averse, and slow to adopt promising technologies without proof of performance in realistic field conditions.

The goal of this study was to compare the daylighting potential of a recently developed OLS installed in the clerestory zone of a facade against a conventional Venetian blind over seasonal changes in sun and sky conditions to test if the optical surface treatment and specific geometry of the OLS consistently resulted in useful daylight illuminance levels and reduced visual discomfort.

2. Measurements and procedures

2.1. Experimental set-up

Experimental tests were conducted in the Window Testbed Facility located in Berkeley, California (latitude 37°4′ N, longitude 122°1′ W) from February 2 to January 19, 2011. The facility consists of three, identical, south-facing, side-by-side, furnished test rooms built to represent a commercial single-occupancy office. The test rooms were unoccupied during this study. Interior surface reflectances of the floor, walls, and ceiling, are 0.18, 0.85, and 0.86, respectively, as measured by a Minolta CM-2002 spectrophotometer.

For these tests, all areas of the window wall, with the exception of the clerestory opening (Fig. 1), were completely occluded with black-out cloth. The clerestory opening was 2.65 m wide by 0.762 m tall and glazed with two, dual-pane, low-emittance windows (type = Viracon VRE-67 glass; visible transmittance = 0.62, back surface visible reflectance[1] = 0.256) separated by a 63.5 mm wide vertical mullion. The window-area-to-wall ratio (WWR) of the vision portion of the window was 0.174, assuming a floor-to-floor

[1] NOTE: back surface visible reflectance is the visible reflectance of the back surface (room side facing) of the IGU at normal incidence. It's a useful number since it indicates how much of the light reflected off the lightlouver system gets reflected back to the interior (25%). Most (75%) of the visible light reflected off LL back toward the window goes back out the window.