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Author

Celik, Kemal

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HYBRID SIMULATION FOR DAYLIGHTING OF COMPLEX FENESTRATION SYSTEMS FOR BUILDING ENVELOPES

Kemal Celik[1,2], Alex R. Mead[3], Khalid Mosalam[3]
[1]Division of Engineering, New York University Abu Dhabi, Abu Dhabi, P.O. Box 129188, UAE
[2]Berkeley Education Alliance for Research in Singapore – BEARS, 138602, Singapore
[3]Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720, USA

ABSTRACT

This paper reports the status of new hybrid simulation for daylight analysis method under development. The method combines both full-scale physical measurements and computational techniques, providing analysis results of complex fenestration system (CFS) with increased realism while keeping costs in check and, for the first time, the repeatability of excitation conditions at full-scale. The simulation method divides the physics of daylighting into the two primary components: direct and diffuse light. Preliminary results of the diffuse component of the system and the current state of the heliodon is presented in the paper for a novel CFS known as translucent concrete panels for energy-efficient building envelopes.

INTRODUCTION

Daylighting within the built environment is currently facing a renaissance as part of the overall "green movement," with motivations ranging from increased health and productivity of the occupants to decreased energy usage of the different building systems (Edwards and Torcellini 2002, Aries, Aarts et al. 2015). As such, building designers are addressing daylight in unprecedented efforts not seen in more than a generation of modern building designs.

Daylighting analysis tools and techniques available today to the designer fall into three main classes: (1) rules-of-thumb, (2) physical models – reduced and full scale, and (3) computational models/simulation (Fakra, Miranville et al. 2011). Each class of analysis has respective advantages and disadvantages. For example: (1) is inexpensive and easy, yet has limited accuracy; (2) is expensive, requiring time and equipment to build, yet is quite accurate; and (3) is of moderate difficulty and comparatively inexpensive, yet has limited accuracy and cannot model the newest and most advanced daylighting technologies.

Simplified techniques such as "rules-of-thumb" are heuristic methods to predict illumination levels. Even though these methods are more tractable and easy to apply calculations, numerous assumptions are made to analyze daylight that generally decrease the precision (Reinhart 2014). A simplified method, for instance, may presume a consistent light position or homogeneous sky condition with simple parameters such as window height and room aspect ratios (Krarti, Erickson et al. 2005). The favored properties of the simplified technique over the physical or computed models involve easy evaluations with simple calculations and low-cost analysis. Yet, the shortcomings of this approach are loose calculations and the accompanying variations from realistic results.

Physical models and experiments for daylighting analysis come in two different categories; (1) full-scale, fully-physical testing such as the FLEXLAB at Lawrance Berkeley National Laboratory (Regnier, Mathew et al. 2016) and the BCA SkyLab at Building and Construction Authority (2) reduced-scale, fully-physical testing such as using either real sunlight (Thanachareonkit, Scartezzini et al. 2005) or artificial sky simulators (Center for the Built Environment 2007). In most cases, the ability to measure the real phenomena and averting modeling assumptions is the advantages of this technique. However, the two main drawbacks of the fully physical testing are the considerable time and cost associated with building physical models and running experiments (Mead and Mosalam 2015).

Computational modeling and simulation techniques are also a powerful analysis tool which is seeing increased use in industry (Larson and Shakespeare 2004) due to several reasons including ease of use, increase of computational power, and relatively low cost of analysis (Reinhart and Fitz 2006). In this method, engineers construct computational models of a space containing scene geometry, material properties and light sources (e.g. solar disk and sky-vault time series, electric luminaires). These models are then used in a simulation engine to compute various daylighting metrics including work plane illuminance, daylight autonomy, and others. There exist significant modeling and simulation exercises. Yet, the numerical techniques are limited due to the computational complexity and the assumptions employed in their construction. There might not be prepackaged component, for instance, that accurately represents the design analyzing. Besides, a numerical simulation requires a significant period of time for precise calculations. Therefore, there is still a healthy community of physical experimentation for daylight investigation.

In more current works, static integration of partial physical measurements, in the way that bidirectional light transmission/reflection distribution functions (BTDF/BRDF) of complex fenestration systems (CFS), with numerical simulation has been studied (Andersen and de Boer 2006, Reinhart and Andersen 2006, Mainini, Poli et al. 2012). This method demonstrates less error compared to the solely computational techniques; nevertheless, the accuracy would be improved with the dynamic interaction between physical component and simulated component.

It is well established that daylight can be analyzed using superposition of the two complementary of direct and diffuse daylight. Direct daylight travels from the Sun to the Earth without any obstruction. Diffuse daylight, on the other hand, is reflected, scattered, admitted and/or obstructed in the atmosphere or terresterially before entering the space (Reinhart 2014). Based on this fact and in order to overcome several of the shortcomings listed above, a new method using hybrid simulation techniques combining direct daylight analysis and diffuse daylight analysis is proposed below.

EXPERIMENT AND SIMULATION

The hybrid-simulation method presented here involving partitioning the physics of daylighting into direct and diffuse daylight by integrating heliodon and testbed components, respectively. The heliodon component involves a reduced-scale physical-based modeling and computational modeling on a custom built Heliodon. Besides, the testbed component is a full-scale physical-based measurement on a daylight testing facility. The automated and programmable control system that is involved in instrumental communication, data collection and storage is configured by using Python 2.7 language environment. Controlling the Heliodon and testbed programmatically allows for the rapid and repeatable investigation of a novel CFS under unique sky conditions. Figure 1 and Figure 2 illustrates how these elements are connected, as well as the relevant internal constituents and platforms.

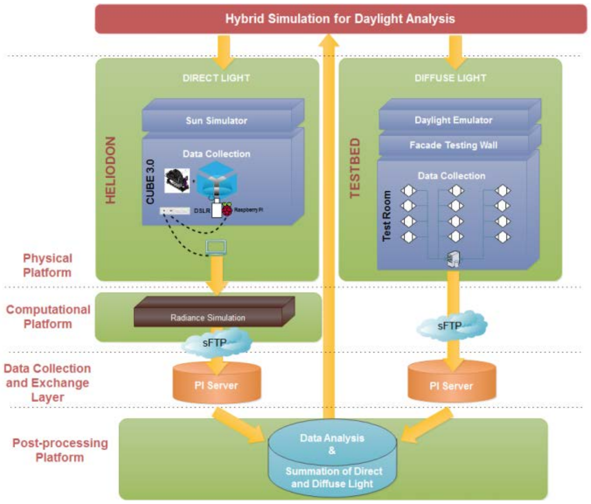
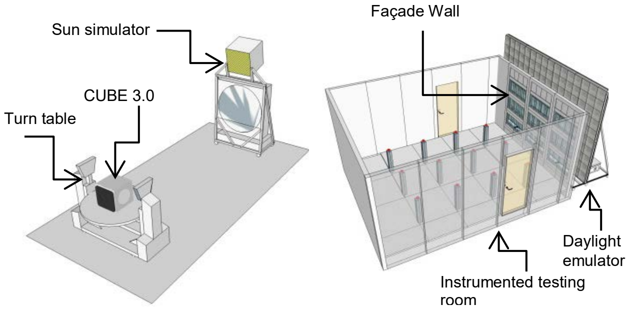


Figure 1 System architecture overview of hybrid simulation technique for daylight analysis



(a) *(b)*

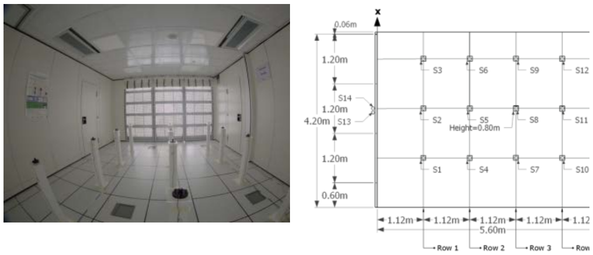
Figure 2 Schematic view of (a) testbed for full-scale measurement (b) custom built heliodon for reduced-scale measurement

The sun simulator and the turntable involved in custom built heliodon reproduces a given sky condition and a angle at which sunbeams strike the CUBE 3.0 where a panel of complex fenestration system (CFS) installed. The transmitted light into the CUBE 3.0 is measured on a hemisphere with a digital camera using high dynamic range imagaing as luminance of the CFS, $L_{direct}(D, \emptyset, \theta)$, in candela/m^2 (Mead and Mosalam, 2017). Transmitted light is governed by D, $\emptyset$ and θ which is the magnitude of direct light component, the azimuth and altitude of the sun simulator where the heliodon is dialed to, respectively. The collected data is transferred to a Radiance model which simulates the direct light distribution into the testing room at the particular locations where the sensors installed. The calculated light distribution is horizontal illuminance at a working plane of 0.8 meters. These values are calcuated using ray backpropagation to solve the Central Radiance Equation (Larson and Shakespeare, 2004). The final simulated results are stored in the central database server (PI server).

In parallel, the diffuse daylighting component is modeled using a full-scale room with three fixed walls and one demountable wall consisting of the same type of novel CFS at the heliodon component. Further, a unique instrument, called the Daylight Emulator (DE) (Fig.3a) with capability to portray varying daylighting conditions, is calibrated to reproduce the diffuse daylight component of same sky condition at the heliodon. The internal illuminance of diffuse light distribution at 12 locations of a full scale testroom is collected with EKO sensors and NI-CDAQ. The sensors are installed on the pillars with a height of 80 cm. The length of spaces among each row of sensors (Y axis) and column of sensors (X axis) is 112 cm and 120 cm, respectively. The exact location of sensors in the testbed is demonsrated in Figure 3c. The collected data is stored into the central database along with the simulation results.

The acquired direct (i.e. heliodon and Radiance simulation) and diffuse (i.e. testbed and DE measurements) components, of the daylighting physics for a CFS are then summed to provide the total horizontal illuminance distribution for the CFS under test for the given sky conditions.

a) Daylight Emulator



b) Full-scale room

c) The layout of tested and sensor location

Figure 3 Testbed for diffuse daylighting

To demonstrate the hybrid simulation for daylight analysis, it is considered to investigate a translucent concrete panel (TCP) that is an innovative light capturing façade consisting of optical fibers embedded in white-ultra-lightweight cement composite (WULCC). Ahuja et al. (Ahuja, Mosalam et al. 2015) studied a geometrical ray-tracing algorithm to find the tilt angle allowing maximum amount of light transmission on TCP. TCP cannot be modeled in Radiance because of the required high number of ray reflections to model its behavior correctly. Hence, it is a good candidate for the hybrid simulation method presented in this study.

On the façade wall 36 parts of TCP are assembled and excited utilizing the DE at the varying intensity representing different sky conditions. The dimensions of each panel are 44cm (in width)×38cm (in height)×5cm (in depth). The optical fibers consists of a cladding and a core that contains methyl methacrylate (MMA). Each panel contains 152 of optical fibers with diameter of 5mm (Fig. 4). The WULCC is made with white cement, silica fume, light-colored cenospheres and microfibers for the enhanced flexural strength of material. The WULCC is almost twice lighter than normal weight concrete, introducing a great benefit for dynamic properties of structure, also handling, transportation and installation of material (Günay, Celik et al. 2015, Günay, Celik et al. 2015). Further, it has been studied for energy savings impacts in buildings and is a promising material for future buildings (Ahuja and Mosalam 2017).

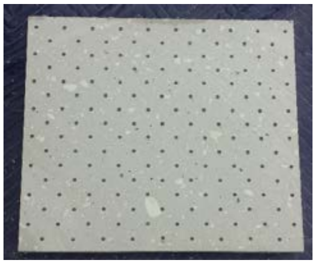


Figure 4: Translucent concret panels made with white ultra-lightweight cement composite

The CUBE 3.0 is currently in development and inspired by the previous version of it, CUBE 2.0, (Mead and Mosalam 2015) with a smaller sample size and enhanced discretization hemisphere that allows to appropirate installation of CUBE 3.0 on the turn table of heliodon component (Fig. 5). The maximum loading capacity and diameter of turntable is 15 kg and 1.40 m, respectively. The dimensions of CUBE 3.0 are 50 cm × 50 cm × 50 cm that is being built with aluminum frame and lightweight poplar plywood to keep the weight of Cube 3.0 in the limit. The proposed design uses an acrylic hemisphere with a diameter of 30 cm. A Raspberry Pi and camera (Mead and Mosalam, 2017) to measure the illuminance distribution on the hemisphere. The sample attached to the CUBE 3.0 is excited with sun simulator at the varying intensity representing the exact sky conditions with the DE. From this excitation, the CUBE

3.0 measures the luminous properties of the panel and transport the data to the computation domain for additional process. Using ray-tracing techniques, the luminance field measured by the CUBE 3.0 is tranformed into an IES file defining a luminare, which is read by Radiance. Afterward, the computation engine takes the created IES file defining the luminance distrubition of the TCP populates a Radiance model that represents the full scale room in the testbed component with a predefined array of locations on the floor (Fig. 3c).

Figure 5. The heliodon component:sun simulator and turntable

DISCUSSION AND RESULT ANALYSIS

While this paper is intended to emphasize the conceptual approach of the novel-hybrid-simulation technique, preliminary results of the testbed experiment are presented here as a first step. The varying sky conditions have a strong influence on the horizontal illuminance in the testing room. Figure 6 shows the measured-indoor-illuminance distribution of diffuse component of daylight. The outdoor sky conditions are reproduced for the diverse illuminance values ranging from 12025 lux to 83370 lux, representing between overcast-shade day and sunny day. The average illuminance of the three readings of first array is 134 lux, while it is 55 lux at the last array for the sky condition of 83370 lux.

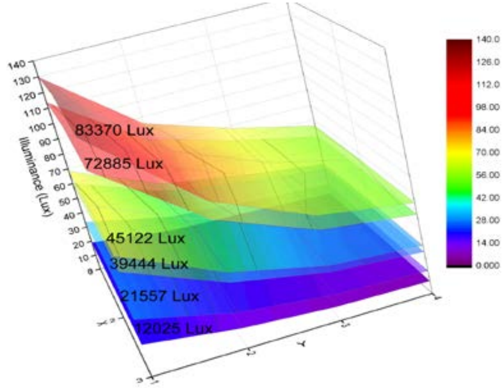


Figure 6: Distribution of measured indoor illuminance at different emulated-sky conditions through a CFS

Figure 7 illustrates that the degradation of horizontal illuminance was exponentially along with the depth of room. The reduction of illuminance readings between the first and the second, the second and the third, and the third and the fourth arrow is about 35%, 24%, and 17%, respectively for all the reproduced sky conditions.

The preliminary analysis of diffuse component of daylight demonstrates promising results; yet, there is no available results of direct light as the CUBE 3.0 is in development. The integration of the heliodon and testbed component will allow for the full evaluation of daylight not only the TCP but also on the different types of CFS.

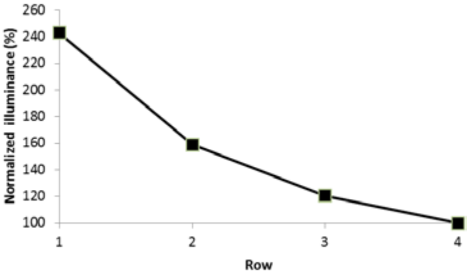


Figure 7: Average normalized illuminance distribution of each row with respect to row 4

CONCLUSION

This paper gives the status report on the development of novel-hybrid-simulation method that integrates direct and diffuse daylight analysis. The direct daylight analysis consist of full-scale physical based measurement and computational analysis, while the diffuse daylight analysis full-scale physical-based experiment on a CFS. This hybrid simulation technique is utilized within the cyber-physical system for high accuracy and optimized cost and, for the first time, the repeatability of excitation conditions at full-scale. The preliminary analysis of diffuse component of daylight is provided on the TCP as a CFS.

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