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Developing an advanced daylight model for building energy tool to simulate dynamic shading device

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ABSTRACT

Recent developments in materials engineering create a possibility of new building envelope systems to increase various aspects of building performance. One of the recent developments is a dynamically responsive material that changes its phase based on ambient environmental conditions. This is a major development in materials engineering, and exemplifies a material that responds to ambient temperature and changes its shape. This is a good candidate as a shading device that changes its location to block or allow sunlight during the daytime, to increase visible and thermal comfort of indoor spaces.

Current building simulation tools are limited in testing new materials. The major hurdle is that existing building simulation tools are developed for conventional materials and have difficulties in modeling new dynamically responsive materials. This paper presents a method to capture the complexity of physical behaviors in new material through building energy simulations. A more efficient simulation tool to test new materials will allow for more reliable results and the advancement in innovative building materials.

This paper develops a method to evaluate a new daylight control system that includes an analysis of a new dynamically tunable material. To assess the daylight control system composed with the new material, the paper integrates a daylight model, a whole-building energy model, and a Kriging model to evaluate the new system's performance.

1. Introduction

Recent developments in materials engineering attract tremendous interest in adapting new materials to improve building performance. Smart windows can become opaque to block or reflect direct sunlight to reduce solar gain, and can return to a transparent state in a low lighting condition to improve indoor light conditions (Azens and Granqvist, 2003; Ge et al., 2015; Thomas et al., 2015). These new materials are not limited to changes in optical phase but also include deformation of materials (Ou et al., 2011; Liu et al., 2012; Turpin et al., 2014; Zheludev and Plum, 2016; Lee et al., 2012; Attard and Grima, 2008; Dudek et al., 2015; Babaee et al., 2013; Florijn et al., 2014; Silverberg et al., 2014; Lv et al., 2014; Eidini and Paulino, 2015; Overvelde et al., 2016; Cho et al., 2014; Tang et al., 2015; Blees et al., 2015; Shyu et al., 2015; Song et al., 2015). These materials can dynamically change their shape in response to surrounding environmental conditions.

From the initial development of new materials to practical applications in actual buildings, new materials require different stages of computational simulations and experimental tests to ensure their intended performance. For this reason, new building materials are frequently simulated and tested in micro (nano) scale to show their potential. However, it is rare to see new materials that have been evaluated on a building scale.

The main reason is that it requires a significant amount of budgeting and time to examine performance in a full-scale test chamber or existing building. Furthermore, if the hypothesis of a new material behaves differently than expected when studied in actual building-scale, this new material then requires withdrawal back to the drawing board for revised design. Materials engineers are able to simulate material responses on small scales to study their performance. In contrast, it is difficult to test new materials in full-scale. For instance, at full-scale there are several uncertainties in the form of real world variables like climate conditions, unlike a controlled environment used at the microscale. This complexity creates an obstacle in the process of implementing this new material in actual buildings.

For these reasons, it is crucial to test new materials in a building-scale computational model to reduce this risk before developing a full-scale model. This paper explores the possibility of reducing the problem

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of scale-up materials evaluations that often occur from transitioning from micro- to building-scale. The paper proposes a computational simulation tool to investigate new material performances before they are fully deployed to an actual full-scale test.

Current building simulation tools have certain limitations that make it difficult to test new materials. Most building simulation tools are developed based on typical building conditions. For instance, most daylight models in building energy simulation tools were based on the Daylight Factor (DF) Winkelmann and Selkowitz, 1985 method. This is mainly because it is too computationally expensive to understand illuminance using advanced physics-based daylight simulations. In short, DF has difficulty addressing daylight conditions with direct sunlight. Literatures (Loura et al., 2009; Yi, 2016) have shown significant differences between daylight illuminance levels computed by energy simulation tools and by advanced daylight simulation tools.

Another major problem is related to capturing the dynamic state change in responsive materials. Current building energy simulation tools are limited in the modeling of daylight control systems. Tools have been developed to simulate static daylight systems, but it is difficult to simulate dynamic daylight systems. The previous literature (Tang et al., 2016) identified this difficulty of capturing physical change of systems with current energy simulation tools.

To eliminate the limitations on the accuracy of simulation tools and capturing performance of kinetic materials, the paper proposes a new method that integrates daylight simulation with building energy simulation to test the new dynamic material's performance. The paper utilizes a new dynamic material system called programmable kirigami structures that can be buckled out of a plane with deformation to reflect or transmit light or heat in response to local changes in solar radiance, lighting, and heat. They represent a potentially new class of adaptive energy-saving building envelope (Tang et al., 2016).

2. Current daylighting calculation in energy simulation

Generally, most advanced light simulation model use Radiosity and Ray-trace or both model to calculate light conditions. Radiosity is particularly good at diffuse effects (matte surfaces, indirect light) and Ray-trace model is good at specular effects (shiny surfaces). However, both models were too computationally expensive to be studied in real time. Even though only a few reference points are selected, it remains a big challenge for energy simulation tools to calculate illuminance for the whole year by hourly or sub-hourly periods. For that reason, energy simulation tools developed methods for calculating daylight that are referred to as simplified time steps (bigladdersoftware).

Instead of using Radiosity and Ray-trace, these energy simulation tools use methods derived from the daylighting calculation in DOE-2.1. First, reference points for one or two DFs are calculated, and then associated windows are integrated to calculate direct light from the window to the illuminance of reference points and the contribution of light reflected from the surrounding surfaces. This calculation is then conducted for clear sky and overcast sky conditions with 20 different solar angles (altitude and azimuth) that cover the annual range of sun positions. The illuminance is interpolated by multiplying the DFs with the current hour exterior horizontal illuminance calculated by the above factors (bigladdershftware).

To identify their limitations and possibilities, three currently possible models, namely DELight, SPOT, and Daysim, were investigated. DElight is a simulation engine for daylight and electric lighting system analysis in buildings. It can calculate interior illuminance levels from daylight and the subsequent contribution required from electric lighting to meet the desired interior illuminance. This is done with user-specified reference points, to evaluate how much electric lighting can be reduced while still achieving illuminance targets. More specifically, DElight provides daylighting analyses of simple apertures (windows/skylights), complex geometric fenestration systems (roof monitors), and optically complicated glazing (prismatic or holographic glass). Factors of daylight illuminance levels include exterior light sources, location, size, visible light transmittance, reflectance of interior surfaces, and the location of specified reference points. DELight can be further utilized for building thermal simulations on a time step basis. Despite its advanced methodology, the energy simulation results from DELight were noticeably different from RADIANCE simulation results (Yi, 2016). Even though DELight is able to capture thermal performance of devices, it uses a simplified calculation method that it is difficult to use to simulate the dynamics of shading devices.

SPOT, Sensor Placement + Optimization Tool, is a user-friendly daylighting tool that calculates electric lighting performance, annual daylighting results, and performance metric reports are provided with photo sensor placements. It evaluates annual daylighting characteristics and daylighting designs, it quantifies electric lighting performance, provides photo sensor system placements/settings, and produces standard metric reports (LEED, CHPS, UDI, and IgCC). The photo sensor analysis provides photo sensor placement and simulates optimization for qualitative (light levels) and quantitative results (energy savings). However, only a limited number of sensors can be used in simulation. It's also worth noting that SPOT employs simplified energy simulation, and therefore the energy simulation result is doubtful.

Different from DElight and SPOT, DAYSIM is an advanced dynamic shading model that can simulate dynamic shading systems for blinds that cover parts of a façade. A limiting factor is that users must specify the shading states in the order of "most opened" to "most closed." This includes fully retracted, fully lowered with slats horizontal, or fully lowered with slats at 45°. The tool will always start with the most opened state followed by closing the shading, and then successively close the shading group until glare can be avoided. DAYSIM also requires a RADIANCE file and material properties, including geometry. Although it is informative, it can be quite time-consuming due to the number of ray-tracing runs required. In addition, it confines shading to limited states (closed, open, or 45°) that make it difficult to capture various changing states of shading devices.

From the discussions above, it can be seen that current daylight models built in building energy simulation tools are developed for static (fixed) shading devices. It will be challenging to apply current simulation tools to adaptive and dynamic building envelopes like the dynamic kirigami structures studied in this paper.

3. Programmable Kirigami

Kirigami originates from the ancient Japanese paper art, which is a close cousin of origami, the paper art of folding. "Kiri" means "cut" and "gami" means "paper." Compared to folding-based origami, kirigami combines cuts or cut-outs with folding, thus brings an extra level of design, dynamics, and deployability to open and close a thin sheet of materials in micro scale, macro scale, and even building scale.

After introducing a pattern of discrete cuts, the original non-expandable thin sheet becomes highly expandable upon stretching. Meanwhile, the originally closed line cuts will be open and the struts between cuts will tilt out of plane depending on the level of stretching. When coated with certain reflective substances on its surfaces, the angled and tilted faces of the expanded sheet will reflect or transmit light or heat in response to local changes of solar radiance, lighting, and heat.

Fig. 1a shows a simple kirigami model structure generated after introducing parallel cuts to a continuous thin sheet with width W_o and length L_o. The geometry of the representative unit cell of the kirigami structure can be characterized by the cut length l, the axis distance h, and transverse distance d between two cuts. When we apply mechanical stretching with its direction perpendicular to the cuts, the connecting struts between cuts will buckle and tilt out of plane with a certain angle θ to open the pore. The tilting angle θ is defined as the angle with respect to the z-axis (Fig. 1b).

Upon further stretching, the pore size increases and the tilting angle