Experimental validation of daylighting simulation methods for complex fenestration systems

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Abstract

The objective of this paper is to assess the capability of existing lighting simulation methods to predict the performance of complex fenestration systems, which are becoming a commonly used component in buildings construction domain. A specific experimental protocol was conducted to collect reliable reference data based on illuminance measurements inside a black box with (and without) one complex glazing sample facing a measured external luminance distribution. Two types of simulation methods were tested and compared: The first is based on modeling the glazing sample in a ray-tracing simulation program and the second is based on use of the samples' BTDF data. The BTDF data sets were combined with the external luminance distribution to predict the flux distribution inside the room and the resulting illuminance values at the reference points. The comparison between the experimental reference data and the simulation results showed that the influence of the CFS could be predicted with good accuracy.

1. Introduction

Since the early nineties, Complex Fenestration Systems (CFS) made their way to the buildings of the 21st century. The first objective of using CFSs is to optimize the availability and uniformity of daylighting inside buildings and to contribute to reducing energy consumption for artificial light during daytime. Predicting the performance of such systems is one of the main difficulties facing the lighting simulation domain.

Many efforts are being investigated internationally to propose new experimental methods for assessing the Bi-directional Transmission Distribution Function (BTDF) of CFS (1, 2) as well as alternative approaches based on ray-tracing simulations (3, 4, 5). The extent to which such simulation methods are accurate is, however, difficult to verify, and predicting the performances of CFS in buildings hence appears as a critical issue. This difficulty is mainly related to the lack of reliable validation data and to the usually high uncertainties in existing experimental reference data (6, 7).

Within this context, this paper proposes and applies a validation approach for assessing the capability and accuracy of existing methods in predicting the performance of a CFS with regard to the illuminance distribution inside a room.

2. Experimental set-up for reference data

To assess the influence of a CFS on the illuminance distribution inside a room, an experimental set-up including a scale model, an artificial sky, a calibrated CCD camera and different photosensors was set-up. The illuminance variation inside the scale model was measured with and without a CFS sample over the opening surface. For each measurement point, the ratio determined the directional transmission of the sample in the direction of the measurement point due to the external hemispherical luminance distribution. This ratio is used as a reference value to which the results of the tested simulation methods will be compared; in this paper, it will be referred to as the hemi-directional transmission (HDT).

2.1 Scale model description

The scale model is a wooden cubic box of dimensions of 80cm×80cm×60cm with a 20cm×20cm (3.6cm thick) roof opening, and with matt black interior surfaces (4.5% reflectance) (7). (see Figure 1 (a))

Photocells were accurately positioned inside the scale model at various locations on the floor, wall surfaces, and on the opening level for external illuminance measurements.

The positioning system provided by the scale model for a CCD camera with a Fisheye lens was used to measure the external luminance distribution as seen from the opening surface level (see Figure 1(b)).

Figure 1

2.2 Luminance maps measurements

To minimize error sources related to the description of the external luminance, we measured the external luminance distribution simulteneously with the illuminance measurements inside and outside the scale model. The luminances were measured by using the Photolux system (7, 8), based on the use of a calibrated CCD camera (Nikon^{TM} Coolpix model 990) equipped with a fish-eye lens and a dedicated software. The Photolux software produces from one or more photos (with different exposures) a luminance map of about 360,000 values providing a quasi-continuous representation of the luminance of a scene. The luminance maps were saved in the Radiance sky format in 1° and 5° steps or into an equivalent intensity distribution file using the IESNA format.

2.3 Scenarii and experimental protocols

Two different types of scenarii were tested, the first with a Serraglaze^{TM} sample under an artificial sky, the second with an LCP sample under external real sky.

Figure 2

2.3.1 Serraglaze^{TM}

The Serraglaze^{TM} material is an optically variable device made of two identical crenellated plastic panels facing each other and shifted by half a period to fit into each other (see Figure 2(b)). The geometric features were given by the manufacturer, and could not be experimentally verified on the available sample.

The Serraglaze^{TM} scenario was conducted inside the artificial sky of the ENTPE, which has a dimension of 2m×2m×2.1m. The Serraglaze^{TM} sample was positioned at the top of the roof opening (see Figure 1(a)), with the linear air gaps perpendicular to the measurement axis. Six measurement points were used inside the model: 4 at the floor and two at a wall surface.

2.3.2 Laser Cut Panel

The Laser Cut Panel (LCP) is made of an acrylic panel of thickness 6 mm and dimensions 300 x 300 mm, through which a series of parallel cuts were made with a laser beam every 4 mm (the cuts themselves extend over 0.3 mm, see Figure 2(a)).

The LCP scenario was conducted on the roof of ENTPE with negligible surrounding masks and under an intermediate sky condition. The sample was positioned at the top of the roof opening with the panel's cuts perpendicular to the measurement axis. Nine measurement points were used inside the model (7 on the floor and 2 on a wall surface) in addition to the one for the external illuminance.

2.4 Estimation of the uncertainties in the reference data

Uncertainties related to the description of the scenarii and to the measurements were estimated and taken into consideration (as tolerance limits) for an objective comparison with the simulation results (6). The different considered error sources are as following (7): photocells calibration, photocells cosine correction, spectral sensibility, flux variation, photocells position, near field, surface reflectance, geometry dimensions, sample position, and the external luminance distribution. The measurements’ uncertainty for the hemi-directional transmission was estimated to +/- 10% for the Serraglaze scenario and to 15% for the LCP scenario.

3. Assessment of BTDFs

Three of the four presented simulation methods in this paper are based on the use of BTDF data. The BTDF data of the tested samples were obtained by means of three different methods: one experimental approach based on digital imaging techniques, and two numerical methods based on ray-tracing techniques. A short description of these methods is given in this section while detailed information can be found in (9).

3.1 Bidirectional video-goniophotometer

The experimental assessment of BTDFs was achieved with a bidirectional goniophotometer based on digital imaging techniques developed at LESO-PB / EPFL. The light flux emerging from the investigated sample is collected by a diffusing flat screen, at which a calibrated Charge-Coupled Device (CCD) camera is aiming, used as a multiple-points luminance-meter. To cover all possible emerging directions (2π steradian), the camera and the screen perform rotations of a 60° angle magnitude.

3.2 Numerical goniophotometers

LESO-PB / EPFL

The experimental conditions described above were reproduced virtually with the commercial forward ray-tracer TracePro® based on Monte Carlo calculations (5). The simulation model included a detection screen (of 6 pannels covering 360°) and a model of each sample as close as possible to the physical elements.

The rays were emitted from an annular grid, composed of 45 rings and sending about 6000 rays at wavelength 555 nm.

FHG-IBP

The FHG-IBP Numerical Goniophotometer represents an automated environment allowing to configure the virtual test set up, to parameterize and combine CFS samples, and to post-process data for further use in daylight simulation. The environment is based on the commercial forward ray tracing tool OptiCad™ and generally follows a flux based method. Generators for different kinds of CFS (like prismatic elements, laser cut panels, venetian blinds, etc.) are provided.

3.3 BTDF datasets and related error sources

The BTDF of both a Serraglaze™ sample and the Laser Cut Panel were determined experimentally (measured) with the bidirectional video-goniophotometer and computationally (calculated) with both numerical goniophotometers. The samples have been numerically modelled according to the manufacturer's specifications.

While the BTDF datasets of both the Laser Cut Panel and the Serraglaze™ showed very close qualitative behaviours between measured and simulated values, the hemispherical transmission values deduced from measurements were significantly lower than for both simulated datasets. For the Laser Cut Panel, this can be explained by the manufacturing inaccuracies. The Serraglaze™ showed bigger differences between measured and simulated data, which most likely are related to the assumptions on geometry and material of the simulated sample. Also manufacturing inaccuracies are inevitable.

4. Applied simulation methods

Two types of simulation approaches were tested: simulations using the samples' BTDF data and simulations based on ray-tracing only (Radiance based simulations).

4.1 Simulation methods using BTDF data

The common procedure for the BTDF based simulations is to combine the measured or calculated BTDF data with the outside luminance distribution to calculate a resulting flux distribution.

4.1.1 Equivalent luminaire method - ENTPE

The ENTPE method for CFS simulations is based on replacing the sample inner surface by an equivalent luminaire associated to an equivalent intensity distribution, which is obtained from the Photolux sky luminance map and the LESO-PB/EPFL measured BTDF data.

To create the equivalent intensity distribution, the 360,000 luminance values from Photolux were first reduced to 145 values representing the average luminance of the 145 zones (covering the whole hemisphere) at the incidence directions for which the BTDF data was measured.

For each of the 145 zones, resulting illuminance at the sample surface was calculated and multiplied by the BTDF value at each of the transmission directions of the BTDF data (every 5 degree in azimuth and zenith) to obtain the transmitted luminance in these directions.

For each transmission direction, the total transmitted luminance was obtained from the addition of the transmitted luminances from the 145 zones (at the incidence directions). This total luminance was then transformed into an intensity value that is equivalent to the combination of the sky and the material (in the given transmission direction).

The obtained intensity values in the different transmission directions were saved into an intensity distribution file using the standard IESNA format. This file was then used to conduct a lighting simulation within Lightscape 3.2.

The simulations with an empty opening were conducted by using the intensity distribution files (1° resolution) produced by Photolux from the measured luminance maps.

4.1.2 CFS algorithm - FHG-IBP

The algorithm is independent of specific lighting simulation programs and generally can be incorporated into different standalone tools like CFS databases and lighting simulation engines.

The main difference in this method is in the use of special filters to pre-process the raw data to avoid artifacts and wrong predictions of the candle power distribution, which can result from the fact that the data resolution on the incident side (145 points) is normally significantly lower than the resolution on the emerging hemisphere. These filters are based on the geometric relations of the hemispherical subdivision scheme. This corresponds in general to a low-pass filtering of the data, i.e. reducing high frequent components and therefore attenuating “bumby” BTDF components in the final intensity distributions. The effect is illustrated in Figure 3.

Figure 3

For this study an implementation of the method into the RADIANCE program system was used. CFS were computed based on both measured (LESO) and simulated (FHG-IBP) BTDF datasets.

4.1.3 DElight

DElight is a general-purpose, radiosity based, daylighting analysis tool (10). The procedure followed to obtain the results can be described as following:

The CFS aperture surface was gridded to 20x20, interior wall surfaces were gridded to 60x80, and the floor interior to 80x80.

The LESO-PB/EPFL BTDFs were pre-processed into an internal DElight data representation, preserving the incident (Tregenza) directions and with a transmitted resolution based on 1250 equally distributed angular directions. Those pre-processed BTDFs were then used with the Radiance sky files in a sky-BTDF integration, to produce a directional luminance map of the light transmitted through the CFS in the aperture into the test box.

Internal surfaces were not defined for 3.6cm high edges of the finite-depth aperture. The actual aperture opening height was assumed to be 63.6cm above the floor for the empty opening and 64.3cm when the CFS was placed over the aperture. DElight instead uses an approximate “Reveal-depth” algorithm.

Because of the low (4.5%) internal surface reflectance, the inter-reflection calculations were limited to a “one-bounce” approximation.

4.2 Ray-tracing based model (Radiance)

This method is based on a calculation algorithm developed to model and simulate LCP in Radiance program system. The LCP transmits and reflects incident light rays, generating three possible emergent rays: the reflected, deflected and undeflected beams. For each ray incident upon an LCP, a linked function file calculates the fractions reflected, deflected and un-deflected, and the directions of these emergent beams (11).

The LCP was modeled in Radiance using the *prism2* material primitive. This material primitive is used to simulate light redirection from prismatic glazings. Using this algorithm, it is possible to model any geometry involving the LCP with cuts normal to the panel surface. The model treats the LCP as a macroscopic entity of homogeneous light redirection properties, rather than a microscopic entity comprising several small air gaps. Multiple internal reflections and internal losses are considered. Two ray redirections are passed to the output, those being the most important of the three possible components.

LCP simulations were performed using Radiance (Desktop Radiance v2.0). The material has a refractive index of 1.49 and D/W ratio 0.66667 (thickness 6mm, cut spacing 4mm). High quality simulation parameters were created, with ambient calculation parameters -ab 6 -aa .125 -ad 512 -as 256 -av 0 0 0.

4. Comparison between simulation results and measurements

4.1 Serraglaze^{TM} scenarii

Bare opening results: Good agreement with reference data was generally observed for the majority of simulation results that were either within the tolerance bounds or very close to the lower boundary (see Figure 4(a)). The exception was for DElight at the upper wall point.

Serraglaze results: Good agreement with reference data is generally observed for DElight and FHG-IBP-Measured BTDF results, but not for the FHG-IBP-Calculated BTDF and ENTPE results. Same as for the bare opening, DElight results showed less agreement at the wall points.

Hemi-Directional Transmittance (HDT) results: Observations were similar to those made for the Serraglaze results with a slightly lower agreement. (see Figure 4(b))

Figure 4

4.2 LCP Scenario

The reference data of the LCP scenario was particularly interesting by highlighting the bi-directional effect of the CFS thanks to the directionality of the sky luminance map.

Bare opening results: Good agreement with reference data was generally observed for the majority of simulation results where only the predictions provided by the FHG-IBP and Radiance algorithms extended outside of the tolerance bounds. The highest disagreement was observed at the wall upper point for FHG-IBP simulation. (see Figures 5(a)

LCP results: All methods gave results within the tolerance bounds except for ENTPE simulation where illuminance values were under-predicted at floor points 6 and 7.

HDT results: Observations were similar to those made for the LCP results except for the FHG-IBP results at the wall upper point (see Figure 5(b)), which reflects the disagreement observed at this point for the FHG-IBP opening results.

Figure 5

4.3 Results analyses

Based on the results and the observations presented above, the following points could be highlighted:

- The decrease in agreement between FHG-IBP-Measured BTDF and FHG-IBP-Calculated BTDF for the Serraglaze scenario can be attributed to the difference in the BTDF data. It can be supposed that this difference is mainly related to the accuracy in the description of the sample knowing that this description could not be confirmed by the manufacturer.
- DElight disagreement at the upper wall point for the Serraglaze scenario can be attributed to the approximations of the window reveal-depth algorithm.
- ENTPE disagreement for LCP results (with the sample) can be attributed to the bumpiness of the calculated intensity distribution as discussed in section 4.1.2.

5. Conclusions

The applied validation approach showed to be useful in assessing the capabilities of the tested simulation methods in predicting the performance of CFS under given sky conditions. The simplicity of the test cases allowed to identify the error sources of the simulation methods.

The results of this study proved the capability of the tested methods to quantitatively simulate CFS light distribution effects in the room: Overall, the comparison of reference data and simulations showed quite satisfactory results. A few difficulties were identified. However, given the quite complex CFS materials and simulation algorithms involved, these results are encouraging. The level of accuracy achieved in this study should be acceptable for design studies.

This work also showed the importance of the accuracy in describing the CFS for ray-tracing simulations or for methods using calculated BTDF. The incident and emerging side resolution of the measured or calculated BTDFs showed to be an important issue too.

The study should provide confidence in the use of recently emerging BTDF based simulation engines in daily design practice; leading to a better understanding of the impact of complex fenestration systems on daylighting as well as the overall energetic building design.

6. References

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Figures

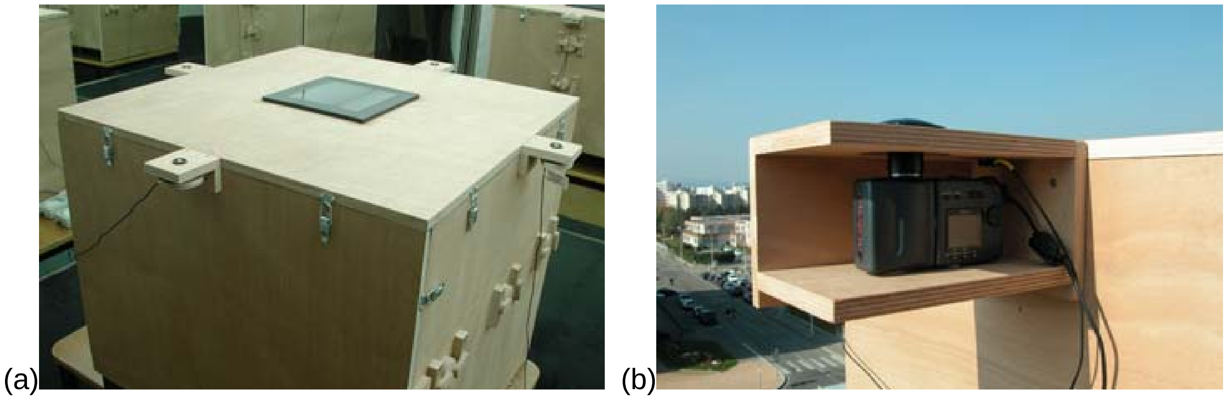

Figure 1. (a) Scale model with the Serraglaze™ sample over the opening surface. (b) Camera positioning system for real sky scenario

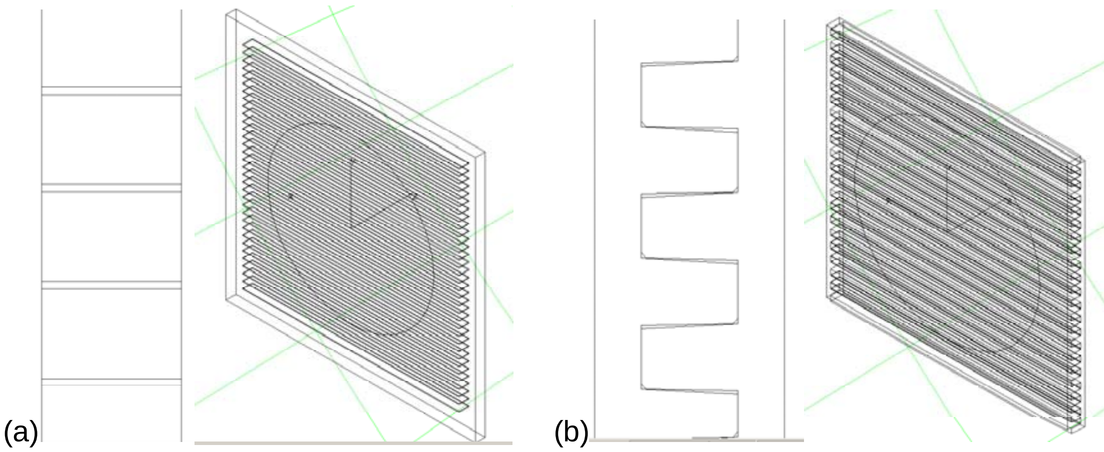

Figure 2. Illustration of the considered complex glazing materials. (a) Laser Cut Panel. (b) Serraglaze™.

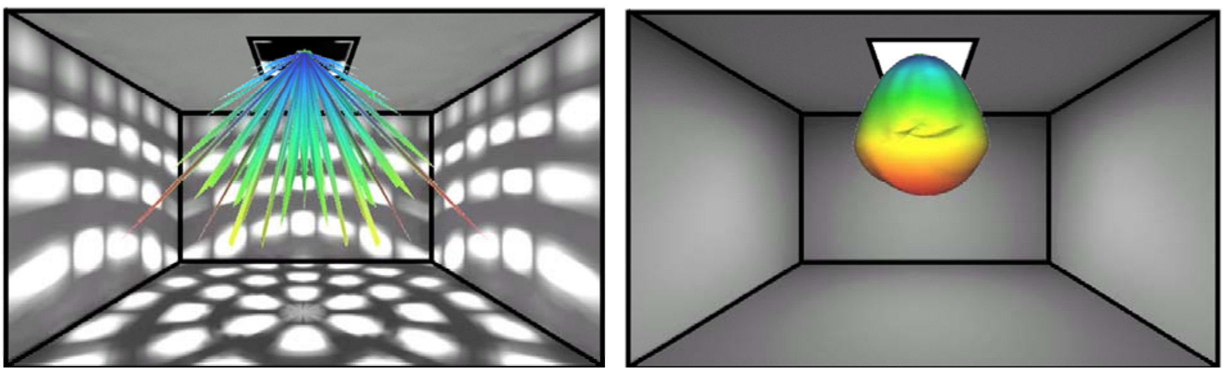

Figure 3. Influence of filter corrections. Left: Superposition of the *unfiltered* indicatrices of diffusion. Right: Superimposed *filtered* indicatrices of diffusion.

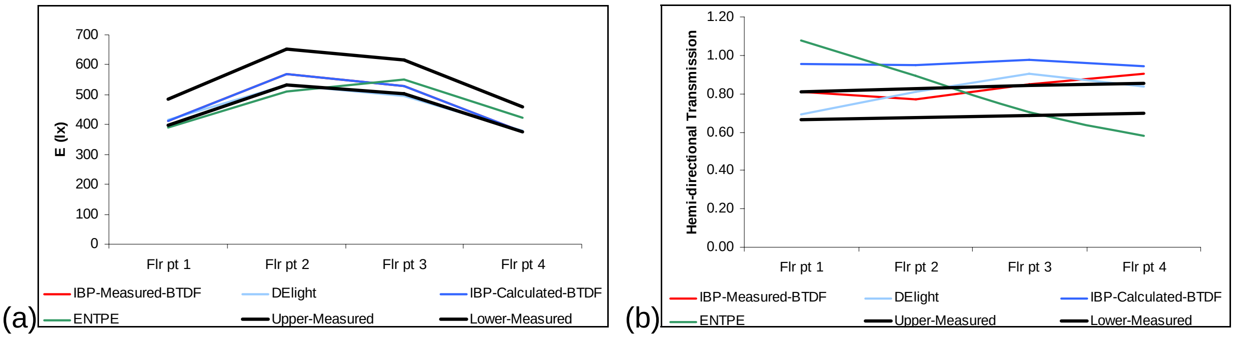

Figure 4. Serraglaze scenario - floor results. (a) bare opening results, (b) HDT results

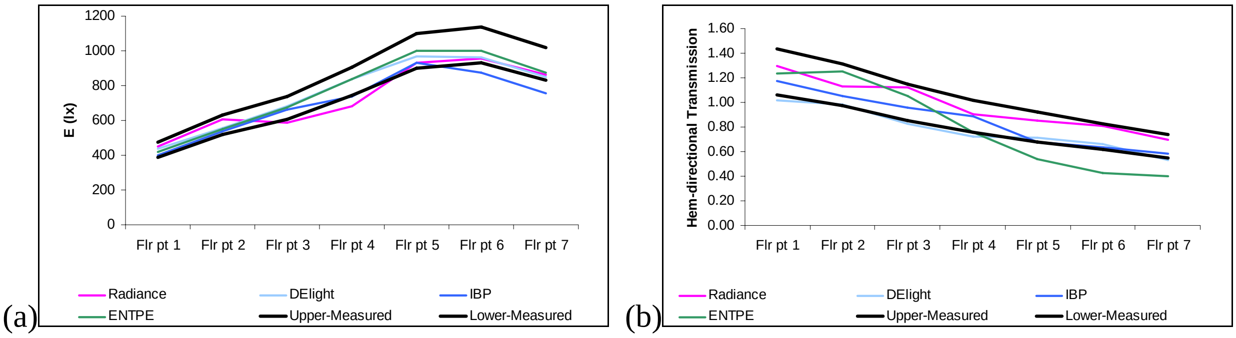

Figure5. LCP Scenario - floor results. (a) bare opening results, (b) HDT results

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