OR-16-C055

Off-Normal Solar-Optical Performance of Pleated Drapery: Simulation versus Measurement

Ned Huang
Student Member ASHRAE

Mike Collins, PhD
Member ASHRAE

John Wright, PhD
Member ASHRAE

ABSTRACT

In recent years, significant advances have been made in modeling fenestration with shading attachments. Most shading devices have great potential for reducing both peak building cooling load and annual energy consumption through the control of solar gains, and the ability to quantify their impact is important. As part of an ASHRAE sponsored research project, several new models were developed for various types of shading devices. One of the most complex of these was the pleated drapery model. This model uses off-normal solar-optical fabric properties to predict the off-normal solar-optical properties of the pleated drapery. In doing so, the model assumes that the system could be represented as a series of uniformly arranged rectangular pleats. The work presented here aims to validate model performance. A Broad-Area Illumination Integrating Sphere (BAI-IS) was used to perform solar transmittance measurements on pleated drape samples. The BAI-IS is capable of measuring optical properties of thick and non-uniform samples. Five pleated drape samples composed of fabrics with different transmittance and reflectance were used in measurements. Results were compared to the model output for different incidence angles. Predicted transmittances were generally within ±0.05 of measured values although there could be an overprediction as much as +0.11 for normal incidence test cases of high transmittance test samples. This discrepancy can be attributed to the geometric difference between the model and the test samples.

INTRODUCTION

Background

Sustainability has become an important pursuit. New buildings are being designed to have good insulation, allowing little heat transfer. Solar radiation is a natural and renewable source of light and heat for buildings. Window areas that are subject to high solar heat gain may cause overheating of a well-insulated building. As well, solar heat gain is usually the largest and most variable heat gain that affects cooling loads of a building. This is especially true given the current architectural trend toward highly glazed facades in commercial buildings.

Indoor space conditioning of a building would be much simpler if window areas could be replaced by walls. Yet windows create aesthetically pleasing spaces in any building design. The key is to find an acceptable and optimized balance among competing factors of building design (e.g., comfort, daylightlighting, energy conservation, indoor environmental quality, view, and etc.). One option is to use a complex fenestration system (CFS), i.e., a window

Author Huang is a Ph.D. candidate in the Department of Mechanical and Mechatronics Engineering at the University of Waterloo, Waterloo, Ontario Canada. Authors Collins and Wright are professors in the Department of Mechanical and Mechatronics Engineering at the University of Waterloo, Waterloo, Ontario Canada.

system that incorporates one or more shading elements. CFS has become essential in meeting multiple objectives of building design, including high building energy-efficiency and lower peak energy demand.

CFS is conventional, economical and is commonly used to regulate sunlight and solar heat gain in high performance buildings. As energy efficiency requirements are increasingly demanding and indoor environmental quality remains a high priority, the ability to accurately predict window energy performance and quantify the impact of shading devices becomes more important than ever before.

Ongoing Research and the Pleated Drape Model

A generalized mutil-layer framework (Wright 2008) has been developed to predict center-glass energy performance indices of glazing systems with shading devices. The impact of a fenestration system on energy consumption can be calculated if the solar optical and thermal properties of individual layers in a CFS are known. Individual layer models for determining the solar optical and thermal properties of each layer in the window system have been developed through ASHRAE sponsored research projects (Barnaby et al. 2009). Effort has also been made to implement shading layer models into building simulation software (e.g., Wright et al. 2011). Of particular interest is the pleated drape layer model developed by Farber et al. in 1963 and refined by Kotey et al. in 2009.

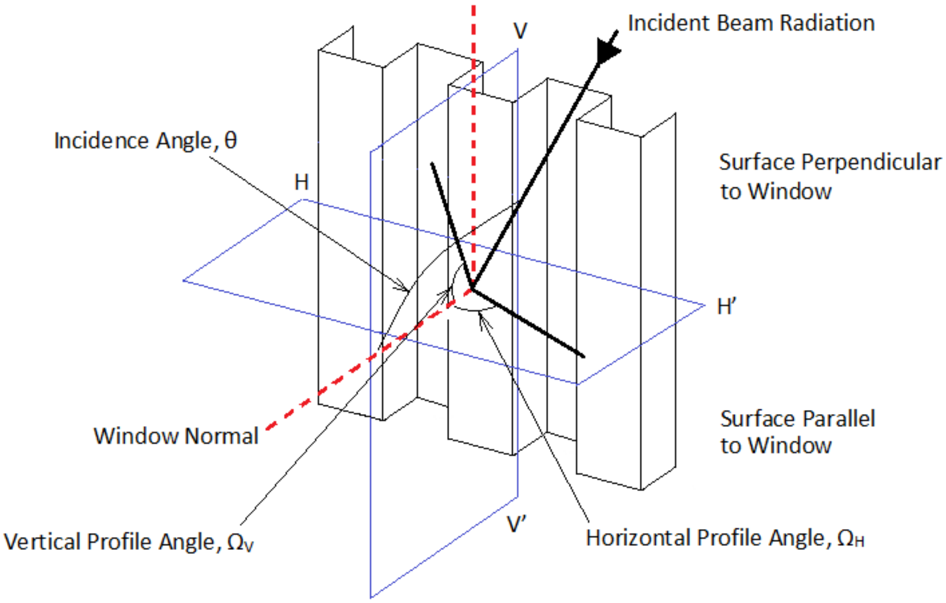


Figure 1 Configuration of pleated drapery model showing solar angles (Kotey et al. 2009).

When beam radiation is incident on a drapery, a fraction of it can be transmitted unobstructed through fabric openings (beam-beam transmission) with the rest being scattered forward (beam-diffuse transmission) and backward (beam-diffuse reflection) through multiple reflections whin the drapery layer. The pleated drape model (Koteys et al., 2009), which is geometrically represented as a series of uniformly arranged rectangular pleats (Figure 1), calculates the effective solar properties of pleated drape layer based on these beam and diffuse radiation components. The model uses angle-dependent properties of the flat fabric in conjunction with drapery geometry and solar angles to calculate the effective solar properties for both incident beam and diffuse radiation. Therefore, the off-normal solar-optical properties of a pleated drapery layer can be determined based on the off-normal solar-optical properties of flat fabric, folding ratio, and incident angle, θ. Koteys et al. (2009) provides a detailed formulation of this model.

The present work aims to validate the pleated drape layer model. A Broad-Area Illumination Integrating Sphere (BAI-IS) was used to perform measurements on pleated drape samples. In this study, total solar transmittance, τ_t, was measured. The BAI-IS is capable of measuring optical properties of thick and non-uniform samples. Pleated drape samples composed of fabrics with different transmittance, $\tau_{t,f}$, and reflectance, $\rho_{t,f}$, are used in measurements. Finally, results are discussed and compared to the model output for different θ.

EXPERIMENT – TRANSMITTANCE OF A DRAPE LAYER

Flat Fabric Measurements Using Commercial UV-Vis-NIR Spectrophotometer

The pleated drape model relies on the solar optical properties of flat fabric as input. A commercially produced spectrophotometer, which is designed for photometric measurements in the 250-2500 nm range, was used to measure the required properties. The spectrophotometer is equipped with a 110 mm diameter integrating sphere. An integrating sphere is a hollow sphere with its inner surface coated with a layer of high reflectance material. An integrating sphere collects and integrates, spatially and directionally, all incoming radiation. Its inner surface is assumed to be Lambertian. An integrating sphere usually has at least one inlet port to admit light and an exit port where detectors are located. One particular technical guide (Labsphere 2013) provides a good discussion on integrating sphere theory and applications.

Construction of Drape Samples

A drape sample frame has been built to support fabrics and for making pleats. The frame is designed to hold strings (fishing line) vertically that enable a piece of soft fabric to fold and wrap around these strings in order to form rectangular pleats. The arrangement of strings will determine the pleat size and folding ratio (Fr) of a sample, which is defined as the ratio of fabric width to the width of window area to be covered. So to cover the whole window area, a minimum of Fr = 1.0 is required (i.e., flat fabric). Figure 2 illustrates various folding ratios. For rectangular pleats, $Fr = 1 + w/s$ where w is pleat depth and s is pleat spacing. Most common folding ratios for drapes range from 2.0 to 3.0. For this study Fr = 2.0 (s = 2 cm and w = 2 cm) was used.

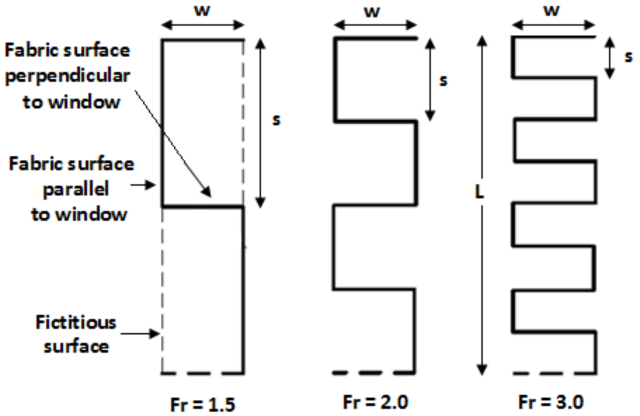


Figure 2 Illustration of folding ratios (Fr) in terms of rectangular pleats.

Note that pleats do not naturally stay in a rectangular shape. Therefore, it is almost impossible to make the folds perfectly square. Although efforts have been made to tighten the strings and make the pleats as close to square as possible, some smooth irregularity can be observed in the test sample folds.

Pleated Drape Layer Measurements Using the BAI-IS System

While the commercial spectrophotometer is easy to use and has excellent capabilities, it cannot measure the solar optical properties of thick and/or spatially non-uniform samples. The commercial spectrophotometer has a small integrating sphere, and therefore a small inlet port. The small inlet port cannot capture all the scattering light. This is known as out-scattering loss. Also, the narrow beam of incident light source cannot irradiate a representative (broad) sample area.

The Broad-Area Illumination Integrating Sphere (BAI-IS) system is a custom-built spectrophotometer specifically designed to overcome the limitations of the commercial spectrophotometer. First, it has a larger integrating sphere with an inlet port area that is big enough to cover a representative area of a non-uniform sample. Second, the radiant source illuminates a large sample area, allowing in-scattering gain to offset out-scattering loss.

The BAI-IS system consists of the following components and sub-systems: radiant source system, sample mount structure, integrating sphere and monochromator, and control and data processing system. Figure 3 shows a schematic layout of the BAI-IS system.

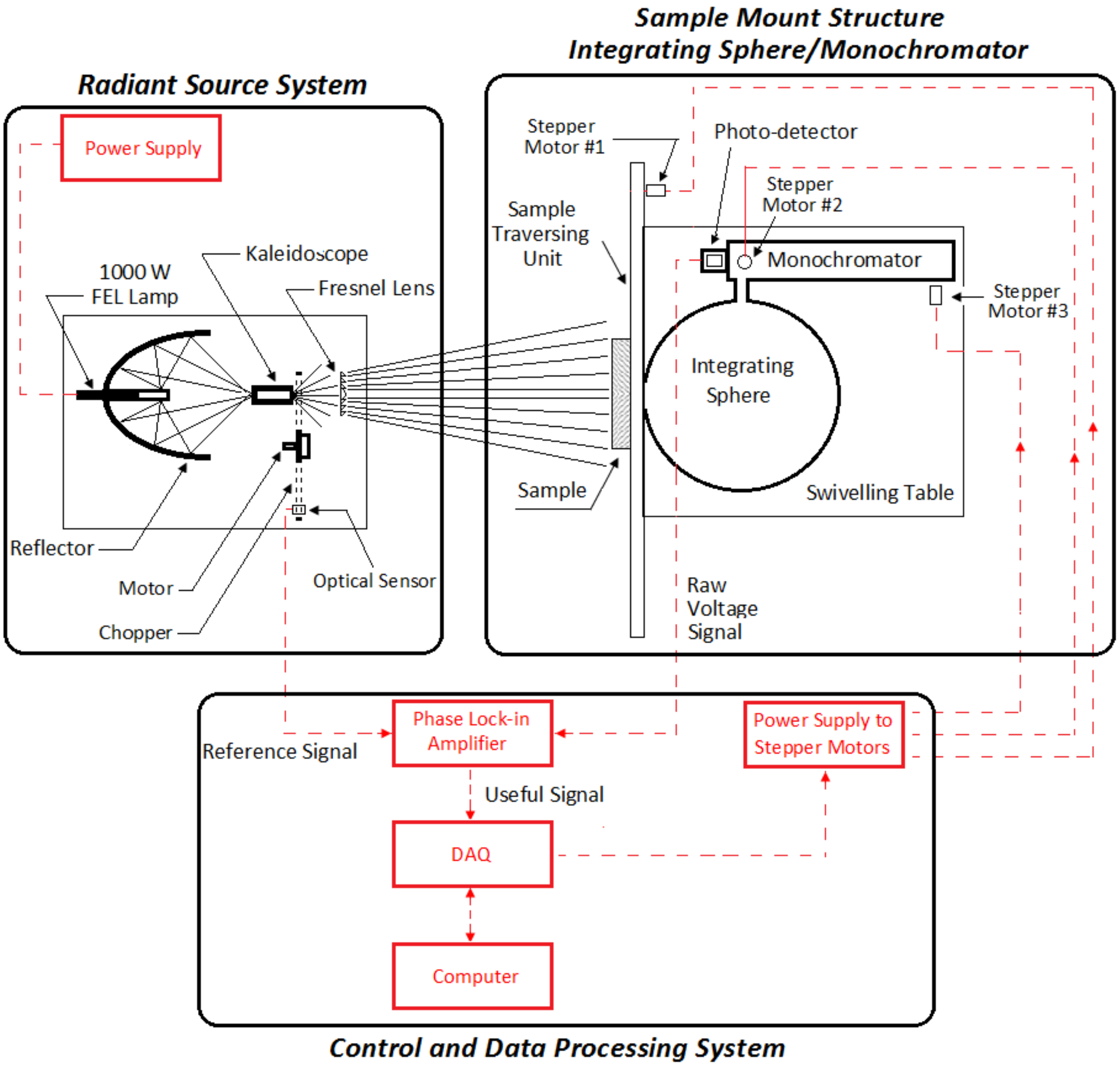


Figure 3 A schematic layout of the BAI-IS system that consists of several sub-systems.

Test Matrix

Keyes universal chart (Keyes 1967) categorized fabrics into nine groups, by weave openness (Open_I, Semi-open_II, and Closed_III) and yarn color (Dark_D, Medium_M, and Light_L). Openness, A_o, is defined as the beam-beam transmittance at $\theta = 0°$. Keyes chart does not cover sheer fabrics ($A_o > 50\%$) that is also a popular choice for draperies. For the purpose of this study, three more groups (S_D, S_M, and S_L) have been added for fabrics with very high A_o. Classification using the Keyes chart and the three additional groups for sheer fabrics are shown in Table 1. Samples chosen for experimentation were I_D, III_L, S_M, and S_L.

Table 1. Classification of Drapery Fabrics by Openness (A_o) and Yarn Color

	Dark (D)	Medium (M)	Light (L)
Sheer (S) (> 50% open)	S_D	S_M	S_L
Open Weave (I) (25 – 50% open)	I_D	I_M	I_L
Semi-open Weave (II) (7 – 25% open)	II_D	II_M	II_L
Closed Weave (III) (0 – 7% open)	III_D	III_M	III_L

RESULTS

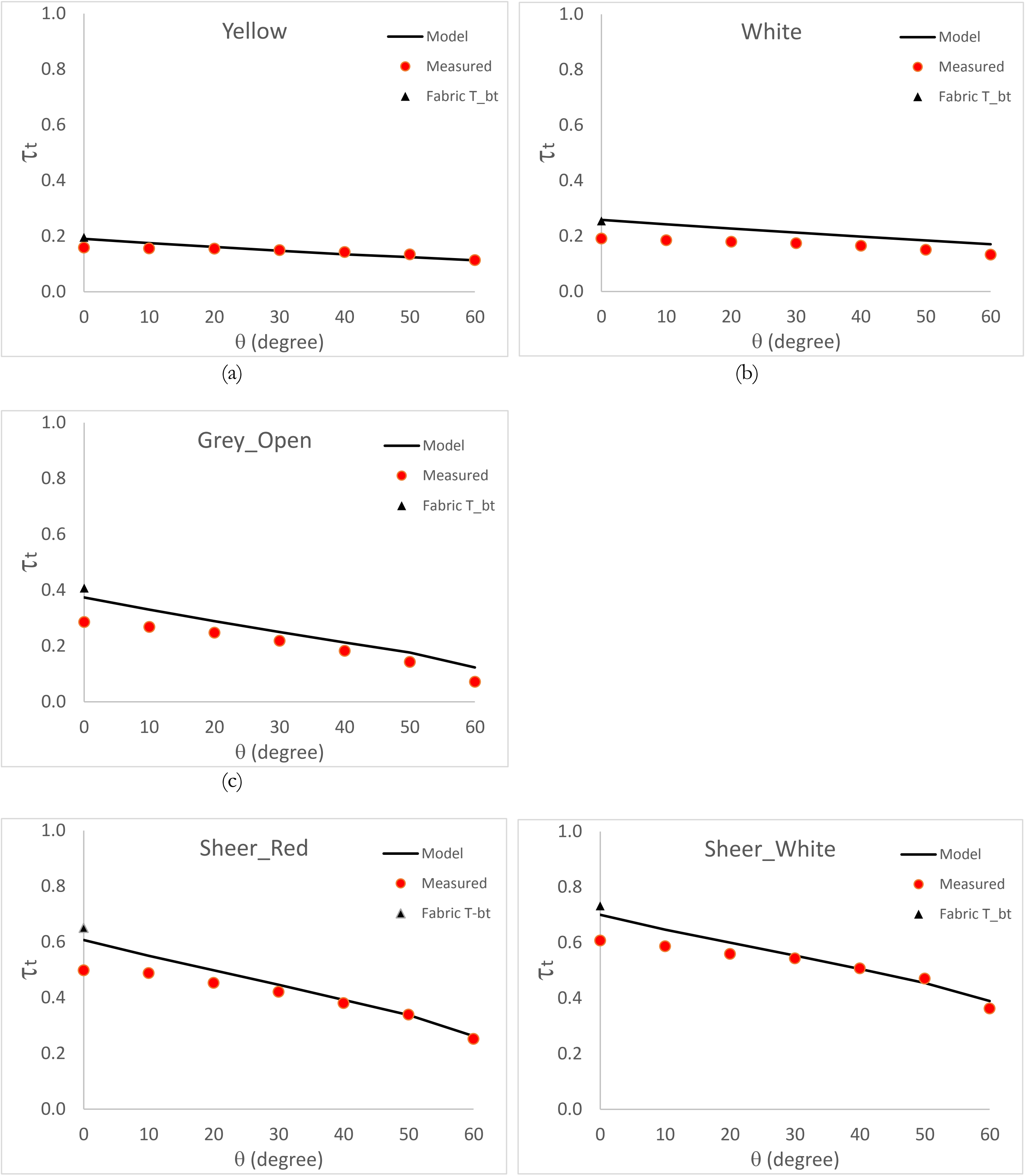
Each sample was measured from $\theta = 0°$ to $\theta = 60°$, with 10° increment. For $\theta = 0°$, incident light is normal to the draped layer surface (i.e., solar altitude angle and surface azimuth angle are both zero for the vertical pleated drape layer). The light source is placed at the same height as the pleated samples so the solar altitude angle stays at 0°. Therefore, θ is equivalent to the horizontal surface azimuth angle, Ω_H, for these experiments.

Table 2 and Figure 4 show results of τ_t measured using the BAI-IS system (dots) versus predictions of the pleated drape model (solid line). Both predictions and measurements follow the expected trend that, in general, τ_t decreases with increasing θ. As well, the results show that rate of decrease depends on the solar optical properties of the fabric. Fabrics with high $\tau_{t,f}$ (Sheer_Red and Sheer_White) have a high rate of decreasing τ_t versus drapes made of fabrics with low $\tau_{t,f}$ (Yellow and White).

For most cases, the difference between prediction and measured τ_t is within ±0.05 except at $\theta = 0°$ and $\theta = 10°$, where the model overpredicts by as much as +0.11 for the Sheer_Red fabric. The authors attribute this overprediction to the irregularity observed in the pleated samples. For instance, the light source shines on a slightly curved surface instead of on a perfectly flat surface. Then, at normal incidence for example, $\theta = 0°$ is only true for the surface area near the center of each pleat. However, θ increases along the curved surface away from the pleat center, near the folds. In other words, θ is actually greater than 0° for surface area away from pleat center and increases toward the folding lines with rounded corners. As a result, the incident angle is not constant across the surface, and the "true" or "representative" θ would be higher than zero.

Total solar transmittance consists of two components: beam-beam transmittance through opening, τ_{bb}, and scattered transmittance, τ_{bd}. τ_{bb} has a much stronger dependence on θ than τ_{bd} does. That is why high transmitting fabrics (mainly due to high A_o) have higher rate of decreasing τ_t with increasing θ. As a result, the integrated effect due to irregularity in the sample is prominent for high A_o fabrics such as sheer fabrics and minimal for fabrics with low A_o (low τ_{bb} and relatively high τ_{bd}), as shown in Figure 4 ((a), (b) for low A_o and (d), (e) for high A_o).

In general, as θ increases, the fabric layer τ_{bb} reduces and τ_{bd} becomes more dominant. In addition, to be transmitted some incident radiation has to pass through multiple layers of fabrics at high θ, further enhancing the dominance of τ_{bd}. When τ_{bd} dominates, as is the case in low A_o fabrics or high θ, the effect of sample irregularity on τ_t diminishes.



(a) (b) (c) (d) (e)

Figure 4 Comparison of BAI-IS transmittance test results to pleated drape model predictions

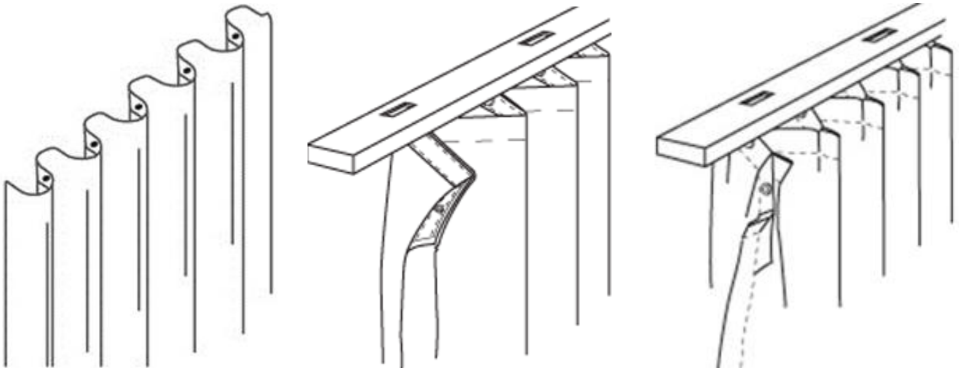
Table 2. Results of Predicted and Measured τ_t of Pleated Drape Layer

	Yellow (a)		White (b)		Grey Open (c)		Sheer Red (d)		Sheer White (e)	
Angle	Model	Measured	Model	Measured	Model	Measured	Model	Measured	Model	Measured
0	0.190	0.158	0.258	0.191	0.374	0.286	0.607	0.498	0.700	0.608
10	0.175	0.155	0.242	0.185	0.330	0.268	0.550	0.488	0.647	0.587
20	0.161	0.155	0.227	0.180	0.289	0.247	0.498	0.453	0.600	0.560
30	0.147	0.150	0.212	0.174	0.250	0.219	0.446	0.421	0.553	0.543
40	0.134	0.143	0.198	0.165	0.212	0.182	0.392	0.380	0.505	0.508
50	0.124	0.134	0.184	0.150	0.176	0.143	0.338	0.340	0.455	0.471
60	0.113	0.114	0.170	0.133	0.123	0.072	0.262	0.252	0.390	0.363

Other Considerations

As discussed above, the measurements and predictions agree reasonably well except for cases with both high A_o and low θ. The discrepancy is caused by the geometric difference between model and test sample. One could simply "correct" the discrepancy between model and measurements by assigning a representative θ for the model. For example, the representative θ is taken to be 10° higher than the true θ for low θ test cases. The overpredictions reduce to less than +0.05.

If all drape pleats were rectangle in reality, one may conclude the pleated drape model works reasonably well. However, most drapes do not consist of rectrangular pleats. For example, Figure 5 shows some common pleating styles. The question becomes "can the rectangular pleated drape model be used to represent drapes with some or all pleating styles?" This question will be addressed by further research.



(a) (b) (c)

Figure 5 Examples of various pleating style

CONCLUSION

The need to predict the effect of a CFS on energy use has fueled development on models for shading devices in the past decade. The present study aims to validate the solar-optical model of a rectangular pleated drape (Kotey et al. 2009).

Fabrics were chosen based on the solar optical properties measured using the commercial UV-Vis-NIR spectrophotometer. A sample drape frame was built to allow pleating and to make the pleats as close to square as possible. Although the intention was to build square-pleated samples to match pleated drape model, curved surfaces and rounded corners could be oberved in all samples. This irregularity results in a representative incidence angle higher than the corresponding apparent (test case) incidence angle.

Measurements was carried out using a BAI-IS system with incidence angle (i.e., horizontal profile angle) as high as 60°. The large integrating sphere and broad beam illumination overcomes the limitations of a commercial spectrophotometer. The measurement results were compared to predictions of the pleated drape model. The rectangular pleat model works very well for the low A_o samples. As the sample irregularity is not captured in the pleated drape model, it can be ignored in the low A_o samples where the τ_{bd} dominates. However, in high A_o samples where the τ_{bb} dominates, irregularity in the supposed flat pleat surfaces must be considered. With a simple adjustment (e.g., using a representative incidence angle that is 10° higher than a low incidence angle), the differences between prediction and measurements are all within ±0.05.

As most drapes do not consist of a series of uniformly arranged rectangular pleats, one must also ask whether the rectangular-pleat drape model can be applied to drapes with different pleating styles. Measurements using V-corrugated samples have been planned. More tests will be done to include other folding ratios and to cover all of the categories shown in Table 1.

ACKNOWLEDGMENTS

The financial assistance of the Natural Sciences and Engineering Research Council of Canada (NSERC) is greatly acknowledged.

NOMENCLATURE

BAI-IS = Broad-Area Illumination Integrating Sphere
CFS = Complex Fenestration System
θ = incidence angle
τ = transmittance
ρ = reflectance

Subscripts

bb = beam-beam
bd = beam-diffuse
bt = beam-total
t = total
f = fabric

REFERENCES

Barnaby, C.S., Wright, J.L., and M.R. Colllins. 2009. Improving Load Calculations for Fenestration with Shading Devices. *ASHRAE Transactions* 115(2): 31-44

Farber, E.A., Smith, W.A., Pennington, C.W., and J.C. Reed. 1963. Theoretical Analysis of Solar Heat Gain through Insulating Glass with Inside Shading. ASHRAE Transactions 69: 392-403.

Keyes, M.W. 1967. Analysis and Rating of Drapery Materials Used for Indoor Shading. *ASHRAE Transactions* 73(1):VIII.4.1-VIII.4.15.

Kotey, N.A., Wright, J.L., and M.R. Collins. 2009. A Detailed Model to Determine the Effective Solar Optical Properties of Draperies. *ASHRAE Transactions*, Vol. 115(1)

Labsphere Inc. 2013. A Guide to Integrating Sphere Theory and Applications. *Labsphere Technical Guide*. Downloaded from www.labsphere.com

Wright, J.L. 2008. Calculating Centre-Glass Performance Indices of Glazing Systems with Shading Devices. *ASHRAE Transactions* 114(2): 199-209.

Wright, J.L., Barnaby, C.S., Niles, P., and C.J. Rogalsky. 2011. Efficient Simulation of Complex Fenestration Systems in Heat Balance Room Models. *Proc. of Building Simulation: 12th Conf. of Int. Building Performance Simulation*: 2851-2858.