Air intrusion and its impact on the energy performance of roofing assemblies

Molleti, S.; Baskaran, B. A.; Beaulieu, P.; Van Reenen, D.

National Research Council Canada   Conseil national de recherches Canada

Air intrusion and its impact on energy performance of roofing assemblies

NRCC-50294

Molleti, S.; Baskaran, B.A.; Beaulieu, P.; Van Reenen, D.

National Research
Council Canada

Conseil national
de recherches Canada

Canada

AIR INTRUSION AND ITS IMPACT ON ENERGY PERFORMANCE OF ROOFING ASSEMBLIES

Suda Molleti, Ph.D[1*], Bas A. Baskaran Ph.D., P.Eng[2], Pascal Beaulieu[3], David Van Reenen[3]

[1]*Research Officer,* [2]*Senior Research Officer,* [3]*Technical Officer*
National Research Council of Canada
1200 Montreal Road, Ottawa, ON, Canada, K1A OR6
* *Corresponding Author. Tel: 613-993-9673; Fax: 613-998-6802;sudhakar.molleti@nrc.ca*

Keywords: Roofs, Air intrusion, Test method, Wind, Energy.

SUMMARY

Air intrusion into roof assembly is a concern for wind uplift resistance and life cycle performance of roofs. Currently, there are no widely accepted standard specifications or test methods to determine air intrusion into roof assemblies. Towards this objective, an experimental procedure has been under development at the National Research Council of Canada. As part of this investigation, five roofing assembly configurations were quantified for air intrusion. Relative performance of the air retarding effect of the five assemblies indicated that assemblies with air barrier/retarder had lower air intrusion rates than without. Measured air intrusion rates are compared with the existing codes of practice and standards. This comparison clearly demonstrates the significance of air intrusion into the roofing assembly and the necessity of a standardized air intrusion test method for the roofing industry. With the measured data, attempts were made to perform energy load calculations using a simplified procedure, and through two case studies the impact of air intrusion on energy performance of roof assembly was estimated.

INTRODUCTION

Built-up roofing assemblies (BUR) have dominated the roofing industry for over a century (Baskaran, et al. 1997). In the BUR, different plies of roofing felt are fully adhered to the substrate and this continuity offered significant resistance to air flow. Recent trends in the roofing industry clearly indicate the evolution of single-ply roofing systems as the next generation low slopped roofing assemblies, replacing the labour intensive BUR. Within the single-ply roofing systems, the membrane can be mechanically attached, fully adhered or partially attached to the substrate. The membrane can be a single ply membrane such as PVC (Polyvinyl Chloride), EPDM (Ethylene Propylene Diene Monomer) and TPO (Thermoplastic Olefin) or a two-ply as in the case of modified bituminous membranes. A roofing assembly in which the membrane is attached, through insulation and other components to the structural deck at discrete points using fasteners is known as a Mechanically Attached Assembly (MAA) and this assembly will be the focus of the present study.

Approximately one-fourth of North American low slope/commercial buildings are roofed with MAA (NRCA 2004). Recently, wind uplift performance studies of the MAA (Baskaran, et al. 2003, 2006) identified air intrusion into the roof assembly as one of the major factors that affect its performance. For airflow to occur, there must exist two prerequisites, one is the pressure difference between two locations, and the other is a continuous flow path or opening connecting the locations. MAA meets these two prerequisites during wind uplift conditions. Figure 1(a) illustrates the airflow mechanism through MAA. Wind induced suction lifts the waterproofing membrane and causes membrane billowing and elongation between the attachments. The magnitude of the wind induced suction; the membrane's elastic properties and the fastening

pattern determine the deflection of the membrane billowing. The momentary displacement or billowing of the membrane creates a relative negative pressure below the lifted membrane and this draws indoor air into the roof, thereby satisfying the first prerequisite. The second prerequisite is met by the lack of airflow control at the deck level (i.e. between deck and insulation). Flow paths are created by the component's air permeability and joints/junctions/penetrations in the roofing assembly.

Being able to control air intrusion is critical in roofing design, as this has several effects on the performance of the roof—on wind uplift, condensation and energy. Addressing these performance issues, Figure 1 (b), 1(c), 1(d) illustrates the details. Despite the significance of air intrusion on roofing systems performance, no study exists in the literature (Molleti, 2006) that addresses the air intrusion characteristics of a roofing assembly. Therefore, a research study was initiated at the National Research Council of Canada (IRC/NRC) with the objective of developing a new test procedure for air intrusion quantification of roofing assemblies. This paper presents air intrusion data from five roofing assemblies. It also compares the measured air intrusion rates of the assemblies with the requirements prescribed in the codes.
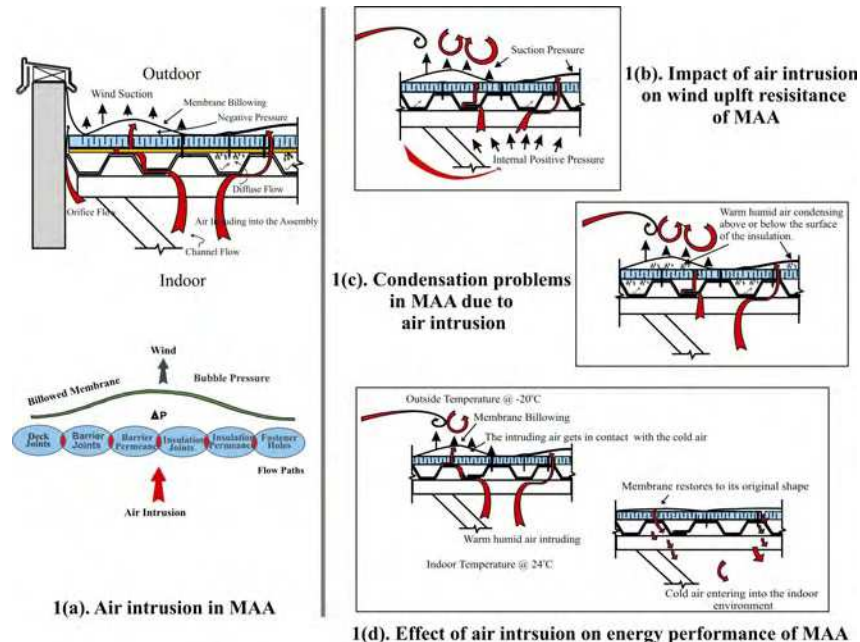
Figure 1: Air Intrusion and its impact on life cycle performance of MAA

EXPERIMENTAL APPROACH

Recently, Molleti and Baskaran (2006) reported the details of the newly developed air intrusion test method for roofing assemblies. Figure 2 illustrates the experimental approach developed for the air intrusion quantification. As shown in Figure 2, the test frame has a dimension of 2 m x 6 m x 0.8 m (79" x 236" x 32"). The test specimen/roof assembly is installed in the frame, which is supported on a lifting mechanism with adjustable jacks. This feature allows for investigating different roofing assembly thicknesses accommodating different roofing components. The parameters measured in the test method are 1) applied test pressure difference across the test assembly and, 2) the corresponding volumetric airflow rate.

Following the above experimental approach (Figure 2) the present study quantified air intrusion rates of five roofing assembly configurations. The five roofing assemblies are:
- Assembly 1 (*A1*) – Steel deck and a layer of insulation

- Assembly 2 (*A2*) – Steel deck and two layers of insulation
- Assembly 3 (*A3*)– Steel deck, a layer of insulation and a building paper
- Assembly 4 (*A4*)–Steel deck, a layer of insulation and a self adhered film
- Assembly 5 (*A5*)–Steel deck, a layer of insulation and a 6-mil polyethylene sheet

Figure 2: Experimental approach for quantification of air intrusion in roof assemblies

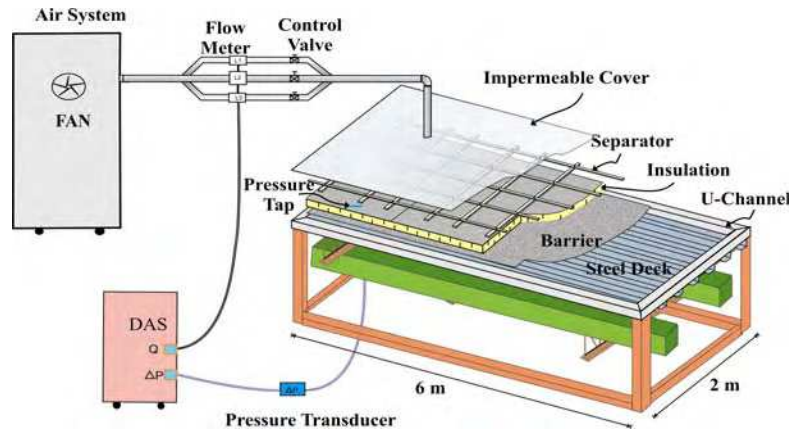The experimental setup assumed that in a roofing assembly the continuous waterproof membrane is airtight and therefore can be excluded from the investigation. Therefore, all the experimental mock-ups were constructed up to the insulation level. As the roof installation is similar for all the tested assemblies, the construction procedure can be classified into four steps as shown in Figure 3. These steps are as follows:

Deck Installation

The edge treatment of the test assembly was handled by installing steel U-channels along the test frame edges as shown in Figure 3(a). One full sheet of 914 mm (36 in.) wide and two cut pieces of 610 mm (24 in.) and 483 mm (19 in.) wide steel sheets were installed along the table length. The black dotted lines as shown in Figure 3(a) indicate the deck overlaps/seams. To eliminate the air intrusion along the edges of the deck, the steel deck edges are butted to the U-channel, and the gap between them was sealed using caulking and adhesive membrane.

Barrier/retarder Installation

In the present experimental setup, barrier/retarder means a component installed in the roofing assembly to prevent air intrusion into the system. Figure 3(b) shows the installation of these three barriers/retarders. *A3* had 5 mil thick (0.015") asphalt-impregnated paper building paper as barrier/retarder. *A4* had 0.8 mm thick (1/32") SBS (Styrene-Butadiene-Styrene*)* modified self-adhered film (SAF) as barrier/retarder. Both these barriers/retarders had two seam overlaps. In *A5,* a continuous layer of 6-mil (0.006 ") polyethylene sheet was used as a barrier/retarder.

Insulation Installation

Figure 3 (c) shows the typical layout of insulation attachment. For all five tested assemblies, 51 mm (2") thick polyisocyanurate boards were used as the insulation. In *A1*, *A3*, *A4,* and *A5* the insulation configuration comprised of a layer of insulation with four full boards of 1219 mm x 2006 mm (48" x 79") and one partial board. In *A2*, the insulation layout is similar to the former assemblies except that it comprises two layers of insulation in staggered arrangement. The insulation boards were mechanically fastened to the steel deck with 8 fasteners per board.

Air Intrusion Setup

With the insulation in position and fastened to the deck, a square meshed wooden separator is installed on top of the insulation as shown in Figure 3 (d). This provides the required gap or space between the test specimen and the impermeable cover. Two pressure taps are installed on either ends of the test specimen to measure the applied differential pressure across the test specimen. With the separator installed a continuous sheet of impermeable cover as shown in Figure 3 (d), is laid on top of the separator and the overhang edges are adhered to the frame edges, thus eliminating any extraneous airflow into the test specimen. Provisions are made to install the flow measurement setup on top of the impermeable cover. One end of the flow measurement setup has an air filter, which is inserted into the test specimen, and the other end is connected to the air system. In between them, the flow-measuring device and the adjustable control valve are installed.

(a) Deck Installation   (b) Barrier Installation   (c) Insulation Installation   (c) Air Intrsuion Setup

Figure 3: Experimental set up of the test assemblies

Test Procedure

To quantify the air intrusion rate, differential pressure in the range of 480 Pa (10 psf) to 2870 Pa (60 psf) in increments of 480 Pa (10 psf) was applied across the assembly. At each applied target pressure, pressure was stabilized for a minimum duration of 60 secs and the airflow measurements were recorded for a minimum duration of 60 secs.

RESULTS AND DISCUSSION

Following the above test procedure, the five assemblies were quantified for air intrusion. All tests were carried out in an indoor laboratory environment (air pressure 101 kPa, ambient temperature 21°C and air density 1. 202 kg/m^3). The tested assemblies can be categorized as assemblies without barrier/retarder – *A1* and *A2,* and assembly with barrier/retarder – *A3*, *A4, A5.* Figure 4 (a) shows a typical measured pressure and flow time histories of one of the assembly *(A5).* The applied pressure at each pressure level comprises three parts: 1) Pressure Build-up; 2) Pressure Stabilization; and 3) Pressure Measured (Molleti and Baskaran, 2006).
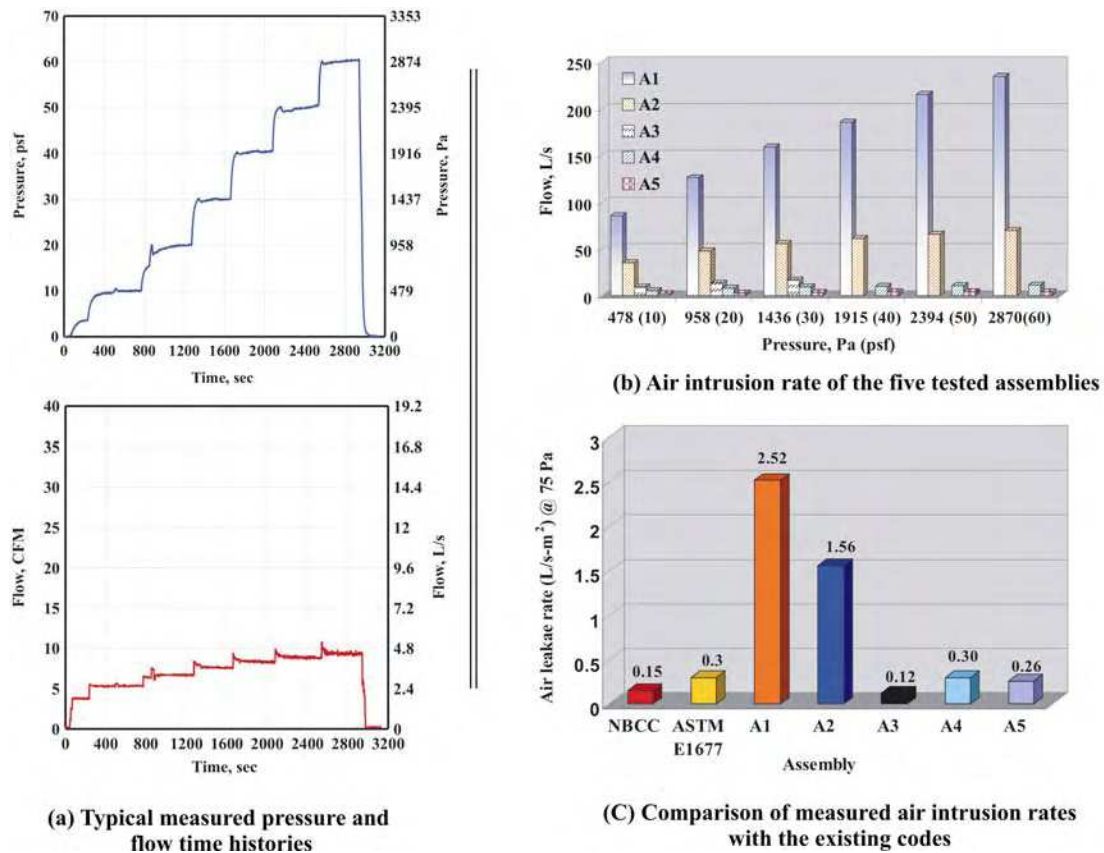
(a) Typical measured pressure and flow time histories

(b) Air intrusion rate of the five tested assemblies

(C) Comparison of measured air intrusion rates with the existing codes

Figure 4: Experimental results of the tested assemblies

Figure 4 (b) presents the measured air intrusion rate of the five assemblies. Data clearly indicates that *A1* and *A2* without barrier/retarder had a greater intrusion rate when compared to the assemblies with barrier/retarder, namely *A3*, *A4* and *A5*. The assemblies with barrier/retarder on an average had 94 % less air intrusion rate compared to the assemblies without one. This high intrusion rate of *A1* and *A2* could be attributed to the channel flow occurring at the deck and insulation joints. With the inclusion of barrier/retarder, the channel flow was minimzed. The present study also attempts to answer whether the staggered arrangement of insulation boards as in *A2* can be as effective as that of having a barrier/retarder in an assembly. The comparison of the data from Figure 4 (b) points out that the staggered arrangement of insulation in *A2* certainly provided the air retarding effect in comparison to *A1*. However, the air retarding effect proved to be not as effective as the assemblies with barrier/retarder *(A3, A4, & A5)*. It is also to be noted that in 4 (b), no air intrusion data is presented for *A3 (with building paper)* beyond 1440 Pa (30 psf). The reason was, during the air intrusion testing of *A3*, one of the corner 45° cuts made for the building paper opened up or enlarged. This lead to a drastic increase in the airflow rate and as a result the test was stopped. Irrespective of this drawback *A3* provided a good air retarding effect up to 1440 Pa (30 psf).

For an air barrier/retarder system in opaque, insulated portions of the building envelope, Part 5 of the NBCC (2005) recommends 0.2 L/s.m^2 (0.04 ft^3/min.ft^2) permissible air leakage rate. at 75 Pa (1.56 psf)). omparison of these data with the NBCC as shown in Figure 4 (b) indicates that none of the assemblies except *A3* comply with the NBCC code requirement. However, once

again it should be remembered here that the assembly set-up of *A3* represents the idealistic construction procedure having proper edge treatment and no seam joints, which has achieved its end result demonstrating the significance of air intrusion. Similarly, ASTM E1677-2005, calls for an assembly air permeance requirement of 0.30 L/s.m^2 (0.06 ft^3/min.ft^2) at 75 Pa (1.5 psf). However, the standard restricts this permissible leakage rate to the opaque walls. Therefore, the comparison presented in Figure 4 (b) relative to ASTM E1677 is not really applicable to roofing assemblies; however, it signifies the necessity of similar air intrusion resistance requirement for roofing assemblies.

Additional research efforts are in progress in the enhancement of this test method such as component requirements, structural capacity, installation techniques, and overall the development of a standard for an air barrier system in roofing assembly, which can lead to development of generalized "best practice" recommended air intrusion rates for the air barrier systems of building envelope.

ENERGY PERFORMANCE OF ROOFING ASSEMBLIES

The impact the roof has on energy use depends on the climate, type of roof, orientation of roof, thickness, quality of the insulation, air permeability of the roof assembly, reflectivity of the roof surface, and maintenance of the roof assembly. Of these, insulation and air permeability merit major consideration. Using the air intrusion data from the above experimental work and combining with the thermal resistance of the insulation, attempts were made to determine the thermal loads of the above five roofing assemblies. Using the thermal load equations described in ASHRAE (2005), simplified energy calculations are performed for two case studies.

Case Study 1

A low slopped commercial building having dimensions of 18 m (60 ft) width, 21 m (70 ft) length and 15 m (50 ft) height is assumed to be located in Toronto**,** Ontario, Canada. Based on the available weather data, Toronto has 4066 Heating Degree Days (HDD) and 252 Cooling Degree Days (CDD) (Source: Environment Canada.). This building is assumed to have mechanically attached assembly as shown in Figure 1. Based on the RSI values of the individual roofing components and the RSI values of the outside- inside air films (ASHRAE, 2005), the RSI value of the roofing assembly is estimated to be 2.25 K.m^2 /W. For the energy calculation, air intrusion at pressure of 75 Pa (1.5 psf) was determined and accordingly the air change rates were adjusted. It should be noted that the test pressure of 75 Pa (1.5 psf) is only for comparative purposes.

Following a simple series of energy equations [1] and [2], the total heat loss through the roof was estimated to be 127940 KWH (HDD) and 7874 KWH (CDD) respectively.

Energy consumption due to heat flow through the roof, Q_1 = A/RSI * 24*HDD (CDD) [1]
Energy consumption due to air intrusion, Q_2 =ρ x C_P x q_{ai} x 24*HDD (CDD) [2]
    Q = heat flow in Kilowatt-hour (KWH) ; RSI = thermal resistance; ρ = specific density of air ; C_P = specific heat capacity of air ; q_{ai} = air intrusion rate,m^3/s at 75 Pa

Using natural gas (29.92 cents / m^3) and electricity (5.9 cents / KWH) as the source of fuels, the heating and cooling loads were estimated. This calculation represents the energy consumption for a low slope commercial building installed with the roof assembly type Assembly 1 *(A1)*. Following this procedure, estimates of energy consumption was determined for the remaining four assemblies *(A2 to A5)*. The estimated annual energy consumption in terms of dollars is shown in Figure 5 (a). These comparative numbers clearly indicate that irrespective of the fuel

type, roof assemblies with barriers provide higher energy savings compared to assemblies without barrier.

Case Study 2

For the second case study, Tampa (Forida) was selected as the building location. With the exception of the weather data, all other parameters remain similar to Case Study 1. Tampa has 577 HDD and 3488 CDD *(Source: National Oceanic and Atmospheric Administration, NOAA)*. Based on this data, Figure 5 (b) presents the heating and loading calculations. Similar to the Case Study 1, roof assemblies with barriers provide higher energy savings compared to assemblies without barrier. However, Florida, being a warm state, the city of Tampa has higher cooling loads compared to heating loads, which was contrary to case study 1.

The purpose of these case study examples is to the show the energy cost reduction potential by the application of barriers/retarders in roofing assemblies. However, the accuracy of this estimate is limited by input uncertainty. Despite these uncertainties, the energy calculations provide an estimate that insulation plus air intrusion control in a roofing assembly could contribute to the overall energy usage of the building envelope.
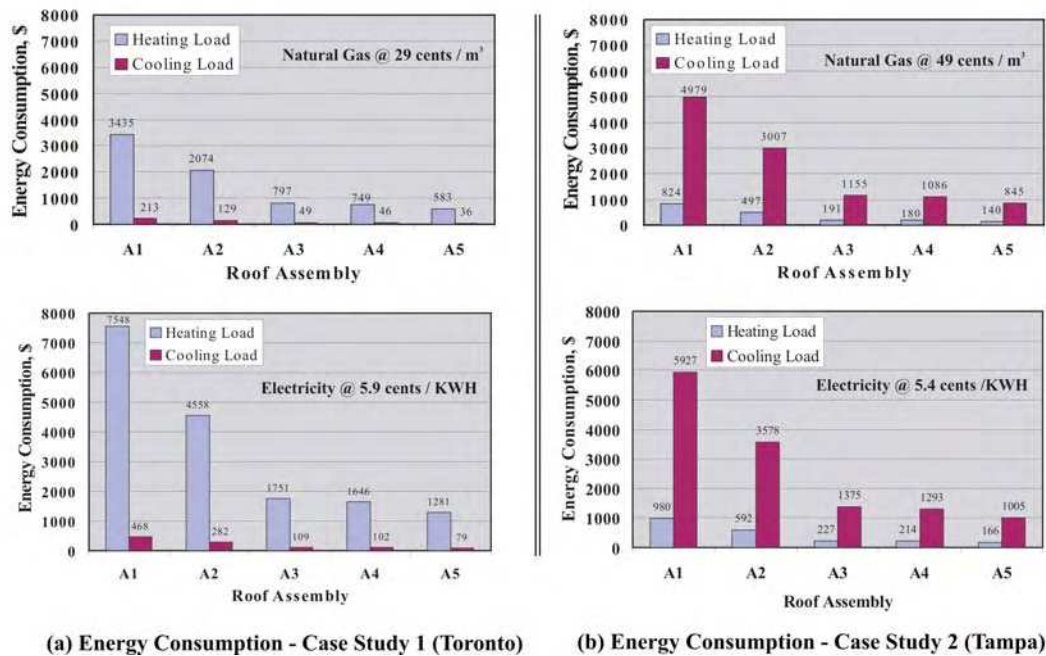

(a) Energy Consumption - Case Study 1 (Toronto)   (b) Energy Consumption - Case Study 2 (Tampa)

Figure 5: Energy load calculations

CONCLUSION

Currently no procedure or standard exists for quantification of air intrusion through roofing assemblies. To quantify the air intrusion performance of this roofing assembly, the authors have developed a test method. Based on this test method, the present paper investigated five roofing assemblies with and without barrier/retarder and quantified their air intrusion rates. Data clearly indicated that assemblies without barrier/retarder had a high rate of air intrusion, compared to assemblies with barrier/retarder. The present experimental study also attempted to solve the myth that currently exists in the roofing industry that the staggered arrangement of insulation boards can be as effective as that of having a barrier/retarder in an assembly. The reality was, the staggered insulation can indeed provide a certain air retarding effect, however, it cannot replace requirement of a barrier/retarder. Comparison of the measured air intrusion rates of the five

assemblies with the NBCC (2005) recommended system air leakage rates clearly demonstrated the significant amount of air intrusion into the roofing assembly and the necessity of air barrier/retarder test standards for roofing assemblies. With the measured data, attempts were made to perform thermal load calculations using a simplified procedure. The energy calculations highlighted the importance of air intrusion and air sealing measures in roof assembly, which might contribute to considerable energy savings.

ACKNOWLEDGMENTS

REFERENCES

ASCE 7.2005. Minimum Design Loads For Buildings and Other Structures, American Society of Civil Engineers Standard.

ASHRAE. 2005.Fundamentals Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

National Building Code of Canada NBCC 2005. National Research Council of Canada, Ottawa, Ontario, Canada, K1A 0R6.

ASTM. Standard E1677-2005. Standard Specification for an Air Barrier (AB) Material or System for Low-Rise Framed Builing Walls", American Society for Testing and Materials

Baskaran, A., R.M. Paroli and R.J. Booth, 1997. Wind Performance Evaluation Procedures for Roofing Systems Current Status and Future Trends. In: *Proceedings of Fifth International Conference on Building Envelope Systems and Technology*, BATH, U.K, Pp. 37-52.

Baskaran, A., Molleti, S. and Sexton, M., 2003. Wind uplift performance of mechanically attached roofing systems with vapor barrier, In: *Proceedings of 9th Conference on Building Science and Technology*, Vancouver, British Columbia, Canada, February 27-28.

Baskaran, A., S. Molleti and R.J. Booth. 2006. "Understanding Air Barriers in Mechanically Attached Low Slope Roofing Assemblies for Wind Uplift." In: *Proceedings of the 3rd International Building Physics/Science Conference*, Montreal, August, Pp. 443-450.

Baskaran, A. and T.L. Smith. 2005. A Guide for the Wind Design of Mechanically Attached Flexible Membrane Roofs. National Research Council of Canada, Ottawa, Ontario, Canada.

Molleti, S. 2006. Performance Evaluation of Mechanically Attached Roofing Systems. *Ph.D. Thesis*, University of Ottawa, Ottawa, Canada.

Molleti, S and Baskaran, A. 2006. Development of a New Test Method for Air Intrusion Quantification of Roofing Assemblies. Accepted to ASTM - Journal of Testing and Evaluation. Will be published in May 2008.

NRCA.2004. Hurricane Charley: A Preliminary Report, *Professional Roofing Magazine*, National Roofing Contractors Association, October.