Towards Codification of Energy Losses From Fasteners on Commercial Roofing Assemblies

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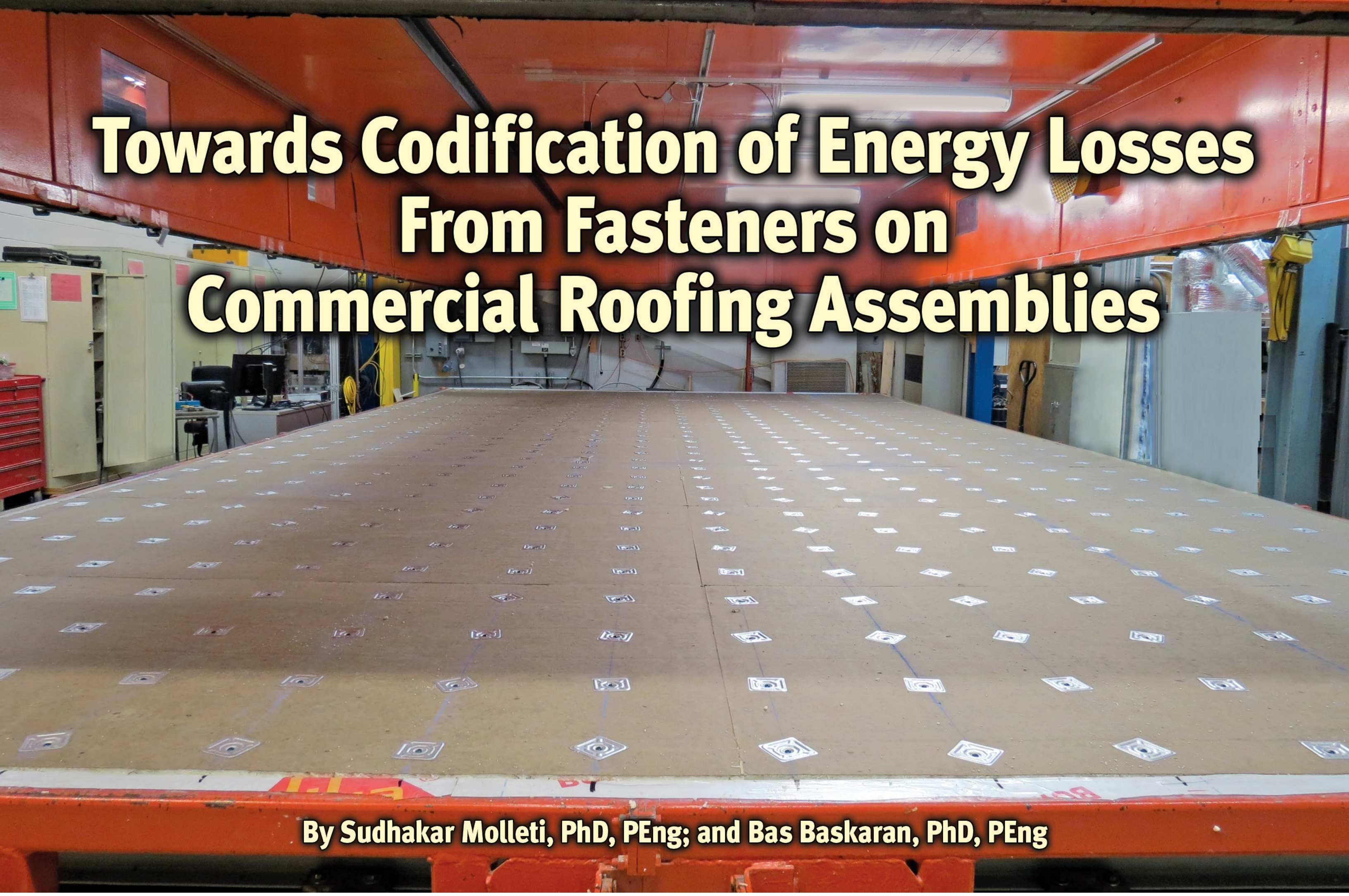


INTRODUCTION

Building energy codes and standards, such as ASHRAE 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*; the *International Energy Conservation Code* (IECC); and the *National Energy Code of Canada for Buildings* (NECB), provide minimum requirements for the design of energy-efficient roofs. They also present approaches to determine the thermal transmittance (U-value) of the roof assembly, but they are limited to roof assemblies with continuous insulation.

The definition of continuous insulation, according to ASHRAE 90.1, is "insulation that is uncompressed and continuous across all structural members without thermal bridges other than fasteners and service openings."[1] This definition acknowledges the importance of thermal bridging but de-emphasizes the issue of thermal bridging as resulting from fasteners (*Figure 1*) or protrusions through the assembly such as pipes, ducts, and rooftop equipment. Some simulation studies on thermal bridging (Burch, Shoback, & Cavanaugh, 1987;[2] Atchley, Desjarlais, & Christian, 2000;[3] Olson, Saldanha, & Hsu, 2015;[4] Gulati, Suddapalli, & Srinivasan, 2016;[5] and Singh, Gulati, Srinivasan, & Bhandari, 2016)[6] have estimated the thermal penalty of fasteners in roofs. Although these studies do not provide general encompassing methods that may be applied to reach the building code design thermal values, they have certainly highlighted the potential significance of thermal bridging of fasteners in commercial roofs.

In low-slope membrane roofing systems, mechanical fasteners are used to secure the individual components and provide resistance against wind uplift forces. Currently in the roofing industry, documents such as ANSI/SPRI-WD1[7] and FM Approvals[8] provide performance-based fastener densities for mechanically attached roofing systems (MARS) and partially adhered roofing systems (PARS) for each area of the roof. For assemblies where performance-based deck securement is not specified, fasteners can be added prescriptively by doubling the density of the fasteners along the perimeter and by at least 2.5 times the density at the corners.

Roofing manufacturers also specify their own performance-based fastener densities. Based on the current industry practice, the fastener densities in both the MARS and PARS can range from 1.6 to 10.8 fasteners/m^2 (0.15 to 1 fasteners/ft^2). See *Figures 1* and *2*. The effects of these fastener densities are not currently acknowledged in the thermal design of roof assemblies.

Thermal bridging occurs in roof assemblies in which the uniform thermal resistance of the assembly is interrupted by full or partial penetration of highly thermal-conductive materials, creating pathways for direct heat loss. Two types of thermal bridging are: linear bridging that occurs at junctions between elements such as a parapet-roof-wall junction, or at rooftop penetrations such as curbs and skylights; and point bridging, which is a localized bridging that occurs at points within the roof assembly caused by roofing fasteners or rooftop photovoltaics.

Energy codes and standards have mainly focused on the insulation requirements in roof thermal design, omitting the impact of thermal bridging on energy loss. One reason

Figure 2 – Typical insulation fastener densities in the design of roofing assemblies (FM Global).

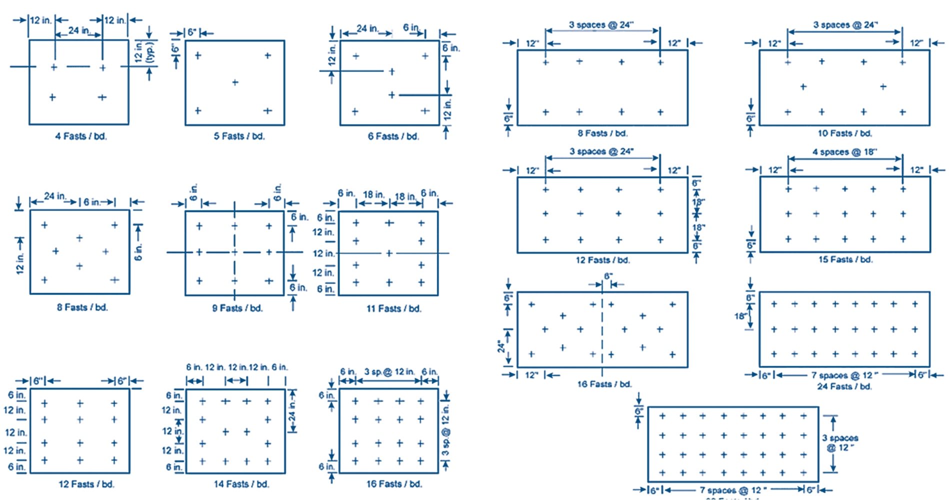


Figure 1 – Visual impact of thermal bridging of roofing fasteners (courtesy: RCABC).

for the omission could be the absence of codifiable data that could determine the impact of thermal bridging on the thermal performance of the roofing assembly. In this era of net-zero buildings and climate resiliency, enhancing the energy efficiency of the built environment should be accounted for in every detail (to the extent possible) and acknowledged at the design stage.

Toward the effort of enhancing the energy efficiency of the commercial roof, the National Research Council Canada (NRC) developed an industry consortium, Energy Resistance of Commercial Roofs (ERCR). These partners include the International Institute of Building Enclosure Consultants (IIBEC), the National Roofing Contractors Association (NRCA), Canadian Roofing Contractors Association (CRCA), Roofing Contractors Association of British Columbia (RCABC), Sika, Trufast, EPS Industry Alliance, Rockwool, Soprema, 2001 Company, and the Natural Resources Canada – Program of Energy Research and Development (PERD).

The ERCR consortium project had two major tasks. In Task 1, the objective was to evaluate the effective thermal resistance of current roof designs and validate their compliance with the energy code requirements. In Task 2, the aim was to quantify the impact of two factors: thermal bridging from fasteners, and thermal bypass from gaps between the insulation boards. Combining the outputs from both these tasks, the final goal was to generate code-compliant solutions that could be applicable to the roof thermal designs to ensure energy-efficient and code-compliant roofs. This paper focuses on Task 2, thermal bridging from fasteners, where it quantifies the thermal effect of roof fasteners in common configurations within widely implemented roof assemblies.

METHODOLOGY

The methodology followed in Task 2 is an extension of Task 1, so this section will begin with a brief overview of Task 1, followed by the Task 2 experimental approach.

In Task 1, the thermal transmittance of roofing systems that are designed with the energy codes' prescriptive requirements was determined. This was achieved by a three-step approach. In the first step, the prescriptive thermal transmittance requirements for roofs as specified in the NECB (*Table 1*) and ASHRAE 90.1-2013 (*Table 2*) are summarized and consolidated into three categories: R-26, R-31, and R-36. ASHRAE climatic zone 1 and NECB climatic zone 8 were excluded from the study. It should be noted that R-26, R-31, and R-36 are effective R-values that include both the outside and inside surface air films. Excluding air films, the design thermal resistances for the roofing assemblies are R-25.21, R-30.21, and R-35.21, respectively. The energy codes require that the roof assemblies have to be designed to meet these minimum effective R-values to achieve a specific level of energy efficiency. This design is achieved using R-values of the components measured at a standard average temperature of 24°C (75°F).

The second step was the selection and design of roof assemblies. The ERCR steering committee members designed three

NECB Climate Zones	Roof Assembly Minimum Effective R-Value	
	Metric ($m^2 \cdot °K/W$)	Imperial ($ft^2 \cdot °F \cdot hr/Btu$)
4	R-4.4	R-25
5	R-5.5	R-31
6	R-6.2	R-35
7A/7B	R-6.2	R-35
8	R-7.1	R-40

Table 1 – NECB climate zone thermal requirements.[9]

ASHRAE Climate Zones	Roof Assembly Minimum Effective R-Value	
	Metric ($m^2 \cdot °K/W$)	Imperial ($ft^2 \cdot °F \cdot hr/Btu$)
1	R-3.7	R-21
2/3	R-4.5	R-26
4/5/6	R-5.4	R-31
7/8	R-6.3	R-36

Table 2 – ASHRAE climate zone thermal requirements.

Board Thickness	R-25.21	R-30.21	R-35.21
Polyisocyanurate (polyiso)	51 mm + 64 mm [2 in. + 2½ in.]	51 mm + 84 mm [2 in. + 3⅓ in.]	51 mm + 102 mm [2 in. + 4 in.]
Expanded Polystyrene (EPS)	80 mm + 80 mm [3⅛ in. + 3⅛ in.]	98 mm + 98 mm [3⅞ in. + 3⅞ in.]	117 mm + 117 mm [4⅝ in. + 4⅝ in.]
Stone Wool/Mineral Wool	64 mm + 102 mm [2½ in. + 4 in.]	102 mm + 102 mm [4 in. + 4 in.]	140 mm + 102 mm [5½ in. + 4 in.]

Table 3 – Design insulation nominal thickness for achieving the respective R-value (determined by ERCR members).

different conventional low-sloped membrane roofing systems: adhesive-applied roofing systems (AARS); a fastener-free assembly, PARS; and seam-fastened MARS. Using the insulation R-values per inch provided by the manufacturers, the overall insulation thicknesses (top and bottom layers) for these three design categories were determined by the ERCR steering committee as shown in *Table 3*.

The third step in Task 1 was designing 36 assemblies from steps 1 and 2 and testing them on the 8- by 20-ft. horizontal calibrated hot box (CHB) at the Dynamic Roofing Facility (DRF) energy lab to determine the effective thermal resistance of roofing assemblies. The results from Task 1 are published in the conference paper[10] submitted to the ASTM D08 Ninth Symposium on Roofing Research and Standards Development.

In Task 2, thermal bridging, the objective was to quantify the heat losses from fasteners and their associated impact on the energy design of roofs. The insulation thickness and layout remain the same as described in Task 1 (*Table 3*), with the exception of test specimen size. The testing for the quantification of thermal bridging was focused on 1.2- by 1.2-m (4- by 4-ft.) insulation aboard and was conducted on the 1.2- by 1.2-m (4- by 4-ft.) horizontal guarded hot box (GHB) (*Figure 3*). The GHB has been designed, constructed, and calibrated in accordance with ASTM C1363, *Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus.*[11] The testing on the GHB allows for the isolation of a component and the in-depth analysis on the thermal performance of that component and its interaction with other roofing components.

More than 100 experiments were conducted on thermal bridging, highlighting the impact of fastener density, fastener location, fastener diameter, and fastener penetration depth. All thermal bridging tests included a steel deck as the structural substrate, fiberglass mat gypsum roof cover board, and thermoplastic membrane as the waterproofing layer. All experiments were conducted at a mean temperature of 24°C (75°F) with climatic chamber maintained at 4°C (39°F) and metering chamber at 44°C (111°F).

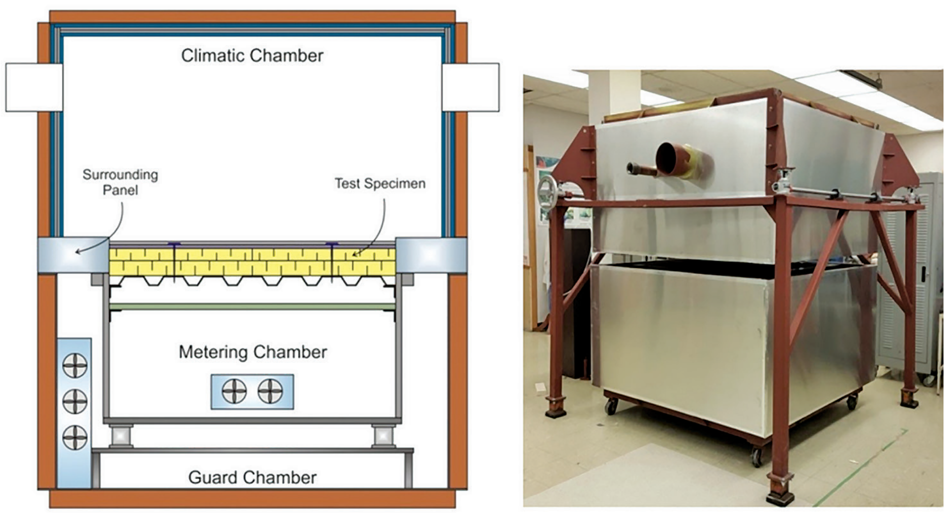


Figure 3 – 1.2- by 1.2-m (4- by 4-ft.) GHB.

IMPACT OF FASTENER DENSITY

To understand the relationship between fastener density and thermal bridging, experimental testing was conducted with three different fastener densities—2.69, 4.04, and 6.73 fasteners/m^2 (0.25, 0.38, and 0.63 fasteners/ft^2)—installed on the three design categories—R-26, R-31, and R-36 roof configurations (*Figure 4*). Fastener #14 (Head diameter = 11.13 mm [0.438 in.], shank diamter = 6.02 mm [0.237 in.]) was the standard fastener used for this investigative study. Metal fastener plates with a 76-mm (3-in.) diameter were used with all the fasteners in the study. *Figure 5* shows the insulation and fastener layout depicting the insulation thickness and fastener lengths.

In each design category, the testing started with quantifying the thermal performance of the assembly without fasteners, and then followed by installing fasteners as per the fastener density and determining the respective effective R-value. The measured effective R-value of each fastener configuration was compared relative to the respective assembly without fasteners, and the percentage decrease in the effective R-value from thermal bridging was determined. Following this approach, the measured data obtained from the testing of each roof configuration with each insulation type in each design category were determined and grouped based on fastener density.

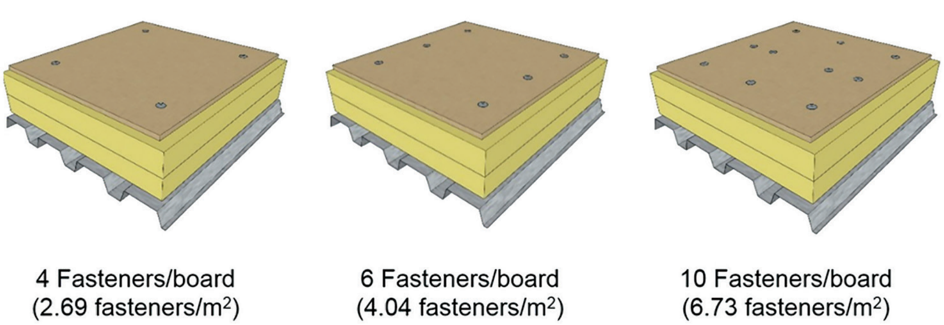


Figure 4 – Fastener density.

These data were fitted with a polynomial curve trend line to obtain the generalized curves as shown in *Figure 6*, which highlights the relationship between fastener density and effective R-value of the roof assembly. The data show that as the number of fasteners per unit area increased, the conductive heat flow increased, lowering the overall thermal performance of the roof assembly. The decrease in effective thermal resistance with fasteners was found to be consistent, irrespective of insulation type having an equivalent thermal resistance. Although the maximum fastener density tested in this study was 6.73 fasteners/m^2 (0.63 fasteners/ft^2), the trend line was extrapolated to 8 fasteners/m^2 as shown in *Figure 6*.

The trend of the generalized curves indicated that the thermal resistance of the insulation influences the thermal bridging effects. For example, with the same fastener density, thermal bridging losses are higher in R-36 assemblies compared to R-31 and R-26. Similarly, the thermal losses are higher in R-31 relative to R-26 assemblies. The R-26 and R-31 assemblies tested with the fastener densities ranging from 2.69 to 6.73 fasteners/m^2 (0.25 to 0.63 fasteners/ft^2) showed an average of 5% to 12% decrease in the effective R-value, and the R-36 assemblies measured 6.4% to 13.3% decrease in the effective R-value. The developed fastener impact factor curves will enable a designer to predict thermal losses for different fastener densities followed in the industry, and design roof assemblies accommodating the resulting losses.

Fastener compensation factors have been developed to identify the additional thermal resistance required to compensate for the thermal bridging losses. These factors were generated from further data analysis of fastener impact factor curves and validated through experimental testing.

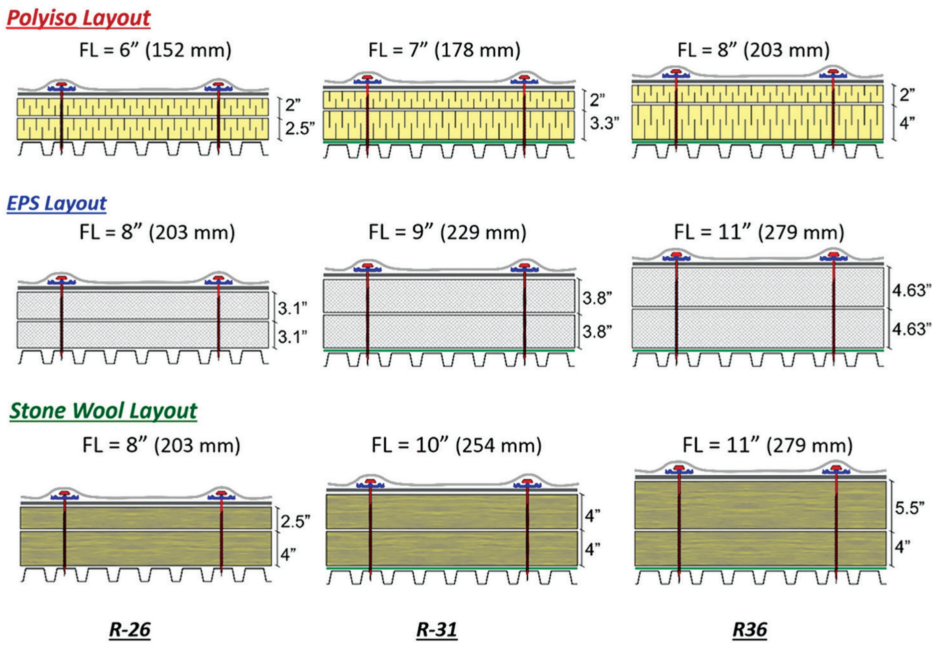


Figure 5 – Insulation and fastener layout (FL = fastener length).

More than 100 experiments were conducted on thermal bridging, highlighting the impact of fastener density, fastener location, fastener diameter, and fastener penetration depth.

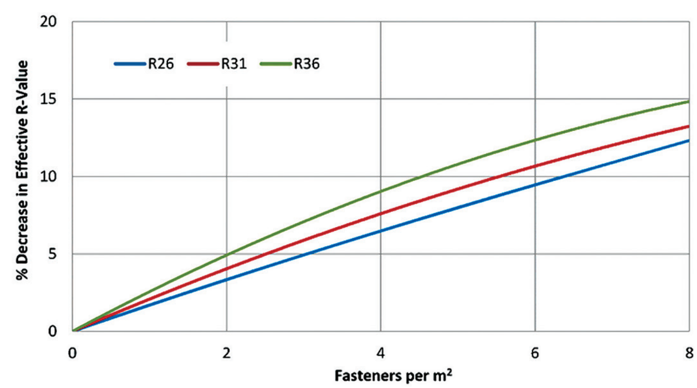


Figure 6A – Fastener impact factors.

Climate Zone		1	2	3	4	5	6	7	8
Effective Thermal Resistance		21	26	26	31	31	31	36	36
Fasteners/ft^2	Fasteners/m^2	% Decrease in Effective Thermal Resistance							
0.250	2.69	-	4.4	4.4	5.3	5.3	5.3	6.4	6.4
0.375	4.04	-	6.5	6.5	7.7	7.7	7.7	9.1	9.1
0.625	6.73	-	10.5	10.5	11.7	11.7	11.7	13.3	13.3

Figure 6B – Data obtained from testing of each configuration, grouped based on fastener density.

Design Effective R-Value	Fastener Compensation Factor %		
	Fastener Density/m²		
	2.69	**4.04**	**6.73**
26	5.04	7.43	12.45
31	6.23	9.21	15.35
36	8.01	12.01	20.09

Table 4 – Fastener compensation factors—the additional thermal resistance required to compensate for the thermal bridging losses caused by fastener density.

Table 4 provides the offset values in terms of fastener compensation factor, which is the required percentage increase in the design effective R-value of the roof assembly to compensate for the thermal bridging losses. For example, the effective R-value of an R-31 roof assembly designed with a fastener density of 6.73/m² (0.63/ft²) has to be increased by 15.35 %, around R-36, to meet a target design value of R-31.

IMPACT OF FASTENER LOCATION

In MARS and PARS, the fasteners are installed on top of the insulation board or the cover board if the assembly has one in its layout. Within PARS, there also exist roof designs where the bottom insulation layer in the multilayer insulation layout is mechanically fastened, while the top insulation is attached with adhesives. To quantify the effect of fastener location in a multilayer insulation layout, three configurations were evaluated in each design category:

- Top through fasteners – fasteners installed on the top of a cover board
- Bottom fasteners – fasteners installed on top of the bottom layer
- Bottom inverted fasteners (B-Invt) – Similar to bottom configuration, but with boards swapped; i.e., top and bottom insulation boards were exchanged.

Figure 7 gives the example layout of R-26 polyiso configuration. The testing was conducted with #14 fasteners, maintaining a fastener density of 2.69/m² (0.25/ft²). The B-Invt testing was conducted to quantify how much impact the thermal resistance of the top insulation layer has on the overall thermal bridging effects with fasteners installed in the bottom insulation.

Figure 8 shows the effect of fastener location in a two-layer insulation layout.

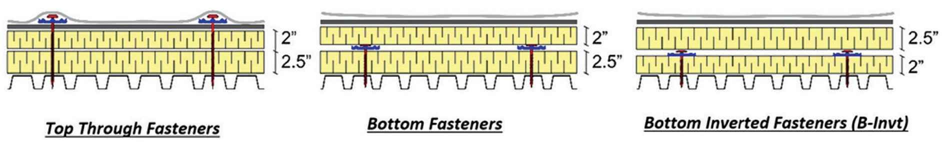


Figure 7 – Fastener location (example of R-26 polyiso layout).

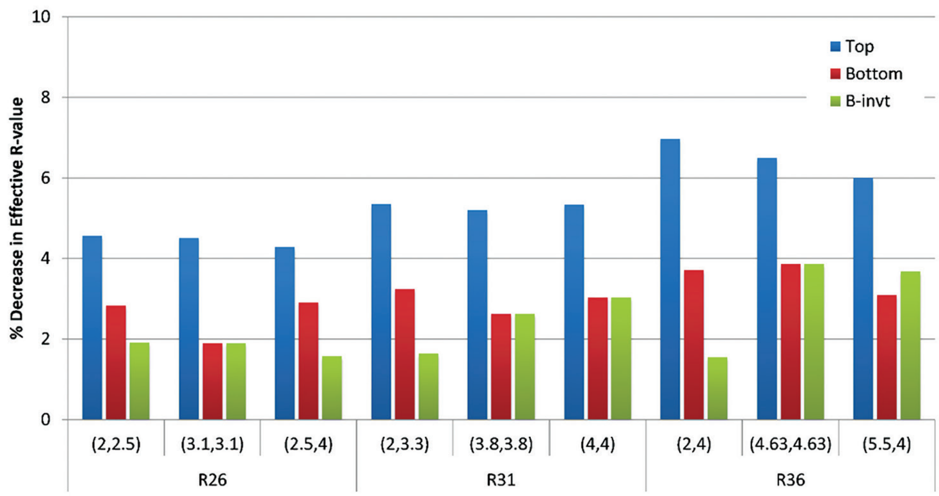
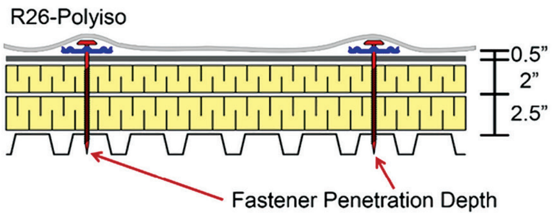


Figure 8 – Effect of fastener location in the roofing system.



Fastener Length	Fastener Penetration Depth
6"	1"
7"	2"
9"	4"

Figure 9 – Penetration depth.

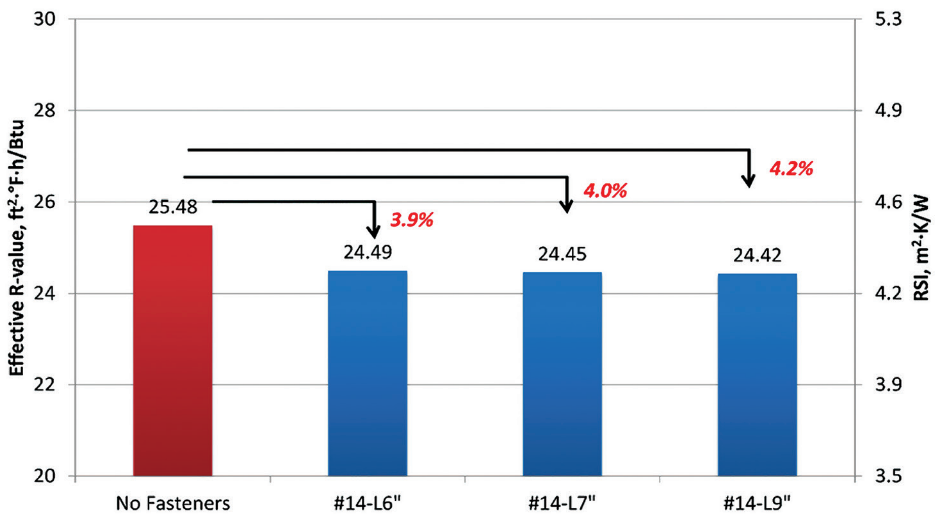


Figure 10 – Effect of fastener penetration depth.

The data represent the percentage decrease in effective R-value relative to the assembly without fasteners in each design category and each insulation type. The location of fasteners within the multilayer insulation arrangement has a significant impact on the overall thermal performance of the roofing system. In the two-layer insulation layout, installing fasteners on the second layer minimized the thermal bridging effects by 30% to 50% compared to the through fastener (i.e., fasteners installed on the top layer). These results represent the scenario where the top insulation layer has a lower thermal resistance relative to the bottom layer. Switching the insulation layout, (i.e., thicker insulation on the top), the thermal bridging was minimized from 40% to 70%, depending on the thermal resistance of the top insulation layer. In a multilayer insulation layout, the thermal resistance of the top insulation layer plays a significant role in shielding the thermal bridging effects from the fasteners installed in the bottom layer.

IMPACT OF FASTENER PENETRATION DEPTH

In commercial roofing installations, when using mechanical fasteners as a mode of roof attachment, the standard practice is to maintain a penetration length of 19 to 25 mm (¾ to 1 in.) below the male flute or upper flange of the steel deck. However, in reality, the installed penetration lengths fall short of the standard practice. The effect of the penetration depth on the overall thermal performance of the roof assembly is evaluated by testing three different fastener lengths of #14 (6 in., 7 in., and 9 in.). The testing was conducted on R-26 polysio roof assemblies (overall thickness = 127 mm [5 in.]) to ensure penetration depths of 25, 51, and 104 mm (1, 2, and 4 in.) below the deck, as shown in *Figure 9*. The fastener density was maintained at 2.69 fasteners/m^2 (0.25 fasteners/ft^2).

Figure 10 summarizes the effect of fastener penetration depth. The two fastener penetration depths of 51 and 102 mm (2 and 4 in.) showed an average of 0.2% variation in the thermal performance compared to the standard practice of 51-mm (2-in.) depth below the steel deck. Therefore, it was established that the fastener penetration depth had a minimal impact on the effective R-value of the roof assembly.

EFFECT OF FASTENER AREA

The fundamental heat flow relationship states that the heat flux is directly proportional to the area of the surface perpendicular to the direction that heat

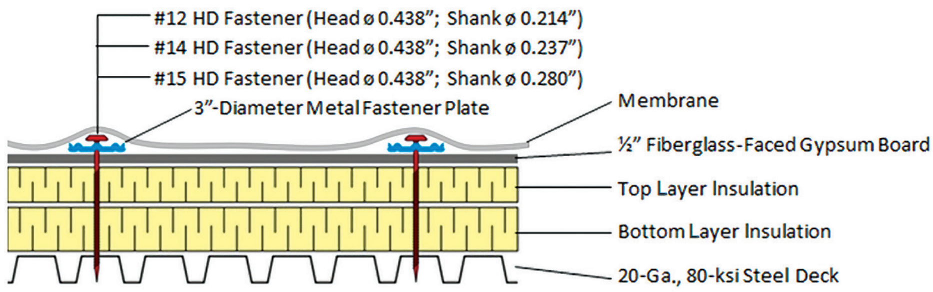


Figure 11 – Fastener area.

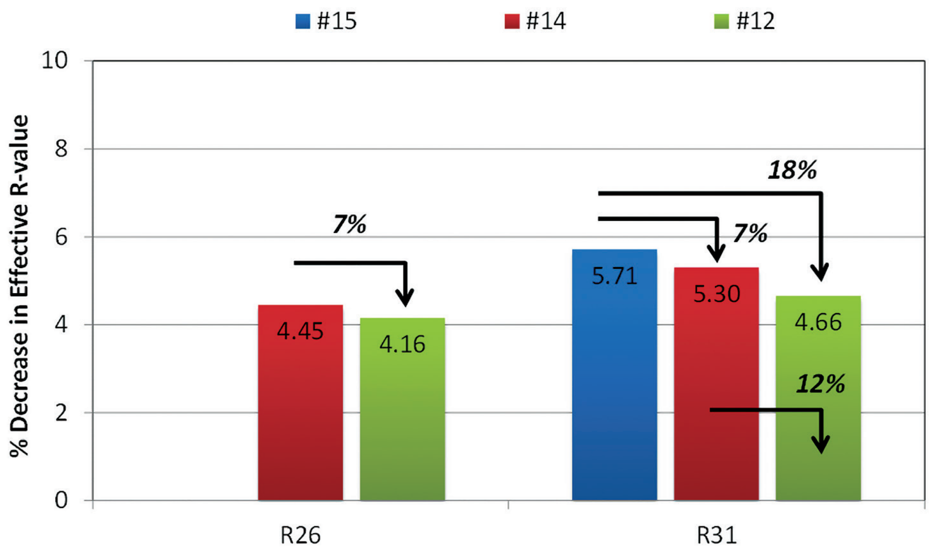


Figure 12 – Effect of fastener diameter.

is flowing. Relating the heat flux theory to the fastener area, three common commercial roofing fasteners were evaluated. The fasteners included #12, #14, and #15, with shank diameters/area of 5.4 mm/23.2 mm², 6.0 mm/28.4 mm², and 7.1 mm/40.0 mm² (0.214 in./0.036 in.², 0.237 in./0.044 in.², and 0.280 in./0.062 in.²), respectively (*Figure 11*).

The testing was conducted on two design categories—R-26 and R-31—with the three insulation types maintaining a constant fastener density of 2.69 fasteners/m² (0.25 fastener/ft²). *Figure 12* shows the data summary for the fastener diameter effects. Irrespective of the insulation type, the data showed that the fastener area had an impact on the overall thermal performance of the roofing assemblies. In the R-26 category, two fastener types—#12 and #14—were tested. The #14 fastener had 30% more heat transfer area than #12, which lowered the thermal performance on average by 7% compared to the roof assembly installed with #12 fasteners. In the R-31 design category, roof assemblies with #14 fasteners measured on average 12% lower thermal performance compared to the roof assembly installed with #12 fasteners. The #15 fasteners, which had almost 40% more conductive area than #14 fasteners and 70% more area than #12 fasteners, increased the thermal bridging on average by 7% and 18%, respectively. Thermal bridging increases with the increasing fastener diameter/area were observed from the measured data.

CONCLUSIONS

Task 2 of the industry consortium project, ERCR, quantified the thermal bridging of fasteners that are typically not considered in the thermal design of roofs. In assessing the impact of thermal bridging, more than 100 experiments were conducted highlighting the effect of fastener density, fastener location, fastener diameter, and fastener penetration depth on the effective R-value of the roof assembly.

Quantifying the effect of fastener density, the measured data indicated that thermal bridging increases with the fastener density and also with the thermal resistance of the insulation. The average loss in effective R-value ranged from 5% to 14%. Generalized fastener impact factor curves representing the three design categories—R-26, R-31, and R-36—were developed, which will allow the designer to predict losses for different fastener densities followed in the industry, and design roof assemblies to appropriately accommodate the losses.

In a multilayer insulation layout, fasteners installed in the bottom layer are shielded by the top insulation and can reduce thermal bridging from 30% to 70% relative to through fasteners (i.e., fasteners installed on the top layer), depending on the thermal resistance of the top insulation layer. The installation of thicker insulation (higher thermal resistance) as the top layer is a preferable design approach.

The fastener penetration depth below the steel deck was found to have a minimal impact on the

Using fasteners as an attachment method in membrane roof assemblies as compared to using adhesives has multiple benefits, such as higher wind uplift resistance, ease of application and faster completion of the roof assembly, flexible installation without issues of mopping and curing, and marginal cost benefits.

thermal performance of the roof assembly.

The increase in the fastener diameter or the fastener area (#12 < #14 < #15) increased the overall heat flow through the assembly. From #14 to #15 there was an average 8% drop in the thermal performance, and from #12 to #15, the reduction was 18%. The results are specific to the R-31 assemblies tested. The comparison of #12 to #14 revealed a decrease of 6.5% to 12% (R-26 to R-31), showing that the thermal bridging effect increases with the increasing thermal resistance.

Using fasteners as an attachment method in membrane roof assemblies as compared to using adhesives has multiple benefits, such as higher wind uplift resistance, ease of application and faster completion of the roof assembly, flexible installation without issues of mopping and curing, and marginal cost benefits. To sustain these benefits, the commercial roof design should acknowledge the thermal bridging effects of fasteners and plates and accommodate them appropriately at the design stage of the roofs.

Towards codification, efforts are underway to potentially implement these thermal bridging factors in the energy codes to update the current thermal design of roofs, which appear to assume thermal bridging of fasteners to have an insignificant impact on effective R-value. This enhancement can lead to optimized roofing energy designs, realistic prediction of commercial building energy savings, and maintenance of an energy-efficient built environment.

ACKNOWLEDGEMENTS

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Dr. Baskaran is a group leader with the NRC and an adjunct professor at the University of Ottawa. He is a member of committees at IIBEC, RICOWI, ASCE, SPRI, ICBEST, and CIB, and he is a research advisor to various task groups of the National Building Code of Canada. He has authored or coauthored over 200 research articles and received over 25 awards, including the Frank Lander Award from the Canadian Roofing Contractors Association and the Carl Cash Award from ASTM. Dr. Baskaran was recognized by Her Majesty Queen Elizabeth II with a Diamond Jubilee medal for his contribution to his fellow Canadians.

Architect Killed by Crumbling Debris From Manhattan Façade

Erica Tishman, 60, AIA, a celebrated architect and VP of project management at Zubatkin, was killed December 17 when struck while walking near her office by a chunk of façade which fell from a Midtown Manhattan building.

Himmel + Meringoff Properties, owners of the 17-story office building at 729 Seventh Avenue (built in 1915), had been fined on April 29 for "damaged terra cotta at areas above 15th floor in several locations which poses [sic] a falling hazard for pedestrians." The company had paid a $1,250 fine. City law requires repair action within 90 days, but despite being issued a second violation notice, it wasn't until November that the city approved plans for façade work which had still not been undertaken at the time of the tragedy.

"No pedestrian should be at risk from dangerous façade conditions," said Department of Buildings spokeswoman Abigail Kunitz. The department has since ordered the property owner to build a sidewalk shed to protect passersby.

Almost 380,000 pedestrians walk the streets in this area of Manhattan every day, according to the Times Square Alliance. A 2015 analysis by the *Wall Street Journal* showed that, on average, one passerby a month is injured by debris falling from New York City construction sites.

Immediately after the tragedy, the Department of Buildings examined approximately 1,300 buildings it said needed immediate façade work.

Tishman also chaired the board of directors for the Educational Alliance, was on the board of trustees at the Riverdale Country School and the Central Synagogue in Manhattan, and was chair for the Alumni Schools Committee of Princeton University. She had a master's degree in architecture from Harvard Graduate School of Design. She is survived by her husband and three children.

