

# Fastener Thermal Bridging in Low-Slope Roofs

## Where do we stand on energy and money loss, codes, and verification?

By Thomas J. Taylor, PhD; Jennifer Keegan, AAIA; Elizabeth Grant, RA, PhD; and Georg Reichard, PE, PhD

When it is summer and your air conditioning is on full power, or it is winter and the heating system is doing its best, do you leave the doors and windows open? Of course not; you keep things as closed up as possible. A tight building enclosure tries to decouple the interior environment from that of the exterior as much as possible. But, by virtue of construction practicalities, there can be many features of a building enclosure that act as thermal bridges between the indoor and outdoor environments. This is specifically true for structural elements such as steel studs and fasteners. In addition, actual penetrations that bridge across or through a building's insulation layer allow for increased heat flow inwards during warm periods and outwards during cold periods.

If insulation is not continuous, heat can flow easily into and out of buildings, reducing energy efficiency and potentially wasting money. This article summarizes recent modeling studies that show the costs of thermal bridging and ways to reduce or eliminate the effect. Also, the potential implications for future code development are discussed. Finally, modeling is just that: a prediction based on theory. Therefore, efforts to experimentally verify the predictions are discussed.

### WHAT IS CONTINUOUS INSULATION?

Building designers are now familiar with the use of continuous insulation (ci). ASHRAE 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, defines continuous insulation as “insulation that is uncompressed

and continuous across all structural members without thermal bridges other than fasteners and service openings.” For walls, one way to meet this requirement is to use foam sheathing installed outboard of any studs or other structural members.



Figure 1. Example of a big-box-style building. Image courtesy of R&R Construction, LLC, Denver, Colorado.

**IS LOW-SLOPE FOAM ROOF INSULATION CONTINUOUS? POSSIBLY NOT!**

Many designers and consultants assume that above-deck roof insulation is continuous. The ASHRAE 90.1 definition does not address the significance of thermal bridging due to fasteners. However, as will be described, modeling and experimental studies have suggested that thermal bridging due to the fasteners used to attach insulation and single-ply membranes can be very significant.

Wall systems use relatively few fasteners per unit area of continuous insulation (typically, around 6 fasteners per 4- x 8-ft. (1.2- x 2.4-m) board, and the impact is therefore assumed to be relatively minor. However, attached single-ply systems installed above fastened insulation boards can contain large numbers of fasteners; up to 48 fasteners per 4- x 8-ft. (1.2- x 2.4-m) board, depending on project-specific wind-uplift pressures.

- A typical big-box building has a roof area of 125,000 ft.<sup>2</sup> (11,613 m<sup>2</sup>); an example with a reflective white roof membrane is shown in *Figure 1*.
- To achieve a wind-uplift resistance of 1-120, roofs of this size would have around 50,000 metal fasteners securing the insulation and membrane, if mechanically attached.
- Metal fasteners are highly conductive, leading to a predicted effective R-value of 25.7 versus a design R-30,<sup>1,2</sup> which is a 14.3% reduction. The prediction was based on earlier modeling studies by Olson et al.<sup>3</sup> and Singh et al.<sup>4</sup>

**THE TRUE COST OF MECHANICALLY ATTACHING LOW-SLOPE ROOFS**

Assuming that thermal bridging due to mechanical attachment with metal fasteners leads to effective R-value reductions of approximately 14% (for a typical fastener density), some significant costs are incurred by the building owner<sup>5</sup>:

- The cost of the insulation value that was lost due to thermal bridging. For example a design R-30 could be reduced to an effective R-25.7. Therefore, R-4.3 of the installed insulation has been lost, which carries an economic cost. It is insulation that was purchased but the R-value was unrealized.
- The loss of energy efficiency due to a lower-than-designed effective R-value. It is worth noting that many good membranes are expected to last over 25 years, meaning that energy efficiency losses

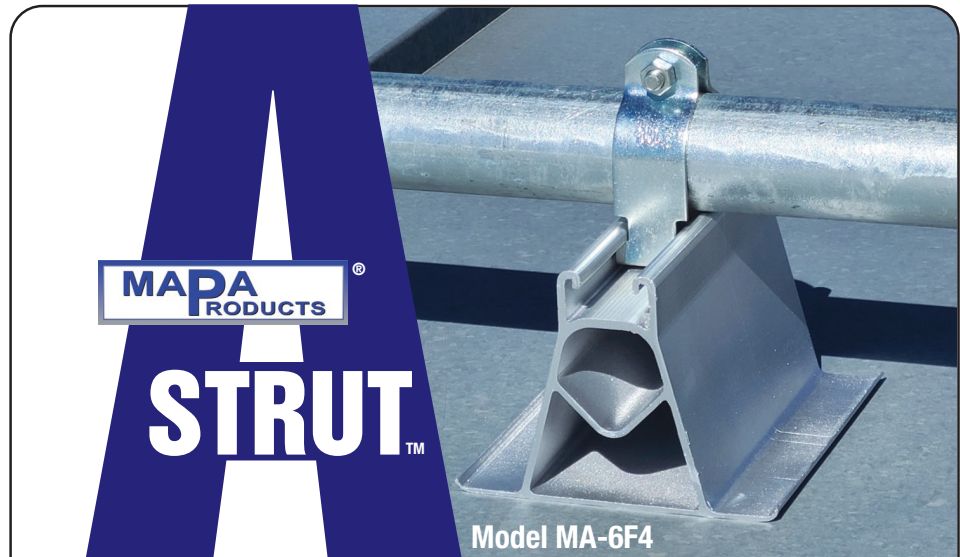
are incurred over that time period.

- Fastener costs, while lower than the cost of adhesives, need to be factored into any analysis of the total cost impact resulting from thermal bridging.

**ALTERNATIVE ROOF ASSEMBLY ATTACHMENT METHODS**

There are several ways to reduce or even eliminate the use of metal fasteners in single-ply low-slope roof assemblies as compared to traditional edge fasteners combined with insulation fasteners:

- Use induction-welded insulation plates to reduce the total number of single-ply membrane and insulation fasteners. These plates are used to attach insulation, and they fuse to the membrane when inductively heated.
- Use fasteners with plastic fastening plates to reduce the extent of thermal bridging, as suggested by Burch et al.<sup>6</sup> However, this approach would need to be validated with respect to wind uplift performance and might only be acceptable for the insulation fasteners.



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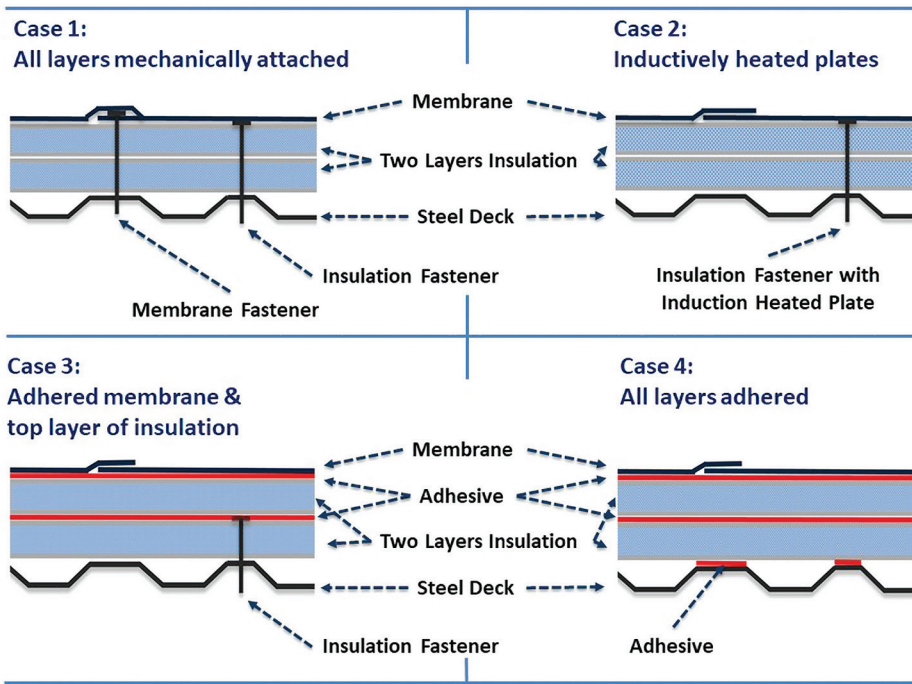


Figure 2. Various approaches to attaching roof assemblies.

- Attach the membrane and top layers of insulation with adhesive. In this way, only the bottom layer of insulation is mechanically fastened. Such practice reduces the total number of fasteners and plates, and those that are used get "buried" under the top layer of insulation. This replicates the code mandate that has emerged in recent standards, and reduces the thermal-bridging effect.
- Eliminate mechanical fasteners so that all the layers of the assembly are adhered. This represents the fully decoupled design intent of code, whereby the specified insulation value is not compromised by fastener thermal bridging. Note that adhering insulation directly to a steel deck is not normally practiced, but is included for comparison purposes to represent an ideal situation.

These approaches are shown schematically in Figure 2.

#### OVERALL COST-BENEFIT

- **Initial installation costs**—While mechanically attached single-ply systems are generally considered to have lower construction costs compared to adhered systems, a simple analysis of construction material costs (that is, metal fastener versus adhesive) rarely takes into account lost insulation costs and reductions in long-term energy efficiency.
- **Design versus effective R-value**—While a designer may specify and the building owner may pay for a specific R-value, the final effective R-value will be lower if thermal bridging is present. That "lost" R-value carries an economic cost. It can be thought of as insulation thickness that was purchased but essentially not used. Also, HVAC systems are specified based on the design R-value even though modeling shows the effective R-value could be significantly lower.

- **Energy efficiency**—Thermal bridging reduces the effective insulation value, thereby leading to lower energy efficiency. Space heating and cooling costs would therefore be higher than anticipated, without any potential remedy, over many decades.

#### TOTAL COST ANALYSIS

Modeling of the total installation and energy-efficiency costs has identified the potential true long-term cost of thermal bridging across a wide range of cities.<sup>5</sup> Results for a 125,000-ft.<sup>2</sup> (11,613 m<sup>2</sup>) building in two cities: Chicago, Illinois, and Miami, Florida, which represent climate zones where HVAC costs are dominated by heating and cooling, respectively. Lost energy efficiency leads to higher energy use, and it is that value that is shown.

By modeling in this way, opportunities to reduce or eliminate thermal bridging to optimize cost and performance can be identified. The cost difference between attachment methods, when totaled, indicates the cost-neutral opportunity to reduce thermal bridging.

- For HVAC use in geographies dominated by heating, such as Chicago, costs totaling \$75,390 could be put towards a totally adhered system. Alternatively, \$75,390 - \$20,795 = \$54,595 could be put toward the buried-fastener approach.
- For HVAC use in geographies dominated by cooling, such as Miami, costs totaling \$84,765 could be put towards a totally adhered system. Alternatively, \$84,765 - \$22,670 = \$62,095 could be put toward the buried-fastener approach.

Whether or not thermal bridging can be cost-effectively reduced or eliminated depends on both material and labor costs for adhered approaches. There are a wide range of adhesive costs, depending on type and whether they are insulation or membrane adhesives. The ability to meet the target costs would need to be

Case	Lost R-Value	Fastener Cost	Lost R-Value Cost	Value of Lost Energy Efficiency		Total Net Cost	
				Chicago	Miami	Chicago	Miami
<b>Mechanically Attached</b>	14.5%	\$15,633	\$44,757	\$15,000	\$24,375	\$75,390	\$84,765
<b>Inductively Welded</b>	11.6%	\$19,217	\$35,802	\$13,125	\$20,625	\$68,144	\$75,644
<b>Buried Fasteners</b>	3.2%	\$5,189	\$9,981	\$5,625	\$7,500	\$20,795	\$22,670
<b>All Layers Adhered</b>	0%	\$0	\$0	\$0	\$0	\$0	\$0

Table 1. Costs associated with various attachment strategies for a 125,000-ft.<sup>2</sup> (11,613-m<sup>2</sup>) big-box-style building in Chicago and Miami.

Fastener Density, #/m <sup>2</sup> (#/ft. <sup>2</sup> )	Modeled Reduction from R-30 Design <sup>3</sup>	Experimental Reduction from R-31 Design <sup>7</sup>
2.69 (0.250)	10.98%	5.3%
4.04 (0.375)	13.96%	7.7%
6.73 (0.625)	19.93%	11.7%

**Table 2. Modeled versus experimental reductions in effective R-value as a function of fastener density.**

validated and could be region dependent. Also, it should be noted that while thermal bridging could be reduced, depending on the extent of the reduction, the impact in terms of lost energy efficiency could still be significant.

### EXPERIMENTAL VALIDATION

Before any changes to energy-efficiency-related codes can be considered, the modeled data suggestive of significant thermal bridging due to fasteners need to be experimentally validated. Molleti and Baskaran<sup>7</sup> used a horizontal guarded hot box to measure the effective R-value of 4- x 4-ft. (1.2- x 1.2-m) insulation using different fastener densities, screw diameters, and lengths. Also, they evaluated different effective R-values, all achieved with two layers of insulation. While their data set is very comprehensive, overall it showed lower amounts of thermal bridging than suggested by the previous modeling work of Olson et al. using HEAT3 version 6.03 finite difference software, as shown in Table 2. The discrepancies between the modeled and experimental approaches may be due to the effects of the testing apparatus, or the limitations of the computer model, or a combination of both.

The goal of the present project is to develop a stepwise examination approach to experimentally validated simulation modeling useful to building enclosure consultants that can later be used to evaluate a broader range of roof assemblies and roof fastener configurations. While consultants and other members of the roofing industry are often reluctant to trust simulation results in any given context due to the many parameters that influence the accuracy of computational models, it is the thorough understanding of simulation limitations that needs to be evaluated and understood. Through the experimental validation of a simulation approach in this project, the researchers aim to provide a tool to give designers an acceptable estimate of effective R-value of a wide range of roofing assemblies that cannot, due to cost and time constraints, all be tested experimentally.

The RCI-IIBEC Foundation sponsored a study titled *Laboratory Testing of Roof Assemblies for Comparison with Simulated*

*Models: Thermal Performance Assessment of Thermal Bridges due to Roof Fasteners* at Virginia Tech. The team, led by Dr. Elizabeth Grant and Dr. Georg Reichard, along with their students, as well as industry sponsors and research contributors Simpson Gumpertz & Heger (SGH) and GAF, is conducting laboratory tests to compare the thermal performance of physical models of simple roof assemblies under different controlled laboratory environmental conditions compared with computational models of these assemblies. The modeling approach will be undertaken using Ansys Simulation Software, a 3-D finite element analysis software tool. The computational model will include a higher level of specificity than that used in previous approaches; for example, it will include the precise geometry of the fasteners and plates as modeled by the manufacturer rather than modeling these elements as square objects as was done in the earlier simulation by Olson et al.<sup>3</sup>

The study at Virginia Tech uses a controllable climate test chamber in the Building Enclosure and Systems Technology (BEST) Lab at Virginia Tech's Myers-Lawson School of Construction to measure heat flow through a roof assembly similar to that found in commercial roofs. Through stepwise analysis of impact factors, the research team

- isolates the thermal effects of fasteners of different lengths and diameters;
- evaluates the effects of individual insulation layers first, before pairing them with a gypsum substrate board, a high-density polyisocyanurate cover board, and finally, a metal deck in conjunction with fasteners; and
- determines the influence of one versus two layers of insulation. While the authors acknowledge that two layers of staggered insulation is the preferred approach to minimize air movement within the roof assembly, results from simulation programs typically will not show any differences, as it treats the joints as a perfect contact problem of the same material. This step is taken to verify these assumptions in experiments and assess potential

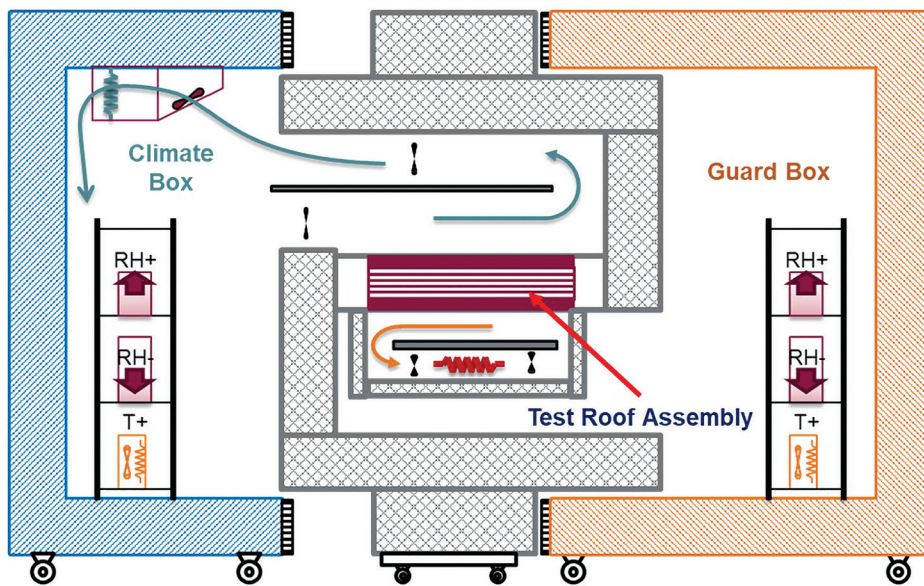
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**Figure 3.** Test apparatus used by Virginia Tech to evaluate the thermal resistance of roof assemblies with and without fasteners.

differences in thermal heat transfer effects introduced by the joints of two-layer configurations.

The results obtained for these individual experimental assemblies are compared to the results retrieved by respective computational models. A schematic of the apparatus is shown in Figure 3.

Unfortunately, due to COVID-19, the project is moving at a slower-than-projected pace and will not be completed until later in 2021.

### CODE IMPLICATIONS

As described previously, energy codes do not address the significance of thermal bridging due to fasteners. However, the experimental data to date and modeling studies of thermal bridging suggest that in systems with large numbers of fasteners, thermal losses may be

significant. That would potentially impact not only ASHRAE 90.1 but also the *International Energy Conservation Code* (IECC) and the *National Energy Code of Canada for Buildings* (NECB). Several solutions to the issue of energy efficiencies being lower than previously expected are possible:

- Make no changes to energy-efficiency codes. Simply accept that previously assumed levels of energy efficiency are lower in some systems than others. Given the overall drive towards reduced energy use, this seems to be an unlikely and ill-advised approach that may have long-term consequences on building performance.
- Increase the levels of insulation to compensate for thermal bridging. This approach would force a choice to be made between increasing insulation


thickness and adhering the membrane and top layer of insulation. This compensation could be nonlinear; that is, designers may need to overcompensate for the lost R-value with the increase in insulation thickness to offset the impact of the thermal bridging. The code would need to define the “acceptable” amount of thermal bridging. It could allow for buried fasteners or not. This approach could be either prescriptive, providing for increased insulation as a function of fastener density, as described by Molleti and Baskaran,<sup>7</sup> or it could allow modeling and experimental testing to determine the loss in R-value and therefore the increased insulation level required.

- Require buried fasteners in all installations in affected climate zones. Again, this approach could be prescriptive in terms of depth of buried fasteners versus fastener density, or it could allow for a modeling-based approach. It would also be dependent on the required wind uplift resistance level and would rule out inductively welded fasteners and membrane fasteners in the seams.

The pathway might be dependent on climate as well as on the degree to which fastener thermal bridging impacts R-value. That will not be accurately known until it has been repeatedly and independently experimentally verified.

### CONCLUSIONS

Modeling by several groups suggests that energy loss and economic cost of thermal bridging due to mechanical fasteners in low-slope roof assemblies could be significant. For a typical fastener density of 5.38 fasteners per square meter (0.5 fasteners per sq. ft.), the reduction in R-value is modeled to be around 14%.

- Further independent experimental validation by independent groups is essential before any code changes could be initiated. Although thermal bridging has been validated experimentally,<sup>7</sup> further such studies could help to more broadly characterize the various fastening approaches that could be used as alternatives.
- The costs of thermal bridging, in terms of lost R-value and reduced energy efficiency, will need to be balanced against the cost of adhesive versus mechanical attachment and the required wind uplift resistance. 

The pathway might be dependent on climate as well as on the degree to which fastener thermal bridging impacts R-value. That will not be accurately known until it has been repeatedly and independently experimentally verified.

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## Roofing Fatalities Up 15% in 2019

A report released by the United States Bureau of Labor Statistics (BLS) in December of 2020 shows that the number of roofing fatalities reported in 2019 was up 15% from 2018. The National Census of Fatal Occupational Injuries report showed that roofers accounted for 111 of 5,333 fatal on-the-job injuries in 2019. This rise is especially concerning considering that in 2018, the roofing industry's death rate was already 51.5 per 100,000, making it one of the most dangerous professions. The average rate across all occupations was 3.5 deaths per 100,000. Rates are also up among Hispanic or Latinx workers (13% higher, the highest it has been since this report started being produced in 1992). The number of fatalities in the private construction industry is up five percent from 2018, which is the highest it has been since 2007.

— *Roofing Contractor, bls.gov*



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