Research Report

Foam Plastic Applications
for Better Building

Repetitive Metal Penetrations in Building Thermal Envelope Assemblies

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of the American Chemistry Council

Report Written by:

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Introduction:

The thermal bridging effects of repetitive metal penetrations, such as cladding connectors and sheathing fasteners or other structural support penetrations, through or into insulated building thermal envelope assemblies is not a new topic. The impact of thermal bridging to the thermal performance of exterior envelopes has been known and studied for some time, and can vary substantially in magnitude or consequence. The *Building Envelope Thermal Bridging Guide* (Morrison-Hershfield LTD, 2014), which expands upon prior work on thermal bridging (e.g., ASHRAE RP-1365, Morrison-Hershfield LTD, 2011), makes the following statement:

> *"Research and monitoring of buildings is increasingly showing the importance of reducing thermal bridging in new construction and mitigation in existing construction. The impact can be significant to whole building energy use, condensation risk, and occupant comfort."* [p. vi]

This statement emphasizes the need to intelligently mitigate thermal bridges rather than attempt to increase insulation amounts in buildings designed and built with details that cause significant unaccounted thermal bridging effects and heat loss or gain. The above statement is informed by energy analyses identifying the significant impact of seemingly negligible or small building envelope detailing conditions (e.g., brick shelf angles, metal flashing around fenestration, columns protruding through the thermal envelope, etc.) and also those that are more obviously significant (e.g., concrete slab balcony projections and slab-wall intersections, structural frames or columns projecting entirely through the thermal envelop, etc.). For example, the BC Hydro report makes the following observation:

> *"The effects of thermal bridging were assumed to be negligible if the cross-sectional areas of these conductive components were small, relative to the rest of the building envelope or they were purposely ignored due to the difficulty in assessing the impact. However, the additional heat flow due to major thermal bridges, including ones with small cross sectional areas such as shelf angles or flashing around windows, can add up to be a significant portion of the heat flow through opaque envelope assemblies. For example, the contribution of details that are typically disregarded ranges from 20 to 70% of the total heat flow through walls."* [p. vi]

The above emphasis on mitigating the impact of thermal bridges is also informed by energy use and cost-benefit analyses showing significant diminishing returns for investment in additional thermal insulation when significant thermal bridges exist in the thermal envelope and remain unmitigated. For example, the chart below shows diminishing returns on energy savings by increasing opaque wall insulation amounts, while addressing unmitigated thermal bridges can yield much more significant energy savings. It should be noted that increasing insulation thickness or improving insulation methods still can produce notable energy saving improvements depending on the specific application, building configuration and use, etc. For example, the *Building Envelope Thermal Bridging Guide* notes that significant energy efficiency improvements can be gained by relocating continuous insulation located on the interior of a masonry/concrete building (where it is broken at every story level by a slab-wall linear thermal bridge) to the exterior side of the assembly where it can be made truly continuous (i.e., it can be extended across the slab-wall linear thermal bridges). The chart below indicates that use of improved details to reduce thermal bridging can, for building conditions with large and repetitive thermal bridges, produce a greater energy savings than doubling the insulation amount in the clear field of a wall assembly.

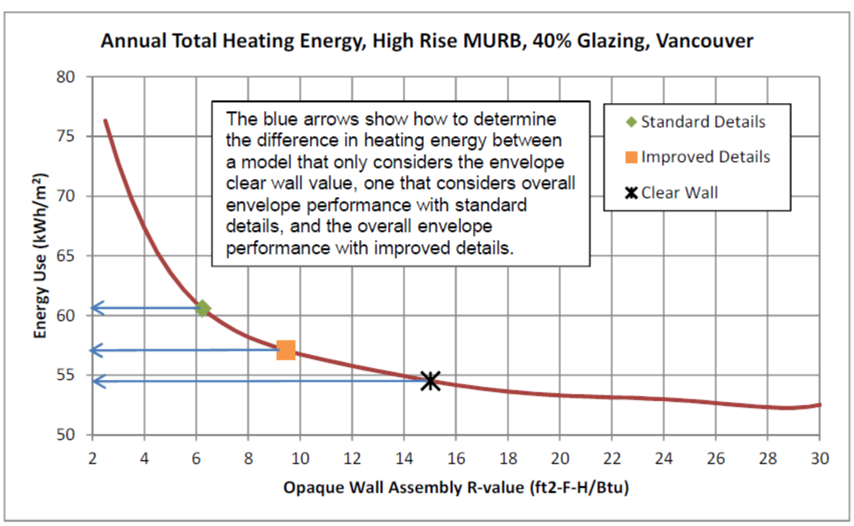


Figure 2.1. Annual Total Heating Energy for a 40% glazed High-Rise MURB in Vancouver

Source: Morrison-Hershfield LTD (2014)

The quantification of thermal bridging impacts and implementation into design and construction practice has faced a number of technical complexities, practical difficulties, and competitive market concerns related to equitable treatment for all affected materials and methods of construction for building envelopes. Even with an equitable, performance-based treatment of thermal bridging across all types of building exterior wall construction, addressing thermal bridging will have market impacts that alter the status quo among competitive construction materials and insulation strategies used to comply with energy codes and standards.

Significant work on linear thermal bridges has been completed by others (e.g., Morrison-Hershfield, LTD 2014; ISO 14683:2007) and is in the early stages of implementation considerations in the US and Canada. Many European nations have already implemented robust thermal bridging requirements for building design. However, less work has been done with quantifying impacts and implementing solutions for point thermal bridges, particularly those bridges that are uniformly distributed over the surface areas of the building thermal envelope assemblies. These bridges cause varying degrees of impact to nominal (clear field) assembly U-factors used by standards and codes in the US for building thermal design and code compliance. These types of distributed point thermal bridges include elements such as cladding and sheathing fasteners and connections. Because these distributed thermal bridges are so closely associated with assemblies (not the intersection of different assemblies and components), they should be appropriately quantified and used to modify the nominal assembly U-factors to account for the impact of such fastenings, connectors, or metal penetrations that are not already included in the basis of the nominal assembly U-factors. Unfortunately, this correction of nominal assembly U-factors also creates significant concern in regard to equitable treatment of these impacts for various assembly types, including structural material types, insulation methods, fastening methods and materials, and construction detailing. Thus, it is important to have a common baseline of understanding and data on what these impacts are and how they may vary in practice. This research report is intended to provide an initial step toward that end.

Point thermal bridge thermal transmittance design value data to support calculation of point thermal bridging effects on the thermal performance (e.g., nominal U-factor) of building assemblies is not readily available. Yet, the implementation of such impacts have already begun to enter building regulations in the U.S. (e.g., Washington State Energy Code) in a manner that attempts to offset the effect by increasing continuous insulation amounts (yet ignoring the impact for other insulation strategies). As mentioned, this can create real or perceived competitive inequities between methods of insulating building envelopes. Furthermore, the U-factors serving as nominal design values for assemblies (such as published in Appendix A of ASHRAE Standard 90.1 (ASHRAE, 2013a)) may incorporate the thermal bridging effect of some nominal amount of metal penetrations for fasteners or connectors (usually just interior and exterior sheathing surfaces, not cladding attachments), or none at all. Accounting for the impact of these distributed types of thermal bridges by way of a correction to nominal design U-factors is faced with inconsistencies in the amount of point thermal bridging already implicit to the nominal U-factor design values. In addition, calculation methods such as reported in the ASHRAE Handbook of Fundamentals (HOF) (ASHRAE, 2013b) may provide for no accounting of any fastener or connector thermal bridging or, if empirical in its basis, the calculation method may inherently include some nominal amount of point thermal bridges as represented in the wall assembly test database used to derive the calculation method. These inconsistencies must be resolved to provide a uniform basis for including a transparent and consistent treatment of fastener/connector thermal bridges in the nominal U-factors used for building assembly thermal design purposes.

Therefore, the focus of this research report is on uniformly distributed point thermal bridges. The main goal is to provide data to help better understand the implications and support an equitable, performance-based treatment of such thermal bridges for common building assembly conditions and variations. To achieve this goal, the following approach was executed:

1. Survey existing literature regarding the magnitude and significance of heat flow associated with point thermal bridges caused by metal penetrations (typically fasteners or connectors) in various wall and roof assemblies.
2. Analyze the existing data and normalize it to a common basis (e.g., thermal transmittance values) and evaluate the ability to use the data to establish a rough approximation of representative thermal transmittance values for use in analyzing various typical assemblies and metal penetration amounts.
3. Evaluate and recommend solutions that may cost-effectively mitigate or minimize the impact of distributed point thermal bridges or metal penetrations in typical assemblies.
4. Recommend additional research as needed to fill significant knowledge gaps.

The above goals are ambitious for a number of reasons related to various technical and practical challenges. First, this Research Report relies heavily on a rather eclectic and disjointed collection of literature on the topic; conducting new thermal modeling or testing was beyond the scope of this research effort. In general, the literature relies on various modeling approaches rather than empirical data to evaluate the significance of fastener thermal bridging in building exterior (thermal) envelopes. But, some empirical data does exist. The modeling methods vary as well as important modeling assumptions, sometimes creating vastly different answers for similar fastening applications. In addition, the magnitude of fastener thermal bridging effects are highly dependent on the geometry of the assembly and the properties of the connected parts, making it difficult to generalize reported findings (but not impossible or impractical).

Furthermore, much of the reviewed research data reported in the literature presents fastener thermal bridging impacts in a RELATIVE manner (e.g., a percentage impact relative to the overall thermal performance of the assembly without the presence of metal penetrations). This relative approach can distort or mask actual trends in the fastener heat flow (point thermal transmittance) due to differences in the overall assembly U-factor to which it is compared in a relative or proportional sense. For example, the relative or proportional impact of a given cladding fastener penetrating an exterior insulation layer in a high performing (high U-factor) assembly may appear large because the heat flow through the overall assembly, to which it is compared, is small. But, in reality, the ABSOLUTE or actual heat flow through the same fastener may be slightly less due to the longer heat flow path created by the thickness of the continuous insulation in the higher performing assembly. Even so, the presence of point thermal bridges through continuous insulation have a notable effect (even though much reduced in magnitude relative to continuous linear thermal bridges such as metal Z-furring often used to penetrate the continuous insulation layer for cladding support).

To complicate matters further, point transmittance values are typically derived on the basis of a temperature difference across the entire assembly, not just the portion of the assembly penetrated by the length of a metal penetration (e.g. cladding fastener or connector). Thus, point thermal transmittance values are unavoidably reported on a basis that is relative to an impact on the entire assembly. Consequently, this tends to show a pattern whereby the point thermal transmittance value at first increases and then begins to decrease with added thickness of the penetrated insulation layer because of the increased heat flow path length. But, in all cases the RELATIVE impact to the overall assembly U-factor always tends to increase with increasing amount of the assembly's overall thermal resistance penetrated by highly conductive metal elements such as fasteners and connectors. This effect is similar in nature to the framing correction factor applied to cavity-insulated cold-formed steel frame walls (see IECC 2018, Section C402.1.4.1).

For reasons mentioned above, the use of exterior insulation on an assembly is often considered to cause fasteners to have a greater RELATIVE impact on the thermal performance of the overall assembly (which is true in a relative sense). In some cases, the impact of fastener thermal bridging may be compensated by increasing the exterior continuous insulation layer, when present, but is otherwise ignored on assemblies without continuous insulation. Rather than address or mitigate the point thermal bridge itself, the RELATIVE approach tends to suggest increasing the penetrated insulation amount to offset the impact. But, this has been shown to be an inefficient means of addressing thermal bridges (Morrison-Hershfield LTD, 2014). This approach could also be executed by decreasing window U-factors or roof U-factors, or even increasing equipment efficiencies to offset energy losses associated with the thermal bridging effect. In fact, this should be considered as it may be a more cost effective way to address the issue than increasing the insulation amount that is penetrated already. But, in general, the first course of action should be to consider practical ways of reducing the source of point thermal bridging by better design, detailing, and material selection for connection methods to avoid or minimize highly conductive metal penetrations through some portion of or all of the thermal envelope.

Literature Review:

The following literature review focuses on available studies that include fastener or point thermal bridging analyses and data with sufficiently detailed assembly information to derive fastener or point thermal bridge thermal transmittance values from the modeled results or test data. Relevant point thermal transmittance data and results from these studies are evaluated and presented later in this research report (see Tables 1 and 2).

ISO 14683:2007, Thermal Bridges in building construction

The ISO 14683 standard provides a framework for including linear and point thermal bridges within the calculation of the overall heat transfer coefficient for a building's thermal envelope. The heat transfer coefficient is consistent with the units of UA (U-factor multiplied by area of assembly) used currently in US model energy codes and standards such as the International Energy Conservation Code (IECC) (ICC, 2018) and the ASHRAE 90.1 standard (ASRHAE, 2013a). The overall heat transfer coefficient, however, in the ISO 14683 standard includes terms to separately account for linear and point thermal bridges that contribute to the building thermal envelope's overall heat loss.

While repetitive framing members common to light frame steel and wood assemblies are incorporated in U-factors in the U.S. practice, linear and point thermal bridges resulting from the intersection of assemblies and various details or attachments to or within these assemblies are not included and must be separately assessed to more accurately determine the thermal performance of a given building thermal envelope assembly. Examples of linear thermal bridges include roof to wall intersections, parapets, structural columns penetrating through the thermal envelope, window perimeter details, steel shelf angles at slab edges, concrete balcony slab projections, etc. Collectively, these linear thermal bridges can account for more than half of the actual heat flow through a building envelope assembly, yet are not accounted for in current and past US model energy codes. Point thermal bridges may include beam penetrations, pipe penetrations, roof equipment support leg penetrations, awning attachment points to building exteriors, anchor bolts for affixing elements to building surface, bolts, screws and fasteners or metal brackets for attachment of claddings, and other items commonly occurring on building envelopes for attachment purposes. Some point thermal bridges (such as a nominal level of sheathing fastening) may or may not be partially incorporated in nominal assembly U-factors applied in U.S. model energy codes and standards. Thus, only point thermal bridges that are not already accounted for in assembly U-factors should be separately accounted for in determining the overall heat transfer coefficient or U-factor for a given building envelope assembly.

The following is an excerpt of Section 4 from the ISO 14683 standard that provides the framework for determining a building's overall heat transfer coefficient including the effect of linear and point thermal bridges. For purposes of this report the main item of interest is the component in equation (3) below that accounts for the sum of all point thermal bridges.

4 Influence of thermal bridges on overall heat transfer

4.1 Transmission heat transfer coefficient

Between internal and external environments with temperatures θ_i and θ_e respectively, the transmission heat flow rate through the building envelope, Φ, is calculated using Equation (1):

$$\Phi = H_T(\theta_i - \theta_e) \tag{1}$$

The transmission heat transfer coefficient, H_T, is calculated using Equation (2):

$$H_T = H_D + H_g + H_U \tag{2}$$

4.2 Linear thermal transmittance

The calculation of the transmission heat transfer coefficient includes the contribution due to thermal bridges, according to Equation (3):

$$H_D = \sum_i A_i U_i + \sum_k l_k \Psi_k + \sum_j \chi_j \tag{3}$$

where

A_i is the area of element i of the building envelope, in m²;

U_i is the thermal transmittance of element i of the building envelope, in W/(m²·K);

l_k is the length of linear thermal bridge k, in m;

Ψ_k is the linear thermal transmittance of linear thermal bridge k, in W/(m·K);

χ_j is the point thermal transmittance of the point thermal bridge j, in W/K.

For point thermal bridges such as cladding and sheathing fasteners, brick ties, and others that are distributed more or less uniformly throughout the surface area of a wall or roof assembly, Equation (3) can be re-formulated to the same units of the U-factor for the assembly such that these point thermal bridges can be addressed as a modification to (adding to) the U-factor of an assembly that may be based on the absence of any fasteners that occur in practice or which may only include a partial effect of fasteners (e.g., the presence of exterior and interior sheathing fasteners, but not cladding fasteners).
The reformulation to incorporate the effect of uniformly distributed point thermal bridges in the U-factor of an envelope opaque assembly is as follows:

$U'_i = U_{nom,i} + \Sigma n_j \chi_j$

Where,

U'_i = the corrected U-factor for the assembly (e.g., roof assembly, opaque wall assembly, etc.) accounting for distributed point thermal bridges not included in the U_{nom} value for the assembly;

$U_{nom,i}$ = the "conventional" or nominal U-factor for the assembly (e.g., ASHRAE 90.1 Appendix A);

n_j = the number of uniformly distributed point thermal bridges of type 'j' per unit area of the assembly in units consistent with the U-factor (e.g., per ft^2 or m^2);

χ_j = chi-factor (W/K or Btu/hr-F) for an individual point thermal bridge (metal penetration) for each type being considered (e.g., cladding fasteners, sheathing fasteners, etc.). Or, if a "normalized" chi-factor (Btu/hr-F per in^2 of metal penetration cross-sectional area) is used as done later in this report, the n_j parameter assumes units of in^2 of metal penetration (cross sectional area) per ft^2 of assembly area.

ASHRAE Handbook of Fundamentals (Chapter 25) (ASHRAE, 2013b)

Chapter 25 of the ASHRAE Handbook of Fundamentals (HOF) includes a similar means of accounting for overall heat flow through the building envelope, including the assemblies comprising the building thermal envelope (i.e., roof and walls) and linear and point thermal bridges. However, it provides no library of nominal design values for linear and point thermal transmittances associated with various types of linear and point thermal bridges. It also includes an equation similar to the above ISO 14683 standard, but the approach incorporates all linear and thermal bridges associated with a given building area or assembly into a modified (increased) U-factor of a given assembly to account for all thermal bridges (rather than treating the thermal bridging elements independently). This may be appropriate only as a matter of convenience in providing a corrected U-factor that can be inputted into whole-building thermal modeling software that otherwise do not incorporate separate means of accounting for thermal bridges.

Unfortunately, the above-described practice can be taken out of context and lead to misconceptions that all thermal bridges should be associated with an impact to the U-factor of the assemblies that they are adjacent to or associated with rather than evaluating the thermal bridges independently as is done to separately optimize each assembly or component of the building thermal envelope. Thus, rather than causing one to focus on mitigating the thermal bridge, one may simply attempt to modify the assembly to offset the impact of the thermal bridge (effectively making a trade-off judgment) while leaving the actual thermal bridge un-mitigated. This approach can lead to inefficient solutions such as increasing amounts of insulation on the opaque assembly which will only accentuate the relative impact or significance of the unmitigated thermal bridge on the overall assembly thermal performance when the matter could be more efficiently addressed by actually mitigating the thermal bridge itself. This approach also ignores the diminishing returns of attempting to increase the thermal performance of an opaque assembly by adding more insulation without first seeking to more effectively reduce the impact of the thermal bridge itself.

Consequently, it may be more cost-effective and efficient to mitigate the thermal bridge as a separate thermal envelope entity, usually associated with structural and non-structural (architectural) detailing of the envelope assembly including things such as cladding attachment specification, cladding type selection, fastener specification, connector material thermal conductivity (e.g., carbon steel vs. stainless steel), etc. Therefore, the approach used in the ISO 14683 standard is a better means of evaluating the overall thermal envelope including the roof and wall assemblies, fenestration, and thermal bridges as separately accounted entities contributing to overall heat flow rate through a building thermal envelope. The one exception would be cases where uniformly distributed point thermal bridges are actually a part of an assembly (e.g., cladding or sheathing connectors) and are not otherwise included in the assembly's nominal U-factor used for design purposes. In this case, the nominal U-factor should be modified to provide a true or corrected U-factor.

ASHRAE Handbook of Fundamentals (Chapter 27) (ASHRAE, 2013b)

The "parallel path" assembly U-factor calculation method in ASHRAE *Handbook of Fundamentals* as commonly used for wood frame construction includes no means of accounting for the impact of sheathing, cladding or interior finish fasteners on an assembly's performance, although each have a measurable impact as reported in the literature. Similar implications (although varying in magnitude) also exist for other U-factor calculation methods in the ASHRAE *Handbook of Fundamentals,* some of which have been empirically calibrated to assemblies with an unspecified amount of cladding or sheathing fastener thermal bridges. Therefore, the accounting of the thermal transmittance impact of fasteners varies by calculation method and the assembly structural material type or configuration to which those calculation methods apply.

The accounting of fastener thermal bridging in tabulated U-factors in Appendix A of ASHRAE 90.1 may rely on tested assemblies and not calculated assemblies using the methods described above from the HOF. For the listed assemblies with published U-factors based on hot box testing, the amount of fastener thermal bridges included in the tested assemblies is generally undisclosed and may vary (often not including cladding attachment or variations in cladding attachments which can creating significant variations in the thermal impact of point thermal bridges). In addition, where point thermal bridges are included (e.g., brick ties for masonry/concrete wall assemblies) they may be based on outdated testing or modeling of the point thermal transmittances and the basis of the determination is not disclosed in sufficient detail (or at all) to allow one to alter the analysis for other conditions (e.g., a greater number of brick ties or larger ties or ties of different steel material or newer point thermal transmittance values for specialty connectors, etc.).

As a result, modification of nominal assembly U-factors that are based on assembly calculation methods or test results in order to determine appropriate corrections for point thermal bridges must be performed in view of the basis of the nominal assembly U-factors and the degree to which point thermal bridges were originally included in the derivation of those values. Unfortunately, this level of detail usually is not clearly defined to properly qualify the nominal tested or calculation-based U-factors. Thus, they are considered “nominal” U-factors for the purpose of this report and are subject to varied levels of correction to reconcile the impact of point thermal bridges not accounted for in the nominal values.

Fig1: Solid metal fastening solution

Fig. 2: Version with plastic sleeve and shorter fastener

Wieland, H. (2006). Heat losses through flat roof fasteners
This study uses finite element (FEA) modeling to evaluate thermal transmittance associated with the following above-deck roof insulation fastening methods for attachment to a typical steel roof deck:

- Carbon steel fastener (~0.19” diameter) with carbon steel load distribution disc (washer)
- Plastic sleeve with recessed (shorter) carbon steel fastener
- Stainless steel fastener with carbon steel load distribution disc (washer)

These roof insulation fastening methods are illustrated in Wieland (2006) as follows:

It is noteworthy that the absolute amount of heat flow per fastener decreases with increasing roof insulation R-value or thickness as shown Figure 6 of Wieland (2006):

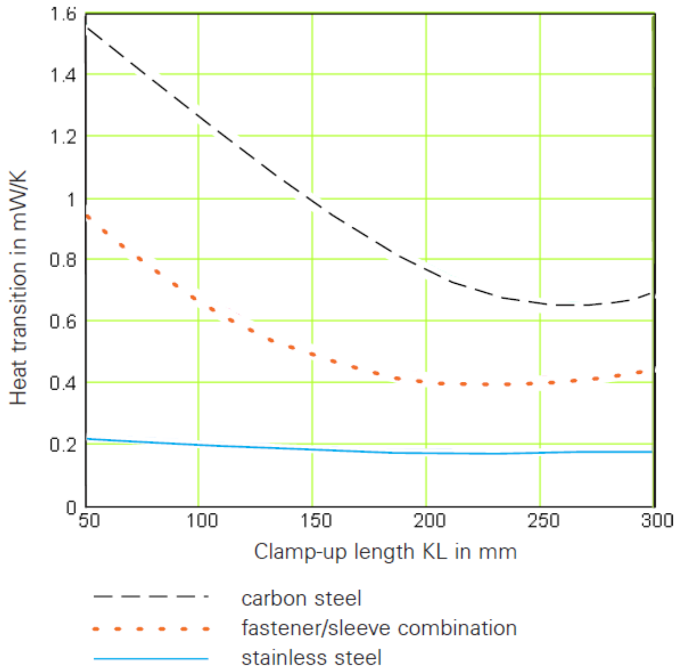


Fig. 6: Heat transition coefficient Ψ of a single fastener combination

The above absolute values and trends in fastener heat flow rate (chi-factor) are then used by Wieland (2006) to derive the following relative percentage increases in overall roof heat transfer for a given fastening schedule and roof assembly insulation (CI) amount:

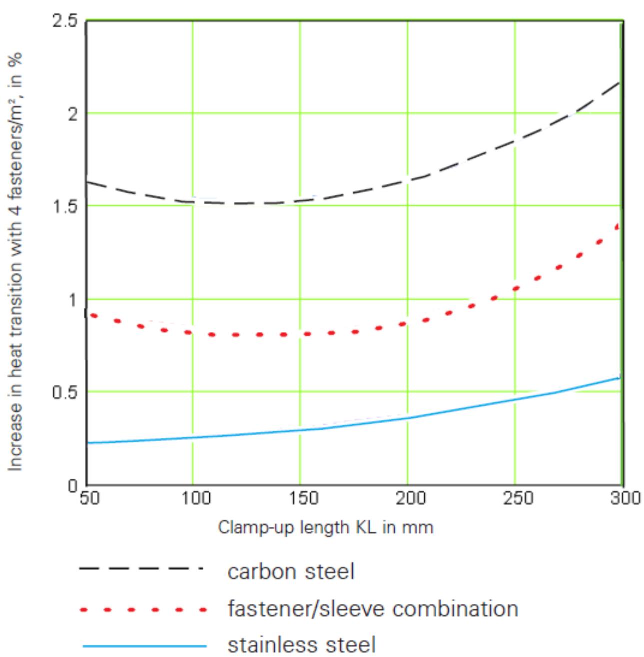


Fig. 7: Percentage increase in heat loss with 4 fasteners/m²

Number of fasteners / m²			100	120	140	160	180	200	220	240	260	280	300
			Thickness of the insulation layer in mm										
U-value undisturbed W/(m² · K)			0.373	0.315	0.272	0.239	0.214	0.193	0.176	0.162	0.15	0.139	0.13
	4	a	1.34%	1.43%	1.49%	1.55%	1.59%	1.64%	1.70%	1.77%	1.86%	1.98%	2.13%
	4	b	0.74%	0.77%	0.80%	0.82%	0.85%	0.89%	0.95%	1.03%	1.13%	1.26%	1.43%
	4	c	0.22%	0.25%	0.27%	0.30%	0.33%	0.36%	0.39%	0.43%	0.47%	0.51%	0.56%
	5	a	1.68%	1.78%	1.87%	1.93%	1.99%	2.06%	2.13%	2.22%	2.33%	2.48%	2.66%
	5	b	0.92%	0.97%	1.00%	1.03%	1.07%	1.12%	1.19%	1.28%	1.41%	1.58%	1.79%
	5	c	0.27%	0.31%	0.34%	0.38%	0.41%	0.45%	0.49%	0.54%	0.58%	0.64%	0.70%
	6	a	2.01%	2.14%	2.24%	2.32%	2.39%	2.47%	2.55%	2.66%	2.80%	2.97%	3.19%
	6	b	1.11%	1.16%	1.20%	1.24%	1.28%	1.34%	1.42%	1.54%	1.69%	1.89%	2.15%
	6	c	0.32%	0.37%	0.41%	0.45%	0.49%	0.54%	0.59%	0.64%	0.70%	0.77%	0.84%
	7	a	2.35%	2.50%	2.61%	2.71%	2.79%	2.88%	2.98%	3.10%	3.26%	3.47%	3.73%
	7	b	1.29%	1.35%	1.40%	1.44%	1.50%	1.57%	1.66%	1.80%	1.97%	2.21%	2.50%
	7	c	0.38%	0.43%	0.48%	0.53%	0.58%	0.63%	0.69%	0.75%	0.82%	0.89%	0.98%
	8	a	2.68%	2.85%	2.99%	3.09%	3.19%	3.29%	3.40%	3.55%	3.73%	3.96%	4.26%
	8	b	1.48%	1.55%	1.60%	1.65%	1.71%	1.79%	1.90%	2.05%	2.26%	2.52%	2.86%
	8	c	0.43%	0.49%	0.55%	0.60%	0.66%	0.72%	0.79%	0.86%	0.94%	1.02%	1.12%

Table 1: ΔU value in % of the U value of the flat roof without fasteners

a) carbon steel
b) fastener/sleeve combination
c) stainless steel

Wieland surmises that fastener impacts have been over-stated in prior research using outdated calculation methods (taken to mean calculation methods not consistent with ISO 10211 requirements for modeling).

Burch, D.M., Shoback, P.J., and Cavanaugh, K. (1987). A heat transfer analysis of metal fasteners in low-slope roofs

Burch et al. (1987) studied the impact of fasteners on the thermal performance of low-slope roof systems, using a finite difference modeling approach. The scope of this study focused only on a carbon-steel fastener used to attach above-deck roof insulation. The primary variables in this study included the amount of above-deck insulation (R4 to R24) and the type of roof deck material (plywood or steel). A 3/16" diameter (~0.19" diameter) carbon-steel rod and a 3" diameter thin metal cap washer were used to model the fastener. Burch et al. (1987) also included thermal resistance on the underside of the roof created by a drop ceiling and air cavity with an estimated R-value of R-2.8 (creating a thermal disconnect between the fastener heat flow path and the interior conditioned space). The assemblies evaluated are illustrated as follows:

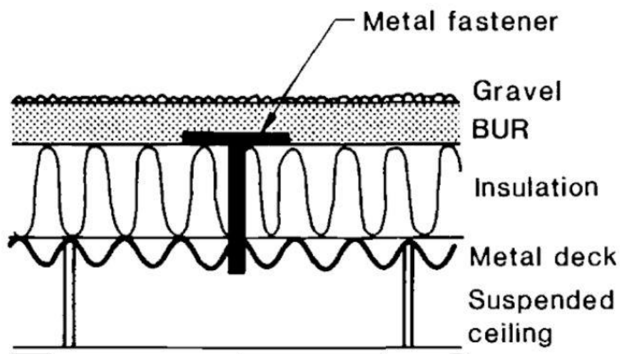


FIG. 1—*Construction details for a metal-deck roof with metal fasteners.*

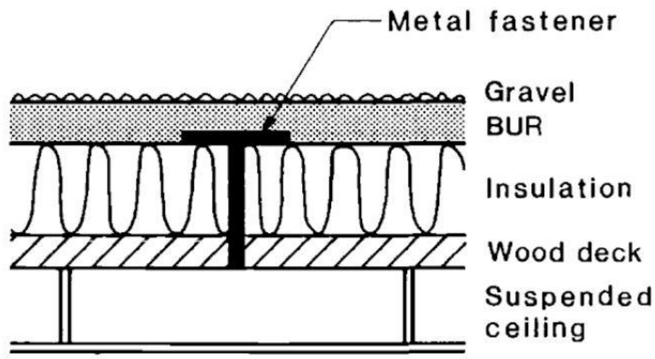
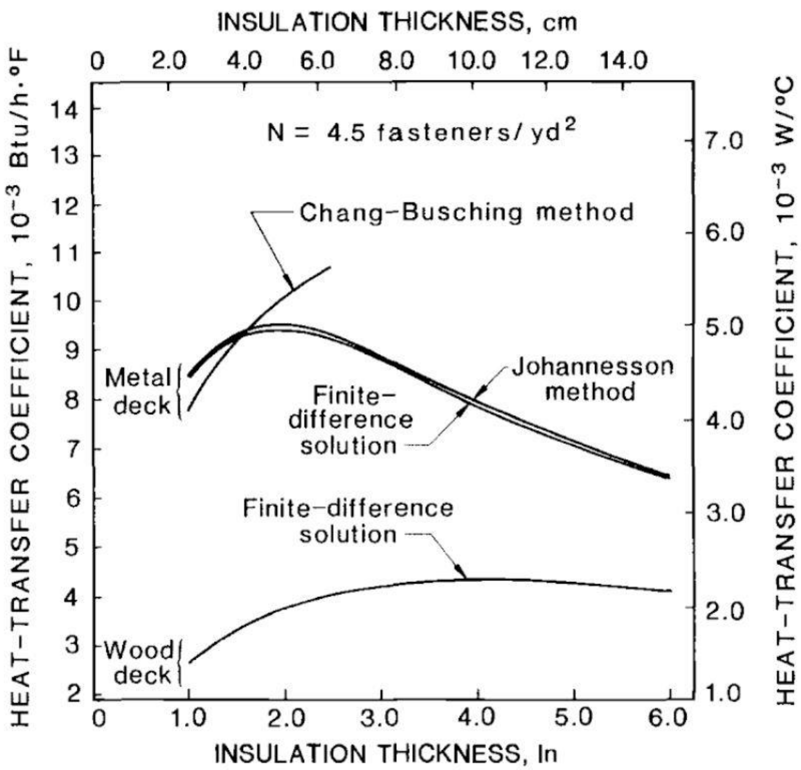


FIG. 2—*Construction details for a wood-deck roof with metal fasteners.*

A trend similar to Wieland (2006) was found whereby the fastener Chi-factor (heat flow rate) decreased with increasing roof insulation amount above R-8 (2-inches thick). However, the Chi-factors modeled by Burch et al (1987) are approximately three times greater than those found by Wieland (2006) for similar connections to a steel roof deck. Also, the results below show a decreasing trend in the Chi-factor for roof insulation amounts less than R-8 (2-inches thick), the minimum limit of the Wieland (2006) modeling study. Moreover, as seen in the graph below from Burch et al. (1987) is the notably reduced Chi-factor for the same fastener into a wood roof deck. While not shown in the graph below, modeling of the same fastening detail with a plastic cap washer instead of a carbon steel cap washer showed a 44% relative decrease in the fastener Chi-factor which, in a relative sense, is reasonably consistent with findings of Wieland (2006).



The Burch et al. (1987) study also evaluated relative impact to the overall roof thermal performance as show below. The impact is plotted against roof deck insulation amount (which for above-deck insulated roofs is sensible way to plot the data given that it is the only insulation component for such assemblies). The estimated relative impact is significantly greater than that predicted by Wieland (2006), by a factor of more than three when compared using an equivalent fastening condition (i.e., fastener schedule of 4.5 fasteners/yd^2 or 5.4 fasteners/m^2, same fastener size and steel material, same insulation amount, etc.).

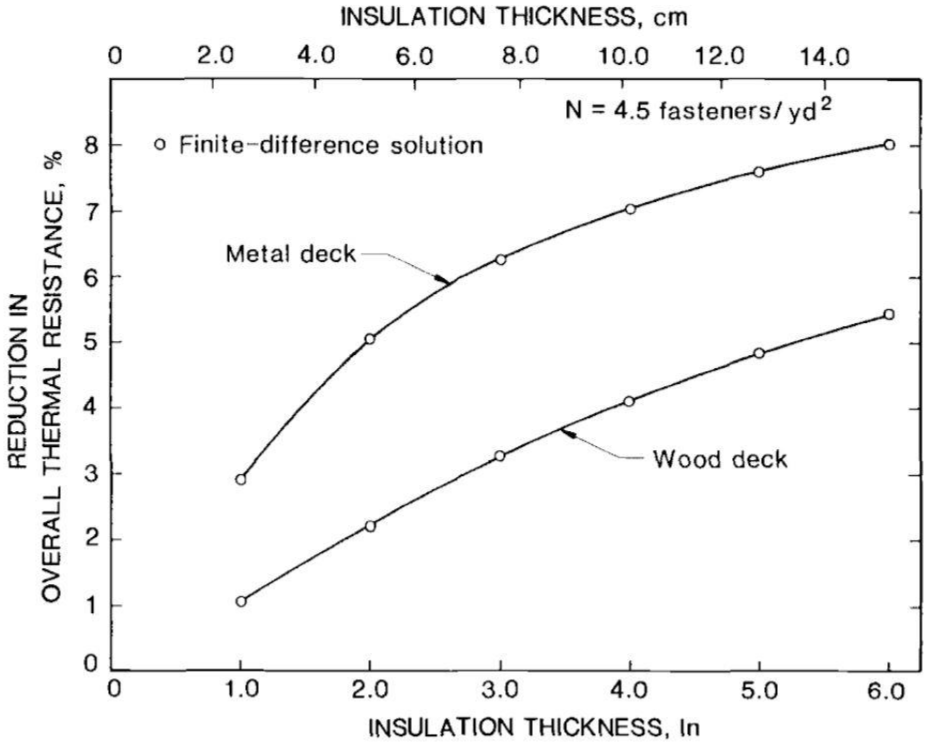


FIG. 5—*Heat-transfer results for the case in which metal fasteners penetrate the entire insulation layer:* (top) *the heat-transfer coefficient for a metal fastener;* (bottom) *the effect of a metal fastener on the overall thermal resistance of the low-slope roof.*

ISO 6946-2017. Standard 6946. Appendix F, Equation F.5

Appendix F.3 of ISO 6946 provides for the correction of assembly U-factors to account for the thermal bridging effect of fasteners (point thermal bridges). The basic form of the correction to the thermal transmittance of an assembly is given as follows as a means to increase the assembly U-factor without fasteners:

$$\Delta U_f = n_f \chi$$

n_f is the number of fastener per unit area of the assembly and χ is the Chi-factor or point transmittance of the fastener as used in the particular assembly. The Chi-factor is determined in accordance with ISO 10211 modeling procedures. Alternatively, an approximate procedure is provided for the case where an insulation layer is penetrated by mechanical fasteners, such as “wall ties between masonry leaves, roof fasteners or fasteners in composite panel systems.” This implies systems with homogenous and uniform layers of materials (perpendicular to the direction of heat flow) and insulation absent of framing thermal bridging pathways and other complications. Furthermore, the derivation of the equation used in the approximate procedure and its goodness of fit to relevant empirical data or modeling data are undisclosed in the standard.

The following is an excerpt from ISO 6946 describing the alternate approximate procedure:

> When an insulation layer is penetrated by mechanical fasteners, such as wall ties between masonry leaves, roof fasteners or fasteners in composite panel systems, the correction to the thermal transmittance is given by:
>
> $$\Delta U_f = \alpha \cdot \frac{\lambda_f \cdot A_f \cdot n_f}{d_1} \cdot \left(\frac{R_1}{R_{tot}}\right)^2 \qquad \text{(F.5)}$$
>
> where the coefficient α is given by:
>
> $\alpha = 0,8$ if the fastener fully penetrates the insulation layer;
>
> $\alpha = 0,8 \times \frac{d_1}{d_0}$ in the case of a recessed fastener (see Figure F.1).
>
> In these expressions
>
> λ_f is the thermal conductivity of the fastener, in W/(m·K);
>
> n_f is the number of fasteners per m^2;
>
> A_f is the cross-sectional area of one fastener, in m^2;
>
> d_0 is the thickness of the insulation layer containing the fastener, in m;
>
> d_1 is the length of the fastener that penetrates the insulation layer, in m;
>
> R_1 is the thermal resistance of the insulation layer penetrated by the fasteners, in m^2·K/W;
>
> R_{tot} is the total thermal resistance of the component ignoring any thermal bridging, as obtained in 6.7.1.2, in m^2·K/W.
>
> NOTE 1 d_1 can be greater than the thickness of the insulation layer if the fastener passes through it at an angle. In the case of a recessed fastener, d_1 is less than the thickness of the insulation layer and R_1 is equal to d_1 divided by the thermal conductivity of the insulation.

Eliminating n_f from the above Equation F.5 provides the heat flow rate (W/K or Btu/h-F) for an individual fastener. With the inclusion of n_f (number of fasteners per unit area of the assembly) the units for thermal transmittance (Chi-factor) are attained which can then be added directly to the thermal transmittance of the total assembly. It should also be noted that this equation appears to be intended for applications where both ends of the fastener are thermally connected to a planar component of high thermal conductivity, such as sheet metal or brick/masonry/concrete layers on either side of a homogenous layer of insulation.

For assemblies with non-homogenous layers (e.g., a framed wall assembly), the thermal bridging attributed to fasteners as determined by use of this equation is not necessarily applicable. This may be of particular concern for fasteners that are installed into framing members (rather than sheathing layers) that continue through the remainder of an insulated assembly such that the fastener thermal bridging path connects with a framing thermal bridging path. The above equation also does not take into account the effect of cap or washer material properties and size or variations in thermal conductivity of materials on either side of the layer of homogenous insulation. Thus, this equation is not able to account for these variations in connection details or conditions. Its predictive ability and design application appears very limited in scope and its intended application seems to be most suitable to applications like above deck roof insulation systems or panelized/layered wall assemblies without framing thermal bridges (i.e., mass wall assemblies with a layer of homogenous insulation in a brick cavity wall).

Posey, J.B. and Dalgliesh, W.A. (2005). Thermal bridges – heat flow models with Heat2, Heat3, and a general purpose 3-D solver

The study by Posey and Dalgliesh (2005) evaluated the point thermal bridging impact of side-mounted brick ties and 2x4 wood furring member lag bolts extending through a 2” thick layer of exterior insulation (R-10). The brick ties were mounted to the side of 33 mil (0.033” thick or 20 ga) steel studs with 6” thick batt insulation in the stud wall cavities and ½” interior gypsum wall board. The 3/8” diameter lag bolts were fastened into 2x4 wood framing members overlain with plywood sheathing and without interior finish or cavity insulation. A plain tie (solid carbon steel) and a perforated tie were evaluated. Carbon steel and stainless steel lag bolts were evaluated. Point thermal transmittance values were reported based on a finite element analysis of the fastening (lag bolt) or connector (brick tie) configurations.

Mayer, R., et al. (2014). Finite element thermal modeling and correlation of various building wall assembly systems

This study used finite element modeling to compare effects of fastener thermal bridging through three different wall assembly conditions, including one wall without exterior insulation, one with exterior insulation only, and one with exterior insulation and a partially filled cavity insulation.

All of the walls were cold-formed steel frame assemblies and included an interior gypsum layer. The effort compared results to hot-box testing of the same wall assemblies, although problems with the reliability of one of the hot box tests was noted. Modeling included analysis of the effective R-value of the assemblies with and without the presence of the fasteners in the gypsum layer (on both sides of the assembly without exterior insulation) and also in the exterior insulation layer when included. All of the fasteners were connected to the steel stud thermal bridge existing in the wall assembly. In all of the assemblies as modeled and tested, cladding and cladding fasteners were excluded.

The results indicate an impact on the overall assembly effective R-value (or 1/U-factor) of about 1.4% for the gypsum sheathing fasteners on both sides of the assembly without exterior insulation and with R-20 batt insulation in the cavity between steel studs. The presence of interior and exterior gypsum fasteners was considered in this case to be of small impact because of the already highly conductive thermal pathway through the steel studs (and possibly also some amount of lateral heat flow through the gypsum sheathing to the steel stud thermal bridge). For the assemblies with exterior insulation (and no or some amount of cavity insulation), the impact of both the interior gypsum fasteners (#6 drywall screws with a fastener shank area to wall area ratio of 0.000094 in^2/in^2) and particularly the exterior insulation fasteners (#8 screws with a fastener shank area to wall area ratio of about 0.000063 in^2/in^2) was about 8 to 9 percent of the overall assembly U-factor as determined by the finite element analysis.

While the modeling followed the trends seen in the three hot-box tested assemblies, the absolute prediction of effective R-value (or 1/U-factor) varied from testing by about 3 to 20% for two assemblies (excluding one tested assembly which was considered anomalous due to suspected flanking problems in the execution of the hot-box test).

Christensen, D. (2011). Thermal Impact of Fasteners in High-Performance Wood-Framed Walls

Christensen (2011) modeled two 2x6 wood frame walls with R22 batt insulation and either R-6 or R10.5 exterior insulation (1” and 1.5” thick exterior insulation). This modeling study evaluated walls with and without the presence of interior gypsum fasteners and exterior wood siding fasteners (no insulation fasteners were evaluated). The finite element method analysis of the assembly without the inclusion of the stated fasteners was compared to the parallel path method (which also does not account for the effect of fasteners) and it was found that the parallel path calculation method over-predicted the wall performance (lower U-factor) relative to the FEA analysis. The FEA analysis was also conducted with the stated fasteners included which demonstrated a reduction in the assembly effective R-value relative to the FEA modeling without fasteners. While the results were reported in terms of the overall effective R-value of the assembly (for different framing factors resulting in different amounts of the same fasteners), thermal transmittance values (point thermal bridge Chi-factors) associated with the fasteners can be derived from the data.

For the fastener amounts considered (on the interior and exterior of the assembly), the relative difference in the effective R-value by FEA analysis for the assemblies with and without fastener was found to be about 5 to 6% (about 1.5 to 1.7 R) for a common range of framing factor (18% to 24% of wall area) for the R22+R10.5ci assembly. Similarly, for the R22+R6ci wall assembly, the impact of the same fasteners was found to be about 3 to 4% reduction in effective R-value of the assembly (a reduction of about 0.8 to 0.9 R). For this wall assembly, the screw fasteners on the interior gypsum board accounted for about 0.1 R of the total fastener impact (or about 6% to 12% of the overall fastener thermal bridging impact to the assembly effective R-value).

In terms of the continuous insulation R-value used, the interior finish and exterior cladding fastener impact to the wall assembly was equivalent to about 15% of the nominal R-value of the exterior insulation used in both cases. However, for reasons stated earlier, there are inefficiencies and even possible errors in arbitrarily attributing the thermal bridging effect of fasteners to the exterior insulation layer. For example, this study did not evaluate the effect of the exterior insulation in minimizing the impact of exterior structural sheathing fasteners if the walls had been modeled with such a sheathing material present (approximately 80% of current US housing construction is built in this manner). The structural sheathing fasteners generally use larger and many more fasteners than used on interior gypsum finishes. The impact of these fasteners would be much larger than the 0.1R determined in this study for the gypsum sheathing fasteners without the presence of the exterior insulation. Based on the typical nail size and fastening schedule for exterior structural sheathing, the impact could be as much as three or more times that of the interior gypsum fasteners (e.g., 0.3R for the exterior sheathing fasteners plus 0.1R for the interior sheathing fasteners for a total reduction of 0.4R for the assembly without exterior insulation). Consequently, the net relative impact of siding fasteners through exterior continuous insulation may actually be 0.8R – 0.3R = 0.5R or about 8 percent of the R-value of the exterior insulation (almost half that determined above without considering the impact of structural sheathing fasteners when not covered by exterior insulation).

Because siding fasteners are present with or without the presence of exterior insulation, their impact should be considered in both cases which would further reduce the net difference of fastener impacts between walls with or without exterior continuous insulation. Presently, the US practice for determining the U-factor or effective R-value of wood frame wall assemblies using the parallel path method accounts for none of the fasteners with or without the presence of exterior insulation. Thus, to account for the fastener impact only when exterior insulation is present and then offset it with a de-rating or increase in the amount of exterior insulation creates not only an analytical inconsistency but it also creates a competitive inequity for different wall insulation strategies commonly used and represented in US model energy codes and standards (i.e., cavity insulation only vs. cavity plus exterior insulation).

Higgins, J., Shane, C. and Finch, G. (2014). Thermal Bridging from Cladding Attachment Strategies Through Exterior Insulation

In the report by Higgins et al. (2014) insufficient description of the cladding fastening schedules is given to determine point thermal bridge transmittance values from the reported information. While it did report point transmittance values (heat flow values) it was unclear if this was related to a single fastener and the size of the fastener was not reported. Therefore, actual point thermal bridge values could not be derived from the limited amount of detailing information provided in the report.

A variety of cladding connection scenarios were evaluated using a finite element model. It was noted that “cladding attachment systems connecting the cladding back to the structure through the insulation have a wide range of thermal bridging effects and can significantly affect effective R-values.” Included in the study were the following attachment systems:

- Stainless steel screws and galvanized (carbon steel) screws through wood or metal strapping
- Intermittent stainless steel and galvanized Z-girt clips
- Fiberglass clips
- PVC isolated galvanized clips
- Aluminum clips

All discrete clips and screw fasteners were modelled at 16”oc horizontal spacing attached through exterior semi-rigid mineral fiber insulation (R4.2/in) to stud framing and vertical fastener or clip spacing was varied from 12”on center to 48” on center. Continuous 14 gage galvanized steel Z-girts were also modeled to demonstrate the significant thermal bridging (in this case a linear thermal bridge) through exterior insulation when discrete cladding attachment is not used.

The results indicate that the intermittent fastening methods (use of intermittent clips or discrete fasteners) had a 4% to 10% impact on the overall effective R-value (1/U-factor) for the 2x6 wood frame assemblies with R22 batt insulation and R16.8 exterior insulation. The use of stainless steel fasteners had the least impact (4%) whereas the aluminum clip connections had the greatest (10%). Again, the amount of fastening associated with these impacts was not described in the report clearly enough to associate them with specific installed conditions and to derive chi-factors for the attachment methods. The use of continuous galvanized girts extending through the exterior insulation layer had about a 20 to 30% impact on the overall assembly effective R-value (1/U-factor) for a girt spacing of 24”oc and 16”oc, respectively. In terms of stating this impact in a manner relative to only the continuous insulation layer, the equivalent percent nominal R-value reduction of the exterior insulation was approximately double that of the percentage impact to the overall wall assembly effective R-value (i.e., 40 to 60 percent). This relative approach to representing point thermal bridging effect in terms of the impact to a particular insulation component is not recommended for reasons stated earlier in this research report.

For the steel frame assemblies with R12 batt insulation and R16.8 exterior insulation, the trends in impacts of the same intermittent fastening methods ranged from about 8% to 20% of the overall effective R-value of the assembly, with the stainless steel fastener method having the least impact. The continuous Z-girt thermal bridging impact was as much as a 55% reduction of the overall assembly effective R-value. This greater impact for steel vs. wood framed assemblies of similar construction may be related to the fact that a greater percentage of the thermal resistance is attributed to the exterior insulation layer (which is penetrated by the connection methodology). Also, the steel frame wall portion of the assembly had less amount of batt insulation and a greater amount of thermal bridging caused by the steel framing. Furthermore, the fasteners were attached to the steel framing members which continued a highly conductive thermal pathway through to the interior side of the wall. Again, specific thermal transmittance values for the specific connections could not be derived from this study because insufficient information regarding the size of fasteners and connection elements was provided. However, the relative impact to the overall U-factor of the evaluated assemblies is reasonably consistent with other sources reviewed.

ASHRAE Standard 90.1 – Appendix A, Table A3.1-1

Table A3.1-1 of ASHRAE 90.1 is for mass walls (concrete/masonry) and includes U-factors for assemblies with continuous insulation having 1" x 0.033" (20g) metal clips or ties extending through the continuous insulation. The clips or ties are presumed to be carbon steel. The basis of thermal bridging chi-factors used to determine the impact to the U-factor of the assembly is not reported, although the impact may have been estimated by application of the isothermal planes method commonly used for masonry and concrete assemblies. Regardless, the chi-factors for the 1"x0.033" metal clips can be "reverse engineered" from the U-factor data presented in Table A3.1-1 for this assembly type. For example, an assembly with 2 inches of R-10 continuous insulation has a U-factor of 0.110 of which a U-factor of 0.74 is associated with the concrete portion of the assembly. In terms of relative impact to the effective R-value of the continuous insulation, the impact may be determined as follows:

$1/U_{tot} = 1/U_{conc} + R_{eff,ci}$
$1/0.110 = 1/0.74 + R_{eff,ci}$

Solving for $R_{eff,ci}$, one obtains R-7.7 for the continuous insulation portion (by assigning the 1" x 0.033" metal clip thermal bridging effect to the continuous insulation layer). This is equivalent to a (R-10 – R-7.7)/R-10 = 23% reduction in the effective R-value of the 2-inch-thick R-10 continuous insulation for clips spaced at 24"oc x 16"oc (1 clip per 2.66 ft^2 of wall area). In terms of metal penetration ratio, this is equivalent to 0.033 in^2 / (2.66ft^2 x 144in^2/ft^2) = 0.000086 in^2/in^2 (square inches of metal penetration per square inch of wall area).

To determine the metal clip's chi-factor associated with the above impact (change in U-factor of the assembly due the presence of the clip), the following calculations are made in comparison to a U-factor without clips:

$\text{Delta\_}U_{clip} = U_{nom,w/clips} – U_{nom,\ w/o\ clips} = U_{nom,w/clips} - 1 / [1/U_{conc} + R_{ci}]$ = 0.110 – 1 / [1/0.74 + R-10] = 0.110 – 0.088 = 0.022 Btu/hr-F-ft^2

Next, the above change in U-factor due to the presence of the clips is divided by the number of clips per area of wall to yield a chi-factor on a "per clip" basis as follows:

Chi-factor (1"x0.033" clip) = (0.022 Btu/hr-F-ft^2) / (1 clip / 2.66 ft^2) = 0.058 Btu/hr-F per clip

The above chi-factor can be normalized by the metal clip cross-section area to determine a normalized chi-factor based on a unit area of metal penetration as follows:

Normalized chi-factor = (0.058 Btu/hr-F-clip) x (1 clip / 0.033in^2) = 1.77 Btu/hr-F per in^2 of metal penetration

The above process can be repeated for various amounts of continuous insulation as reported for assemblies in Table A3.1-1 of ASHRAE 90.1. These are reported later in Table 1 of this report.

Van Geem and Shirley (1987). Heat Transfer Characteristics of Insulated Concrete Sandwich Panel Walls

In the study by Van Geem and Shirley (1987), full-scale concrete sandwich panel walls with R-10 insulation located between two outer layers of 3-inch-thick concrete were hot-box tested without any cross ties penetrating the internal continuous insulation layer and also with stainless steel cross ties and proprietary fiberglass ties. The fiberglass ties caused a negligible difference in the tested U-factor of the assembly in comparison to the control without ties. However, the point thermal bridges caused by the stainless steel cross ties caused a 7 percent increase in the measured U-factor from U-0.091 to U-0.097 (or a decrease in effective R-value from R-10.2 to R-9.6). From this data, a point thermal transmittance value (chi-factor) can be derived for the stainless steel ties as is reported later in Table 1 of this report. Carbon steel ties were not evaluated, but would be expected to increase the impact to the U-factor and chi-factor (e.g, see the discussion above regarding metal tie chi-factors derived from data in ASHRAE 90.1).

Analysis:

Analysis of Chi-Factors (Point Thermal Transmittance Values)

Most of the reports summarized in the literature review presented impacts of fasteners on different assemblies with different building material and insulation characteristics and connection geometries, all of which impact the magnitude of heat flow through the fastener or connector point thermal bridges. In addition, impacts were reported in a relative sense (e.g., percent reduction in overall assembly U-factor or equivalent percent reduction of exterior insulation thermal performance). Consequently, much of the relative data reported in the literature had to be converted into the absolute format of a point thermal bridge transmittance value or Chi-factor. Chi-factors for the various point thermal bridges (fastening and connector methods) as derived from the literature are presented in Table 1.

The point thermal bridge conditions represented in Table 1 include metal fastenings or connector penetrations associated with the following conditions:

- Above-deck roof insulation penetrated by metal fasteners to attach the insulation or roof membrane to a metal or wood roof deck.
- Exterior continuous insulation (typically foam plastic insulating sheathing) penetrated by metal fasteners for sheathing or cladding installation and brick ties for anchored masonry veneer attachments.
- Non-insulating sheathing materials (e.g., wood structural panels or gypsum board) penetrated by metal fasteners for sheathing attachment.

Table 1 reports the findings on the common basis of a Chi-factor (Btu/hr-F) and this is further normalized by fastener size (cross-sectional area of fasteners). The normalized Chi-factor assumes the units of Btu/hr-F-in^2 where the in^2 parameter is the cross section area of the fastener or connector (not the area of the assembly). Thus, these normalized Chi-factor values can be used for direct comparisons in analyzing the impact of increased heat flows caused by variations in metal penetration configurations (e.g., fastener or connector schedule and size) for assemblies and connections methods consistent with the scope of conditions represented in Table 1.

TABLE 1
Fastener Normalized Chi-factors (Btu/hr-°F-in$^2_{fastener}$)
Compiled and Derived from Various Literature Sources

Fastener Type and Size	Assembly Description	Chi-Factor (Btu/hr-°F per fastener)	Normalized Chi-Factor (Btu/hr-°F per in^2 of fastener cross-section)	Normalized Chi-Factor ISO6946:2017 Eq. F.5 (comparative)	Source
Through-fastened Low-Slope Roof Above-Deck Insulation					
Carbon steel roof fastener (0.189" diameter; 0.154" core diameter) with carbon steel washer/disc at head (3.2"x1.6")	Above deck roof insulation through fastened to metal low-slope roof deck	0.003 – R8 CI (2" thick) 0.0013 – R38 CI or more (8" thick or more)	0.107 0.046	0.217 0.059	Wieland (2006)
Same as above except use of plastic recessed fastener sleeve with shorter carbon steel fastener of same diameter	Above deck roof insulation through fastened to metal low-slope roof deck	0.0019 – R8 CI (2" thick) 0.00076 – R27 CI or more	0.067 0.027	0.108 0.039	Wieland (2006)
Same as first row except stainless steel fastener of same diameter	Above deck roof insulation through fastened to metal low-slope roof deck	0.00038 - any R-value or thickness of CI	0.014 (R8 to R38 ci)	0.074 (R8 ci) 0.020 (R38 ci)	Wieland (2006)
Carbon steel fastener (0.188" diameter) with a carbon steel cap washer (3" diameter)	Above deck roof insulation through fastened to metal low-slope roof deck	0.008 – R4 CI (1" thick) 0.009 – R8 CI (2" thick), peak 0.0065 – R24 CI (6" thick)	0.29 0.33 0.24	0.255 0.171* 0.107	Burch et al. (1987) – included below deck ceiling and air-cavity valued at R2.8.
Same as above except plastic cap washer	Above deck roof insulation through fastened to metal low-slope roof deck	0.0053 – R8 CI (2" thick)	0.19	0.171* *Does not distinguish washer size/material	Burch et al. (1987)
Carbon steel fastener (0.188" diameter) with a carbon steel cap washer (3" diameter)	Above deck roof insulation through fastened to wood low-slope roof deck	0.0025 – R4 CI (1" thick) 0.004 – R12 to R24 CI (3" to 6" thick)	0.091 0.145	0.275 (R4ci) 0.128 (R12ci) 0.071 (R24ci)	Burch et al. (1987)
Wall Fasteners and Connectors/Ties					
Carbon steel brick tie (2" x 0.063") side-mounted to 6" steel stud	Tie penetrates 2" XPS (R-10) CI and is spaced 16"oc along studs at 16"oc; Wall includes R13 batt insulation and ½" GWB on interior	0.028	0.222	0.774 (equation not applicable)	Posey and Dalgliesh (2005)

Fastener Type and Size	Assembly Description	Chi-Factor (Btu/hr-°F per fastener)	Normalized Chi-Factor (Btu/hr-°F per in² of fastener cross-section)	Normalized Chi-Factor ISO6946:2017 Eq. F.5 (comparative)	Source
Wall Fasteners and Connectors/Ties					
Carbon steel 3/8" diam lag bolts through 2x4 wood furring to un-insulated wood frame assembly	(2) lag bolts at each furring/stud crossing through 2" XPS (R-10) and 5/8" plywood (R0.7).	0.0095	0.125	-	Posey and Dalgliesh (2005)
Same as above except stainless steel lag bolts	Same as above	0.0076	0.100	-	Posey and Dalgliesh (2005)
Carbon steel screws through R10.5 (1.5") CI to steel stud framing with GB interior finish	#8 carbon steel screws (0.164 diam.) through R10.5 (1.5") CI only, stud cavity partially insulated or not at all with ½" GB interior finish.	0.0053 to 0.0065	0.25 to 0.31	-	Mayer et al. (2014)
Drywall screws through ½" GWB to steel studs	#6 carbon steel screws (0.141" diam.)	0.000496	0.041	-	Mayer et al. (2014)
Carbon steel screw into steel framing through CI	#9 screw penetrates 2" (R8) ci into steel studs without cavity insulation and ½" gypsum on interior	0.0089	0.36		Based on unpublished hot-box data for two identical walls with and without screws attaching CI
Carbon steel drywall #6 screws through ½" GWB to wood studs	Heat flow addition of drywall fasteners only	-	0.009	-	Christensen (2010)
Carbon steel nail through CI only into wood studs (siding and CI fasteners not separately addressed)	Heat flow through fasteners penetrating CI of 1.5" thick with R-value of R6 or R10.5		0.083 to 0.110	-	Christensen (2010)
Unspecified, other than a "metal" penetration through mass wall CI	The effective thermal transmittance is derived from difference in U-factor attributed to increased CI required for 0.08% metal penetration		0.121 (R-9.5ci) 0.095 (R-13.3ci)	-	Washington State Energy Code (Commercial); source data unknown
Unspecified, other than "metal" penetration through CI layer on roof	The effective thermal transmittance is derived from difference in U-factor attributed to increased CI required for 0.08% metal penetration		0.043 (R-38ci)	-	Washington State Energy Code (Commercial); source data unknown

Fastener Type and Size	Assembly Description	Chi-Factor (Btu/hr-°F per fastener)	Normalized Chi-Factor (Btu/hr-°F per in² of fastener cross-section)	Normalized Chi-Factor ISO6946:2017 Eq. F.5 (comparative)	Source
Wall Fasteners and Connectors/Ties					
Unspecified, other than "metal" penetration through CI layer of steel frame wall	The effective thermal transmittance is derived from difference in U-factor attributed to increased CI required for 0.08% metal penetration		0.061 (R-13+R7.5ci) 0.061 (R-13+R13ci) 0.052 (R-19+R8.5ci) 0.043 (R-19+R16ci) 0.052 (R-20+R3.8ci)	-	Washington State Energy Code (Commercial); source data unknown
Concrete sandwich panel with 3" outer plys of concrete and 2" XPS (R10) core penetrated by stainless steel cross-ties. NOTE: Testing with proprietary fiberglass ties showed negligible thermal bridging	Chi-factors derived from difference in hot-box tests with and without ties.		0.57 (R-10ci core)	0.26	VanGeem & Shirley (1987)
1"x0.033" (20g) metal tie/clip through continuous insulation on a mass wall (concrete/masonry); NOTE: carbon steel ties presumed.	Chi-factors are derived from Table A3.1-1 of ASHRAE 90.1	0.072 (R-5 ci) 0.059 (R-10ci) 0.045 (R-15ci) 0.037 (R-20ci) 0.024 (R-40ci)	2.2 (R-5ci) 1.8 (R-10ci) 1.4 (R-15ci) 1.1 (R-20ci) 0.7 (R-40ci)	-	ASHRAE (2013a)
Steel tube penetration (3"x3"x1/8") – as additive or super-imposed to a steel column linear thermal bridge already in the wall assembly	Tube cantilevers from a steel column in steel frame wall with R12 cavity insulation and R5 to R25 exterior insulation	0.16	0.11	-	Morrison-Hershfield (2014), BC Hydro Thermal Bridging Guide, Detail 5.7.1

The following observations can be drawn from Table 1:

1. In general, the data shows a wide range of point thermal bridging impacts and some of this may be due to differences in modeling method and assumptions. But, much of the variation appears to be due to differences in the metal penetration and assembly configurations or details.
2. In general, the data shows a trend of decreasing metal penetration point thermal bridge Chi-factor (thermal transmittance) with increasing thickness of the continuous insulation.
3. The data also indicates that the Chi-factor may tend to peak at a given thickness or R-value of continuous insulation and then decreases as the insulation thickness increases (apparently due to increasing length of the heat flow path). The chi-factor also decreases from a peak value as the insulation thickness and R-value decreases (apparently due to the metal penetration affecting a lesser portion of the overall thermal resistance of and temperature differential across an assembly.
4. For similar metal penetration conditions through exterior insulation or non-insulating sheathings, the magnitude of impact is different for wood, steel, and concrete/masonry substrates.

5. The magnitude of chi-factor for a metal penetration also depends on the material type of the penetrating metal element (i.e., carbon steel vs. stainless steel).
6. The use of stainless steel metal penetrations (such as stainless steel fasteners, brackets, or ties) appears to have a much greater beneficial effect (reduced Chi-factor) for concrete/masonry and steel substrates than wood substrates.
7. Connection details or devices that disrupt the thermal pathway to, from or through the metal penetration element also have a significant impact, such as the use of recessed plastic washers or flat plastic cap washers instead of galvanized carbon steel washers to secure continuous insulation to a steel roof deck substrate (reduction of 35% to 40% compared to a Chi-factor for a fastener with a thin steel cap washer).
8. Fastening roof insulation or membranes to wood roof deck sheathing instead of steel roof decking also produced a similar ~40% reduction in the Chi-factor, even without changing from a steel cap washer to a plastic cap washer as noted above. However, these effects are likely not additive.
9. The ISO 6946 approximate method (Appendix F, Equation F.5) appears erratic in comparisons made to various sources of data in Table 1.
10. The newer modeling data in Table 1 appears to provide more consistent (comparable) results across various studies where similar point thermal bridging conditions were analyzed by older modeling methods.
11. Non-negligible thermal bridging appears to occur as a result of metal penetrations, connectors, and fasteners on walls without continuous insulation and should considered to ensure an equitable and consistent treatment of thermal bridging effects on all types of insulated assemblies.
12. Chi-factor values estimated from the Washington State Energy Code (Commercial) provisions do not appear to align well with data from other sources reported in Table 1. For the large amount of metal penetration addressed in the code (e.g., more than 0.04% metal penetration area ratio to overall opaque wall area), the thermal bridging impacts on assembly U-factor (or as represented by an offsetting increase in exterior insulation amount) appear to be significantly under-estimated.
13. Chi-factor values as derived from ASHRAE 90.1 Table A3.1-1 for 1"x0.033" metal (carbon steel) clips through continuous insulation on mass walls appear to be conservative but are approximately 3 times greater than one empirical data point where stainless steel ties connected two concrete sandwich panel layers separated by a core of otherwise continuous insulation. It is noted that stainless steel is three times less conductive than carbon steel, but this difference in fastener material property may not translate to the same difference in actual 3-D assemblies. Regardless, this data tends to show relatively large chi-factors for mass walls for cases where metal penetrating elements are embedded in cementitious material layers and penetrating the only insulation layer on the assembly that, otherwise, would have no thermal bridges. This data may not be applicable (i.e., conservative) where one of the layers to either side of the insulation layer is not concrete or masonry, but is instead wood or steel furring, for example, which would affect lateral heat transfer to the fastener as well as contact resistance with the fastener.

Representative Chi-Factors

Given the findings and observed trends in Table 1, an attempt was made to characterize representative chi-factors as shown in Table 2. These values are considered preliminary "ballpark" estimates for the purpose of roughly characterizing point thermal bridging effects for the types of assemblies and the uniformly distributed point thermal bridges (metal penetration) conditions represented. Additional research is needed to provide a more robust and consistent analysis of Chi-factors for these "small" uniformly distributed thermal bridges. This additional research is needed to ensure an accurate means of predicting the impact of point thermal bridges (fasteners and connectors) when added to the nominal U-factors of assemblies that are commonly based on tested or calculated U-factors without consideration of all the point thermal bridges associated with the assemblies in end use (e.g., cladding connections are frequently ignored and sometimes all connections are ignored).

The values in Table 1 are largely based on solid carbon steel elements (fasteners, ties, connectors, etc.) that extend through the entire thickness of the penetrated insulation component and attach to the substrate framing material (wood or steel studs, or wood or steel deck sheathing, and concrete or masonry substrates). The values are based on fasteners or connectors that themselves may penetrate only a part of the overall thermal envelope and attach to materials within the remainder of the thermal envelop that vary in thermal conductivity (e.g., wood, steel, concrete, masonry) and configuration (e.g., a stud, a monolithic wall or roof, or to a planar material such as wood or steel roof deck). Thus, the temperature difference through the length of the fastener or connector may be different than the overall temperature difference across the entire thermal envelope assembly; yet, the Chi-factors are based on the overall assembly temperature difference. This causes the Chi-values to vary because the temperature difference across the metal penetration thermal pathway varies with the amount of insulation penetrated by the fastener relative to the effective amount of insulation in the remaining portion of the assembly. This approach was necessary so that the chi-factors for the various connection scenarios can be applied consistently with the way U-factors are derived based on the overall temperature difference across an assembly. To some degree, this effect also may partially account for the "humped" shape of the Chi-factor vs. penetrated insulation R-value as represented by the data in Table 2 and illustrated in Figure 1 by a smoothed curve fit to the approximated data. This shape is consistent with the trends seen in Chi-factor data presented in Wieland (2006) and Burch et al. (1987) (see literature review).

TABLE 2
Representative Point Thermal Bridge Thermal Transmittance Values
(Chi-Factors, Btu/hr-F per in^2 of fastener area)
for Various Assembly Types and Metal (Carbon Steel) Penetration Conditions
(based on rough approximations from data in Table 1)[1]

R-value of insulation component layer penetrated by metal element	Steel Framing		Wood Framing		Concrete/Masonry
	Roof (Metal Deck)	Wall (Steel Studs)	Roof (WSP Deck)	Wall (Wood Studs)	Walls or Roof Deck
	Carbon steel fastener/connector through above deck insulation to steel deck	Carbon steel fastener/connector through exterior insulation or sheathing to studs	Carbon steel fastener/connector through above-deck roof insulation to wood sheathing	Carbon steel fastener/connector through exterior insulation or sheathing to studs	Carbon steel fastener/tie penetrating continuous insulation and embedded in two outer layers of concrete/masonry
R-0.5 (e.g., non-insulating sheathing)	0.03[2]	0.04 (Mayer et al., 2014)	0.01[2]	0.01 (Christensen, 2010)	0.3[2]
R-5ci	0.13[2]	0.2[2]	0.1 (Burch et al., 1987)	0.08 (Christensen, 2010)	2.2 (ASHRAE 90.1)
R-10ci	0.2 (Wieland, 2006; Burch et al., 1987; ISO 6946 Eq. F.5)	0.3[3] (Mayer et al., 2014; Posey and Dalgliesh, 2005; and unpublished data)	0.15 (Burch et al., 1987; ISO 6946 Eq. F.5)	0.12 (Christensen, 2010; Posey & Dalgliesh, 2005)	1.8 (ASHRAE 90.1) or 0.6 stainless steel (Van Geem & Shirley, 1987)
R-40ci	0.05 (Weiland, 2006; ISO 6946 Eq. F.5)	0.05[2]	0.05[2]	0.05[2]	0.7 (ASHRAE 90.1)

Table Notes:

1. Interpolation is permissible between R-values of penetrated insulation in the left column.
2. Values are based at least in part on data trends in adjacent cell(s) or columns of table and are provided only as a means to facilitate completeness of the table and interpolation. Additional research and confirmation is recommended.
3. Based on other modeled data for energy efficient brick ties (e.g., wire ties with hinged connections that disrupt the heat flow path), the normalized chi-factor may be as low as ~0.1 Btu/hr-F per in^2 of tie cross-section area penetrating insulation (pers. comm. Patrick Roppel, Morrison-Hershfield, Jan. 15, 2016).

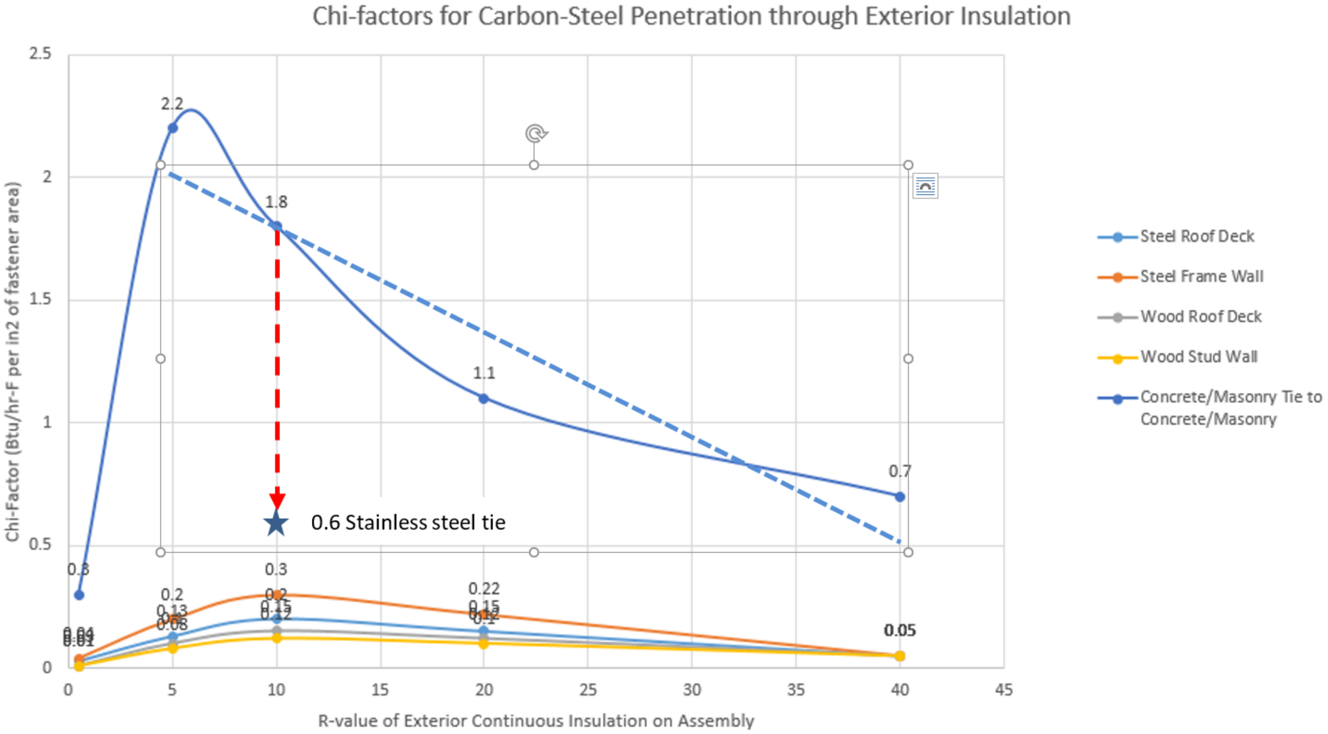


Figure 1. Representative Chi-factors for Carbon Steel Penetrations (fastener, connector, tie etc.) through Exterior or Interior Sheathing Layers on Wood or Steel Frame Assemblies or Through an Insulation Layer Sandwiched Between Two Masonry/Concrete Layers (lower R-values are intended to represent common non-insulating sheathing types used on frame walls or an air-space between two interconnected mass wall layers).

The data from Table 2 and Figure 1 may be represented (approximately) as linear functions for ranges of continuous insulation R-value as indicated in Table 3 below.

TABLE 3
Linear Functions to Estimate Chi-factors Derived from Table 2 and shown in Figure 1

Assembly Type	Chi-factor linear equations based on data ranges (Table 2 and Figure 1):			
	Penetrated Layer R-value			
	Rci-0.5	0.5 <= Rci <= 10	10<= Rci <=40	Rci=40
Steel roof deck:	0.04	Chi = 0.018(Rci)+0.021	Chi = -0.005(Rci) + 0.25	0.05
Steel frame wall:	0.04	Chi = 0.027(Rci)+0.026	Chi = -0.008(Rci) + 0.38	0.05
Wood roof deck:	0.01	Chi = 0.015(Rci)+0.003	Chi = -0.003(Rci) + 0.18	0.05
Wood stud wall:	0.01	Chi = 0.012(Rci)+0.004	Chi = -0.002(Rci) + 0.14	0.05
	Rci-0.5	0.5 <= Rci <= 5	5 <= Rci <=40	Rci=40
Concrete/Masonry:	0.3	Chi = 0.378(Rci)+0.111	Chi = -0.043(Rci) + 2.21	0.5

Table Notes: Rci units = hr-F-ft^2 / btu (R-value); Chi units = Btu/hr-F per in^2 of metal penetration

The Chi-factor values as determined above are not applicable to specialty connection materials or devices that create partial thermal breaks in the metal penetration's heat flow path. There are a variety of such specialty products available that provide lower (mitigated) Chi-factors for cladding connections and various other applications to support exterior building materials and components. Also, the values in Table 2 do not account for important but seemingly minor detailing considerations. For example, the values in Table 2 for connection through above-deck roof insulation to a metal deck are based on the use of a thin carbon steel cap washer (approx. 3" diameter). However, the literature suggests that use of a plastic cap washer can reduce the Chi-factor by as much as 40%.

Finally, stainless steel metal penetrations (fasteners/connectors) also are known to reduce the Chi-factor relative to use of carbon steel materials. For roof deck insulation connections to a steel deck (and presumably also wall insulation or siding connections to steel stud framing), the reductions in Chi-factors can be substantial (e.g., up to a factor of 3, but with substantial variation, depending on the R-value or thickness of the penetrated insulation component and configuration of the heat flow path through the insulated assembly). For wood construction and connection of wooden parts through an insulation component layer, the benefit of using stainless steel fastenings appears to be much reduced (e.g., a 20%

reduction in Chi-factor as shown by Posey and Dalgliesh (2005)). As shown in Figure 1, the greatest potential benefit for use of stainless steel ties through an insulation layer (core) between two highly conductive outer material layers (e.g., concrete sandwich panel construction).

Analysis of Thermal Impacts to Assemblies

Based on the approximated representative Chi-factor values reported in the previous section, U-factors for insulation R-value conditions (with and without inclusion of metal penetrations) are evaluated for a select number of assemblies representing current IECC 2015 or ASHRAE 90.1 energy code requirements. The following analyses may be considered as rough approximations ("ballpark estimates") of the impacts of metal penetrations (fasteners, connectors, etc.) on the U-factor of wall and roof thermal envelop assemblies in comparison to those without fastenings or with fastening completely or partially ignored.

Mechanically attached above-deck continuous insulation (CI) roof system

	IECC 2015 Insulation by Climate Zone					
Roof Component	**Zone1**	**Zone2-3**	**Zone4-6**	**Zone7-8**	**Fastener area ratio (FAR) for mechanically attached component layers:**	
Outside air film	0	0	0	0	FAR = fastener cross-section area (in^2) per in^2 of roof area x 100%	
Roof membrane	0	0	0	0	**0.0015%**	See below for mechanically attached roof membrane
Cover Board	0.2	0.2	0.2	0.2	**0.0000%**	See below for mechanically attached cover board
Above Deck Insulation	**20**	**25**	**30**	**38**	**0.0045%**	See below for insulation attachment
Metal Deck + any concrete	0	0	0	0	**0.0060%**	Total
Below deck insulation	0	0	0	0		
Inside air film	0.68	0.68	0.68	0.68	Typical fastening schedule:	
Nom. U-factor (no fasteners)	**0.048**	**0.039**	**0.032**	**0.026**	membrane= 12"oc in rows at 8'oc, 0.0186in^2 fastener = 0.0015%	
Eff. R (no fasteners)	**20.9**	**25.9**	**30.9**	**38.9**		(minimum, may double with higher wind zones)
U-factor increase due to fastener heat loss (delta-U = Chi x FAR x 144in^2/ft^2):					cover board = same as insulation or in lieu of insulation fasteners	
Membrane fasteners	0.00032	0.00027	0.00021	0.00013		(0% if adhered to insulation)
Cover board fasteners	0.00000	0.00000	0.00000	0.00000	insulation = 1 screw per 2 to 4 ft^2, 0.0186in^2 fastener, = 0.0032 to 0.0065%	
Insulation fasteners	0.00096	0.00080	0.00064	0.00039		(0% if insulation is adhered)
Total add to nominal U-factor:	**0.00128**	**0.00107**	**0.00086**	**0.00051**		
U-factor (with fasteners)	**0.0492**	**0.0397**	**0.0332**	**0.0262**		
Effective R (with fasteners)	**20.33**	**25.18**	**30.08**	**38.12**		
Factor increase in nom. U	**1.03**	**1.03**	**1.03**	**1.02**		

Figure 2. Mechanically attached roofing analysis of fastener thermal bridging impact
(insulation above metal roof deck with carbon steel fasteners for membrane and insulation attachment)

The impact of mechanical fastening on the U-factor of a mechanically attached roof membrane and insulation is relatively small, generally ranging from a 2 to 3 percent increase to the nominal U-factor (reduction in effective R-value) for a typical mechanical fastening schedule. Use of stainless steel fasteners (through insulation into a metal roof deck) may reduce thermal bridging impact to roughly one-third of the above impact for carbon steel fasteners. Use of plastic cap washers for insulation attachment may reduce thermal bridging of fasteners by roughly 40 percent. However, if only applied to insulation attachment (not to the roof membrane attachments), then the net benefit would be approximately 0.0045%/0.0060% x 40 percent = 30 percent reduction of the assembly U-factor impact stated above (based on ratio of insulation attachment fasteners to roof membrane fasteners, both of which are considered to have the same Chi-factor). Attachment to a wood roof deck instead of metal deck would have a similar magnitude of benefit in mitigating thermal bridging through fasteners. The above mitigating actions should not be considered as cumulative.

Steel Frame Wall Assemblies with and without Exterior Continuous Insulation (CI)

	2015 IECC Climate Zones & Insulation (C402.1.4.1 Calculation Method)						
	Zone 1, 2	Zone 2-8		Zone 7res	Zone 8res	n/a	n/a
Wall Component	**4"C-stud**	**4" C-stud**	**6" C-stud**	**4" C-stud**	**4" C-stud**	**6" C-stud**	**6" C-stud**
Outside air film	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Siding	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Continuous insulation	**5**	**10**	**8.5**	**15.6**	**17.5**	**0**	**3.8**
Gypsum Sheathing 1/2"	0.45	0.45	0.45	0.45	0.45	0.45	0.45
subtotal exterior R-value:	6.07	11.07	9.57	16.67	18.57	1.07	4.87
Cavity Insulation	**13**	**13**	**19**	**13**	**13**	**19**	**21**
Cavity Correction Factor	0.46	0.46	0.37	0.46	0.46	0.37	0.35
Eff. Cavity insulation	**5.98**	**5.98**	**7.03**	**5.98**	**5.98**	**7.03**	**7.35**
1/2 drywall (int. R-value)	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Inside air film	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Nom. U-factor (no fasteners)	**0.075**	**0.054**	**0.056**	**0.042**	**0.039**	**0.106**	**0.074**
Effective R (no fasteners)	**13.4**	**18.4**	**17.9**	**24.0**	**25.9**	**9.4**	**13.5**
U-factor increase due to fastener heat loss (delta-U = Chi x FAR x 144in^2/ft^2):							
Siding fasteners	0.00547	0.00848	0.00819	0.00719	0.00675	0.00158	0.00454
CI fasteners	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Ext Gyp fasteners	0.00060	0.00044	0.00051	0.00033	0.00031	0.00097	0.00070
Drywall fasteners	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Total add to U:	**0.00607**	**0.00892**	**0.00870**	**0.00752**	**0.00706**	**0.00255**	**0.00523**
U-factor (with fasteners)	**0.0810**	**0.0634**	**0.0646**	**0.0493**	**0.0457**	**0.1089**	**0.0792**
Effective R (with fasteners)	**12.35**	**15.77**	**15.49**	**20.29**	**21.86**	**9.18**	**12.63**
Factor increase in nom. U	**1.08**	**1.16**	**1.16**	**1.18**	**1.18**	**1.02**	**1.07**

Figure 3. Steel frame wall assembly fastener thermal bridging impact analyses

The following attachment conditions are associated with the above impacts to the assembly U-factor:

Fastener area ratio for penetrations through interior and exterior surface layers:	
FAR = fastener cross-section area (in^2) per in^2 of wall area x 100%	
0.020%	Siding fastener area ratio (see below)
0.000%	Continuous insulation fastener ratio (see note below)
0.018%	Gypsum exterior sheathing fastener ratio (see note below)
Notes on fasteners as addressed in C402.1.4.1 calculation method:	
1. CI fasteners are implicit to the derivation of cavity correction factors for steel framing	
2. Exterior gypsum fasteners may only be partially addressed in the cavity correction factors	
3. Interior gypsum fasteners are accounted for and implicity to the cavity correction factors	
0.000%	Interior gypsum board fastener ratio (see note above and below)
	Typical steel frame wall framing surface layer connections:
	gysum int. = 12"x16" #6 screws, 0.016in^2 = 0.008%
	Gypsum ext. = 62 #8 screws per 32sqft, 0.021in^2 = 0.028%
	CI board = 42 #8 screws per 32sqft, 0.0.021in^2 = 0.019%
	6" Lap Siding = 1screw,0.016in^2, per 80in^2 = 0.02%
	Brick Ties = 2"x0.033" tie at 16"x24", 2.67ft^2 = 0.017%

The impact on the U-factor of steel frame wall assemblies tends to vary closely with the amount of continuous insulation, mainly due to the continuous insulation acting as a more efficient thermal barrier than cavity insulation. However, fasteners through continuous insulation have a thermal bridging effect on continuous insulation similar to (but much reduced from) that of steel studs on the effectiveness of cavity insulation. The fasteners are point thermal bridges while steel studs are linear thermal bridges which are accounted for in the cavity insulation correction factor. Furthermore, the fasteners are affixed to the steel studs which creates a continuous thermal bridge path through the assembly (not just ending at the fastener attachment point). Consequently, Chi-factors for steel framed walls tend to be greater than those for wood frame walls, resulting in a greater impact on the overall U-factor of the assembly as shown in Figure 3 above. For typical cladding and sheathing fastening amounts and continuous insulation ranging from R-3.8 to R17.5, the assembly overall U-factor is increased by 7 to 18 percent (even though the Chi-factor and heat flow through the fastener is decreased for the thicker insulation for reasons mentioned earlier). Considering siding fasteners on a steel frame wall assembly without exterior continuous insulation may increase the nominal U-factor (which excludes siding fasteners) by about 2 percent.

As with the above-deck insulated metal deck roof assembly analyzed previously, significant improvements (reductions in chi-factor and reduced impact to overall U-factor of assembly) can be made by use of stainless steel fasteners. This mitigation action is much less effective for wood frame assemblies. Other mitigation actions to reduce fastener thermal bridging effects for steel frame wall assemblies may include use of a lower conductivity exterior sheathing material (such as wood sheathing) as a fastener base rather than placing fasteners directly into the highly conductive steel framing members. This action could conceivably produce as much as a 40% reduction in the carbon steel fastener chi-factor (heat flow) based on the effect mentioned previously for metal roof deck vs. wood roof deck attachments.

Wood Frame Wall Assemblies with and without Exterior Continuous Insulation (CI)

	2015 IECC Climate Zones and Insulation (parallel path calculation)						
	Zone 1, 2	Zone 3, 4, 5		Zone 6, 7, 8		Zone 7com	Zone5-7com
Wall Component	**2x4**	2x4	**2x6**	2x4	2x6	2x4 com	2x6 com
Outside winter air	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Siding	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Continuous insulation	**0**	**5**	**0**	**10**	**5**	**15.6**	**3.8**
OSB - 7/16	0.62	0.62	0.62	0.62	0.62	0.62	0.62
subtotal exterior R-value:	1.24	6.24	1.24	11.24	6.24	16.84	5.04
SPF stud	4.375	4.375	6.875	4.375	6.875	4.375	6.875
SPF header	4.375	4.375	6.875	4.375	6.875	4.375	6.875
Cavity insulation	**13**	**13**	**20**	**13**	**20**	**13**	**20**
1/2 drywall (int. R-value)	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Inside air film	0.68	0.68	0.68	0.68	0.68	0.68	0.68
R-value stud path	6.92	11.92	9.42	16.92	14.42	22.52	13.22
R-value header path	6.92	11.92	9.42	16.92	14.42	22.52	13.22
R-value cavity path	15.54	20.54	22.54	25.54	27.54	31.14	26.34
Framing factor - studs	21%	21%	21%	21%	21%	21%	21%
Framing factor -header	4%	4%	4%	4%	4%	4%	4%
Framing factor - cavity	75%	75%	75%	75%	75%	75%	75%
Nom. U-factor (no fasteners)	**0.084**	**0.057**	**0.060**	**0.044**	**0.045**	**0.035**	**0.047**
Effective R (no fasteners)	**11.8**	**17.4**	**16.7**	**22.7**	**22.4**	**28.4**	**21.1**
U-factor increase due to fastener heat loss (delta-U = Chi x FAR x 144in^2/ft^2):							
Siding fasteners	0.00022	0.00091	0.00022	0.00139	0.00091	0.00126	0.00074
CI fasteners	0.00011	0.00069	0.00011	0.00119	0.00070	0.00109	0.00056
OSB fasteners	0.00031	0.00022	0.00032	0.00018	0.00025	0.00014	0.00026
Drywall fasteners	0.00012	0.00012	0.00012	0.00012	0.00012	0.00012	0.00012
Total add to U:	**0.00075**	**0.00194**	**0.00076**	**0.00287**	**0.00197**	**0.00261**	**0.00168**
U-factor (with fasteners)	**0.0852**	**0.0594**	**0.0606**	**0.0470**	**0.0465**	**0.0378**	**0.0491**
Effective R (with fasteners)	**11.74**	**16.82**	**16.50**	**21.27**	**21.48**	**26.46**	**20.38**
Factor Increase in nom. U	**1.01**	**1.03**	**1.01**	**1.07**	**1.04**	**1.07**	**1.04**

Figure 4. Wood frame wall assembly fastener thermal bridging impact analyses

The following attachment conditions are associated with the above impacts to the assembly U-factor:

Fastener area ratio for penetrations through interior and exterior surface layers:	
FAR = fastener cross-section area (in^2) per in^2 of wall area x 100%	
0.008%	Siding fastener area ratio (see below)
0.007%	Continuous insulation fastener area ratio (see below)
0.020%	Ext. str. sheathing fastener area ratio (see below)
0.008%	Int. gypsum board fastener area ratio (see below)
	Typical wood wall framing surface layer connections:
	gysum int. = 12"x16" #6 screws, 0.016in^2 = 0.008%
	OSB ext. = 62 nails per 32sqft, 0.0135in^2 = 0.018%
	CI board = 42 nails per 32sqft, 0.0.0077in^2 = 0.007%
	6" Lap Siding = 1 nail,0.0077in^2, per 80in^2 = 0.01%
	Brick Ties = 1"x0.03" tie at 16"x24", 2.67ft^2 = 0.008%
	10" Vinyl Siding = 1 nail, 0.0113in^2, 10"x16" = 0.007%

Wood frame assemblies with exterior continuous insulation ranging from R-3.8 to R-15.6 experience an increase in nominal U-factor of about 3 to 7 percent, less than half the impact experienced for similar steel frame wall assemblies. The wood framing effectively creates a "thermal break" of the highly conductive carbon steel fastener heat flow path through the assembly. Thus, the impact on the assembly U-factor is reduced as well as the chi-factor (heat flow) attributed to the fastener. For wood frame walls without exterior continuous insulation, the impact of fasteners on the assembly nominal U-factor is about 1 percent. While this impact may seem insignificant (and it is small in magnitude), it is an impact or bias that is significant when one considers that an assembly with exterior continuous insulation of R-5 experiences a 3 percent increase in overall U-factor. From a competitive standpoint (and assuming fastener impacts will be considered at some time in the future), ignoring a 1% difference and accounting for a 3% difference can create marginal competitive inequities for assemblies that are on the competitive edge of energy code compliance (e.g., dependent on the third decimal place of the U-factor). This same competitive "level playing field" concern applies to steel frame wall assemblies.

Mass Wall Assemblies (Masonry/Concrete) with a Continuous Insulation Layer Sandwiched Between Mass Layers

	2015 IECC - ASHRAE 90.1 Insulation by Climate Zone (Appendix A3.1 Calculation)						
Wall Component	**Zone1-2**	**Zone2-3**	**Zone3-4**	**Zone4-5**	**Zone4m,5-6**	**Zone6-7**	**Zone 8**
Outside air film	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Brick + Vented Airspace	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ext.Continuous insulation	**5.7**	**7.6**	**9.5**	**11.4**	**13.3**	**15.2**	**25**
Ext. Membrane	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Int. Cont. Insulation	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Block/Concrete R-value	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
1/2 drywall + 3/4"airspace	0	0	0	0	0	0	0
Inside air film	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Nom. U-factor (no fasteners)	**0.116**	**0.095**	**0.080**	**0.070**	**0.062**	**0.055**	**0.036**
Effective R (no fasteners)	**8.7**	**10.6**	**12.5**	**14.4**	**16.3**	**18.2**	**28.0**
U-factor increase due to fastener heat loss (delta-U = Chi x FAR x 144in^2/ft^2):							
Siding fasteners (brick ties)	0.03230	0.04161	0.02301	0.02195	0.02090	0.01984	0.01438
CI fasteners	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Ext membrane (n/a)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Drywall/furring fasteners	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Total add to U:	**0.03230**	**0.04161**	**0.02301**	**0.02195**	**0.02090**	**0.01984**	**0.01438**
U-factor (with fasteners)	**0.1479**	**0.1364**	**0.1033**	**0.0916**	**0.0824**	**0.0749**	**0.0502**
Effective R (with fasteners)	**6.76**	**7.33**	**9.68**	**10.91**	**12.13**	**13.35**	**19.94**
Factor increase in nom. U	**1.28**	**1.44**	**1.29**	**1.32**	**1.34**	**1.36**	**1.40**

Figure 5. Mass (concrete/masonry) wall assembly carbon-steel tie thermal bridging impact analyses

The following attachment conditions are associated with the above impacts to the assembly U-factor:

Fastener area ratio for penetrations through interior and exterior surface layers:	
FAR = fastener cross-section area (in^2) per in^2 of wall area x 100%	
0.009%	Brick tie area ratio (see below)
0.000%	Continuous insulation fastener area ratio (see below)
0.000%	Ext. Membrane fastening, not applicable
0.000%	Use 0.008% fastener area ratio as typical (see below)
Typical mass wall surface layer connections:	
	Brick Ties = 1"x0.033" tie at 16"x24", $2.67ft^2$, FAR = 0.009%
	CI board = minimal/adhesive, negligible (not embedded in both mass layers)
	gysum int. = 12"x16" #8 screws or furring tap-cons, $0.021in^2$, FAR = 0.01%
	(negligible, not embedded in both mass layers)

While the heat flow through the carbon steel metal penetrations (fasteners and ties) tends to decrease with increasing thickness (R-value) of exterior continuous insulation, the net impact on the U-factor of the overall assembly increases in a relative sense. For mass walls with exterior continuous insulation ranging from R-5.7 to R-25, the percentage relative increase in U-factor ranges from 28% to 44%. These impacts are based on Chi-factors represented in Table 2 and Figure 1 as derived from tabulated U-factors for mass walls with metal ties reported in Appendix A of ASHRAE 90.1 as explained in the literature review section of this report and also included in Table 1. These impacts appear to be somewhat excessive and should be viewed with some skepticism until verified or re-evaluated. However, the chi-factors used in the analysis (see Table 2, Table 3, and Figure 2) are approximately three-times greater than indicated by actual hot-box tests of concrete sandwich panel assemblies with internal continuous insulation penetrated by stainless steel ties (embedded in each outer layer of the mass wall assembly) when adjusted for an equivalent amount of metal penetration (Van Geem and Shirley, 1987). Thus, if the factor of three difference in stainless steel vs. carbon steel thermal conductivity applies directly to this assembly, then the estimated impacts shown in Figure 5 for use of carbon steel ties may not be significantly in error. Consequently, the use of stainless steel ties (or other less conductive tie designs) may provide significant thermal bridging mitigation benefits for these type of walls.

For example the estimated impact to U-factor shown in Figure 5 would be reduced to a 9% to 15% increase in U-factor. The use of stainless steel also has the added benefit of improving the durability of those connections, particularly on applications where the tie failure over time may carry significant life-safety implications. It is also important to recognize that metal penetrations through insulation or materials other than the internal continuous insulation material and that are not embedded in both mass layers will have significantly reduced heat flow (Chi-factors) than represented in Figure 5. It is for this reason that potential use of fasteners to temporarily attach just the internal continuous insulation layer or any interior finishes or furring were ignored in the analysis of Figure 5. The actual impact of various types of point thermal bridge conditions for mass walls should be further investigated and expanded.

Interior "Continuous Insulation" on Mass Buildings

For mass buildings, U.S. model building codes and standards also refer to insulation materials (including framed walls with cavity insulation) placed on the interior side of the assembly as "continuous insulation". Typically clips or furring are used to also fasten these interior insulated assemblies to the mass wall substrate; thus, they too have point thermal bridging impacts to consider. However, that is not the specific subject of this section. Instead, this section evaluates a major non-continuity of the "continuous insulation" that occurs when such insulation is placed on the interior side of mass wall buildings. Typically, these buildings have concrete slab floors that intersect with the exterior walls for the entire building perimeter at every story level. While slab-wall assembly intersections are not point thermal bridges, they cause a linear thermal bridge that is of much greater significance than the point thermal bridges evaluated in the previous section associated with carbon steel metal ties through a layer of continuous insulation. While the use of exterior continuous insulation mitigates these major linear thermal bridges on mass buildings, the interior application of so-called "continuous insulation" or framed assemblies with cavity insulation does not. Therefore, the following paragraph provides an analysis of the linear thermal bridge impact and assigns it as an impact to the U-factor of the mass wall interior "continuous insulation" assembly to allow comparison to the analysis in the previous section which addressed exterior continuous insulation with carbon steel tie penetrations. Basically, the intent is to explore the question: What is the trade-off of performance between exterior and interior continuous insulation strategies for mass wall assemblies?

From the Morrison-Hershfield LTD (2014) study, a typical slab edge linear thermal bridge Psi-factor (Btu/hr-ft-F) is approximately 0.5 Btu/hr-ft-F for mass wall assemblies that are interior insulated. The additional heat flow for each 1-foot length of the building perimeter is (0.5 Btu/hr-ft-F) x 1-ft = 0.5 Btu/hr-F. Distributed over a 1-foot length of wall assembly for a 10-ft story height (a 10-ft^2 area of assembly), the contribution of the slab edge linear thermal bridge to the mass wall assembly U-factor is (0.5 Btu/hr-F) / 10 ft^2 = 0.05 Btu/hr-ft^2-F. For a mass wall in a mixed (moderately cold) climate, the nominal U-factor for the assembly is approximately 0.070 Btu/hr-ft^2-F (see Figure 5 above). With the slab edge linear thermal bridge added, the effective U-factor is increased to 0.120 Btu/hr-ft^2-F. This amounts to a 71% increase in the assembly U-factor and is about double the impact of point thermal bridges (carbon steel ties) through continuous insulation in a concrete sandwich panel or mass cavity wall with internal insulation as shown in Figure 5.

Consequently, the placement of insulation on the interior side of mass (concrete/masonry) walls is of much greater consequence than a reasonable amount of point thermal bridges through exterior continuous insulation on the same walls (although this too is not insignificant). This inequity should be addressed in the two insulation methods (interior vs. exterior) that appear to be both called "continuous insulation" (or considered equivalent to each other) in current U.S. energy codes and standards. But, in fact, they provide very different levels of thermal performance in real mass buildings with common thermal bridges. Such action will also encourage the cost-effective use of exterior insulation to address the "big" thermal bridges on many building thermal envelopes, such as floor slab edges that would otherwise entirely penetrate the thermal envelope. Together with the use of mitigation techniques for point thermal bridges (e.g., use of stainless steel ties or specially designed ties), such an approach may provide optimal insulation and thermal performance for many types of mass wall assemblies used in concrete/masonry construction.

Conclusions and Recommendations:

This report has accomplished an initial assessment of the literature to roughly characterize and quantify point thermal bridge thermal transmittance values. From this data, thermal performance impacts (U-factor increases) to typical building envelop assemblies were assessed. The types of point thermal bridges addressed in this study focused on uniformly distributed metal penetrations, such as fasteners, connectors, and brick ties which are closely associated with a roof or wall assembly. The assessment included evaluation of assemblies with and without exterior continuous insulation on wood frame, light-frame steel, and concrete/masonry structural systems. In so doing, recommendations were made in regard to various means of mitigating thermal bridges, rather than focusing solely on less cost-effective solutions, such as increasing insulation amounts in an attempt to make up for point thermal bridging heat losses.

It is recommended that additional research be conducted to uniformly model and test a representative matrix of wood, steel, and concrete/masonry assemblies with varying degrees of metal penetrations for cladding connections and other common attachments. This test matrix should serve as a basis for model calibration and verification. Then, the model can be used for direct design solutions or to develop a more consistent, accurate, and expanded set of Chi-factors as a design value library. In addition, the model could be used to develop simplified and improved predictive equations for calculating Chi-factors (e.g., improve upon and expand the scope of application of ISO 6946 Equation D.5).

Finally, it is recommended that a means to consistently and equitably account for uniformly distributed point thermal bridges be provided for all assemblies comprehensively by way of appropriate assembly U-factor adjustments performed in manner consistent with the approach taken in this study. Thus, nominal U-factors for assemblies should represent a "base assembly" without or with a nominal amount of metal penetrations. The nominal U-factor can then be adjusted (for any assembly) to account for the impact of additional metal penetrations in a particular application (e.g., siding type and fastening method, etc.). As a result, an adjusted U-factor can be determined for a multitude of actual end use conditions based on a single nominal U-factor for a base assembly. With Chi-factors available, such adjustments to assembly nominal U-factors rely on simple calculation. Such an approach will also provide a means for innovative fastening and connector technologies to enter the market with a transparent framework for recognition of their performance advantages. Such technologies may hold the greatest promise for cost-effective mitigation of many types of thermal bridges.

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