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Thermal Bridge Mitigation in Army Buildings

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ABSTRACT

High-performance buildings are becoming more prevalent in new Army construction projects. Unfortunately, these new designs often do not take into account preventive procedures to avoid thermal bridging effects, which are localized heat flow between the building interior and exterior. These effects become much more significant as buildings are designed to be highly insulated and better sealed against air leakage. Researchers from the U.S. Army Engineer Research and Development Center—Construction Engineering Research Laboratory (ERDC-CERL) visited several Army installations and used infrared imaging to survey buildings to identify places in the building envelope where thermal bridging commonly occurs. Characteristic construction sections were selected for heat transfer modeling to quantify and qualify the thermal bridging impact and develop general mitigation solutions. This manuscript presents examples of the developed U.S. Army ERDC-CERL Thermal Bridge Mitigation Catalog, which includes architectural details thermal bridge modeling values (Ψ-values and U-factors), and schematics of good construction practices to improve the building envelope performance of typical Army facilities. In addition, this work highlights specific and simple-to-follow mitigation strategies plus visual step-by-step sequencing examples to be used by the construction practitioner for the assembly of a properly mitigated thermal bridge detail in the building envelope.

INTRODUCTION

Energy Losses in U.S. Army Installations

The U.S. Department of Defense (DoD) has been spending a considerable amount of resources to satisfy the energy demands of its stock of buildings. It manages more than 500 fixed installations worldwide, with almost 300,000 buildings that account for approximately 30% of the DoD's total energy use (DoD 2014). With respect to the Army, it was required by law to reduce energy intensity by 30%, as compared to the 2005 consumption (U.S. Congress 2007). More recently, the Army's Net Zero Initiative has the further goal of reaching net zero energy for all fixed installations (NREL 2014). This goal implicitly includes an enormous stock of existing buildings, and achieving this goal will require the implementation of building envelope performance requirements not yet seen in the Federal government. Energy efficiency of the overall building envelope, however, is impacted significantly by thermal bridges, which occur when materials that are poor insulators come into contact with other building components and allow undesired heat flow through the path created. In addition, new Anti-Terrorism Force Protection requirements may mandate the use of heavier steel framing, so, to prevent a higher likelihood for thermal bridging with the additional structural enhancement, the mitigation techniques will need to be carefully considered in the building design and construction. In the past when buildings were less energy efficient and the building envelope not as tight, the impact of energy losses due to thermal bridges on the overall building performance was minimal. With more efficient, high-performance buildings with tighter building envelopes, the energy losses through the building envelope due to these thermal bridges can now become significant, and they are often still an unresolved puzzle that causes extra energy losses and additional costs.

Unfortunately, adequate prevention of thermal bridges in Army constructions is often not addressed in current building design and construction practices. Developing strategies to

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reduce building envelope energy losses caused by thermal bridges will help the Army to be able to meet its energy targets. Attaining higher performance Army buildings will explicitly include rethinking the methods, materials, equipment, schedules, etc. used in the design and construction process.

Thermal Bridges: Impact at the Building Enclosure

Thermal bridges in building enclosures are localized areas with higher thermal conductivity than the neighboring areas. A typical thermal bridge in a building enclosure would be where a material of high conductivity, such as a structural element or metal flashing, penetrates the insulation layer. Another type depends on geometry, which can occur when the heat-emitting surface is larger than the heat-absorbing surface, such as on building corners. For example, interior surfaces in the corner can be colder than other interior surfaces because more heat can flow out due to the larger, exterior, emitting surfaces.

The presence of a thermal bridge in a building assembly would result in the following:

- Higher heat transfer through the assembly
- Colder surface temperatures on the warm side of the assembly
- Warmer surface temperatures on the cold side of the assembly

The possible consequences of these conditions include the following:

- Higher energy use for heating or cooling
- Undesired air filtration due to poor sealing of the joint between the dissimilar construction materials
- Lack of full performance achievement within codes
- Discomfort due to cold surfaces
- Condensation or frosting on chilled surfaces, which could lead to corrosion of metal elements and structure, decay of wood-based materials, and mold growth and associated heath concerns
- Visible patterns on interior or exterior surfaces due to variations of surface temperature and drying cycles

The rate of heat flow though a local area of high conductivity for a thermal bridge depends on a number of factors such as temperature difference between the heat source and heat sink, thermal conductivity of the materials passing through the insulation layer, and the cross-sectional area of the thermal bridge.

In principle, a primary design consideration for any building enclosure assembly is to have a continuous and aligned layer of insulation, minimizing the number, size, and impact of thermal bridges. Heat transfer through common thermal bridges in a building of noncombustible construction can easily exceed the heat transfer through the insulated opaque enclosure (new and existing) assemblies. If the impact of thermal bridging is not considered in new construction or retrofit plans, the design intent for energy performance may not be met.

In the case of a deep energy retrofit project, the building enclosure will require specific attention to controlling heat flow through the opaque portions. Adding insulating materials to the enclosure assemblies is one way to do this, but insulation is not effective if there are easy heat flow paths around it. This is why, for instance, Canadian codes and standards, and good design practice, are progressively moving to requirements based on effective thermal resistance (Brown et al. 1998); this requires identifying and mitigating thermal bridges.

Categorization

Thermal bridges are classified into three categories: clear field, linear, and point. These are visually shown in Figure 1, and are described as follows:

- Clear field results from multiple, evenly distributed thermal bridges such as metal studs, brick ties, or cladding attachments. It is usual to calculate their impact and add it to the thermal transmission or U-factor of the wall or roof type.
- Linear thermal bridges are details that occur lengthwise. For these, one can determine the linear thermal transmission or psi value (Ψ) that would be multiplied by the length over which it occurs to get the heat loss per degree Fahrenheit, and then add this to the building heat losses.
- Point thermal bridges are those that occur, for example, when a steel beam penetrates a wall/roof/floor.

The most significant thermal bridges tend to occur at interfaces between building enclosure assemblies (Figure 2). The significance of the heat loss depends on the transmission rates and the quantity of thermal bridges. Some of these thermal bridges include the following:

- Where slabs or structures penetrate the insulation
- Roof wall intersections such as parapets or roof truss extensions
- Window/wall connections
- At-grade assemblies

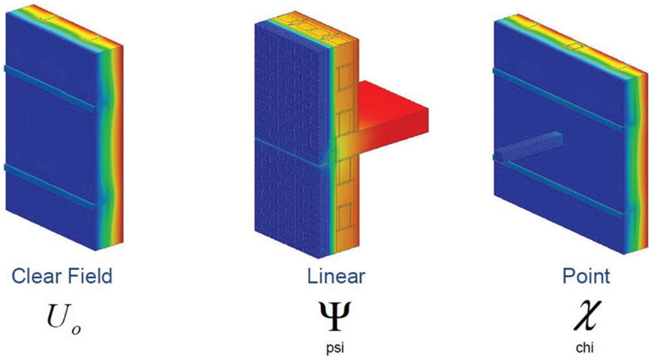


Figure 1 *Thermal bridge type of transmittances.*

- Interior wall/ exterior connections that penetrate insulation
- Curbs or pedestals that penetrate roof insulation

There are, of course, many other smaller thermal bridges at penetrations, corners, door thresholds, ducts, wiring, and pipes that are generally not significant to the building as a whole. However, these can cause significant infiltration/exfiltration and therefore, additional energy loss problems if construction practices such as adequate sealing/caulking are not followed. Notwithstanding, these smaller thermal bridges are out of the scope of this work.

METHODS

Thermal Bridge Identification

The U.S. Army Engineer Research and Development Center—Construction Engineering Research Laboratory (ERDC-CERL) Technical Report (Barnes et al. 2013) summarizes some of the most relevant items to consider developing a Thermal Bridge Mitigation Catalog. Among them, it was recommended to physically identify what particular thermal bridging problems will be dealt with. In this context, the initial considered approach was to perform a survey using an infrared camera to capture the temperature profiles of the building exteriors of representative facilities. Although exact thermal characteristics would not be achieved with the infrared camera technology, this approach will generate good qualitative information for the desired problem to be addressed. Samples of the survey are shown in Figure 3. The survey revealed that, among the identified problems, the most significantly drastic and unfortunately frequent ones were the window junction and building foundation thermal losses (Figure 3, rows a and b).

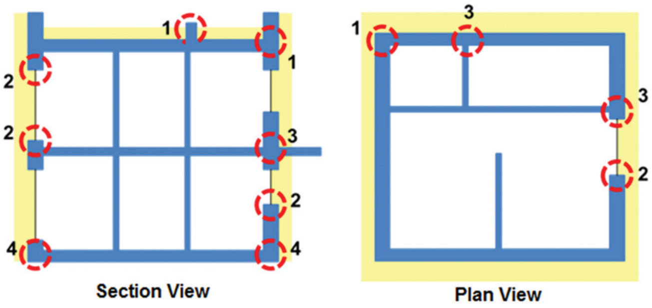


Figure 2 *Building envelope thermally vulnerable locations. Section view: (1) eaves/ridge, (2) window and door fittings (head, sill and jamb), (3) projections, shades or intermediate floors, (4) grade (building foundation). Plan view: (1) wall corner, (2) threshold or door, (3) internal-walls-to-external-walls intersections.*

Common Army Constructions with Thermal Bridge Problems

The inspection of several Army facilities led to identifying the most prominent building features suffering from thermal bridging problems. The initial thought was to capture and organize the building deficiencies based on facility functionality; however, the implemented approach was different. The conducted surveys have shown that it will be more relevant to relate thermal bridge problems based on the building construction type instead of functionality. That is, categorizing the facilities based on their thermally relevant building envelope features could bring forth common characteristics for future mitigation impact and detailed evaluation.

The evaluated buildings were categorized based upon the following construction criteria:

- Concrete masonry unit (CMU) or concrete wall with interior insulation
- CMU or concrete wall with exterior insulation
- Steel stud wall with interior and exterior insulation
- Steel building with insulated metal panel
- Precast sandwich panel
- Important clear wall details or sections whose overall heat transfer effects can be reasonably evaluated and assumed as one-dimensional heat flow
- Historical details with interior insulation

After identifying the most distinctive thermal bridging problems, the next step was to look for the as-built drawings of the identified section, as it should be logical to think that drawings for every building could be obtained. Alternatively, general drawings corresponding to the identified facility types during the survey were obtained from the U.S. Army Corps of Engineers Database (USACE n.d.). These building drawings provide a basic standard from which buildings for the entire Army should follow.

Heat Transfer Analysis

The thermal bridge heat transfer analysis process was conducted through numerical modeling. Software packages were used to model generic and specific Army facilities architectural sections to quantify the loss effects attributed to thermal bridging. The numerical models, obviously, possesses inherent assumptions that will affect the overall intended results. The present study is prominently subjected to the following assumptions:

- Geometric definition of thermal bridges: Whole-building energy modeling and enclosure heat flow analysis depend on both enclosure component U-factors and their respective surface areas. In this approach, the exterior dimensions (including floor slab thicknesses) are entered. As a direct implication, psi (Ψ) and chi (χ) transmittance values are computed on exterior dimen-

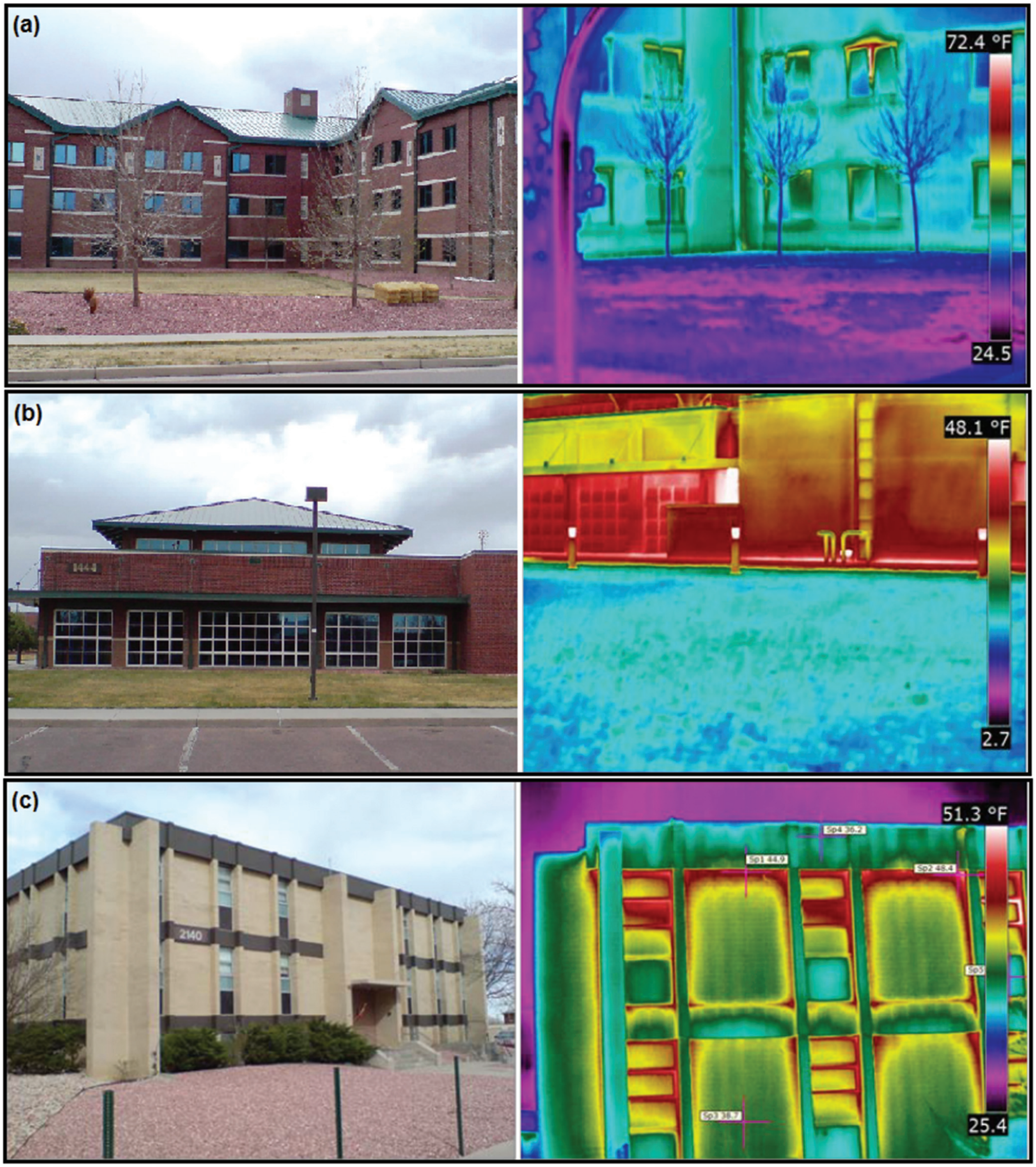


Figure 3 *Visual and accompanying infrared thermograms at various Army facilities showing thermal bridging losses at (a) window frames at a barracks, (b) foundation and slab junctions at a dining facility, and (c) parapet at a company operations facility.*

sions. See the ISO report (2007) for detailed explanation of the Ψ and χ values.

- Choice of thermal conductivity of materials: Because of the unavailability of all the specific construction material information corresponding to the selected architectural details for modeling, the material properties were mainly selected from A*SHRAE Handbook—Fundamentals* (ASHRAE 2009).
- Choice of heat transfer coefficients at surfaces (*surface films*) and in air-filled cavities and voids: These were selected based upon ASHRAE tables (ASHRAE 2009) because they provide detailed tables of numerous factors affecting heat transfer across airspaces. The value for heat transfer given for a mean temperature of 50°F (10°C) with a temperature difference of 62°F (16.7°C) is recommended for basic analysis.
- Simplifications of construction geometry to model: It is important to recall that the geometry of all models is a simplified version of reality. For instance, two-dimensional simplifications were employed whenever the gradient of any property in the third dimension can be judiciously neglected. Also, some of the models were constructed by conglomerating several materials' properties with a single, homogeneous U-factor or R-value in accordance with ISO 10211 (ISO 2007). This simplification methodology is implemented in "Thermal Performance of Building Envelope Details for Mid- and High-Rise Buildings", RP-1365 (Morrison Hershfield 2011).
- Time-dependent effects: Thermal mass (heat capacity) and temperature-dependent effects were ignored.

CALCULATION

One of the main purposes of the Army thermal bridge mitigation guidelines is to allow the building energy modeler to incorporate quantitative values regarding the energy consumption penalty for not addressing thermal bridge problems appropriately. These thermal bridge effects are compiled under the parameters denominated as Ψ and χ values. Is not usual for building energy software packages, such as EnergyPlus (DoE 2013), to have built-in capabilities to incorporate Ψ and χ values. Therefore, to compensate the absence of building thermal bridge energy modeling software, the ASHRAE RP-1365 (Morrison Hershfield 2011) methodology was adopted in this work. In this approach, the U-factor of building envelope sections (roof, walls, and/or floor slabs) can be corrected to incorporate thermal bridge effects using the following expression:

$$U_{corr} = U_o + [\Sigma(\Psi_i \cdot L_i) + \Sigma(\chi_j \cdot n_j)] / A \qquad (1)$$

where

U_o = the original envelope section clear field U-factor

L_i = the length on which the linear thermal transmittance Ψ_i acts upon

n_j = the number of point thermal bridges of type j in the building envelope section under analysis

A = the total area of the building envelope section from which the clear field U_o was used. For this study, the building exterior dimensions were selected for the computation of the Ψ_i factor

Recalling that, depending on the energy modeling software used to conduct building-level energy analysis, instead of prompting for U-factors, the software might require the use of R-values. If this is the case, it might be required to subtract the inside and outside surface film coefficients (ASHRAE 2009). The corrected R-value could be obtained based on computed U_{corr} as the following:

$$R_{corr} = 1/U_{corr} - 1/h_o - 1/h_i \qquad (2)$$

where

h_o = exterior surface transfer coefficients

h_i = the interior transfer coefficients

OVERALL BUILDING IMPACT

To gain a better understanding of the effects of thermal bridging on buildings, ERDC-CERL performed an analysis of various methods used to estimate the energy losses over the course of a year for a typical U.S. Army barracks building with 5,577 ft^2 (1700 m^2) footprint and 50 ft (15 m) elevation (Pagan-Vazquez and Lux 2014). The first method was a simulation using EnergyPlus software and incorporated the effects of thermal bridging into the values of thermal conductivity for the highest thermal resistance layer of the analyzed construction section. The second method was implemented through multiplying the building footprint dimensions by the thermal bridge linear thermal transmittance while also accounting for the heating/cooling days from climate data at Chicago O'Hare International Airport in Chicago, IL.

The sections of the building—an energy inefficient and old Army barracks construction—evaluated in the study were the related to the windows, foundation, corners, and intermediate floor slabs, with details on the dimensions and Ψ-value shown in Table 1. Conventional thought might assume that the thermal bridge with highest Ψ-value should be addressed first, but evaluating the energy losses over the course of a year provides a more accurate prediction. Figure 4 shows the results of the analysis using the two methods and indicating that the window connections and intermediate floor slabs are the areas of the building with the highest potential for thermal bridge energy losses. Additionally, while the Ψ-value for the building foundation was relatively high, the calculations reveal that it has less of an impact on energy consumption.

The the estimated losses from thermal bridging ranged from 0.5 to 3.1% of the facility, depending on the section and calculation method. While the impact of thermal bridges in this particular case study might not be as signif-

Table 1. Metrics Used for Thermal Bridge Analysis in Pagan-Vazquez 2014

Ψ-Value Implementation Method	Thermal Bridge Sections						
	Window Connections—Internal Report			Building Foundation	Wall Corners		Intermediate Floor Slab
	Head	Sill	Jamb		External	Internal	
Building section total length in which the thermal bridge acts upon ft (m)	502 (153)	502 (153)	840 (256)	764 (233)	148 (45)		764 (233)
Thermal bridge Section Linear Transmittance Ψ-Value, Btu/h ft °F (W/m-K)	0.308 (0.533)	0.182 (0.315)	0.322 (0.558)	0.359 (0.622)	0.116 (0.2)	0.087 (0.150)	0.486 (0.841)

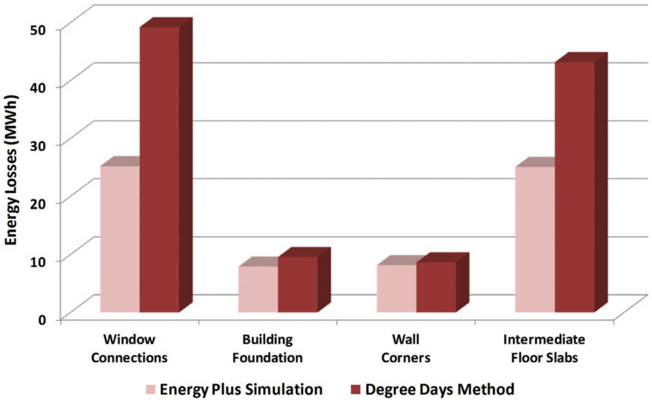


Figure 4 *Estimated annual energy losses in a U.S. Army barracks facility as result of thermal bridging (figure adapted from Pagan-Vazquez 2014).*

icant as those in a high-performance building, the results would suggest that mitigation efforts should be considered during the retrofit phase of a building.

Additional research literature contains more detailed thermal bridge impact at building system level. BC Hydro Power Smart (2014) elaborated a very comprehensive thermal bridge guide, covering typical building constructions of in the region of British Columbia. In particular, the guide discusses and provides section details performance, thermal bridge losses, and construction improvement associated costs and inputs for detailed energy study analyses. Among these, it was simple to identify the potential impact that thermal bridge associated losses can induce. Figure 5 and Table 2 show a case study of the guide, in which includes a multi-unit residential building and its associated building envelope thermal losses. This shows how significant the correct treatment of thermal bridge issues can reduce the costs associated with transmittances of 15,300 Btu/h°F (8000 W/K), multiplied by the respective length where the thermal bridge acts.

RESULTS AND DISCUSSION

Mitigation Approach and Catalog of Details

The main outcome of the Army facilities thermal bridge studies and surveys is a thermal bridge mitigation guideline. The guideline, adopting the format of a catalog of details, provides recommendations on remediation strategies for existing facilities, and prevention strategies for new facilities for 30 types of thermal bridges. Particularly, it presents simulation results (represented as Ψ, χ, or effective clear field U-factors) of an existing and a recommended construction architectural section based on general mitigation approaches, general risks, and responses. Figure 6 exemplifies a typical catalog detail page.

Each page contains the following blocks of information:

- Notes: General background, and details of the problems and mitigation method(s)
- Detail identification (ID): Number, whose detail name and description corresponds to the construction and building architectural type, respectively
- Existing detail: Illustration of the area on the structure experiencing the thermal bridging effects
- Proposed solution: Illustration of the proposed thermal bridge mitigation solution with noted changes
- Modeling values: Table defining the material thermally relevant properties and thicknesses for the modeling of thermal bridging mitigation performance
- Thermal performance: Table noting quantitative improvements following implemented mitigation method(s)
- Quality control/sequencing: Step-by-step description of how to transform existing detail into proposed solution
- Detail callout: Enlarged view of region of interest providing detailed visual description of relevant components requiring special attention

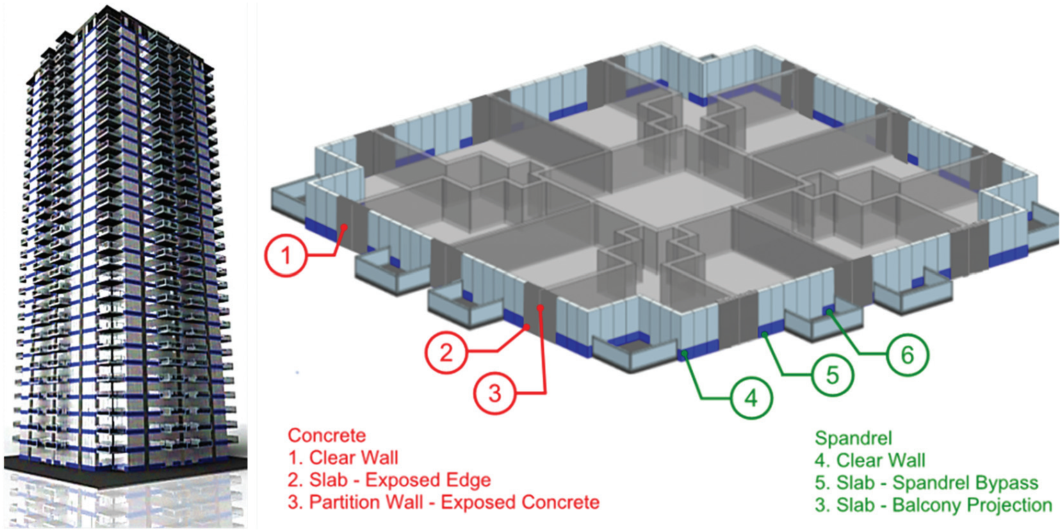


Figure 5 *High-rise multi-unit residential building overall building envelope energy performance. Left: building rendering, right: floor plan and thermally relevant sections. Images used with author's permission (BC Hydro Power Smart 2014).*

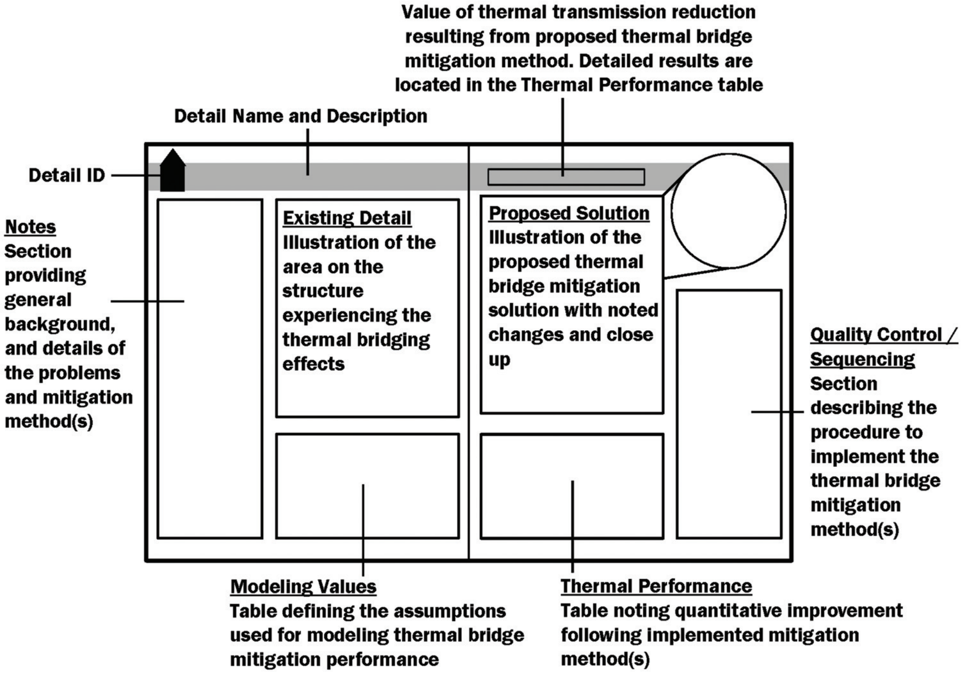


Figure 6 *Catalog page layout.*

- Ψ-value reduction: Maximum achievable thermal bridge effects reductions following the recommended mitigation strategy(ies)

The explored and considered mitigation strategies encouraged by the catalog can be summarized (but not limited) as the following:

- Provide a continuous layer of insulation outboard of the structure. Providing insulation outboard of slabs, columns and metal framing can hugely impact heat flow.
- When installing new windows, align the thermal break in the windows with wall insulation. Because the length of window/wall transition in many buildings is so large, reduction in linear transmission rates of the window/

Table 2. Results from BC-Hydro Power Smart (2014) Study Based Upon Overall Building Energy Performance, Including Thermal Bridging Effects

	Transmittance Type	Quantity	Detail Ref.	Transmittance	Heat Flow, Btu/h °F (W/K)	% of Total Heat Flow
Concrete Wall	Clear Field	32,152 ft^2 (2,987 m^2)	6.2.2	0.07 Btu/h ft^2 °F (0.42 W/m^{2}K)	2377 (1254)	16%
	Parapet	89 ft (27 m)	6.5.3	0.45 Btu/h ft °F (0.78 W/mK)	40 (21)	<1%
	Exposed Floor Slab	3576 ft (1090 m)	6.2.5	0.58 Btu/h ft °F (1.0 W/mK)	2066 (1085)	14%
	At-Grade Transition	89 ft (27 m)	ISO-14863	0.43 Btu/h ft °F (0.75 W/mK)	38 (20)	<1%
	Partition Wall	4314 ft (1315 m)	6.2.2	0.39 Btu/h ft °F (0.67 W/mK)	1670 (876)	11%
Overall Concrete Wall U-Factor, Btu/h ft^2 °F (W/m^{2}K)					0.192 (1.09)	
Overall Concrete Wall R-Value, h ft^2 °F/Btu (m^{2}K/W)					5.2 (0.92)	
Window-Wall Spandrel	Clear Field	1792 m^2 (19,288 ft^2)	1.1.1	0.19 Btu/h ft^2 °F (1.07 W/m^{2}K)	3632 (1917)	24%
	Parapet	82 m (269 ft)	1.3.2	0.42 Btu/h ft °F (0.72 W/mK)	112 (59)	<1%
	Slab Bypass	1635 m (5364 ft)	1.2.1	0.34 Btu/h ft °F (0.58 W/mK)	1797 (945)	12%
	Balcony Slab	1635 m (5364 ft)	8.1.9	0.64 Btu/h ft °F (1.11 W/mK)	3440 (1815)	23%
	At-Grade Transition	82 m (269 ft)	2.5.1 (estimated)	0.40 Btu/h ft °F (0.86 W/mK)	134 (70)	<1%
Overall Spandrel Wall U-Factor, Btu/h ft^2 °F (W/m^{2}K)					0.472 (2.68)	
Overall Spandrel Wall R-Value, h ft^2 °F/Btu (m^{2}K/W)					2.11 (0.37)	
Total Btu/h °F (W/K)					15,306 (8063)	100%
Overall Opaque Wall U-Factor, Btu/h ft^2 °F (W/m^{2}K)					0.297 (1.68)	
Overall Opaque Wall R-Value, h ft^2 °F/Btu (m^{2}K/W)					3.4 (0.59)	

wall junction can make an extraordinary difference to building heat loss. If the window is not aligned with the wall insulation, there will be a “flanking path” allowing heat loss. If alignment is not practical, provide lateral insulation to block the flanking path (Figure 11).

- Do not install metal flashings that bypass insulation. Closure flashings around windows should be attached to the window outside the thermal break. Through-wall flashings can be made with low-conductivity membranes, protected with a counter flashing that is thermally isolated from the interior structure.
- Thermally isolate parapets. Reroofing projects can be taken as an opportunity to insulate up and on top of parapets (Figure 12) or, better still, provide thermal break at the base of the parapet.
- Insulate foundation walls, preferably from the outside. For below-grade, insulation can be expanded polystyrene, extruded polystyrene, or high-density stone wool/mineral wool. However, in all cases, this insulation requires protection from impact, and, in the case of foam plastics, ultraviolet radiation. In addition, it is often of importance to consider an insulation with enough termite resistance, especially in warmer climates. An aesthetically appealing finish is also often desired. This finish can be provided by a cement-based stucco with corrosion-resistant reinforcing, a polymer-modified stucco reinforced with glass fiber, metal, or PVC sheets (Figure 10).
- Thermally isolate masonry claddings from the foundation wall. Brick bearing on a heated foundation wall are a thermal fin. This heat flow path can be minimized by having the brick bear on a stand-off shelf angle or a course of low-conductivity masonry units such as aerated concrete or foam glass.
- Minimize the cross-sectional area of metal elements passing though insulation. There are now many systems for attaching cladding that use clips or thermally broken elements that minimize heat transfer past the insulation. Using such systems provides better thermal resistance for the money and allows the wall insulation to perform

as intended. For structural connections, a clever structural engineer can use small tension and compression elements to replace moment-bearing elements.

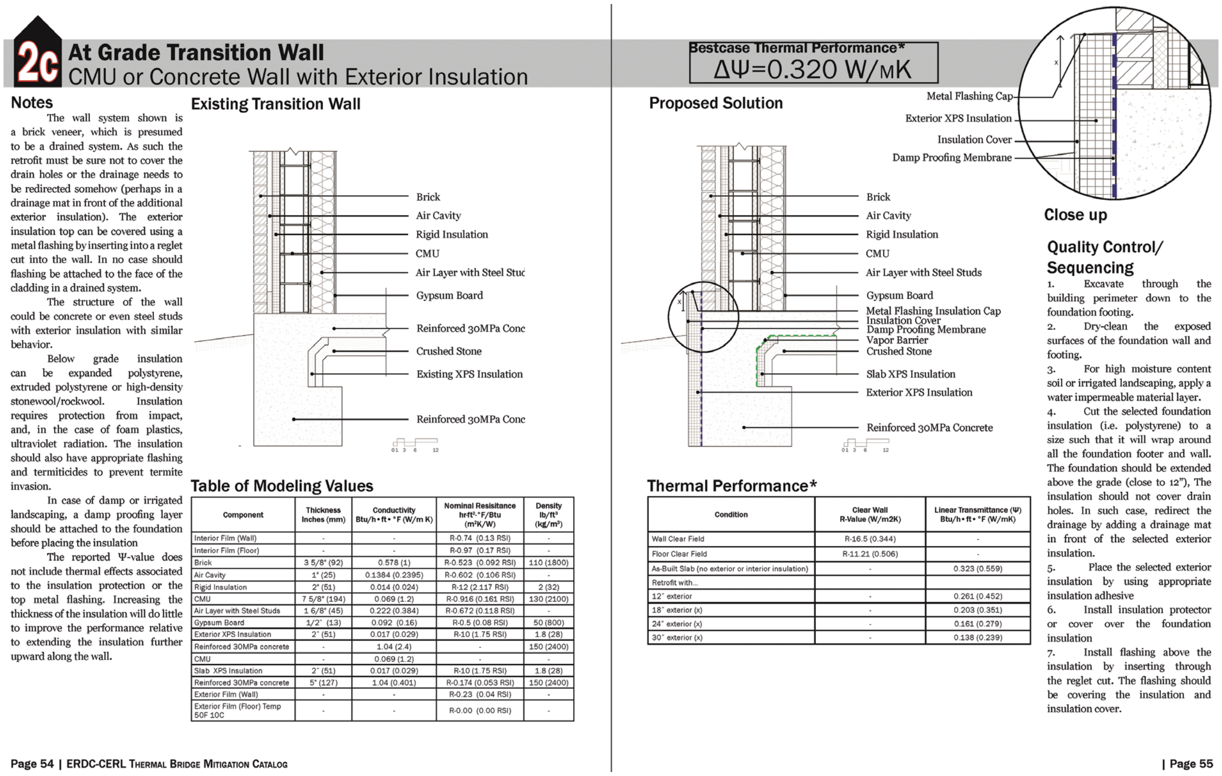
It is worth to mention that the Passive House Institute requirements provides one the most (if not actually the most) stringent construction standards for higher-energy performance (Passive House Institute 2015). For instance, and analogous to this work, using infrared imaging, a passive-house-mitigated at-grade thermal bridge construction detail was documented (Passive House Institute 2006). The current study selected three examples of the Thermal Bridge Mitigation Catalog to illustrate the concept. The first case is thermal bridging problems in a generic Army building with a concrete wall insulated at its exterior (Figure 7). The existing construction is vulnerable to a heat flow path that connects the exterior and interior of the building through the concrete of the foundation and the floor slab. The proposed solution consists of insulating the exterior face of the foundation perimeter from its footing up to several inches above the grade level. Higher thermal bridge reduction is subjected to the higher extension of the foundation insulation.

The second example, shown in Figure 8, highlights one of the most serious thermal bridge problems within the Army stock of buildings. In this case, a thermally broken window inserted in a steel-stud wall presents the commonly denominated *thermal flanking thermal bridge type*. This effect could arise by the lack of continuity in the thermal barrier layer of the building envelope system—in this case, the window-wall junction. The mitigation of the window thermal flanking can be achieved by making sure that the wall system's thermal barrier is contiguous to the window thermal break. That is, the window frame's thermal break is aligned with the wall insulation, especially making sure that no or very minimal junction details connect with the building exterior and interior sides.

The third example described in this work illustrates a building parapet lacking insulation continuity between the roof and the exterior wall (Figure 9). Once more, a temperature difference between the interior building conditions and exterior environment will naturally induce heat flow through the thermally bridged envelope detail. In one solution, the heat flow can be significantly reduced by wrapping the parapet with insulation, making it contiguous between the roof and the exterior wall insulations. Alternatively, the thermal barrier continuity could be obtained by replacing the roof parapet CMU footing block with a highly thermally-resistive construction block, and consecutively extending both the wall and roof insulation until they make contiguous contact with the replaced footing block.

Construction Step-by-Step Sequencing

The previous section describes the use of the mitigation catalog to transform a thermally deficient architectural detail into a thermal-bridge-mitigated one. Concurrently, it was



2c At Grade Transition Wall
CMU or Concrete Wall with Exterior Insulation

Bestcase Thermal Performance*
ΔΨ=0.320 W/mK

Notes

The wall system shown is a brick veneer, which is presumed to be a drained system. As such the retrofit must be sure not to cover the drain holes or the drainage needs to be redirected somehow (perhaps in a drainage mat in front of the additional exterior insulation). The exterior insulation top can be covered using a metal flashing by inserting into a reglet cut into the wall. In no case should flashing be attached to the face of the cladding in a drained system.

The structure of the wall could be concrete or even steel studs with exterior insulation with similar behavior.

Below grade insulation can be expanded polystyrene, extruded polystyrene or high-density stonewool/rockwool. Insulation requires protection from impact, and, in the case of foam plastics, ultraviolet radiation. The insulation should also have appropriate flashing and termiticides to prevent termite invasion.

In case of damp or irrigated landscaping, a damp proofing layer should be attached to the foundation before placing the insulation

The reported Ψ-value does not include thermal effects associated to the insulation protection or the top metal flashing. Increasing the thickness of the insulation will do little to improve the performance relative to extending the insulation further upward along the wall.

Table of Modeling Values

Component	Thickness Inches (mm)	Conductivity Btu/h • ft • °F (W/m K)	Nominal Resisitance hr·ft²·°F/Btu (m²K/W)	Density lb/ft³ (kg/m³)
Interior Film (Wall)	-	-	R-0.74 (0.13 RSI)	-
Interior Film (Floor)	-	-	R-0.97 (0.17 RSI)	-
Brick	3 5/8" (92)	0.578 (1)	R-0.523 (0.092 RSI)	110 (1800)
Air Cavity	1" (25)	0.1384 (0.2395)	R-0.602 (0.106 RSI)	-
Rigid Insulation	2" (51)	0.014 (0.024)	R-12 (2.117 RSI)	2 (32)
CMU	7 5/8" (194)	0.069 (1.2)	R-0.916 (0.161 RSI)	130 (2100)
Air Layer with Steel Studs	1 6/8" (45)	0.222 (0.384)	R-0.672 (0.118 RSI)	-
Gypsum Board	1/2" (13)	0.092 (0.16)	R-0.5 (0.08 RSI)	50 (800)
Exterior XPS Insulation	2" (51)	0.017 (0.029)	R-10 (1.75 RSI)	1.8 (28)
Reinforced 30MPa concrete	-	1.04 (2.4)	-	150 (2400)
CMU	-	0.069 (1.2)	-	-
Slab XPS Insulation	2" (51)	0.017 (0.029)	R-10 (1.75 RSI)	1.8 (28)
Reinforced 30MPa concrete	5" (127)	1.04 (0.401)	R-0.174 (0.053 RSI)	150 (2400)
Exterior Film (Wall)	-	-	R-0.23 (0.04 RSI)	-
Exterior Film (Floor) Temp 50F 10C	-	-	R-0.00 (0.00 RSI)	-

Thermal Performance*

Condition	Clear Wall R-Value (W/m2K)	Linear Transmittance (Ψ) Btu/h • ft • °F (W/mK)
Wall Clear Field	R-16.5 (0.344)	-
Floor Clear Field	R-11.21 (0.506)	-
As-Built Slab (no exterior or interior insulation)	-	0.323 (0.559)
Retrofit with...		
12" exterior	-	0.261 (0.452)
18" exterior (x)	-	0.203 (0.351)
24" exterior (x)	-	0.161 (0.279)
30" exterior (x)	-	0.138 (0.239)

Quality Control/ Sequencing

1. Excavate through the building perimeter down to the foundation footing.
2. Dry-clean the exposed surfaces of the foundation wall and footing.
3. For high moisture content soil or irrigated landscaping, apply a water impermeable material layer.
4. Cut the selected foundation insulation (i.e. polystyrene) to a size such that it will wrap around all the foundation footer and wall. The foundation should be extended above the grade (close to 12"), The insulation should not cover drain holes. In such case, redirect the drainage by adding a drainage mat in front of the selected exterior insulation.
5. Place the selected exterior insulation by using appropriate insulation adhesive
6. Install insulation protector or cover over the foundation insulation
7. Install flashing above the insulation by inserting through the reglet cut. The flashing should be covering the insulation and insulation cover.

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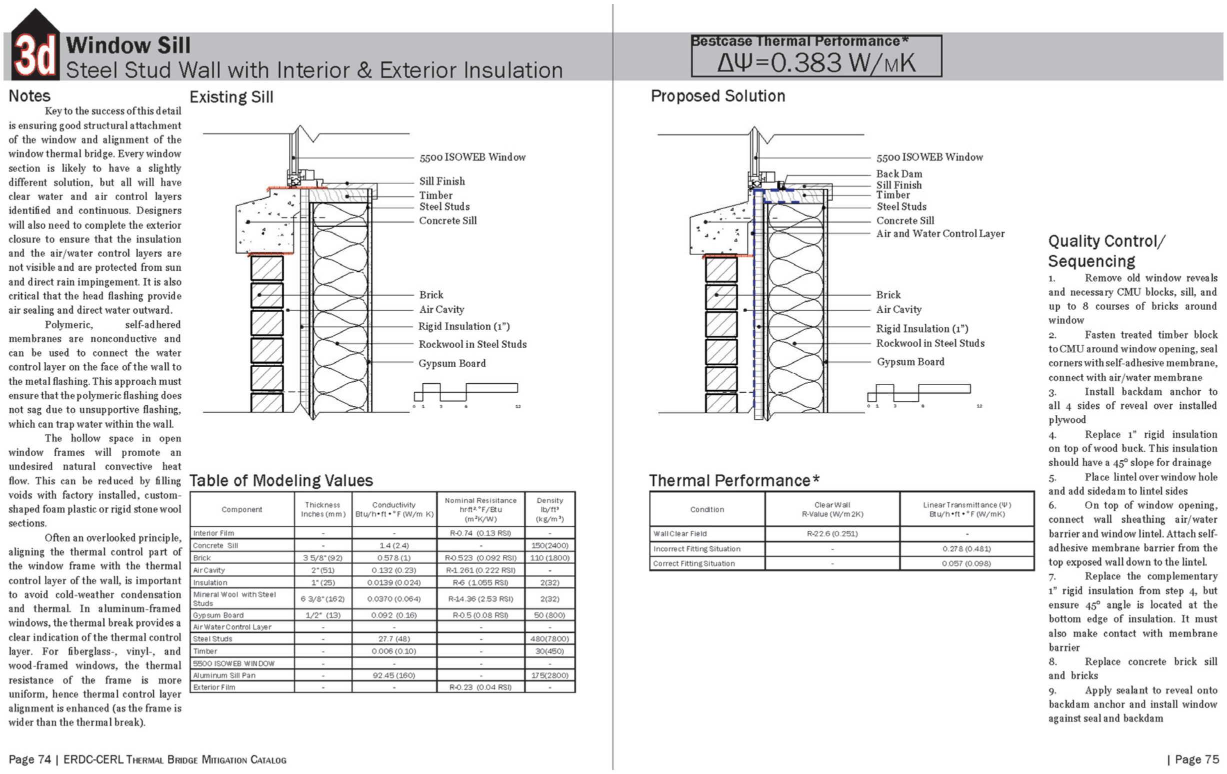
Figure 7 *Catalog detail 2c—At-grade stem wall.*



Window Sill
Steel Stud Wall with Interior & Exterior Insulation

Bestcase Thermal Performance*
ΔΨ=0.383 W/mK

Notes

Key to the success of this detail is ensuring good structural attachment of the window and alignment of the window thermal bridge. Every window section is likely to have a slightly different solution, but all will have clear water and air control layers identified and continuous. Designers will also need to complete the exterior closure to ensure that the insulation and the air/water control layers are not visible and are protected from sun and direct rain impingement. It is also critical that the head flashing provide air sealing and direct water outward.

Polymeric, self-adhered membranes are nonconductive and can be used to connect the water control layer on the face of the wall to the metal flashing. This approach must ensure that the polymeric flashing does not sag due to unsupportive flashing, which can trap water within the wall.

The hollow space in open window frames will promote an undesired natural convective heat flow. This can be reduced by filling voids with factory installed, custom-shaped foam plastic or rigid stone wool sections.

Often an overlooked principle, aligning the thermal control part of the window frame with the thermal control layer of the wall, is important to avoid cold-weather condensation and thermal. In aluminum-framed windows, the thermal break provides a clear indication of the thermal control layer. For fiberglass-, vinyl-, and wood-framed windows, the thermal resistance of the frame is more uniform, hence thermal control layer alignment is enhanced (as the frame is wider than the thermal break).

Existing Sill

Table of Modeling Values

Component	Thickness Inches (mm)	Conductivity Btu/h•ft•°F (W/m K)	Nominal Resisitance hr·ft²·°F/Btu (m²K/W)	Density lb/ft³ (kg/m³)
Interior Film	-	-	R-0.74 (0.13 RSI)	-
Concrete Sill	-	1.4 (2.4)	-	150(2400)
Brick	3 5/8" (92)	0.578 (1)	R-0.523 (0.092 RSI)	110 (1800)
Air Cavity	2" (51)	0.132 (0.23)	R-1.261 (0.222 RSI)	-
Insulation	1" (25)	0.0139 (0.024)	R-6 (1.055 RSI)	2(32)
Mineral Wool with Steel Studs	6 3/8" (162)	0.0370 (0.064)	R-14.36 (2.53 RSI)	2(32)
Gypsum Board	1/2" (13)	0.092 (0.16)	R-0.5 (0.08 RSI)	50 (800)
Air Water Control Layer	-	-	-	-
Steel Studs	-	27.7 (48)	-	480(7800)
Timber	-	0.006 (0.10)	-	30(450)
5500 ISOWEB WINDOW	-	-	-	-
Aluminum Sill Pan	-	92.45 (160)	-	175(2800)
Exterior Film	-	-	R-0.23 (0.04 RSI)	-

Proposed Solution

Thermal Performance*

Condition	Clear Wall R-Value (W/m 2K)	Linear Transmittance (Ψ) Btu/h•ft•°F (W/mK)
Wall Clear Field	R-22.6 (0.251)	-
Incorrect Fitting Situation	-	0.278 (0.481)
Correct Fitting Situation	-	0.057 (0.098)

Quality Control/ Sequencing

1. Remove old window reveals and necessary CMU blocks, sill, and up to 8 courses of bricks around window
2. Fasten treated timber block to CMU around window opening, seal corners with self-adhesive membrane, connect with air/water membrane
3. Install backdam anchor to all 4 sides of reveal over installed plywood
4. Replace 1" rigid insulation on top of wood buck. This insulation should have a 45° slope for drainage
5. Place lintel over window hole and add sidedam to lintel sides
6. On top of window opening, connect wall sheathing air/water barrier and window lintel. Attach self-adhesive membrane barrier from the top exposed wall down to the lintel.
7. Replace the complementary 1" rigid insulation from step 4, but ensure 45° angle is located at the bottom edge of insulation. It must also make contact with membrane barrier
8. Replace concrete brick sill and bricks
9. Apply sealant to reveal onto backdam anchor and install window against seal and backdam

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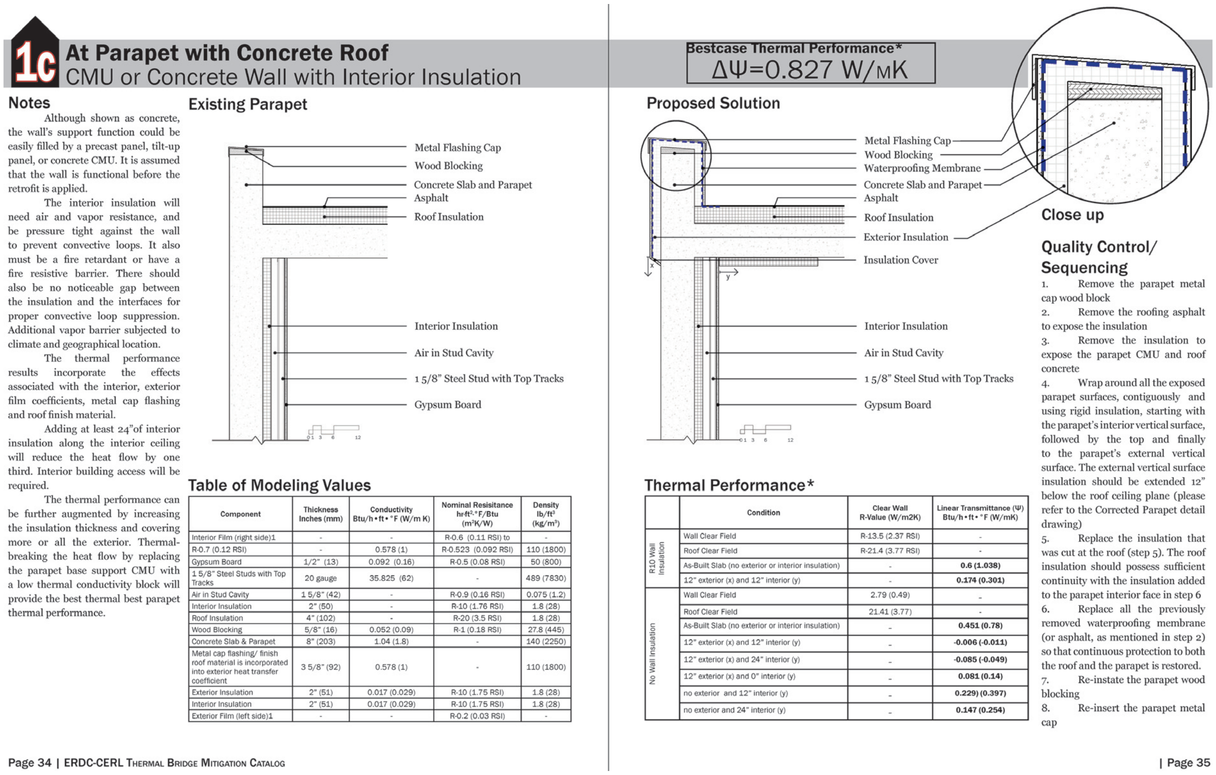
Figure 8 *Catalog detail 3d—Window sill.*



At Parapet with Concrete Roof
CMU or Concrete Wall with Interior Insulation

Bestcase Thermal Performance*
ΔΨ=0.827 W/mK

Notes

Although shown as concrete, the wall's support function could be easily filled by a precast panel, tilt-up panel, or concrete CMU. It is assumed that the wall is functional before the retrofit is applied.

The interior insulation will need air and vapor resistance, and be pressure tight against the wall to prevent convective loops. It also must be a fire retardant or have a fire resistive barrier. There should also be no noticeable gap between the insulation and the interfaces for proper convective loop suppression. Additional vapor barrier subjected to climate and geographical location.

The thermal performance results incorporate the effects associated with the interior, exterior film coefficients, metal cap flashing and roof finish material.

Adding at least 24"of interior insulation along the interior ceiling will reduce the heat flow by one third. Interior building access will be required.

The thermal performance can be further augmented by increasing the insulation thickness and covering more or all the exterior. Thermal-breaking the heat flow by replacing the parapet base support CMU with a low thermal conductivity block will provide the best thermal best parapet thermal performance.

Existing Parapet

Table of Modeling Values

Component	Thickness Inches (mm)	Conductivity Btu/h•ft•°F (W/m K)	Nominal Resisitance hr·ft²·°F/Btu (m²K/W)	Density lb/ft³ (kg/m³)
Interior Film (right side)1	-	-	R-0.6 (0.11 RSI) to	-
R-0.7 (0.12 RSI)	-	0.578 (1)	R-0.523 (0.092 RSI)	110 (1800)
Gypsum Board	1/2" (13)	0.092 (0.16)	R-0.5 (0.08 RSI)	50 (800)
1 5/8" Steel Studs with Top Tracks	20 gauge	35.825 (62)	-	489 (7830)
Air in Stud Cavity	1 5/8" (42)	-	R-0.9 (0.16 RSI)	0.075 (1.2)
Interior Insulation	2" (50)	-	R-10 (1.76 RSI)	1.8 (28)
Roof Insulation	4" (102)	-	R-20 (3.5 RSI)	1.8 (28)
Wood Blocking	5/8" (16)	0.052 (0.09)	R-1 (0.18 RSI)	27.8 (445)
Concrete Slab & Parapet	8" (203)	1.04 (1.8)	-	140 (2250)
Metal cap flashing/ finish roof material is incorporated into exterior heat transfer coefficient	3 5/8" (92)	0.578 (1)	-	110 (1800)
Exterior Insulation	2" (51)	0.017 (0.029)	R-10 (1.75 RSI)	1.8 (28)
Interior Insulation	2" (51)	0.017 (0.029)	R-10 (1.75 RSI)	1.8 (28)
Exterior Film (left side)1	-	-	R-0.2 (0.03 RSI)	-

Proposed Solution

Thermal Performance*

	Condition	Clear Wall R-Value (W/m2K)	Linear Transmittance (Ψ) Btu/h•ft•°F (W/mK)
R10 Wall Insulation	Wall Clear Field	R-13.5 (2.37 RSI)	-
	Roof Clear Field	R-21.4 (3.77 RSI)	-
	As-Built Slab (no exterior or interior insulation)	-	**0.6 (1.038)**
	12" exterior (x) and 12" interior (y)	-	**0.174 (0.301)**
No Wall Insulation	Wall Clear Field	2.79 (0.49)	-
	Roof Clear Field	21.41 (3.77)	-
	As-Built Slab (no exterior or interior insulation)	-	**0.451 (0.78)**
	12" exterior (x) and 12" interior (y)	-	**-0.006 (-0.011)**
	12" exterior (x) and 24" interior (y)	-	**-0.085 (-0.049)**
	12" exterior (x) and 0" interior (y)	-	**0.081 (0.14)**
	no exterior and 12" interior (y)	-	**0.229) (0.397)**
	no exterior and 24" interior (y)	-	**0.147 (0.254)**

Quality Control/ Sequencing

1. Remove the parapet metal cap wood block
2. Remove the roofing asphalt to expose the insulation
3. Remove the insulation to expose the parapet CMU and roof concrete
4. Wrap around all the exposed parapet surfaces, contiguously and using rigid insulation, starting with the parapet's interior vertical surface, followed by the top and finally to the parapet's external vertical surface. The external vertical surface insulation should be extended 12" below the roof ceiling plane (please refer to the Corrected Parapet detail drawing)
5. Replace the insulation that was cut at the roof (step 5). The roof insulation should possess sufficient continuity with the insulation added to the parapet interior face in step 6
6. Replace all the previously removed waterproofing membrane (or asphalt, as mentioned in step 2) so that continuous protection to both the roof and the parapet is restored.
7. Re-instate the parapet wood blocking
8. Re-insert the parapet metal cap

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Figure 9 *Catalog detail 1c—At parapet with concrete roof.*

understood that achieving good practices for thermal bridging losses reduction will require thorough descriptions of construction sequencing, because some of the analyzed sections involve the direct interaction of many components. For instance, a windows junction detail (Figure 8) involves the proper placement of a thermally broken window in a steel-stud wall construction, while maintaining a continuous control layer along the window-wall junction. Incompleteness or incorrect implementation of the mitigation catalog's specified construction steps could lead to severe local envelope damage such as water penetration or considerable infiltration of moist air.

Given the significance of maintaining the specified procedures for achieving good construction details, a complementary architectural detail sequencing guide was developed. This complementary guide is intended to do the following:

- Provide illustrated sequencing descriptions (images and diagrams) required to achieve a mitigated thermal bridge section for a retrofit or new construction. Although the final upgraded section (retrofit or new construction) will perform alike, the construction process could be significantly dissimilar
- When applicable, show different mitigation options, differentiating complexity versus effectiveness
- List Ψ-values for existing remediated details

The next pages are dedicated to exemplify three cases of the sequencing guide.

Existing Construction At-Grade (Building Foundation) Mitigation Sequencing

The foundation thermal bridge mitigation sequencing process (Figure 10) is detailed as follows:

1. If the slab edge cannot be retrofit, then insulating the external perimeter can help to contain heat within the ground and raise internal surface temperatures
2. The ground is excavated at the perimeter of the slab to expose the area for upgrade
3. A chase is cut in the mortar joint allowing for the flashing to be added later

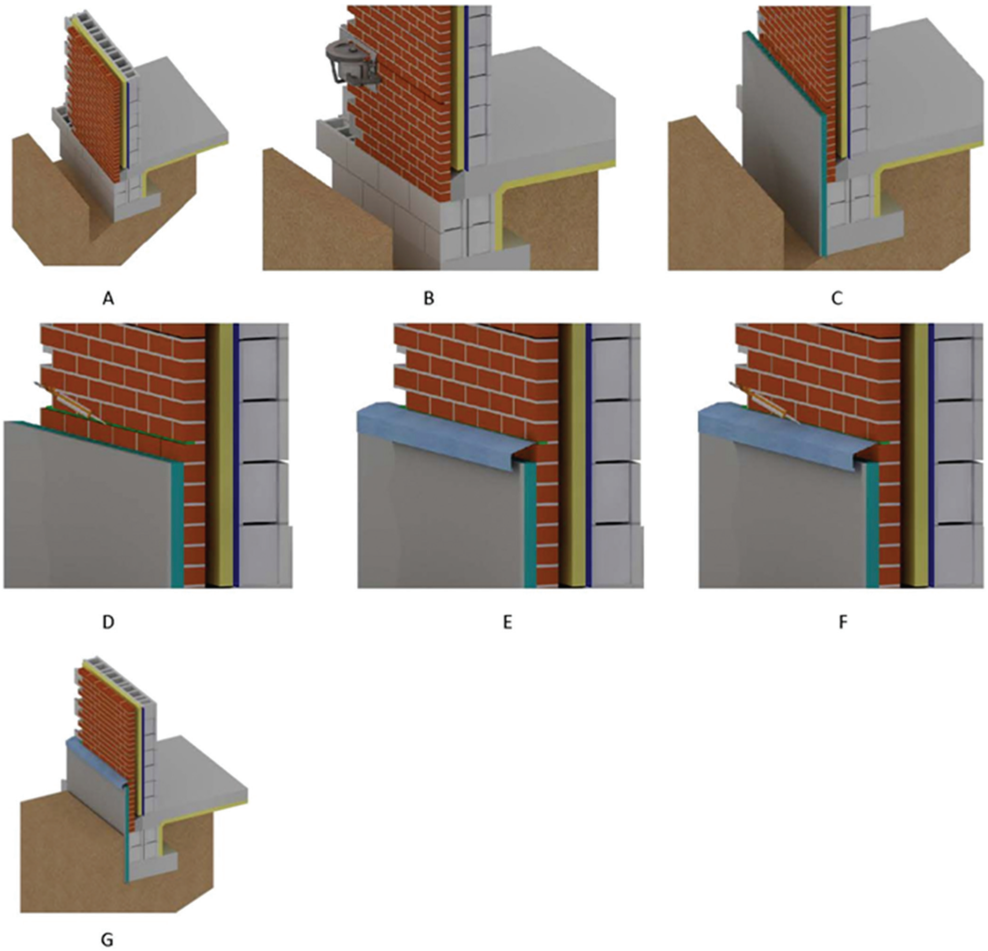

Figure 10 *Foundation at-grade transition. CMU block wall with exterior insulation.*

4. A cement board is prefixed to a grooved, water-resistant extruded polystyrene board and affixed to the perimeter of the slab
5. A bead of sealant is added to the chase
6. A flashing is bedded into the bed of sealant
7. Add an additional bead of sealant to provide watershed
8. The remaining soil can then be added. This may also be an opportunity to add a gravel drain, depending on site conditions

New Construction—Window Connection Mitigation Sequencing

The construction process of a steel stud wall with exterior insulation and brick façade and the recommended window installation (Figure 11) are indicated with the following steps:

1. Starting out, there are the steel studs
2. Gypsum wall board is then added to exterior

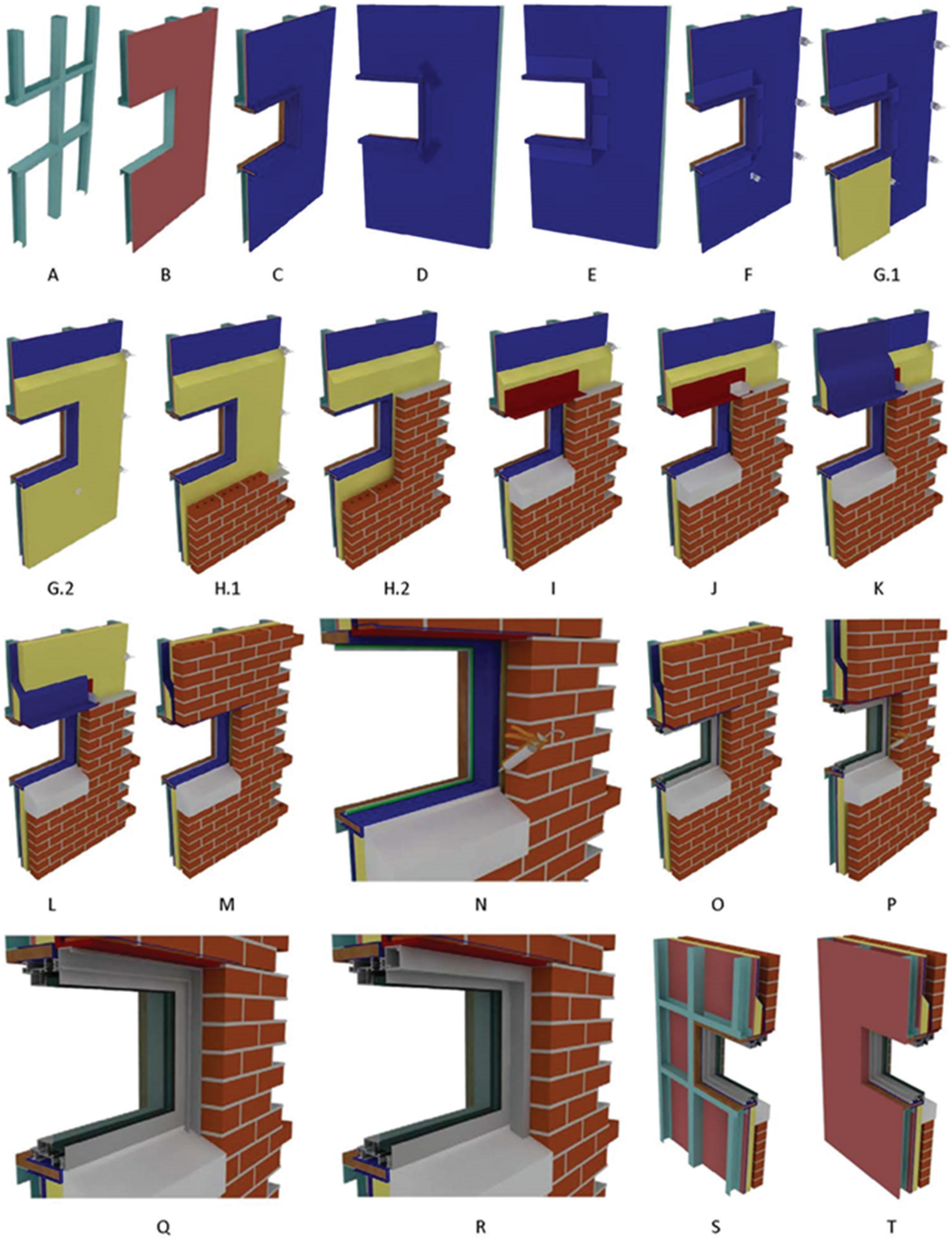

Figure 11 *Window installation in steel stud wall with exterior insulation and brick façade.*

3. After that, an air/water barrier can be placed over the sheeting. A prewrapped, treated timber or plywood buck is added to all four sides of the reveals
4. The wood buck needs to be sealed at the corners
5. Then it must be connected with self-adhesive membrane to the air/water control membrane
6. The anchors can be added to hold the insulation and tie the steel studs with the outer brick veneer. A back dam anchor is then added to all four sides of the reveal
7. Insulation can then be placed between the anchors
8. Brick courses are laid to the level of the lintel
9. The lintel is then placed over the window
10. Before adding the through-wall flashing, a side dam is added to the sides of the lintel
11. Once the through-wall membrane at the head is added, then the water and air sealing is complete
12. Insulation can then be continued
13. Brick courses can then be continued
14. Before adding the window, a bead of sealant is applied to all four sides of the reveal onto the back dam anchor to form an air seal
15. The window is then pushed into position, forming an airtight seal with the sealant
16. When the window is fully placed the outer edges can also be filled with sealant while leaving gaps at the sill to allow drainage
17. The edges of the window can also be covered by proprietary snap on trims
18. Next, the cover strip is clipped onto the angle giving a desirable finish
19. Services are then added
20. Now that the external materials are sealed, the internal finishes can be completed

Existing Construction Roof Parapet Insulation Discontinuity Mitigation Sequencing

The third example consists of contiguously wrapping a CMU parapet wall with the concrete roof (Figure 12). The recommended involved steps are the following:

1. Remove capping
2. Remove flashings and roof coverings
3. Expose CMU wall and roof insulation
4. Add rigid insulation to the rear and top of the parapet as well as the cavity if possible
5. All waterproofing, flashings and coping needs to be reinstated
6. Replace capping

CONCLUSION

U.S. Army installations have been spending significant resources to meet facility energy demands. In response, higher compliance requirements were established along with new construction philosophies, which include high-performance constructions. It has been recognized that achieving high-performance standards will require, among other energy-use

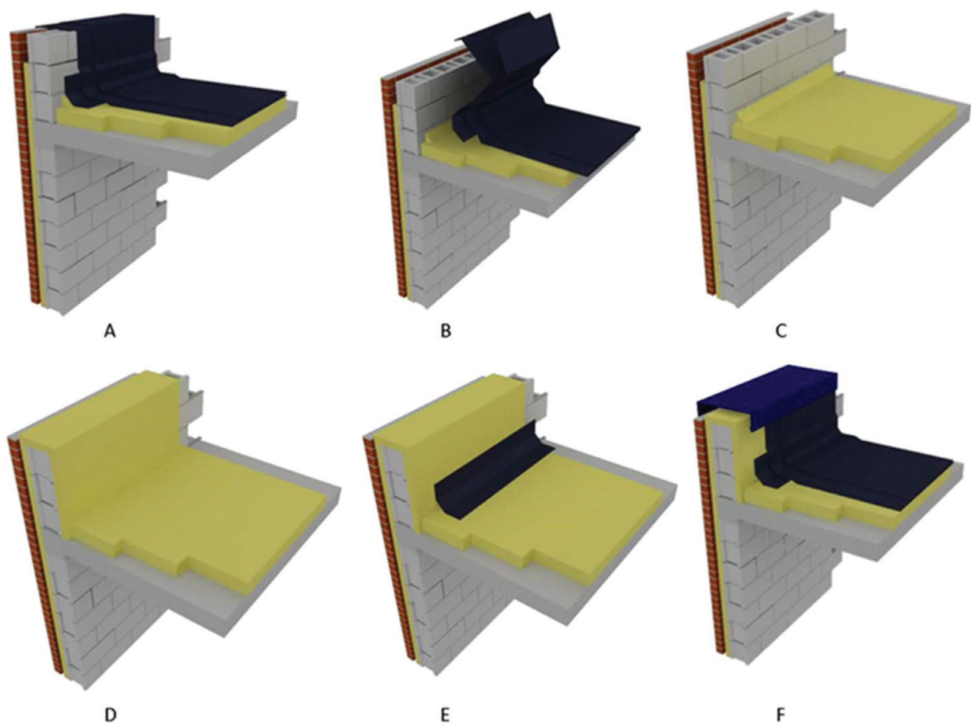

Figure 12 Parapet wrapping on CMU block wall with concrete roof.

concerns, a building enclosure that operates with the minimal amount of heat transfer through it. Addressing this goal, thermal bridge issues in Army buildings were identified as the next level of problems requiring solutions. Surveys and studies were carried out at different installations, simulations and analyses were conducted, and a Thermal Bridge Mitigation Details Catalog has been developed. The catalog provides data inputs to incorporate thermal bridge effects into whole building energy analysis, and instructions to construct improved construction details. Illustrated step-by-step guidance was developed to aid the Thermal Bridge Mitigation Catalog, promoting the correct and easy understanding of the sequencing required to achieve high-performance building enclosure details. As a final remark, products of these studies were already incorporated in a draft Army construction bulletin for further evaluation and will be a section of the international effort contained in EBC Annex 61 (Lohse and Zhivov 2015). Similarly, it is the envisioned that thermal bridge prevention will be part of future Army construction guidelines and/or policies.

ACKNOWLEDGMENTS

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