

Strategies for Improving Air Leakage, Thermal Resistance, and Moisture Control in the Building Enclosure

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This paper was presented at the 2025 IIBEC International Convention and Trade Show.

THE BUILDING ENCLOSURE as an assembly of material layers, penetrations, and transitions plays a significant role in the overall performance of a structure, serving as the physical barrier between the exterior weather-cycling environment and the conditioned interior space. The building enclosure encompasses all six sides of a building: the roofs, walls, floors, and foundations. Improper design, coordination, installation, or maintenance of the building enclosure can negatively affect energy efficiency, occupant comfort, and the long-term durability and performance of the structure.

This paper explores strategies for improving airtightness, thermal resistance, and moisture control within the building enclosure through model energy code compliance, physical tested results, and thermal analysis. By applying these strategies, architects, engineers, building enclosure consultants, and general contractors can design and construct buildings with high-performance building enclosures that stand the test of time and have a minimized environmental impact.

This paper focuses on opaque wall assemblies. It does not directly account for but takes into consideration the addition of transitions, windows, balconies, canopies and other interface details that will change the wall system's thermal resistance, potential condensation risk, and the likelihood of air leakage.

IMPORTANCE OF AIR LEAKAGE, THERMAL RESISTANCE, AND MOISTURE CONTROL

According to the US Department of Energy, 70% of commercial construction litigation is due to moisture related issues, while the World Health Organization has reported that 30% of all new commercial buildings experience SBS or "sick building syndrome." SBS is related to indoor

air quality and is a condition in which people develop symptoms of illness from the time they spend within the building in which they work or reside. Aside from bulk water intrusion, these statistics are directly related to air leakage.

Air leakage refers to the infiltration and exfiltration of air through gaps, cracks, and holes within the building enclosure. This uncontrolled air movement can significantly reduce the energy efficiency of a building, increasing heating and cooling demands and thus leading to higher energy consumption and costs. Additionally, incidental air leakage (infiltration) can compromise indoor air quality, and air leakage via exfiltration can lead to the development of moisture within a roof or wall assembly; these issues affect durability and could potentially cause health issues for occupants.

Model building and energy codes represent the minimum air leakage, moisture control, and thermal resistance criteria for the design, detailing, testing, construction, operation and performance of a building structure. States, cities, and local authorities having jurisdiction frequently implement amendments to the model energy code that they adopt. For example, codes such as the Massachusetts Stretch Energy Code (<https://www.mass.gov/info-details/building-energy-code>) apply stricter requirements. "Stretch" energy code provisions typically include more restrictive measures for building energy performance as compared to prescriptive requirements. For example, stretch codes may include the use of the U-factor

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method in lieu of the *R*-value method for determining thermal resistance and they may prescribe whole building air leakage testing. Additionally, the requirements for air leakage in a stretch code may mandate the use of Passive House standards for airtightness.

As energy codes increase the minimum requirements for building enclosure efficiency, a primary challenge for designers is navigating the complexity associated with model energy code adoptions, stretch amendments, and alternative standards. It is critical for designers to know exactly how the governing codes and the owner's requirements will affect the design of a project. Will the building be designed to comply with minimum or base code requirements, or will it be required to operate at a higher performance level?

Let's not forget that a building designed to comply with only model or base code requirements is the worst building that the jurisdiction will allow to be built. In many cases, it does not take much effort or, frankly, much added cost to quickly achieve a high-performance building when those goals are desired and more comprehensive research, analysis, and effort are implemented.

Reducing energy consumption is a critical step toward reducing operational carbon. Operational carbon refers to emissions from a building's use, maintenance and energy consumption. It can be influenced by efficiency measures and is a concern throughout the building's life. Improving airtightness and thermal resistance saves energy.

COMPATIBILITY AND ADHERENCE

Energy code requirements for air leakage and improved thermal resistance require that all enclosure components work together as an air barrier system. As defined in the *International Energy Conservation Code* (IECC), "An air barrier is one or more materials(system) joined together in a continuous manner to restrict or prevent the passage of air through the building enclosure and its assemblies."¹ The selection of building materials that make up the air barrier system can have a significant impact on the durability of the building over its life cycle. Important considerations in the materials selection process include compatibility, long-term adhesion and air leakage performance. Mixing materials which are not validated through testing for compatibility and engineered to work together will lead to failures.

Materials are considered compatible when objects that are in contact with one another exhibit neither adverse reactions nor loss

of performance properties. Incompatibility can result in staining, streaking, discoloring, bubbling, damage to the substrate or failure. Adhesion is a surface phenomenon that enables two dissimilar materials to bond together. It can be influenced by compatibility. For example, a sealant may be compatible with a specific substrate but may not adhere to that substrate—in other words, compatibility does not guarantee proper adhesion. Likewise, just because two materials have proper adherence does not mean they are compatible.

To be considered continuous, an air barrier must be fully adhered. How well the sheet or fluid applied membrane adheres to the wall substrate will greatly affect performance and airtightness. Poor adhesion can allow air to migrate behind the membrane and into and out of the wall assembly. Proper adhesion therefore impacts the building enclosure performance. The air barrier system plays a critical role in the building enclosure by conserving energy, providing a healthy indoor environment and by protecting structural integrity.²

To properly specify an air barrier system, it is important that the designer understands the chemistry, compatibility and connectivity of the system materials and their effect on each other. This can reduce the risk of enclosure failures that would lead to air leakage, water ingress, and moisture problems. Moreover, designers should also verify that the air barrier system materials submitted by the general contractor and intended for installation are compatible and comply with code.

THE ENERGY CODE EFFECT ON WALL ASSEMBLY DESIGN

Of the many potential strategies that can be implemented to meet base energy codes or achieve a high-performance building, this evaluation of several commercial wall assemblies addresses reduced air leakage, proper moisture control, and increased thermal resistance. To demonstrate thermal energy code compliance, focus was placed on US Climate Zones 4 through 7 (Fig. C301.1, IECC 2021) where the required *R*-values are the highest and the *U*-factors are the lowest (Tables 1 and 2).

Modern energy codes require continuous insulation on the exterior of wall assemblies in addition to cavity insulation when they are metal framed (Table 1). Continuous insulation or "ci" involves the installation of insulation across the entire building enclosure, without thermal bridges or interruptions. This approach is particularly effective in improving the overall thermal performance of the building. However, thermal and moisture considerations must be simultaneously considered since the thermal design strategy has a significant influence on controlling water vapor condensation.³ The surface temperature on the inside face of the sheathing should always be above the dew point temperature of the indoor air to avoid condensation within the stud cavity.⁴

Condensation within walls is more likely to occur due to air leakage (exfiltration in cold climates) rather than vapor diffusion through the materials in a wall assembly. Continuous air and vapor control layers can reduce the quantity and occurrence of condensation, while the exterior insulation serves to keep the critical surface

TABLE 1. Opaque thermal envelope insulation component minimum requirements, *R*-value method. Cavity insulation and continuous exterior insulation (ci) required. Walls above grade.

Climate zone	0 and 1	2	3	4 except marine	5 and marine 4	6	7
mass wall	5.7 ci	5.7 ci	7.6 ci	9.5 ci	11.4 ci	13.3 ci	15.2 ci
metal framed	13 + 5 ci	13 + 5 ci	13 + 7.5 ci	13 + 7.5 ci	13 + 10 ci	13 + 12.5 ci	13 + 12.5 ci

Source: IECC 2021, Table C402.1.3

TABLE 2. Opaque thermal envelope assembly maximum requirements, *U*-factor method. *U*-value requirement for entire wall assembly. Walls above grade.

Climate zone	0 and 1	2	3	4 except marine	5 and marine 4	6	7
mass wall	0.151	0.151	0.123	0.104	0.09	0.08	0.071
metal framed	0.077	0.077	0.064	0.064	0.055	0.049	0.049

Source: IECC 2021, Table C402.1.4

of the sheathing warm, thereby reducing the potential risk of condensation. Ultimately, the best scenario in cold climates for protection against possible air leakage condensation and diffusion is to have all the insulation on the exterior of the AWRB. However, it is almost impossible to achieve this scenario when the effects of thermal bridging are involved. Cavity insulation of some value can be required to meet energy code *R*- and *U*-values even when the effects of thermal bridging are mitigated. Adding permeable insulation if necessary to the stud cavity will increase condensation risk⁵ and the proper insulation ratio is required.

It is important to note that the insulation ratio pertains only to the area of the wall between the studs since the inside surface of the sheathing is the most vulnerable to temperature change. The steel studs will always be warm due to their high thermal conductivity. In summary, for cold climates, a continuous air and vapor barrier and the proper insulation ratio will keep the wall system safe from condensation due to air leakage.

Thermal bridging due to cladding attachments (girts, clips, brick ties, shelf angles) and other sources (balconies, canopies, windows) derates the nominal *R*-value of exterior insulation in the same way that steel studs derate the nominal *R*-value of cavity insulation. Thermal bridging can also “cool” the surface temperatures of the materials within the wall assembly, which can affect the insulation ratio calculation. In short, while the insulation ratio and the rationale behind the ratio are valid and obviously important, the designer must evaluate the thermal and moisture implications created by any thermal bridges. Conducting a dew point analysis early in the design phase to verify if condensation is likely to occur due to thermal bridging is prudent to prevent moisture problems and significant conductive heat loss.

From Table 1 using the prescriptive *R*-value method by climate zone, all above-ground, steel stud wall assemblies must meet $R-13 + 7.5c_i$ (zone 4), $R-13 + 10c_i$ (zone 5), or $R-13 + 12.5c_i$ (zones 6 and 7). If local energy code requires compliance using the *U*-factor method (Table 2), the wall assemblies must have an effective *U*-factor of 0.064, 0.055, 0.049, and 0.049 respectively.

When an energy code requires the *U*-factor method, it is usually because the *R*-value method allows for a range of values depending on the spacing of the steel studs, sometimes referred to as the “framing effect.” This is due to the thermal bridging associated with the studs (Fig. 1). For example, batt insulation with a nominal *R*-value of 13 will be derated to an effective *R*-value of

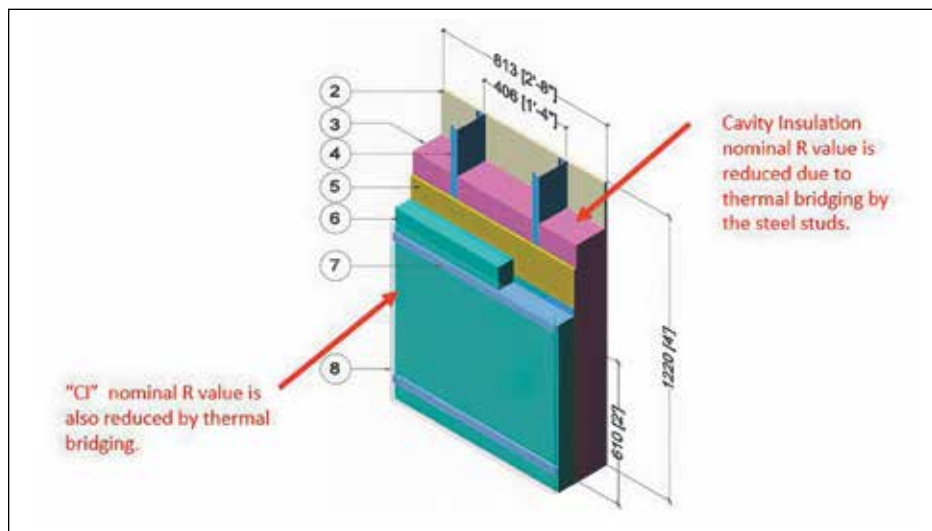


Figure 1. Typical steel stud wall assembly with cavity and exterior insulation. Source: BC Hydro Building Envelope Thermal Bridging Guide.⁶

TABLE 3. Insulation in stud cavity, rated *R*-value versus effective *R*-value

Stud Cavity Depth (in)	Stud Spacing (in)	Rated <i>R</i> -Value	Effective <i>R</i> -Value
3.5	16.0	11.0	5.5
3.5	16.0	13.0	6.0
3.5	16.0	15.0	6.4
6.0	16.0	19.0	7.1
6.0	16.0	21.0	7.4
3.5	24.0	11.0	6.6
3.5	24.0	13.0	7.2
3.5	24.0	15.0	7.8
6.0	24.0	19.0	8.6
6.0	24.0	21.0	9.0

Source: ASHRAE 90.1, Table A3.3

either 6 or 7.2 if placed between 3½ in. studs (Table 3). Therefore, the effective *R*-value for a wall varies. The *U*-factor method is more accurate, stating an effective value that must be met for the wall assembly. Either method must also include the effects of thermal bridging on the external “*c*” to meet compliance.

Wall Assembly A: Steel Stud Frame

Steel stud framed wall assembly is a popular choice and commonly implemented in commercial building design. Our wall assembly A (Fig. 2, left) does not declare a specific cladding but attempts to take a least restrictive approach by incorporating horizontal (perpendicular to studs) galvanized steel girts, exterior continuous insulation (*R*-value to vary), exterior gypsum

sheathing, an AWRB (air and water-resistive barrier), steel studs and interior gypsum board. For the analysis of this common wall assembly, all insulation was first placed to the exterior. A three-dimensional (3-D) thermal analysis was run with a range of nominal *R*-values (continuous insulation thickness) (Table 4, left). The results show that due to the thermal bridging associated with the steel girts, the effective *R*-value of the assembly is much lower than expected. While this wall assembly complies with the *R*-value required for Climate Zone 4 (Table 1), it falls just slightly short of meeting the *U*-factor requirement of 0.064 for Climate Zone 4 (Table 2).

To comply with the model energy code requirements for the *R*-value and *U*-factor in

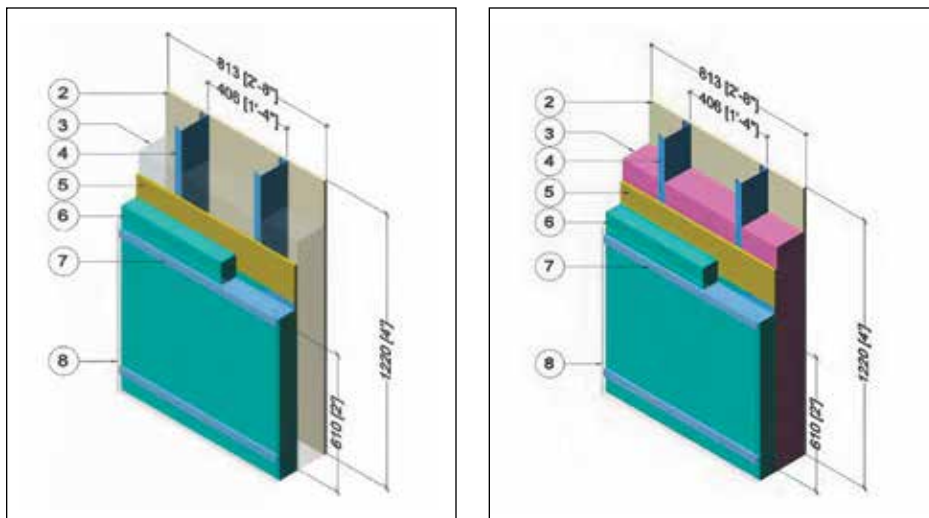


Figure 2. Typical steel stud wall assembly with (right) and without (left) cavity insulation and exterior insulation. Source: BC Hydro Building Envelope Thermal Bridging Guide.⁶

TABLE 4. Thermal analysis results using steel Z-girts and no cavity insulation (left) and with R-13 cavity insulation (right). R_{1D} is the nominal R -value of the wall assembly and R_0 and U_0 are the effective R - and U -values of the wall assembly.

Exterior Insulation 1D R -Value (RSI)	R_{1D} ft ² ·hr·°F / Btu (m ² K / W)	R_0 ft ² ·hr·°F / Btu (m ² K / W)	U_0 Btu/ft ² ·hr·°F (W/m ² K)
R-5 (0.88)	R-8.2 (1.44)	R-6.8 (1.21)	0.146 (0.83)
R-10 (1.76)	R-13.2 (2.32)	R-9.4 (1.66)	0.106 (0.60)
R-15 (2.64)	R-18.2 (3.20)	R-11.3 (1.99)	0.088 (0.50)
R-20 (3.52)	R-23.2 (4.08)	R-13.1 (2.31)	0.076 (0.43)
R-25 (4.40)	R-28.2 (4.96)	R-14.5 (2.56)	0.069 (0.39)

Exterior Insulation 1D R -Value (RSI)	R_{1D} ft ² ·hr·°F / Btu (m ² K / W)	R_0 ft ² ·hr·°F / Btu (m ² K / W)	U_0 Btu/ft ² ·hr·°F (W/m ² K)
R-0 (0)	R-14.2 (2.50)	R-9.2 (1.62)	0.109 (0.62)
R-5 (0.88)	R-19.2 (3.38)	R-13.4 (2.36)	0.075 (0.42)
R-10 (1.76)	R-24.2 (4.26)	R-16.3 (2.87)	0.061 (0.35)
R-15 (2.64)	R-29.2 (5.14)	R-18.5 (3.35)	0.054 (0.31)
R-20 (3.52)	R-34.2 (6.02)	R-20.5 (3.61)	0.049 (0.28)
R-25 (4.40)	R-39.2 (6.90)	R-22.1 (3.90)	0.045 (0.26)

Source: BC Hydro Building Envelope Thermal Bridging Guide

Climate Zones 4, 5, 6, and 7, additional cavity insulation is required. A second thermal analysis was performed using cavity insulation with an R -value of 13 (Fig. 2, right). The results (Table 4, right) show that the wall assembly now complies with the R -value and U -factor requirements for Climate Zones 4 through 7. However, the highly conductive steel girts fastened up against the sheathing create a thermal bridge

where they cross the steel studs behind. A dew point analysis at that location was conducted to verify if the steel girts had lowered the surface temperature of the sheathing or the studs below the internal dew point temperature. In our thermal model we applied Climate Zone 5 winter conditions to the exterior with an inside temperature of 70°F and a relative humidity of 40%. In our thermal model (Fig. 3), we removed

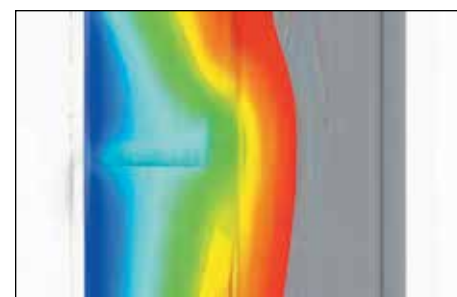


Figure 3. Cross section of steel stud wall at steel girt. Source: Thermal Bridging Solutions.

all material surface temperatures that were above the internal dew point temperature. The results indicate that there is a potential condensation risk (moisture) at the location where the steel Z-girt crosses the steel stud. This condition is risky and could promote deterioration of the sheathing and perhaps mold growth if this area cannot dry properly.

Schoenhard⁷ evaluates the use of steel girts further using a WUFI analysis. WUFI is passive building energy modeling software that considers not only the thermal properties of an assembly and their impact on heat losses but also its moisture performance since heat and moisture are closely related.³ In his research, Schoenhard uses WUFI hygrothermal analysis to determine the drying potential and wetting risk based on the wall assembly materials and climate. The purpose of this type of analysis is to help the designer and owner ensure that the wall is capable of drying should a leak or condensation occur. In his wall assembly located in Climate Zone 5, the WUFI results show condensation within the exterior insulation in winter as well as the potential (relative humidity greater than 80%) for trapped moisture at the interior vapor retarder in the summer.

From a design standpoint, replacing the steel girts with a thermally broken cladding attachment system that will keep the surface temperature of the sheathing above the internal dew point temperature will eliminate condensation risk. Moreover, cavity insulation is not required to comply with the effective R -value and U -factor targets. However, the designer must be cognizant of and consider that the AWRB and sheathing surfaces play a critical role in the airtightness of the assembly by recognizing the effects of the thousands of fasteners that must be driven through the AWRB for the cladding attachment, as well as the many stick pins possibly used to hold the exterior insulation in place. Fasteners can be treated to prevent a potential water breach (leak path) through/past the AWRB layer and into the sheathing,



Figure 4. Traditional brick veneer with steel stud cavity wall.

but this is an added cost (labor and material); the stick pin penetrations cannot be treated in a similar manner.

Wall Assembly B: Brick Masonry Veneer

Steel framed, masonry cavity walls (Fig. 4) with brick veneer are a traditional/historical option, and they are a popular choice in certain areas of North America for the aesthetic that they provide. Masonry veneer and its related mortar joints function as a reservoir cladding (absorbs and holds moisture) and are susceptible to damage such as spalling, efflorescence, mortar failure, brick rot and cycles of freezing and thawing. This cladding type also negatively impacts the AWRB/sheathing layers requiring significant penetrations for brick ties and possible insulation pins. Shelf angles, through-wall flashing, and lintels, as well as the brick ties, can contribute to significant thermal bridging negative effects.

Our modeled wall assembly (Fig. 4) consists of a single wythe of brick with galvanized brick ties, a galvanized steel shelf angle, 3 in. (7.62 cm) of exterior extruded polystyrene (XPS) insulation (R-15), sheathing with an AWRB, air cavity, steel studs, and interior gypsum board. Based on previous thermal modeling and WUFI analyses, we first considered supporting the shelf angle on knife plates to reduce thermal bridging and keep the critical material surface temperatures above the dew point temperature. We also included cavity insulation with an R-value of 13 in an effort to meet the target R-value and U-factor. The thermal model of the opaque wall (without the shelf angle) results in an R-value of 17.6 (U-factor of 0.057) which complies with the required R-value and U-factor for Climate Zones 4 and 5 but not for Climate

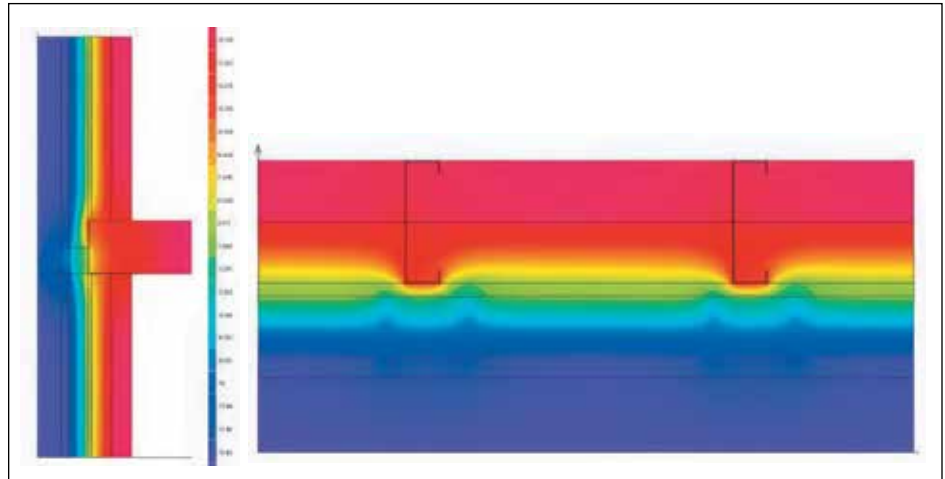


Figure 5. Thermal model showing thermal bridging at a) steel shelf angle supported by a knife plate (left) and steel brick ties (right).

Zones 6 or 7. It is typical for brick ties to derate the expected R-value by 25% to 35%, depending on the type, spacing, and material used. When the shelf angle is added, it creates a linear thermal bridge along its length (Fig. 5). The wall's R-value is then reduced to 14.3 (U-factor of 0.07), which does not comply with the R-value requirements for Climate Zone 4, let alone 5, 6, or 7.

Various strategies to improve the effective R-value and reduce the U-factor were applied. The addition of exterior insulation returned extremely small gains in overall thermal resistance (+R-0.5 when adding 1 in. XPS). Insulation thickness was held at 3 in. maximum to keep the size and depth of the shelf angle and the overall wall thickness at a minimum. We analyzed stainless steel shelf angle and brick tie options because stainless steel conducts less heat than carbon steel. Using a stainless-steel shelf angle on knife plates returned an R-value of 17.8 (U-factor of 0.056) which only meets the energy code requirements for Climate Zones 4 and 5. Other stainless steel bracket systems and thermal break strategies returned similar results. In our opinion, the improved performance associated with using stainless steel likely does not outweigh the projected increase in material cost. However, changing just the brick ties to stainless steel yields an R-value of 16.7 (U-factor of 0.059), which does meet the R-value required in Climate Zone 5 but falls short of meeting the U-factor.

For purely investigative reasons, other scenarios were modeled with the goal of obtaining an effective R-value of at least 20, thereby meeting requirements for Climate Zones 4 through 7. Theoretically, a design with 8 in. of exterior XPS and a stainless-steel shelf angle on knife plates using stainless steel brick

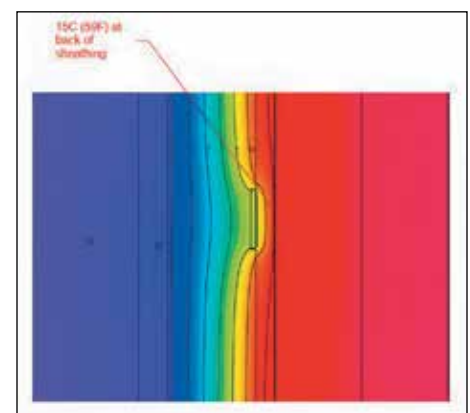


Figure 6. Thermal model showing brick tie connection at exterior sheathing.

ties achieve this objective. However, this is not a practical solution since both the cost and thickness of the resultant wall are not feasible.

For the model that meets the R-value requirements for Climate Zones 4 and 5, we performed a quick dew point analysis (winter conditions) to check for potential condensation at the brick tie connections to the steel studs and at the shelf angle connection to the floor slab. Using galvanized brick ties creates a surface temperature of 50°F (Fig. 6) on the inside surface of the sheathing. The internal air dew point was calculated to be 41°F. Stainless steel ties reduced condensation risk, increasing the surface temperature to 59°F.

Wall Assembly C: Exterior Insulation and Finish System

What cost-effective options do designers have when the owner wants a brick veneer and is in Climate Zone 5, 6, or 7? One solution is an exterior insulation and finish system (EIFS) with a brick veneer specialty finish.

The benefits of using EIFS are many when compared to the traditional brick veneer wall. EIFS are lighter weight; do not require shelf angles, lintels or brick ties; and are not prone to the same sources of deterioration as full brick or brick veneer reservoir cladding. EIFS also reduces costs and is constructed faster. Most importantly to the intent of this paper, it results in a much more energy-efficient wall assembly for three reasons: (a) there is no derating of the thermal resistance due to thermal bridging by cladding attachments or necessary structural supports; (b) EIFS provides true continuous insulation; and (c) EIFS can provide a continuous AWRB by eliminating cladding attachment and insulation pinning that would normally penetrate the AWRB/sheathing layers. In house testing to the ASTM E2357 standard for air barrier assemblies has shown air leakage rates of $< 0.001 \text{ cfm/ft}^2$ at 75 Pa, which compares favorably to the IECC 2021 air leakage requirement of 0.04 cfm/ft^2 at 75 Pa.

Our modeled EIFS wall assembly (**Fig. 7**) consists of an acrylic textured finish applied over a mesh-reinforced base coat lamina applied over 4 in. EPS continuous insulation ($R-15.4$) adhesively applied with a vertical notched trowel supporting a drainage plane, a fluid-applied AWRB, exterior gypsum sheathing, steel studs, cavity insulation ($R-13$), and interior gypsum board. The thermal modeling results return an effective R -value of 24.0 (U -factor of 0.041), which complies with the requirements for R -value and U -factor methods in Climate Zones 4 through 7. EIFS allows designers to meet energy code requirements more effectively and economically. Since the AWRB is vapor permeable and a vapor retarder is used on the interior, this wall system, which is sometimes called a “flow through assembly” it dries internally and externally and implements the drainage plane as a back-up mechanism to common exterior enclosure failures should they

happen without concern for moisture retention or associated degradation.

The continuous insulation used in the construction of this wall type keeps the interior cavity warm in cold climates, preventing the possibility that any air leakage would allow condensation to form on the inside surface of the sheathing. Therefore, a dew point or WUFI analysis was not performed as the performance of this wall assembly has been previously vetted by others.^{8,9}

Wall Assembly D: Brick Veneer Using Insulated Concrete Formwork

Insulated concrete forms (ICFs) are engineered and constructed as single-sourced complete wall assemblies composed of a frontside and backside of molded EPS, held together with embedded/molded polyethylene ties which once stacked together are filled with reinforced concrete in accordance with code and structural design requirements (**Fig. 8**). These types of wall systems may be considered alternatives to traditional steel stud-framed wall assemblies previously examined herein.

The EPS faces of an ICF are typically $2\frac{1}{2}$ to $2\frac{5}{8}$ in. (63.5–66.7 mm) thick with a density of $1.5 \text{ lb (24 kg/m}^3\text{)}$. These faces plus the concrete fill and galvanized steel brick ties (**Fig. 9**) yield an opaque R -value of 23.75 (U -factor of 0.042), thereby complying with all the requirements for an above-grade mass wall in Climate Zones 4 through 7. ICF forms are sized for reinforced concrete thicknesses of 4, 6, 8, 10, or 12 in. (101.6, 152.4, 203.2, 254, or 309.8 mm). The thickness of the reinforced concrete does not substantially affect the wall R -value; however, the heat capacity of the wall, which is dependent on the concrete thickness, is positively influenced. Heat capacity is a measure of how much heat a material can hold per unit mass. For this reason, wall assemblies built with ICF are considered mass walls due to their inherent thermal mass.

Aside from exceptional steady-state thermal resistance, the primary benefit of a mass wall is that it has a mass-enhanced R -value (which may be referred to as an “M” factor). This type of wall stores energy and releases it more slowly than other wall types, minimizing indoor air temperature fluctuations, thereby reducing peak heating and cooling demands/loads. As a result, the wall provides unparalleled energy performance and reduced operational carbon.

With respect to air infiltration, the reinforced concrete fill functions as a continuous air barrier and works together with the EPS insulation faces as an air barrier system. Because an ICF wall assembly is classified as a mass wall, it may not require the application of an additional air barrier

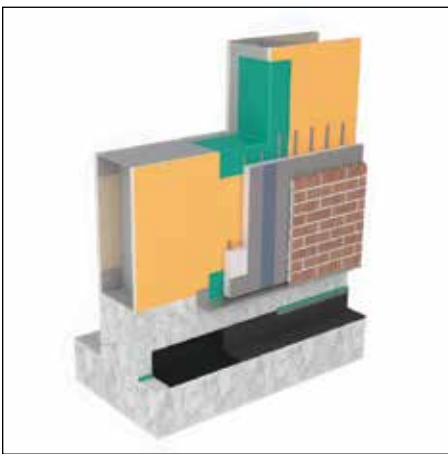


Figure 7. Traditional EIFS wall assembly with steel stud cavity wall.

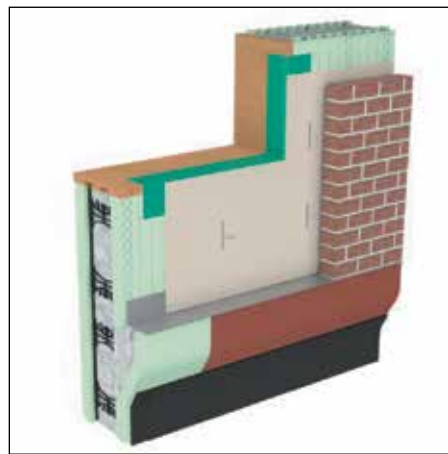


Figure 8. Traditional brick veneer with insulated concrete formwork wall.

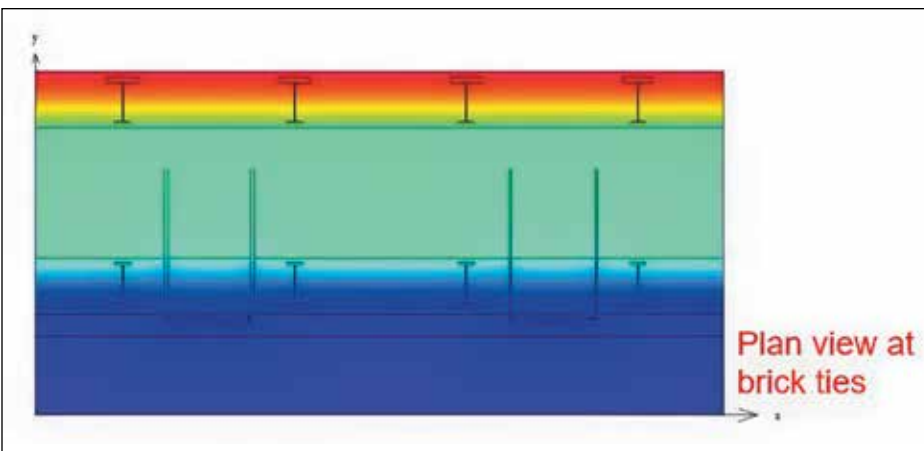


Figure 9. Thermal model showing plan view of ICF wall with brick veneer. Note the steel brick ties do not create thermal bridging which would normally derate the nominal R -value of the exterior insulation.

material; however, that premise does not align completely with accepted assumptions about building code compliance. Additionally, it is the opinion of these authors that the application of a permeable air- and water-resistive barrier would improve overall air and water resistance. At a minimum, the ICF form joints should be detailed with a compatible sealant treatment.

With respect to moisture control, it should be noted that an ICF has horizontal joints where the ICF forms stack and vertical joints where the ICF forms are butted together. These joints are not intended to be moisture or air resistant, but they can be treated in various ways to resist air and moisture. As part of this investigation, in-house air and water leakage testing in accordance with

ASTM¹⁰ standards E283, E2357, and E331 of just the outside insulation face indicated that air leakage rates of the assembly were as low as 0.007 cfm/ft² (0.034 L/S * m²) at 75 Pa *without* an additional air barrier material, concrete fill or inside EPS insulation face.

Our ICF wall assembly consists of the EPS formwork and a 6-in.-thick reinforced concrete core with treated form joints. A galvanized shelf angle (Fig. 10) has been added to support a brick veneer facade, which means the wall looks identical to wall type B. The thermal model reveals an effective *R*-value of 22.2 (*U*-factor of 0.045), which complies with requirements for above-ground mass walls for Climate Zones 4 through 7.

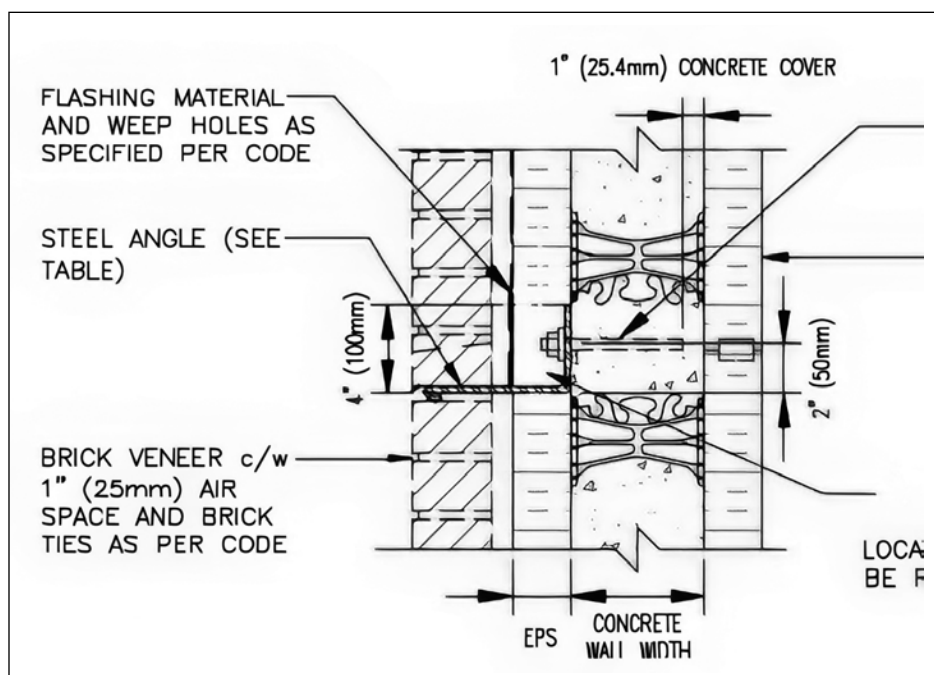
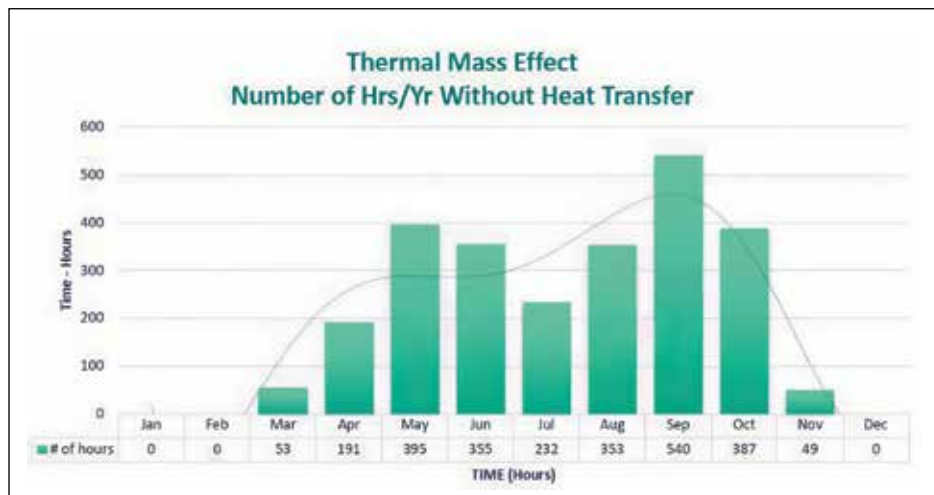


Figure 10. Shelf angle detail using insulated concrete formwork.

TABLE 5. Hours per month with no heating or cooling demand using an ICF wall assembly, Chicago, IL



We also ran a second thermal model where steel girts were fastened through the front face of EPS and into the face flange of the polyethylene ties of the formwork. The fasteners were maintained within the EPS insulation face. This wall looks the same as wall type A. Any type of girt supported cladding can be attached. The thermal model shows zero reduction in thermal resistance due to the metallic cladding attachment. The wall's effective *R*-value remains 23.75.

To further illustrate the benefits of building with thermal mass, we performed an annual energy-savings analysis comparing wall type B (traditional brick veneer with steel stud framing) to wall type D (brick veneer with ICF). The analysis uses the steady-state thermal resistance of both wall types and the energy costs and climate conditions for a particular location, and it factors in the effect of the thermal mass (heat capacity) offered by wall type D. The effective *R*-values include the effects of brick ties only and do not include any derating due to a shelf angle. **Table 5** shows the number of hours in each month during a year that there is no heat transfer through the ICF wall assembly, which means there is no heating or cooling demand to keep the indoor temperature constant. In this example, the wall assemblies are in Chicago, IL. There are over 2,500 hours during the year without heat transfer. It was estimated that this would translate into an annual cost savings of \$1,100 USD per year due to the mass enhanced *R*-value of the ICF wall.

Another benefit of using ICF construction is that it can provide a very high level of airtightness due to the sealing effect of the concrete and the low permeability of the insulating formwork. This combination provides a highly effective air barrier system. As part of the energy savings analysis, we estimated the annual energy cost due to air leakage. A 2007 study found that compared with traditional construction, a building built with ICF had an air leakage rate of 60% less.¹¹ Applying that reduction to our example, an additional annual savings of \$7,800 USD can be estimated (**Table 6**). In total, greenhouse gas emissions (operational carbon) were reduced by the equivalent of nearly 45 metric tons of carbon dioxide.

From a total heating/cooling energy standpoint, buildings with mass walls outperform those with lightweight framed walls designed as necessary to comply with energy code requirements, even though the *U*-factors allowed by energy code (Table 2) for mass walls are greater than those for lightweight walls.¹²

TABLE 6. Estimated annual energy savings associated with reduced air leakage using ICF



INTEGRATION OF STRATEGIES FOR OPTIMAL BUILDING ENCLOSURE PERFORMANCE

Strategies to improve air leakage, thermal resistance, and moisture control should be viewed as interconnected aspects of building enclosure design and construction. A holistic approach is essential to ensure that all components of the building enclosure work together to achieve optimal performance. By implementing the strategies outlined in this paper, building enclosure professionals can enhance the performance of new and existing structures, reduce energy consumption, and contribute to a more sustainable built environment.

The key to success lies in an approach that considers all aspects of the building enclosure and integrates them into a cohesive system. As the demand for energy-efficient and sustainable buildings continues to grow, the importance of the building enclosure will only increase. By staying informed of best practices and emerging technologies, building enclosure professionals can continue to push the boundaries of what is possible in building enclosure design and construction, creating structures that are not only environmentally responsible but also provide lasting value for their occupants. 

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