Building Enclosures
Thermal-Control Fundamentals – Part 2 of 3

AIA CES Course Number: K1812T1

Welcome to this continuing education seminar. This is the second of three parts of the Building Enclosure Fundamentals series.

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Course Description

Control of building enclosure energy loss is critical for avoiding condensation and to achieve high levels of energy efficiency. However, buildings haven't gotten much better in this regard over the years.

In this presentation, the fundamentals of thermal control are presented and applied to modern buildings. Effective methods of addressing thermal bridging, with a focus on continuous exterior insulation, will be discussed through illustrations of common wall assembly details.

Learning Objectives

At the end of this course, participants should be able to:

1. Comprehend the importance of building enclosure thermal control for high-performance buildings.
2. Explain the building science fundamentals of thermal control for enclosures.
3. Express the difference in various insulation material options.
4. Apply building science fundamentals to thermal control for detailing high-performance building enclosures.

Building Enclosures

Thermal-Control Fundamentals – Part 2 of 3

What We'll Cover Today:

- Why thermal control is important
- Fundamentals of thermal control
- Thermal control for high-performance buildings
- Effective insulation details

Why Thermal Control Is Important

Importance of Thermal Control

- Occupant comfort
  - Thermal comfort has major impact on worker productivity
    Fisk, W. J. "Health and productivity gains from better indoor environments and their relationship with building energy efficiency." *Annual Review of Energy and the Environment*. November 2000.
  - Thermal comfort is greatest tenant complaint by far
    "Temperature Wars: Savings vs. Comfort." IFMA. August 2009.
- Risk of condensation on cold surfaces
- HVAC equipment capacity (perimeter heating, heating plants)
- Energy consumption

There are several reasons why thermal control is very important:

- The number-one reason thermal control is so important is because it strongly affects the comfort of the occupants. A study from 2000 has shown that thermal control has a major impact on our work productivity. A study from 2009 has shown that thermal control is the greatest tenant complaint by far.
- Thermal control is the major factor to prevent surface condensation on cold spots within the enclosure.
- Thermal-controlled building enclosures create an optimal environment for HVAC systems to work. Well-insulated buildings function without perimeter heating systems and have smaller HVAC systems. Thermal control saves energy costs due to reduced heating or cooling energy, avoiding claims due to condensation problems and complaints due to thermal comfort.

Our industry is currently fixated on energy performance, but it is only one reason to strive for great building enclosures. It is routinely seen that energy models calculating the energy cost savings for building enclosures measure and miss the more important considerations.

We have been doing a pretty lousy job of occupant comfort. The slew of comfort complaints is only partially explained by the differences in temperature preferences. Most studies on the subject focus on HVAC systems, but that is only partly to blame. Where high-performance building enclosures are used, the demands on HVAC systems are reduced which, in effect, decreases HVAC performance risk because they don't have to work as hard to provide comfort.

Surface condensation in buildings similarly share blame between poor HVAC humidity control and cold surfaces. Cold surfaces are due to excess and often concentrated heat loss. Better thermal performance = higher indoor surface temperatures = less condensation risk.

Many buildings with good enclosures do not have perimeter heating. That is an up-front cost and complexity savings. There is a movement toward all electric heating using ground-source and air-source heat pumps. Reducing heating demand for these buildings results in huge capacity savings for such equipment. Campus buildings on district heating systems all place a capacity demand on the central plant, which limits potential growth or makes it more costly to upgrade the central plant. Better thermal performance reduces those costs. For some reason, projects seem to struggle to include these potentially huge savings when analyzing building enclosure upgrades.

Heating is the major energy consumption for many buildings. For many building types, heat loss through the enclosure is the bulk of the heat loss. (The types for which it isn’t are the buildings with a lot of ventilation like hospitals and buildings with more internal heat gain than loss—deep floor plans and high internal heat sources).

So a well-insulated building enclosure is very important. Now let’s review how insulation performance of buildings has been evolving.

This old building is a good example of the first attempts at thermal control. The entire building envelope was made of solid stone construction, which was probably not very comfortable but much better than sleeping outside in the winter and cool in the summer. This building only had an R-value of 2 but was so thermally massive that the reaction to thermal changes was smooth. This enclosure also had excellent moisture-control properties like huge moisture-storage potential and rainwater shedding characteristics.

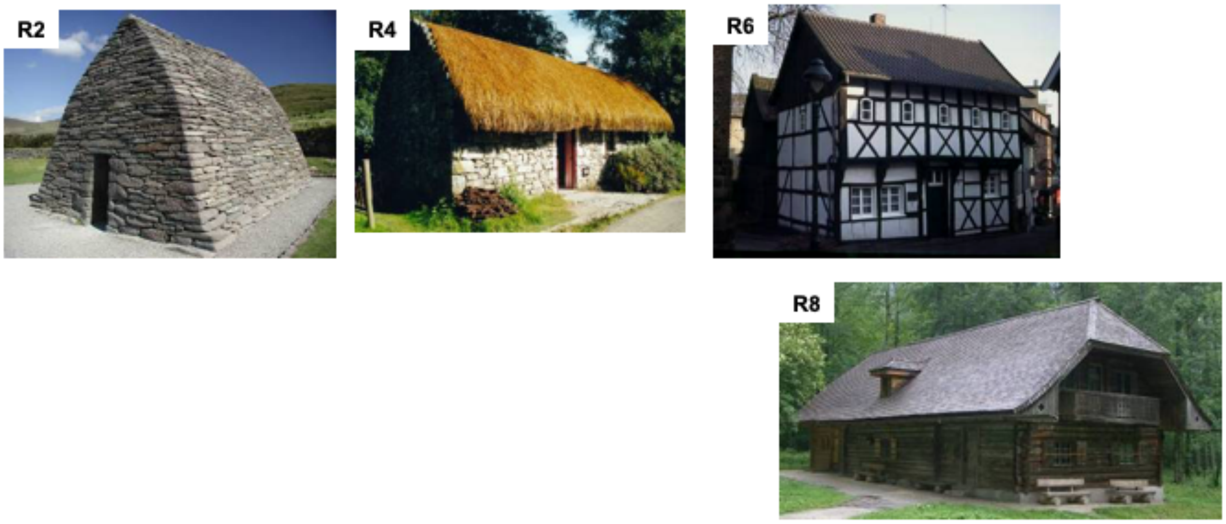
Over time, buildings improved their R-value with the use of mortar for tighter stone walls and features like wood doors and windows and better roofs with overhangs, which kept rainwater off the building.

Thatch roofs, stone walls with mortar, wood doors, and windows = about R-4.

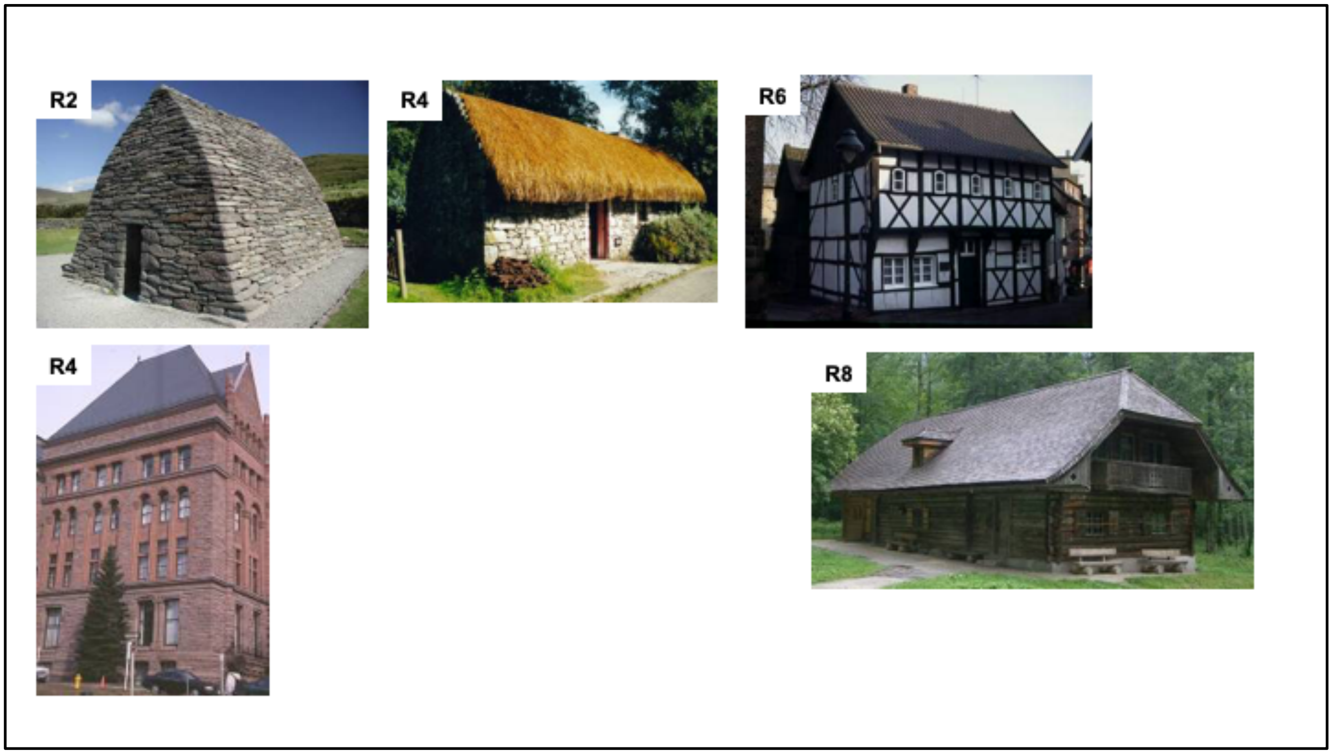
Moisture management in second photo:

- Now complete with overhangs that keeps the water off the building
- Similar stone, but now we have tackled the “roof” heat loss

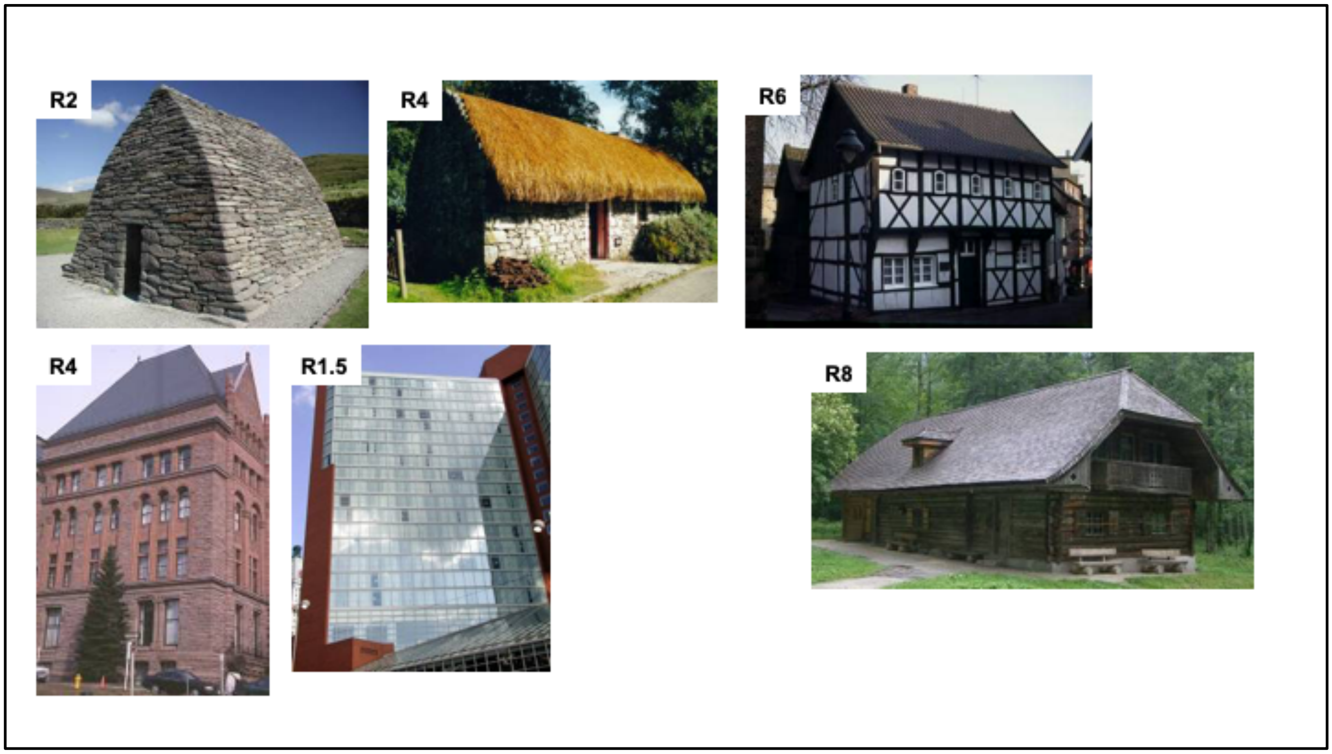
Here in the third photo, in Germany, half-timbered walls were once built out of wooden beams filled with plaster. The whole wall with small, single-pane windows had a pretty good thermal performance of R-6. Sometimes, even the attic was insulated with straw or some other natural material.



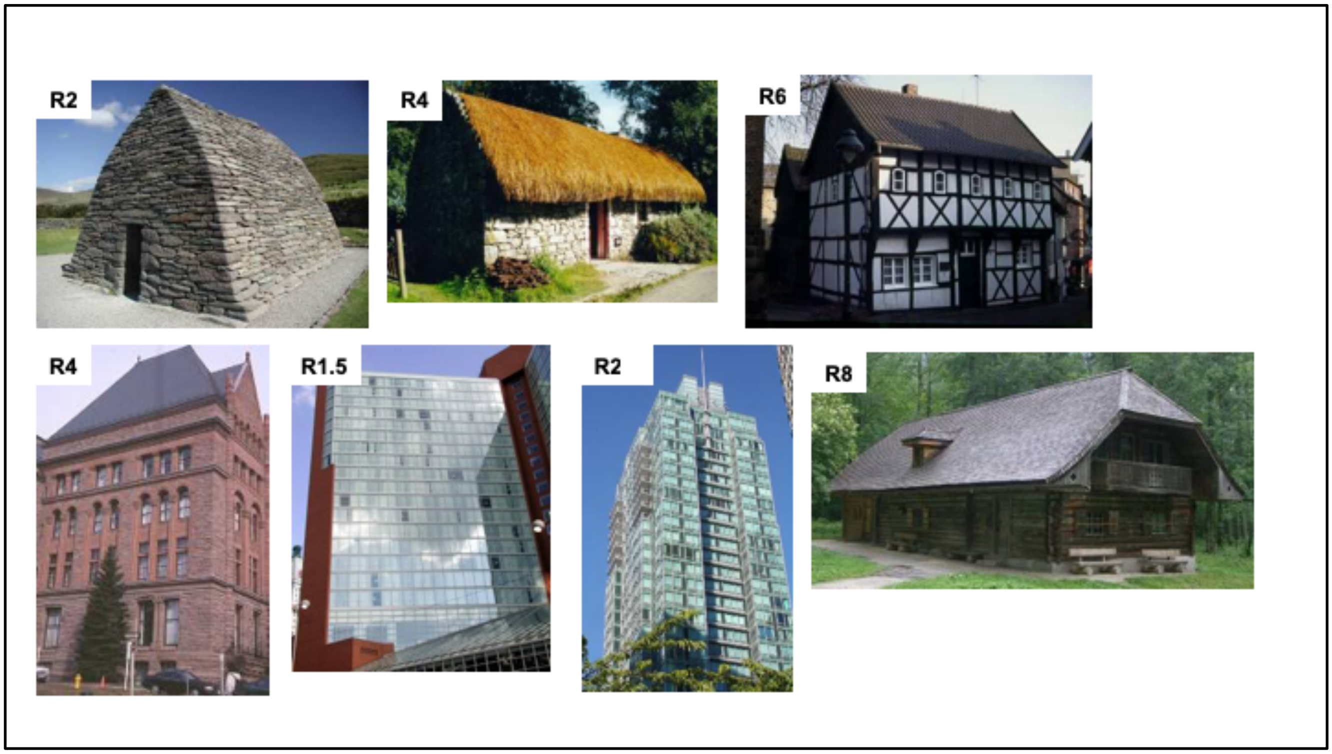
In the fourth photo, in the Alpine regions of Europe, log wall design and cedar shingle roofs had an R-value of around R-8. Despite the fact they still had single-pane, wood-framed windows, they were approaching high performance.



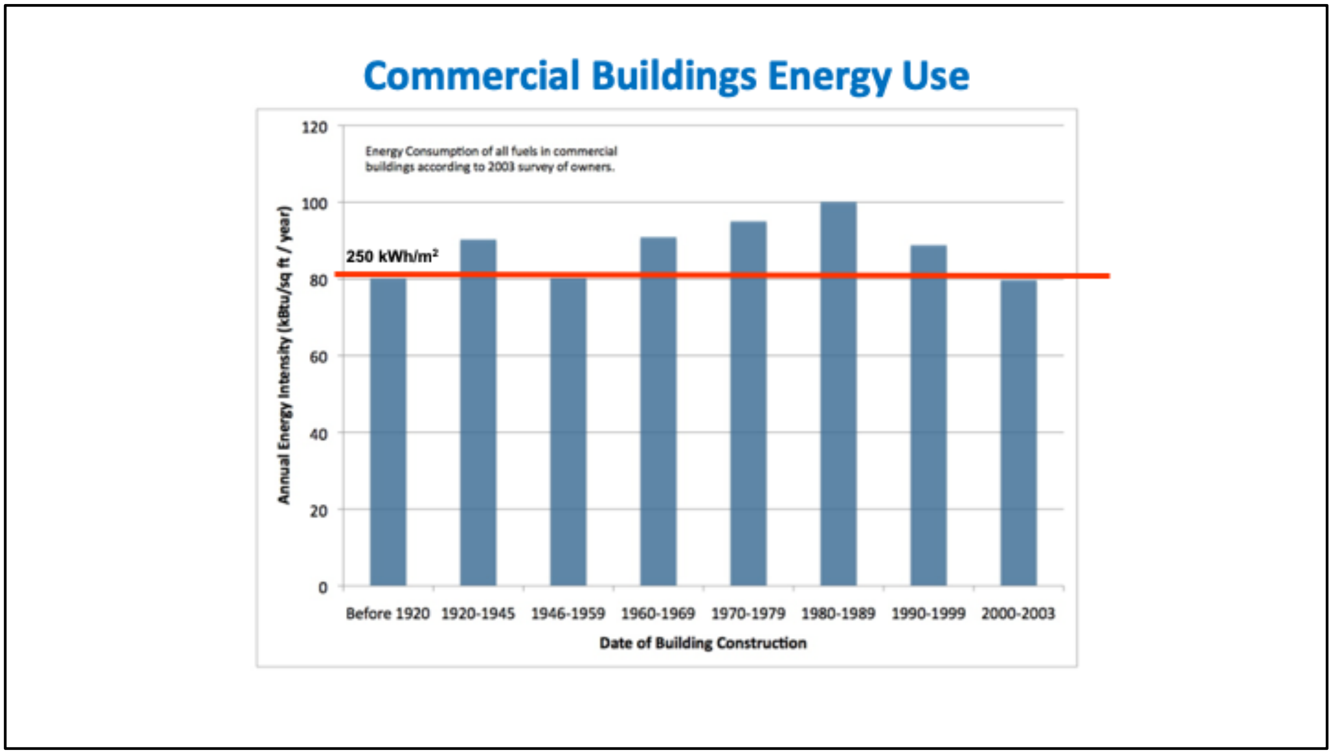
The fifth photo of the old Toronto City Hall shows the new architecture at the time with a higher window-to-wall ratio, which led to a lower R-Value of R-4. Even if the used stone with enclosed air space had a decent thermal performance, the whole wall was worse than the log wall construction.



In the sixth photo, with the beginning of the big glazed apartment buildings in the 1980s, the thermal performance went down to R-1.5. Even the use of double-pane windows could not compensate for the missing insulation.



In the seventh photo, the newer apartment buildings, like the Toronto condominium complex, slightly improved their R-value up to R-2, but compared to all our examples, we are, from a thermal-performance standpoint, back to the stack stone hut. Fully glazed wall assemblies, even with advanced window technology, are not anywhere near as good as opaque walls.



The data shows that the energy consumption of commercial buildings has not improved in nearly 100 years. One reason for the stagnant energy performance is the poor thermal performance of our building enclosures, which has not been improved at all.

Why Such Poor Performance?

Thermal insulation approach is not effective

- Insulation used in ineffective ways
- Too much enclosure glazing
- Too much air leakage
  - As much as 50 percent heat loss

In the next slides, we will discuss why our buildings have such poor performance.

One reason is that our insulation approach is not effective, and we use too much enclosure glazing.

Another major point is air leakage. Fifty percent of heat loss can be caused by air leakage within the enclosure. Because air control is so important, it will be addressed in Part 3 of this presentation series.

* In fact, Thermal Performance hasn't gotten much better through the years

Fundamentals of Thermal Control

Modes of Heat Transfer

- Conduction
  - Requires direct contact
- Convection
  - Air as transport fluid
- Radiation
  - Requires line of sight
  - Around half of human body heat loss is radiation to cool surfaces

Heat Transfer Units

- R-value
  - Conductance term
  - Typically imperial units °F sq ft/(btu/hr)
- R-value per inch
  - Conductivity term—multiply by thickness for R-value
  - °F sq ft/(inch btu/hr)
- U-value
  - Conductance term
  - Includes conductive and radiative surface effects (air films)
  - btu/hr /°F sq ft or in metric units W/°C m^2

There are different units to measure heat transfer:

- The R-value indicates in imperial units such as degree Fahrenheit times square feet per hour, the resistance to conductive heat transfer for the complete thickness of a material or an assembly.
- The R-value per inch indicates the resistance to conductive heat transfer per inch of material.
- The U-value indicates the heat transfer for a whole assembly, including radiative surface effects by considering heat transfer resistance indicators into the calculation.

Material Conductivity

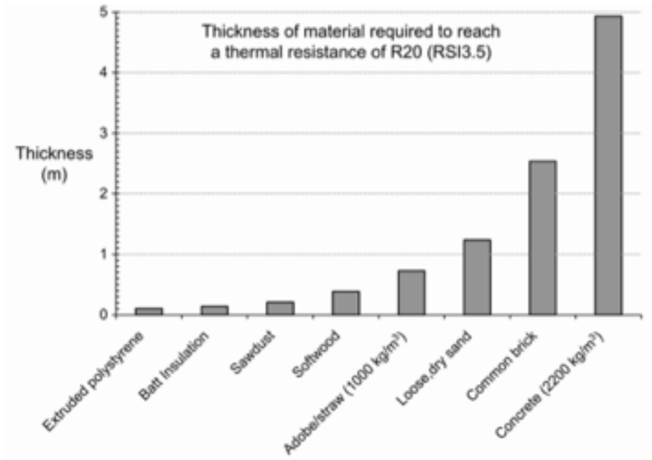


Image : *Building Science for Building Enclosures*

This comparison gives a good impression of how well different materials are conducting heat energy.

This table compares the required thickness of different materials to reach an R-Value of R-20.

Where extruded polystyrene requires just a couple of centimeters, concrete would be 5 meters thick to have the same conductivity.

Insulation Materials

This is an overview of materials that are used as common insulation materials.

From left to right: spray polyurethane foam, cellulose, polyurethane foam board insulation, fiberglass batt insulation, mineral wool insulation, and polystyrene foam board.

Thermal Insulation

Insulation	R-value/inch	U-value (W/m²K)
Empty airspace 0.75”–1.5” (20–40 mm)	2–2.75	0.36–0.5
Empty airspace 3.5” –5.5” (90–140 mm)	2.75	0.5
Batt (mineral fiber)	3.5–3.8	0.034–0.042
Semi-rigid mineral fiber	3.6–4.2	0.034–0.04
Spray fiberglass	3.7–4	0.034–0.038
Expanded polystyrene (EPS)	3.6–4.2	0.034–0.04
Extruded polystyrene (XPS)	5	0.029
Polyisocyanurate	6–6.5	0.022–0.024
Open-cell spray foam (0.5 pcf) ocSPF	3.6	0.040
Closed-cell spray foam (2 pcf) ocSPF	5.8–6.6	0.022–0.025
Aerogel	8–12	0.012–0.018
Vacuum Insulated Panels (VIP)	20–35	0.004–0.008

This comparison table shows the R-value per inch and the U-value of different insulation materials.

Air is a good insulator, but the conductance doesn’t get better with wider spaces because heat energy will circulate more in wider spaces than in smaller ones.

Smaller air spaces as found in insulation materials are better because the air circulates less in them.

A replacement of the air in the cells with gas improves the performance of the insulation materials as we find in polyisocyanurate foam insulation.

The next step to improve insulation materials is to remove the air and gas completely out of the cells. The created vacuum is the best insulation material we have.

Rated R-value

Rated R-value: the theoretical R-value of the insulation, sometimes called the nominal or advertised R-value

e.g., R-13 batt, R-5/inch foamboard, etc.

What is the rated R-Value? This is simply the tested R-value of the material itself. These numbers lend themselves to simple thermal performance calculations where you just add up the R-value of the insulation in your walls.

* Most insulation materials trap small pockets of air or some other gas to resist heat flow.

Often, these insulation materials are installed between structural components like steel studs or wood beams.

Thermal Bridging

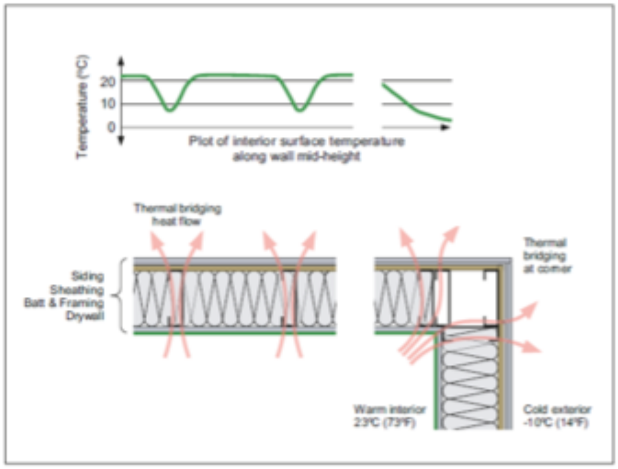
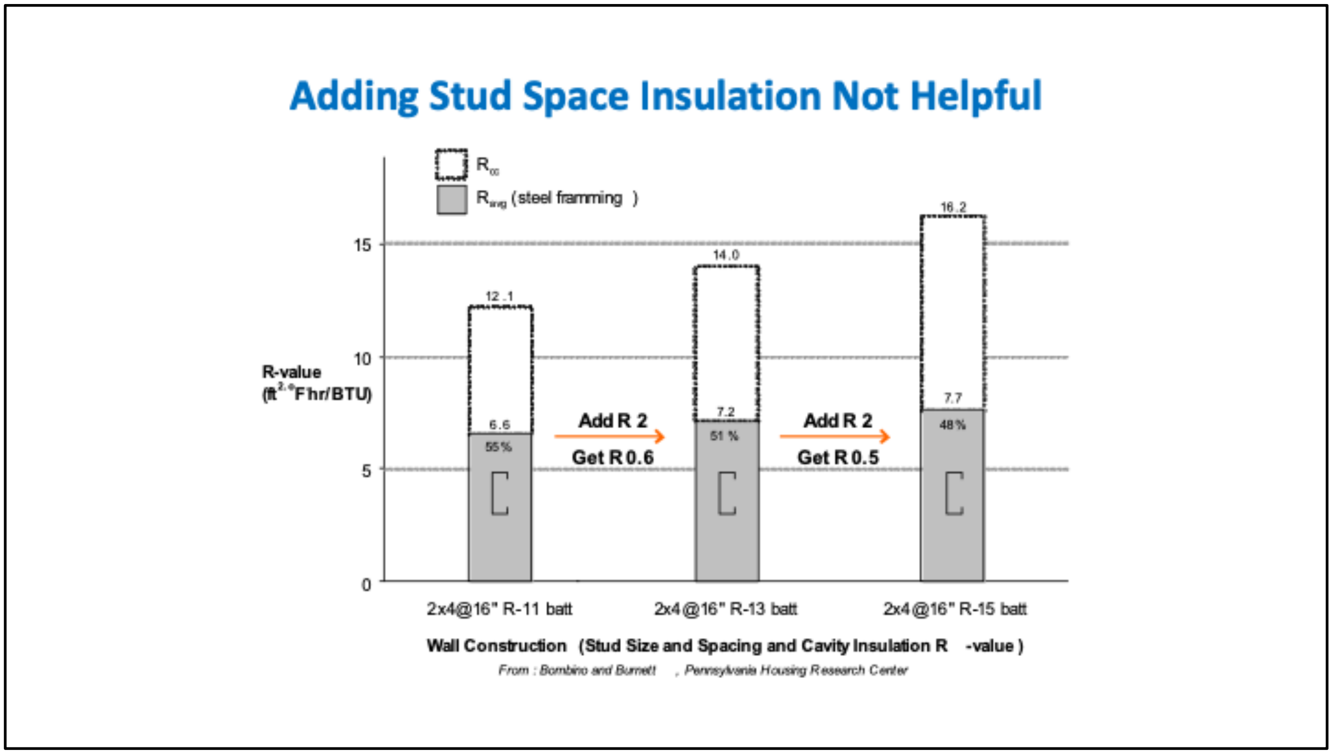


Figure 8: Thermal bridging can cause localized temperature depressions during cold weather, resulting in condensation, mold growth, and staining.
(From John Straube, High Performance Enclosures, Building Science Press.)

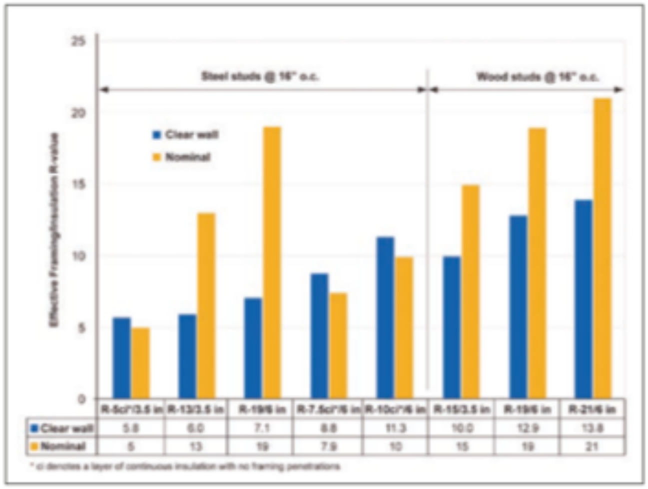
Thermal bridging happens when poorly conductive insulation materials are installed between structural materials like steel studs, which are highly conductive. The localized temperature depressions this causes can, during cold weather, cause condensation, which can lead to mold growth within the assembly.



This graph shows that using more and more insulation without addressing thermal bridging limits improvements in actual performance. This would apply even if a vacuum insulation panel was used. Hint: this is a major challenge with finding good applications for that technology.

The difference between nominal and effective insulation is dramatic when installed between steel studs. Adding nominal insulation of R-4 to an R-6.6 effective wall assembly only results in adding R1.1 effectively.

Thermal Bridging



	R-5ci*/3.5 in	R-13/3.5 in	R-19/6 in	R-7.5ci*/6 in	R-10ci*/6 in	R-15/3.5 in	R-19/6 in	R-21/6 in
Clear wall	5.8	6.0	7.1	8.8	11.3	10.0	12.9	13.8
Nominal	5	13	19	7.9	10	15	19	21

Figure 7: Effective R-value of the framing/insulation layer in wood and steel framed walls (adapted from ASHRAE 90.1- 2007; Table A9 2B)

On this table we can clearly see the major difference when we add exterior insulation to a framed insulated wall. When insulation is installed between structural materials, their effective R-value is much lower than their nominal.

But when continuous exterior insulation is added, the performance of the walls increases drastically.

Are Studs Usually 16 Inches O.C.?

The examples shown on the former table are indicated with a spacing of 16 inches on center. But many times, as shown on this picture, the spacing between the steel studs is much less. That magnifies the effect of thermal bridging dramatically.

Effective R-value

- **Rated R-value:** The <u>theoretical</u> R-value of the insulation, sometimes called the nominal or advertised R-value (e.g., R-13 batt, R-5/inch foamboard, etc.)
- **Effective R-value:** The <u>functional</u> R-value of the insulation as installed in the wall assembly, de-rated if necessary due to <u>thermal bridging</u> at framing members

The difference between the rated R-value and the effective R-value is that the rated R-value is a theoretical R-value of an insulation material, whereas the effective R-value is the functional R-value of the insulation as installed in the wall assembly, taking also the reduction caused by the thermal bridging into account.

* Thermal bridging can overwhelm the ability of insulation materials to stop heat flow in wall assemblies.

Windows

- Our most expensive thermal bridges
- Aluminum is four to five times as conductive as steel
- Difficult to buy commercial aluminum windows/ curtain wall over R-3
- Also allow solar heat in
  - Useful in cold weather
  - Requires cooling in summer

The most critical thermal bridges are windows. This is not only because the window frame is often made of very conductive aluminum. It is also because the glazing allows solar radiation energy into the building. This is quite useful in the winter but often leads to the need for cooling in the summer.

Whole Wall R-Value Concept

Combined Impact of Opaque Wall and Glazing

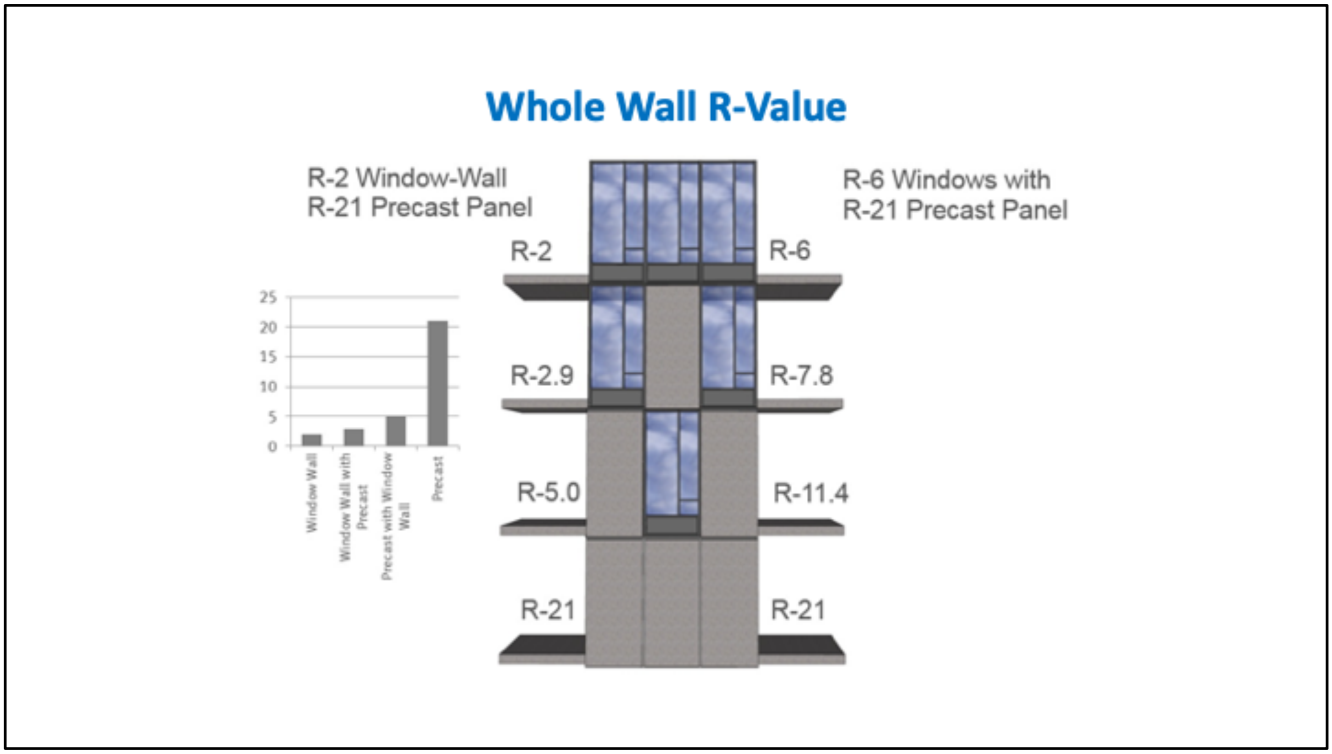
60% R-3 window and 40% R-20 wall

$$R_{\text{whole wall}} = \frac{1}{40\% \cdot 1/R_{\text{wall}} + 60\% \cdot 1/R_{\text{windos}}} = \frac{1}{40\% \cdot 1/R20 + 60\% \cdot 1/R3} = R4.5$$

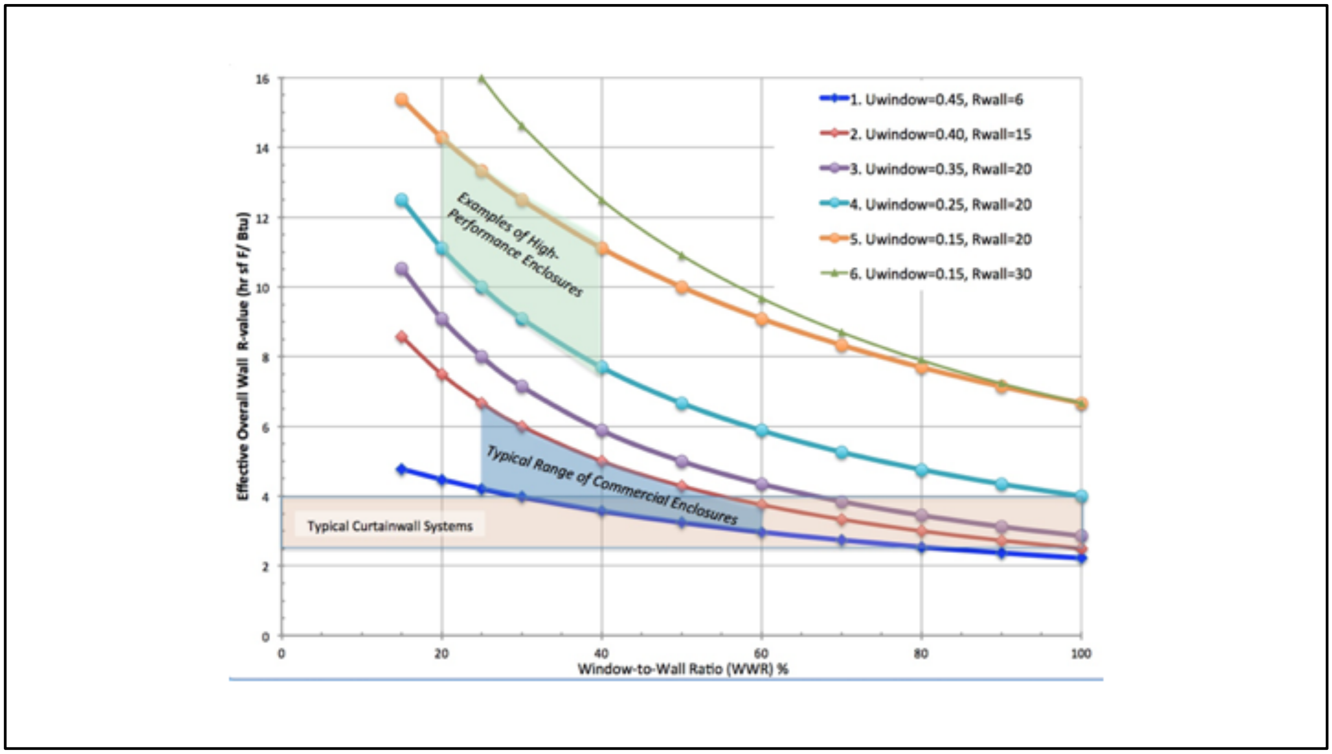
30% R-3 window and 70% R-20 wall

$$R_{\text{whole wall}} = \frac{1}{70\% \cdot 1/R_{\text{wall}} + 30\% \cdot 1/R_{\text{windos}}} = \frac{1}{70\% \cdot 1/R20 + 30\% \cdot 1/R3} = R7.4$$

These calculations show that the effective R-value of a whole wall assembly changes drastically, depending on the opaque wall-to-window ratio. Even with good thermally performing windows, the thermal performance of the whole wall system is almost double when the windows are halved.



The performance of wall systems with significant window-to-wall ratios is largely dependent on window performance. Even the use of R-6 windows still demands reasonable window-to-wall ratios to achieve overall high performance (using R-10 as a high-performance threshold).



This graph shows the range of the typical wall system and typical window-to-wall ratios with the typical U-value windows compared to the same requirements needed to achieve a high-performance wall. Two main variables that affect performance: U-value of the window or size of the window. Note that curtain wall is stable (and low) due to poor spandrel performance.

Thermal Resistance Terminology

- **Rated R-value:** The theoretical R-value of the insulation, sometimes called the nominal or advertised R-value (e.g., R-13 batt, R-5/inch foamboard, etc.)
- **Effective R-value:** The functional R-value of the insulation as installed in the wall assembly, de-rated if necessary due to thermal bridging at framing members
- **Whole-wall R-value:** The equivalent R-value of the walls and windows combined

The rated R-value is the theoretical R-value of the insulation.

The effective R-value is the functional R-value of the insulation in the wall assembly.

The whole-wall R-value is the equivalent R-value of the walls and windows combined (the effective R-value combined with the R-value of windows).

* Windows can overwhelm the performance of a wall system when a high window-to-wall ratio is used.

Thermal Control for High-Performance Buildings

Thermal Control: Exterior Insulation

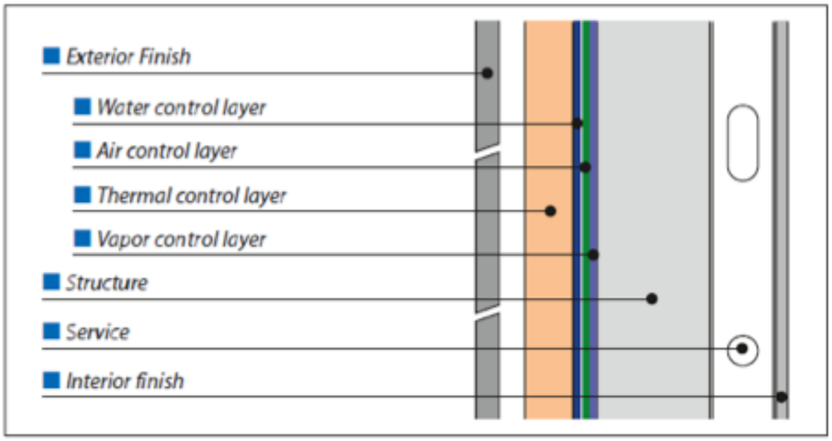
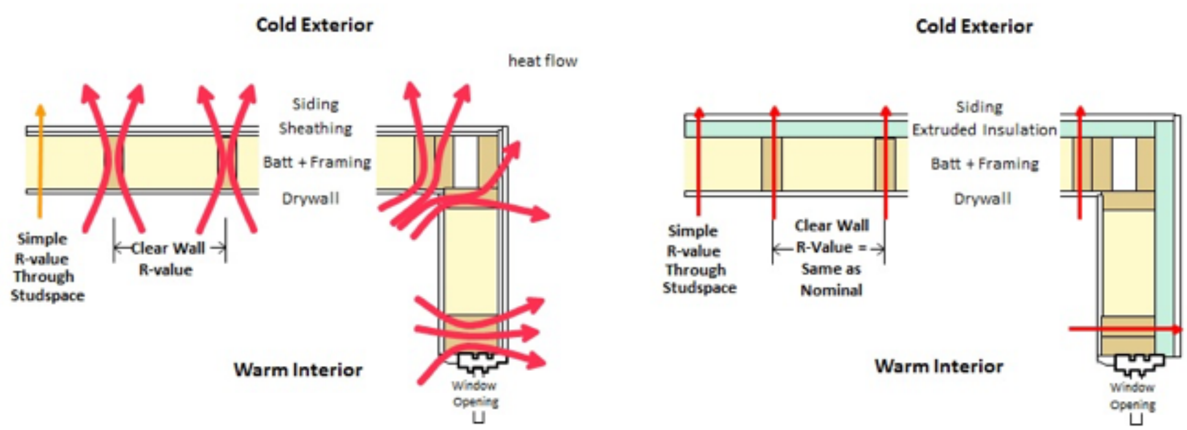


Figure 1: Diagram of the "Perfect" Wall showing ideal sequence of assembly layers
(From John Straube, High Performance Enclosures, Building Science Press)

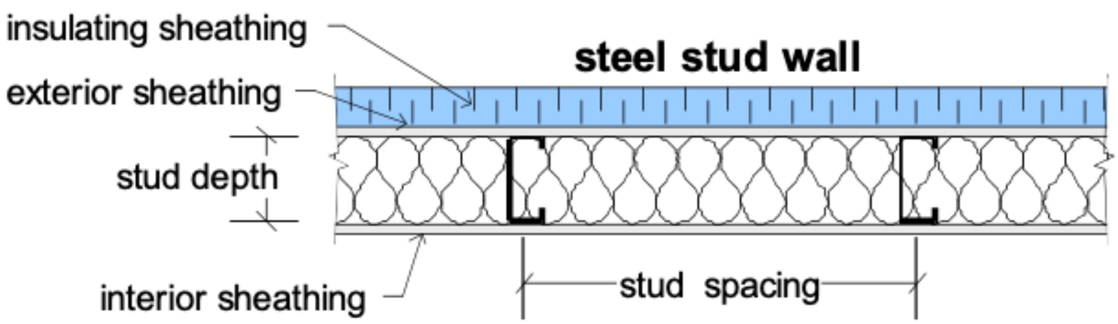
The perfect wall is a theoretical concept that separates the structure from the control layers. By locating the control layer outside of the structure, thermal bridging, condensation, and potentially poor installation are drastically reduced.

Continuous Exterior Insulation

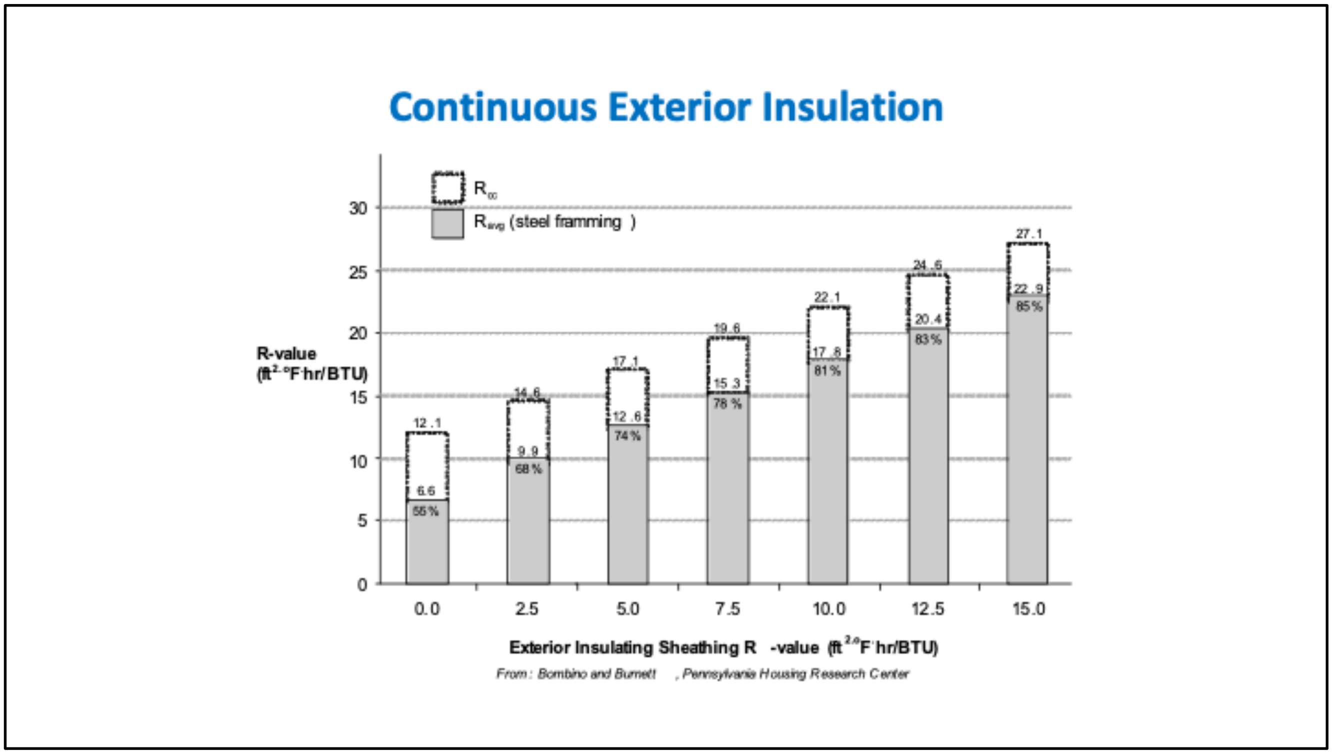


With continuous exterior insulation, thermally weaker spots, like steel studs and corners, are covered by insulation, and the thermal performance of the whole wall improves significantly.

Continuous Exterior Insulation



Shown is an in-plane view of a steel stud wall with continuous insulation to reduce thermal bridging.



This chart shows the net-effective R-value gained in a steel-stud wall with insulation between the studs when varying thicknesses of continuous insulation are added. The earlier slide similar to this one showed that the addition of R-value between the studs without continuous insulation led to very little net gain in effective R-value. In contrast, this chart shows that the addition of R-value as continuous insulation leads to significant improvement in the effective R-value of the wall system.

Commercial Buildings: Often Exterior Thermal Control Is Only Solution

Exterior thermal control is often the only solution to achieve a satisfactory result. The installation of an exterior insulation layer is often the only way to guarantee the required performance and avoid unsolvable details.

Thermal Continuity/Thermal Bridges

- Some short circuiting is normally tolerated
- High-performance walls tolerate few bridges
- Major offenders/weak spots
  - Penetrating slabs (<R1)
  - Steel studs (<<R1)
  - Windows (R2-R3)
- Small details are important

It is not always possible to avoid thermal bridges, but we should strive to reduce them as much as possible—whether it's by selecting a different material, steel studs instead of galvanized studs (because the steel is much less conductive), or reducing other thermal bridging components as much as possible, such as the usage of facade clips instead of linear fasteners.

High-performance walls tolerate some bridges.

The major weak spots are penetrating slabs, steel studs, and windows. Rigorous standards aim for thermal-bridge-free design. It is a focus in Passive House, for instance.

* Continuous exterior insulation is necessary in modern enclosures to achieve high thermal performance.

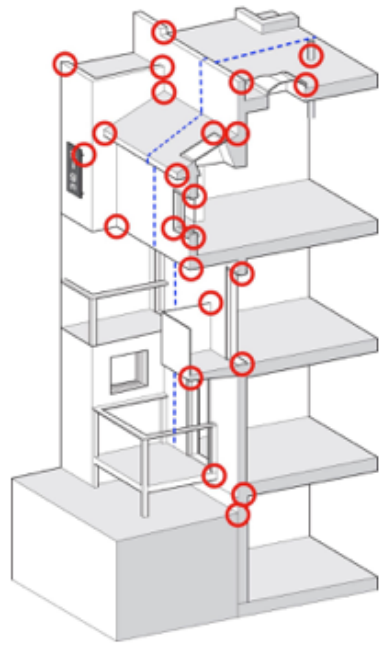
Effective Insulation Details

Enclosure Details

Details demand the same approach as the typical enclosure assemblies:

- Support
- Control
- Finish

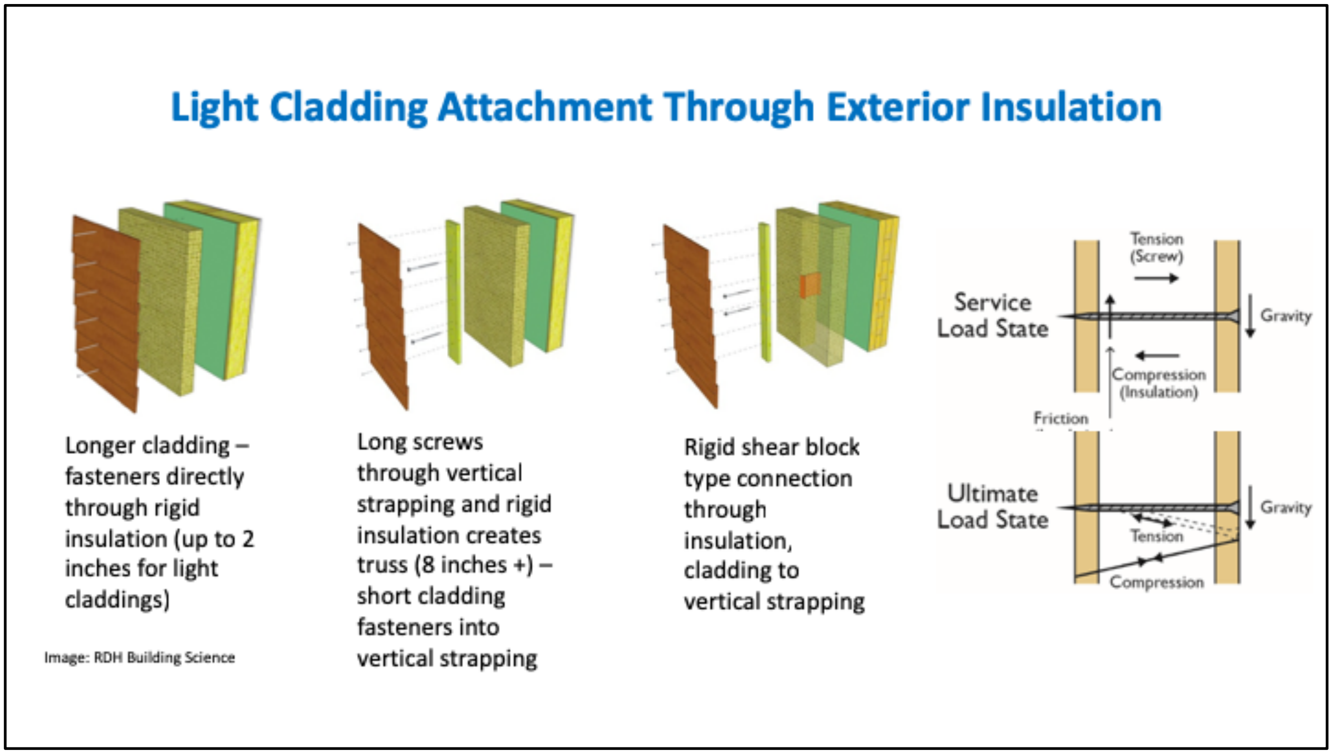
Scaled drawings required at



To avoid thermal bridges, it is critical to address them and detail them.

If details are not addressed properly, the decision on how to detail the different control layers is left to the installer on the job site.

So, make sure, like in this example, every detail circled in red is known, addressed, drawn, and discussed with the installers.



There are several options to attach light cladding in an exterior insulation wall assembly.

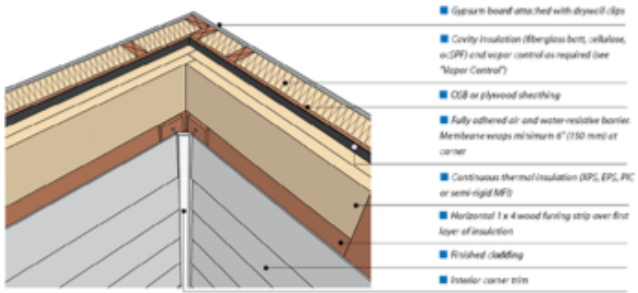
Long screws directly into the structure can be used for up to 2 inches of exterior insulation.

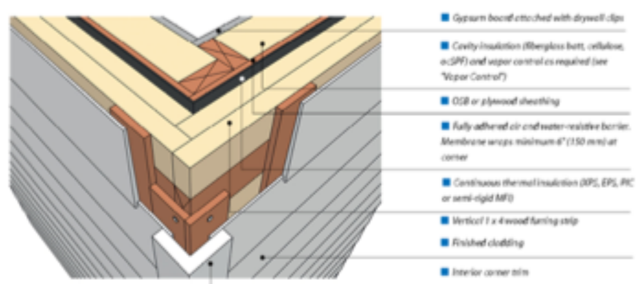
For more than 2 inches of exterior insulation, the use of strapping attachment is required.

Usually, the vertical strapping will be fastened with long screws into the structure, and the cladding will be attached to them with short screw fasteners.

This example shows the use of exterior insulation and vertical strappings for the cladding attachment.

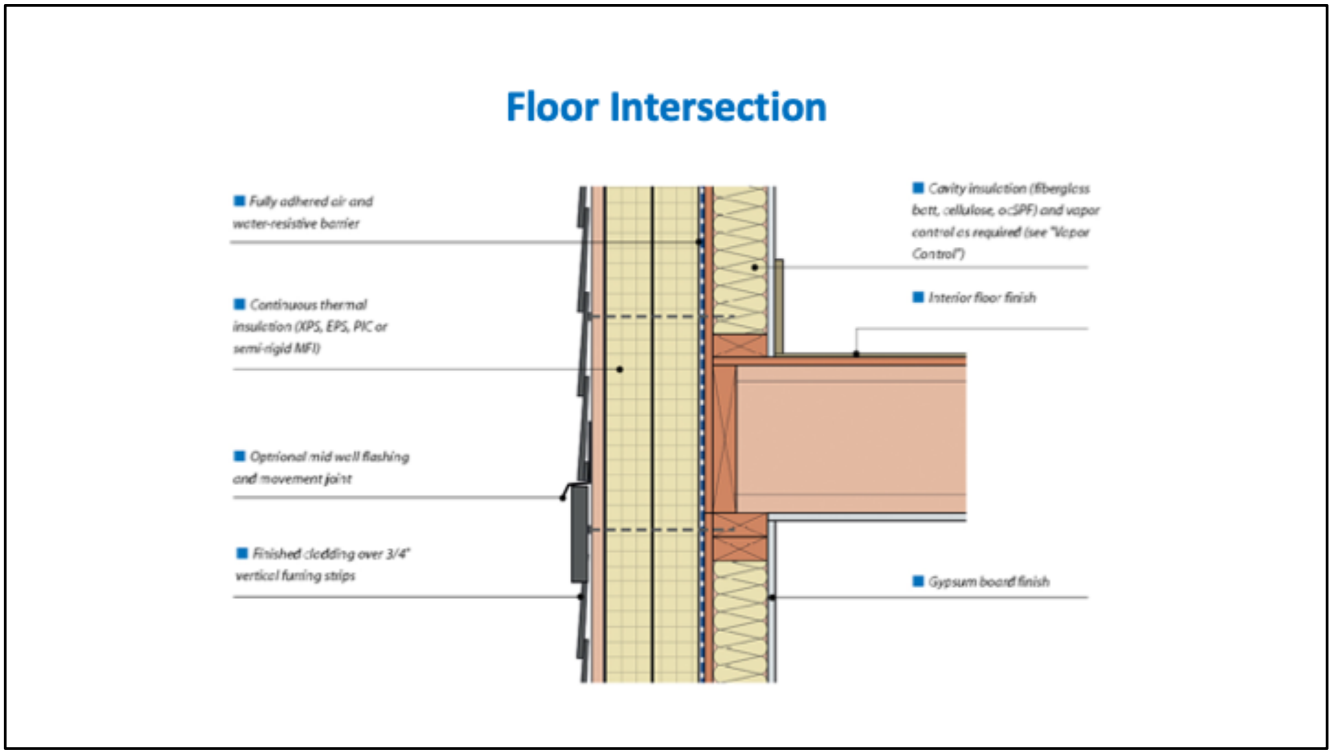
Wall Corners





Wall corners are critical points when it comes to thermal control and performance.

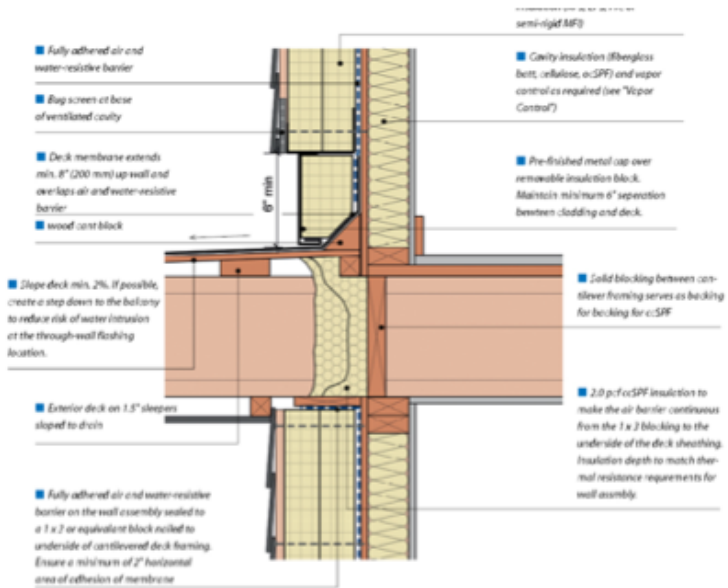
To lower the impact of joining panels, it is recommended to install the panels offset so that they overlap each other and one continuous gap will be avoided.



This is an excellent example of how exterior insulation compensates structural thermal bridges.

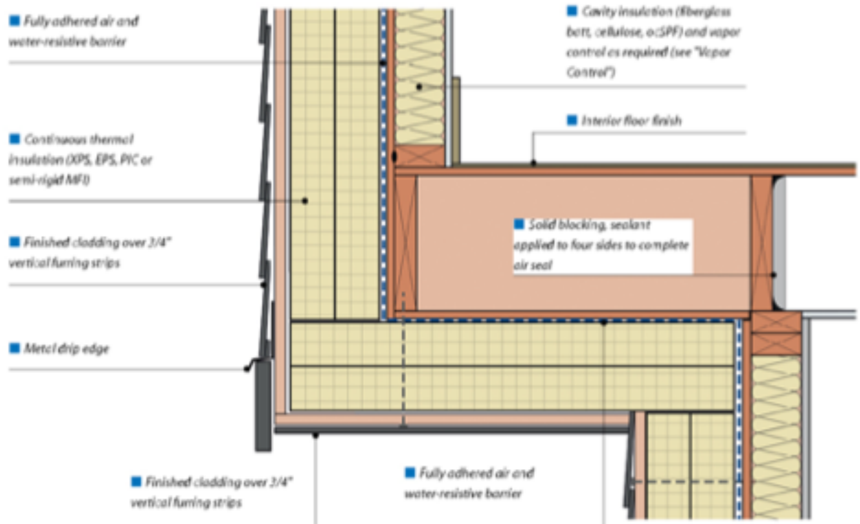
Without exterior insulation, the floor-wall connection would be hard to thermally detail and control.

Cantilever Balcony



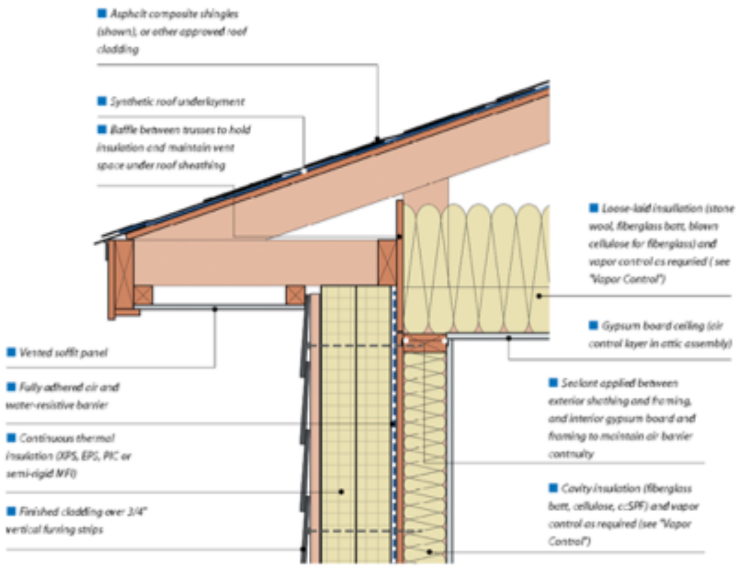
This cantilever balcony detail shows how to avoid thermal bridging. It is important to address the cantilever connection point between the structural walls.

Soffit under Cantilever Floor

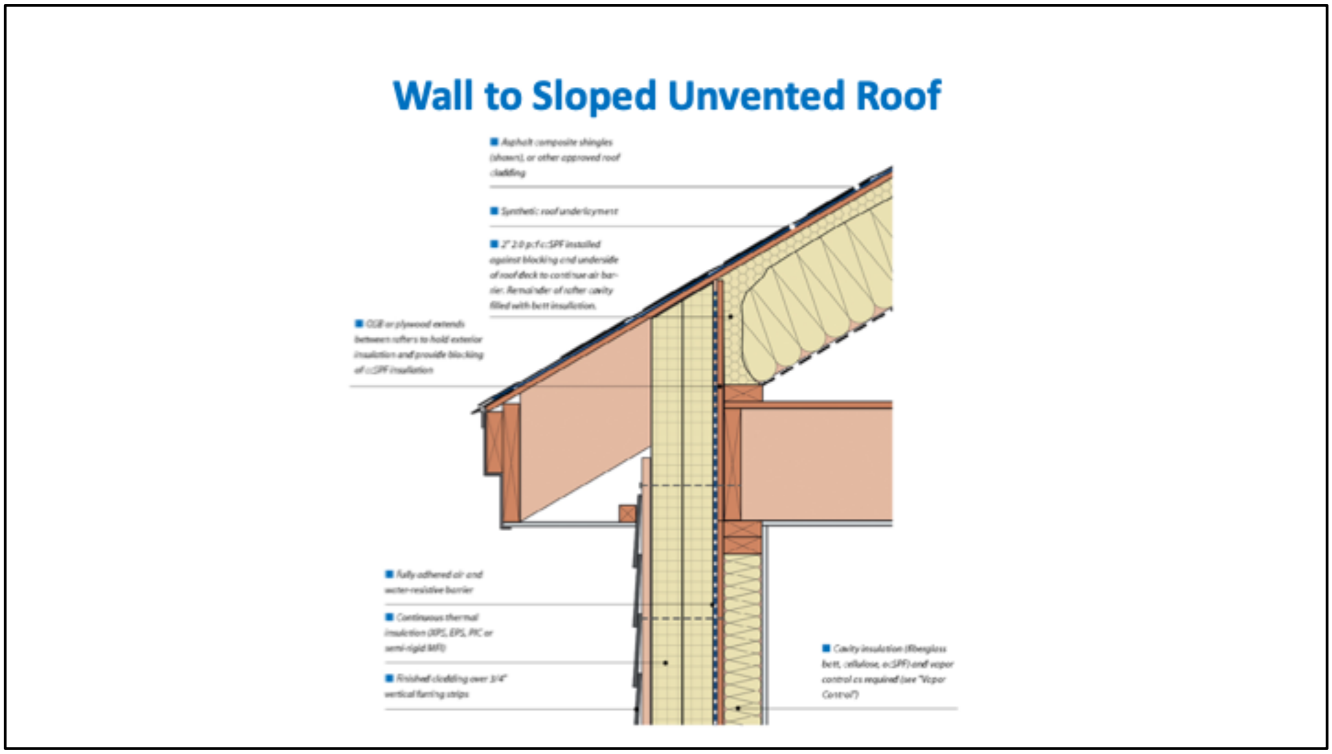


To be continuous, even soffits under cantilever floors should be addressed and detailed.

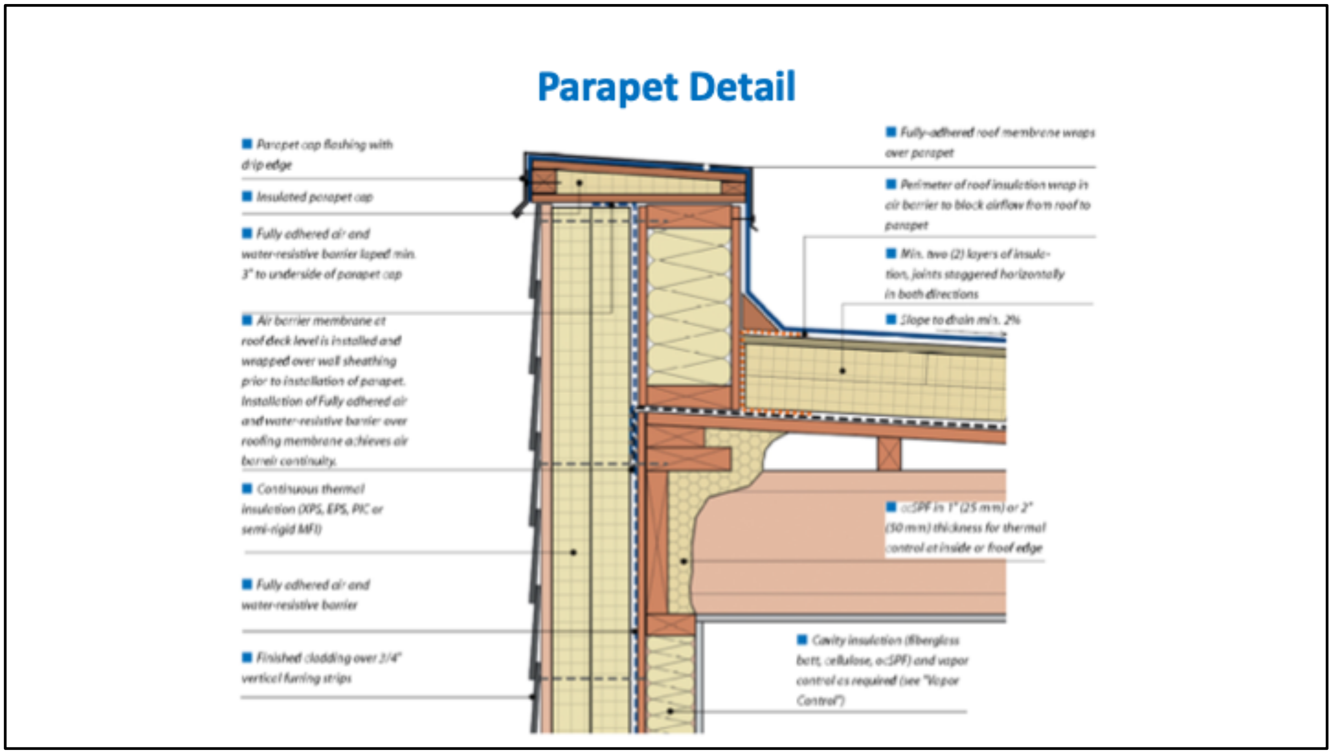
Wall to Sloped Vented Roof



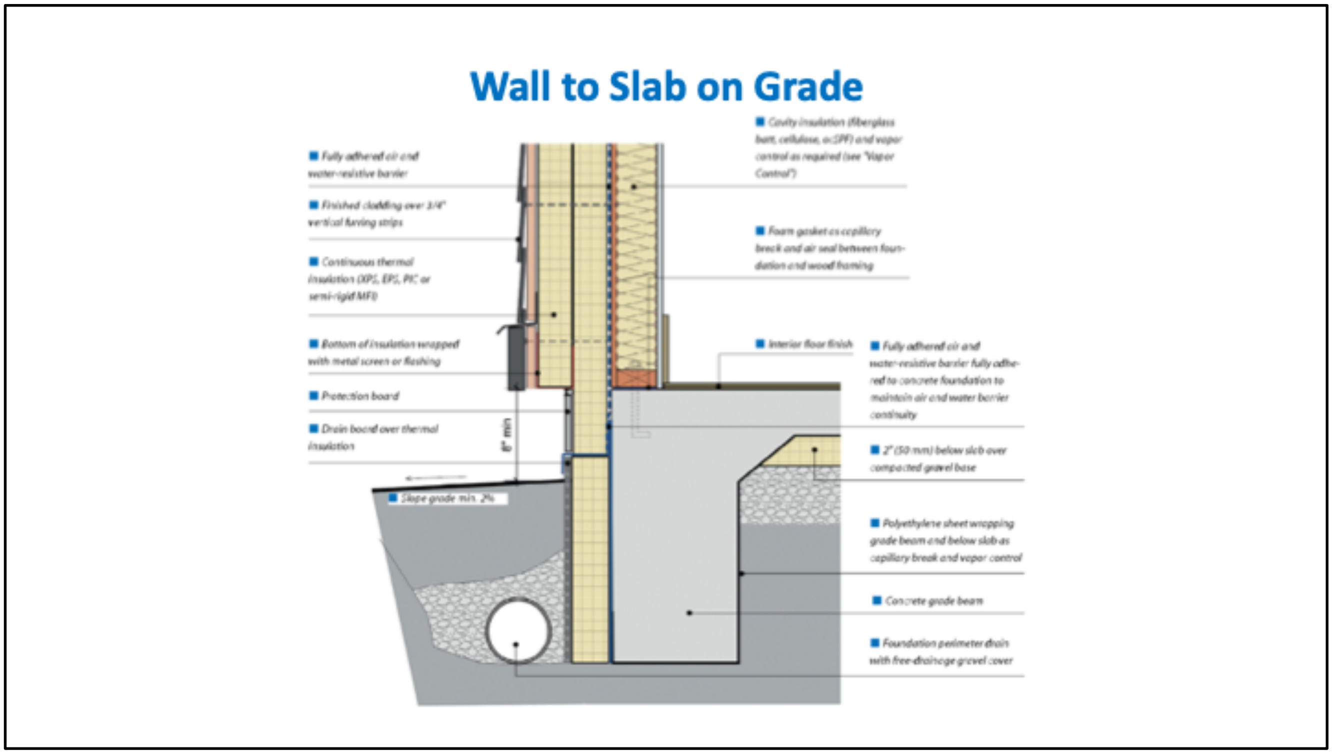
It is critical to close the connection gap between an insulated envelope and a ventilated roof. It is important to connect the attic floor insulation without interruptions to the wall insulation. Otherwise, this point could cause a lot of moisture-related problems within the structure.



As this example shows, with continuous exterior wall insulation, it is much easier to close the connection between an insulated roof and the wall assembly.

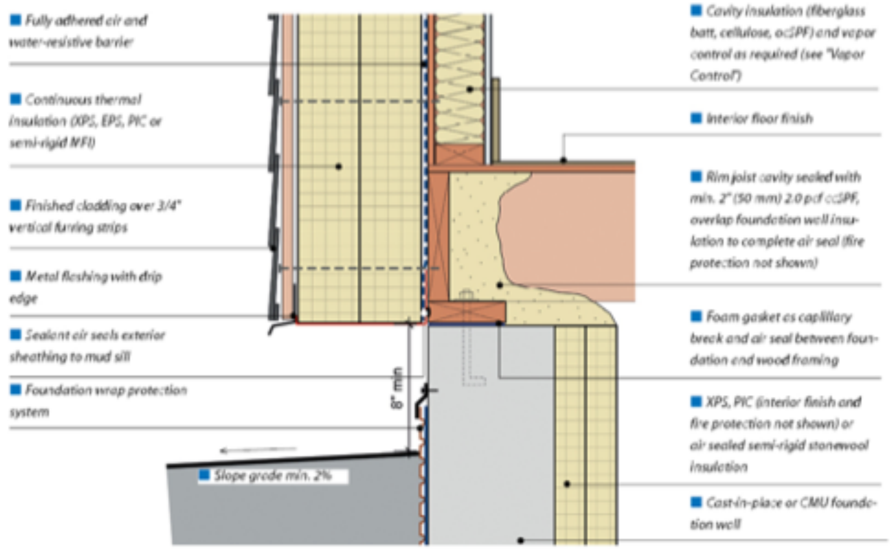


If not addressed, a parapet can be a huge thermal bridge that would suck the heat out of the building like a chimney.



To avoid cold floor spots and corners, it is critical to carry the insulation over the heat-conducting concrete surface into the below-grade section.

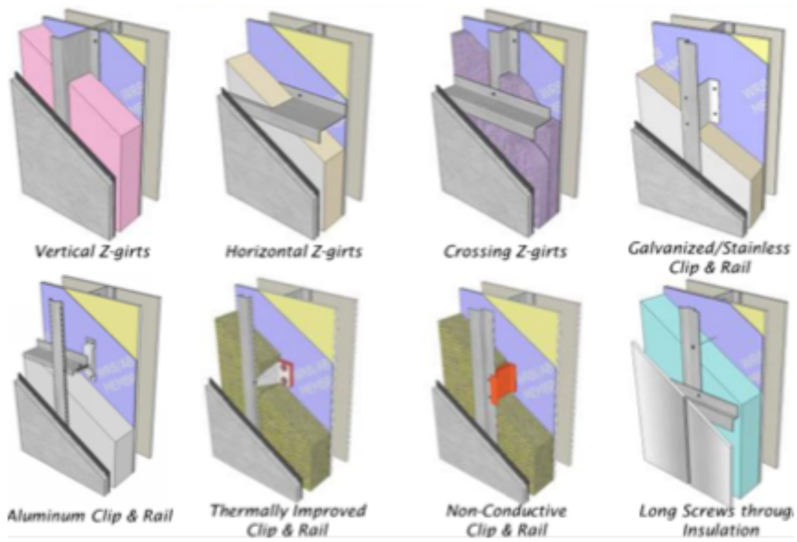
Wall to Foundation



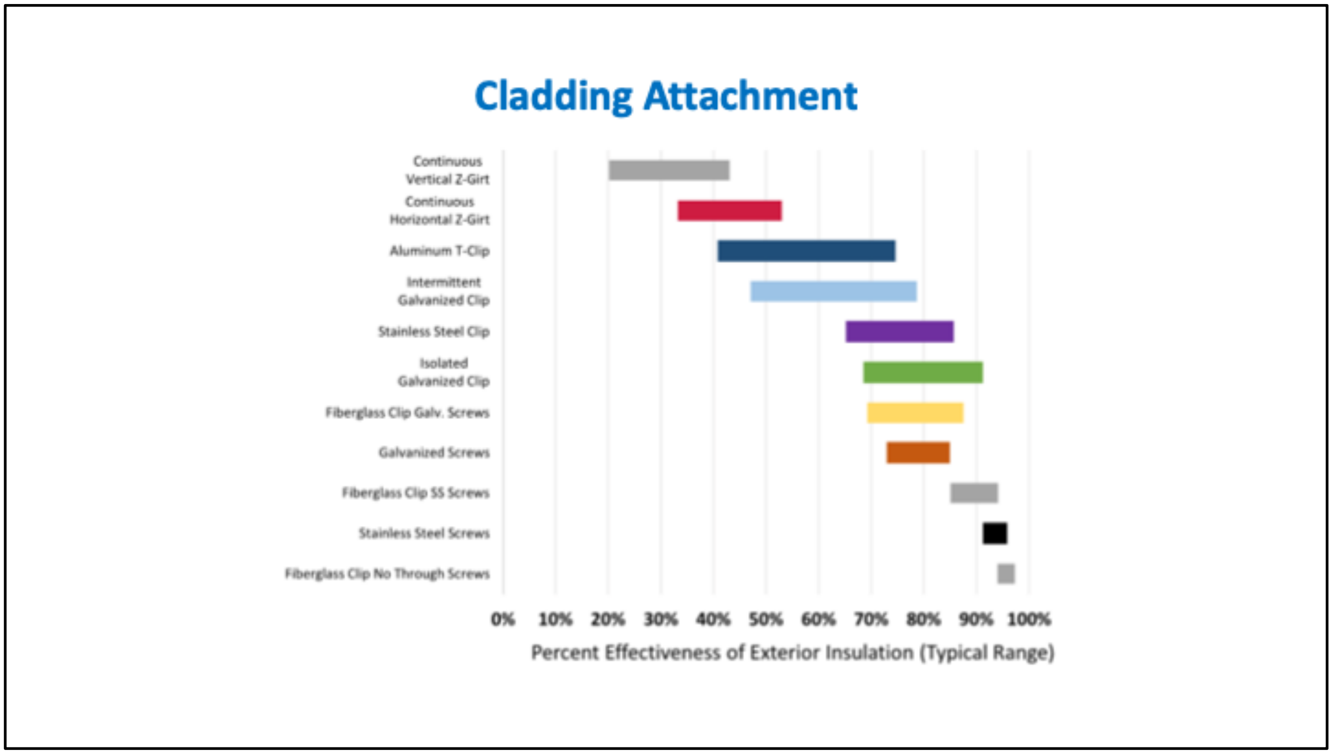
The rim joist cavity is a critical detail for all control layers. The thermal-control layer should be continuous as well as the vapor-, air-, and rain-control layers.

Steel and Concrete Building Details

Cladding Attachment



There are a lot of options for attaching claddings outside of continuous insulation, from Z-girts to rail systems and a nonconductive clip-rail combination to long screws attached through the insulation.

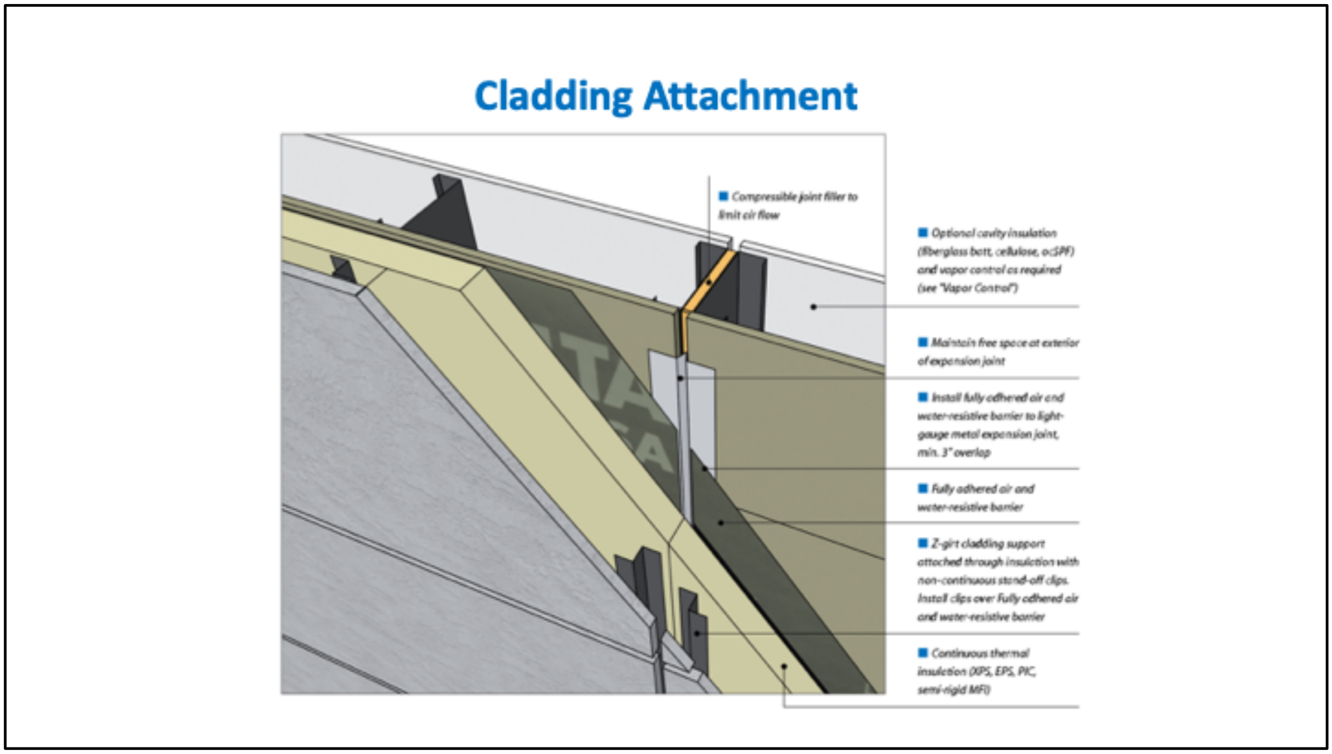


Cladding attachments have a huge impact on the thermal performance of the exterior insulation. The performance of the different systems varies based on the used material and the structure of the attachments.

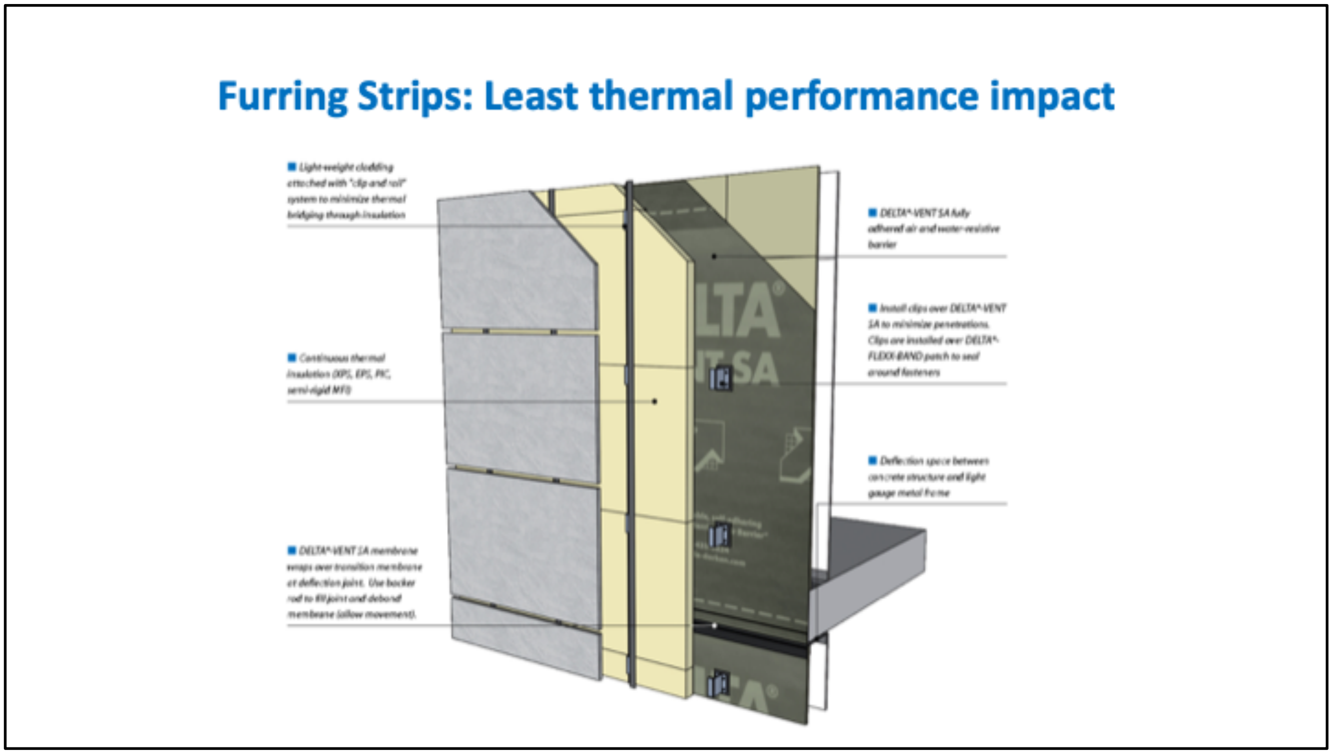
Continuous attachment systems like vertical or horizontal Z-girts reduce the thermal performance the most.

Clip-rail combinations have a much better performance but vary drastically depending on the material from which they are made. Aluminum clips are much more conductive than fiberglass clips.

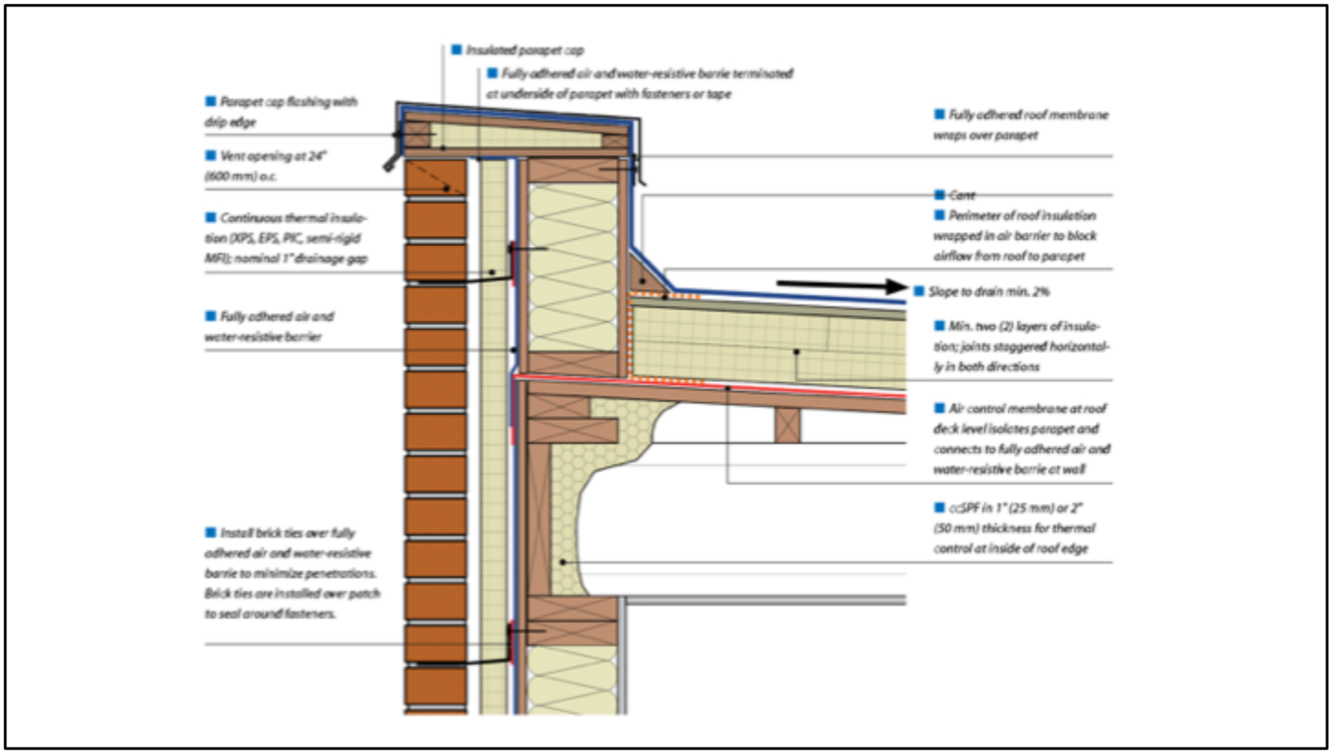
The best performance can be achieved by using a system with the smallest possible transmission surface made from less-conductive material; for example, fiberglass clips with stainless steel screws.



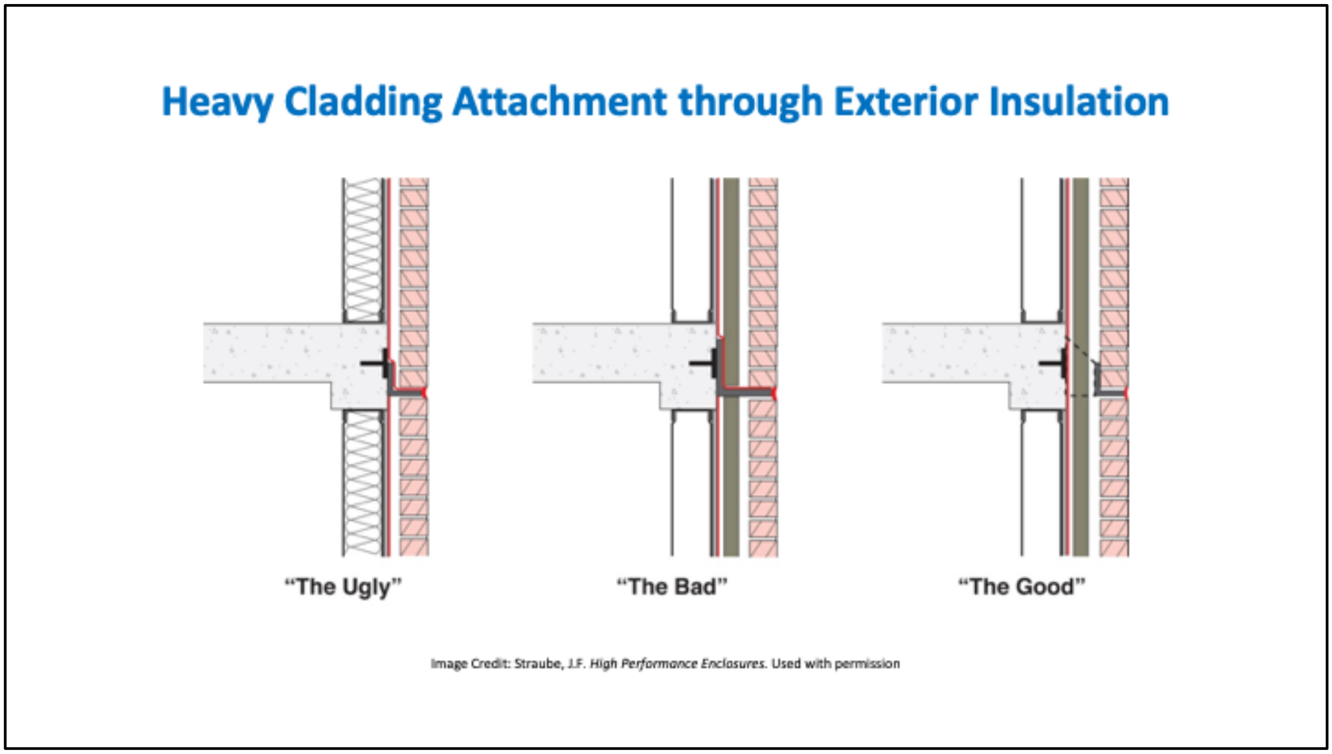
A good example for an effective cladding attachment is a Z-girt attachment installed over the exterior insulation layer attached to noncontinuous stand-off clips that are attached to the framing structure.



A clip-rail system with furring strips is the most effective attachment system to attach cladding to an exterior insulation wall system. The only thermal bridges are the minimally conductive fiberglass clips.



This ventilated brick tie wall with continuous insulation and air-, water-, and rain-control layer outboard of the structural wall is a good example of the perfect wall system. Every detail is addressed, and thermal bridges are reduced to a minimum.

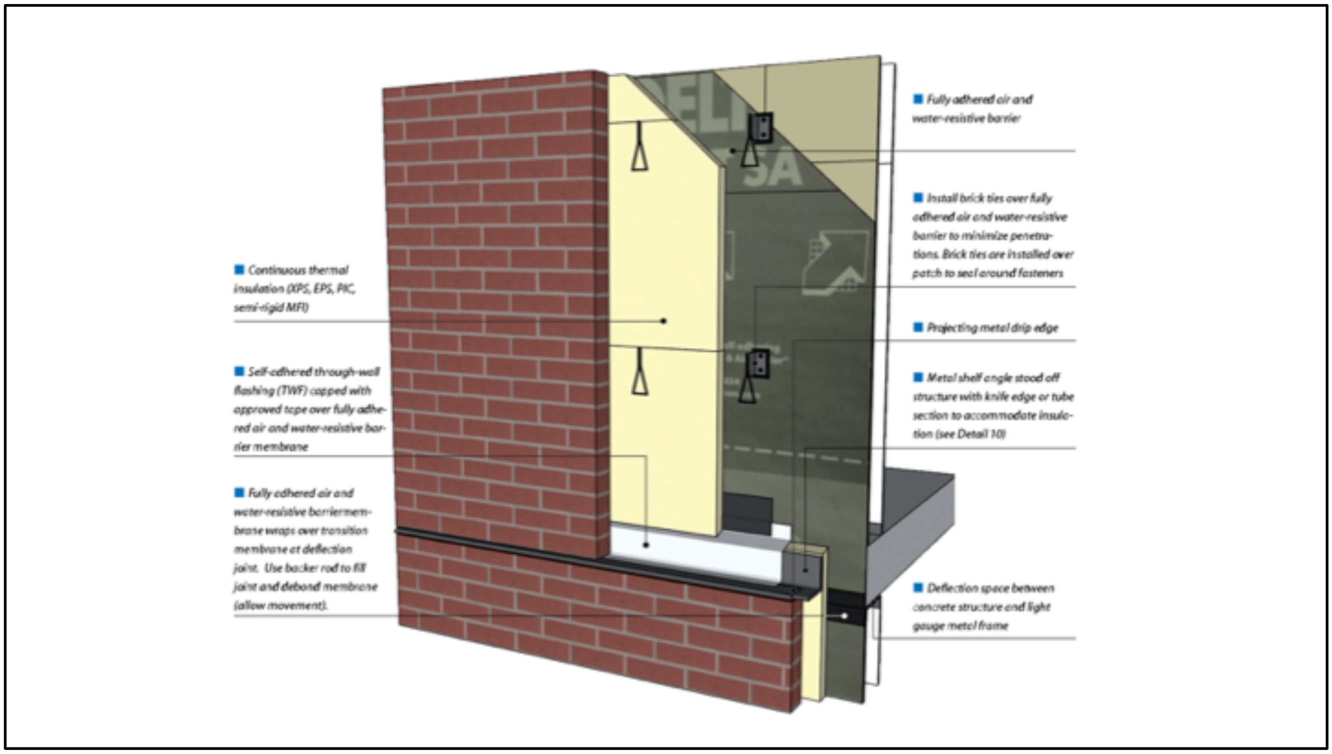


Shelf angles are necessary attachments for heavy wall claddings like brick walls.

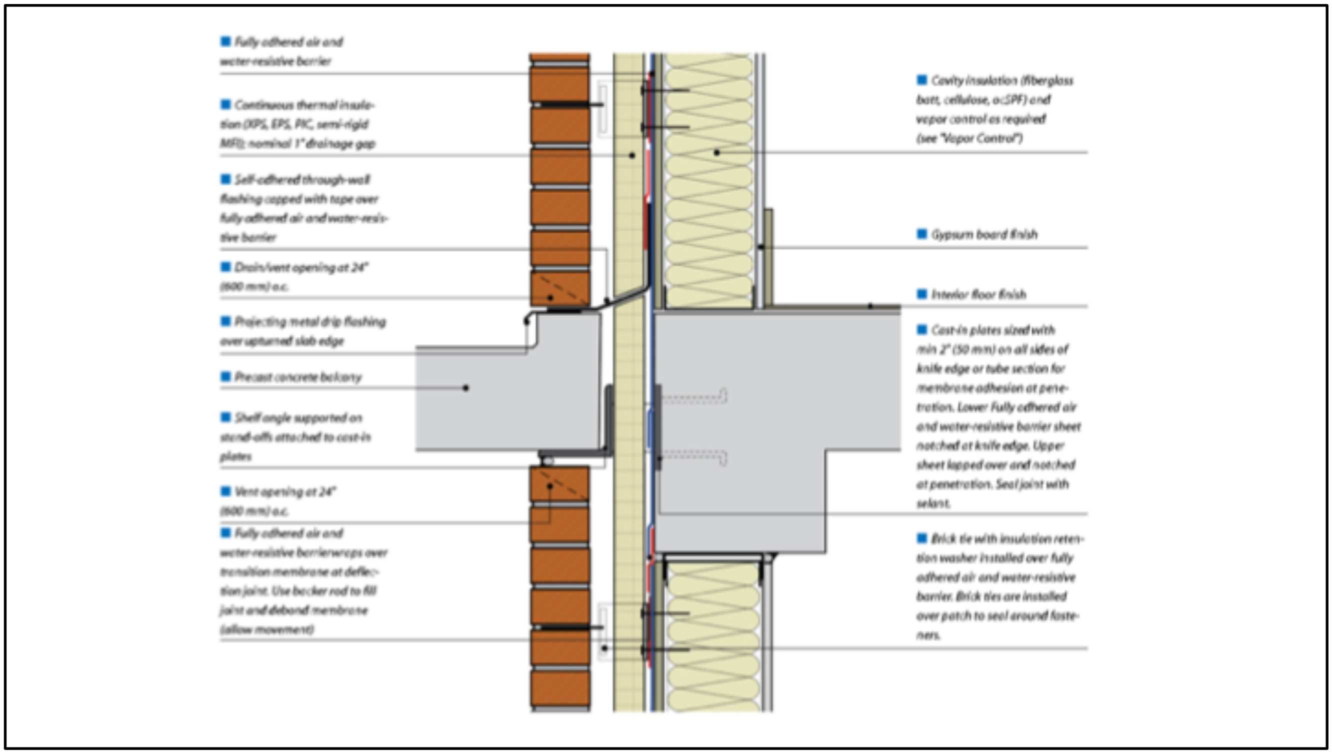
The ugly shelf angle version, in a wall assembly without exterior insulation, is a huge thermal bridge, conducting heat directly from the interior through the concrete floor.

The bad one is integrated into an exterior insulation system, but still a huge thermal bridge.

The good one is attached outboard of the continuous insulation and therefore not a thermal bridge itself. Only the screw fasteners are a little conductive but don't impact the effectiveness of the insulation very much at all.

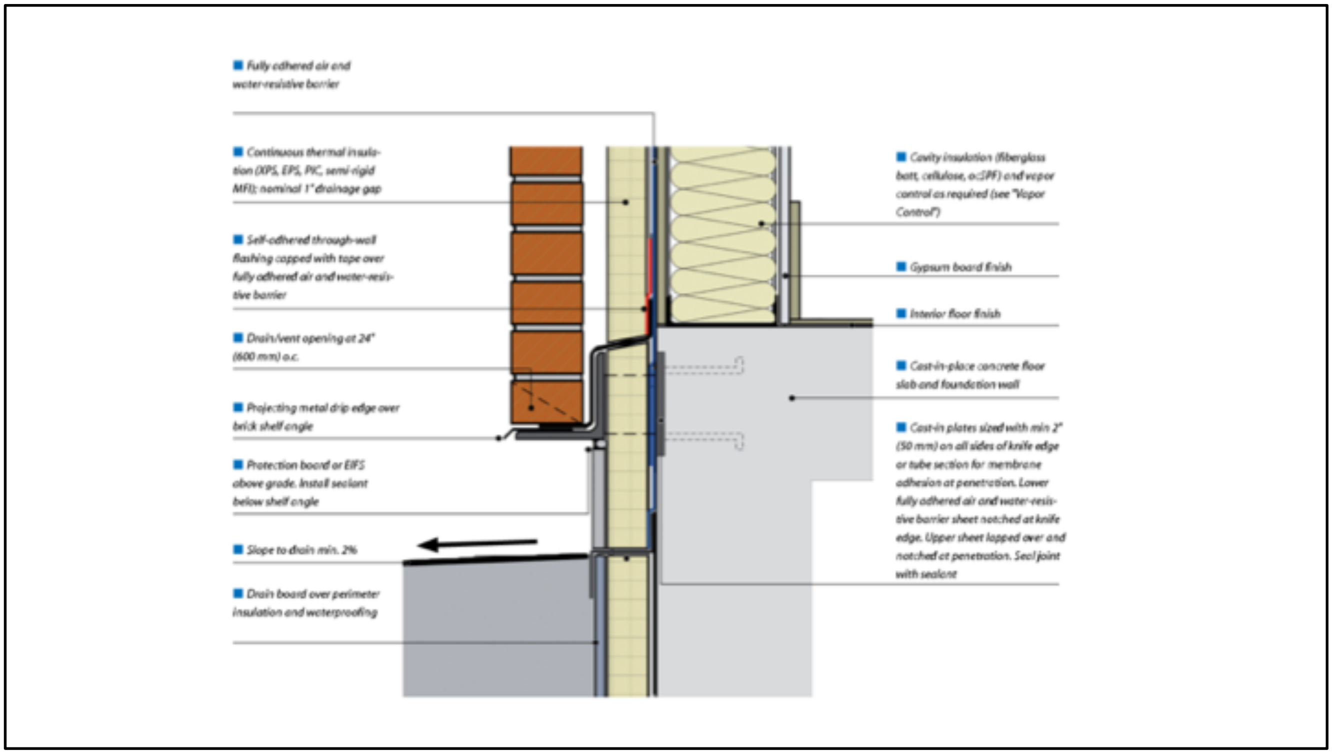


The brick tie fasteners are covered by exterior insulation. Just the connecters are going through the exterior insulation.

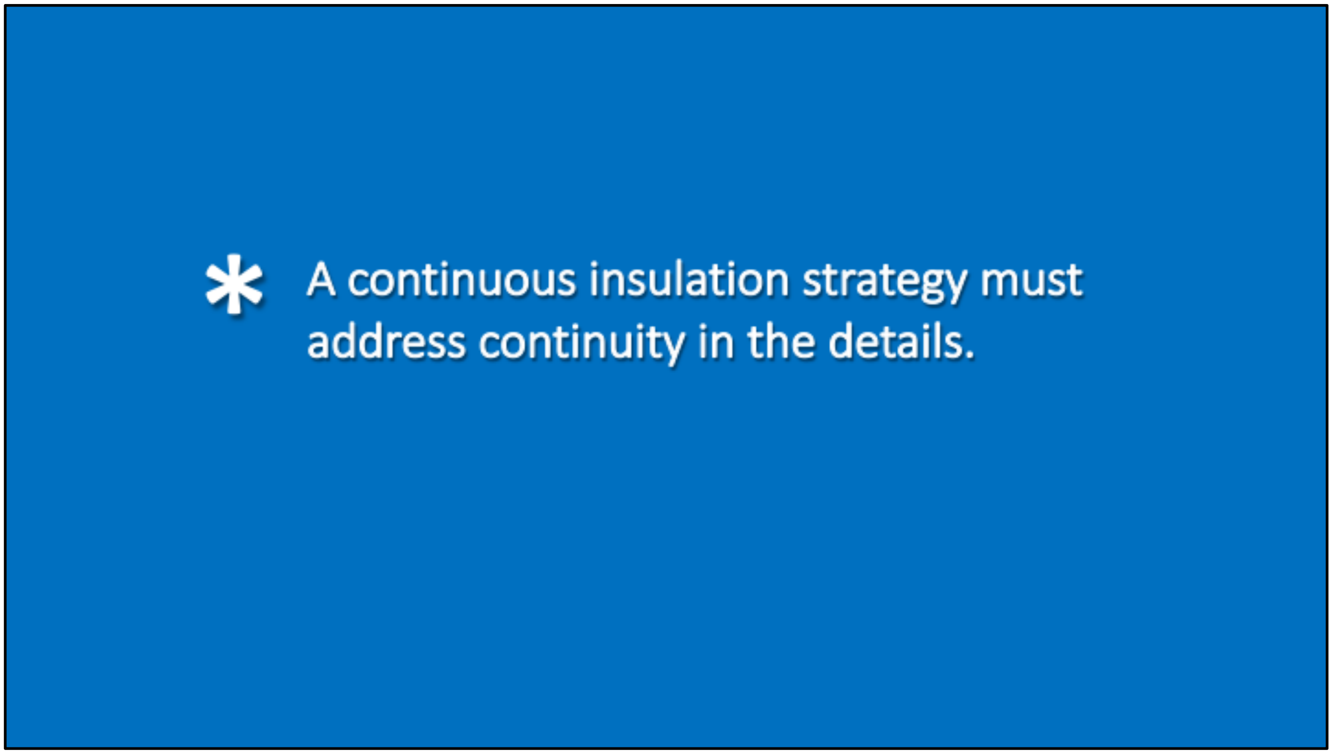


Cantilever elements are huge thermal bridges within the enclosure, but there are solutions to avoid thermal bridges nearly completely. Use an attachment system that thermally decouples the two structures and is integrated into exterior insulation.

A simple solution can have a huge impact on the entire thermal performance of the building. The decoupling of the cantilever balcony is not only a theoretical solution but also a practical one, as shown in this picture.



The same principals for avoiding thermal bridges can be applied to nearly every detail. Avoid huge conductive transmissions within the wall assemblies and replace them with thermally friendly elements.


* A continuous insulation strategy must address continuity in the details.

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Summary

- Thermal performance hasn’t gotten much better through the years.
- Most insulation materials trap small pockets of air or some other gas to resist heat flow.
- Thermal bridging can overwhelm the ability of insulation materials to stop heat flow in wall assemblies.
- Windows can overwhelm the performance of a wall system when a high window-to-wall ratio is used.
- Continuous exterior insulation is necessary in modern enclosures to achieve high thermal performance.
- A continuous insulation strategy must address continuity in the details.

This concludes the American Institute of Architects Continuing Education Systems Course.

Thank you for completing this educational course by Dörken Systems.

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