CAE 463/524
Building Enclosure Design

Fall 2012

Lecture 4: Finishing heat transfer

More complex conduction, thermal bridges, and multi-D heat transfer simulations

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Housekeeping

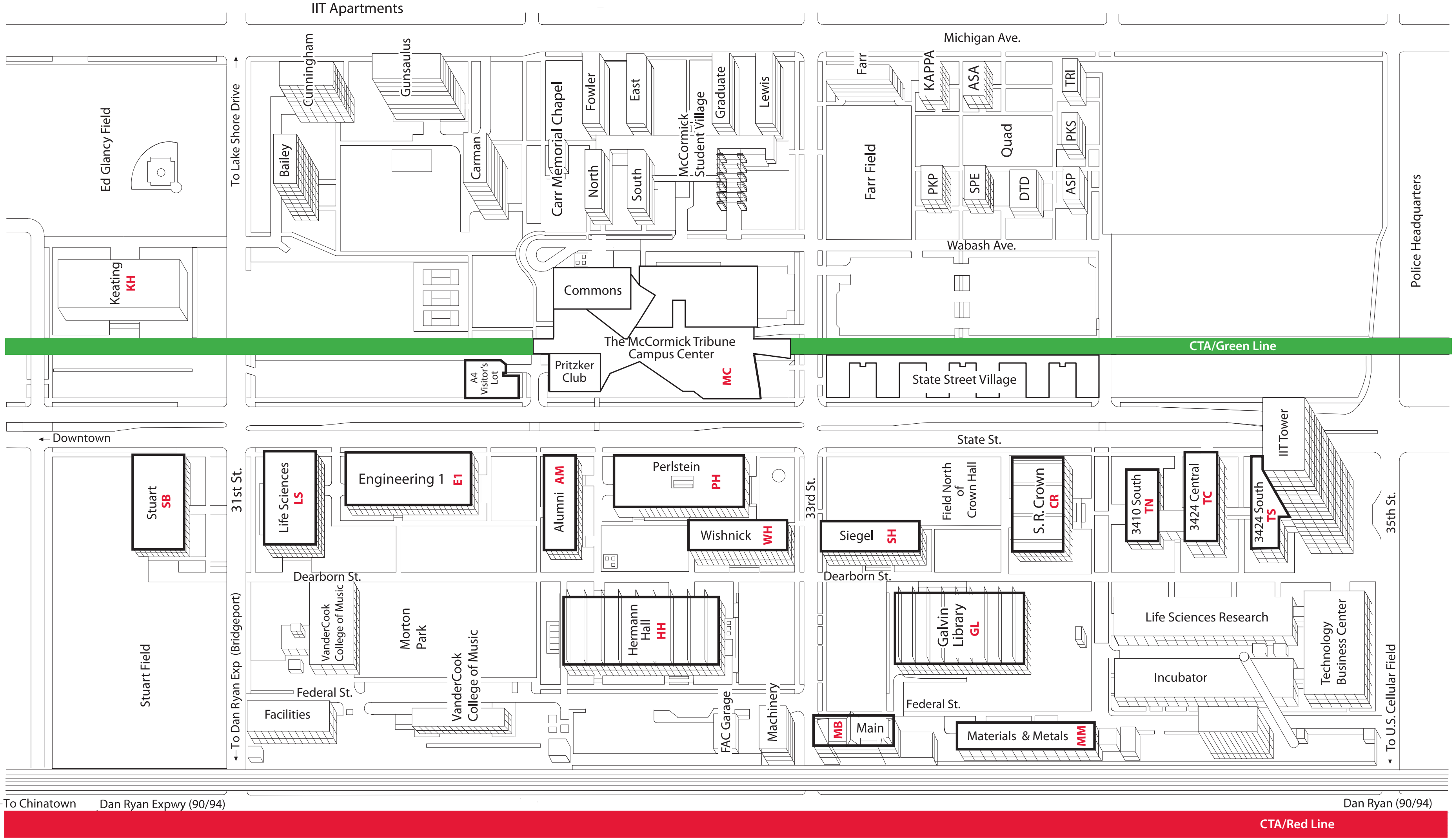
- HW 2 due today
  - Will grade and post grades online to Blackboard **ASAP**
  - Solutions to HW 1 will **finally** be posted by tomorrow
- More schedule changes
  - Nothing big, just holding off on airflows in enclosures
  - Schedule within the syllabus updated on BB and on website
- Career fair
  - This Thursday September 20
  - 12:00 to 4:00 PM Hermann Hall
  - Career Management Center can help w/ resumes, interviews
    - http://www.cmc.iit.edu/
- Project groups: Campus building project
  - Assigning teams today

Teams for campus project

- Some self-selected, but mostly random

Team	**Member 1**	**Member 2**	**Member 3**	**Architect**
1 - Siegel Hall	Angulo, Melissa	Diaz, Nestor	El Orch, Zeineb	Mies, 1956
2 - Alumni Hall	Russo, Lynda	Daras Ballester, Alejandro	Kayo, Luciana	Mies, 1945
3 - Crown Hall	Sebastian, Dan	Gomez Soriano, Maria	Gonzalez, Arturo	Mies, 1950
4 - Hermann Hall	Vagner, Inna	Diaz, Giovanni	Espinoza, Juan	SOM, 1962
5 - Stuart Building	Mcgreal, Tommy	Mejia, Jennifer	Morris, Frank	Goldsmith, 1971
6 - Life Sciences or Engineering 1	Huo, Yechen	Wright, Mike	Zwang, Stuart	both Goldsmith, 1966 (pick one)
7 - MTCC	Gonzalez, Alvaro	Foley, Patrick	Zylstra, Robert	Koolhaas, 2003

IIT Campus Map



Review from last time

- Continued heat transfer in building enclosures
  - Covered most of the relevant equations
  - Started with single-mode heat transfer examples
  - Then combined modes for surface energy balance
  - Then focused on conduction only
    1. Conduction through multiple (continuous) layers
       - Sum resistances in series to find total R (then U)
       - Learned to find temperature at each layer

    2. When each layer is not the same material:
       - Parallel path and isothermal path methods

Today’s topics

- Continue conduction through more complicated enclosures
  - ASHRAE Zone Methods
- Thermal bridges
  - General discussion
- Introduce 2-D and 3-D conduction and modeling software
  - THERM from LBNL

Building enclosures in daily life

- Prof. Lili Du's office
  - Alumni Memorial Hall
  - No blinds
  - Maintenance installed a blue tarp for her, turning her office blue

Learning more about building enclosures

- ASHRAE has two regular publications that are helpful for learning more about building enclosures
  - Shameless plug: there is an IIT student chapter of ASHRAE
  - http://ashraeiit.wix.com/ashraeiit
  - Melissa Angulo is president, I am faculty adviser
  - I encourage you to get involved!

- ASHRAE Journal (monthly)
  - http://www.nxtbook.com/nxtbooks/ashrae/ashraejournal_201209/#/0

- ASHRAE High Performance Buildings (quarterly)
  - http://www.nxtbook.com/nxtbooks/ashrae/hpb_2012fall/

ASHRAE Journal

- Joe Lstiburek from Building Science Corp. has a standing *near*-monthly column
  - Usually dedicated to building enclosures in some way
  - We will look at one of his previous articles today

ASHRAE High Performance Buildings

- Typically highlights several case studies of "high performance buildings"
  - Documents energy saving or IAQ-enhancing features
  - Often describes lighting, HVAC equipment, design or actual energy usage, occupant schedules, on-site energy supply, and building enclosure design choices separately

ENERGY AT A GLANCE

Annual Energy Use Intensity (EUI) (Site) 18.2 kBtu/ft²
Electricity (From Grid) 18.2 kBtu/ft²

Annual Source Energy 60.5 kBtu/ft²

Annual Energy Cost Index (ECI) $0.30/ft² credit

Annual On-Site Renewable Energy Exported (From PV) 17.8 kBtu/ft²

Annual Net Energy Use Intensity 0.39 kBtu/ft²

Savings vs. Standard 90.1-2004 Design Building 52.8%

ENERGY STAR Rating 100

Heating Degree Days (base 65°F) 2,710

Cooling Degree Days (base 65°F) 2,650

Average Operating Hours per Week 45

BUILDING ENVELOPE

Roof
Type Metal roofing with two, 3 in. layers of R-17 polyisocyanurate insulation
Overall R-value 34.9
Reflectivity/Emittance 69%/87%

Walls
Type 6 in. and 8 in. thick insulated concrete form walls
Overall R-value 28
Glazing percentage 26.8%

Basement/Foundation
Slab Edge Insulation R-value 24
Basement Wall Insulation R-value 24
Basement Floor R-value 0

Windows

	View Window	Daylighting Window
Effective U-factor for Assembly	0.29	0.47
Solar Heat Gain Coefficient (SHGC)	0.38	0.78
Visual Transmittance	0.7	0.81

Location
Latitude 36.8°N
Orientation East/West

1. ASHRAE ZONE METHODS FOR CONDUCTION AND THERMAL BRIDGES

Last time

- When layers have same area and material properties…

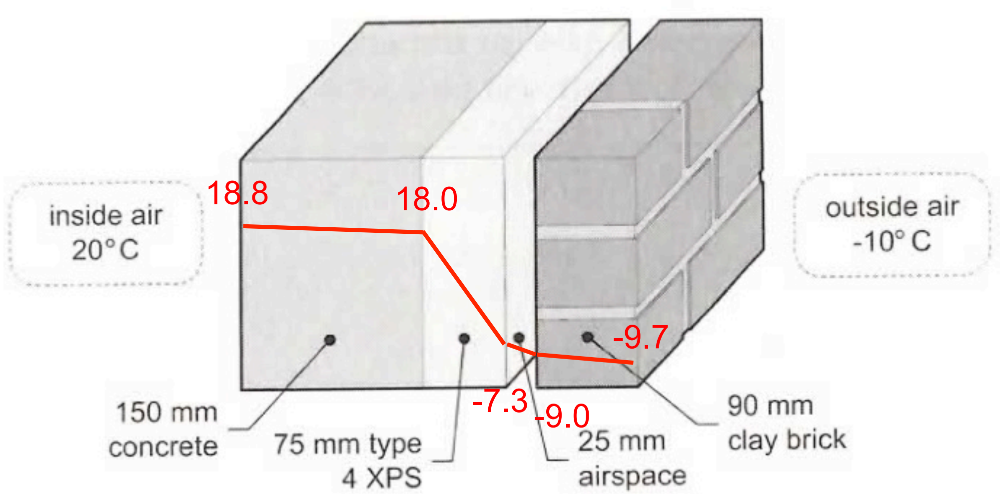
Sum the resistances:

$$q = \frac{t_1 - t_2}{R_1} = \frac{t_2 - t_3}{R_2} = \frac{t_3 - t_4}{R_3}$$

$$q = \frac{t_1 - t_4}{R_{total}} \quad \text{where} \quad R_{total} = R_o + R_1 + R_2 + R_3 + R_i$$

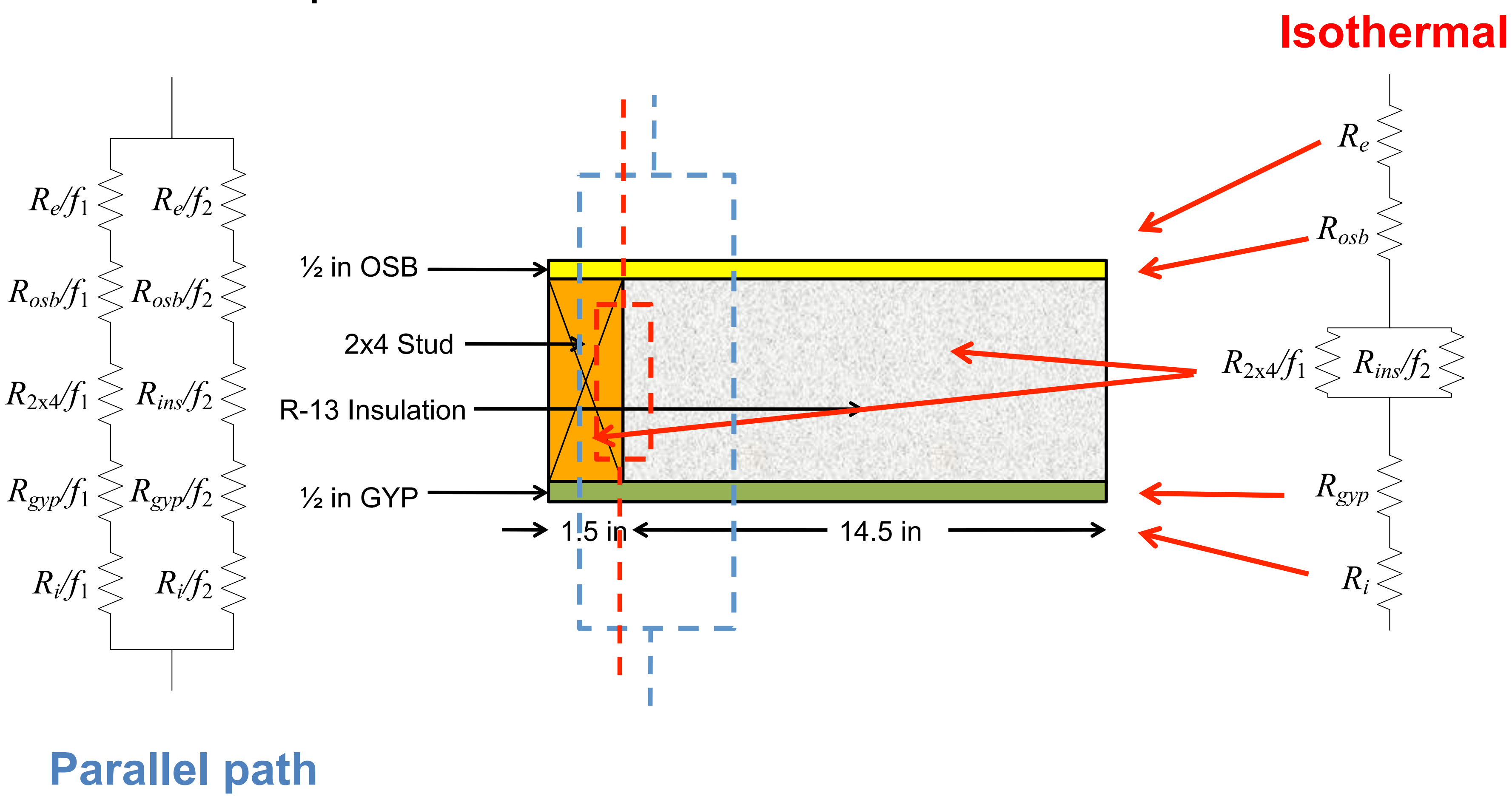
Temperature across each layer:

$$\boxed{\Delta T_i = \frac{t_{internal} - t_{external}}{\sum_{i=0}^{n} R_i} R_i}$$



Last time

- When material areas and properties differ…
  - Parallel path and isothermal methods



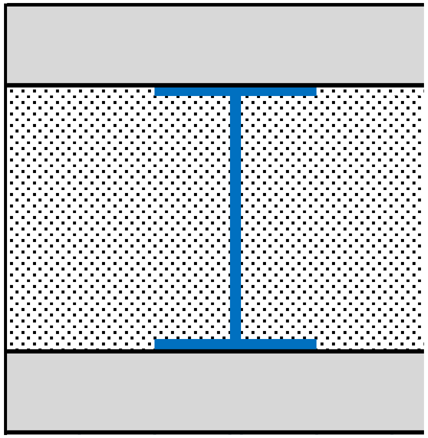
Limitations to these methods

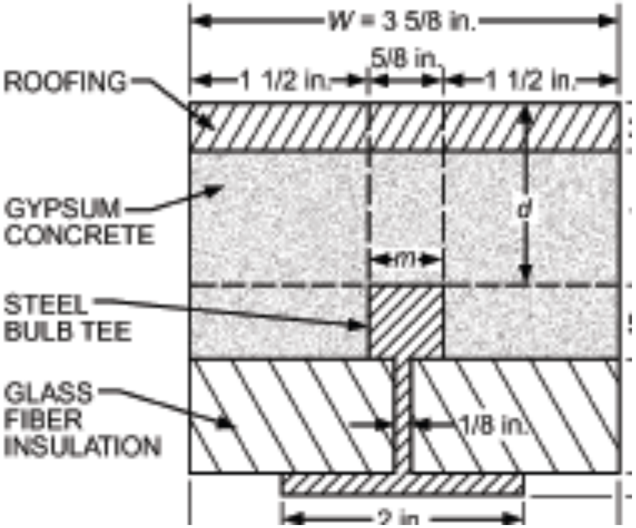
- Previous methods do not work well when the assembly has **metal** thermal bridges
  - A thermal bridge is an element of high thermal conductivity that spans through enclosure layers
  - For example:
    - Embedded steel beams can create thermal bridges

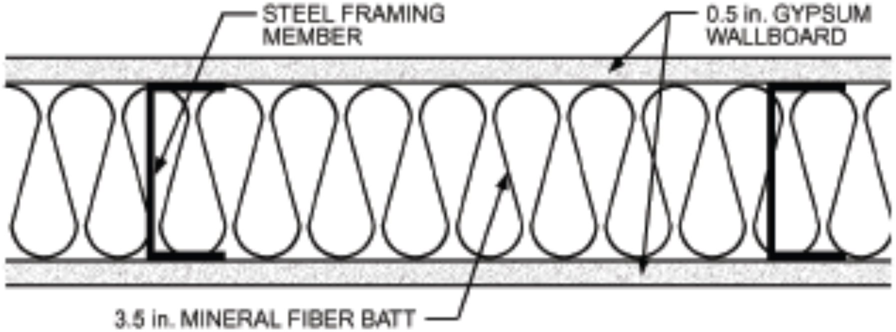
- Any flanges on metal beams draw heat into metal areas that cross through layers
  - Increases heat transfer
  - Often odd geometries
    - We need more accurate methods of estimating U-values

Metal thermal bridge examples

- I-beams sandwiched between sheathing
- Metal stud walls
- Metal embedded in concrete



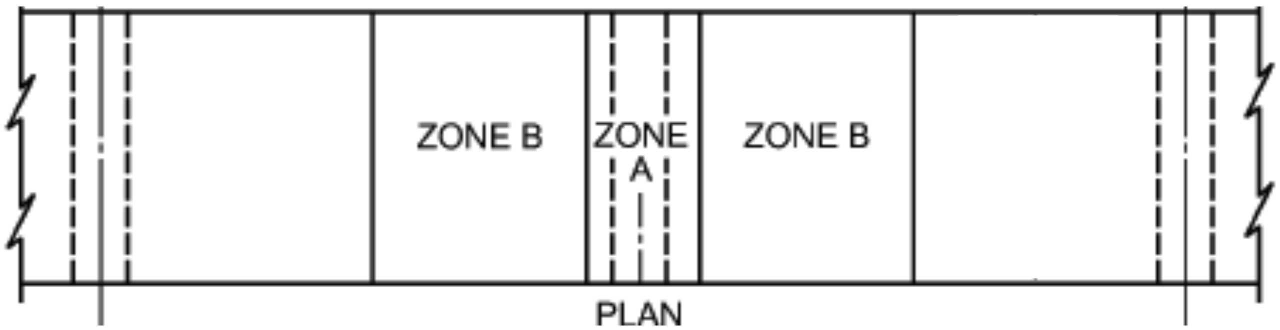




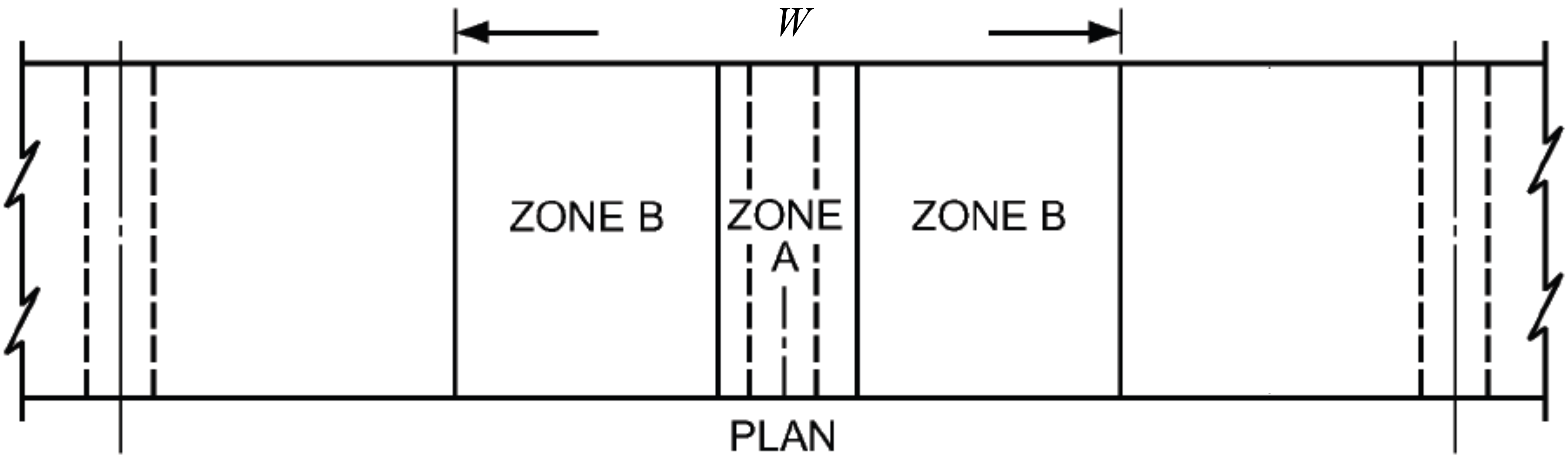
ASHRAE zone method for metal thermal bridges

- Involves two separate calculations (in two zones):
  - Zone A contains the highly conductive element (the thermal bridge)
  - Zone B is the remaining portion of simpler construction

  - The two zones are then combined using a modified parallel path
  - We add the “area conductances” (U×A) of elements in parallel
    - And add “area resistances” (R/A) of elements in series
    - This method stemmed from an old ASHRAE Research Project
      - But it’s not explained extremely well in HOF (I’ll do my best)



Analysis: First find repeated bridges



- Bridges repeat at a distance W
- Find width of Zone A, W_a using the following slides
  - Then $W_b = W - W_a$
- Determine area transmittance for each zone (U×A)
- Then find area resistances (R/A)
  - Add them in series

Finding W_a

- Identify the width of any flange associated with the bridges toward the outside and inside of the construction and call them m_{out} *and* m_{in}
- Determine the distance of the flanges from the inside or outside surface, call them d_{out} and d_{in}
  - If either d_{out} or d_{in} is less than 0.5 inches (13 mm):
    - Set that d_{out} or d_{in} to 0.5 inches (13 mm)

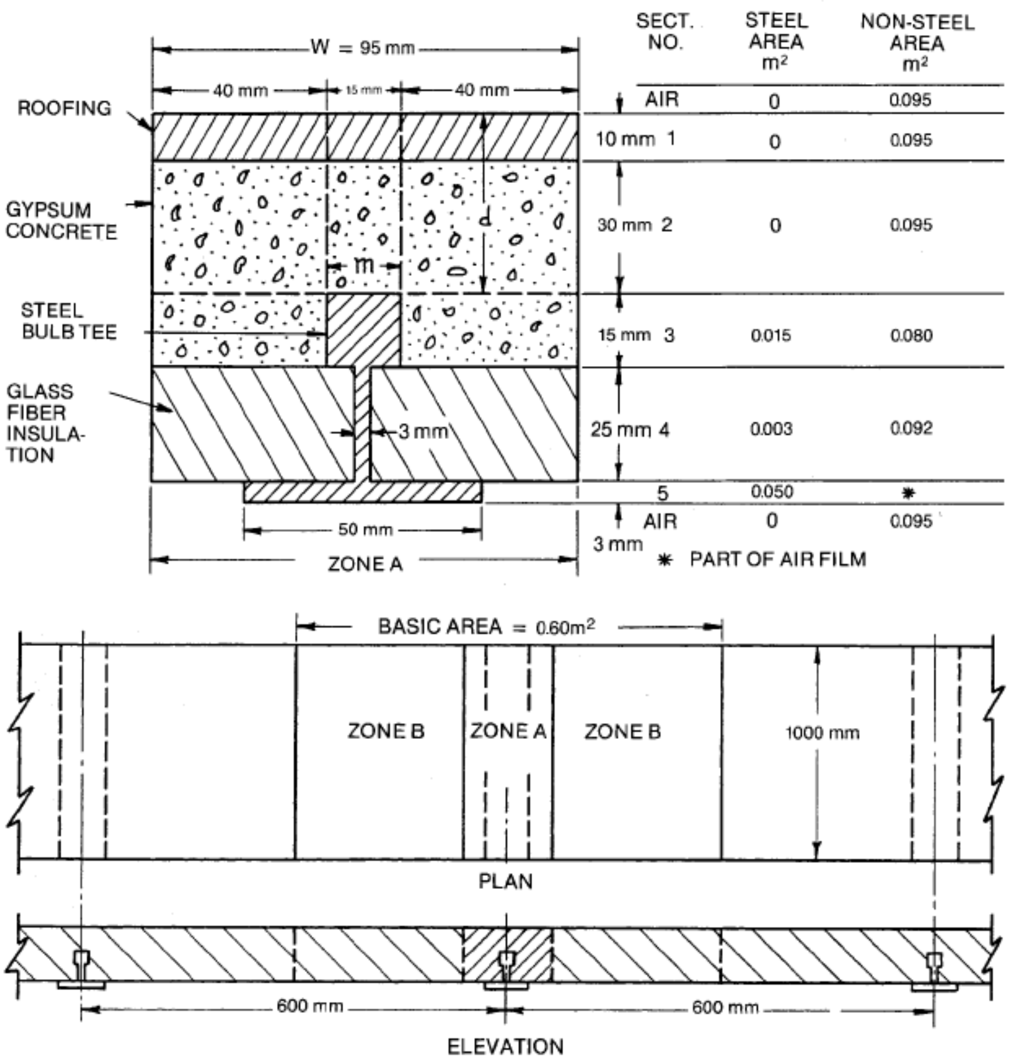
Then calculate:

$$W_{in}=m_{in}+2d_{in} \qquad W_{out}=m_{out}+2d_{out}$$

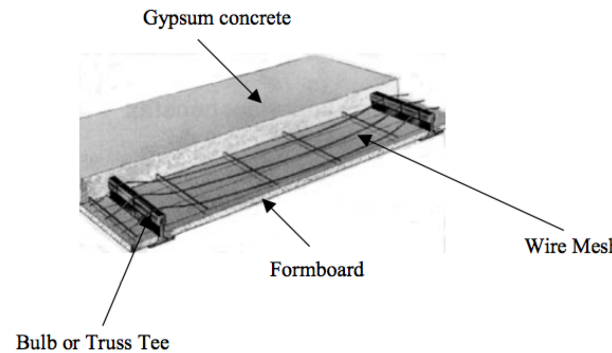
- W_a is the larger of W_{in} and W_{out}

Example 4.1: Concrete roof deck with tees

- Best explained using an example



	SECT. NO.	STEEL AREA m^2	NON-STEEL AREA m^2
	AIR	0	0.095
10 mm	1	0	0.095
30 mm	2	0	0.095
15 mm	3	0.015	0.080
25 mm	4	0.003	0.092
	5	0.050	*
3 mm	AIR	0	0.095

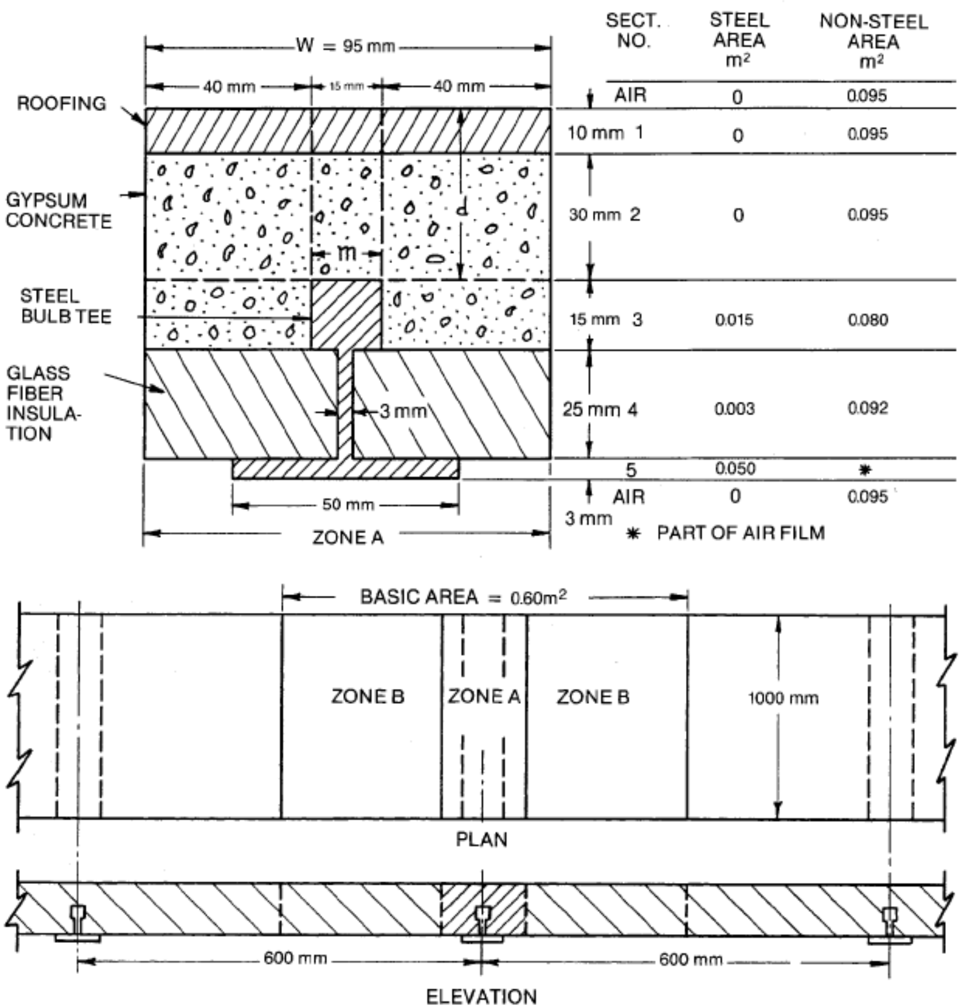


Calculate U-value of the roof deck shown here.

Tee bars 600 mm OC. They support glass fiber boards, gypsum concrete, and built-up roofing.

k_{steel} = 45 W/(mK)
$k_{concrete}$ = 0.24 W/(mK)
$K_{fiber\ board}$ = 0.036 W/(mK)
$k_{roofing}$ = 17 W/(mK)

Example 4.1: Concrete roof deck with tees



SECT. NO.	STEEL AREA m²	NON-STEEL AREA m²
AIR	0	0.095
10 mm 1	0	0.095
30 mm 2	0	0.095
15 mm 3	0.015	0.080
25 mm 4	0.003	0.092
5	0.050	*
AIR	0	0.095

* PART OF AIR FILM

- Basic area
  - 600 mm x 1000 mm
  - 0.6 m²
  - Tee-bar across middle
- Divided into zones A and B
  - Determine area of zone A

Top side

$W_{out} = m + 2d$

$W_{out} = 15 + 2*(10 + 30) = 95$ mm

Bottom side

$W_{in} = m + 2d$

$W_{in} = 50 + 2*(13) = 76$ mm

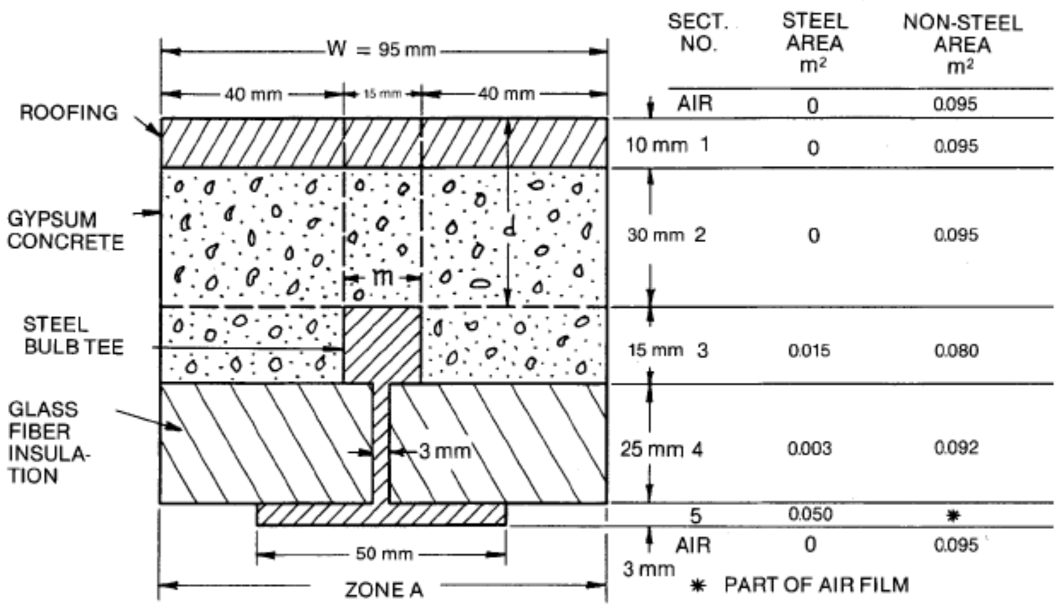
*Use 13 mm as minimum (previous slide)

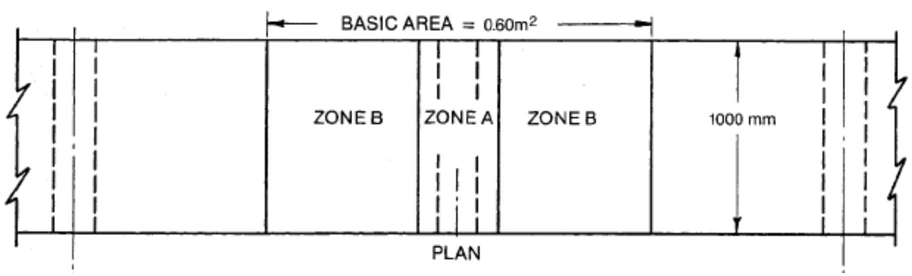
Use 95 mm (larger of two W values)

Area zone A = (0.095 m)*(1 m) = 0.095 m²

Area zone B = 0.6 m² – 0.095 m² = 0.505 m²

Example 4.1: Concrete roof deck with tees





*Remember: total depth is 1 m (1000 mm)

- Finding U-value for Zone A
- Divide zone into 7 sections parallel to top and bottom surfaces
  1. Outdoor air
  2. Roof
  3. Concrete
  4. Concrete + steel
  5. Insulation + steel
  6. Steel
  7. Air

- Calculate area for each steel and non-steel portion

  Example: 3 mm of steel extending through insulation

  A_{steel} = 3 mm x 1 m = 0.003 m^2

  A_{insul} = (95 – 3)mm x 1 m = 0.092 m^2

Example 4.1: Concrete roof deck with tees

- For total conductance of Zone A:
  - Multiply each section and element area by its conductance (U x A)
  - R of each = 1/U where U = k/L
  - For multiple materials in a layer: $R = 1 / (U_1A_1 + U_2A_2 \ldots)$

Section	**Area**	×	**Conductance**	= ***CA***	$\frac{1}{CA} = \frac{R}{A}$
Air (outside, 24 km/h)	0.095	×	34	3.23	0.31
No. 1, Roofing	0.095	×	17	1.62	0.62
No. 2, Gypsum concrete	0.095	×	0.24/0.030	0.76	1.32
No. 3, Steel	0.015	×	45/0.015	45	0.022
No. 3, Gypsum concrete	0.080	×	0.24/0.015	1.28	
No. 4, Steel	0.003	×	45/0.025	5.4	0.181
No. 4, Glass fiberboard	0.092	×	0.036/0.025	0.13	
No. 5, Steel	0.050	×	45/0.005	450	0.002
Air (inside)	0.095	×	9.26	0.88	1.14
				Total *R*/*A* = 3.59	

Area transmittance of Zone A = $1/(R/A) = 1/3.59 = 0.279$.

Note: Weird units
$UA = W/(m^2K) \cdot m^2 = W/K$
$R/A = (m^2K)/W/m^2 = K/W$

These are "area" conductances and resistances, applicable only to the unit we're analyzing

Example 4.1: Concrete roof deck with tees

- For total conductance/resistance of Zone B
  - Sum unit resistances per normal
  - Get conductance (U = 1 / R)
  - Multiply by Zone B area for “area transmittance” (UA)

For Zone B, the unit resistances are added and then converted to area transmittance, as shown in the following table.

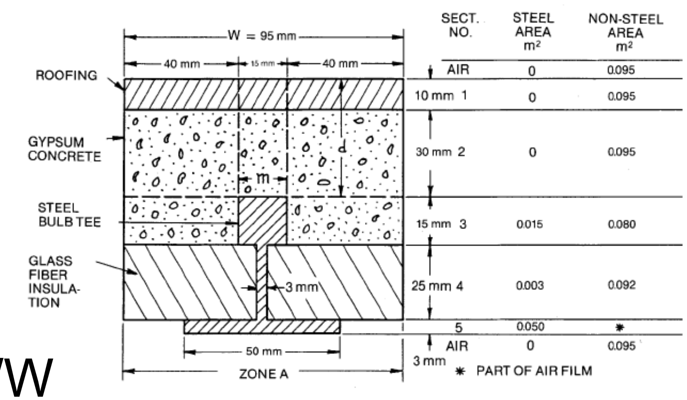
Section	Resistance, R
Air (outside, 24 km/h)	1/34 = 0.029
Roofing	1/17 = 0.059
Gypsum concrete	0.045/0.24 = 0.188
Glass fiberboard	0.025/0.036 = 0.694
Air (inside)	1/9.26 = 0.108
Total resistance	= 1.078

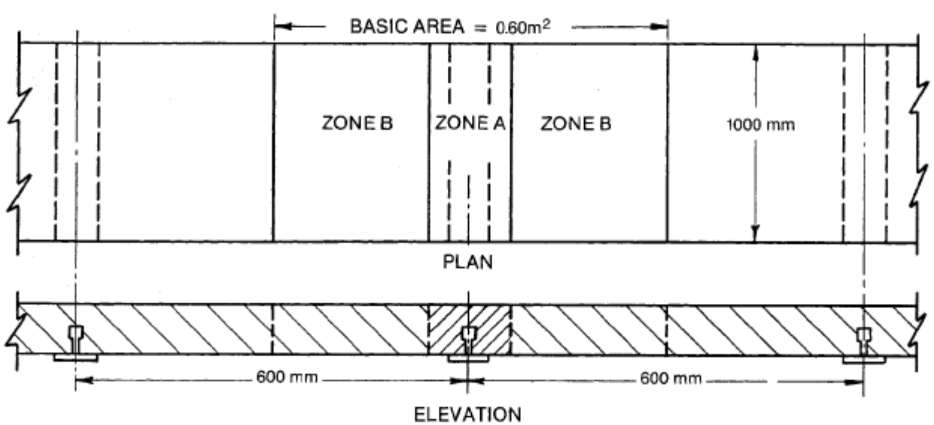
Because unit transmittance = $1/R = 0.927$, the total area transmittance UA is calculated as follows:

$$\text{Zone B} = 0.505 \times 0.927 = 0.468$$

Example 4.1: Concrete roof deck with tees

- Total area transmittance (UA)
  - Zone A = 0.279 W/K
  - Zone B = 0.468 W/K
  - Total UA = 0.279 + 0.468 = 0.747 W/K
  - Total Area R/A = 1/(UA) = 1/0.747 = 1.34 K/W
  - Multiply by total section area to get resistance, R
    - R_{total} = R/A x A = 1.34 K/W x 0.6 m^2 = 0.80 (m^2K)/W = 4.6 (IP)





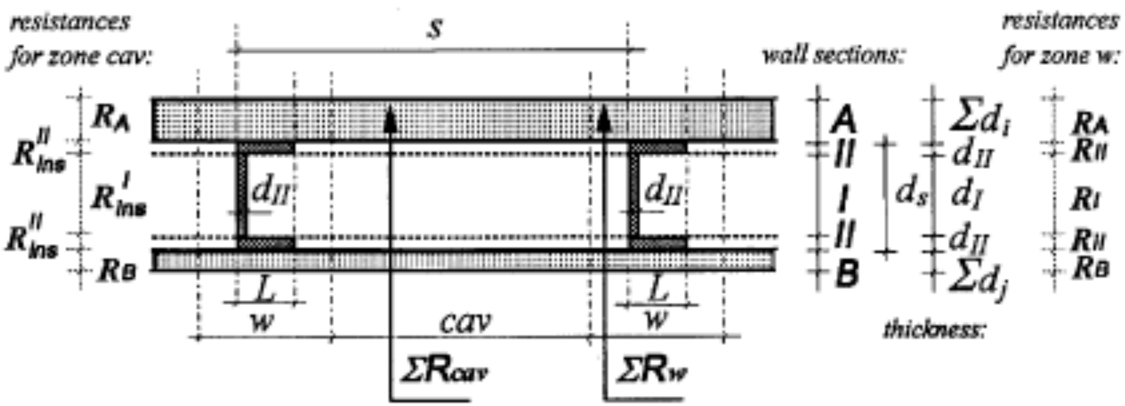
If we had ignored the steel tee:

	L, mm	L, m	k, W/mK	U, W/m²K	R, m²K/W
exterior air				34	0.03
roof	10	0.01	17	1700	0.00
concrete	45	0.045	0.24	5.3	0.19
insulation	25	0.025	0.036	1.4	0.69
interior air				9.3	0.11
				R, m²K/W	1.02
				R (IP)	5.79

Note that this is a somewhat empirical approach. The authors of this method compared to lab studies of enclosure elements and got reasonable agreement

"Modified" Zone Method

- There is also a "modified zone method" in ASHRAE HOF
  - Designed specifically for metal stud walls with both cavity insulation and external insulation



- Essentially: the width of the metal zone changes to:

$$W = m + Z_f d$$

where the zone factor Z_f varies depending upon the configuration of cavity and external insulation

  - See ASHRAE HOF
  - Not going to cover this, but good to know it's there

Modified zone calculator

- There are some online modified zone calculators developed by Oakridge National Laboratory

http://www.ornl.gov/sci/roofs+walls/calculators/modzone/index.html

http://www.ornl.gov/sci/roofs+walls/calculators/modzone/modzone2.html

- The first of these has pull-down menus to select standard construction values for stud sizes and thermal conductivities

- The second is a more free-form version where you input all your dimensions and material properties

Combining elements in an actual enclosure

- So far we have been exploring single assemblies
  - Just roofs or just walls without windows and doors
  - If you design a building without windows and doors, something probably went wrong!
- Concept of **combined thermal transmittance**: U_o
  - U_o is the combined thermal transmittance of the respective areas of a gross exterior wall, roof, or floor
    - It is basically an area-weighted average U-value

$$U_o = (U_{wall} A_{wall} + U_{window} A_{window} + U_{door} A_{door}) / A_o$$

where

U_o = average thermal transmittance of gross wall area
A_o = gross area of exterior walls
U_{wall} = thermal transmittance of all elements of opaque wall area
A_{wall} = opaque wall area
U_{window} = thermal transmittance of window area (including frame)
A_{window} = window area (including frame)
U_{door} = thermal transmittance of door area
A_{door} = door area (including frame)

Example 4.2: Combined thermal transmittance

- Calculate U_o for a 10 m x 2.4 m wall with two double-glazed windows with wood/vinyl frames and one solid core door
  – One window is 1.5 x 0.86 m; the other window is 0.9 x 0.76 m
    - Let's say we looked up window U-value in a table
    - U_{window} = 2.90 W/(m^{2}K)
  – The door is 0.86 x 2 m
    - Let's say we also looked up its U-value in a table
    - U_{door} = 1.42 W/(m^{2}K)
  – The wall has a U value of U_{wall} = 0.404 W/(m^{2}K)

$$A_{window} = (1.500 \times 0.860) + (0.900 \times 0.760) = 1.97 \text{ m}^2$$

$$A_{door} = (0.860 \times 2.000) = 1.72 \text{ m}^2$$

$$A_{wall} = (10 \times 2.4) - (1.97 + 1.72) = 20.31 \text{ m}^2$$

Therefore, the combined thermal transmittance for the wall is

$$U_o = \frac{(0.404 \times 20.31) + (2.90 \times 1.97) + (1.42 \times 1.72)}{10 \times 2.4}$$

$$= 0.68 \text{ W}/(\text{m}^2 \cdot \text{K})$$

A note on materials and *k*, *U*, and *R* values

- We've already looked up material properties several times
  - Many are listed in ASHRAE HOF
  - It's important to have a good working knowledge of these values for common building materials (particularly **high conductivity** materials)
  - I've uploaded a new ASHRAE HOF chapter to Blackboard
    - From 2005: Ch. 39 - Physical properties of materials
  - Pay special attention to metals, in addition to those values we already know
  - Thermal conductivity (*k*) of common materials
    - Insulation ~0.03 W/(m-K)
    - Wood ~0.1-0.2 W/(m-K)
    - Rubber ~0.1 W/(m-K)
    - Brick/stone/concrete ~0.5-2.0 W/(m-K)
    - **Steel ~45 W/(m-K)**
    - **Cast iron ~50 W/(m-K)**
    - **Aluminum ~220 W/(m-K)**

Increasing conductivity ↓

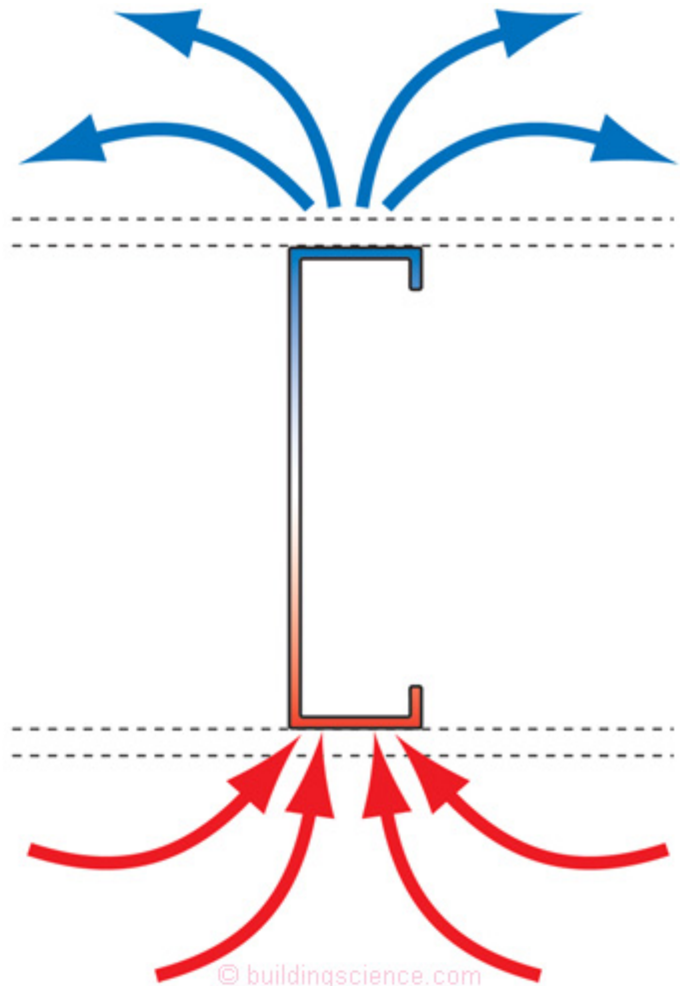
Decreasing resistance (also depends on thickness) ↑

2. THERMAL BRIDGES

Thermal bridges

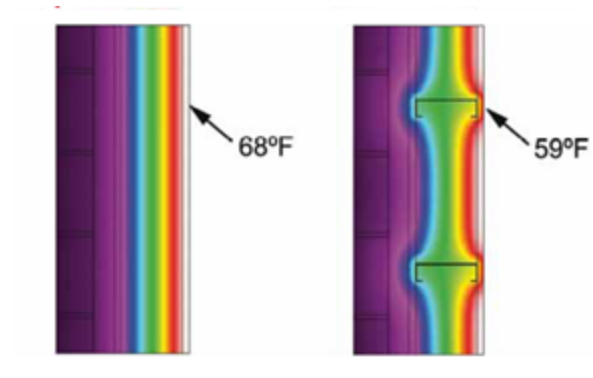
- A thermal bridge is a high conductivity portion of an assembly that penetrates insulating layers and significantly reduces the overall R value of the assembly

- These bridges act as thermal "short circuits"



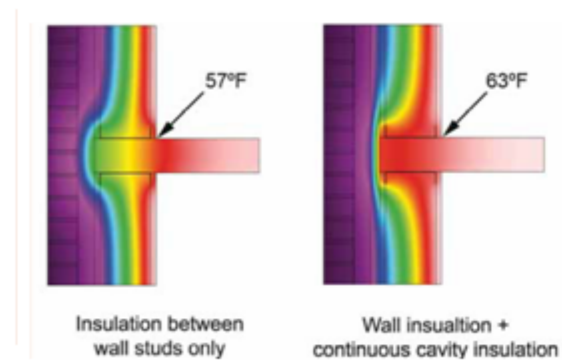
Common thermal bridges

- Metal studs in insulated walls without external insulation

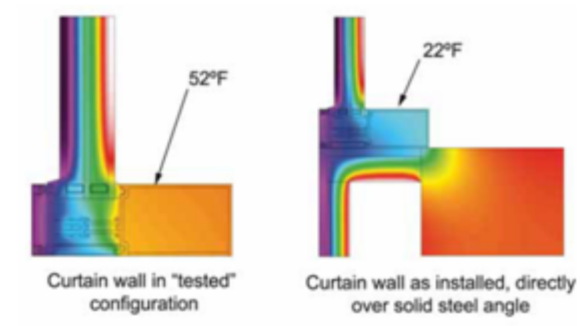


Thermal Bridging through Light Gauge Steel Studs

- Floor planks without continuous external insulation



- Curtain Walls in contact with steel framing



Thermal Bridging at Curtain Wall Connection

Identifying thermal bridges

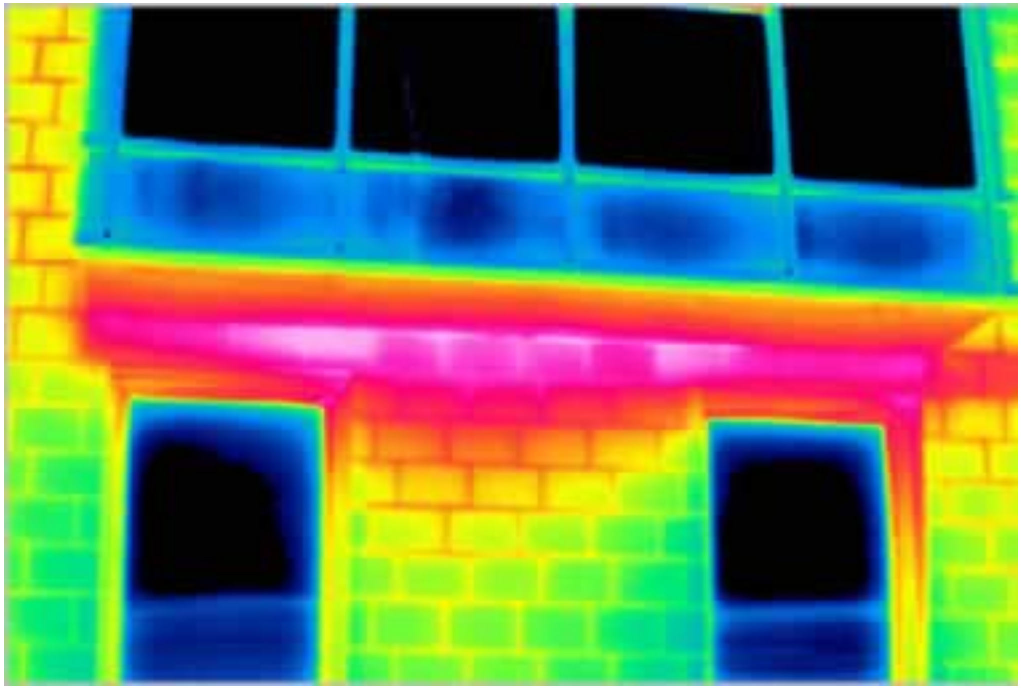
We can identify thermal bridges in many ways

- Inspection of detail drawings
  - Use this to identify potential problems
- Thermal analysis of detail drawings
  - Use to quantify the extent of thermal bridging
- Thermal imaging
  - Useful way to find bridges in existing construction

Thermal imaging

- One way to find existing thermal bridges in the built environment is to use thermal imaging
  – Particularly when the inside-outside temp difference is large
- Regions around thermal bridges will have vastly different temperatures than the rest of the wall
  – This will be visible

$$q = \varepsilon T^4$$

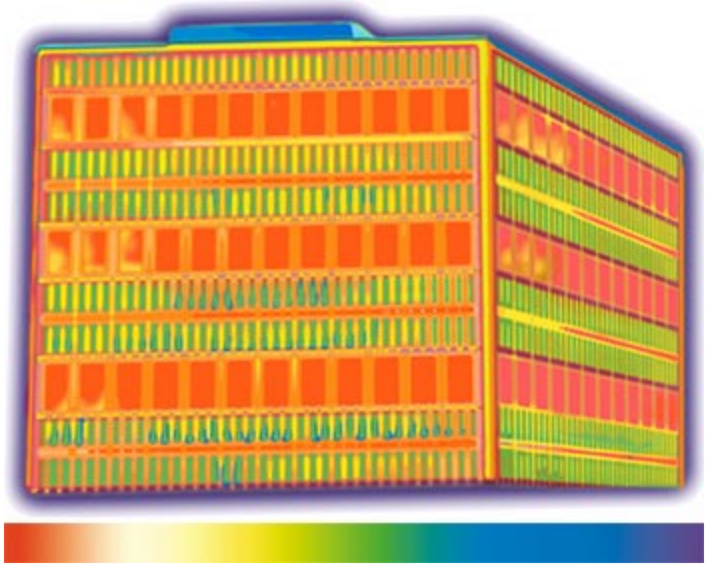


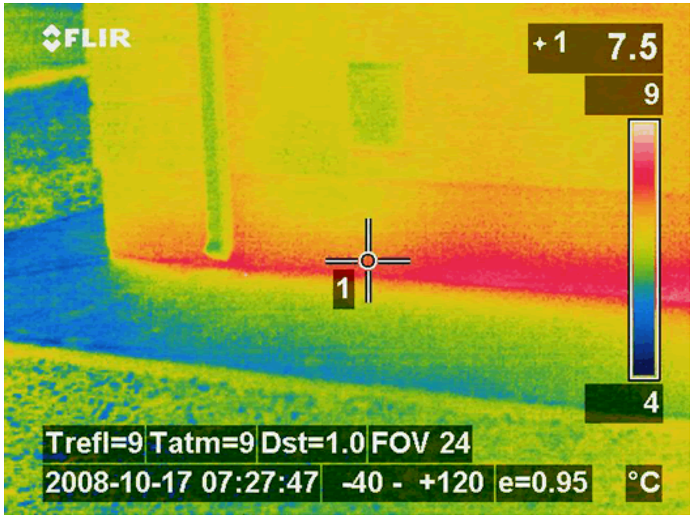
The red here indicates a thermal bridge created by a structural beam below the window

Cold outside, hot inside

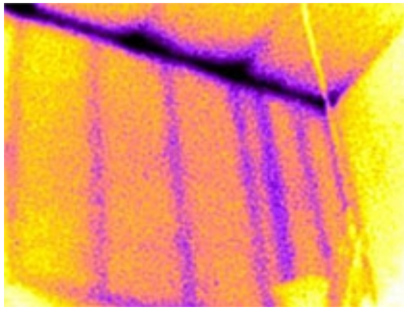
More thermal imaging

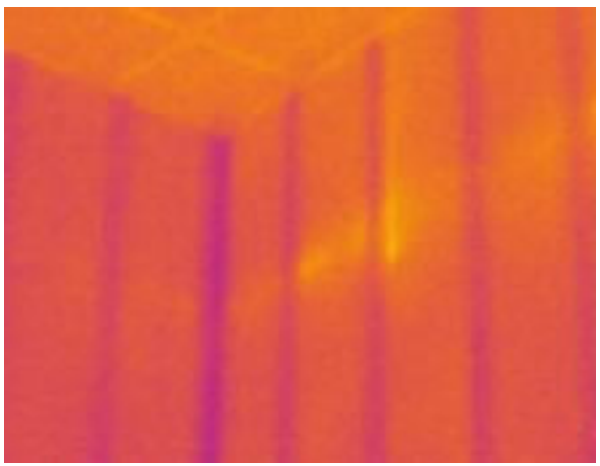
- These figures show hot spots in red
- The windows, frames, and locations where the floor meets the walls are clearly visible bridges in the top figure
- The floor/foundation junction in the bottom has clear thermal bridges





Framing effect



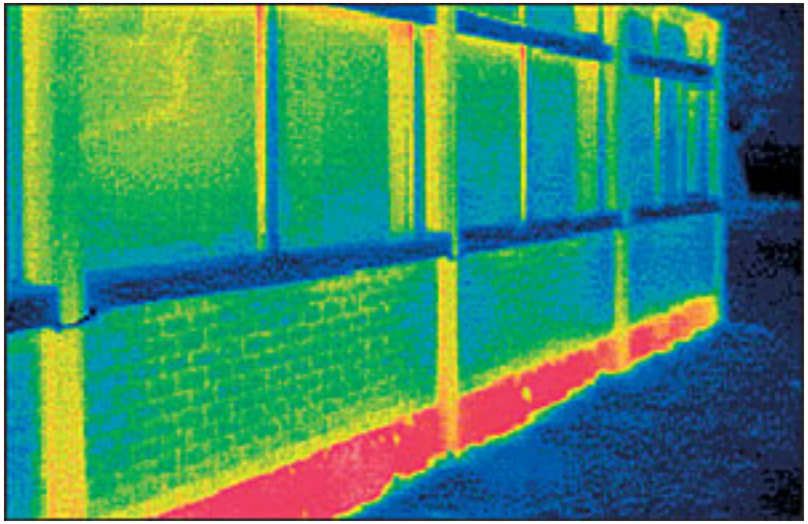


Thermal bridges show up in blue on these figures. Notice that corners seem to have the worst thermal bridges

- The “framing effect” is a term used to denote the reduction in R-value from thermal bridging of the framing
  - Steel stud walls commonly have a framing effect of 40%-50%
  - That’s huge!
- A reduction in the framing effect means an increase in the effective R-value of a wall

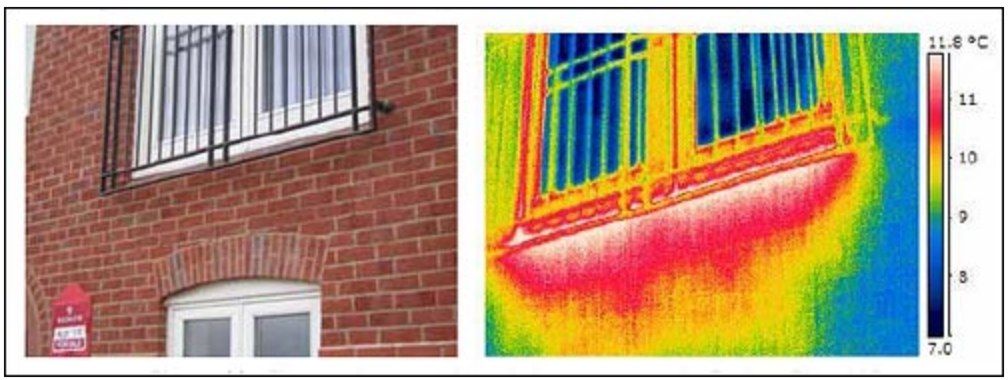
Foundation thermal bridges

Here are some thermal images showing thermal bridges where a slab floor or foundation meets a wall

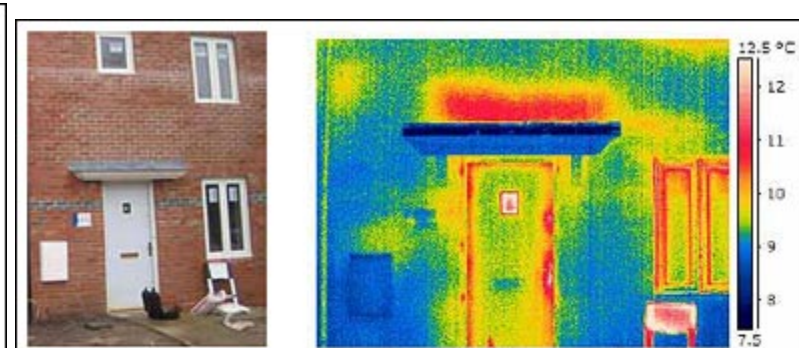


Wall-Floor Thermal Bridges

- Here are some examples of thermal bridges where interior floors and supports meet with exterior walls



Thermal bridge for support under the window



Thermal bridge from lintel over the door

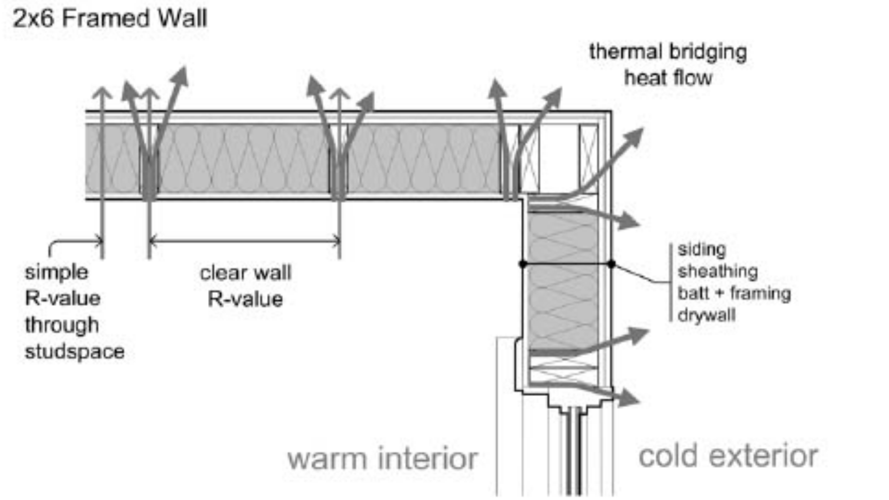
Reducing thermal bridging

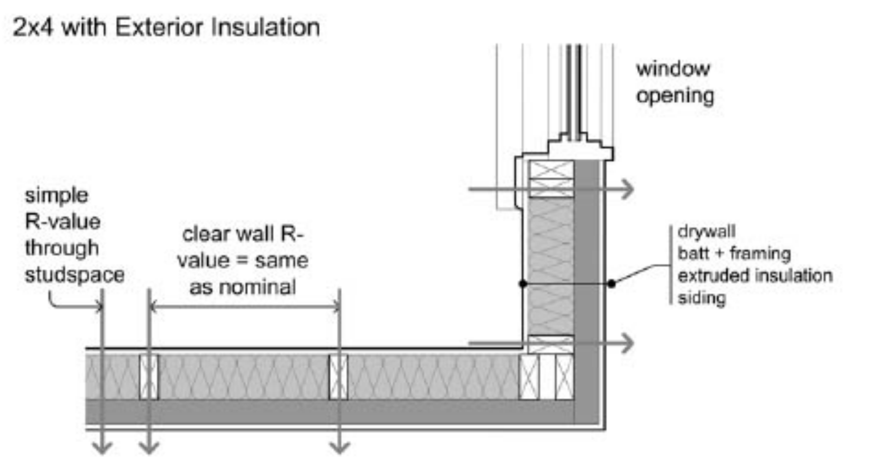
Basic concept:

- To reduce thermal bridging we need to provide a thermal break in the high-conductivity heat transfer path
  - Add insulation to the path to reduce direct heat flow

An important solution: external insulation

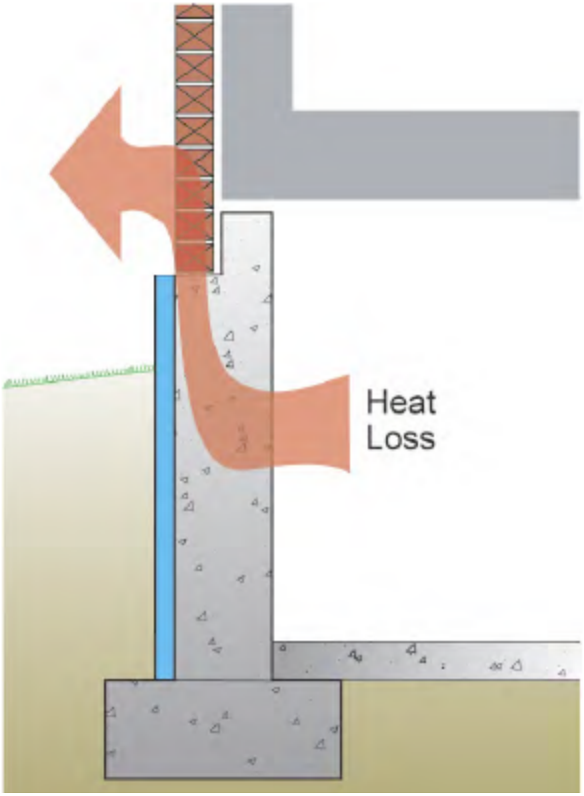
- The use of external insulation is a very effective way of reducing the bridging effects
  - It also increases the R value of the non-bridge areas
    - A 2x4 wall with 2 inches external insulation is much better than a 2x6 wall with 6 inches interior insulation
  - Need a continuous (or near continuous) layer of external insulation to break the path of high-conductivity material
    - Add to the exterior to ensure as much continuity as possible





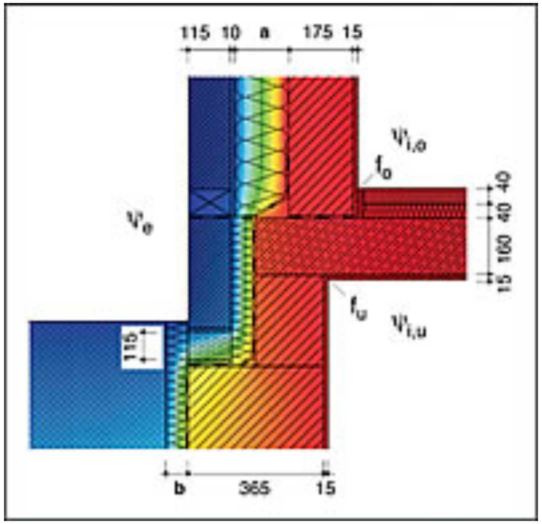
Foundation thermal bridges

Thermal bridges between brick veneer and foundation are common

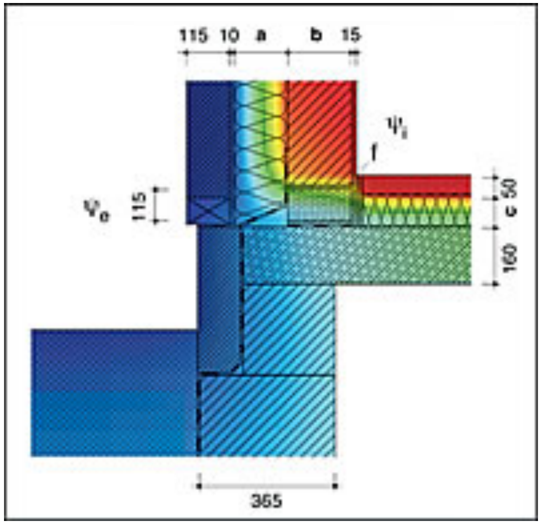


Fixing wall-floor bridges

- To correct this problem we need to break the heat flow path



External insulation added down along the foundation breaks the thermal bridge



Insulation added to the floor also breaks the thermal bridge

*In both of these two designs the floor insulation breaks the thermal bridge

More on “framing effect”

Steel studs create bad thermal bridging – why use them?

- Steel can be recycled
  - Can get 100% recycled steel studs
  - Can recycle old studs when you remodel/rebuild
- Steel studs can be locally produced
  - Reduced transportation costs and environmental impact
- Reduced size and weight
  - Reduces storage and transportation costs
- Faster construction
  - Stronger material means fewer studs (24”oc instead of 16”oc) which means faster construction
- Better sound isolation

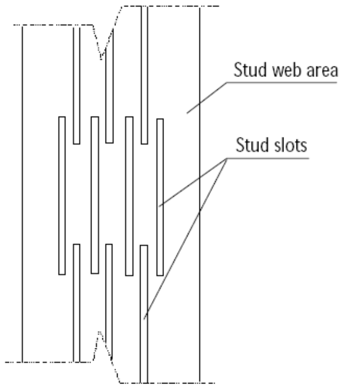
So, it would be great if we could find a way to reduce the thermal bridging of steel studs

Steel stud design suggestions

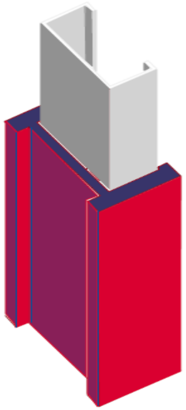
- Minimize stud area with 24” OC instead of 16” OC
- To achieve high R-Value there must be a good thermal break between the stud and the exterior
  - Exterior insulation is most effective
- Can also use lower conductivity studs if possible
  - Or consider foam covered/combined studs
- Become friends with your structural engineer!

Modified steel studs

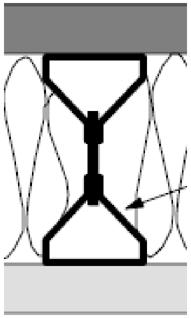
Slotted Studs



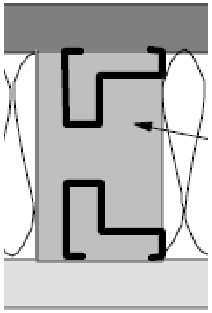
Stud Snuggler Insulated Studs



Triangular Studs

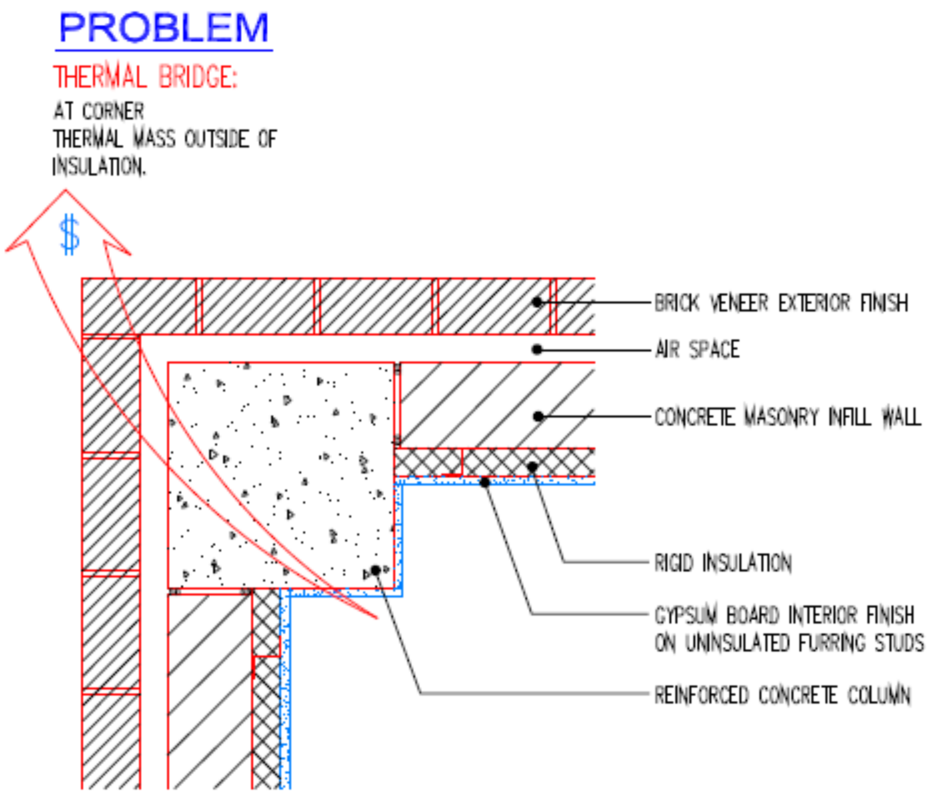


Small Studs + Foam Binder

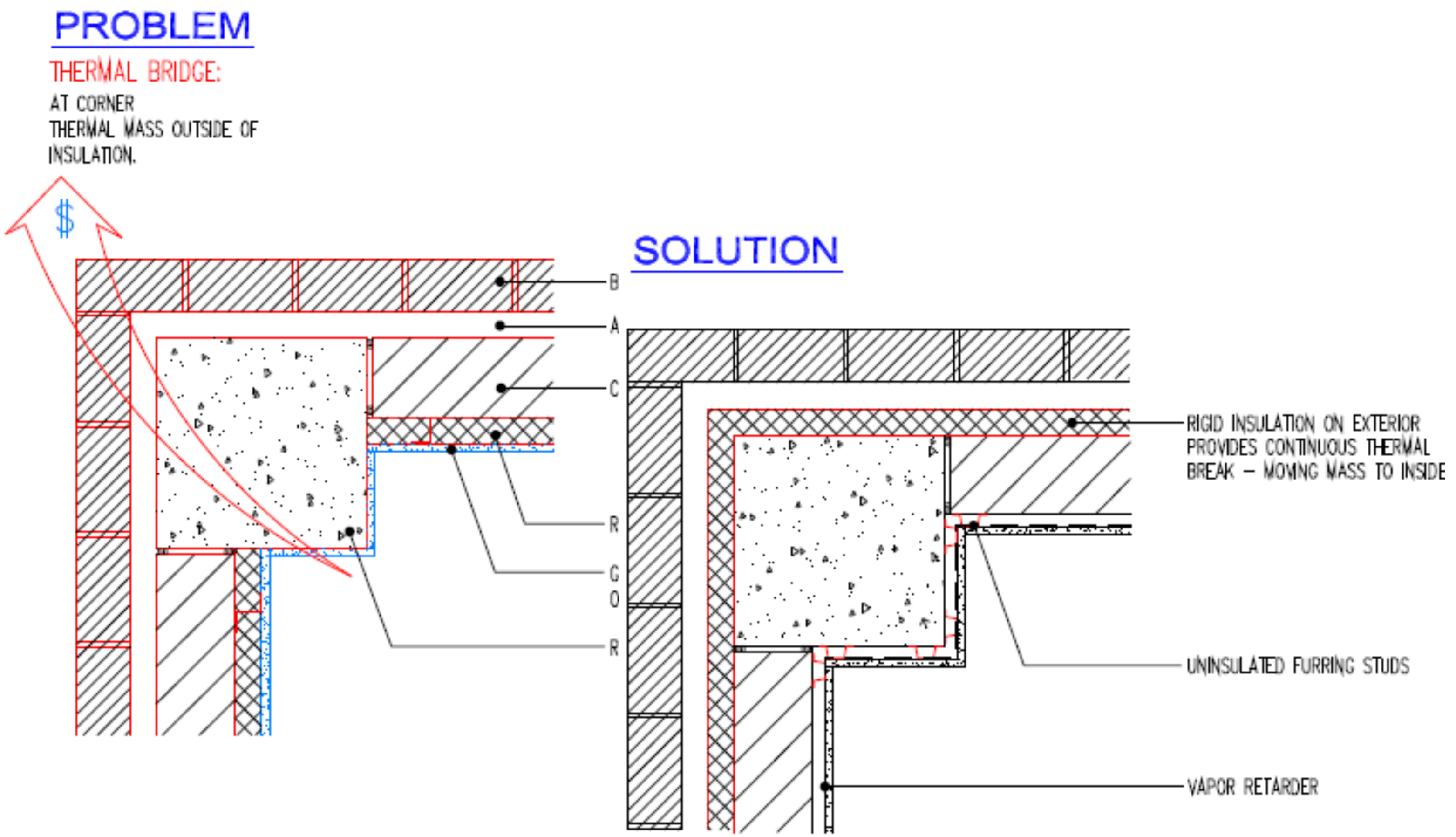


AISI/DOE report from 2003 on alternative steel options with better insulation: http://steeltrp.com/finalreports/finalreports/9703NonPropFinalReport.pdf

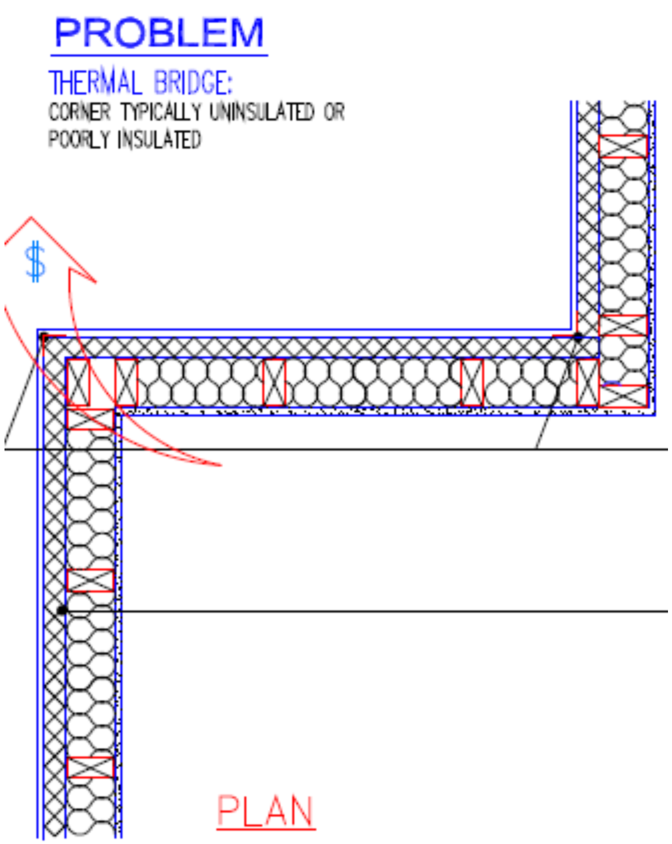
Corner Columns

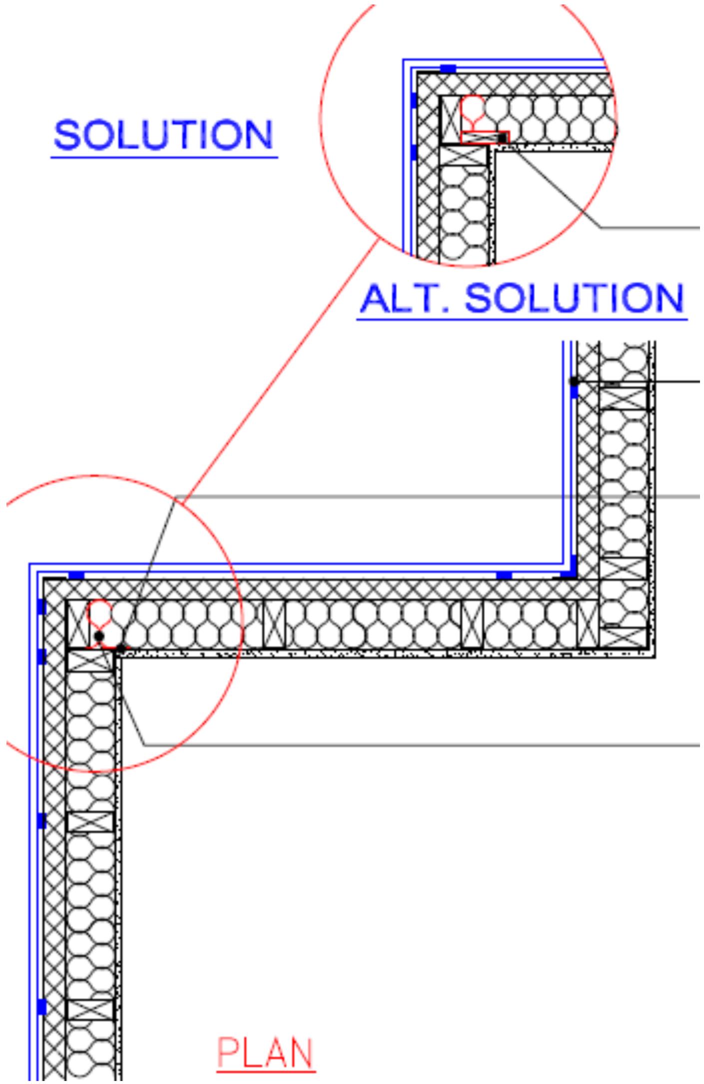


Corner Columns

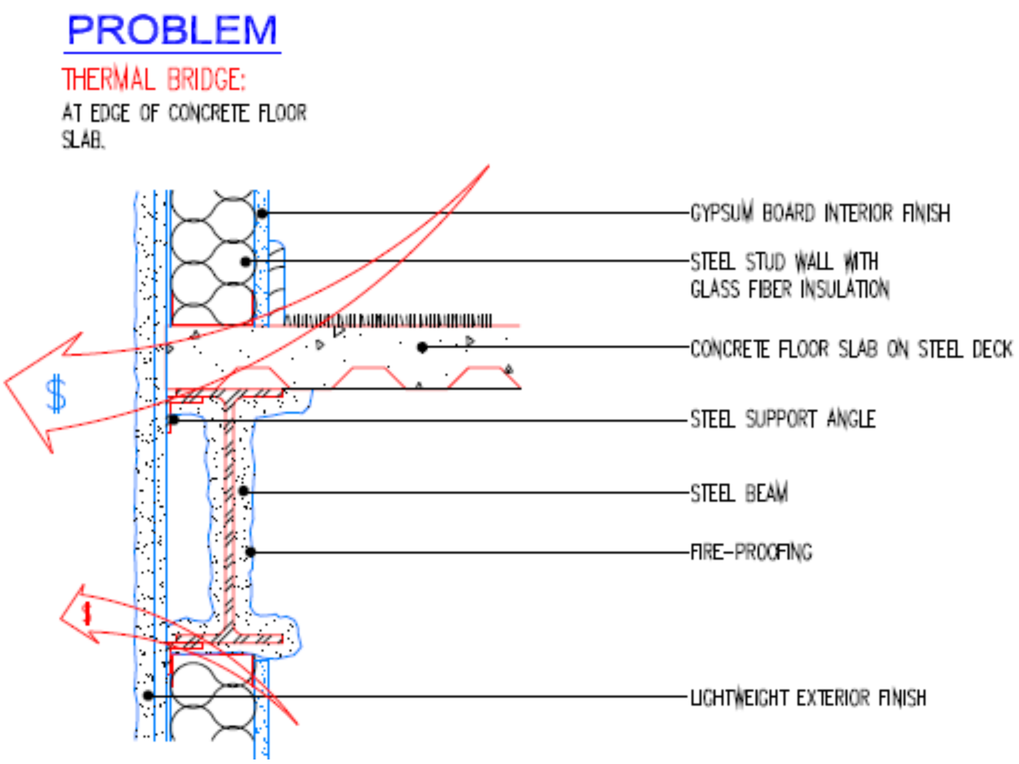


Wood Stud Corners

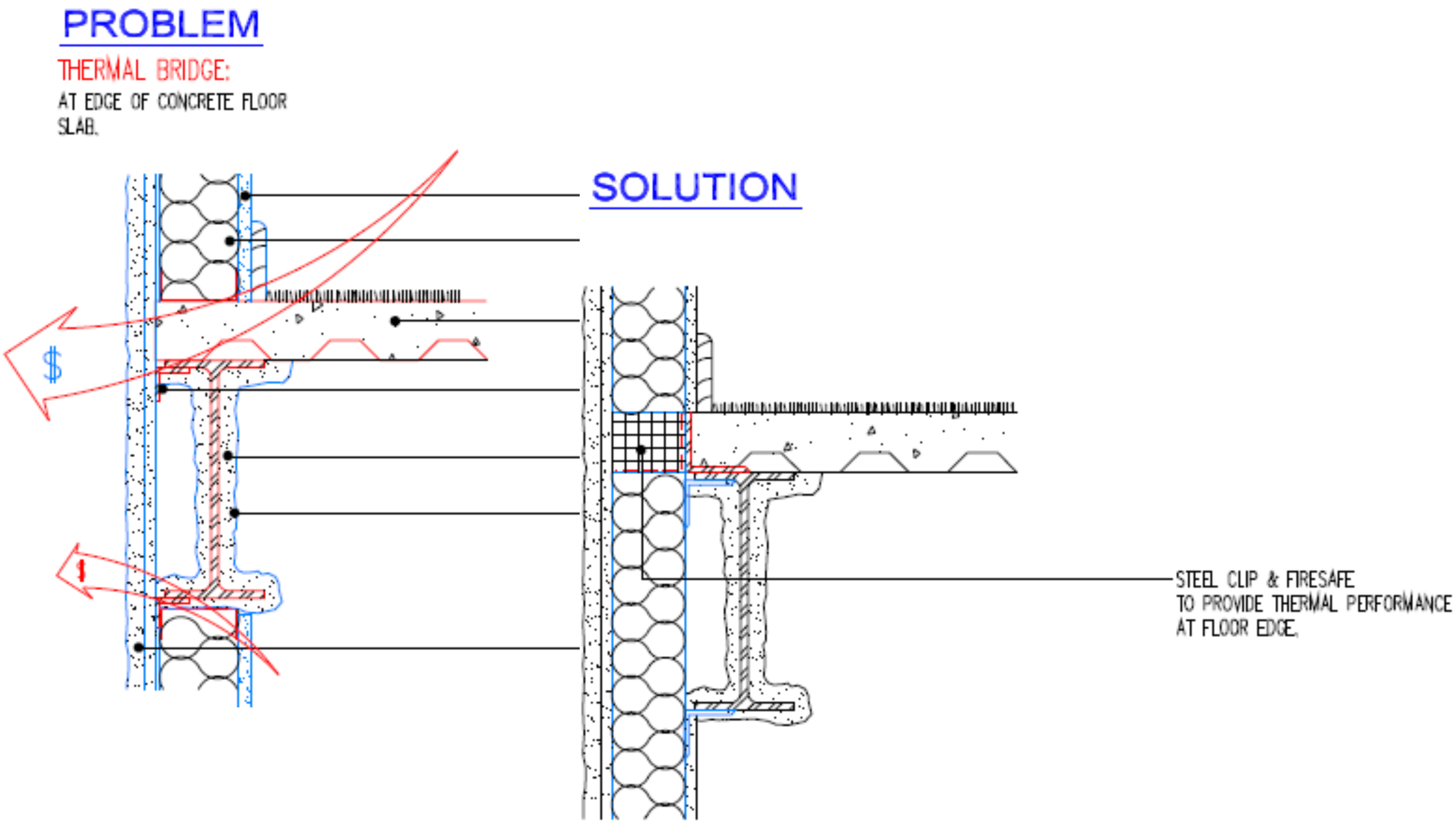




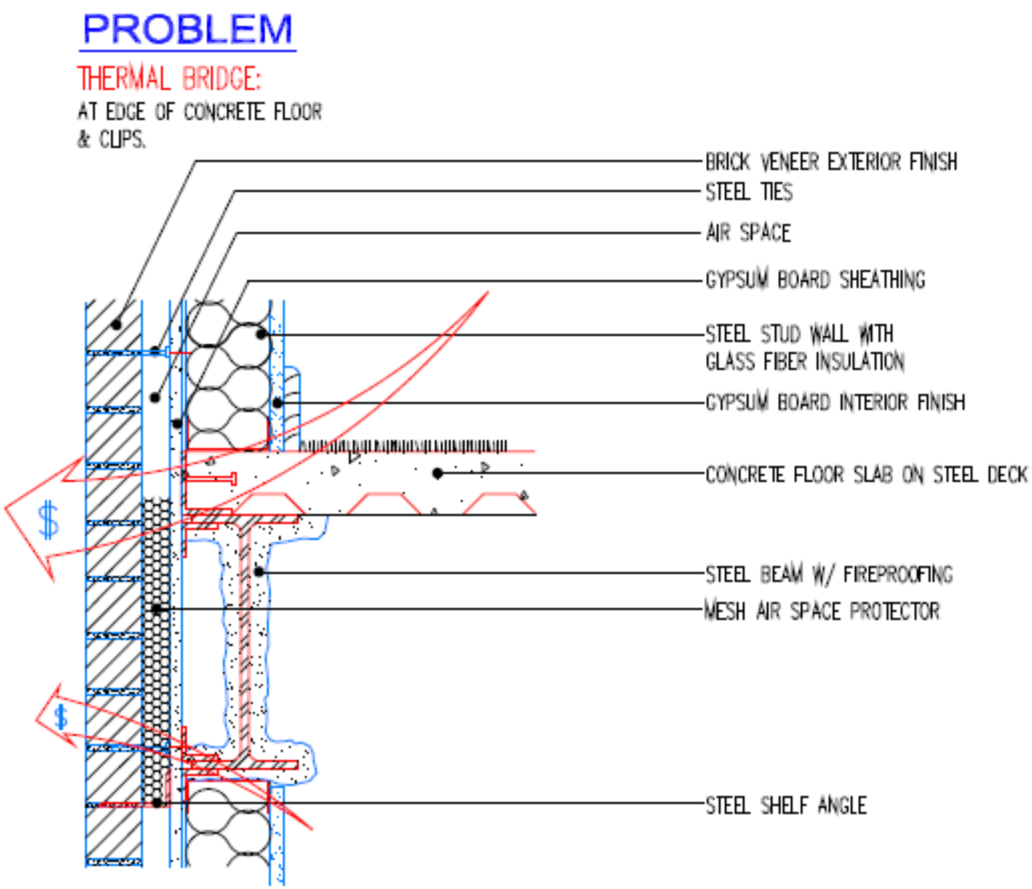
Slab Edge Stud Wall



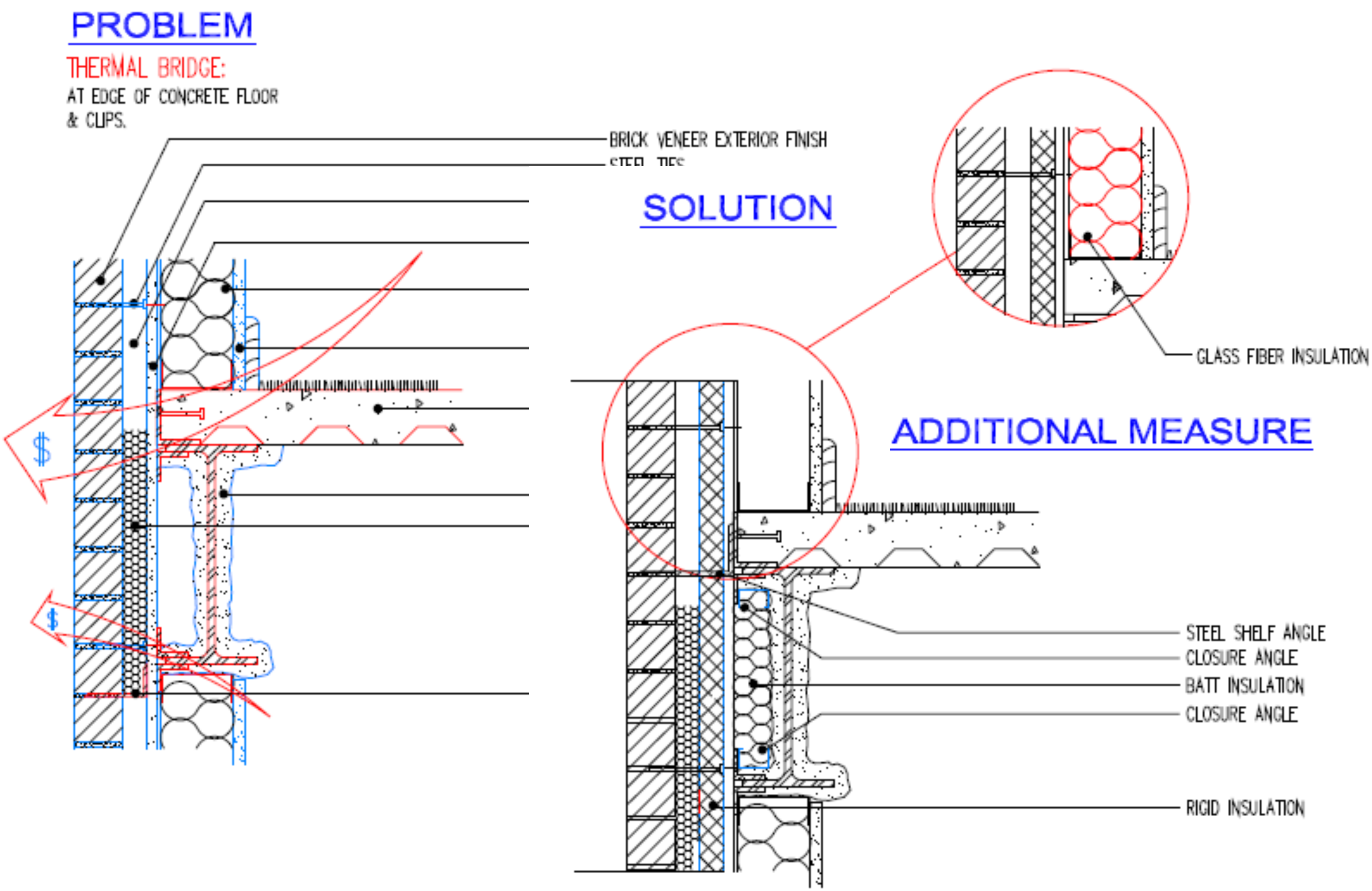
Slab Edge Stud Wall



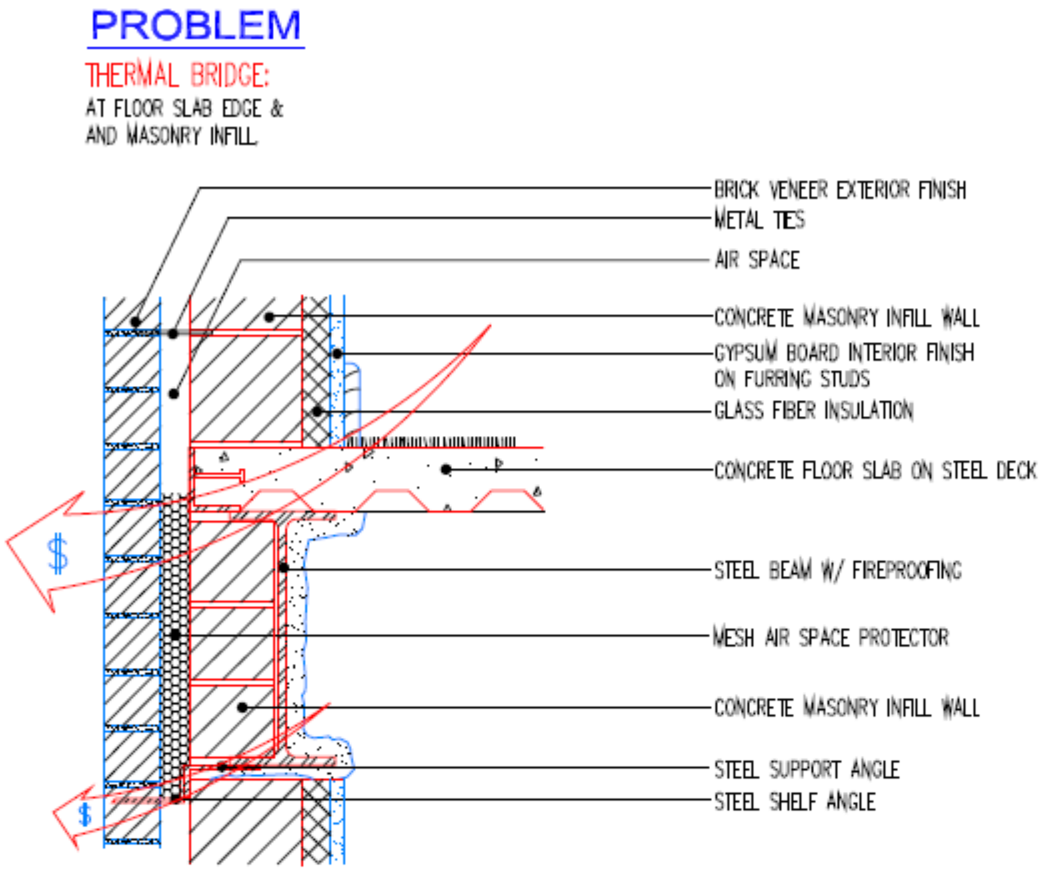
Slab Edge Brick/Stud Wall



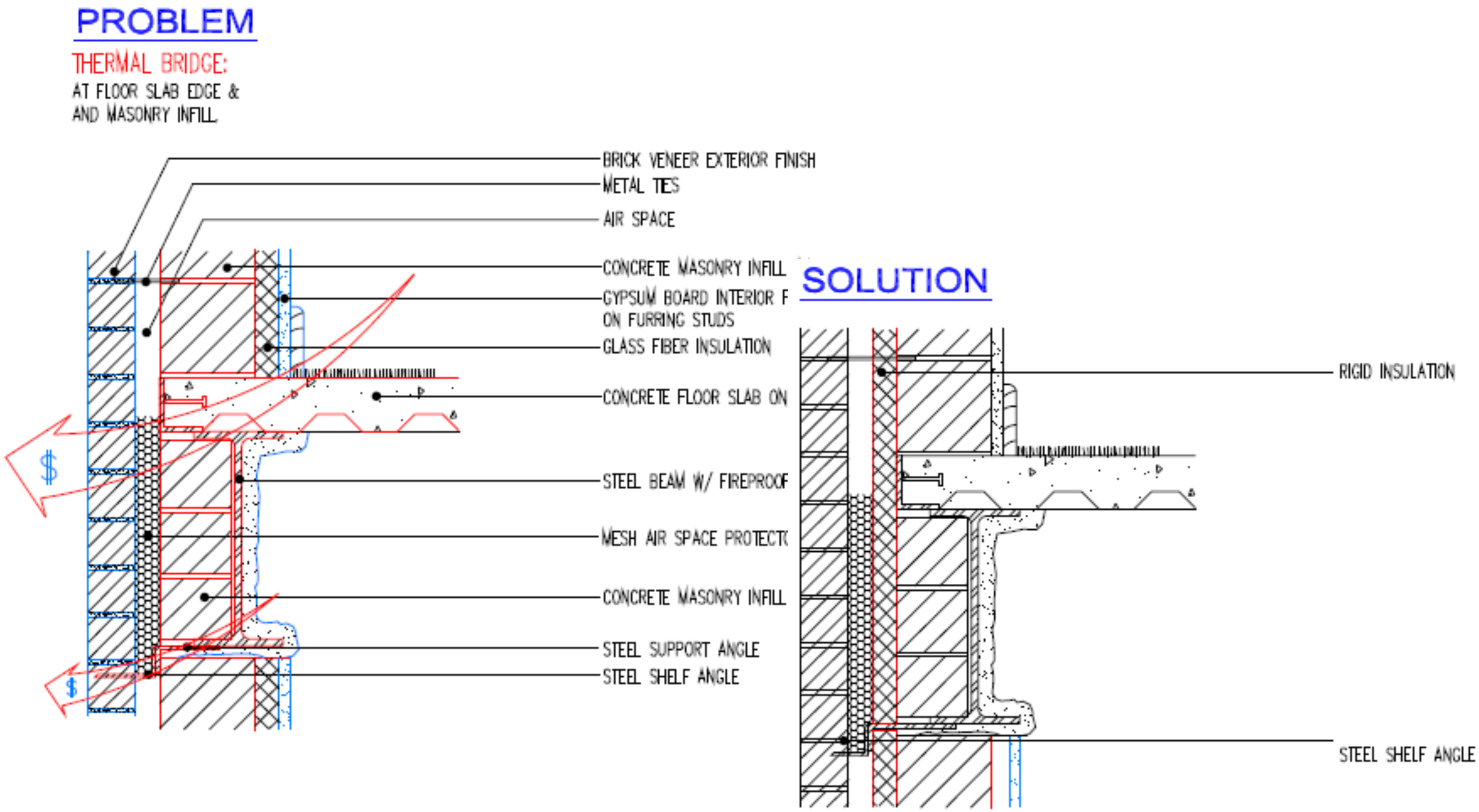
Slab Edge Brick/Stud Wall



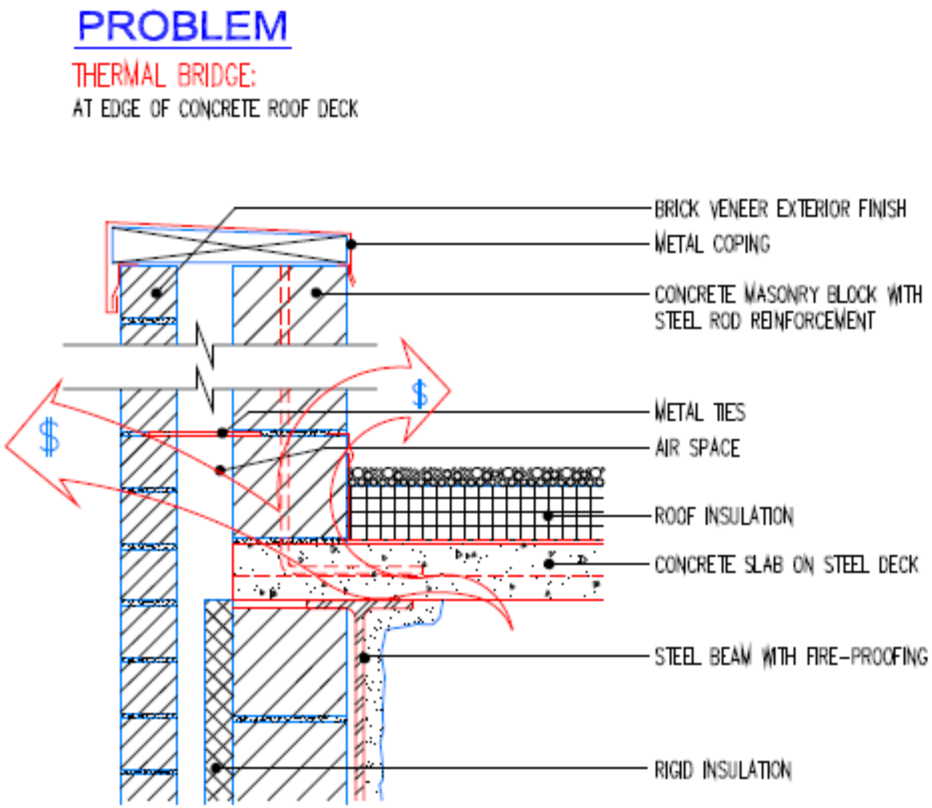
Slab Edge Masonry Wall



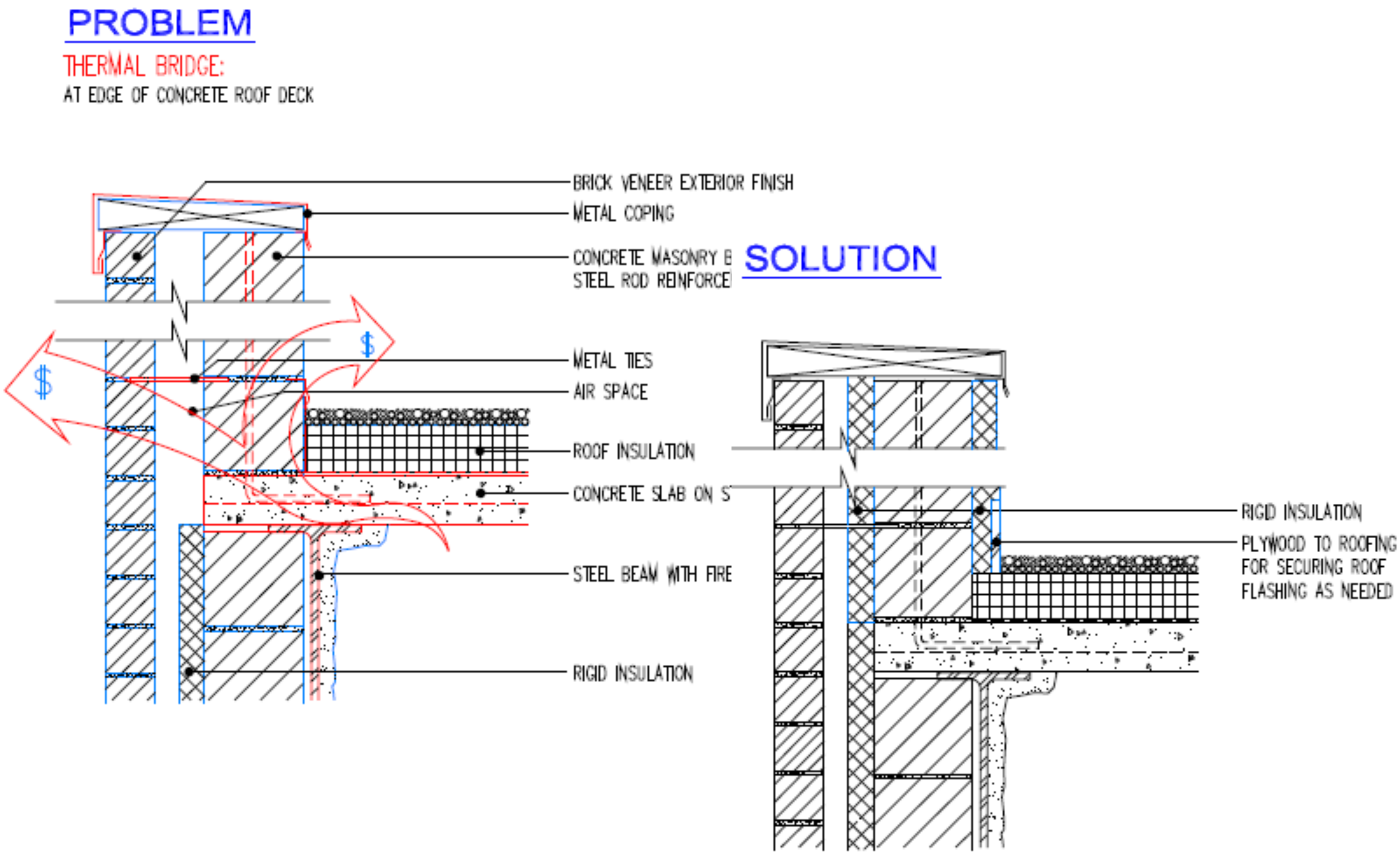
Slab Edge Masonry Wall



Roof Parapet



Roof Parapet

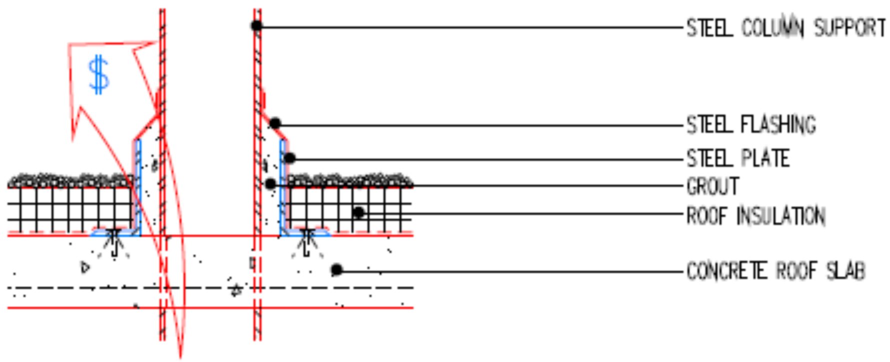


Steel Column Support

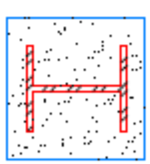
PROBLEM

THERMAL BRIDGE:

AT STEEL EQUIPMENT SUPPORT



SECTION



PLAN

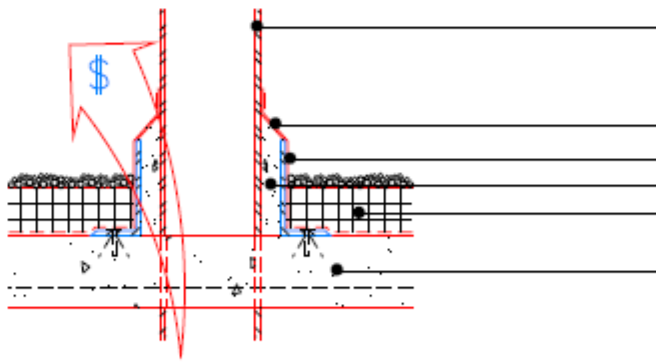
Steel Column Support

PROBLEM

THERMAL BRIDGE:

AT STEEL EQUIPMENT SUPPORT

SOLUTION



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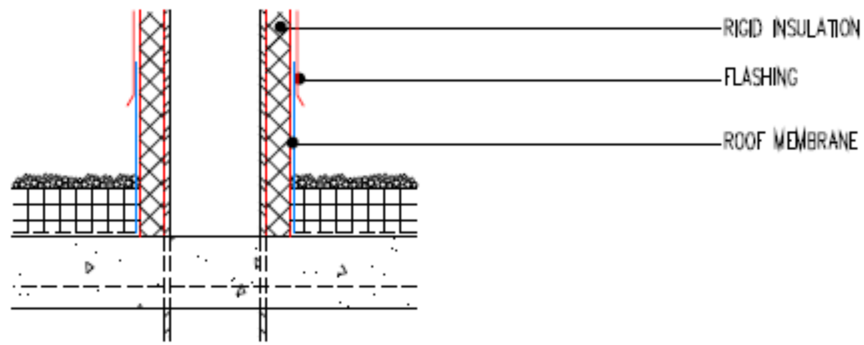
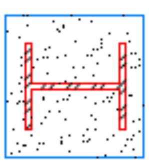


SECTION

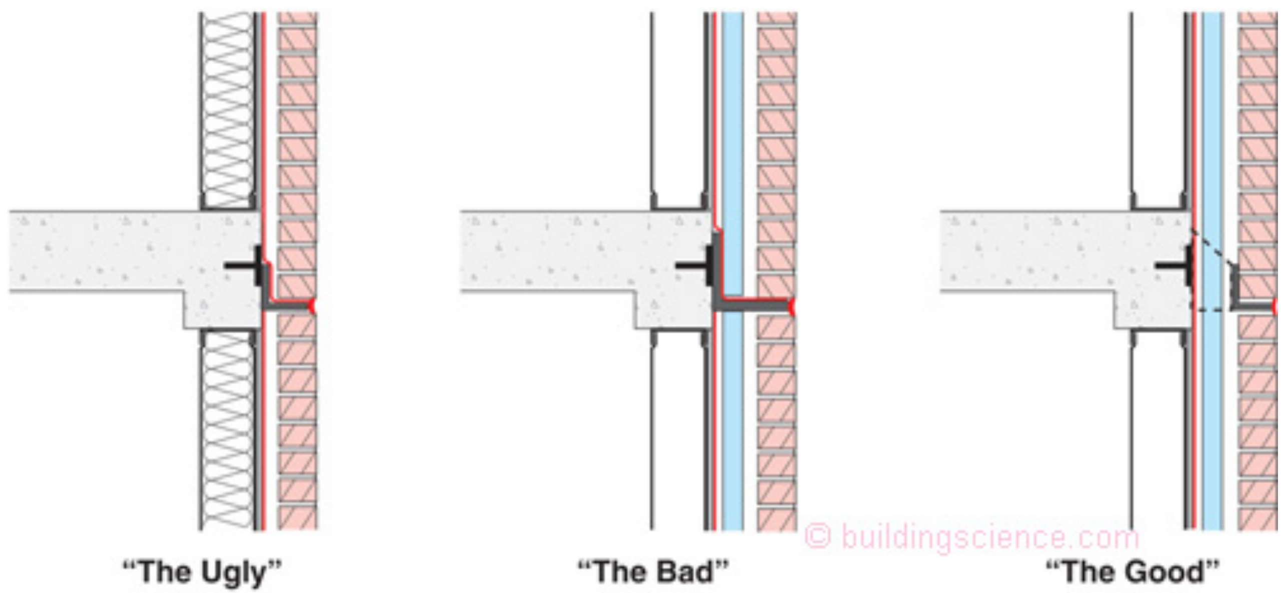


PLAN

PLAN

Exterior Wall Connections

- Exterior veneer connections can also be significant thermal bridges. Here are three different design examples



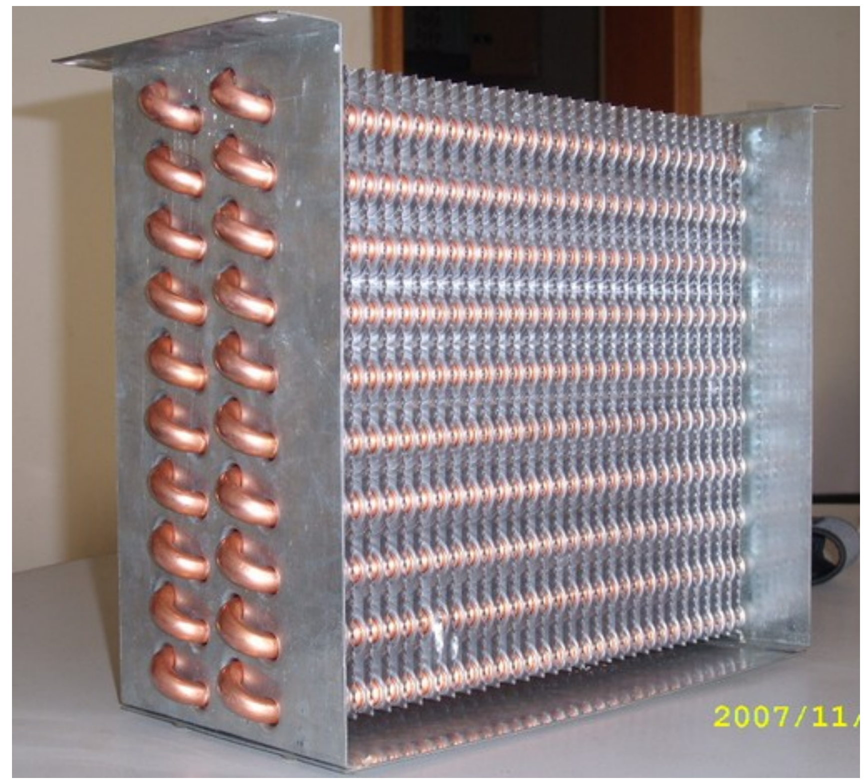
Ultimate Thermal Bridge?

- This cantilevered balcony design provides a thermal connection from the interior to an exterior heating/cooling fin

- The balcony makes a fantastic heat exchanger to make the thermal bridge worse

Ultimate Thermal Bridge?

=



Balconies can act as a heat exchanger – heat exchangers are designed to use fins to increase surface area for heat transfer!

What about this building?

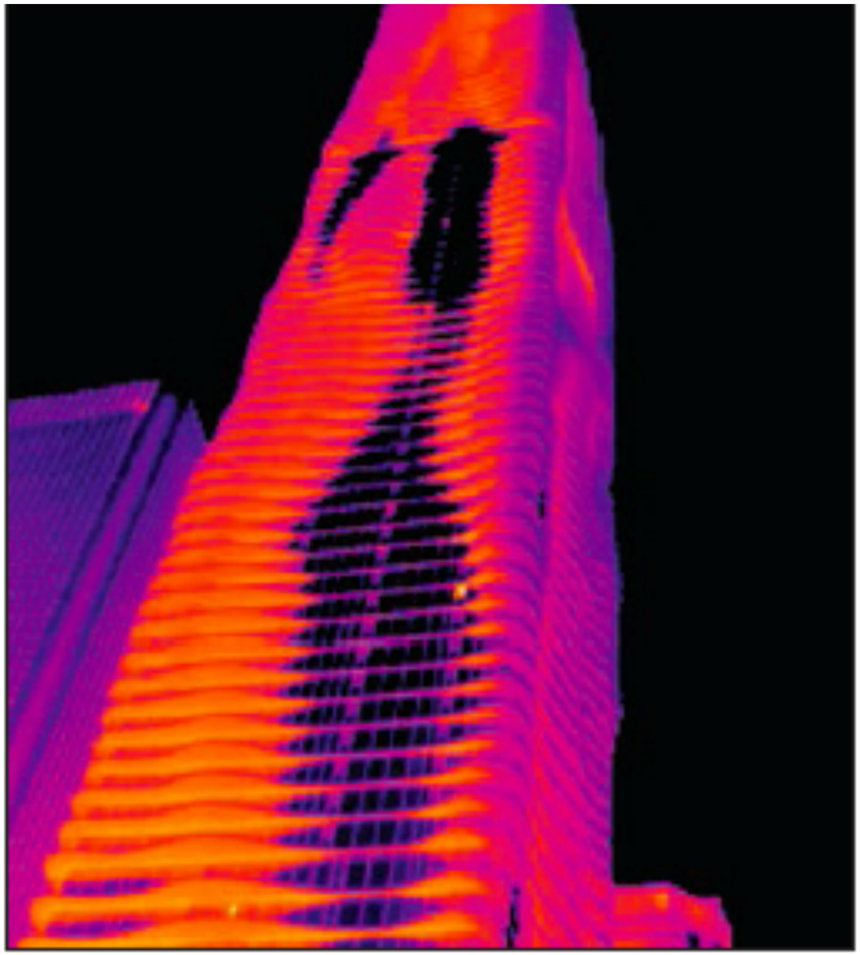
Aqua Tower

- Designed by Jeanne Gang, of Studio Gang

- This design has won many awards but it consists of many cantilevered concrete slabs

- They did NOT use insulated cantilevers
  - Used “insulating paint” which isn’t insulating – it just changes the reflectivity/emissivity/absorptivity
  - May help solar gains in summer but does nothing for conduction, particularly in the winter

“Thermal Bridge Redux” by J. Lstiburek, ASHRAE Journal July 2012



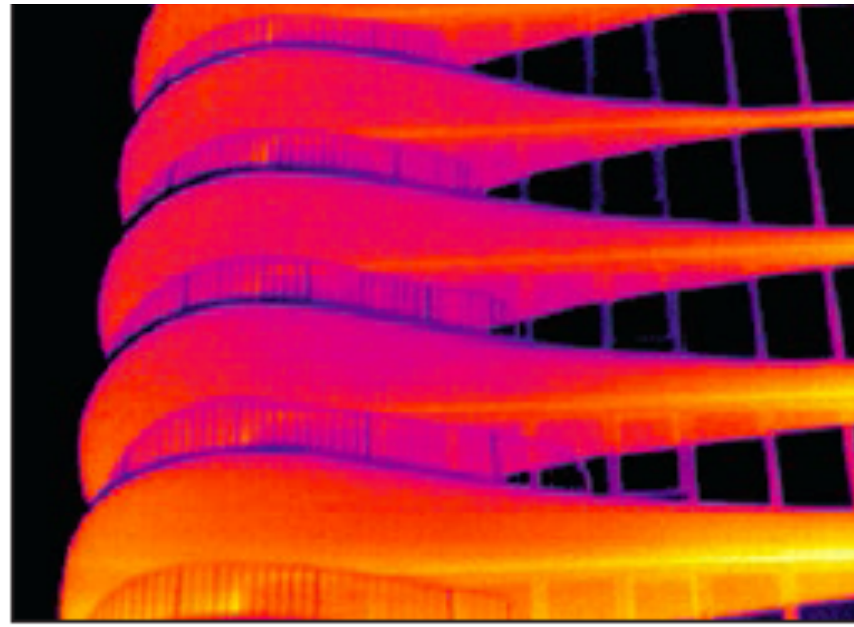


Photo 1f (left): Infrared of Aqua Tower. **Photo 1g (right):** Infrared of Aqua Tower Balcony.

Thermographic images courtesy of Dave Robley, Thermographer, Fluke

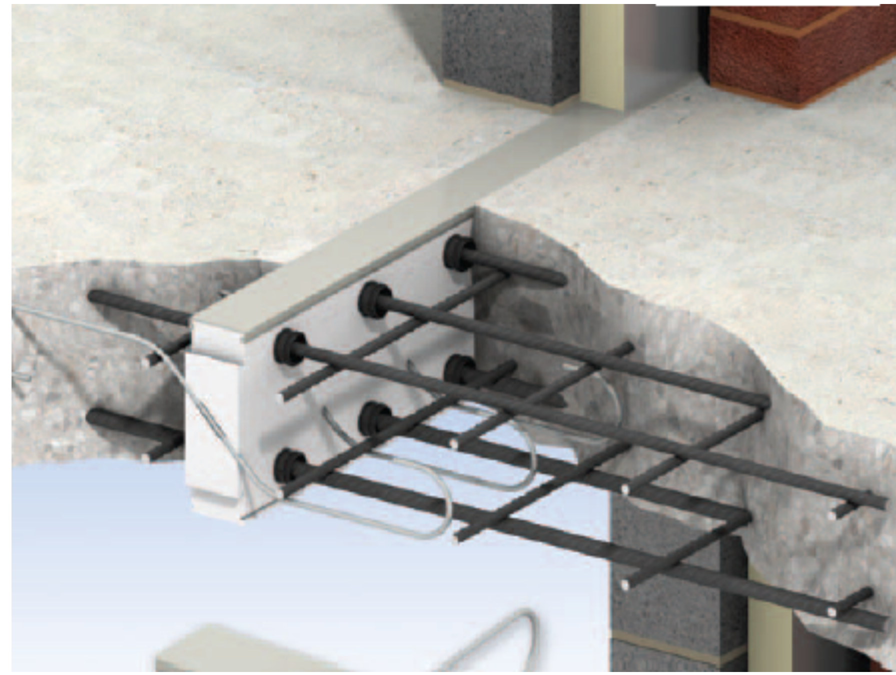
Solution 1: Hanging Balconies

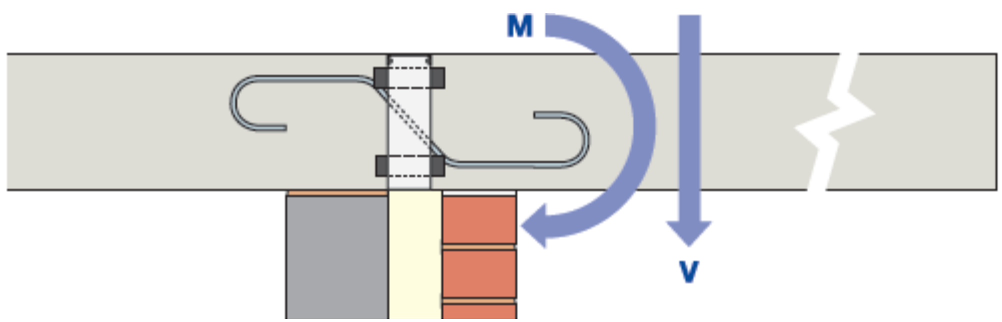
- These balconies are precast concrete that is connected with offset point supports and tie rods
- A foam thermal break is easily incorporated into this design
- Of course, this wouldn't work for the Aqua aesthetic

Solution 2: Insulated Cantilever

- Insulated connectors for balcony cantilevers are now available on the market and used throughout Europe

- Search for:
- Ancon, Egcobox, Halfen





Solution 2: Insulated Cantilever

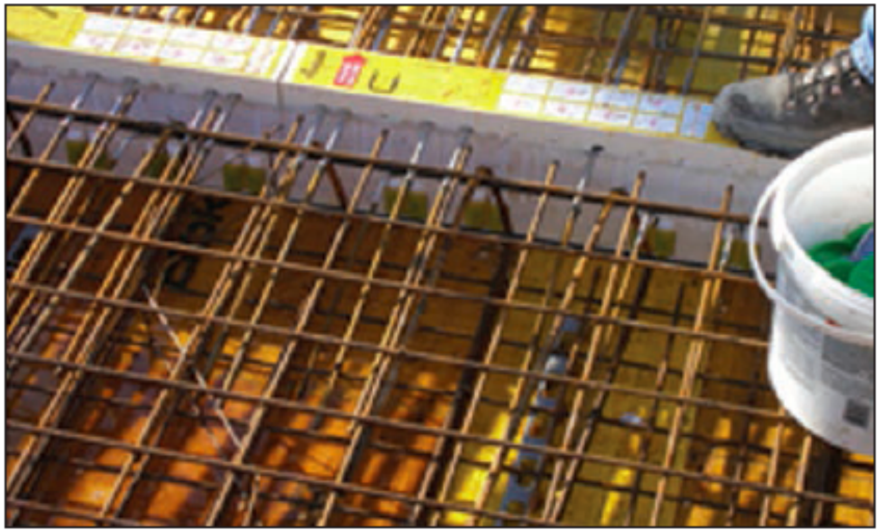


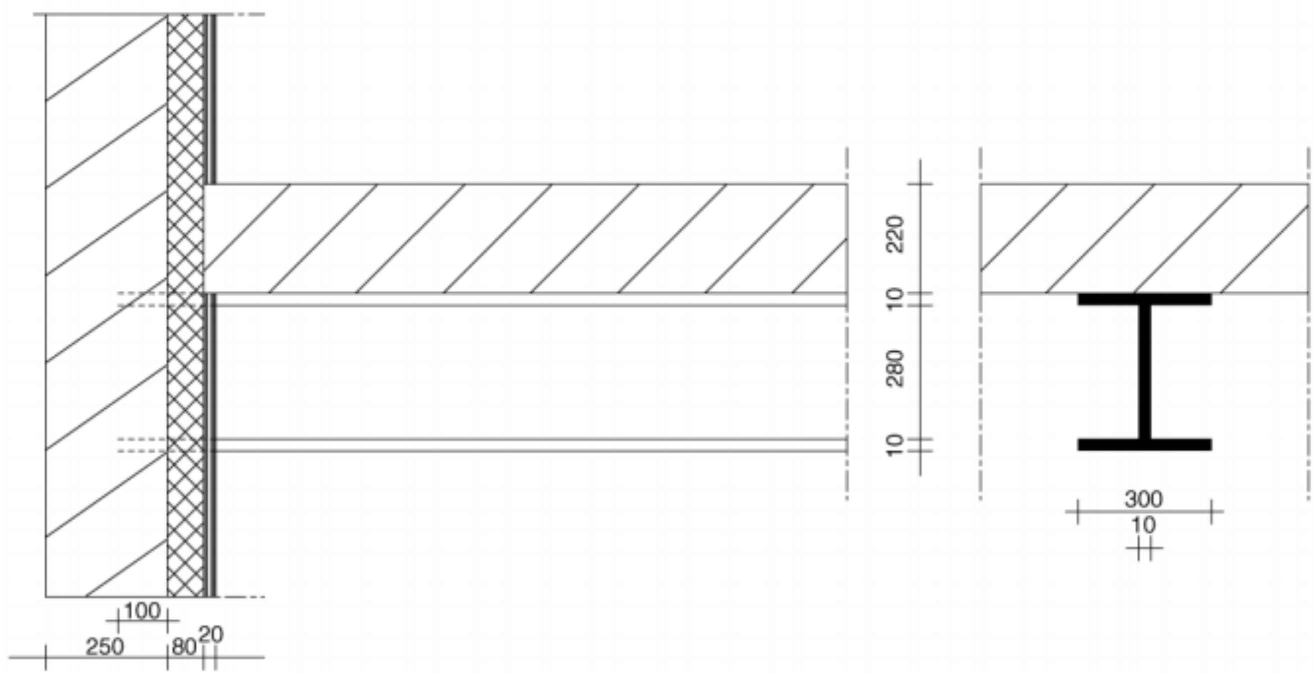
Photo 2: Premanufactured Thermal Break. High density graphite enhanced expanded polystyrene. Note the reinforcing rods penetrating the foam are stainless steel not carbon steel. Stainless steel has less than half the thermal conductivity of carbon steel. Neat, eh? Image courtesy of Schoeck Canada, Inc.

Photo 3: Belgrade Balcony. Nice view of the Danube River from a thermally broken balcony. OK, the river is out there somewhere. I have not been to Serbia recently, but apparently they can afford more efficiency than Chicago. Image courtesy of Beodom, Inc., Belgrade, Serbia.

“Thermal Bridge Redux” by J. Lstiburek, ASHRAE Journal July 2012

Thermal analysis of these even more complex geometries

- How do we estimate U and R values for complex geometries and combinations of materials like this one?



- Simple 1-D calculations can have significant errors
  - Hard (or impossible) to capture all phenomena
- Need to model 2-D or 3-D heat transfer using computer simulations

3. 2-D AND 3-D HEAT TRANSFER USING NUMERICAL SOLVERS

Numerical solutions

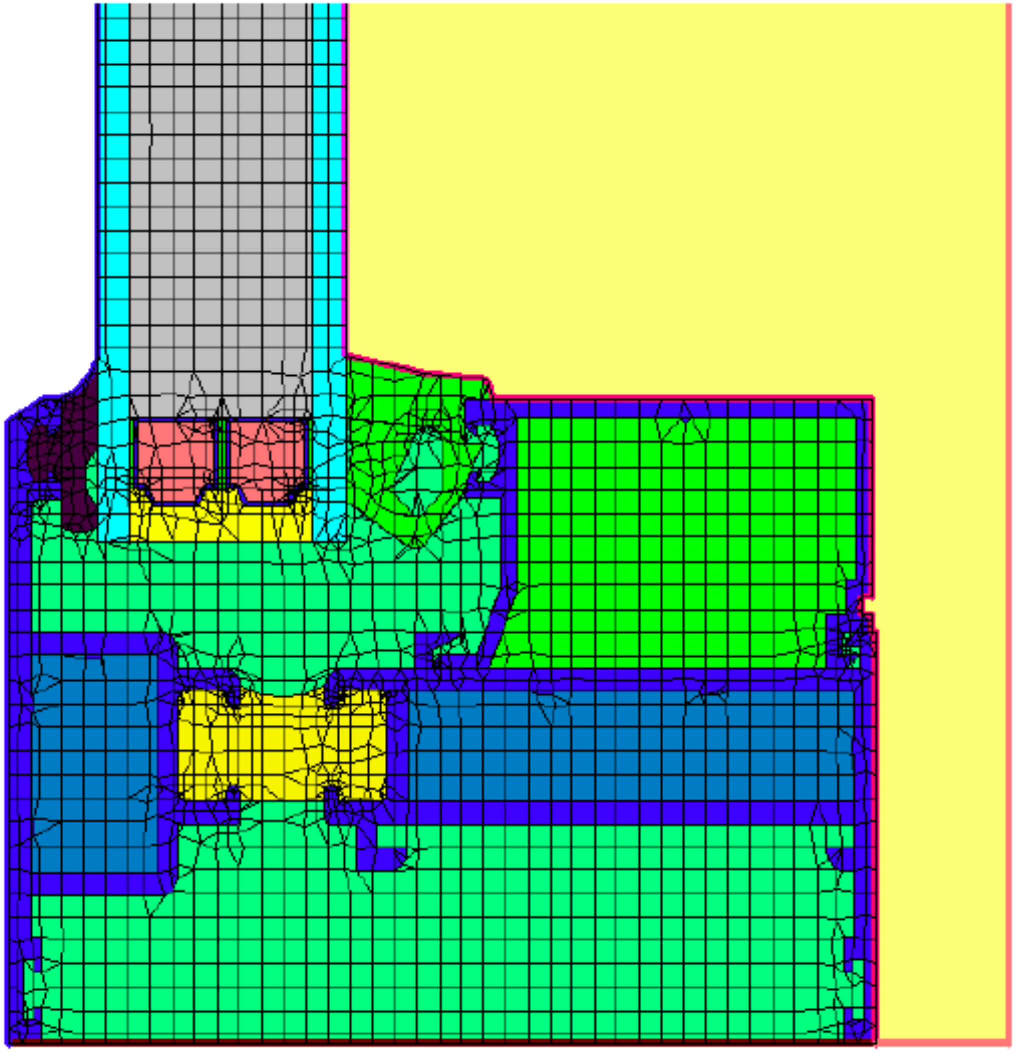
- In addition to our analytical solution methods, there is another way to solve these problems:
  - Numerical analysis using computers

- For assemblies with thermal bridges, it is probably a better solution to utilize finite-element or similar heat transfer software to estimate the U-value, R-value, temperatures in the assembly, and contribution to heating/cooling load

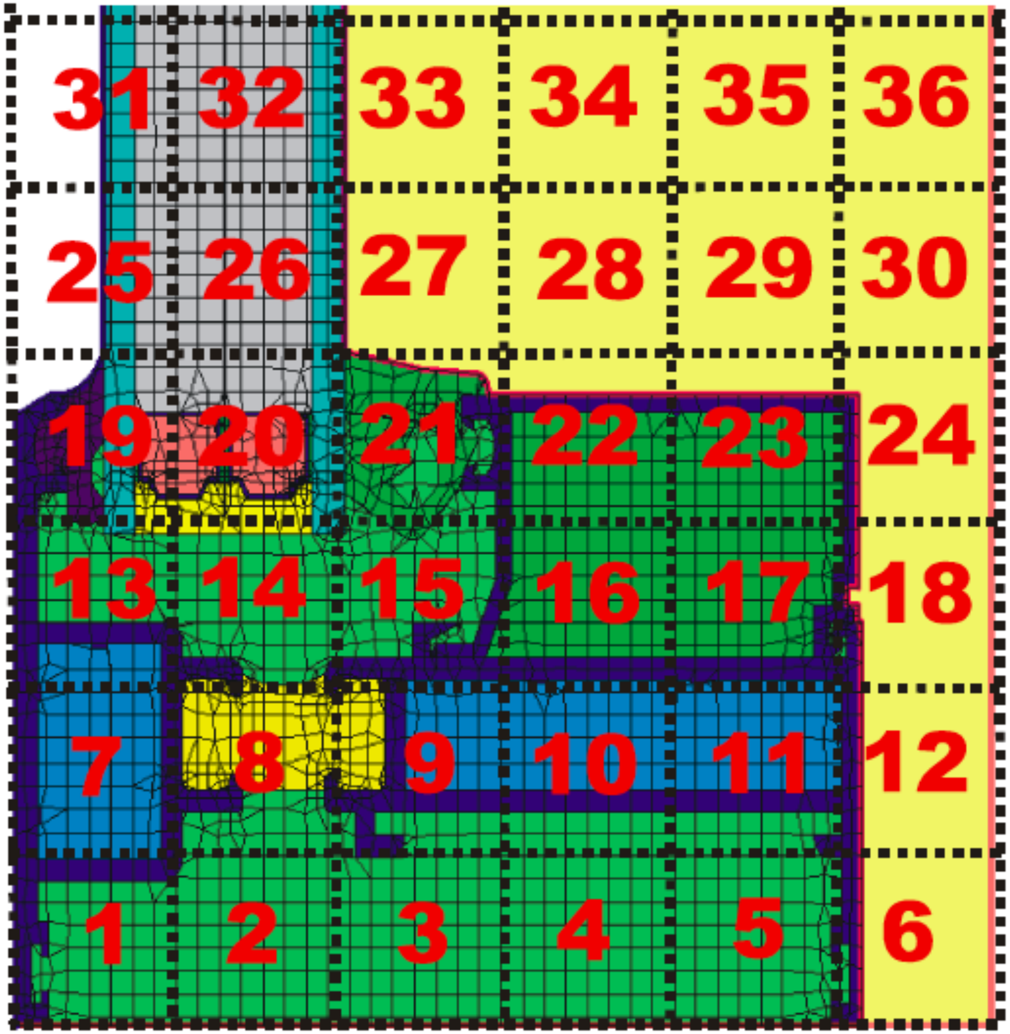
Basic idea

- Break assembly into a hundreds or thousands of homogenous elements
- Use the basic equations of heat transfer and heat balance on each element to create a huge set of simultaneous equations
- Solve the simultaneous equations numerically to find heat flow and temperatures throughout the system

Grid for numerical solver

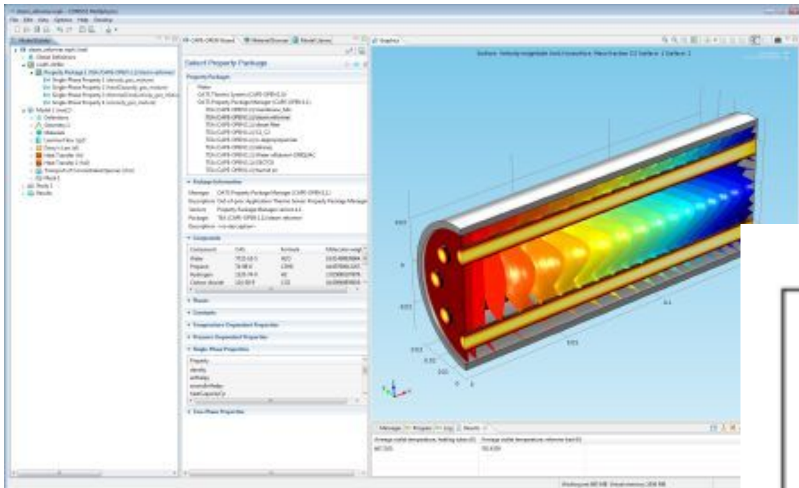


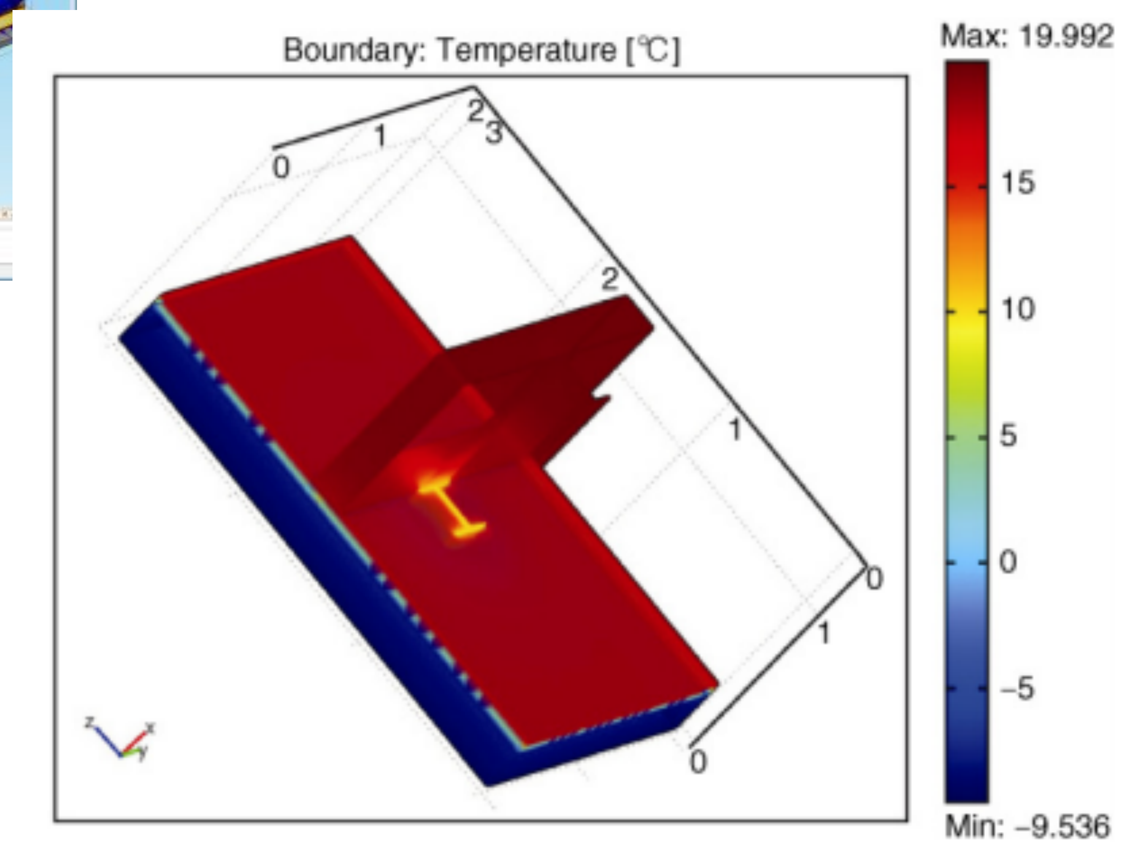
Grid for numerical solver



3-D solvers

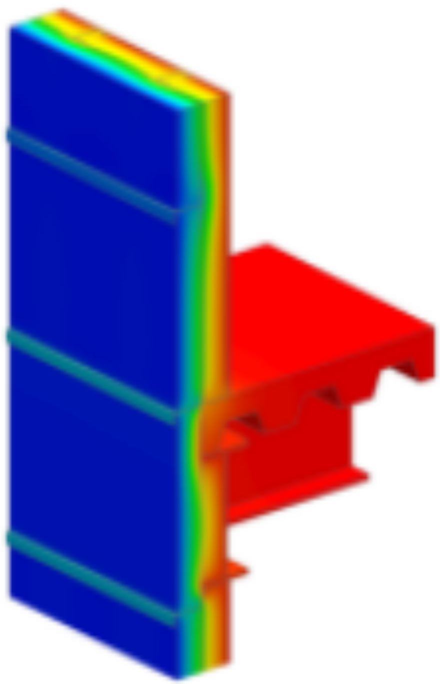
- COMSOL finite element solver

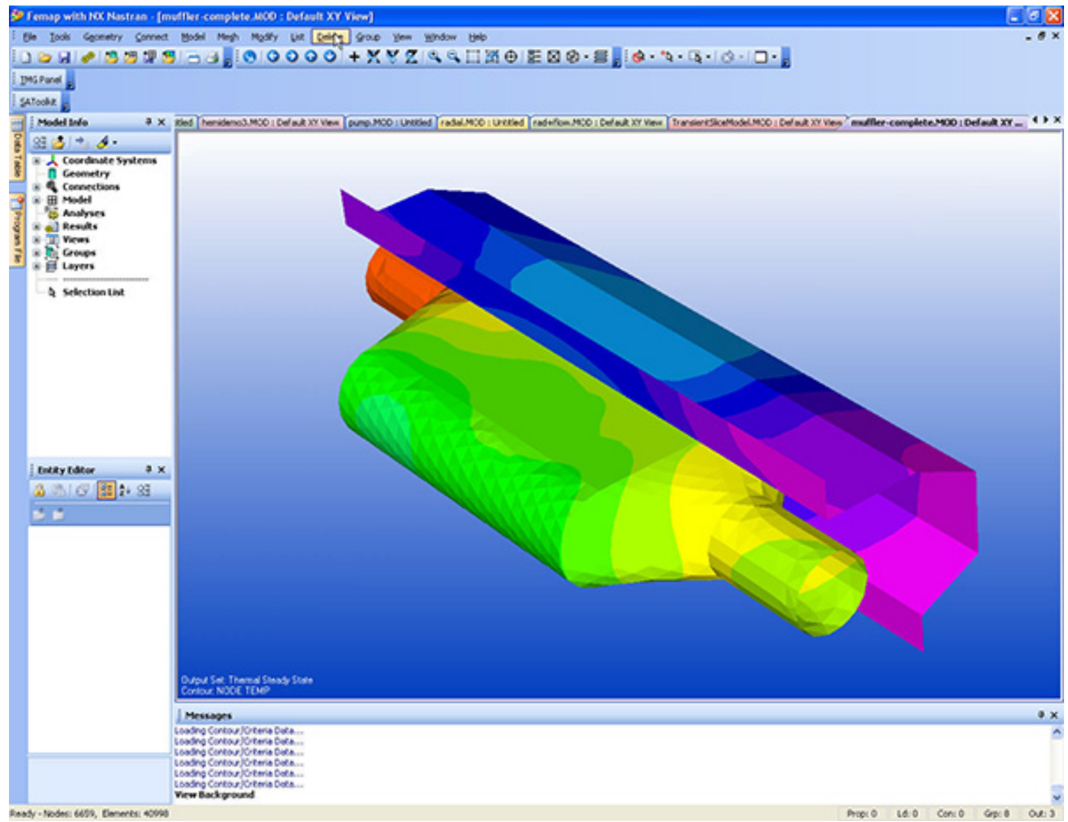




3-D solvers

- Femap finite element analysis





SIEMENS

THERM – popular 2-D solver

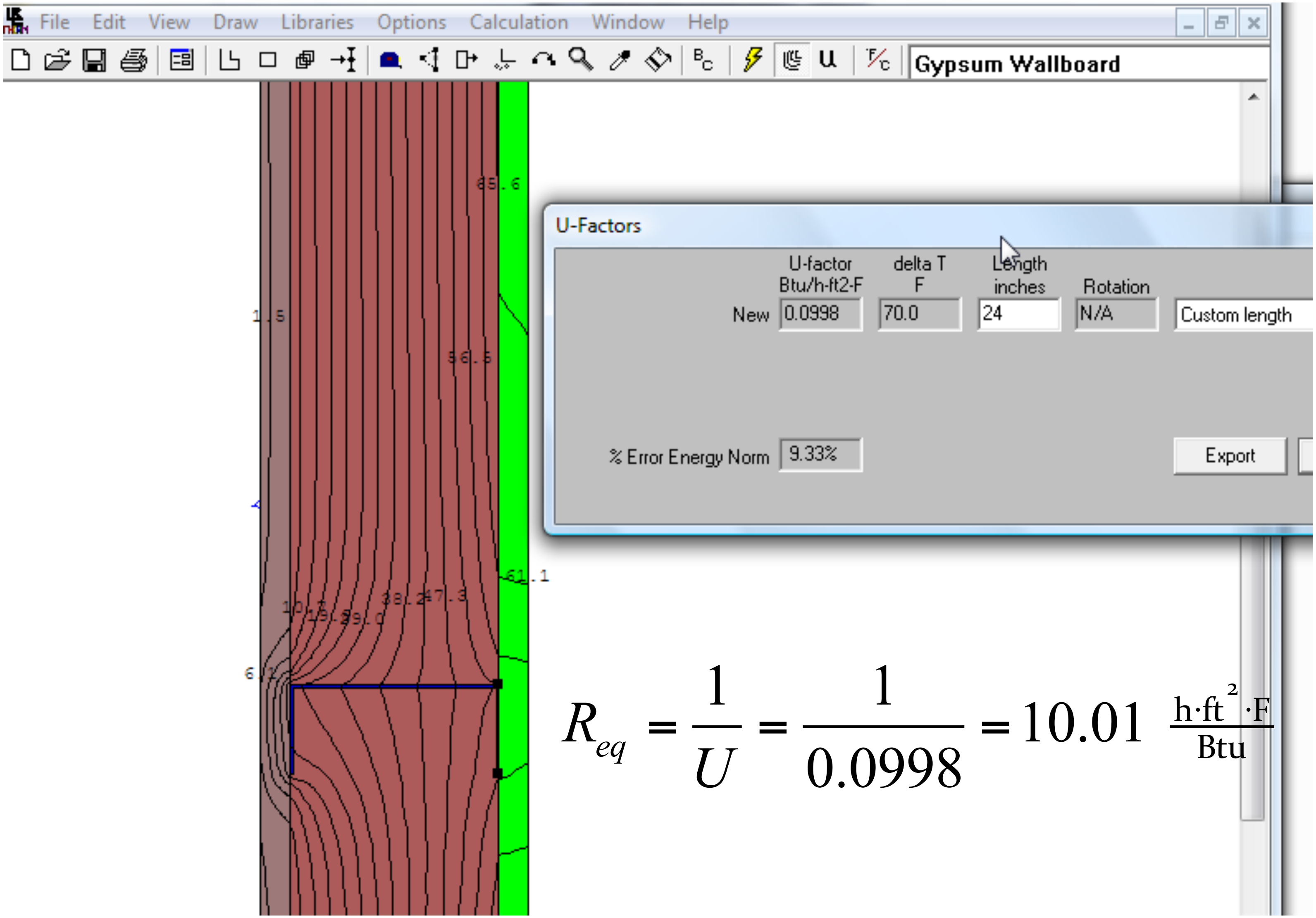
- A very popular 2-D heat transfer program used in the US – especially for window analysis - is called THERM
  - THERM should be installed in the AM 218 CAD Lab
  - URL to download: http://windows.lbl.gov/software/therm/therm.html
  - Requires registration but is FREE
- THERM is used with WINDOW for designing windows
  - But can also be used as a stand alone program for any assembly
  - Very similar 2-D and 3-D programs often used in Europe are called heat2 and heat3
- You will use THERM on HW 3
  - I will show a demo today
  - You may also be able to download from my website: http://built-envi.com/wp-content/uploads/2012/09/THERM63Setup.exe
  - If you have a Mac, you might be able to run using IIT's Virtual Computer Lab: https://vcl.iit.edu/vcl/

Using THERM

- In therm you "draw" out an assembly
  - Assign materials
  - Assign boundary conditions
  - And let the program solve for the temperatures and heat flow throughout the assembly

- The program then can analyze that output to calculate a U value for the entire 2-D assembly
  - You can then calculate R = 1/U for the assembly

Example screenshot: THERM analysis of steel stud



$$R_{eq} = \frac{1}{U} = \frac{1}{0.0998} = 10.01 \ \frac{\text{h}\cdot\text{ft}^2\cdot\text{F}}{\text{Btu}}$$

Governing equations for THERM

1-D Conduction

$$q_{cond} = -k\frac{dT}{dx} = -\frac{k}{L}dT$$

2-D Conduction

$$q_{cond} = -k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

- Energy balance at a surface of each discretized element is the same as previously, except the conduction term contains X and Y components

- Set boundary conditions on interior and exterior and the solver will compute temperature throughout assembly
  - Then it can calculate a U-value for the whole assembly

HW 3 – Using THERM

HW Assignment 3

Due Monday September 24, 2012
50 points total

1) Use THERM to analyze the thermal bridge of a wall.
   (50 total points)

A basic brick veneer-CMU wall intersection with a concrete floor/ceiling element is shown below. The floor-to-floor height of the wall is 10 ft. The brick veneer is on the exterior and the CMU block is on the interior.

Use THERM to:

a) Estimate the overall U-value of the wall section.
   (30 points)

b) Estimate the overall U-value if 2 inches of XPS insulation is added to the wall interior (i.e., to the inside of the CMU block).
   (10 points)

c) Estimate the overall U value if 1 inch of continuous XPS insulation is added to the wall cavity (leaving only a 0.5" air space).
   (10 points)