BUILDING ENERGY 15
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AIA Provider: Northeast Sustainable Energy Association

Provider Number: G338

The Enlightened Structure

Reducing Material-Based Carbon Emissions

Course Number BE1532

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4 March 2015

Credit(s) earned on completion of this course will be reported to AIA CES for AIA members. Certificates of Completion for both AIA members and non-AIA members are available upon request.

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Course Description

The role of a building's structure, and of the structural engineer, in achieving sustainability goals is frequently marginalized. Yet it represents a majority of a new building project's material mass and embodied energy, and is responsible for a large portion of its CO_2e emissions. It can also play a role in the annual energy usage of a building, both in good ways (i.e. thermal mass) and bad (i.e. thermal bridging). This presentation will look at quantifying the CO_2e of conventional structural systems (concrete, steel, masonry, timber), and alternative systems (SIPs, ICFs, strawbale), and what might be done differently, if CO_2e reduction was a design parameter. We will then explore a structural system designed for deconstruction (DfD) and how this approach might influence CO_2e emissions. Finally, we will identify some structural details which can cause significant thermal bridging, and strategies to reduce or eliminate the energy loss resulting from these conditions.

Learning Objectives

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

1. Compare the CO_2e emissions of various structural construction systems.
2. Consider strategies to minimize CO_2e emissions from building structures of various types.
3. Explore the benefits of structural systems designed for deconstruction.
4. Realize the benefits of practical strategies to minimize structural thermal bridging on building envelope energy losses.

Agenda

- Carbon and Structures 20 min.
  - Jim D'Aloisio
- LCA of DfD Structural System 20 min.
  - Mark Webster
- Structures and Thermal Bridging 20 min.
  - Russ Miller-Johnson
- Thermal Bridging of Cladding Systems 20 min.
  - Kara Peterman
- Questions, Answers? 10 min.

Carbon and Structures

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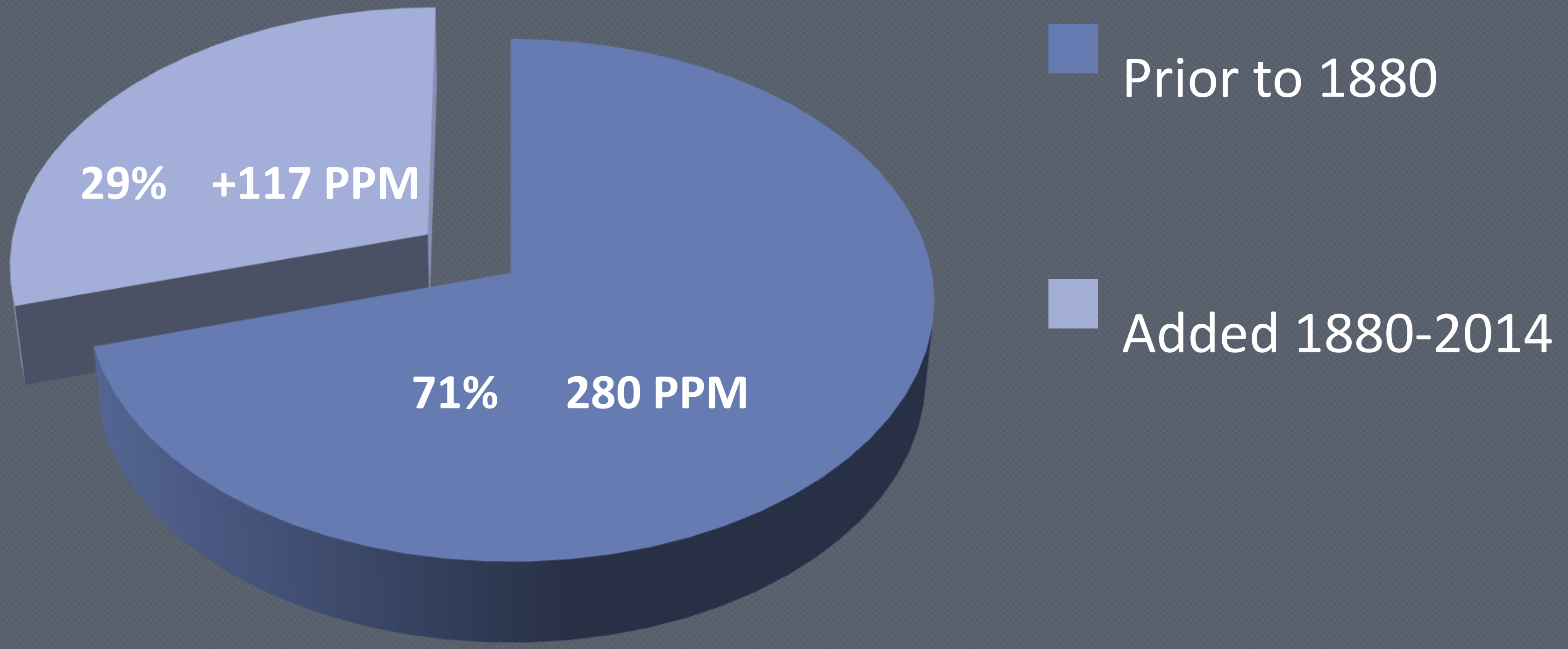
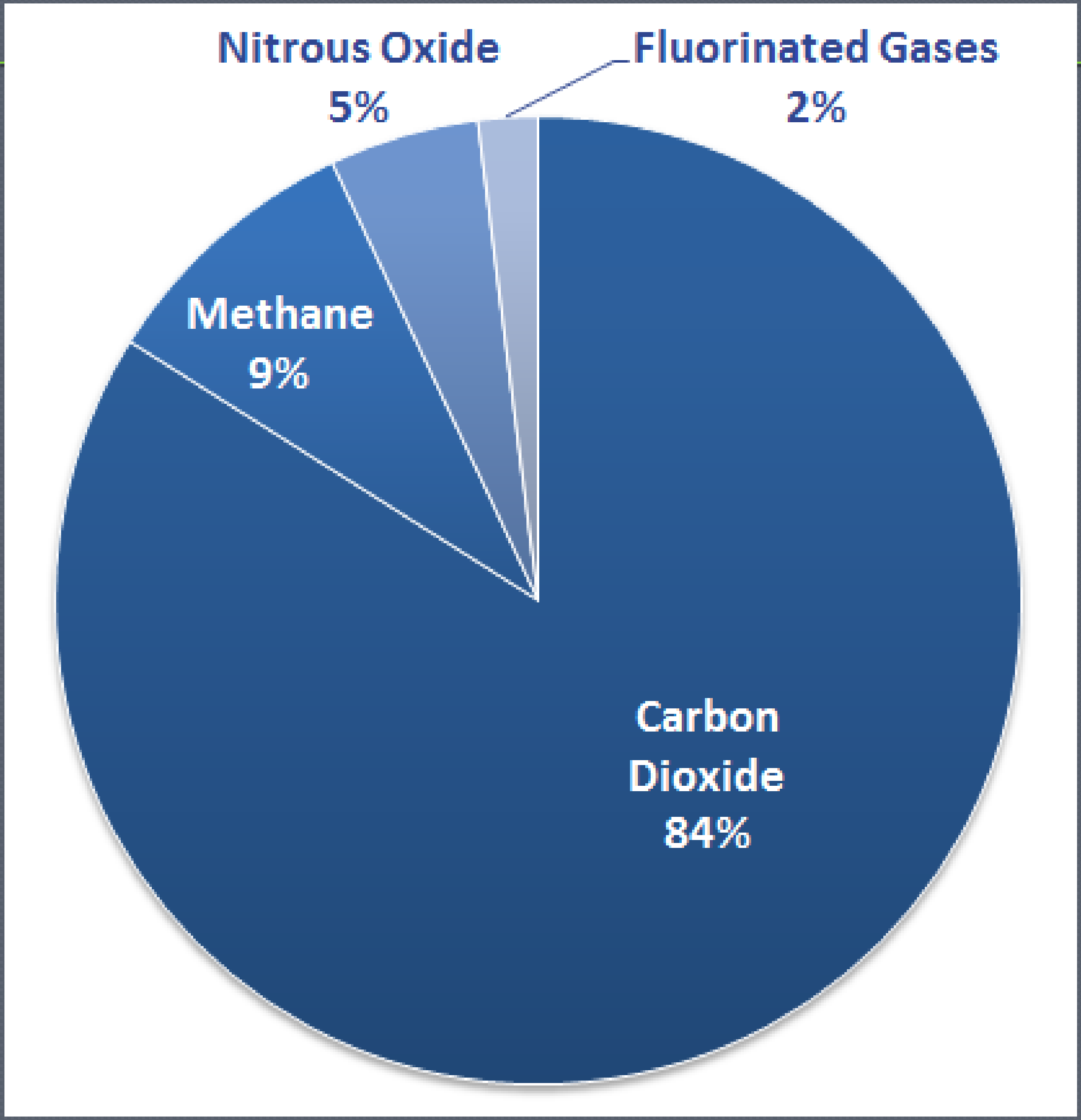
CO_2 Increase Since 1880



41% increase in atmospheric CO_2 since 1880

U.S. Greenhouse Gas Emissions in 2011

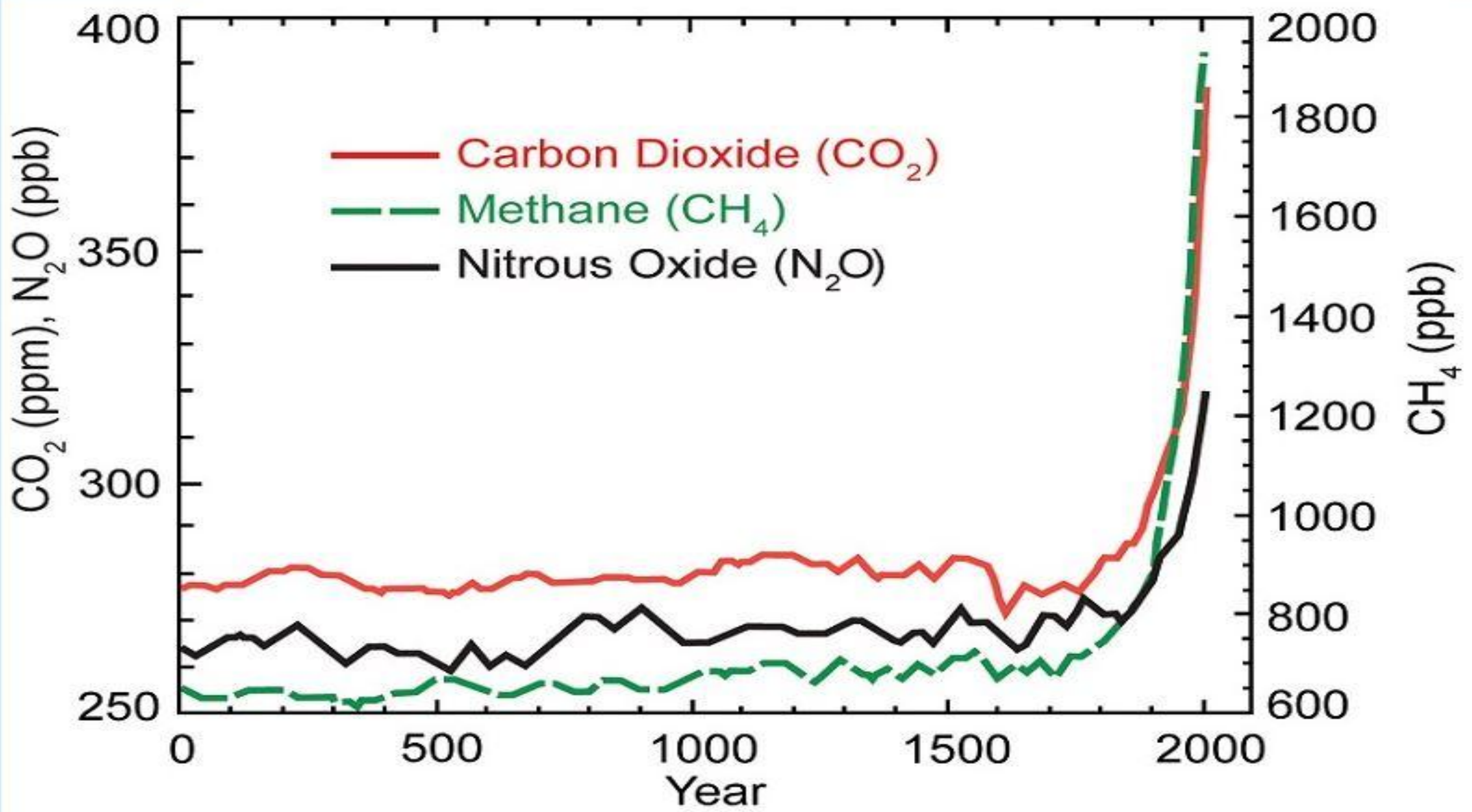


Source: www.epa.gov/ climatechange

GWP Gases

It's not just CO_2!

CO_2-e = Carbon Dioxide Equivalent



This graph shows the increase in greenhouse gas (GHG) concentrations in the atmosphere over the last 2,000 years. Increases in concentrations of these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air.

Carbon Pallet – Concrete

- NRMCA EPD Tally!
  - http://www.nrmca.org/sustainability/EPDProgram/Downloads/NRMCA%20EPD%2010.08.2014.pdf
- Approximations
  - 1.0 lb. CO_2 for every 1 lb. of Portland cement in mix
  - 0.1 lb. CO_2 for every 1 lb. of concrete placed
  - Varies from about 350 to 800 lbs. per cubic yard
- CO_2 Reduction Strategies:
  - Use fly ash & slag, other SCM's
  - Do not over-specify strength or cement content
  - Minimize concrete volume when possible
- Construction – Idling vehicles, worker travel, etc.

Carbon Pallet – Masonry

- Precast Concrete Masonry Units (CMU)
  - Typical footprint similar to concrete
  - Use of fly ash & slag can have significant CO_2 redux
  - Ask your supplier for reduced-cement units. Lightweight?
- Masonry Grout
  - Typical footprint similar to concrete
  - Proportion method results in cement-rich grout
  - Use of fly ash & slag can have significant CO_2 redux
- Other Masonry Products
  - Brick – Clay firing, transportation
  - Stone – Harvesting, finishing, transportation
  - Fly Ash Brick – NO cement, NO firing, transportation

Carbon Pallet – Steel

- Electric Arc Furnace
  - Rolled sections, reinforcing bars, OWSJ's
  - Averages around 0.85 lbs. CO_2 per lb. of steel
- Basic Oxygen Furnace
  - Hollow sections, sheet metal
  - Averages around 1.2 lbs. CO_2 per lb of steel
- Reused (Salvaged) Structural Steel
  - Not commonly considered – steel is normally recycled and recast, not reused
  - Feasibility - and cost - depends on availability
  - Can reduce CO_2 footprint from 1.0 lbs./lb. to 0.1 lbs./lb.
  - Must be "clean," inspected, shipped, fabricated, shipped

Carbon Pallet - Assumptions

- For Insulation:
  - 100% of blowing agents included in tally
  - XPS assumed HFC-134a
- For wood – value of carbon sequestration during its service life is not included
- Nominal amount of waste assumed
- Nominal worker travel assumed

Insulation Material	R-value R/inch	Density lb/ft³	Emb. E MJ/kg	Emb. Carbon $kgCO_2/kg$	Emb. Carbon $kgCO_2/ft^2 \cdot R$	Blowing Agent (GWP)	Bl. Agent kg/kg foam	Blowing Agent GWP/bd-ft	Lifetime GWP/ $ft^2 \cdot R$
Cellulose (dense-pack)	3.7	3.0	2.1	0.106	0.0033	None	0	N/A	0.0033
Fiberglass batt	3.3	1.0	28	1.44	0.0165	None	0	N/A	0.0165
Rigid mineral wool	4.0	4.0	17	1.2	0.0455	None	0	N/A	0.0455
Polyisocyanurate	6.0	1.5	72	3.0	0.0284	Pentane (GWP=7)	0.05	0.02	0.0317
Spray polyurethane foam (SPF) – closed-cell (HFC-blown)	6.0	2.0	72	3.0	0.0379	HFC-245fa (GWP=1,030)	0.11	8.68	1.48
SPF – closed-cell (water-blown)	5.0	2.0	72	3.0	0.0455	Water (CO_2) (GWP=1)	0	0	0.0455
SPF – open-cell (water-blown)	3.7	0.5	72	3.0	0.0154	Water (CO_2) (GWP=1)	0	0	0.0154
Expanded polystyrene (EPS)	3.9	1.0	89	2.5	0.0307	Pentane (GWP=7)	0.06	0.02	0.036
Extruded polystyrene (XPS)	5.0	2.0	89	2.5	0.0379	HFC-134a[1] (GWP=1,430)	0.08	8.67	1.77

1. XPS manufacturers have not divulged their post-HCFC blowing agent, and MSDS data have not been updated. The blowing agent is assumed here to be HFC-134a.

GWP of Insulation Types

Source: BuildingGreen

Snapshot: Jobsite Labor

Hypothetical Labor Situation

12 workers, driving
12 trucks that get
12 mpg,
12 miles to and from jobsite, for
12 weeks….

$12 \cdot 20$ lbs. CO_2/g/12 mi./g $\cdot$ 12 mi. $\cdot$ 12 $\cdot$ 5 =

14,400 lbs. CO_2

De-Materialization

- Reducing quantity of material usage on a building project
- A ton of steel saved is a ton of steel CO_2-e footprint eliminated.
- Must maintain function, safety, redundancy
- Considerations include maintaining versatility, flexibility, future usage and adaptability.
- Usually requires more engineering effort
- May or may not be cheaper than the use of slightly oversized, repetitive similar units

Example Prototype Building

- Two-story office building
- Footprint: 80 X 125 = 10,000 sf
- Perimeter: 2 X (80 + 125) = 410 lf
- 12.2’ floor-floor → 410 X 12.2 X 2 = 10,000 sf
- Fenestration on 20% of walls
  - Opaque walls: 80% X 10,000 = 8000 sf
  - Fenestration: 20% X 10,000 = 2000 sf

Example Prototype Building (cont.)

- ROOF
  - Single-Ply Roofing System: EPDM, EPS, recovery board, VB - 10,000 sf
  - Roof Deck: 20 ga. galv. steel roof deck – 10,000 sf
  - Roof Joists: 2.5 psf x 10,000 - 25,000 lbs.
  - Steel Framing: girders, spandrels, columns, bracing, lintels, etc.: 3 psf X 10,000 - 30,000 lbs.
- SECOND FLOOR
  - Concrete Floor Slab: 4000 psi, 2.75” effective thickness -
  - Composite Steel Deck: 1½” 20 ga. – 10,000 sf
  - Slab Reinforcing: #4@16” both ways for 10,000 sf
  - Steel Framing: purlins, girders, spandrels, columns, bracing, lintels, 2 sets of stairs, etc.
- FIRST FLOOR
  - Concrete Floor Slab: 5” thick, 3000 psi
  - Slab Reinforcing: #4@16” both ways

Example Prototype Building (cont.)

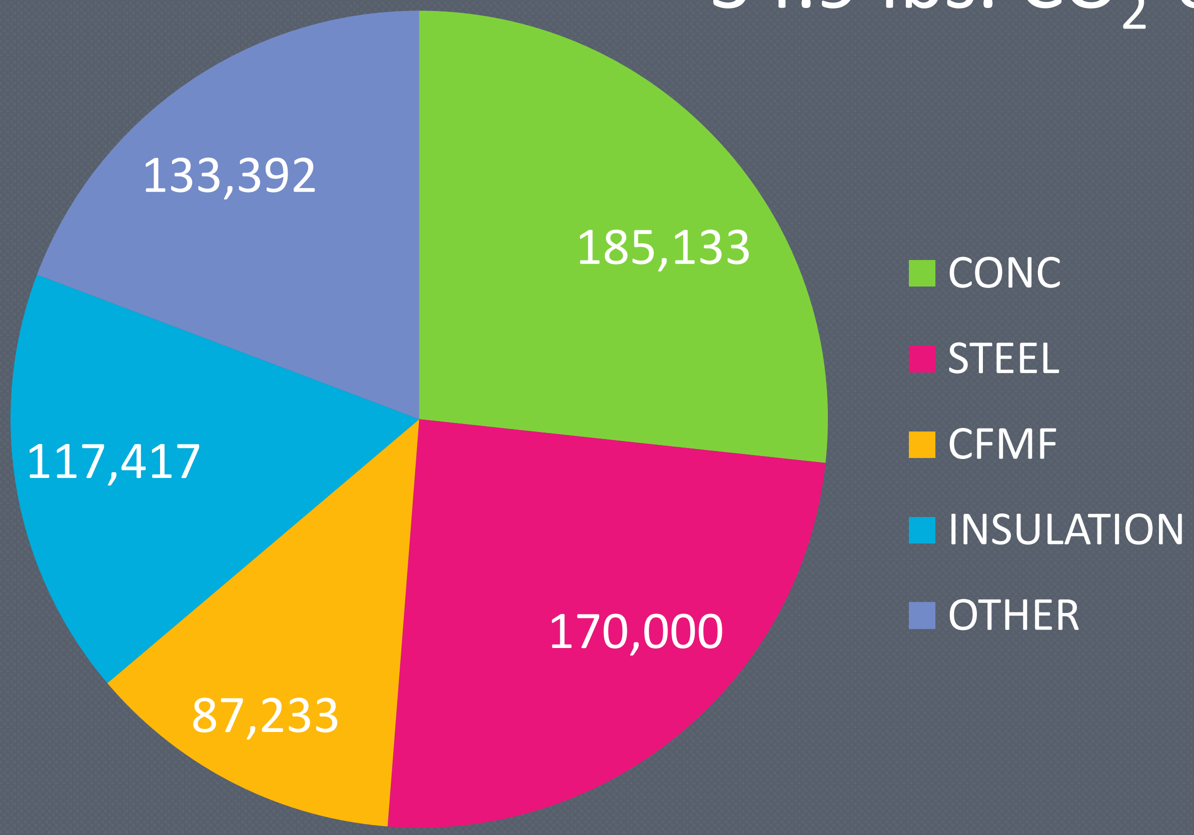
- EXTERIOR WALLS
  - Interior Sheathing: 5/8” gypsum board - 8000 sf
  - Vapor Barrier: 4 mil polyethylene - 8000 sf
  - Studs: 6” 18 ga, 18” o.c. - 8000 sf
  - 6” Fiberglass batt insulation between studs - 8000 sf
  - Exterior Sheathing: 5/8” exterior gyp board - 8000 sf
  - Continuous Insulation: 2” rigid EPS - 8000 sf
  - Brick: 8000 sf
  - Brick Ties: for 8000 sf of brick
  - Windows: Assume wood frames, E-code compliant
- FOUNDATIONS
  - Perimeter Strip Footings and Foundation Walls
  - Interior Spread Footings
  - Perimeter Insulation: 2” XPS, 4 feet deep X 410 lf = 1640 sf

CARBON CALCULATION	AMOUNT	UNIT	CO2e/UNIT	lbs. CO2-e	TOTAL
Roof					
Single-Ply Roofing System: EPDM - 10,000 sf	10,000	sf	3.00	30,000	30,000
Roofing Insulation: 7" polyiso - 10,000 sf	5,833	cu. Ft.	7.26	42,350	42,350
Roof Deck: 20 ga. galv. steel roof deck – 10,000 sf - 2.2 psf	22,000	lbs.	1.79	39,380	39,380
Roof Joists: 2.5 psf x 10,000 sf	25,000	lbs.	1.00	25,000	25,000
Steel Framing: girders, spandrels, columns, bracing, lintels, etc.: 3 psf X 10,000	30,000	lbs.	1.00	30,000	30,000
Second Floor					
Concrete Floor Slab: 4000 psi, 4.5" total thickness 3.5" effective conc. thickness	437,500	lbs.	0.13	56,875	56,875
Composite Steel Deck: 2" 20 ga. – 10,000 sf - 2.3 psf	23,000	lbs.	1.79	41,170	41,170
Slab Reinforcing: #4@16" both ways for 10,000 sf - 0.67 plf X 12/16 X 2 =	17,867	lbs.	0.59	10,541	10,541
Steel Framing: purlins, girders, columns, bracing, lintels, stairs, etc. - 12 psf	120,000	lbs.	1.00	120,000	120,000
First Floor					
Concrete Floor Slab: 5" thick, 3000 psi	625,000	lbs.	0.10	62,500	62,500
Slab Reinforcing: #4@16" both ways for 10,000 sf - 0.67 plf X 12/16 X 2 =	17,867	lbs.	0.59	10,541	10,541
Exterior Walls					
Interior Sheathing: 5/8" gypsum board - 8000 sf	8,000	sf	0.12	960	960
Vapor Barrier: 4 mil polyethylene - 8000 sf x .004 x 19 lbs./1000 sf	152	lbs.	0.00	0	0
Studs: 6" 18 ga, 18" o.c. - 8000 sf - 0.56 lbs/lf X 8000*12/18 x 1.25	3,733	lbs.	1.79	6,683	6,683
6" Fiberglass batt insulation between studs - 8000 sf	4,000	lbs.	1.40	5,600	5,600
Exterior Sheathing: 5/8" exterior gypsum board - 8000 sf	8,000	sf	0.12	960	960
Continuous Insulation: 2" rigid EPS - 8000 sf	1,333	lbs.	2.90	3,867	3,867
Brick: 8000 sf	304,000	lbs.	0.16	48,032	48,032
Brick Ties: for 8000 sf - say 2 psf	16,000	lbs.	0.59	9,440	9,440
Windows: Say wood frames	2,000	sf	22.00	44,000	44,000 fi
Foundations					
Perimeter Strip Footings and Foundation Wall: 410 lf X 6 sf	369,000	lbs.	0.10	36,900	36,900
Spread Footings: say 12, 6X6 footings	77,760	lbs.	0.10	7,776	7,776
Perimeter Insulation: 2" XPS, 4 feet deep X 410 lf = 1640 sf	547	lbs.	120.00	65,600	65,600
TOTAL CO2-e				698,175	698,175
TOTAL CO2-e per SF				34.908766	

Results for 2-Story, 10,000 sf Office Building:

698,000 lbs. CO_2-e

= 34.9 lbs. CO_2-e per sf of floor



Some Possible Variations

1. Frost-protected shallow foundations
2. PLUS concrete to have 25% less cement
3. PLUS rock wool insulation instead of XPS
4. PLUS wood structural framing and studs instead of steel
5. Base case using aluminum frame windows instead of wood

Frost-Protected Shallow Foundations

LEFT:

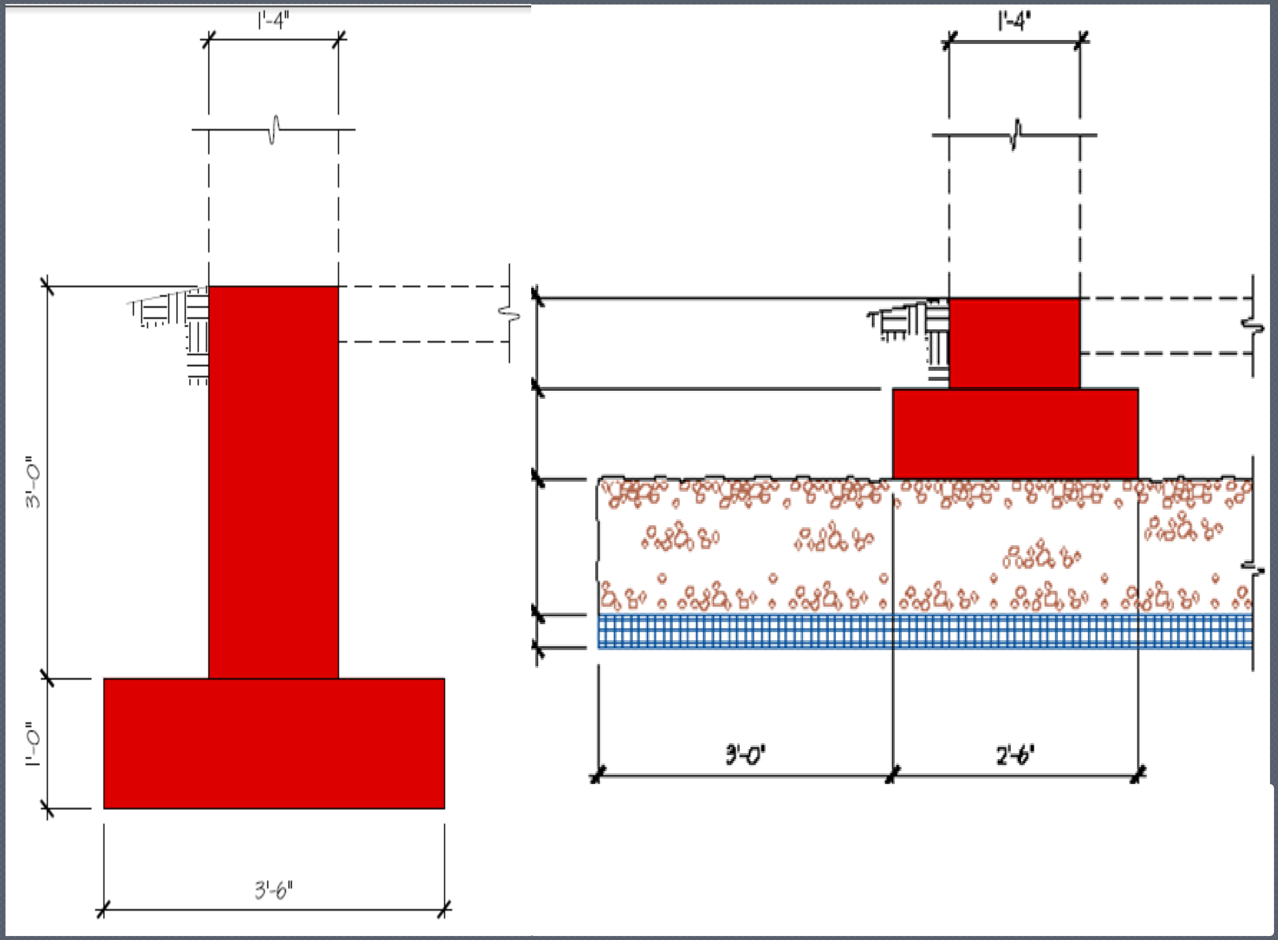
Conv. Ftg/fdn wall

Aconc = 7.5 sf/ft.

RIGHT: FPSF

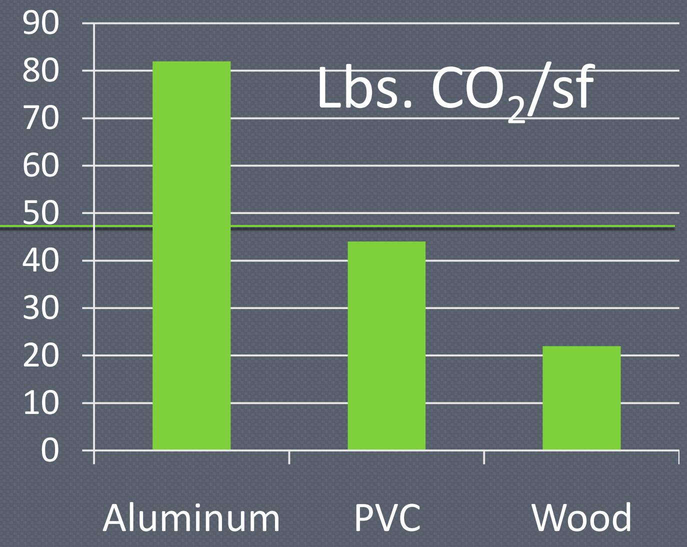
Aconc = 2.6 sf/ft.

65% redux of conc!



Using 25% SCM substitution → 74% redux of Portland cement!

Window Footprints



1 m^2 of window pane = 10.76 sf
add for frame = 12.9 say 13 sf

1 kg = 2.2 lbs. 1m = 3.28 feet

- **Aluminum**

486 kg = 1070 lbs. /13 sf = 82 lbs. CO_2/sf

- **PVC**

258 kg = 568 lbs. / 13 sf = 44 lbs. CO_2/sf

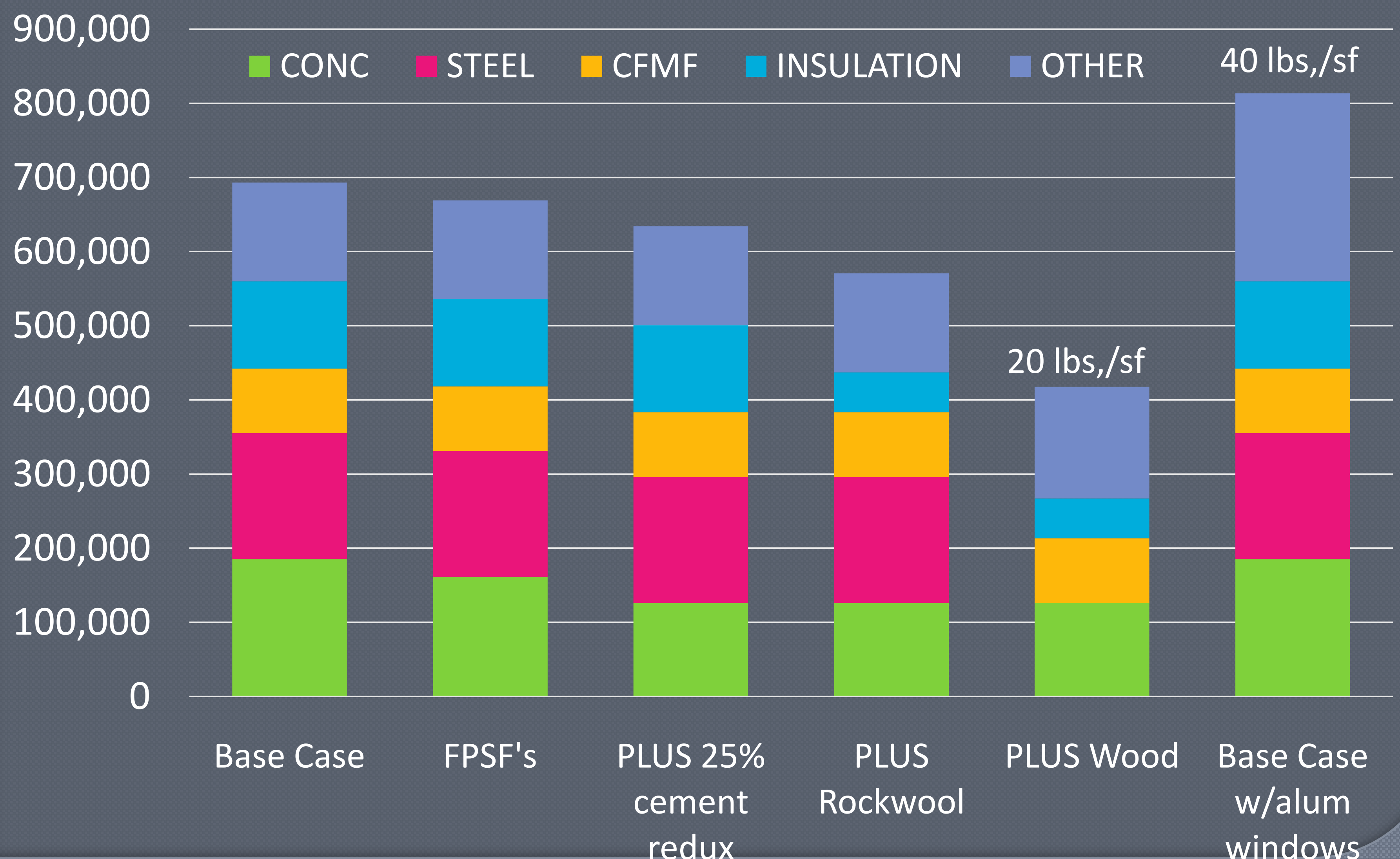
- **Wood**

130 kg = 286 lbs. / 13 sf = 22 lbs. CO_2/sf

Source: http://www.mdpi.com/2075-5309/2/4/542/htm

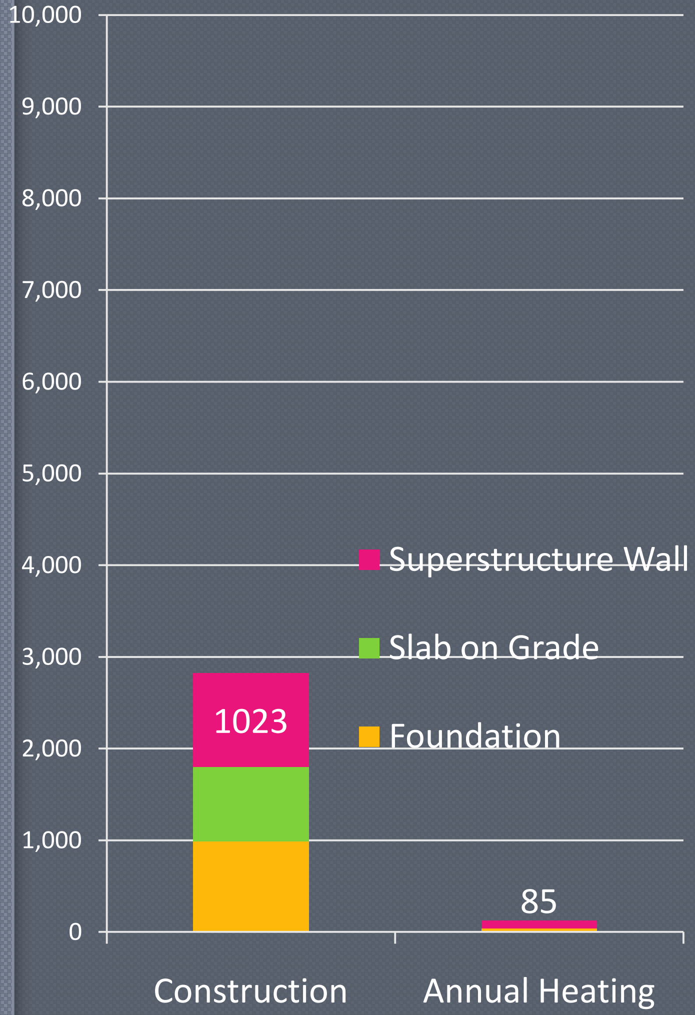
Some Possible Variations

Lbs. CO_2 from Construction of 20,000 sf Bldg.



Insulated Concrete Forms

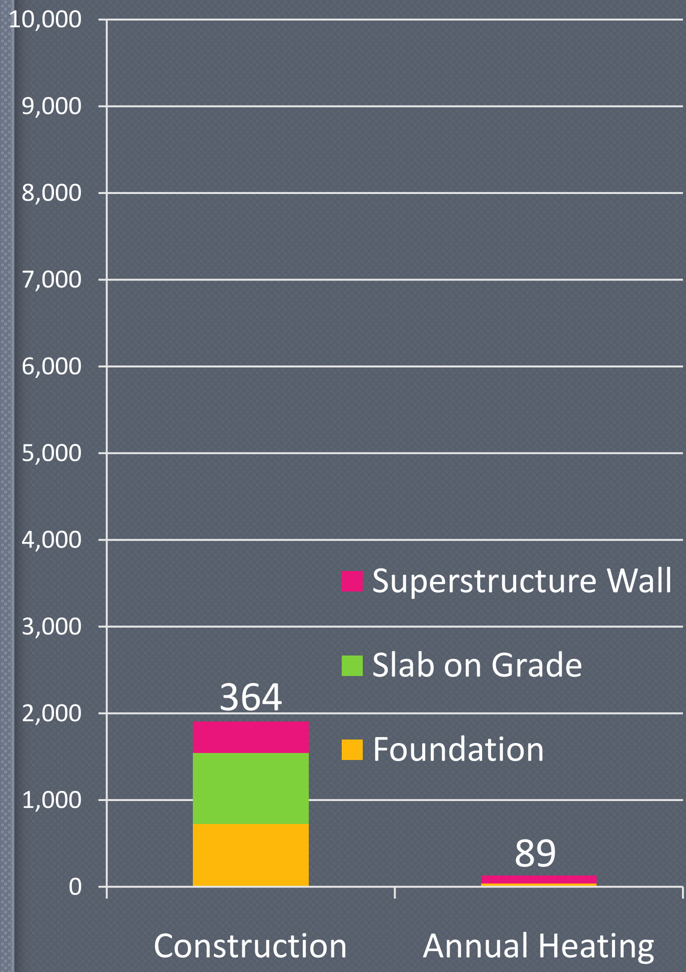
Insulated Concrete Forms GWP Gas Emissions



MATERIAL	Thickness	Unit	R-factor	Weight (lbs.)	lbs. CO2e	lbs. CO2e/sf
Exterior composite siding	1	assembly	0.08		85	
(2) 2 1/2 layers EPS Insul.	5	inches	19.5	42	121	
Exterior CFMF hat channels	1	layer		40	72	
5" 40% SCM Concrete	5	inches	0.4	6250	500	
Reinforcing - (2) #4@12" EW	1	assembly		275	162	
Interior CFMF hat channels	1	layer		40	72	
Interior gypsum sheathing	1	layer	0.56		12	
Interior/exterior air film	1	layer	0.85			
Thermal mass effect			2.1			
TOTAL			23.5		1023	10

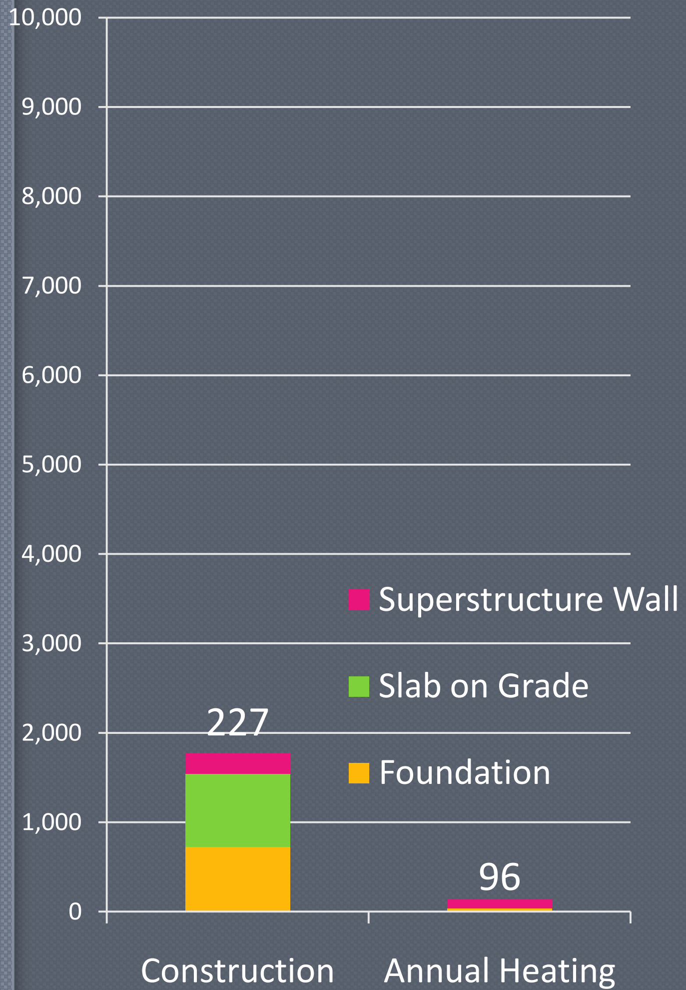
Structural Insulated Panels

Polyiso Structural Insulated Panel GWP Gas Emissions



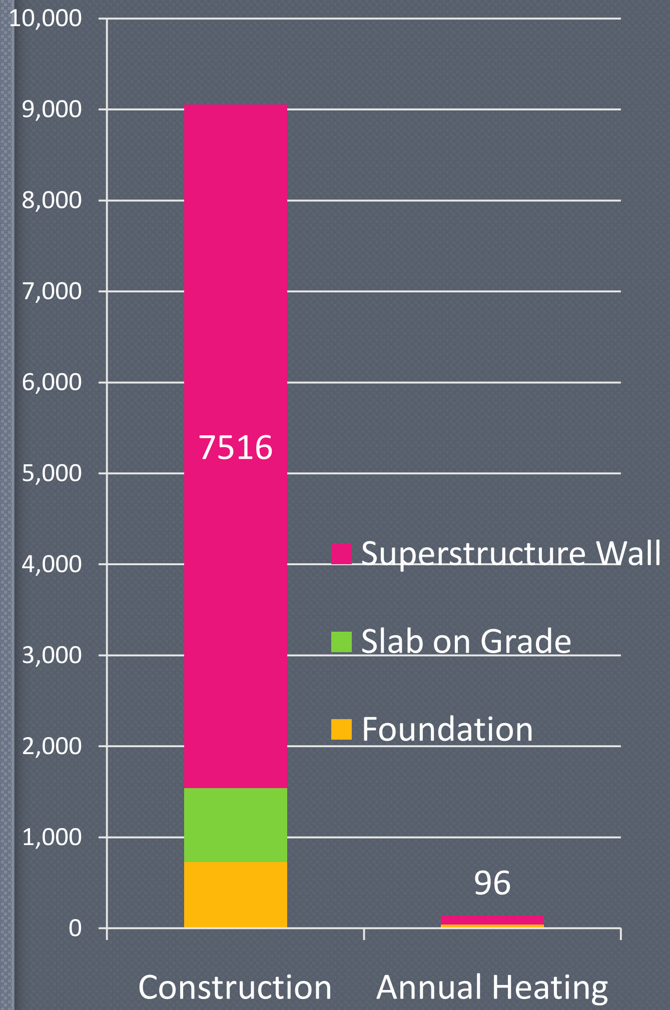
MATERIAL	Thickness	Unit	R-factor	Weight (lbs.)	lbs. CO2e	lbs. CO2e/sf
Exterior composite siding	1	assembly	0.08		85	
(2) 7/16" OSB	1	assembly	1.25		30	
3 11/16" Polyiso Insulation	3.6875	inches	20.3	68	223	
Exterior gypsum sheathing	1	layer	0.56		12	
Misc. wood framing	1	assembly	-1	20	2	
Interior gypsum sheathing	1	layer	0.56		12	
Interior/exterior air film	1	layer	0.85			
TOTAL			22.6		364	4

EPS Structural Insulated Panel GWP Gas Emissions



MATERIAL	Thickness	Unit	R-factor	Weight (lbs.)	lbs. CO_2e	lbs. CO_2e/sf
Exterior composite siding	1	assembly	0.08		85	
(2) 7/16" OSB	1	assembly	1.25		30	
3 11/16" EPS Insulation	3.6875	inches	14.4	31	89	
Exterior gypsum sheathing	1	layer	0.56		12	
Misc. wood framing	1	assembly	-1	20	2	
Interior gypsum sheathing	1	layer	0.56		12	
Interior/exterior air film	1	layer	0.85			
TOTAL			16.7		230	2

XPS Structural Insulated Panel GWP Gas Emissions



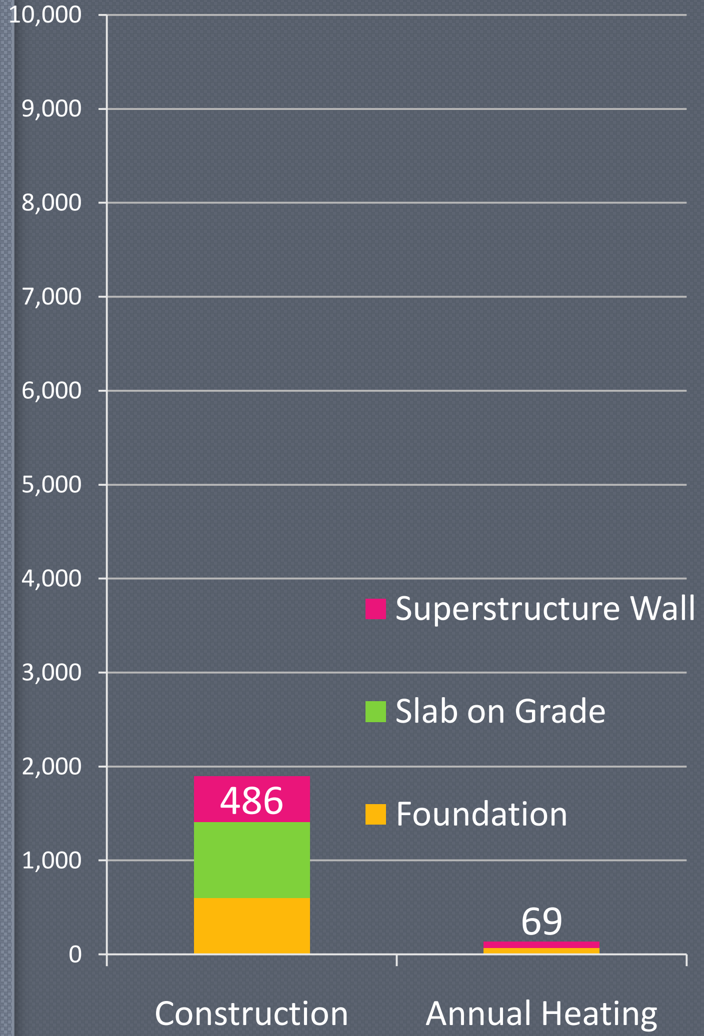
MATERIAL	Thickness	Unit	R-factor	Weight (lbs.)	lbs. CO2e	lbs. CO2e/sf
Exterior composite siding	1	assembly	0.08		85	
(2) 7/16" OSB	1	assembly	1.25		30	
3 11/16" XPS Insulation	3.6875	inches	18.4	61	7375	
Exterior gypsum sheathing	1	layer	0.56		12	
Misc. wood framing	1	assembly	-1	20	2	
Interior gypsum sheathing	1	layer	0.56		12	
Interior/exterior air film	1	layer	0.85			
TOTAL			20.7		7516	75

Straw Bale Construction: GWP Gas Aspects

- Straw GWP is very small - especially locally sourced
- Location of building greatly affects footprint
- Erection - can be very low
- Small amounts of steel and wood
- Stucco - usually cement
- Wide concrete footings

www.texastinyhomes.com

Straw Bale Construction: GWP Gas Emissions



MATERIAL	Thickness	Unit	R-factor	Weight (lbs.)	lbs. CO2e	lbs. CO2e/sf
Exterior composite siding	1	assembly	0.08		85	
Exterior CFMF hat channels	1	layer		40	72	
Straw Bales	18	inches	27	1050	11	
Baling ties and mesh	1	assembly		25	15	
Timber framing	1	layer	-2	30	54	
Interior/exterior cement stucco	2	layers	0.4	1000	250	
Interior/exterior air film	1	layer	0.85			
Thermal mass effect			2.6			
TOTAL			29.0		486	5

Practical Take-Aways

- Watch your windows!
- Avoid XPS and closed-cell spray foam
- De-materialize as much as practical
- Consider wood for structural framing + studs
- Consider wood-framed windows
- Consider pre-manufactured components
- Minimize labor-intensive jobsite activities

Material-Specific Recommendations to Reduce CO_2-e Emissions

- **Concrete**
  - Do not over-specify concrete strength
  - Use SCMs as much as possible
  - Minimize foundation concrete area
- **Masonry**
  - Specify CMU's with SCM and minimize Portland cement
  - Specify SCM in grout, and avoid prescription-based mixes
  - Consider alternative low-cement masonry units
- **Steel**
  - Consider salvaged or reuse of steel
  - Specify steel produced in Electric Arc Furnaces, not BOF's
- **Wood** – Consider its use where codes allow

LCA of DfD Structural System

Mark Webster

SIMPSON GUMPERTZ & HEGER

Engineering of Structures
and Building Enclosures

What is DfD?

- Deconstruction is a demolition method where a structure is carefully and methodically disassembled so as to salvage as many components as possible.
- “Design for Deconstruction” is an approach to new design that anticipates and facilitates the future deconstruction of the structure.

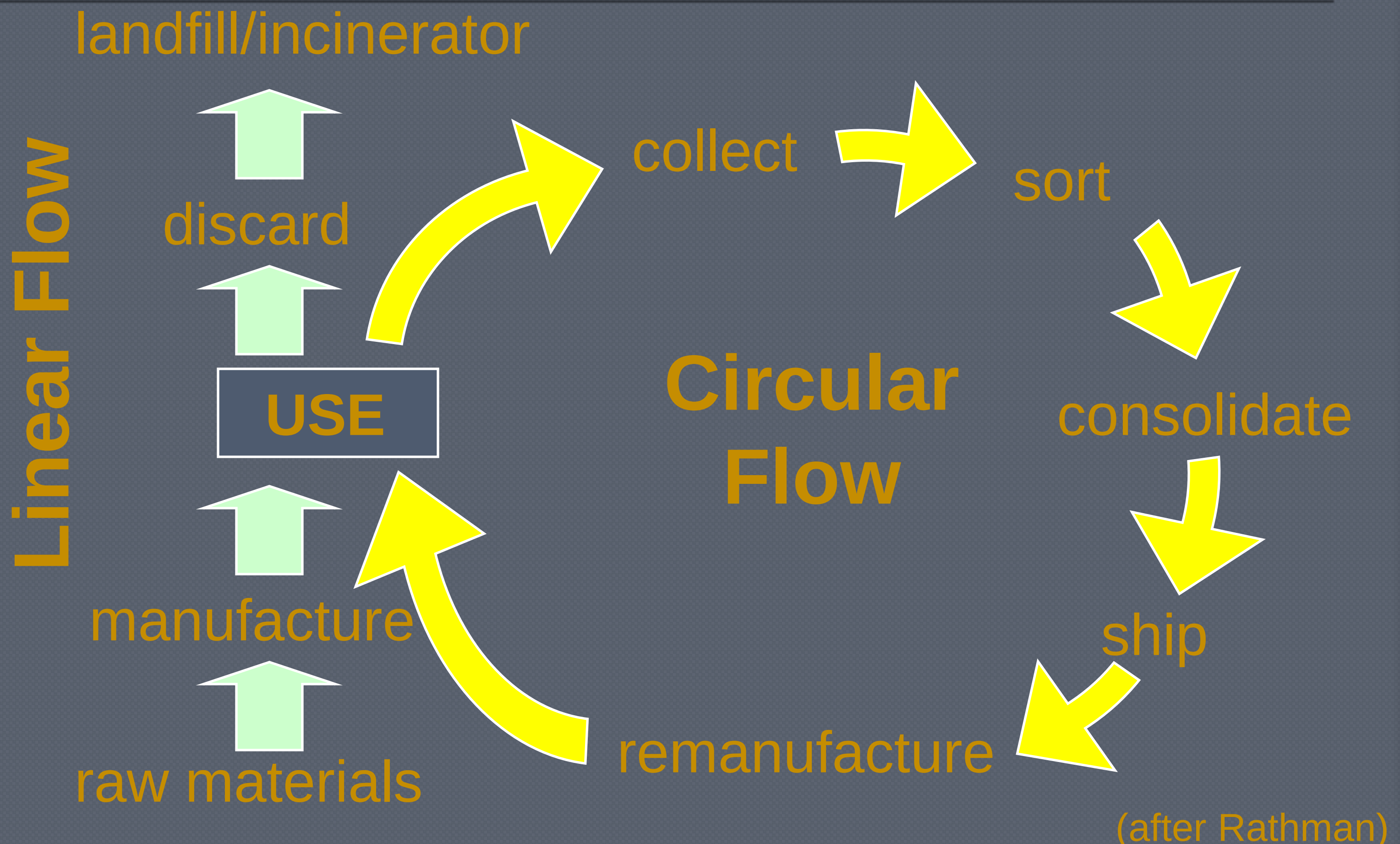
Why DfD?

- Increase salvage and recycling rates, and building end-of-life value
- Reduce consumption of raw materials ("close the materials loop")
- Reduce consumption of energy
- Reduce waste and landfill demand

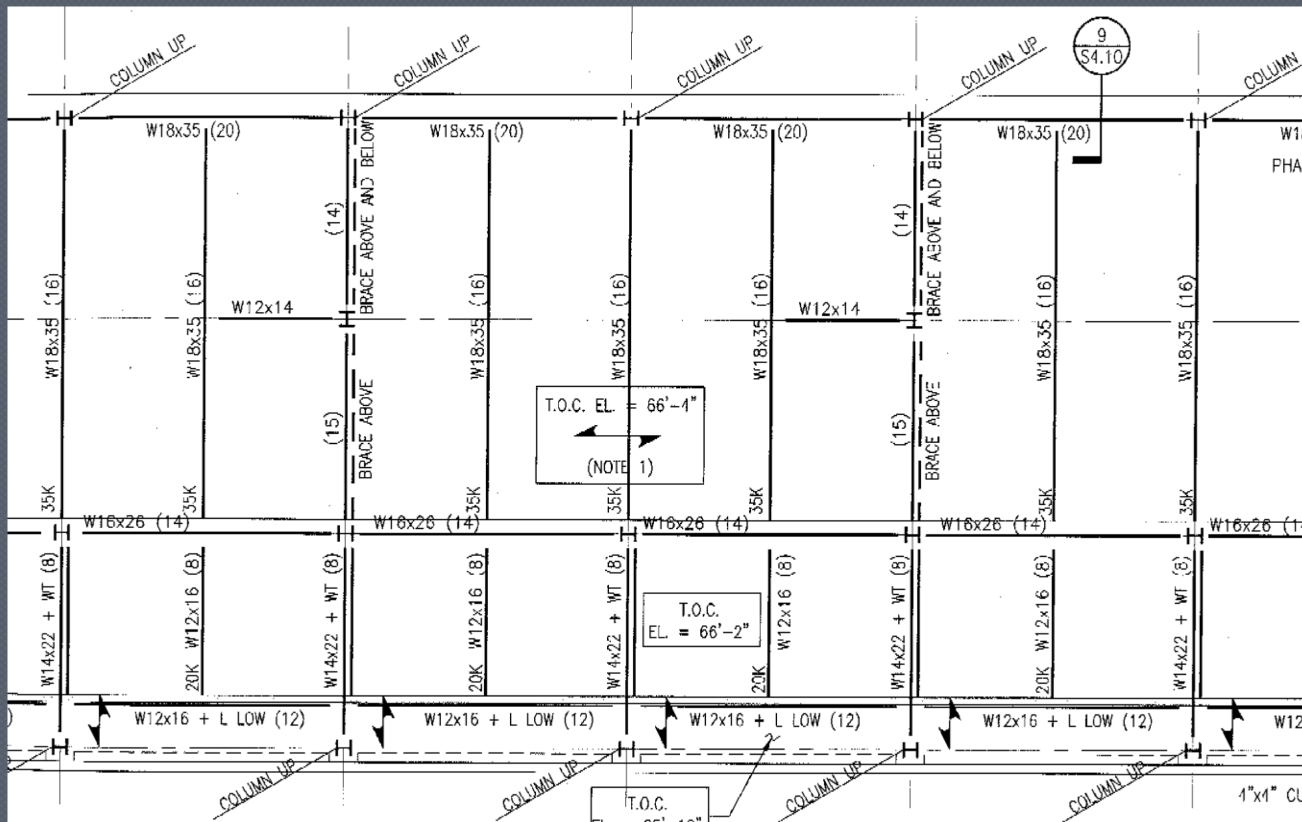
What is DfD *not*?

- Although DfD an excellent strategy for reducing the carbon footprint of buildings (as we will see), it is *not* a strong climate-change mitigation strategy because the benefits of DfD occur in the long-term rather than the short-term.

Closing the Materials Loop

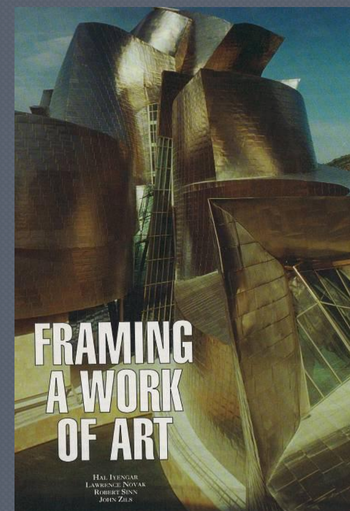


Simple, Regular Layout



This framing system has repeating bays with similar geometry, beam sizes, and connection types.

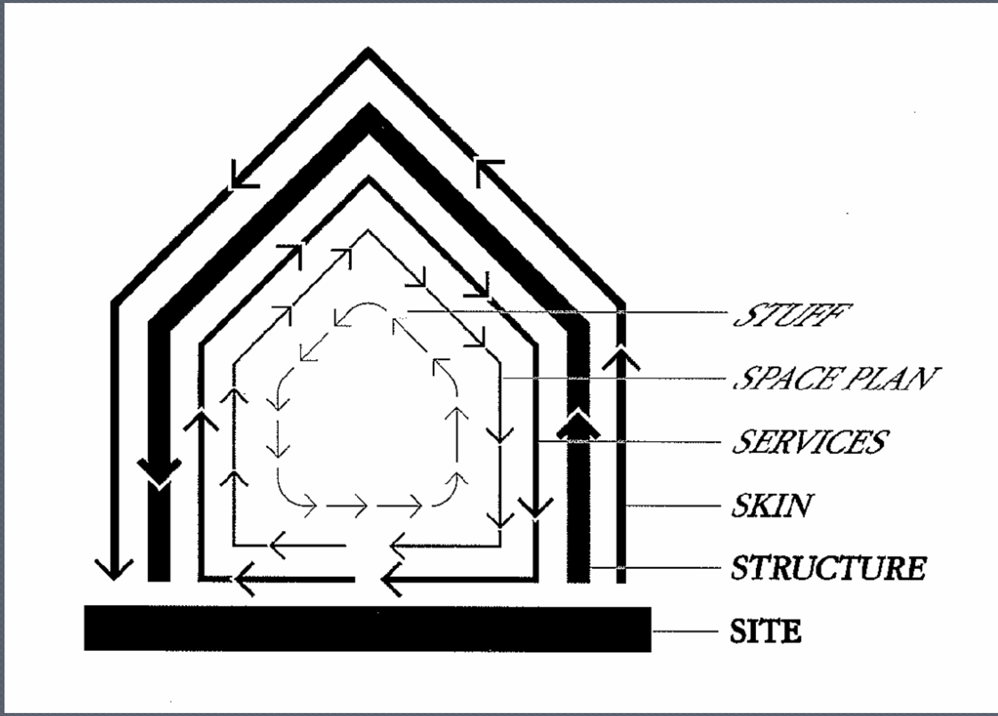
Simple, Regular Layout



from "Framing a Work of Art," *Civil Engineering*, March 1998

This framing system has many unique pieces that will be impossible to reuse in a different building.

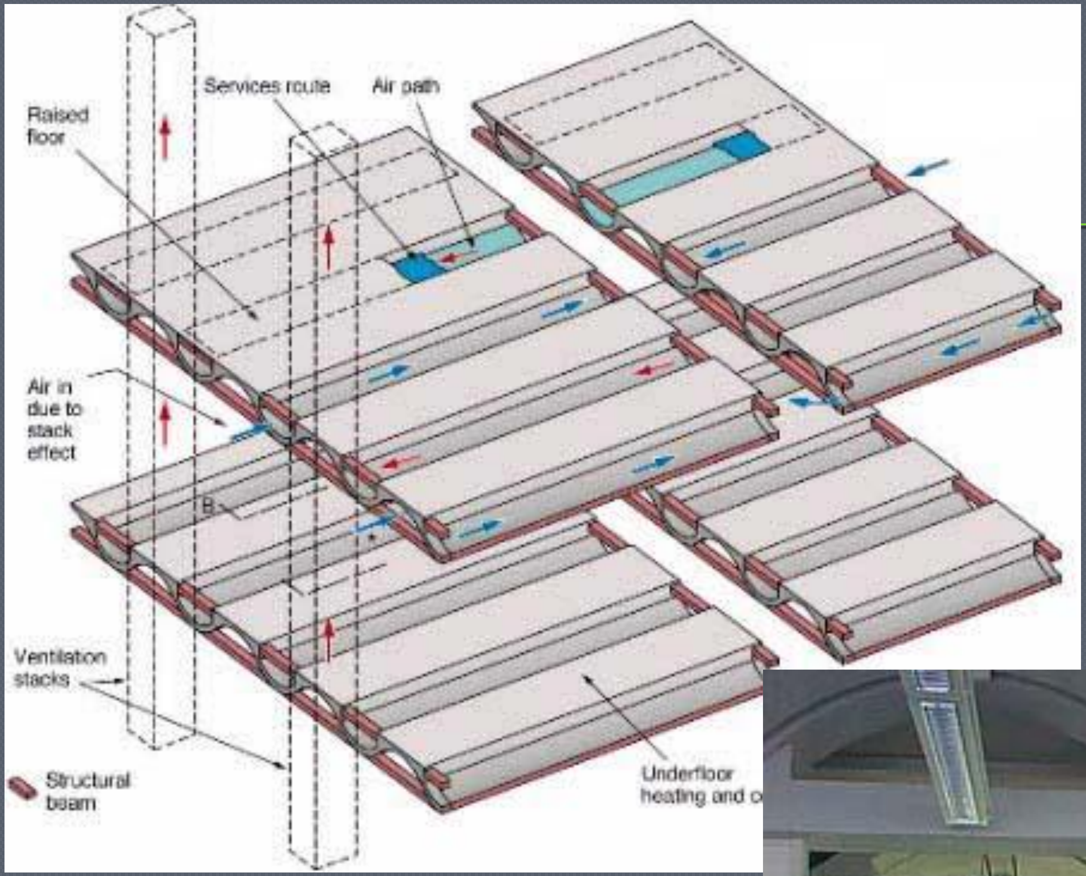
Layered Building Systems



from *How Buildings Learn*, by Stewart Brand (after Frank Duffy)

Building systems have different longevities. Keeping systems separate makes renovations easier, and also deconstruction.

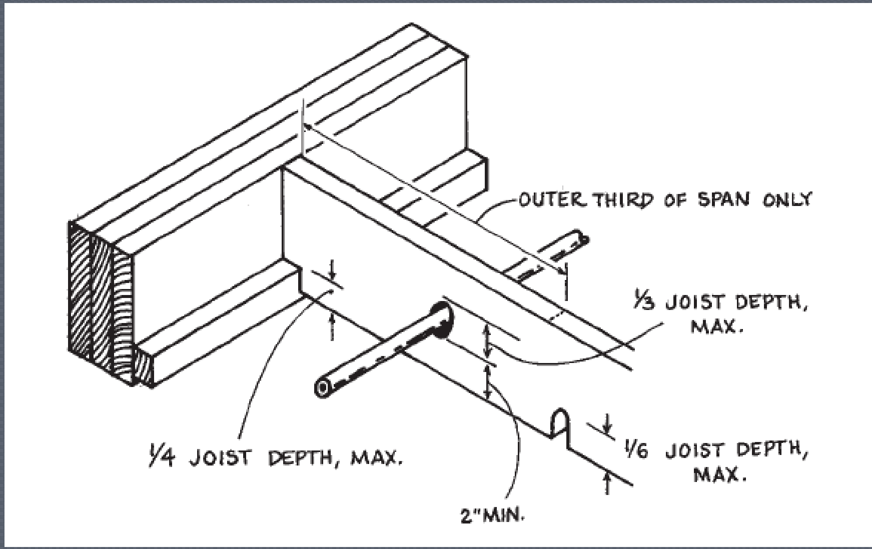
BRE: The Environmental Building



from http:// projects.bre.co.uk/

from http:// projects.bre.co.uk/

Layered Building Systems

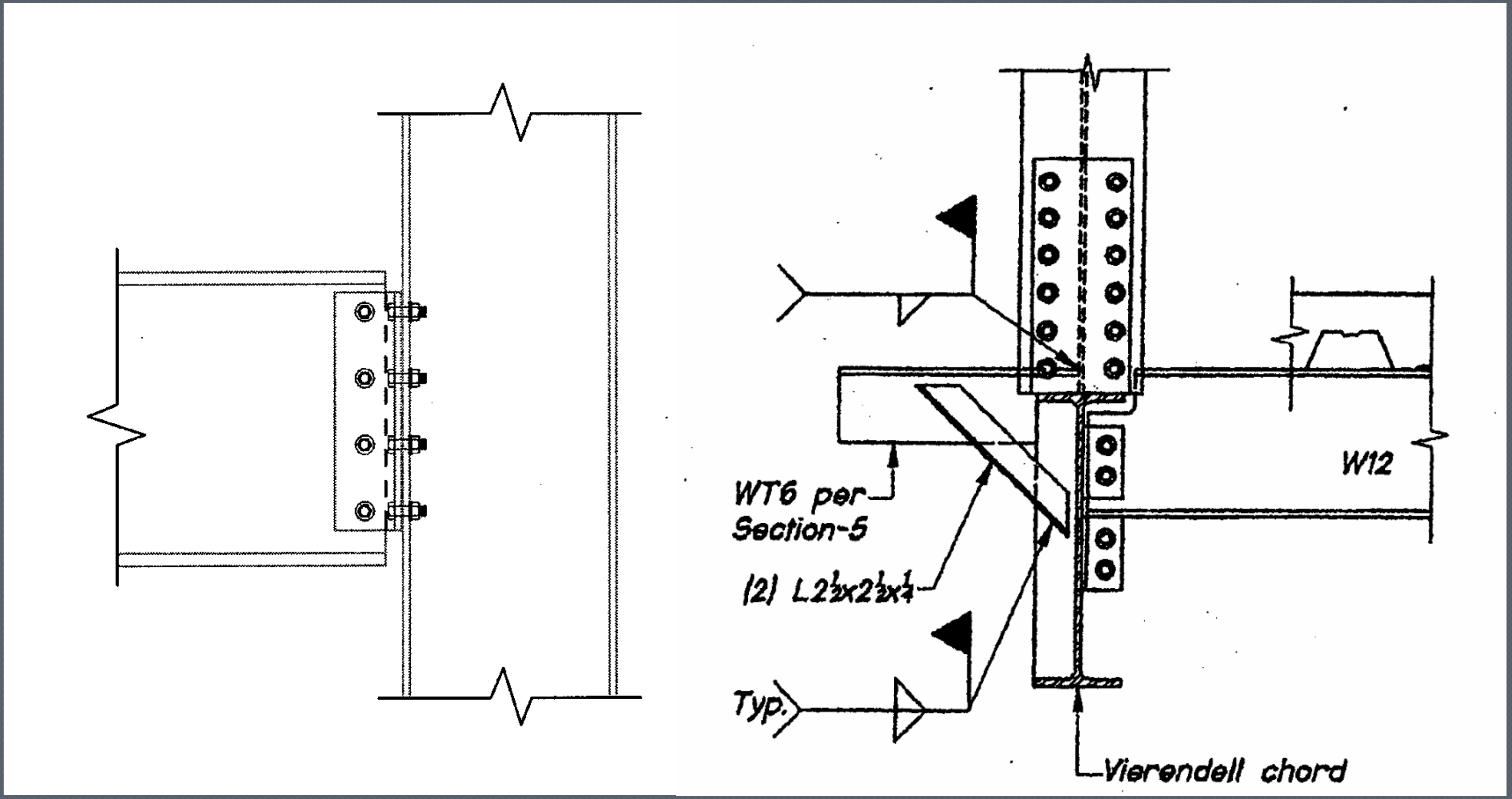


from *Details for Conventional Wood Frame Construction*, by the American Forest & Paper Association

from the Bensonwood web site, www.bensonwood.com

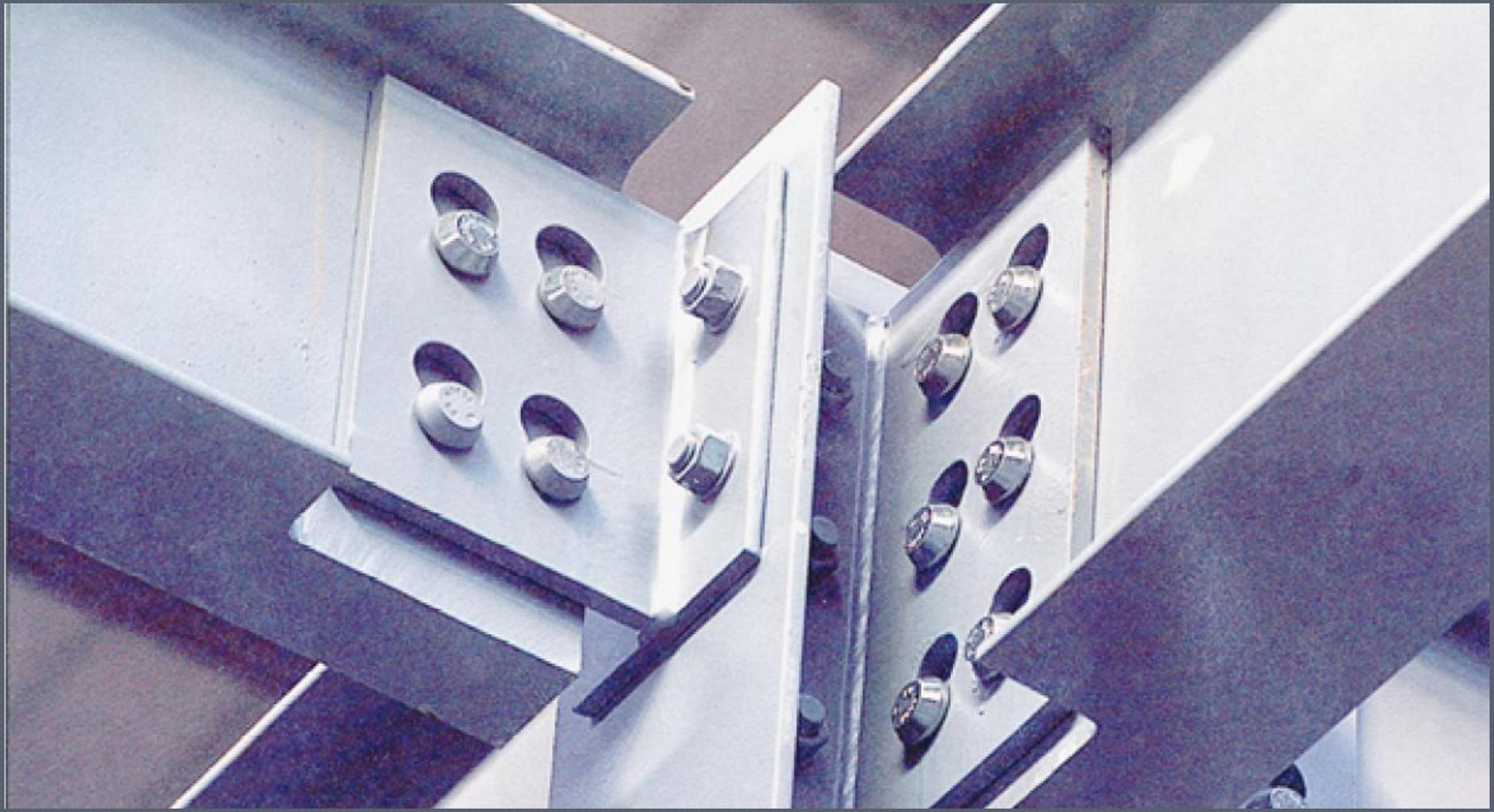
Conventional Wood Framing Details vs.
Bensonwood Open-Built® Floor System

Common Standard Shapes and Connections



Which connection would you rather take apart?

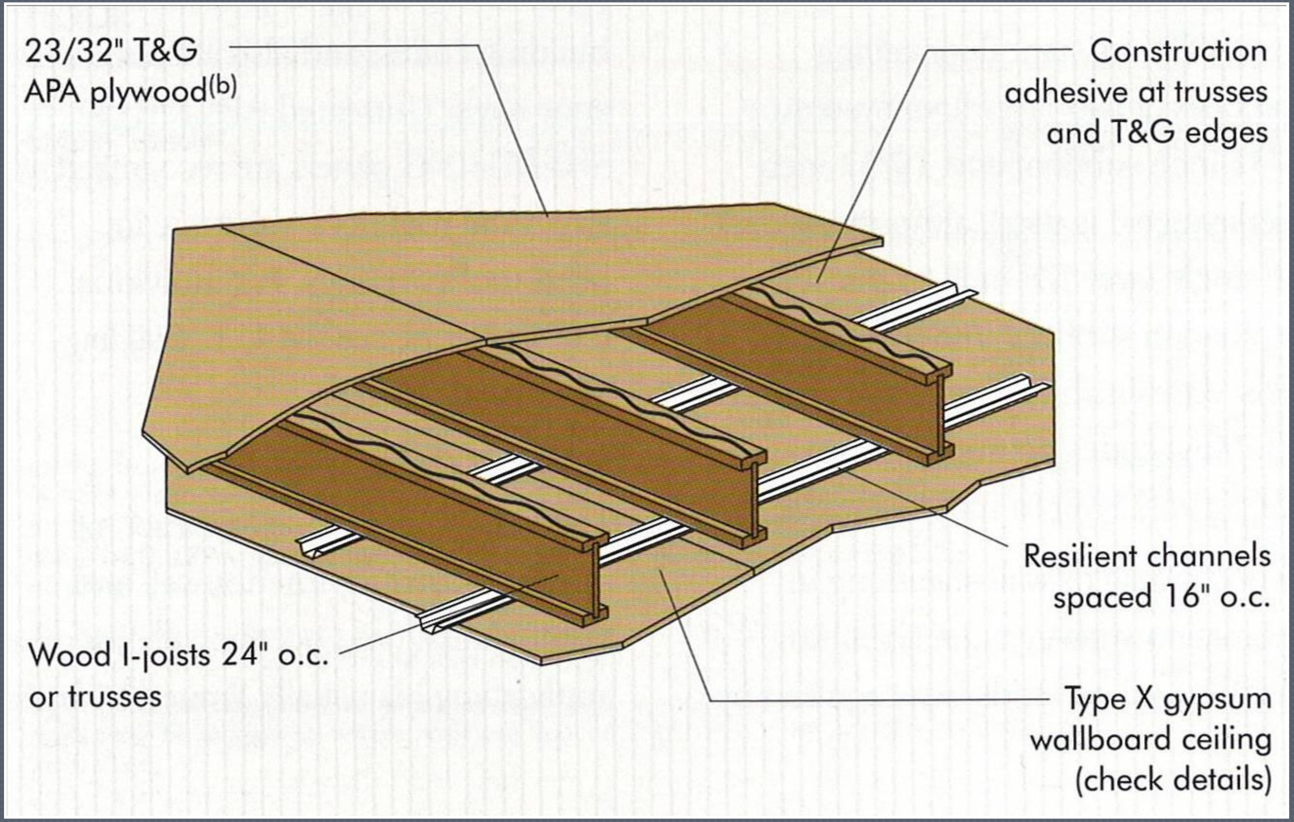
Common Standard Shapes and Connections



from the Quicon web site, www.quicon.com

The Quicon™ connection system uses standard interlocking connections.

Removable Fasteners, Avoid Adhesives and Welds



from *Design/Construction Guide: Residential & Commercial*, by APA – The Engineered Wood Association

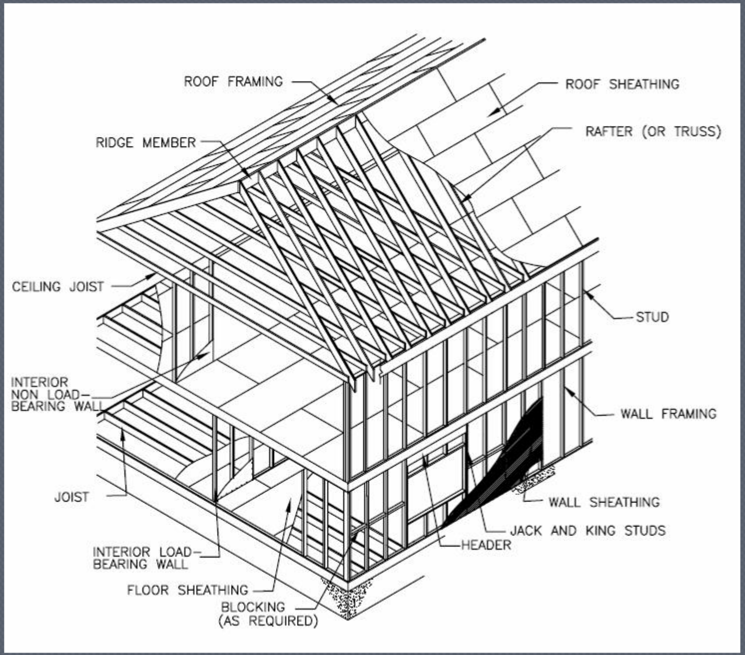
This glued plywood floor system will be virtually impossible to take apart. Use screws.

Removable Fasteners, Avoid Adhesives and Welds

Lindapter Clamped Connections

Few Large Members vs. Many Small Members

from the Bensonwood web site, www.bensonwood.com



from *Residential Structural Design Guide*, by the U.S. Dept. of Housing and Urban Development

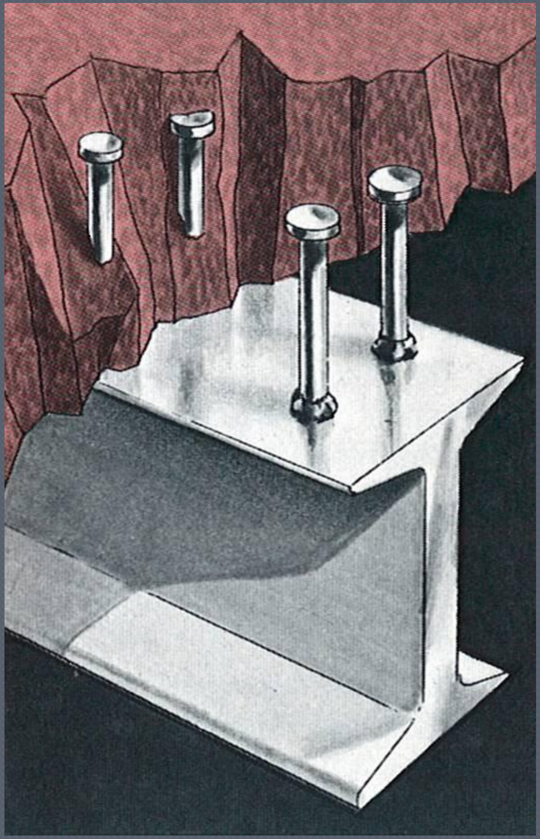
Larger members are more robust and less subject to damage during use and deconstruction. Fewer pieces to handle will likely reduce deconstruction costs.

Salvaged Materials

photo by Mark D. Webster

This vegetable market is constructed of salvaged timber, which will be reusable again at the end of the building’s life.

Avoid Most Composite Systems

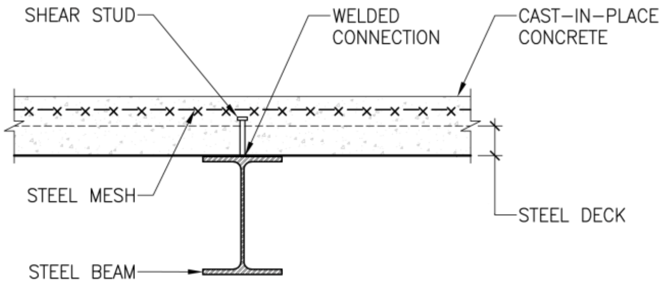


from *Stud Welding for Non-Residential Construction*, by Nelson Stud Welding

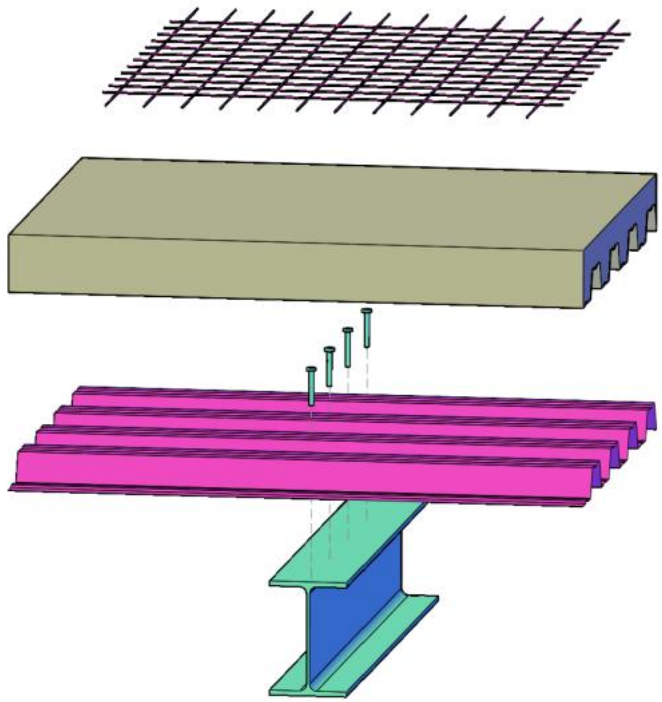
from Murus Structural Insulating Panels Brochure

Composite systems typically increase deconstruction difficulty and reduce reuse options. Some composite systems may be reusable as assemblies.

Conventional Composite Slab



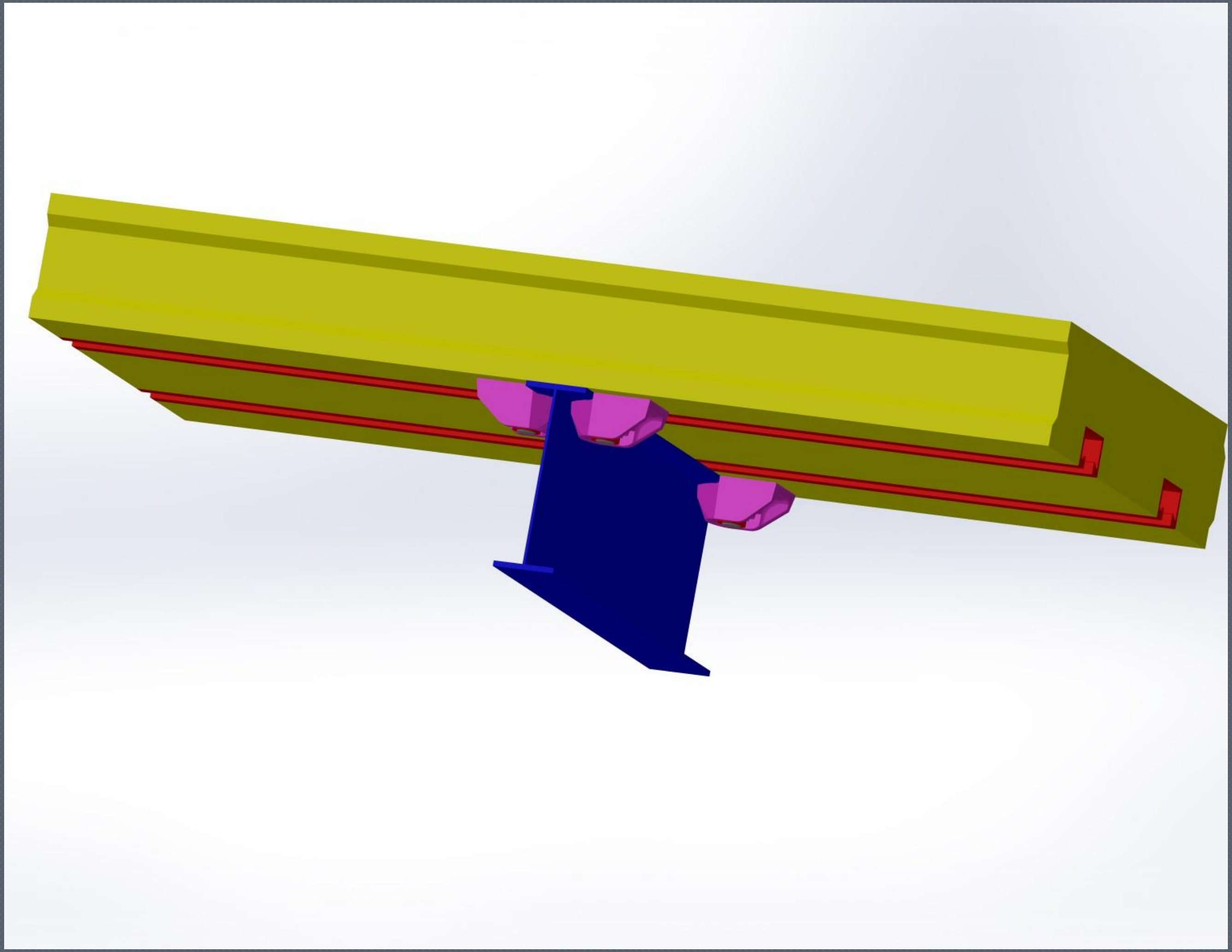
CROSS-SECTION VIEW OF ASSEMBLED SYSTEM



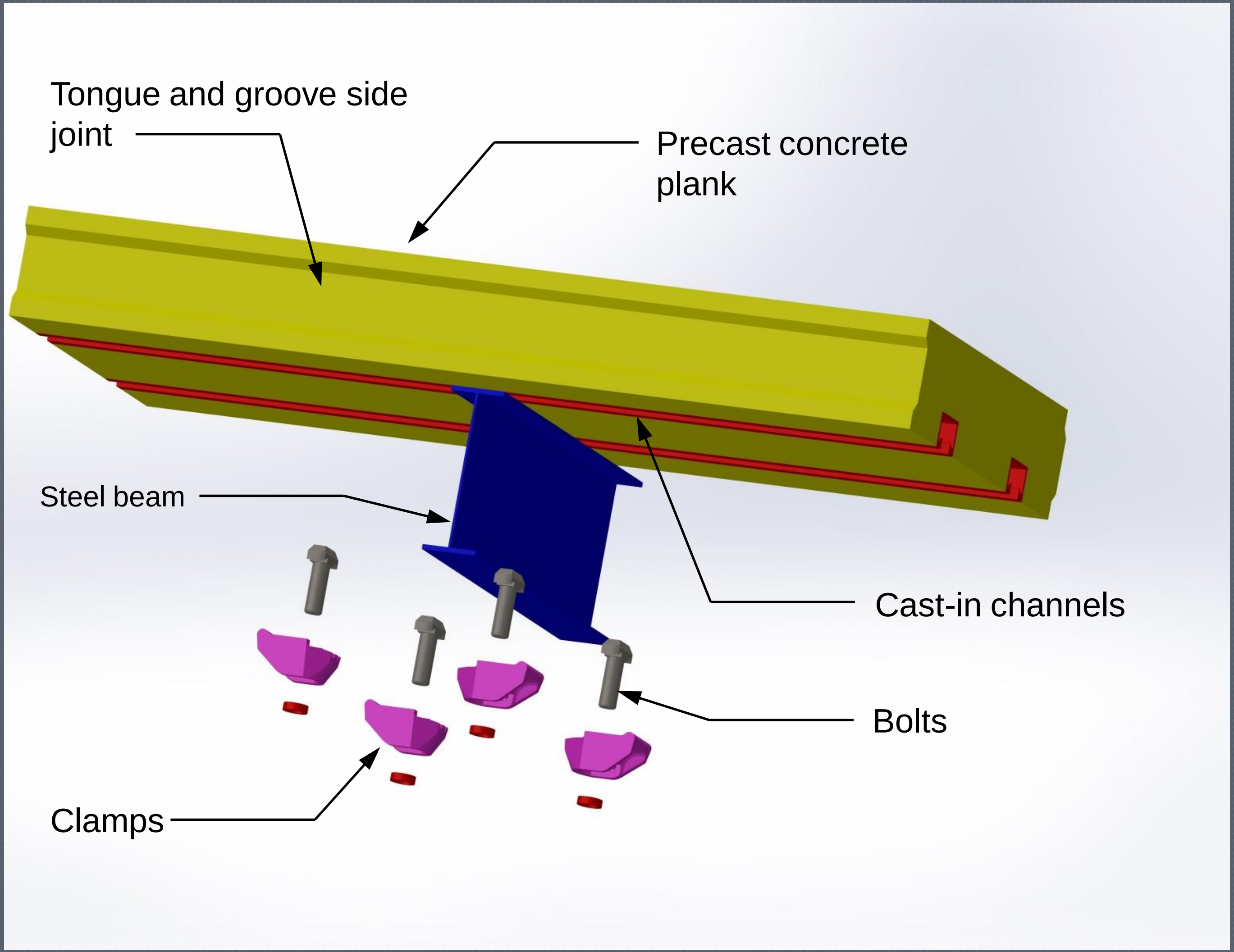
EXPLODED VIEW

- STEEL MESH, CONCRETE, & STEEL DECK NOT REUSABLE
- STEEL BEAM MAY BE REUSABLE, BUT SHEAR STUDS MUST BE REMOVED

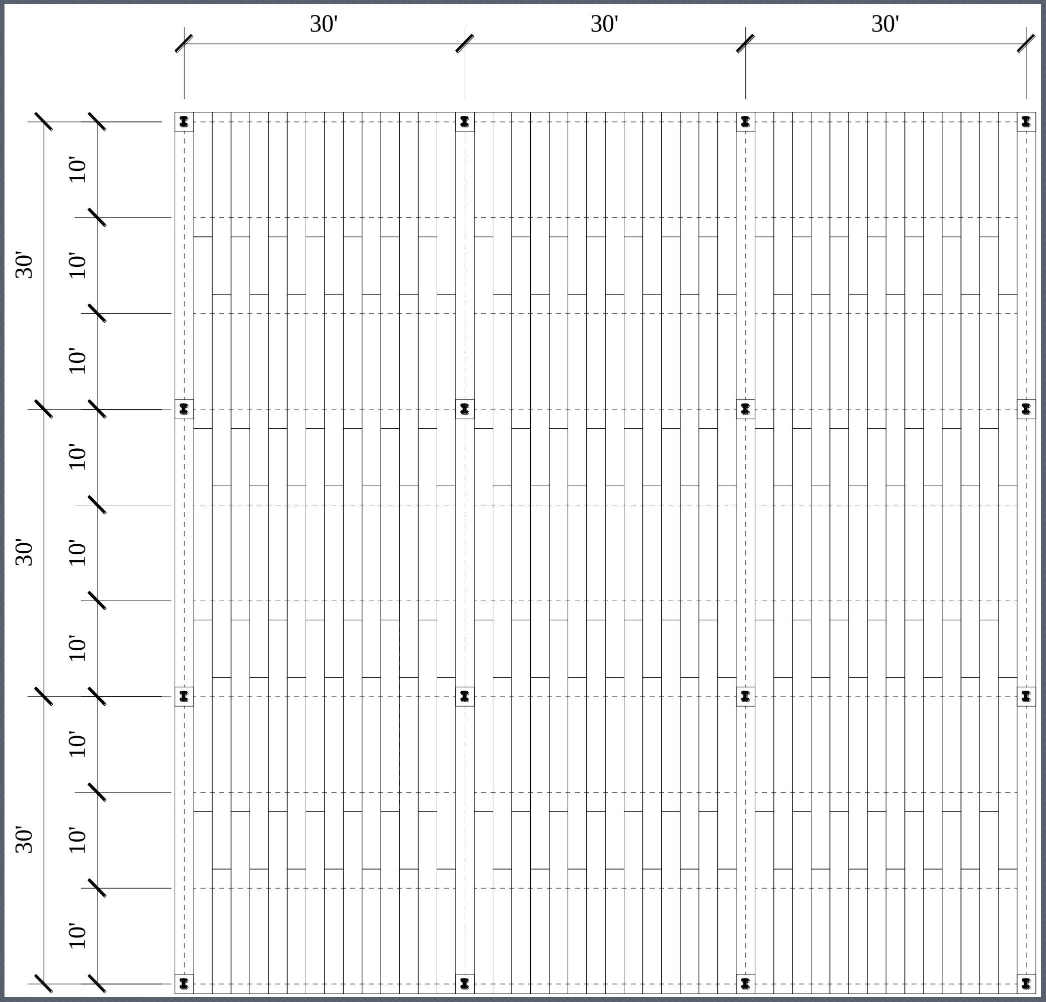
Deconstructable and Reusable Composite Slab



Deconstructable and Reusable Composite Slab



Deconstructable composite floor system



Typical floor plan for DfD system

Staggering plank pattern

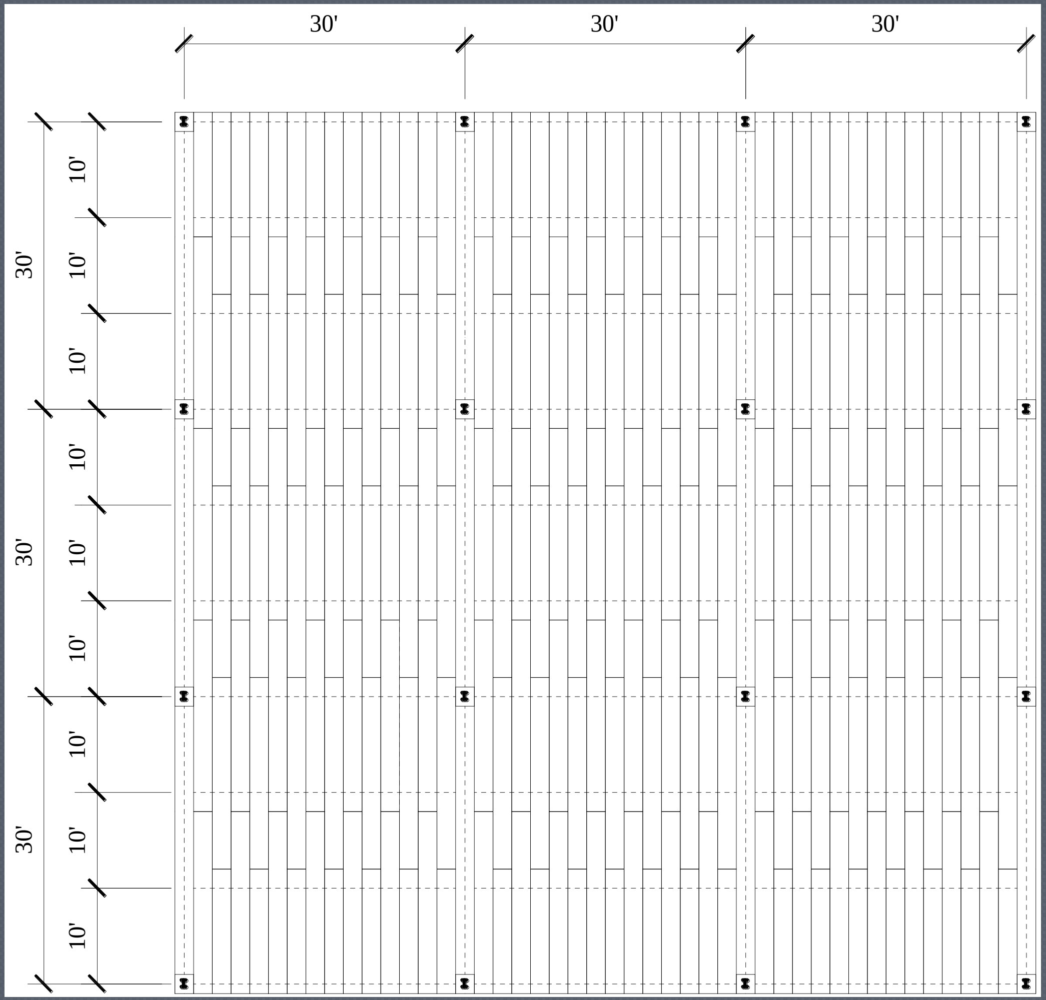
Why?

- Clamp connectors require planks being continuous over the steel beams.
- Enhanced localized stability of floor system

Benefits:

- Enables a two-plank strip to behave like a continuous beam by load transfer between the planks
- Adds flexibility to the floor plan

Deconstructable composite floor system



Typical floor plan for DfD system

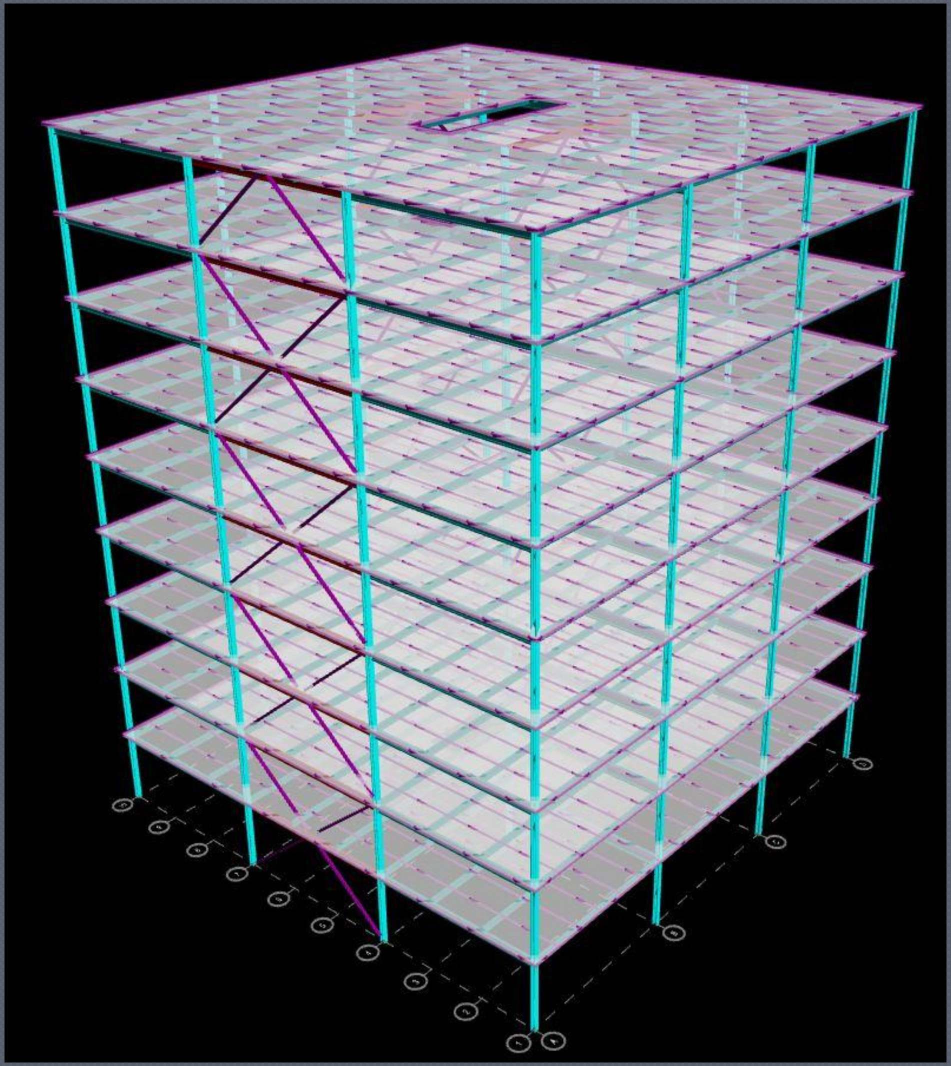
End-to-end connections:

- Located at the inflection points to reduce the load transfer between planks

Longitudinal rebar configuration in plank:

- Designed using twice the moment and shear obtained from continuous beam analysis
- The channels cannot be used as flexural reinforcements.

Archetype Office Building



- Nine Stories
- 30-Foot Bays
- Braced Frame Lateral System
- Steel Columns and Beams
- Conventional Composite Construction or Deconstructable Planks

LCA Analysis

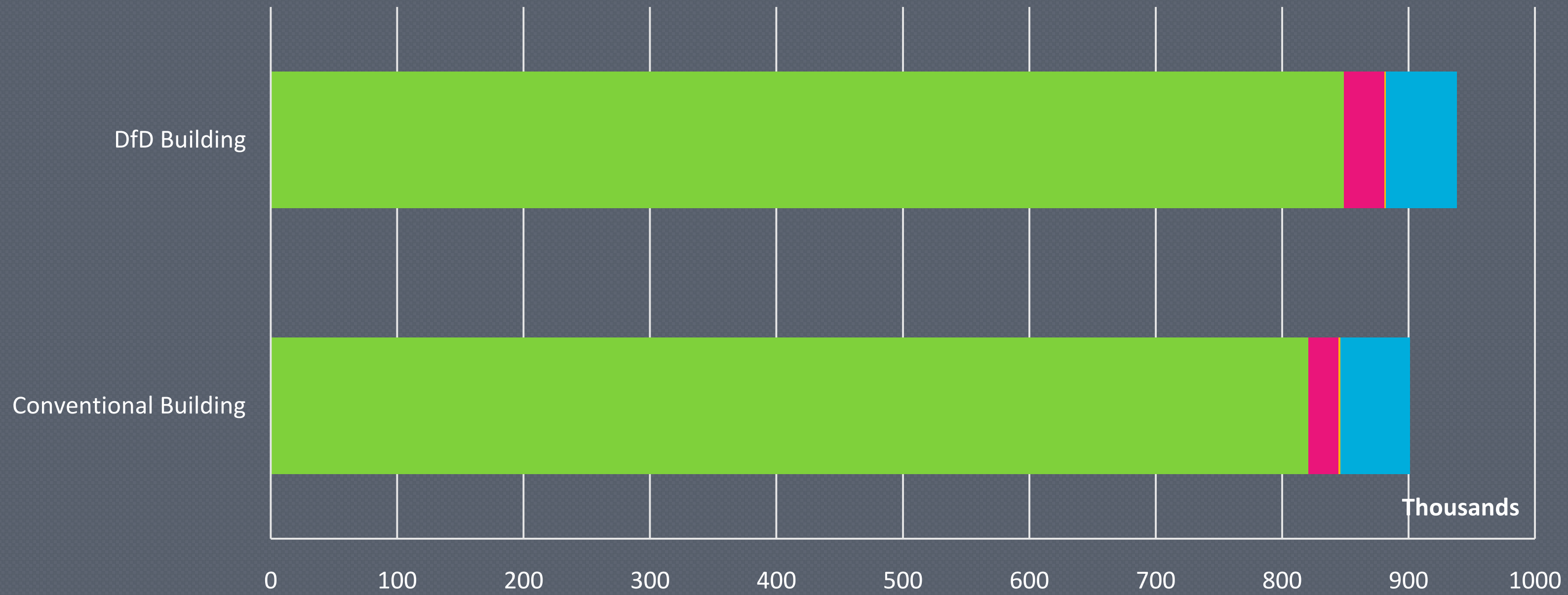
- Comparison of conventional composite construction to DfD slab construction.
- Used Simapro LCA software.
- Used U.S. Ecoinvent 2.2 and European Life-Cycle Database for material and transportation LCIs.
- Used TRACI 2.1 for environmental impact assessment.
- Modelled material transportation impacts and construction-phase labor transportation impacts.
- Assumed DfD components could be reused three times.

LCA Analysis

- Assumed that material and labor transportation impacts are the same regardless of whether the DfD components are new or reused.

Preliminary LCA Results

Global Warming Potential No Reuse

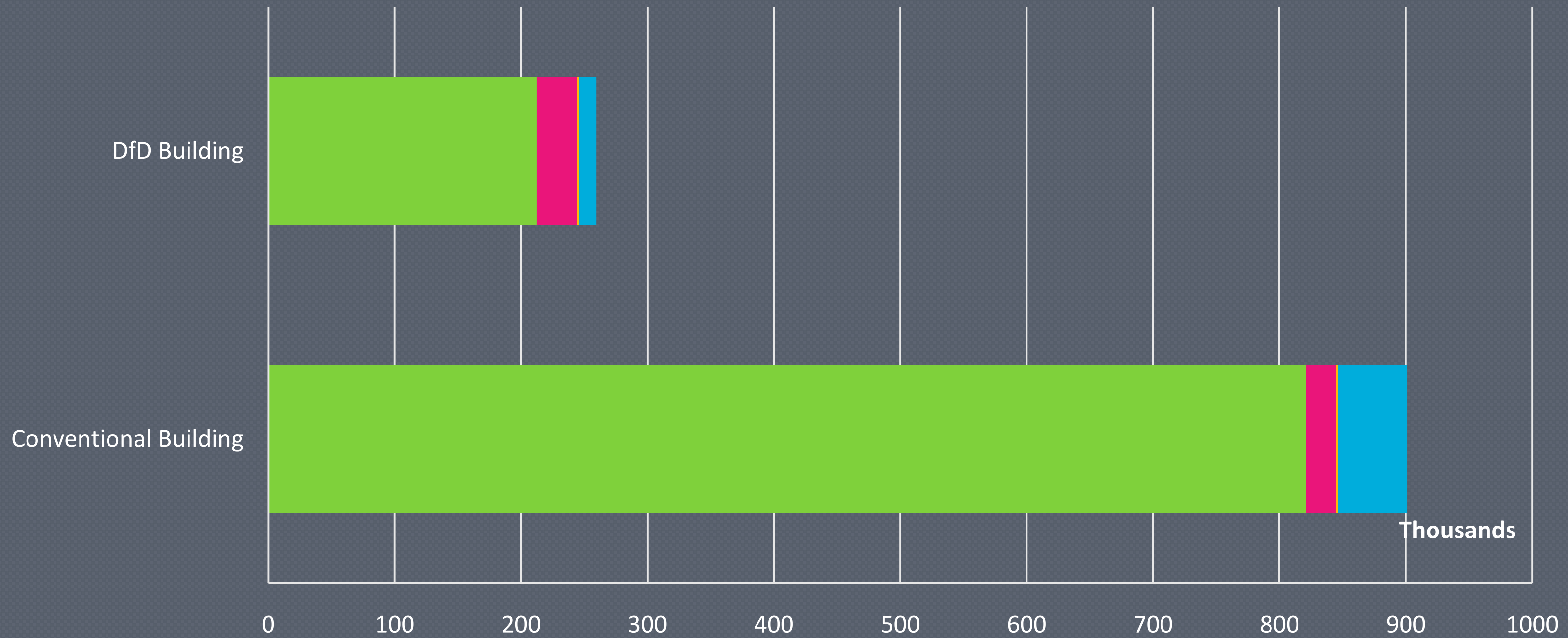


	Conventional Building	DfD Building
Production	821000	849000
Mat Transp	23600	32100
Worker Transp	1690	1370
Disposal	55000	56000

kg CO_2 eq

Preliminary LCA Results

Global Warming Potential Four Uses



	Conventional Building	DfD Building
Production	821000	212250
Mat Transp	23600	32100
Worker Transp	1690	1370
Disposal	55000	14000

kg CO_2 eq

Conclusions

- Assuming the DfD system is reused three times, it reduces carbon emissions by 71% relative to conventional composite construction.
- If reused only twice, carbon emissions are still reduced by 63%.
- If reused four times, carbon emissions are reduced by 76%.

Conclusions

- DfD requires a new mind-set for designers. We're not accustomed to thinking about the end-of-life (much less the after-life) of our building designs.
- DfD will be most successful for routine building development, such as low- to mid-rise commercial development and housing (which accounts for most construction). These buildings are the most likely to have regular, repeating floor plans, simple construction, and relatively short life-spans.

Concluding Thoughts on DfD

- DfD is attracting the attention of building designers in the North America and Europe. The Building Materials Reuse Association in the U.S. is promoting DfD, and excellent DfD guides have been published by the Canadian government, the Scottish government, and CIRIA, a British construction research and educational association.

Structures and Thermal Bridging

Russ Miller-Johnson

What do we mean when we say Thermal Bridging

- Highly Conductive Material that by-passes insulation layers
- Areas of high heat transfer
- Greatly effect the thermal performance of assemblies

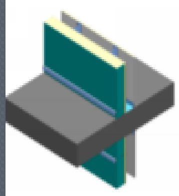
- BC Hydro, Building Envelope Thermal Bridging Guide, Overview Presentation, www.bchydo.com

and Condensation performance

Why do anything about Thermal Bridging

- Total Losses for Structural Bridges

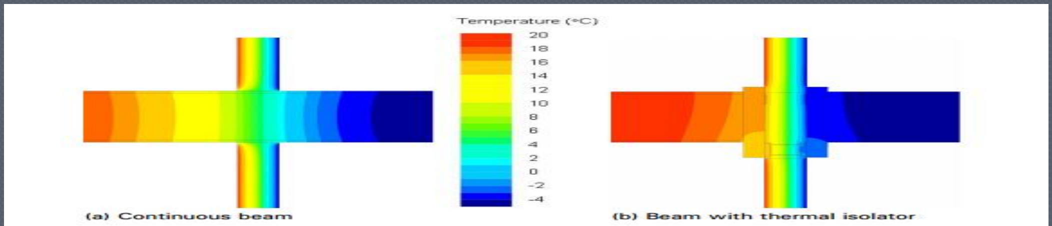
- *"Thermal Performance of Building Envelope Details for Mid-and High-Rise Buildings," ASHRAE , TC 4.4, 1365-RP*



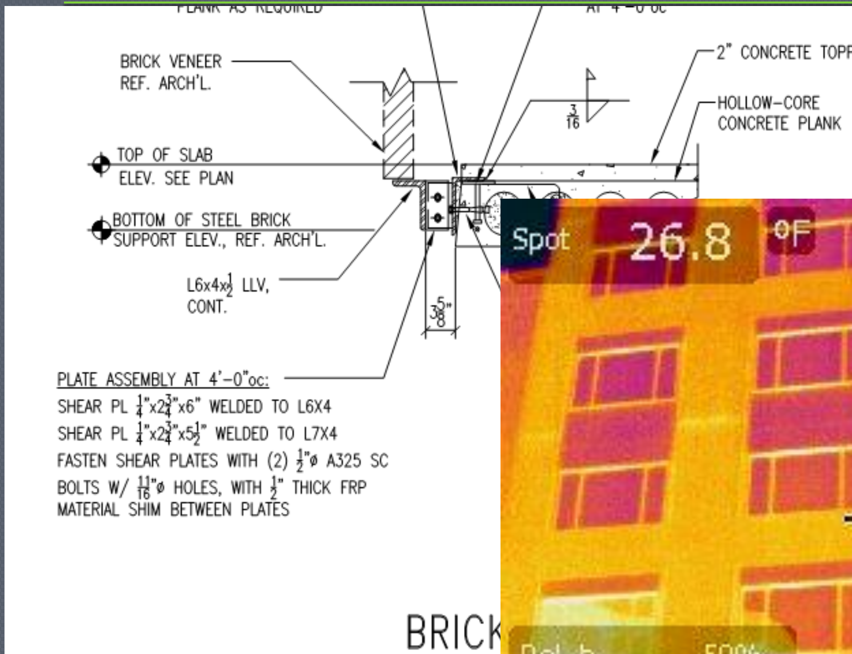
Detail 6[19] shows the significant effect that an un-insulated slab has on the heat loss through a wall assembly. For a 3.1 m (10 ft) high wall and exterior insulation in the range of R-5 to R-25, by adding a slab, the assembly thermal transmittance is increased 29-60% compared to the 'clear wall' values.

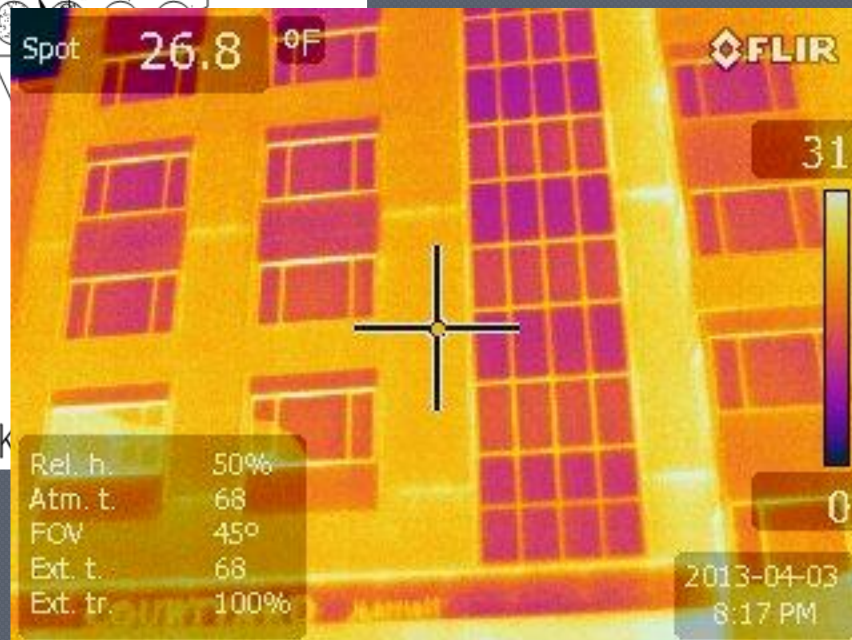
- Localized, Short Circuit Losses more important as thermal performance of the building envelope improves.

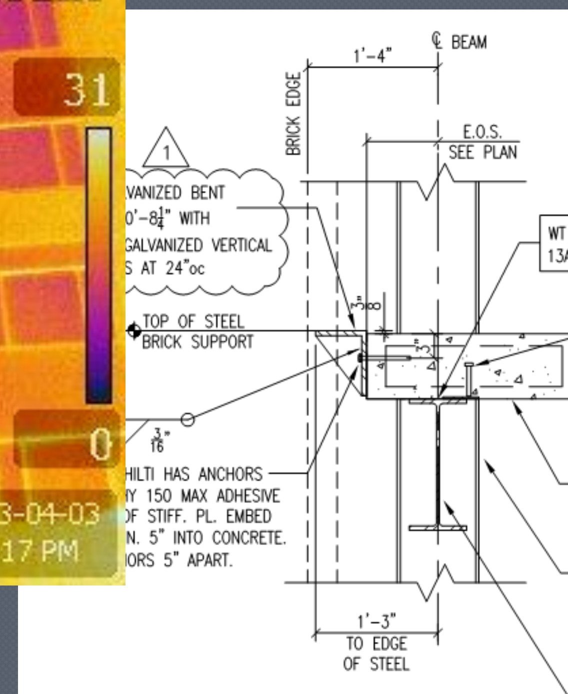
- *"Avoidance of Thermal Bridging in Steel Construction," SCI Publication P380*



Why do anything about Thermal Bridging







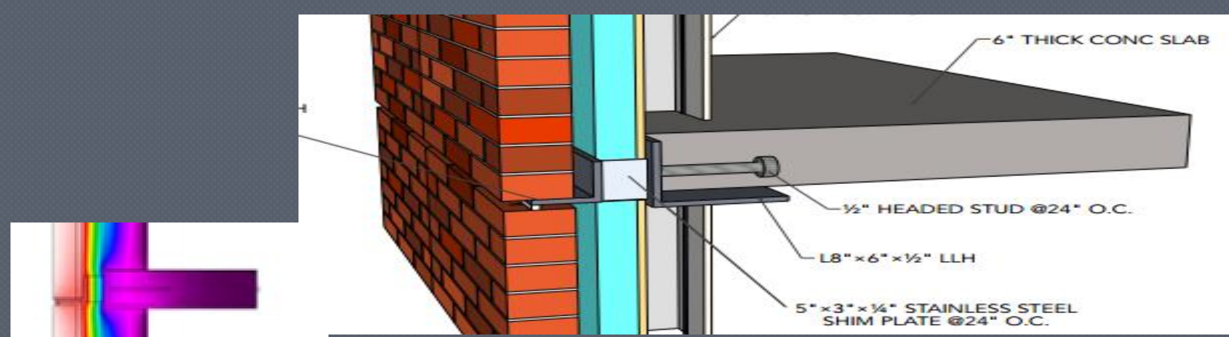
Phase 2 and Phase 1

What do we do about Thermal Bridging

Thermal Break Design Strategies

1. Utilize geometric separation when possible
2. Use discrete bridging elements
3. Use less conductive materials, e.g. stainless steel at bridging elements instead of carbon
4. Consider Manufactured Structural Thermal Breaks Assemblies

- *"Thermal Bridging Solutions: Minimizing Structural Steel's Impact on Building Envelope Energy Transfer" a Supplement to "Modern Steel Construction" (AISC)*



What is the weight of Thermal Bridging

- Energy losses throughout the life of the building vs. effects of addressing

One pound of CO2
- NRDC

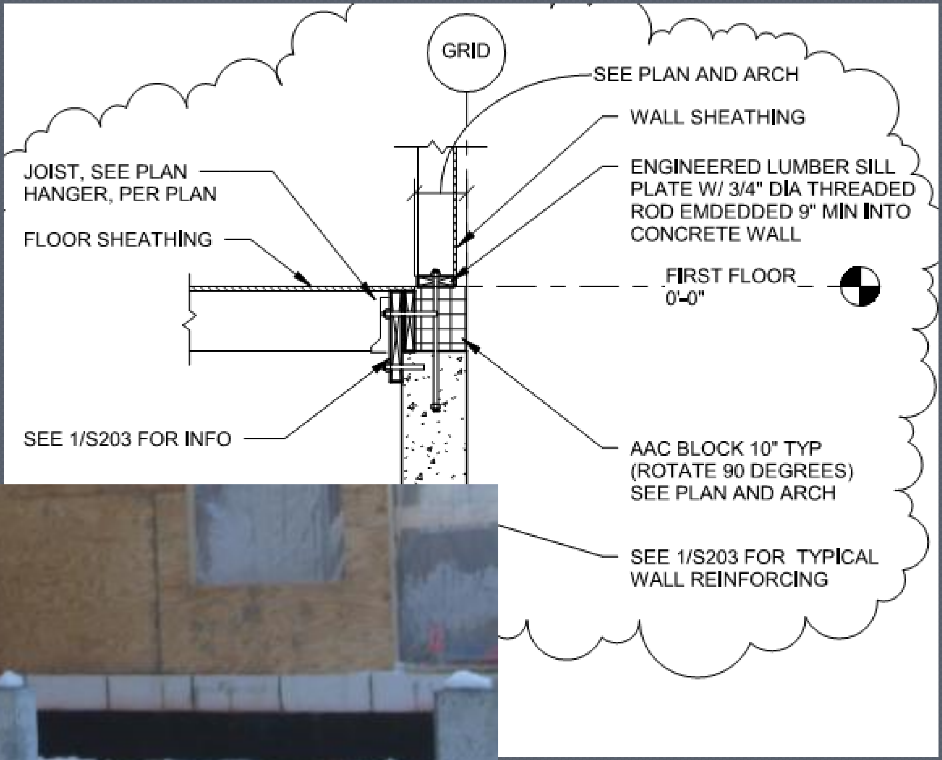
Insulation Material	R-value R/inch	Density lb/ft³	Emb. E MJ/kg	Emb. Carbon $kgCO_2/kg$	Emb. Carbon $kgCO_2/ft^2 \cdot R$	Blowing Agent (GWP)	Bl. Agent kg/kg foam	Blowing Agent GWP/ bd-ft	Lifetime GWP/ $ft^2 \cdot R$
Cellulose (dense-pack)	3.7	3.0	2.1	0.106	0.0033	None	0	N/A	0.0033
Fiberglass batt	3.3	1.0	28	1.44	0.0165	None	0	N/A	0.0165
Rigid mineral wool	4.0	4.0	17	1.2	0.0455	None	0	N/A	0.0455
Polyisocyanurate	6.0	1.5	72	3.0	0.0284	Pentane (GWP=7)	0.05	0.02	0.0317
Spray polyurethane foam (SPF) – closed-cell (HFC-blown)	6.0	2.0	72	3.0	0.0379	HFC-245fa (GWP=1,030)	0.11	8.68	1.48
SPF – closed-cell (water-blown)	5.0	2.0	72	3.0	0.0455	Water (CO_2) (GWP=1)	0	0	0.0455
SPF – open-cell (water-blown)	3.7	0.5	72	3.0	0.0154	Water (CO_2) (GWP=1)	0	0	0.0154
Expanded polystyrene (EPS)	3.9	1.0	89	2.5	0.0307	Pentane (GWP=7)	0.06	0.02	0.036
Extruded polystyrene (XPS)	5.0	2.0	89	2.5	0.0379	HFC-134a[1] (GWP=1,430)	0.08	8.67	1.77

1. XPS manufacturers have not divulged their post-HCFC blowing agent, and MSDS data have not been updated. The blowing agent is assumed here to be HFC-134a.

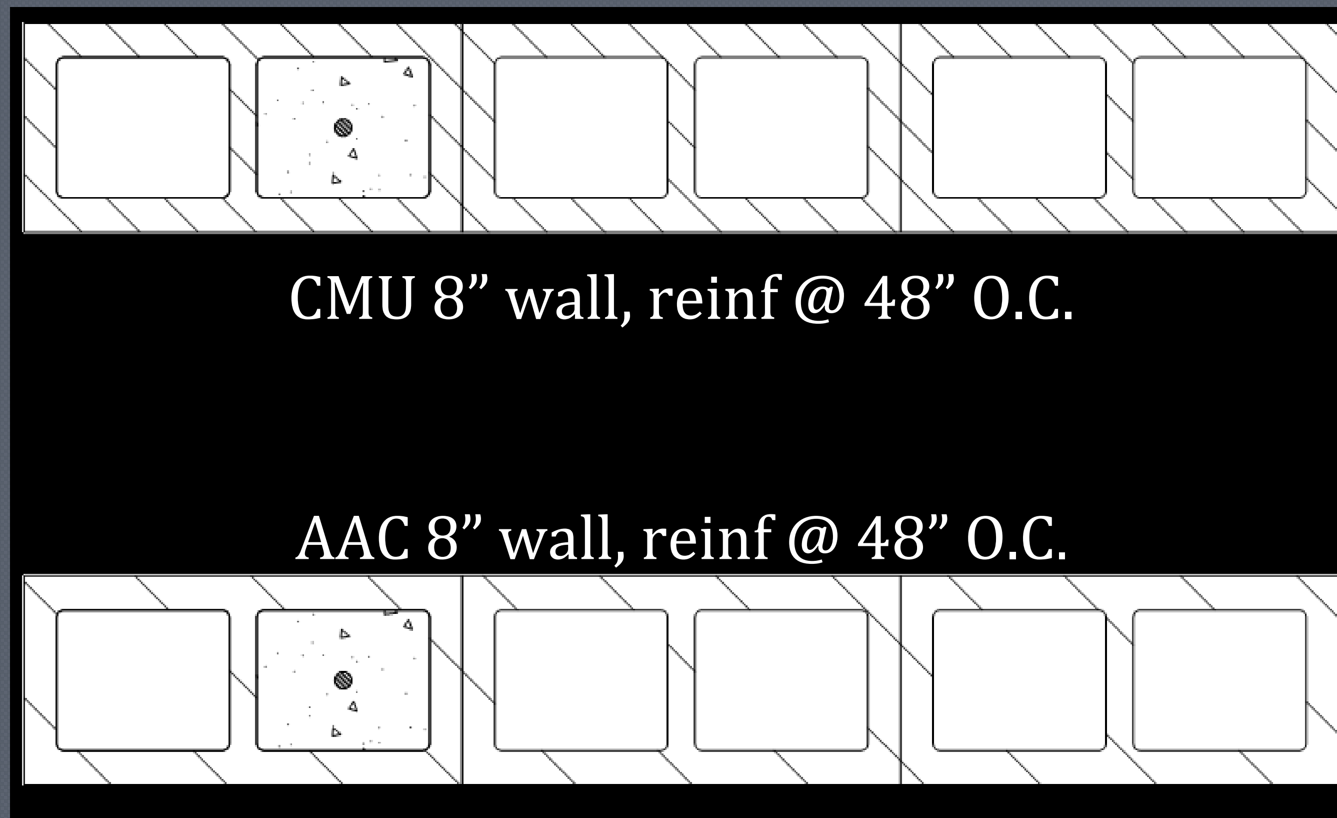
Carbon Count *- Building Green*

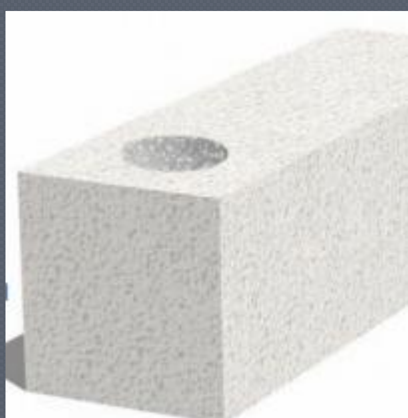
Masonry –AAC Structural Thermal Break

AAC Insulated Load-Bearing Sill for 4- story structure



Masonry - CMU & AAC





Thermal Resistance (h ft² °F/Btu	AAC-2/400	AAC-4/500	AAC-4/600
8"	10.00	8.70	7.77

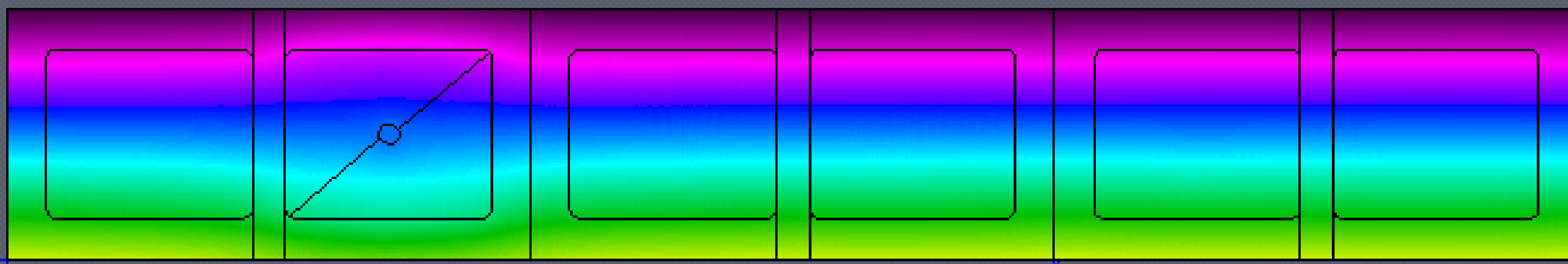
Hebel

THERM models by Laura Dolak, Halvorson

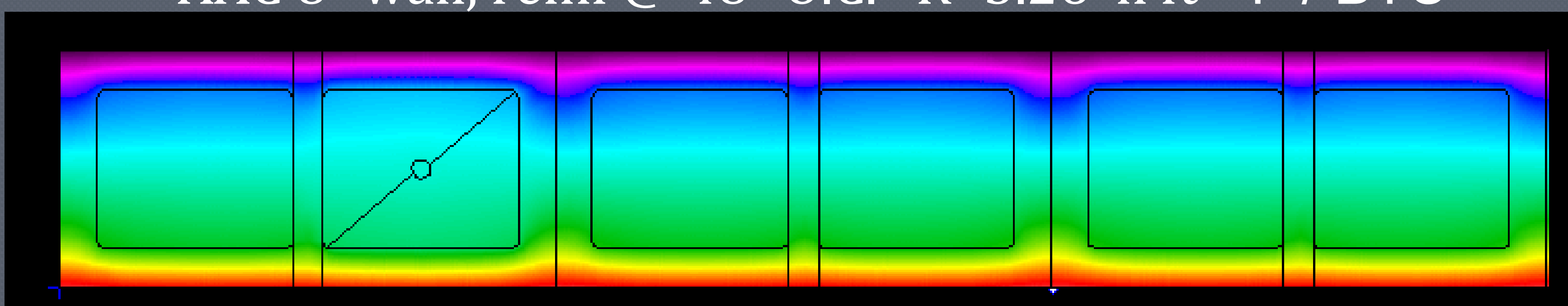
ASCE SEI Sustainability Committee, Thermal Bridging Working Group

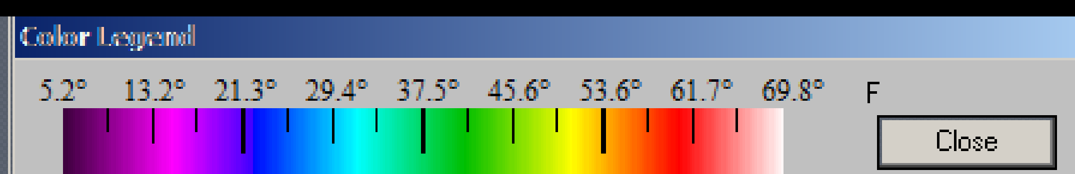
Masonry – CMU & AAC

CMU 8” wall, reinf @ 48” O.C.   R=2.32 h ft^2 °F / BTU



AAC 8” wall, reinf @ 48” O.C.   R=5.26 h ft^2 °F / BTU





LCA Comparison
Masonry – CMU & AAC

Masonry – Alternatives

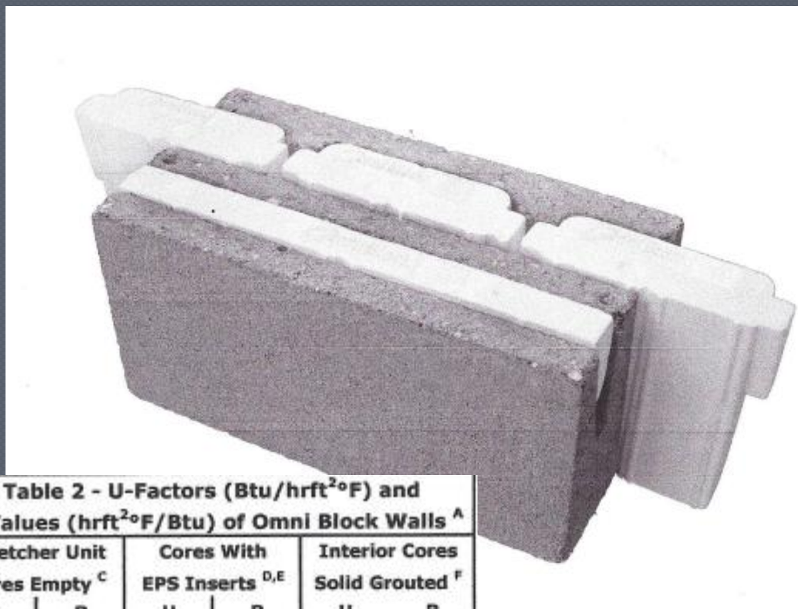
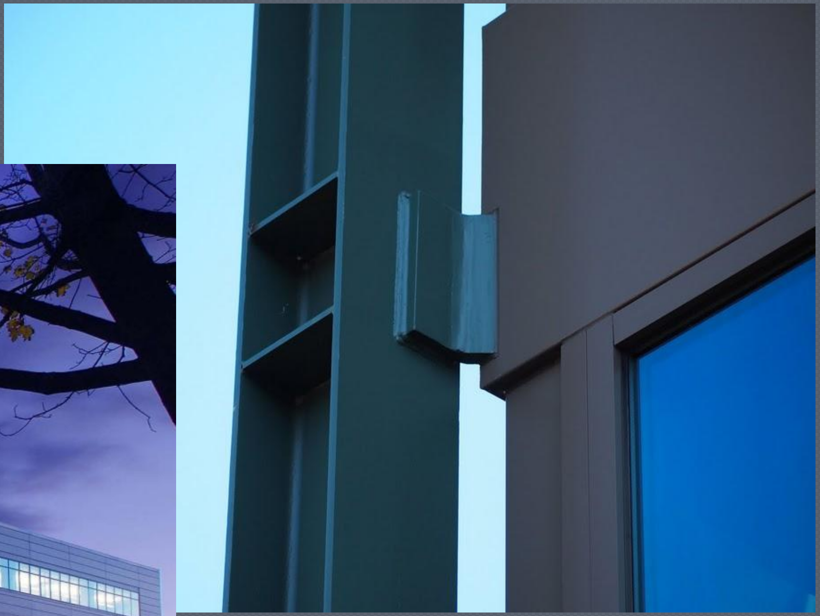


Table 2 - U-Factors (Btu/hrft²°F) and R-Values (hrft²°F/Btu) of Omni Block Walls [A]					
Stretcher Unit Cores Empty [C]		Cores With EPS Inserts [D,E]		Interior Cores Solid Grouted [F]	
U	R	U	R	U	R
0.151	6.6	0.051	19.7	0.087	11.5
0.164	6.1	0.052	19.2	0.091	11.0
0.172	5.8	0.053	18.9	0.093	10.7
0.180	5.6	0.054	18.7	0.096	10.5
0.189	5.3	0.054	18.4	0.098	10.2
0.199	5.0	0.055	18.1	0.101	9.9

Wall Type	Nominal R-value	Whole Wall R-value
Durisol WF30 T3 (12" R-20)	R-20	R-19.8

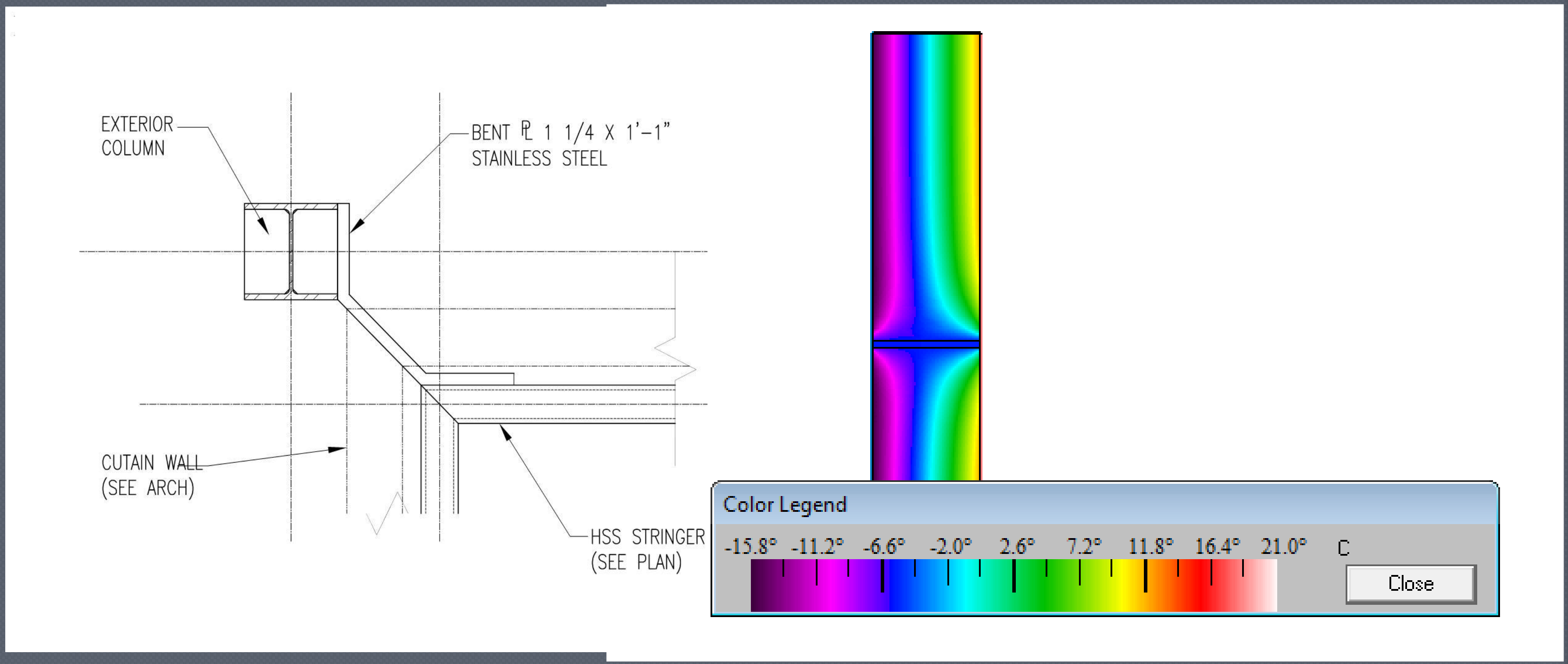
Proprietary Insulated CMU or Blended Insulative Materials

Steel – Stainless
Structural Thermal Break



Stainless Steel Connection through Envelope

Steel – Stainless & Carbon



- Carbon Steel or Stainless Steel
- Effect on Energy Model using proscriptive assembly values

Steel – Stainless & Carbon

Cross Section Element	Material	Conductivity [W/mK]	Depth [m]	R [m²K/W] (Depth/Cond.)	R{US}
1	Insulation at Curtain Wall Panel (Extruded Poly only)	0.033	0.102	3.091	17.618

Cross Section Element	Material	Keff [W/mK]	Element Depth [m]	R equiv [m²K/W]	R{US}
2	Insulation at Curtain Wall Panel w/ SS	0.049	0.102	2.082	11.865

Cross Section Element	Material	Keff [W/mK]	Element Depth [m]	R equiv [m²K/W}	R{US}
3	Insulation at Curtain Wall Panel w/ Carbon Steel	0.090	0.102	1.133	6.460

Ref: THERM Manual; Non Continuous Thermal Bridge Elements

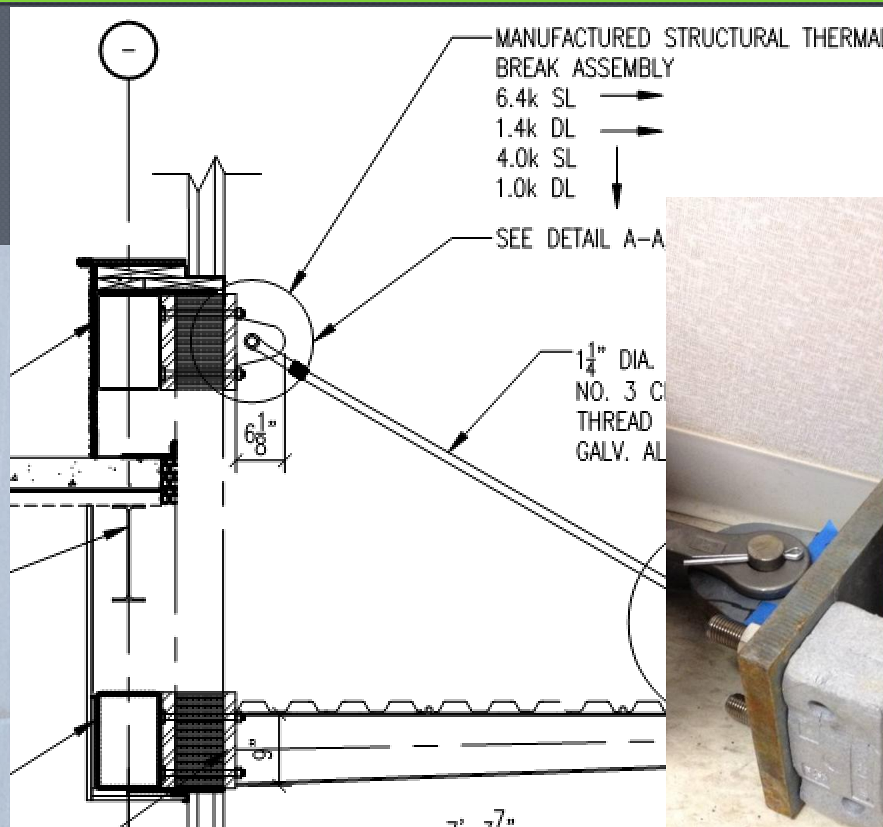
[illegible]	[illegible]	[illegible]	Conductivity [W/mK] "K"	"F x K"	Sum "Keff"
[illegible]	[illegible]	[illegible]	14.300	[illegible]	
Tributary Curtain wall panel [4x25 ft2]	[illegible]	[illegible]	0.033	0.033	0.049

Materials	Area [m2]	% Area "F"	Conductivity [W/mK] "K"	"F x K"	Sum "Keff"
CS Plate [1.25x13 in²]	0.010	0.001	51.000	0.057	
Tributary Curtain wall panel [4x25 ft2]	9.290	0.999	0.033	0.033	0.090

- Assess Non-Continuous Thermal Bridge Elements
- Effective Conductivity by “Weight” @ -32% w/ SS & -63% w/ CS (Relative comp. only)

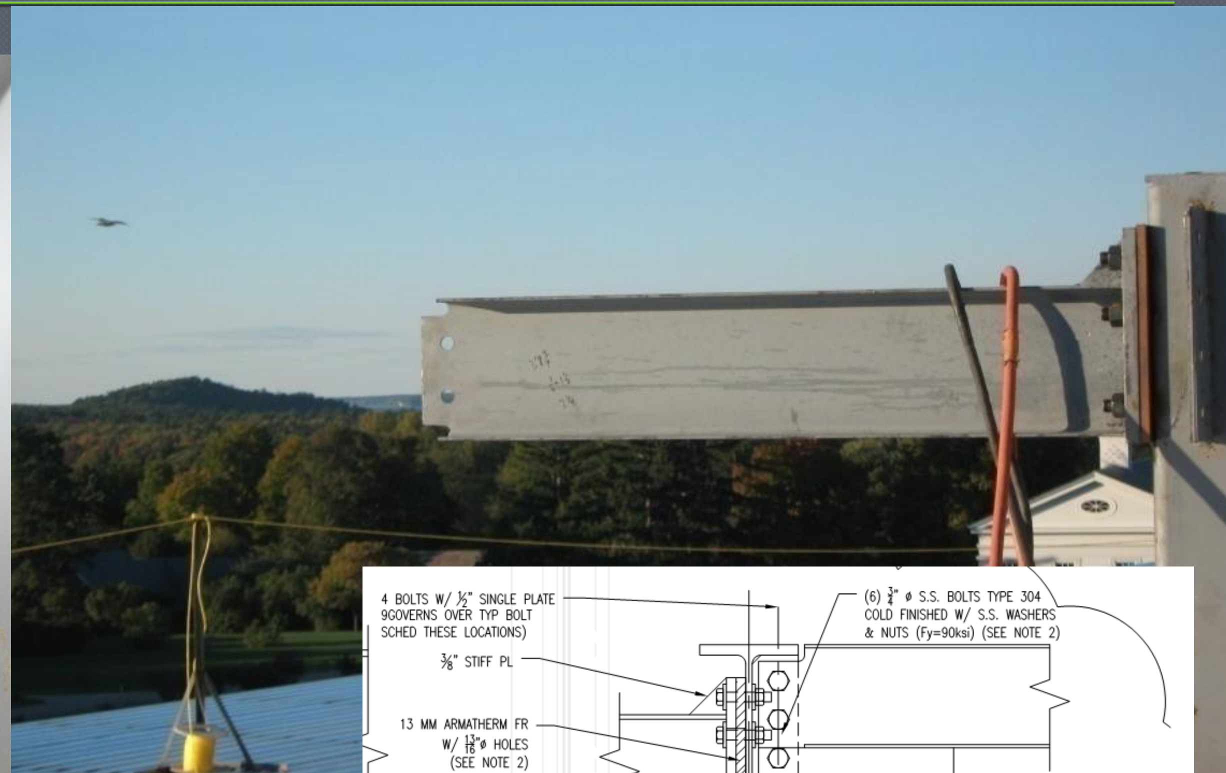
LCA Comparison
Steel – Stainless & Carbon

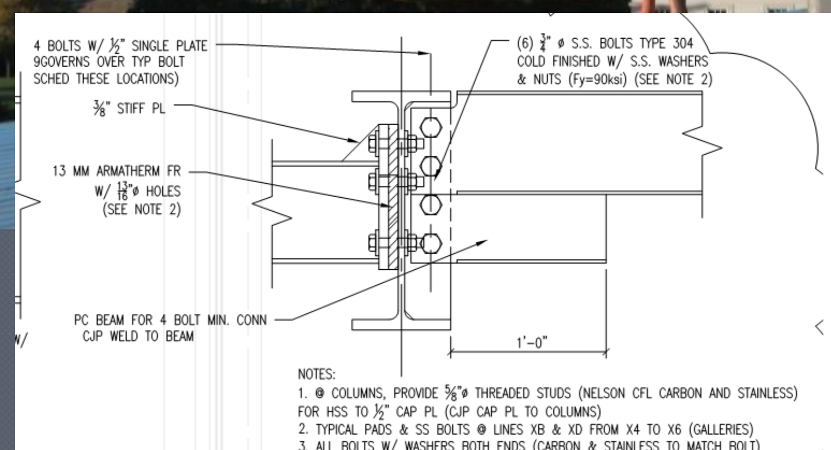
Steel – Alternatives



Performance Specified Connection (MSTBA)

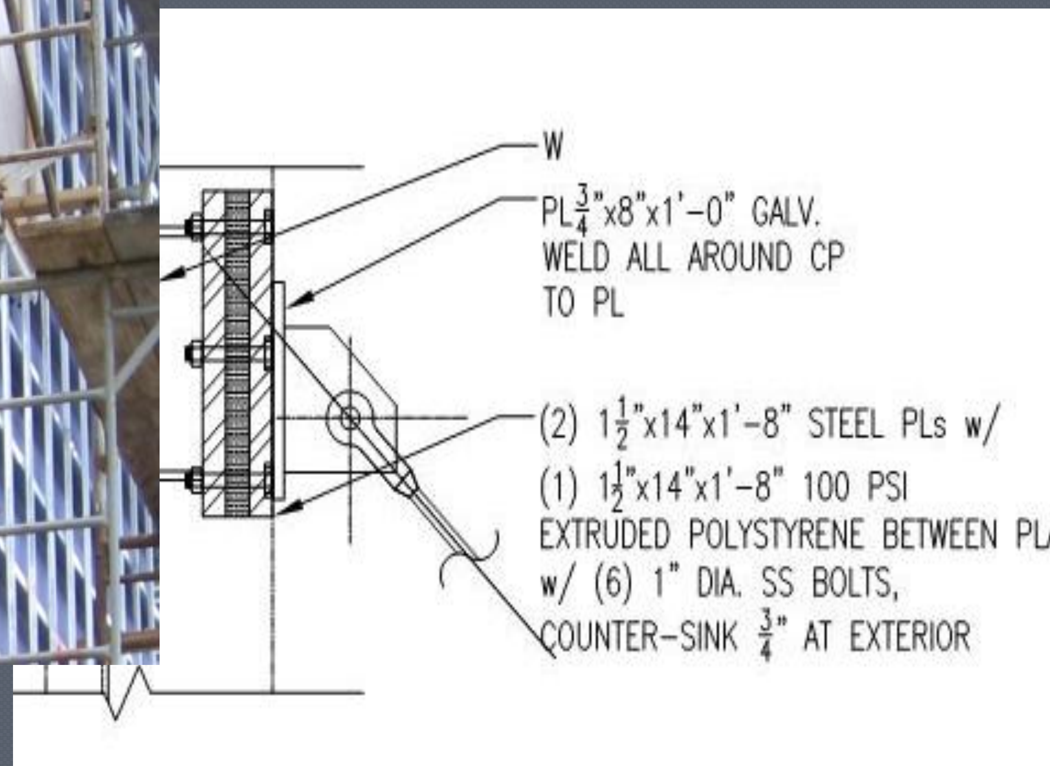
Steel – Alternatives





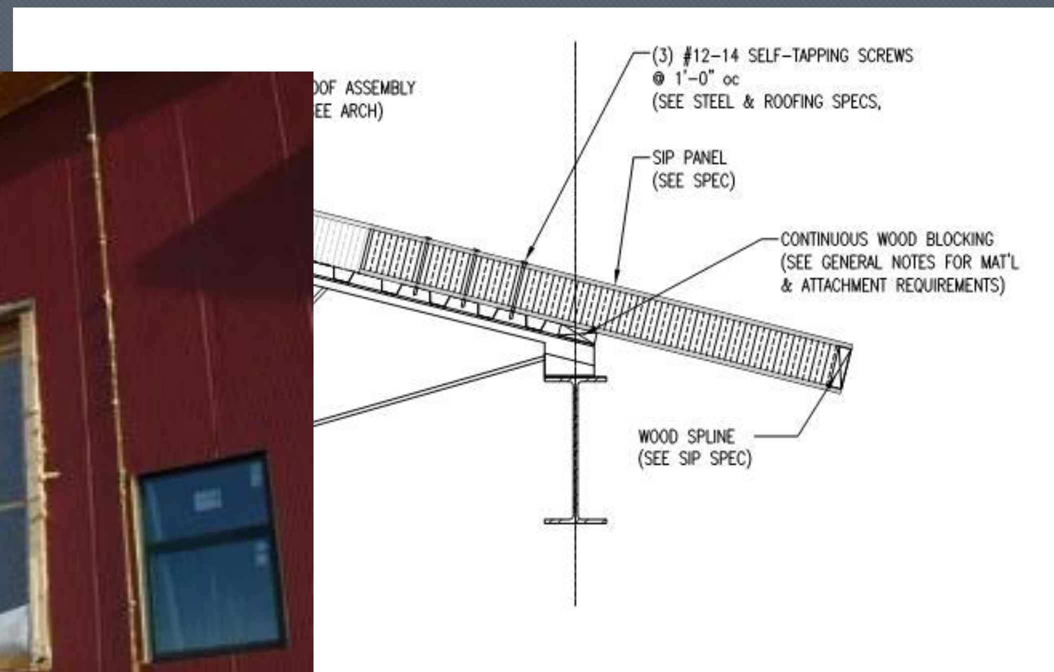
Performance Specified Connection (MSTBA)

Steel – Alternatives



Designed Connections

Steel – Alternatives



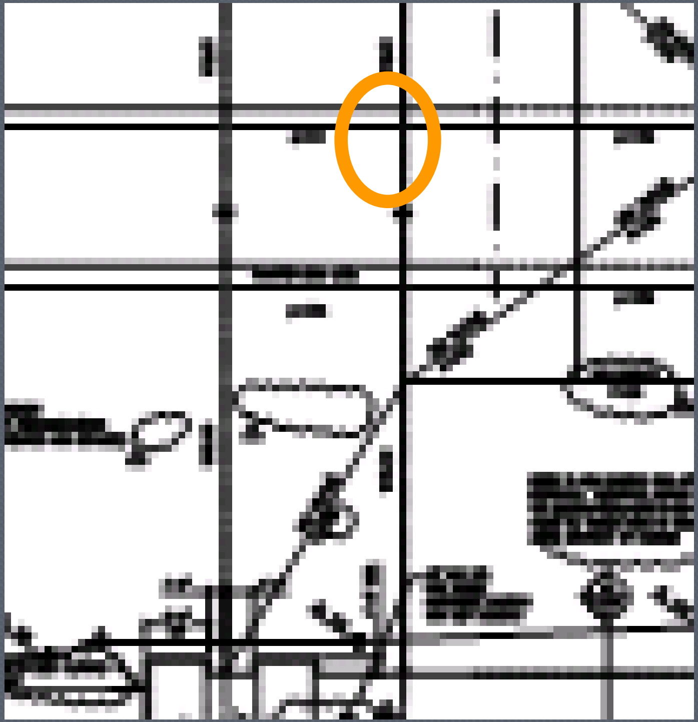
Less Conductive Framing

Insulated Connection Structural Thermal Break

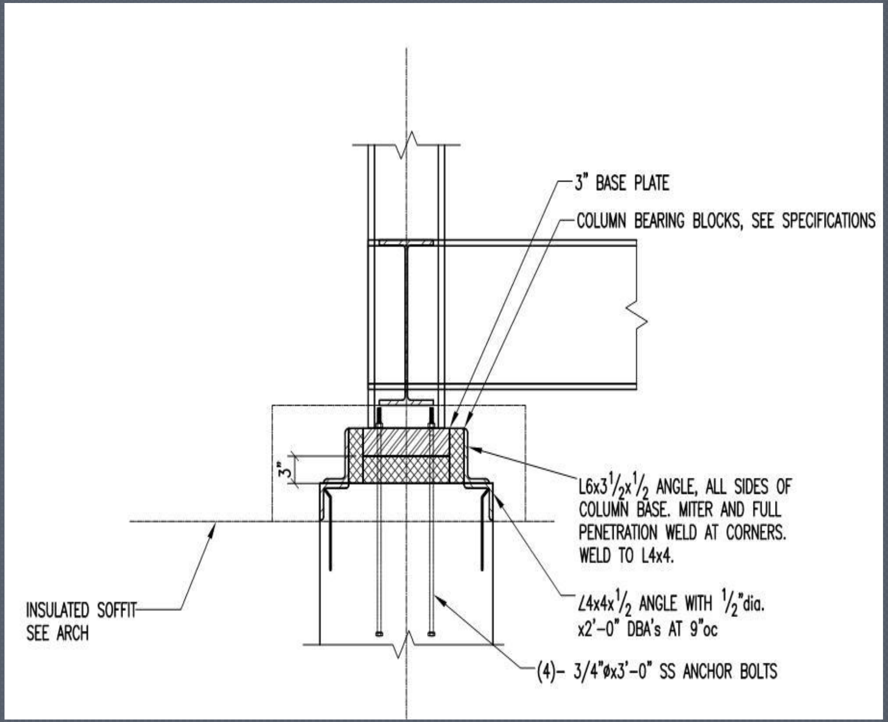
Uninsulated Connection & Insulated Enclosure

Insulated Connection & Insulated Enclosure

Insulated & Uninsulated Column Base Connection

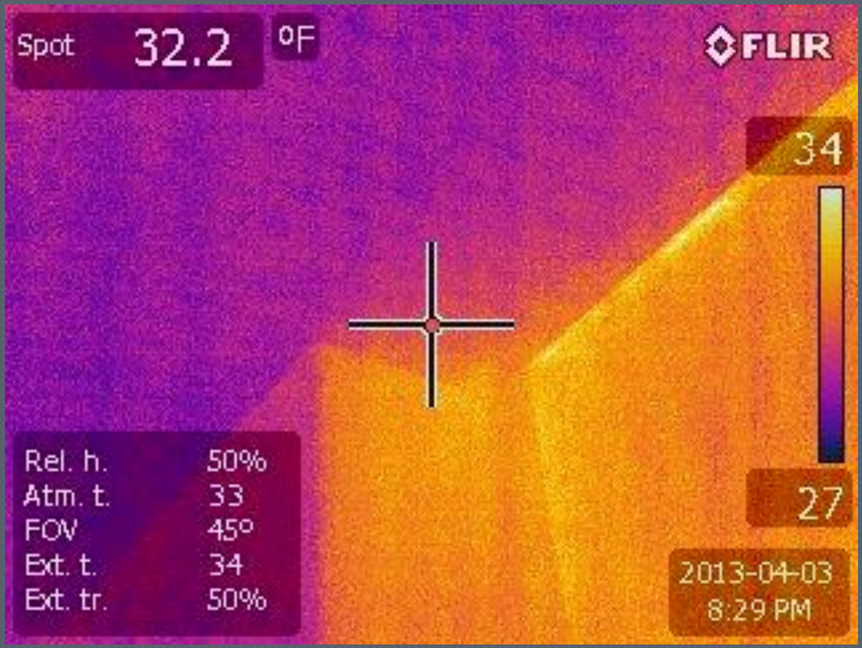


Uninsulated Connection



Insulated Connection

Insulated & Uninsulated Column Base Connection

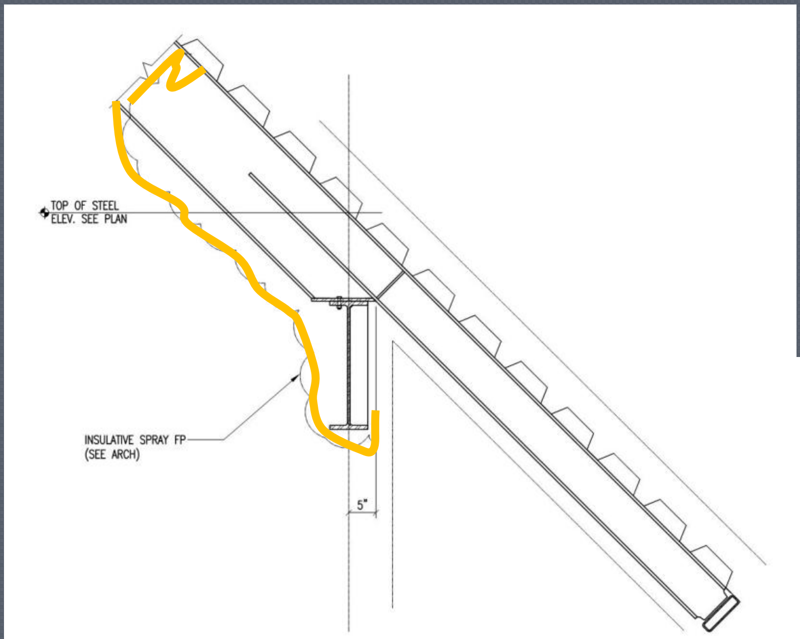


Uninsulated Connection

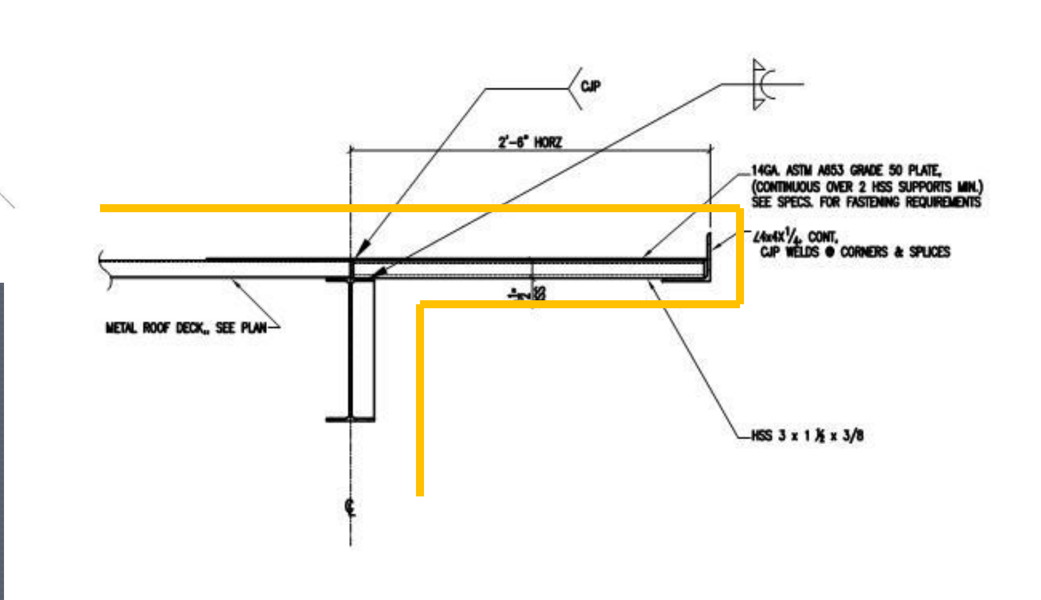
Insulated Connection

LCA Comparison
Insulated & Uninsulated Connection

Insulation - Alternatives

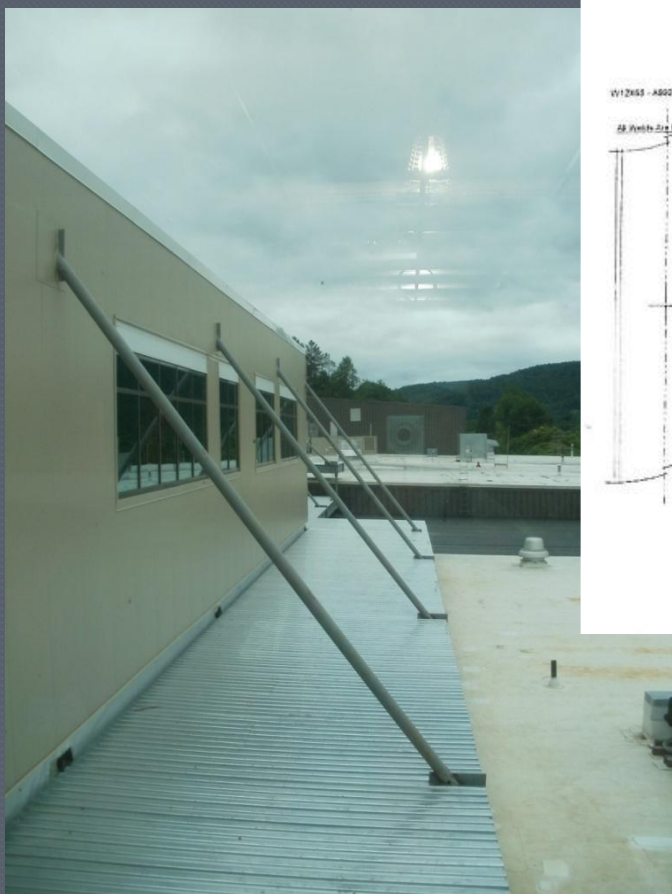


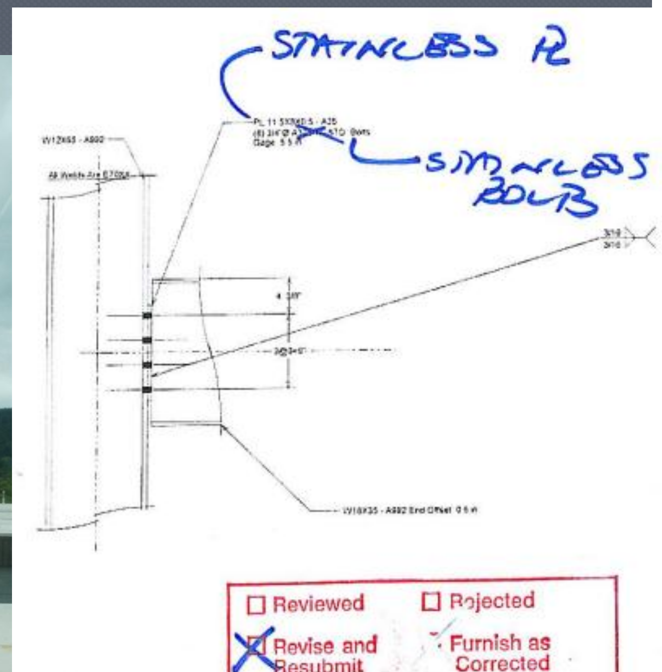
Insulation around framing on outside

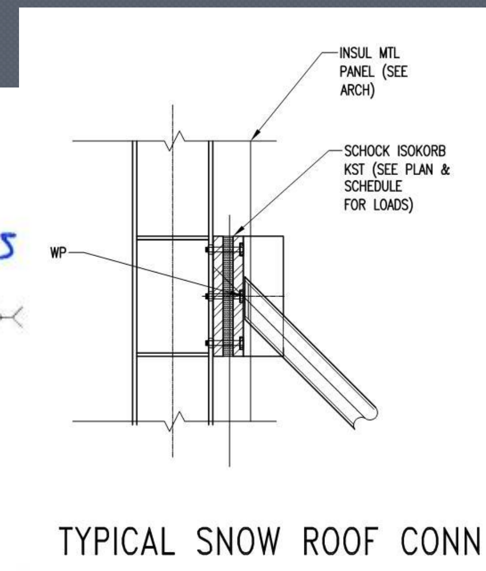


Insulation for portion of framing on inside

Insulation - Alternatives







Steel – Alternatives

Redux

Thermal Bridging in Cladding Systems

Kara Peterman

Northeastern

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Northeastern University

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Kara Peterman, Ph.D.: Post-Doctoral Research Associate, Department of Civil and Environmental Engineering

Klepper, Hahn & Hyatt

James D'Aloisio, P.E., SECB, LEED AP BD+C: Principal: Structural engineer, chair of ASCE/SEI Technical Committee on Sustainability, member, Thermal Bridging Working Group; co-author of AISC Modern Steel Construction article on Thermal Bridging Solutions, March 2012

Simpson Gumpertz & Heger Inc.

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Mehdi S. Zarghamee, Ph.D., P.E., Senior Principal : Structural engineer, project coordinator for the development of draft ASCE standard for LRFD design of pultruded fiber-reinforced polymeric structures

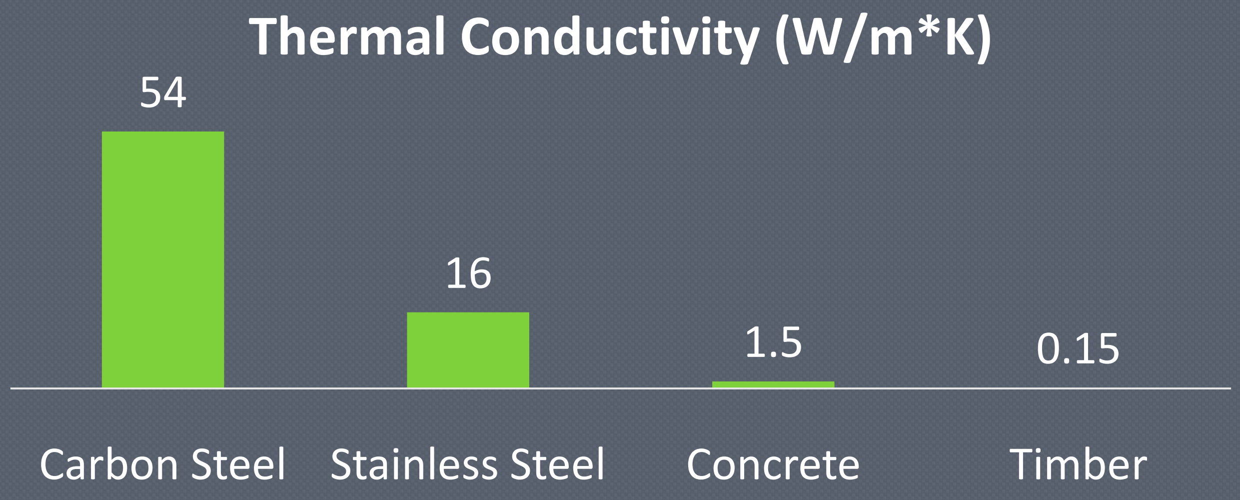
Sean M. O'Brien, P.E., LEED AP, Associate Principal : Thermal modeling and energy expert; voting member and program chair, ASHRAE Technical Committee 4.4 – Building Materials and Building Envelope Performance

Outline

- What is a thermal bridge? Thermal break?
- Common thermal bridges in steel structures
- Mitigation strategies
- Thermal performance
- Experimental test program
- Future work and conclusions

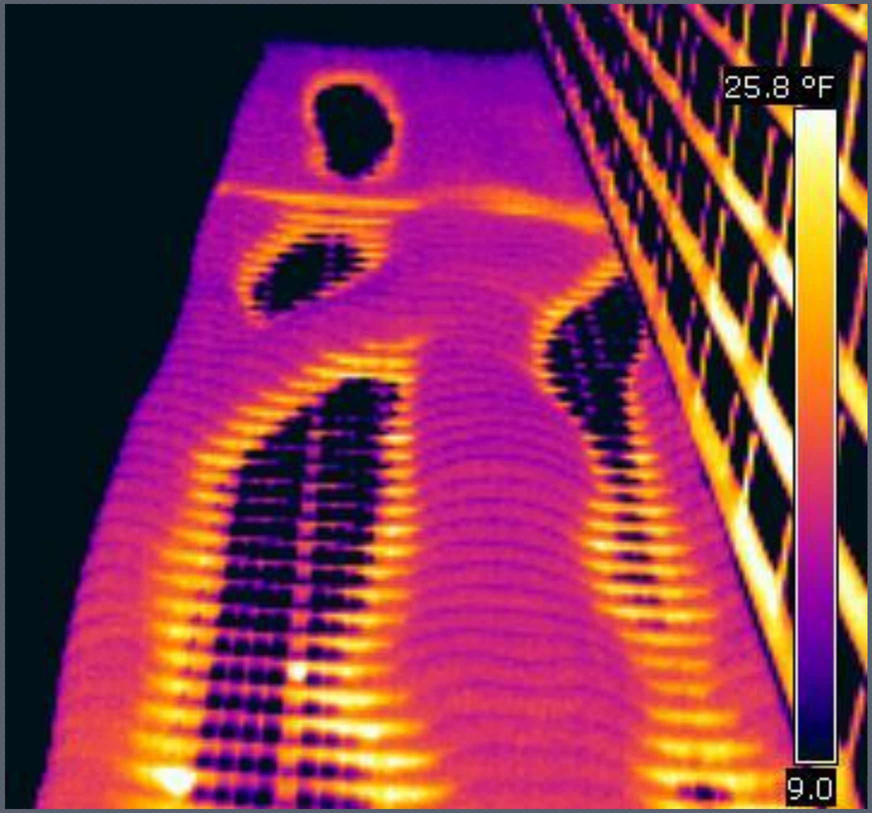
Thermal Bridges

- Structural elements that span the building envelope result in heat transfer between building interior and exterior
- This is especially true with steel structural elements

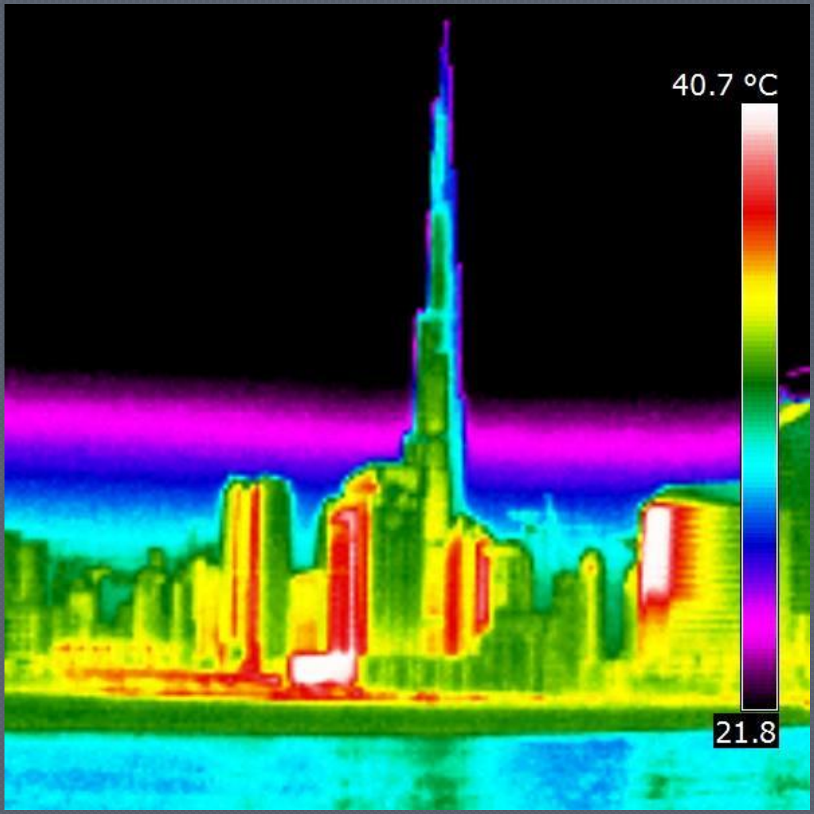


Thermal Bridges

Aqua Tower, Chicago



Burj Khalifa, Dubai



Thermal Breaks

- Thermal bridges must be physically broken to prevent energy loss → thermal breaks
- Thermal breaks involve splicing the steel member and inserting a thermally improved material or system
- These breaks must also be effective at load transfer

Outline

- What is a thermal bridge? Thermal break?
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Archetype Building

General information:

- Location:
  - Los Angeles: exposure type B (wind load); soil property D (seismic load)
  - Boston: exposure type B (wind load); soil property B (seismic load)
- Structural configuration: 3 bays by 3 bays; 13’ story height; special concentrically braced frame (SCBF)
- Material properties: structural steel: A992; Stud: 3/4 in.; concrete: 4 ksi

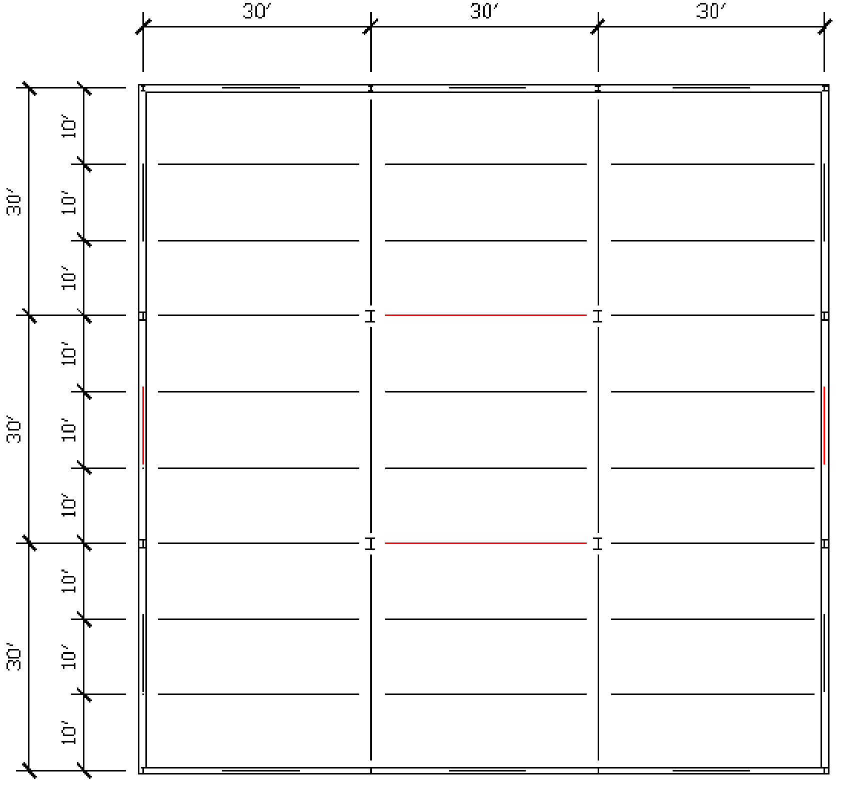
Parameters:

- Bay width: 30’ x 30’ and 20’ x 20’
- Stories: 3 stories(high gravity)and 9 stories(low gravity)
- Concrete plank thickness: 6 inch and 8 inch
- Systems: composite system using shear studs

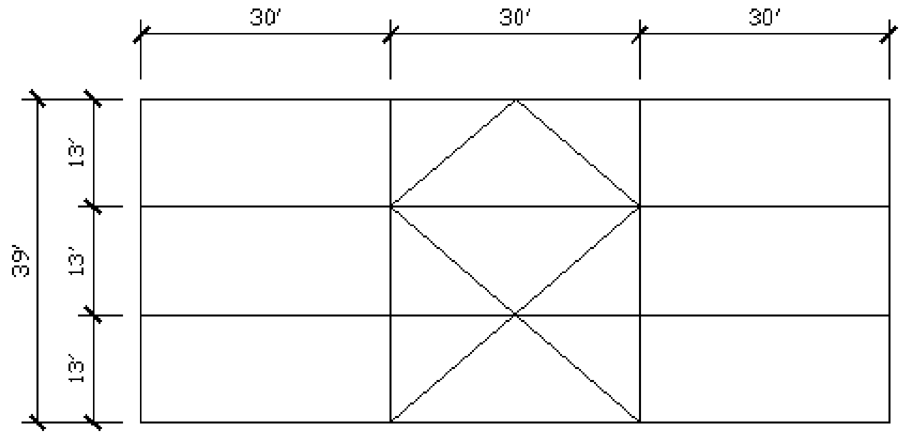
Provisions:

- ASCE 7-10 (*Minimum Design Loads for Buildings and Other Structures)*
- AISC 360-10 (*Specification for Structural Steel Buildings)*
- AISC 341-10 (*Seismic Provisions for Structural Steel Buildings)*

Archetype Building



Floor Plan



Elevation

Archetypal Thermal Bridges

- Shelf angles:
  - Slab-supported
  - Kicker-supported
- Supports brick veneer – deflection limited

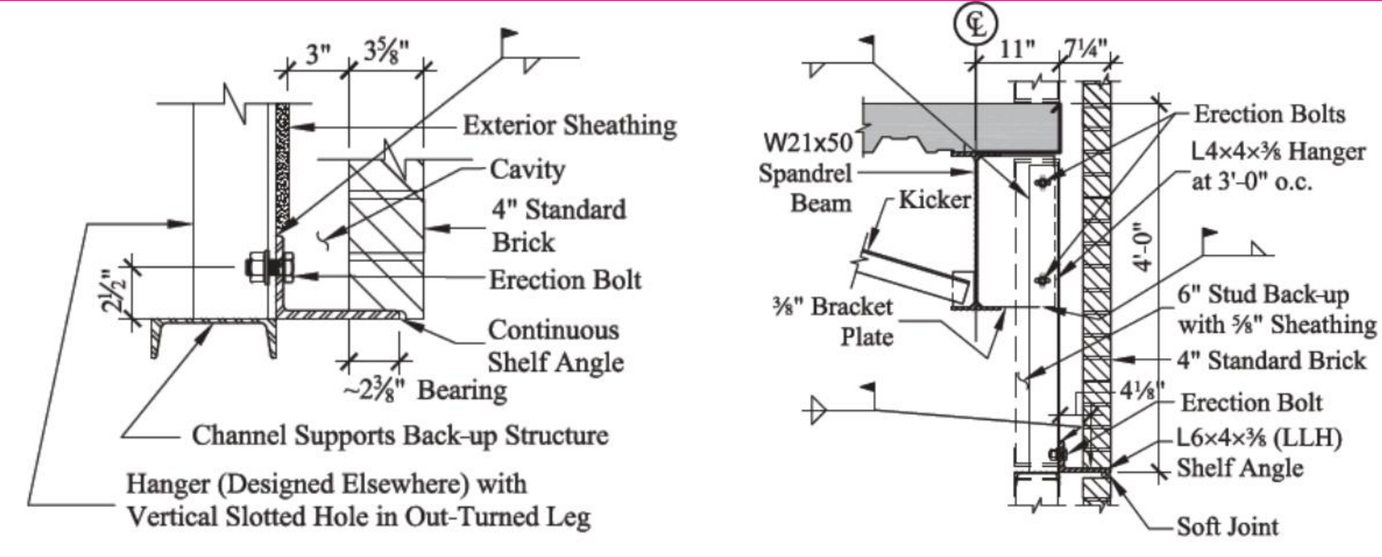
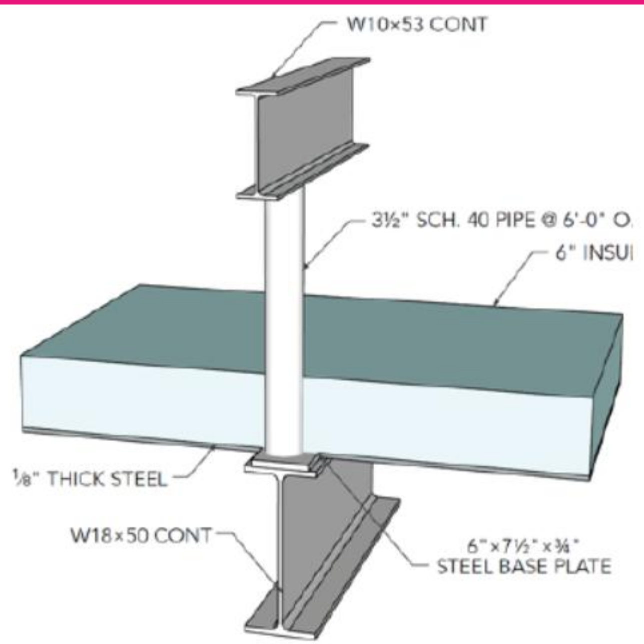


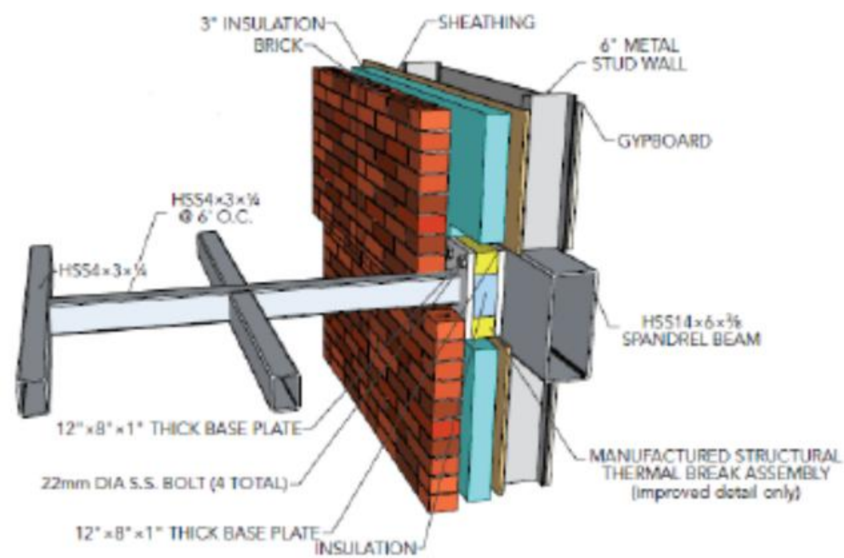
Fig. 7-16. Section of shelf angle supporting brick veneer.

Fig. 7-17. Section of spandrel beam with hanger system.

Archetypal Thermal Bridges

- Beams and cantilevers:
  - Roof posts
  - Canopy beams





Mitigation Strategies

- Add a thermally improved shim (FRP, steel foam, stainless steel)
  - Takes advantage of intermittent spacing
  - Easy to install
  - Structurally promising
- Replace structural steel member with thermally improved member (FRP)
  - Available member sizes not large enough
  - May not be structurally effective for these applications
- Use a manufactured thermal break assembly

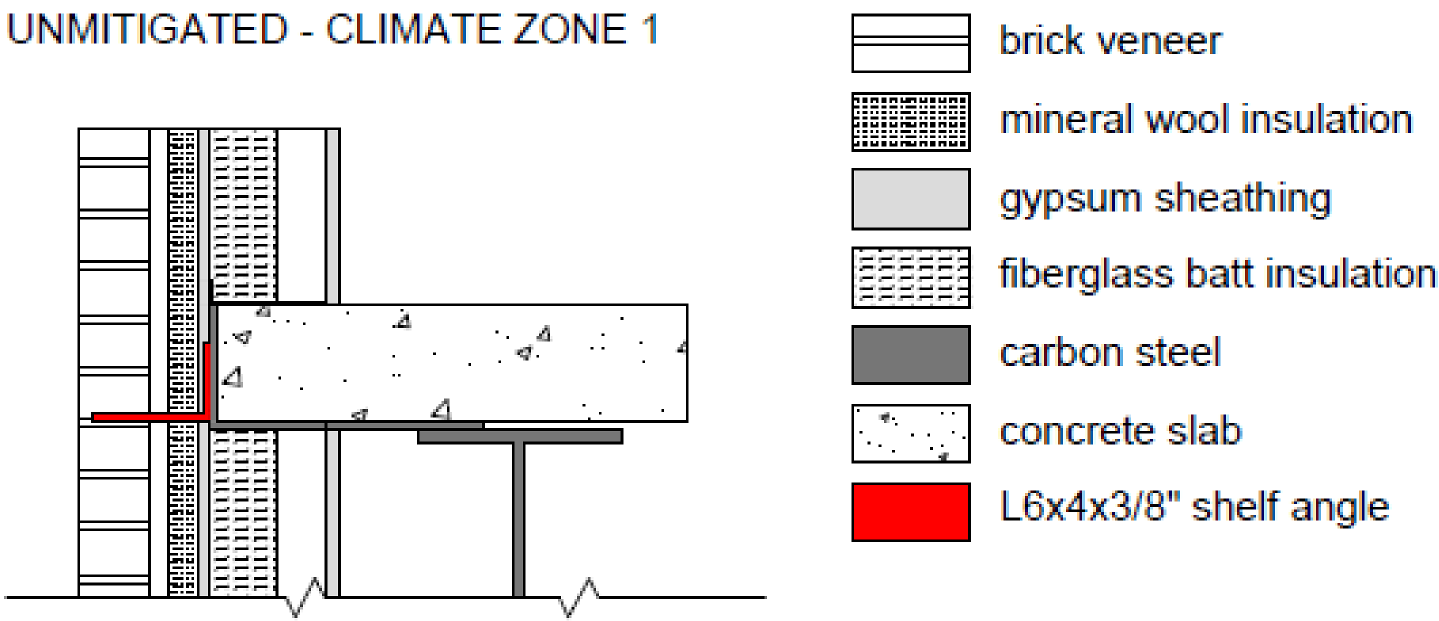
Challenges

- Maintain structural integrity
  - Monotonic and cyclic loads
  - Creep performance
  - Connection performance
  - Performance under elevated temperatures
- Field adjustability
  - Must be able to be installed in the field
  - Adjustable according to construction
- Geometric constraints
- Thermally effective

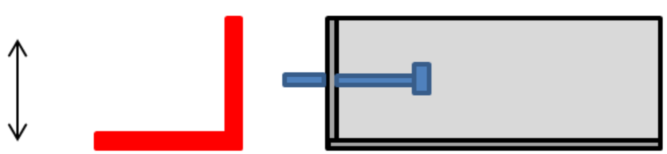
Challenges

- FRP-to-steel connections have not been validated in the experimental literature
- FRP-to-FRP and FRP-to-Steel connections are not clearly approved for structural use in national building code specifications

Proposed Thermal Breaks

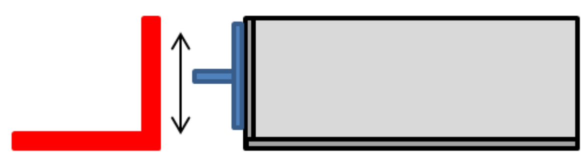


Original detail:



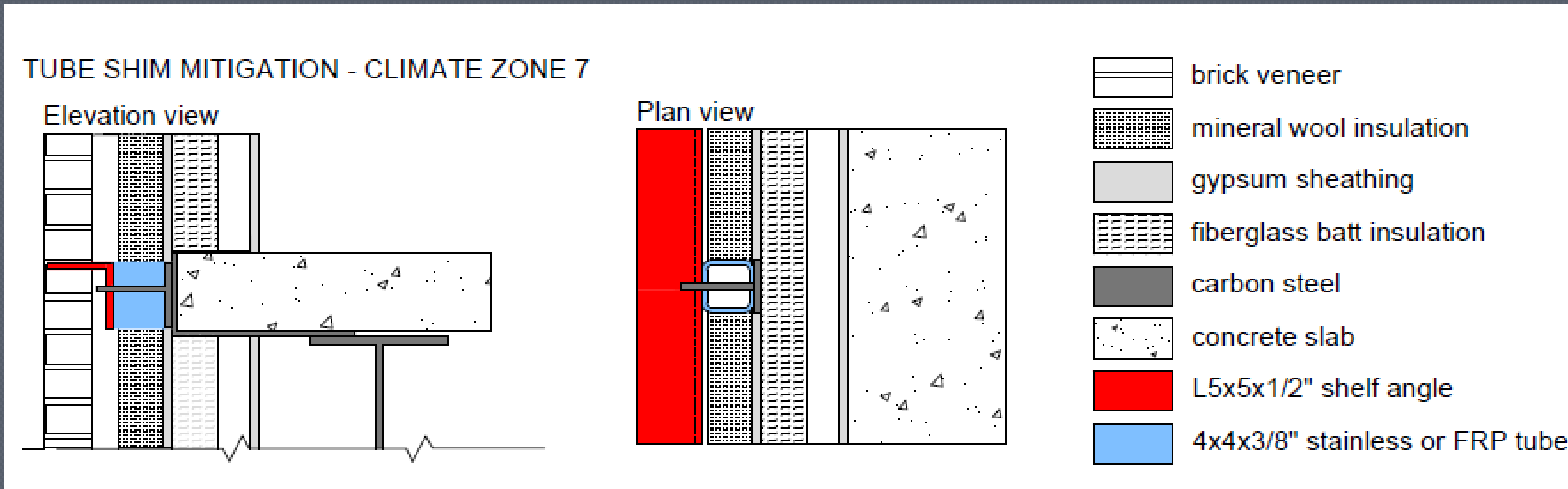
Angle height is adjustable due to long slotted holes

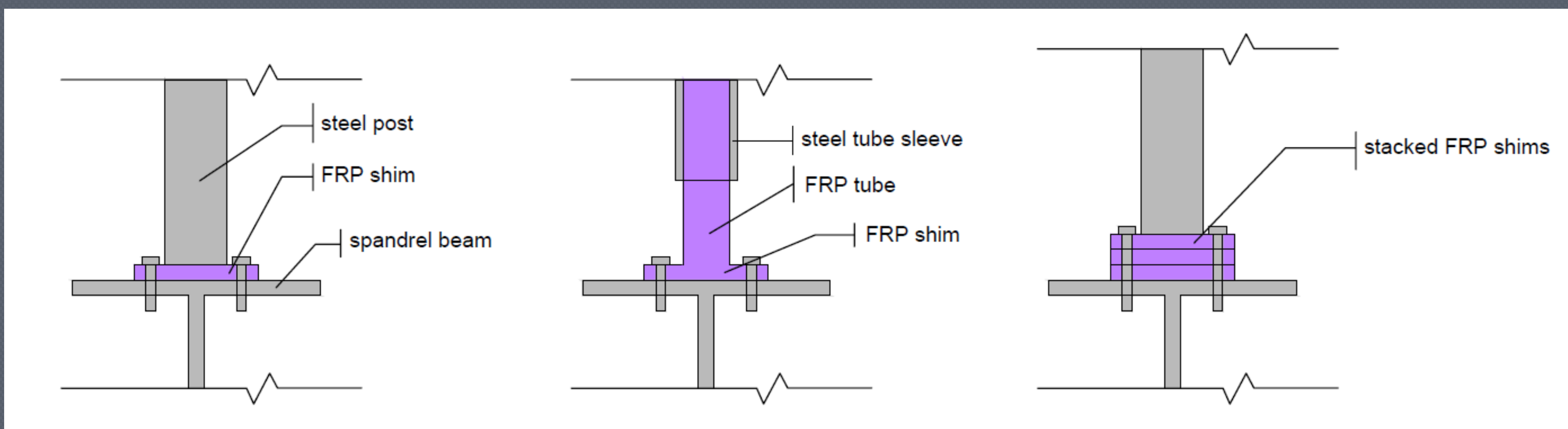
Proposed detail:



Additional plate with stud pre-welded can be field-adjusted on slab
Shelf angle has standard holes

Proposed Thermal Breaks





Outline

- What is a thermal bridge? Thermal break?
- Common thermal bridges in steel structures
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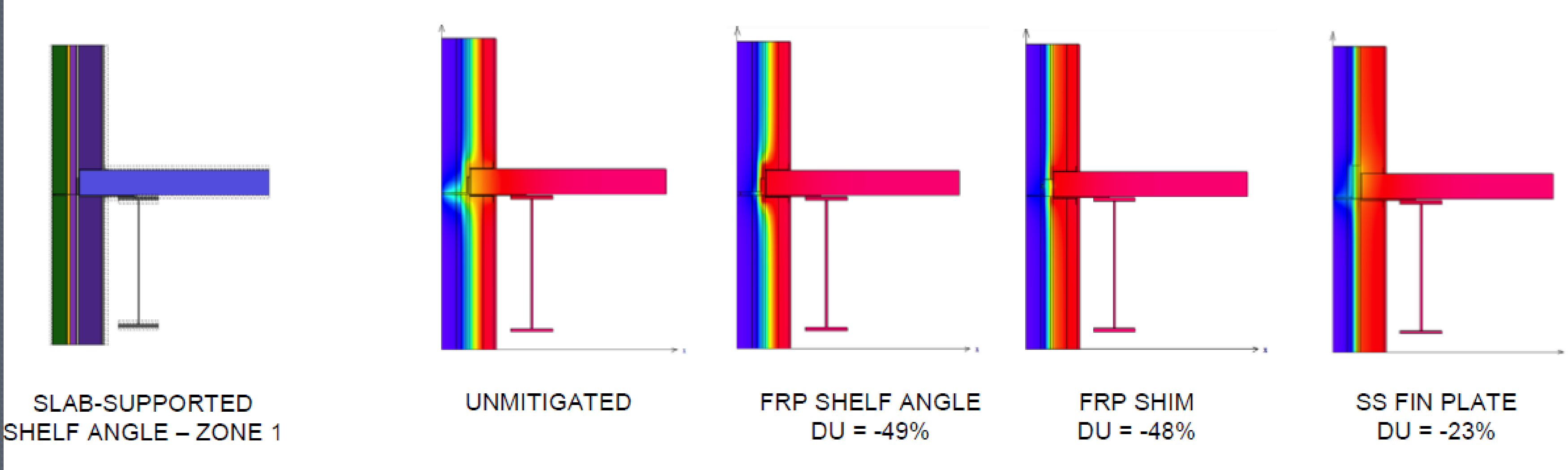
Thermal Results

- Preliminary thermal models demonstrate efficacy in proposed solutions
- But how much improvement is good enough?
- Structural testing still necessary.

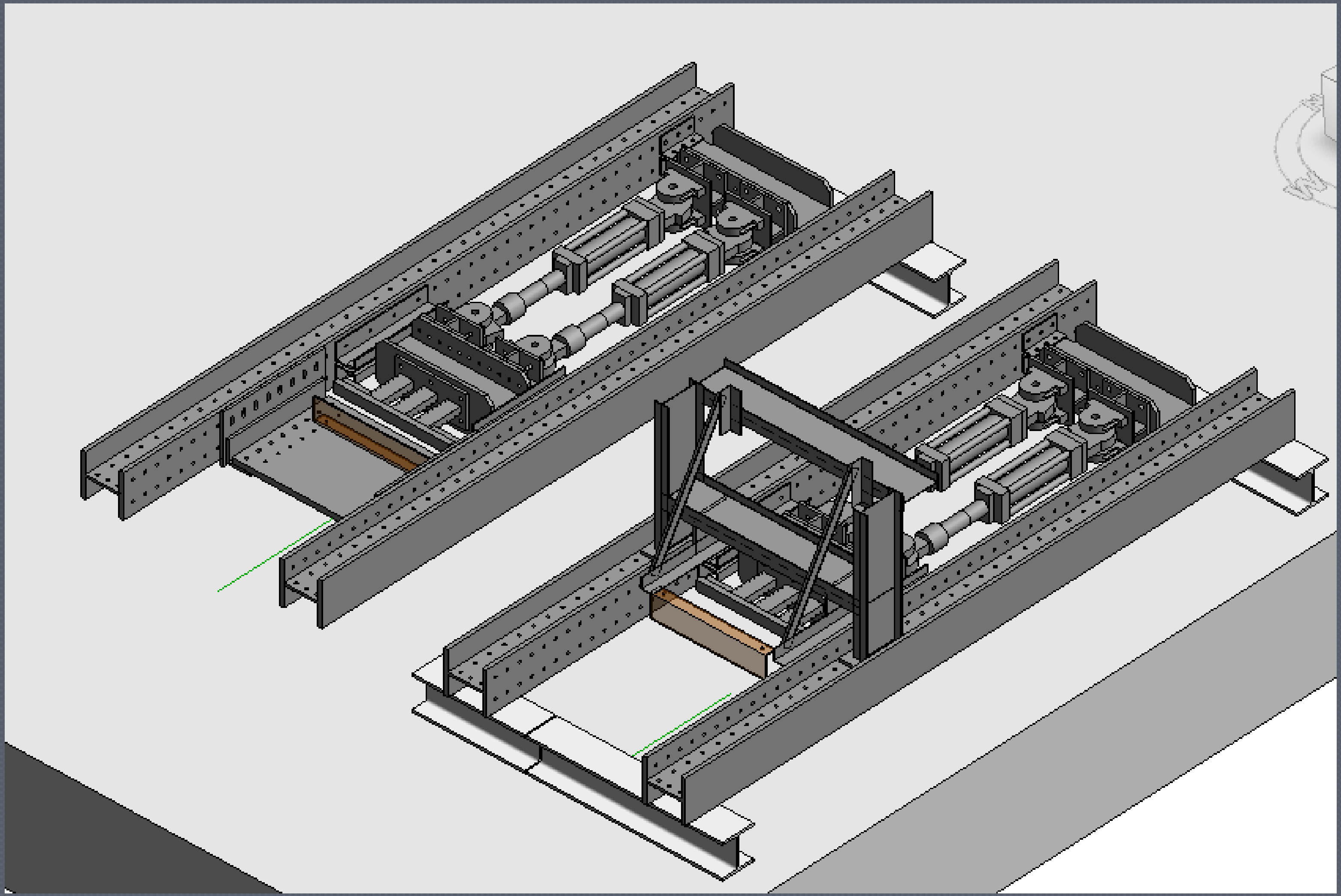


Shelf Angle Testing

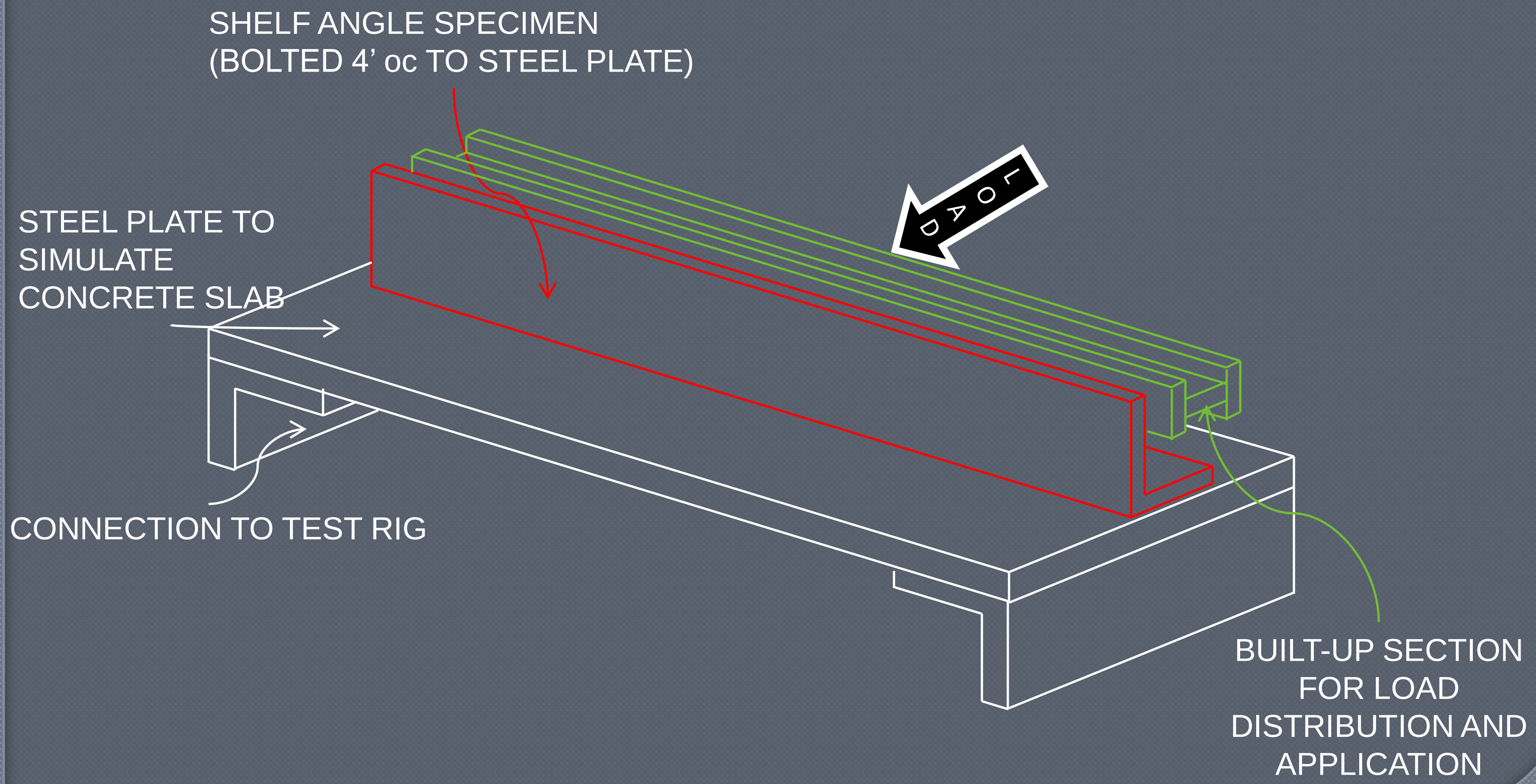
Test Name	Mitigation	Zone	Connection	Shelf Angle	Loading	Note
U1	unmitigated	1	weld	L6x4x3/8	Monotonic	-
U2	unmitigated	7	weld	L8x4x1/2	Monotonic	-
U3	unmitigated	7	A325 bolt	L8x4x1/2	Monotonic	-
U4	unmitigated	7	AP	L8x4x1/2	Monotonic	-
S1	FRP shim - vinylester	1	AP	L4x4x3/8	Monotonic	2 1/8" shim*
S2	FRP shim - vinylester	7	AP	L5x5x1/2	Monotonic	3 5/8" shim
S3	FRP shim - proprietary product 1	1	AP	L4x4x3/8	Monotonic	2 1/8" shim
S4	FRP shim - proprietary product 1	7	AP	L5x5x1/2	Monotonic	3 5/8" shim
S5	FRP shim - proprietary product 2	1	AP	L4x4x3/8	Monotonic	2 1/8" shim
S6	FRP shim - proprietary product 2	7	AP	L5x5x1/2	Monotonic	3 5/8" shim
SF1	steel foam shim	1	AP	L4x4x1/2	Monotonic	2" shim
SF2	steel foam shim	7	AP	L4x4x3/8	Monotonic	3" shim
AS1	FRP angle with plate stiffeners	1	AP	L6x4x1/2	Monotonic	with 1/2" plate stiffeners
AS2	FRP angle with plate stiffeners	7	AP	trimmed L5x10x3/8	Monotonic	with 1/2" plate stiffeners
T1	stainless steel tube	7	AP	L5x5x1/2	Monotonic	stainless 4x4x3/8
T2	FRP tube	7	AP	L5x5x1/2	Monotonic	FRP 4x4x3/8

*shims greater that 1 inch thickness are comprised of thinner shims adhered together with Pliogrip adhesive (3 inch shim = 3x(1 inch) shims)

Shelf Angle Tests



Shelf Angle Tests

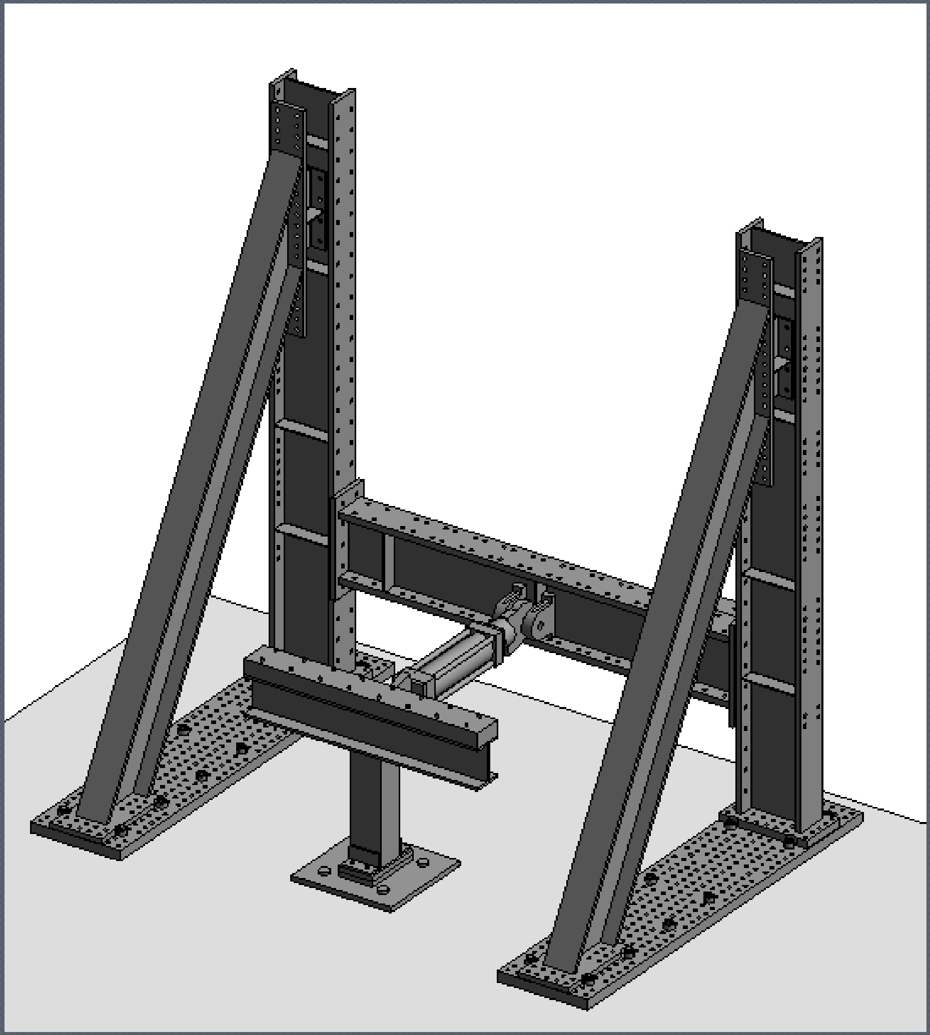


Beam and Cantilever Tests

Test Name	Mitigation	Zone	Connection	Loading	Note
U1	unmitigated	1	weld	eccentric monotonic	-
U2	unmitigated	7	weld	eccentric monotonic	-
U3	unmitigated	7	bolt	eccentric monotonic	-
U4	unmitigated	7	AP	eccentric monotonic	-
S1	FRP shim - vinylester	1	AP	eccentric monotonic	3" shim*
S2	FRP shim - vinylester	7	AP	eccentric monotonic	6" shim
S3	FRP shim - Fabreeka TIM	1	AP	eccentric monotonic	3" shim
S4	FRP shim - Fabreeka TIM	7	AP	eccentric monotonic	6" shim
S5	FRP shim - Armatherm	1	AP	eccentric monotonic	3" shim
S6	FRP shim - Armatherm	7	AP	eccentric monotonic	6" shim
SF1	steel foam shim	1	AP	eccentric monotonic	3" shim
SF2	steel foam shim	7	AP	eccentric monotonic	6" shim
AS1	FRP tube with steel tube sleeve	1	AP	eccentric monotonic	with 1/2" plate
AS2	FRP tube with steel tube sleeve	7	AP	eccentric monotonic	with 1/2" plate
MTBA	manufactured assembly	1	bolt	eccentric monotonic	-
U1	unmitigated	1	weld	cyclic	-
U2	unmitigated	7	weld	cyclic	-
U3	unmitigated	7	bolt	cyclic	-
U4	unmitigated	7	AP	cyclic	-
S1	FRP shim - vinylester	1	AP	cyclic	3" shim*
S2	FRP shim - vinylester	7	AP	cyclic	6" shim
S3	FRP shim - Fabreeka TIM	1	AP	cyclic	3" shim
S4	FRP shim - Fabreeka TIM	7	AP	cyclic	6" shim
S5	FRP shim - Armatherm	1	AP	cyclic	3" shim
S6	FRP shim - Armatherm	7	AP	cyclic	6" shim
SF1	steel foam shim	1	AP	cyclic	3" shim
SF2	steel foam shim	7	AP	cyclic	6" shim
AS1	FRP tube with steel tube sleeve	1	AP	cyclic	with 1/2" plate
AS2	FRP tube with steel tube sleeve	7	AP	cyclic	with 1/2" plate
MTBA	manufactured assembly	1	bolt	cyclic	-

*shims > than 1" thickness are comprised of thinner shims adhered together with Pliogrip adhesive (3" shim = 3x(1") shims)

Beam & Cantilever Test

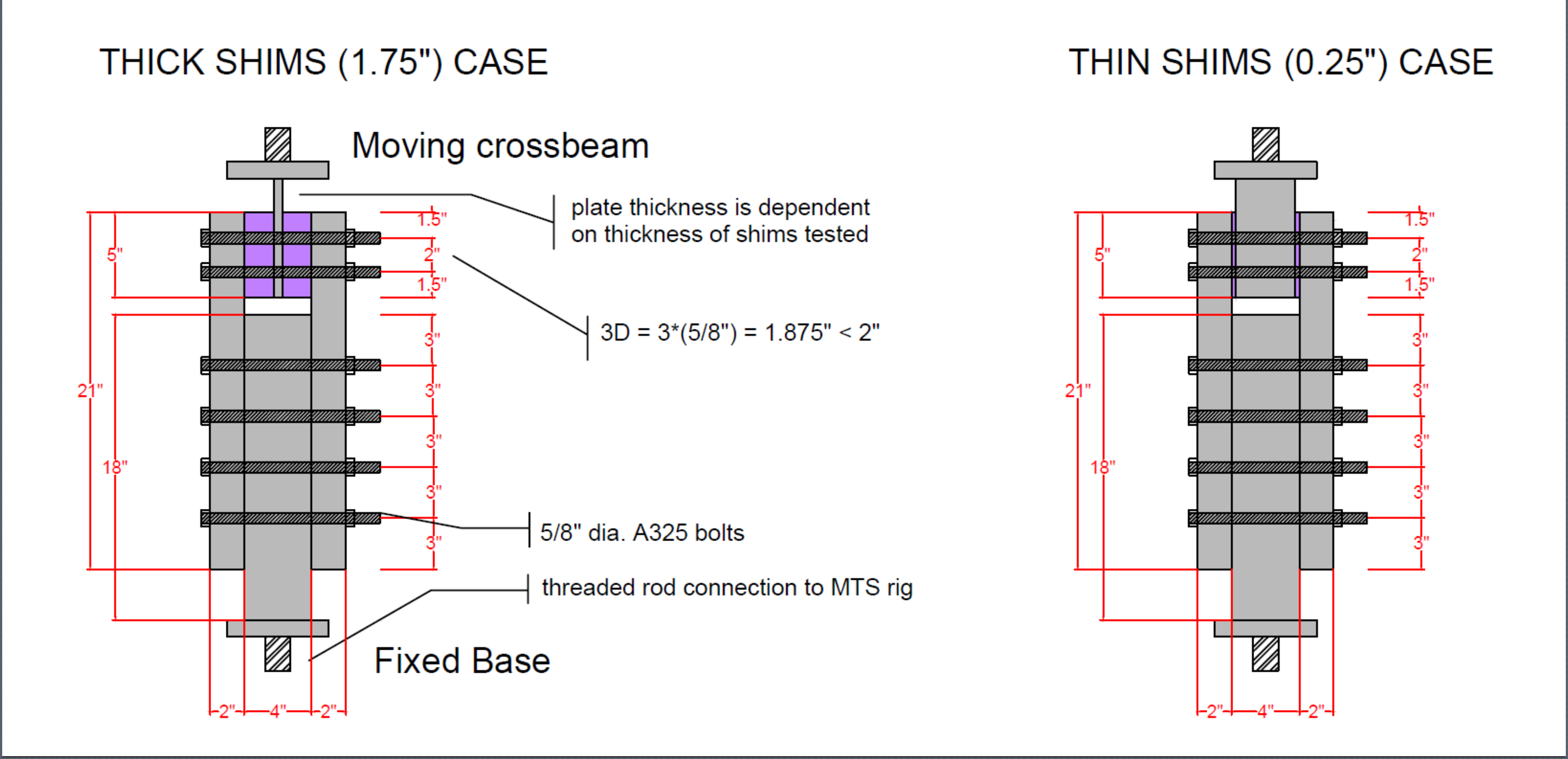


- Cantilever test with dead weight as axial loads for roof posts
- 200 k actuator
- Cyclic, monotonic
- Specimens 4’ long

Connection Testing

Specimen	Type	Adhesive	Shim Thickness	Bolt type
FRP1	polyurethane	-	1/4"	A325
FRP1-s	polyurethane	-	1/4"	A307
FRP2	vinylester	-	1/4"	A325
FRP2-s	vinylester	-	1/4"	A307
FRP9	phenolic	-	1/4"	A325
FRP9-s	phenolic	-	1/4"	A307
FRP4	vinylester	X	2x1/2" multiple plies	A325
FRP4-s	vinylester	X	2x1/2" multiple plies	A307
FRP5	vinylester	-	1"	A325
FRP5-s	vinylester	-	1"	A307
FRP6	vinylester	X	2x1" multiple plies	A325
FRP6-s	vinylester	X	2x1" multiple plies	A307
FRP7	vinylester	X	2x1" + 1/8" multiple plies	A325
FRP7-s	vinylester	X	2x1" + 1/8" multiple plies	A307
FRP8	vinylester	X	3x1" multiple plies	A325
FRP8-s	vinylester	X	3x1" multiple plies	A307
FRP10	Fabreeka	-	1/4"	A325
FRP10-s	Fabreeka	-	1/4"	A307
FRP11	Armatherm	-	1/4"	A325
FRP11-s	Armatherm	-	1/4"	A307
SF1	steel foam	-	2"	A325
SF2	steel foam	-	3"	A325
SF-FRP1	steel foam + FRP	X	2" foam + 1/8" FRP	A325
SF-FRP2	steel foam +FRP	X	3" foam + 5/8" FRP	A325

Connection Testing



Creep Testing

- Creep – does the material experience strain at prolonged loads? 1000 hours? 8000 hours? 1 million hours?
- Currently developing test standard for FRP in flatwise compression
- Range of loads will be tested
  - 90% maximum capacity → ~1 hour test
  - 40% maximum capacity → ~1000 hour test
  - And everything in between!

Current & Future Work

- Experimental test program (lots of testing!!)
- Structural analysis of tested specimens
- Condensation analysis
- Form recommendations for design

This concludes The American Institute of Architects Continuing Education Systems Course

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