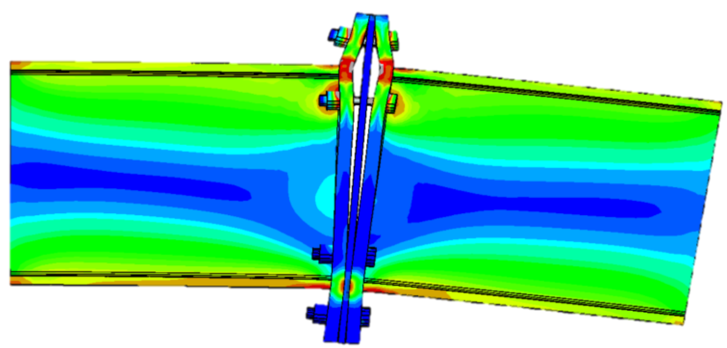
Thermal and mechanical modeling of thermal breaks in structural steel point transmittances



Presented to the UAA College of Engineering Seminar Series

Scott Hamel P.E., Ph.D.

01/25/2017

Presentation outline

- Introduction to Thermal bridges and breaks
- Industry Survey
- Calibrated hot box
- Thermal FEA
- Structural Testing
- Structural FEA
- Conclusions

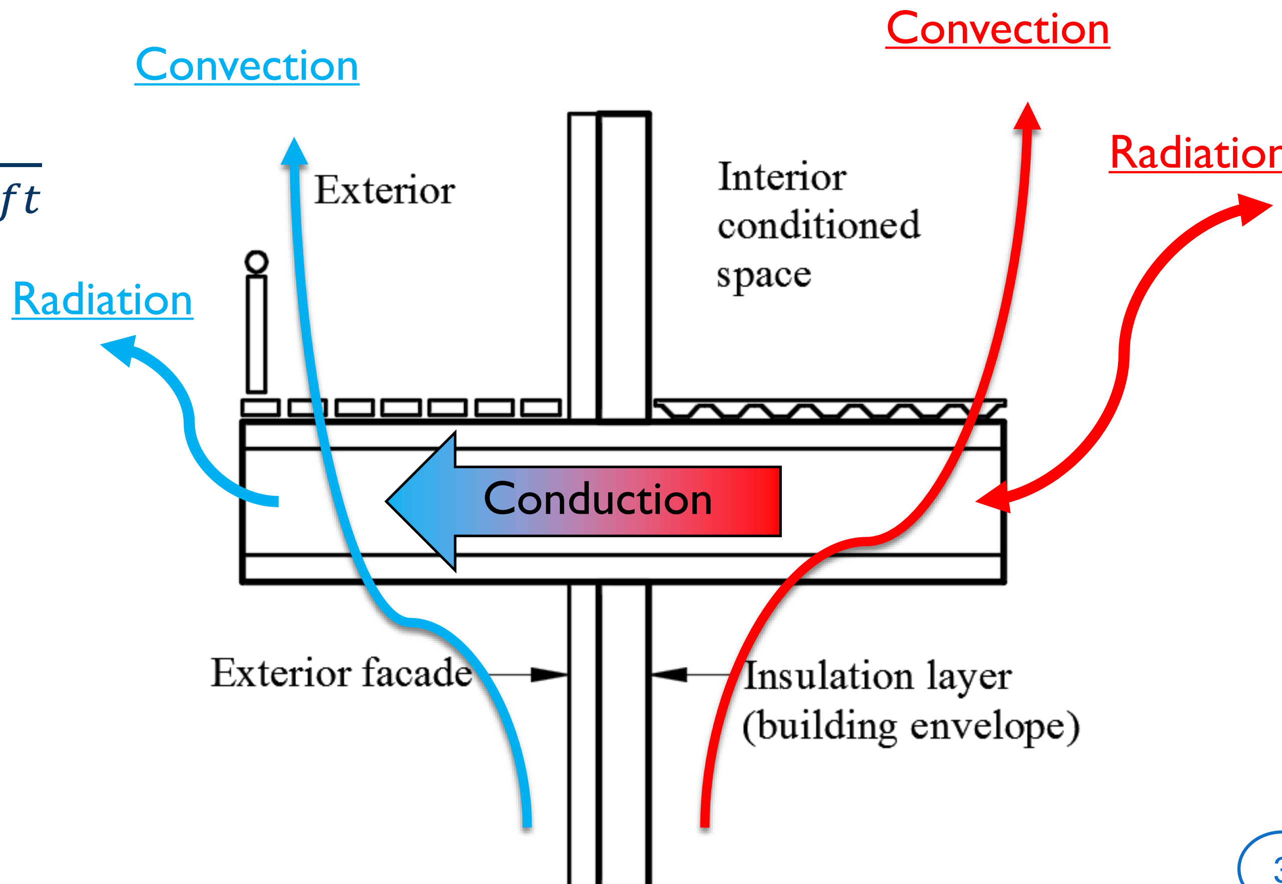
Project Goal:

Experimentally and computationally evaluate the thermal and mechanical characteristics of a set of common structural steel thermal break details

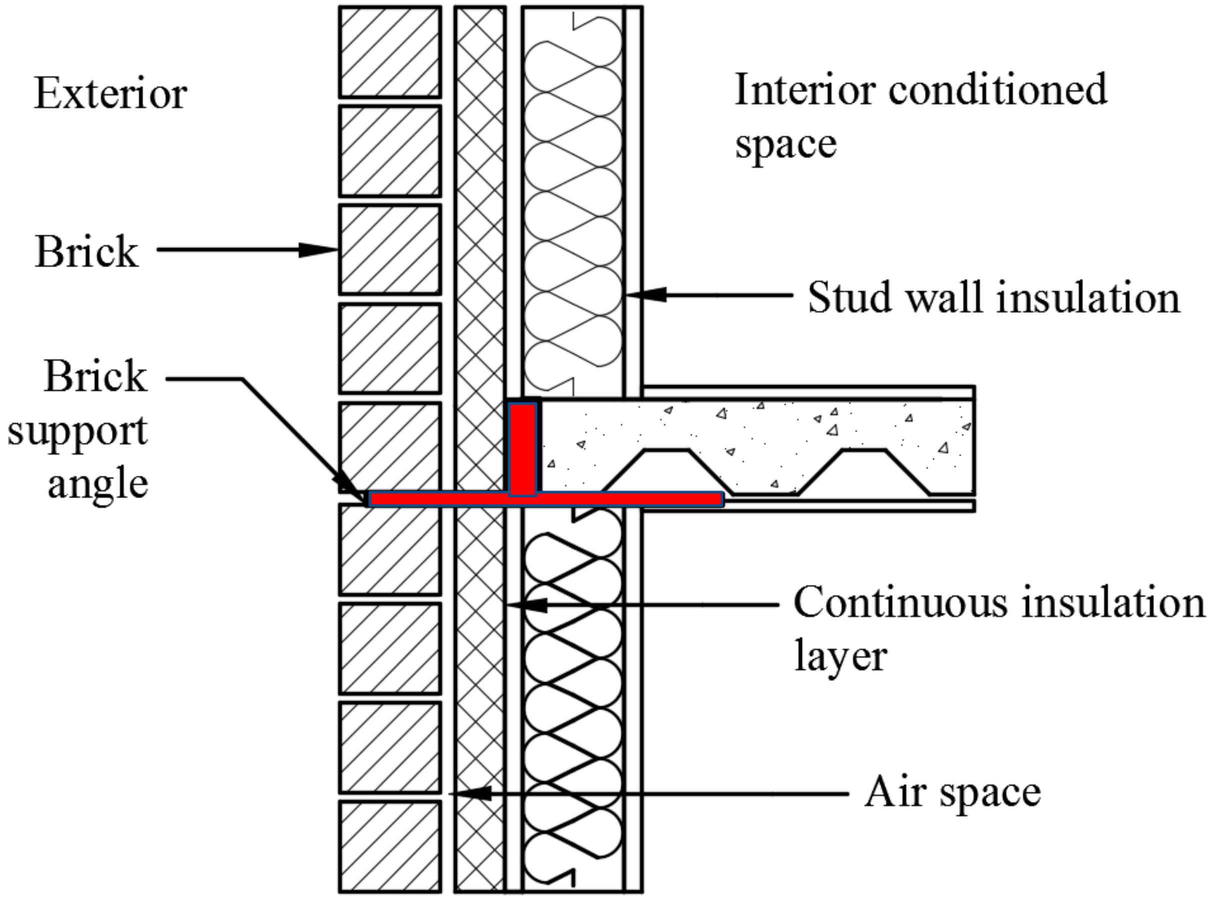
Thermal bridging

"Excessive heat flow through the building envelope by a highly conductive element"

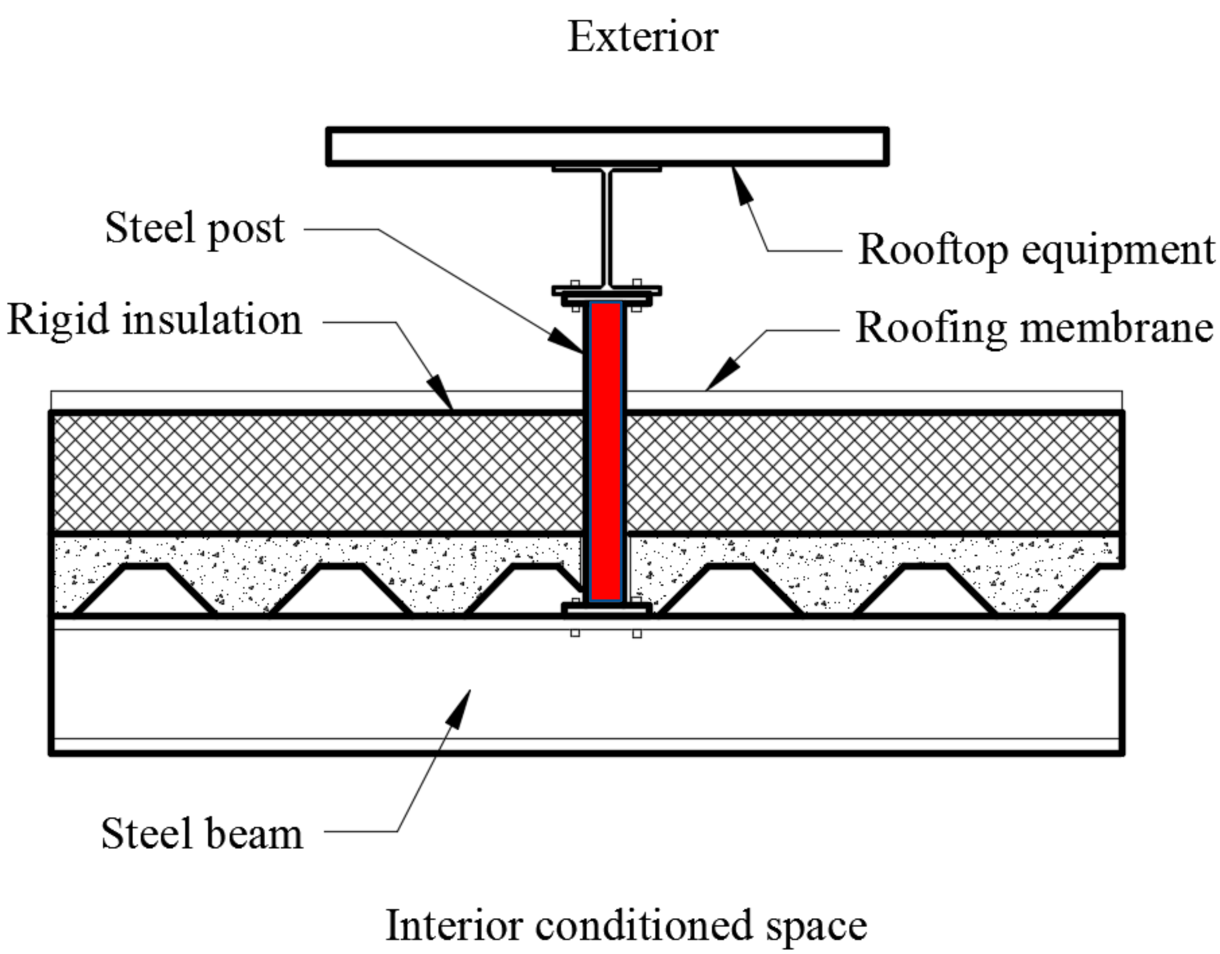
- Linear
  - Units of: $\frac{Btu}{hr \cdot °F \cdot ft}$
- Point
  - Units of: $\frac{Btu}{hr \cdot °F}$



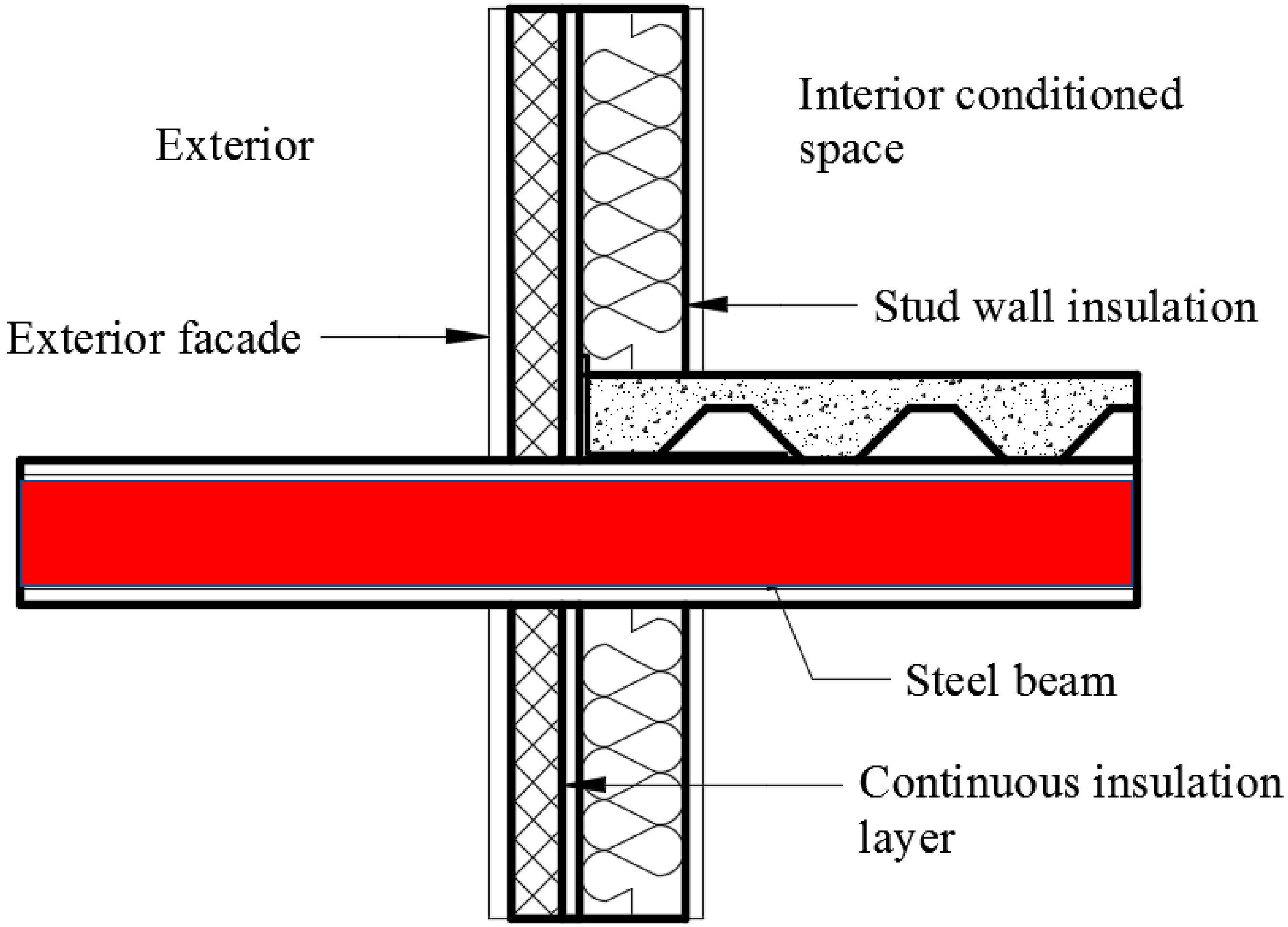
Linear thermal bridge



Point thermal bridge



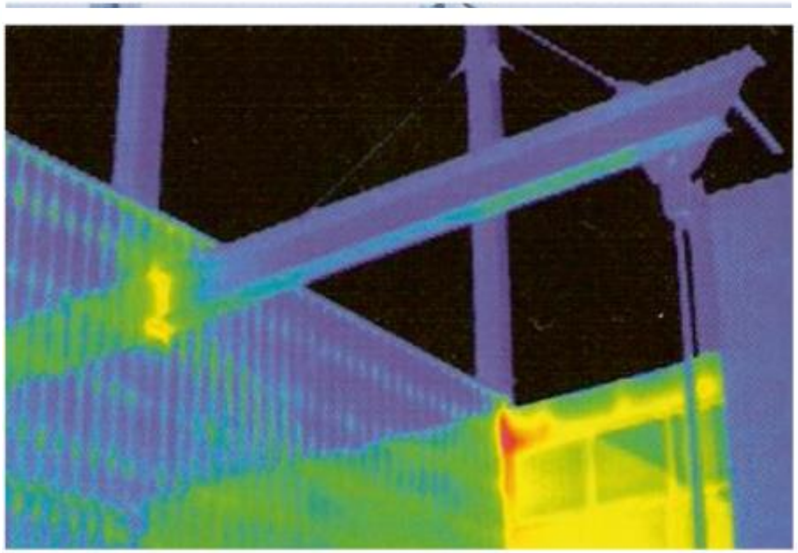
Point thermal bridge

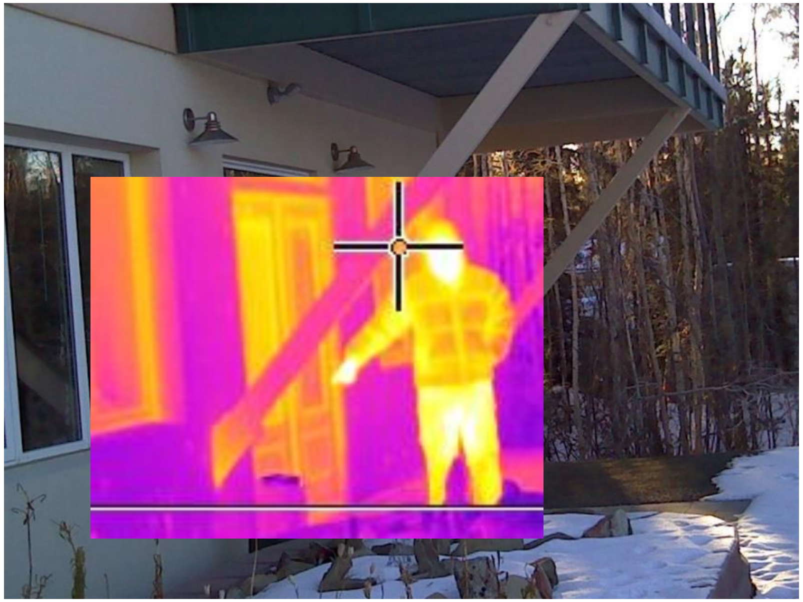


Thermal bridging in structural steel

$$k_{steel} = 347\,\frac{Btu \cdot in}{hr \cdot ft^2 \cdot {}^\circ F}$$

$$k_{XPS\ insul.} = 0.2\,\frac{Btu \cdot in}{hr \cdot ft^2 \cdot {}^\circ F}$$





Issues with thermal bridges

- Heat loss
- Cooling loss
- Condensation
  - Corrosion
  - Façade and interior coverings damage
  - Mold growth
- Occupancy comfort
- Indoor humidity problems

Thermal breaks

- Bearing pads
  - Neoprene
  - Wood
  - FRP

Proprietary thermal breaks

- Manufactured thermal break assemblies (MSTBAs)

AISC/ RCSC Code provisions

- AISC / RCSC 2014
  - Section 3.1, p. 16.2-17

"Compressible materials shall not be placed within the grip of the bolt."

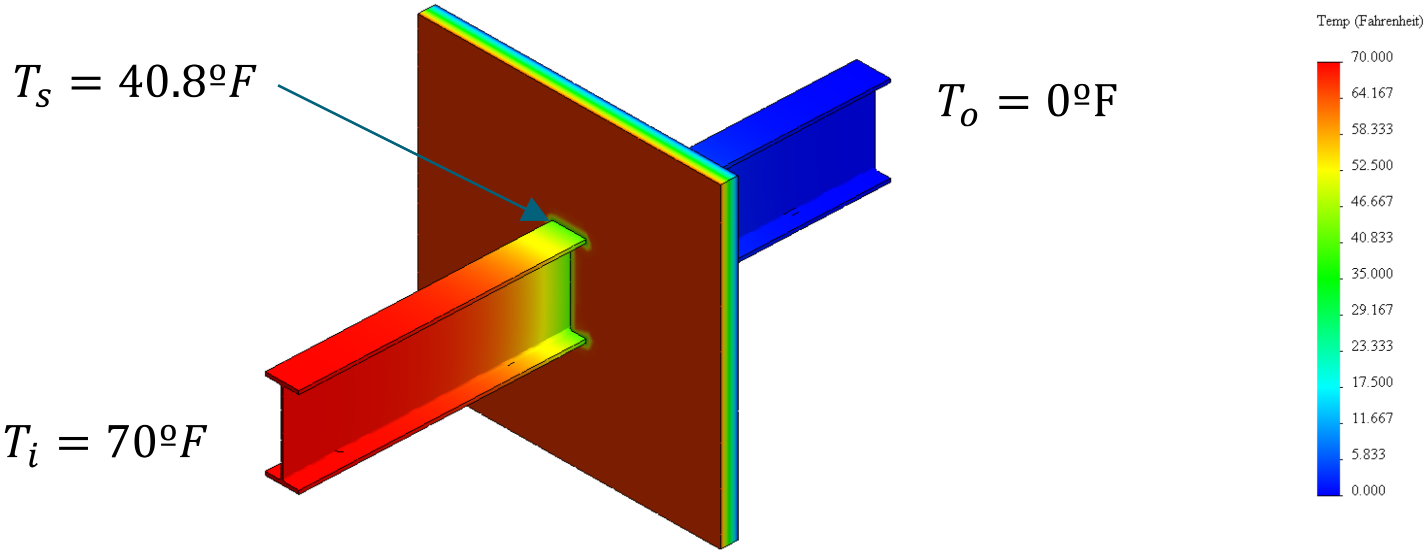
- Commentary

"…Compressible materials … preclude the development and/or retention of the installed pretensions in the bolts, when required."

"….Greater slopes [than 1:20, of connected elements] are undesirable because the resultant localized bending decreases both the strength and the ductility of the bolt."

Condensation

- Calculating condensation potential:
- Dew point, indoor temp
  - Temperature index: $TI = \frac{T_s - T_o}{T_i - T_o} = \frac{40.8 - 0}{70 - 0} = 0.58 < 0.70, \text{ not good}$



Industry survey & results

Industry survey

- Local interviews
- AISC members
  - May 2014
  - 269 responses

Map of survey respondents

Survey results

Most Common Details:

#	Answer		Response	%
1	Cantilever levels/ beams		113	74%
2	Facade elements		113	74%
3	Roof protrusions		96	63%
4	Foundation penetrations		30	20%
5	External braces		22	14%
6	Other		10	7%

Survey results

How is Thermal-Bridging Addressed?

#	Answer		Response	%
1	Avoid entirely (e.g., double columns, etc.)		39	27%
2	Use gasket material (e.g., plywood, neoprene, fiberglass, etc.)		67	46%
3	Use a Manufactured Structural Thermal Break Assembly (MSTBA)		34	23%
4	Replace member with less conductive material (such as stainless steel, timber, etc.)		35	24%
5	Surround protruding steel member with insulating material		104	71%
6	Do nothing		63	43%
7	Other		17	12%

Survey results

What Materials are used for Gasket?

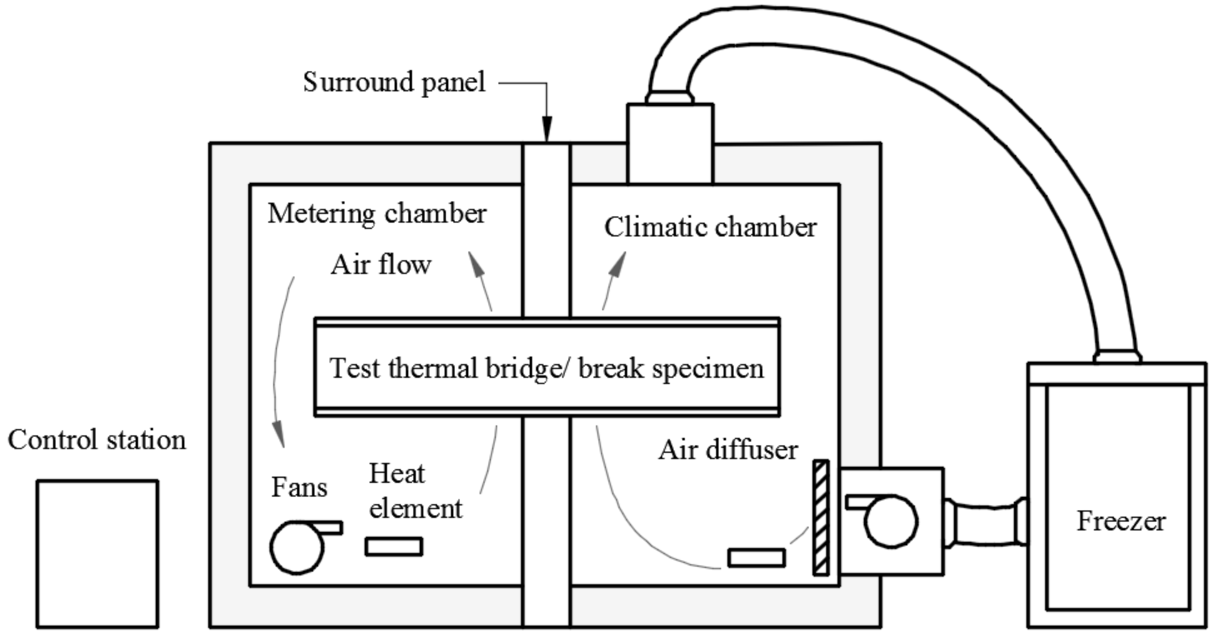
#	Answer		Response	%
1	Neoprene		43	56%
2	Nitrile		1	1%
3	High Density Polyethylene (HDPE)		31	40%
4	Wood/ engineered wood		35	45%
5	Fibre-reinforced polymer (FRP)		26	34%
6	Fibre-reinforced polymer bolts		5	6%
7	Stainless steel		31	40%
8	Stainless steel bolts		29	38%
9	Other (list as many as apply)		9	12%

Calibrated Hot-Box Testing

Experimental Thermal Performance

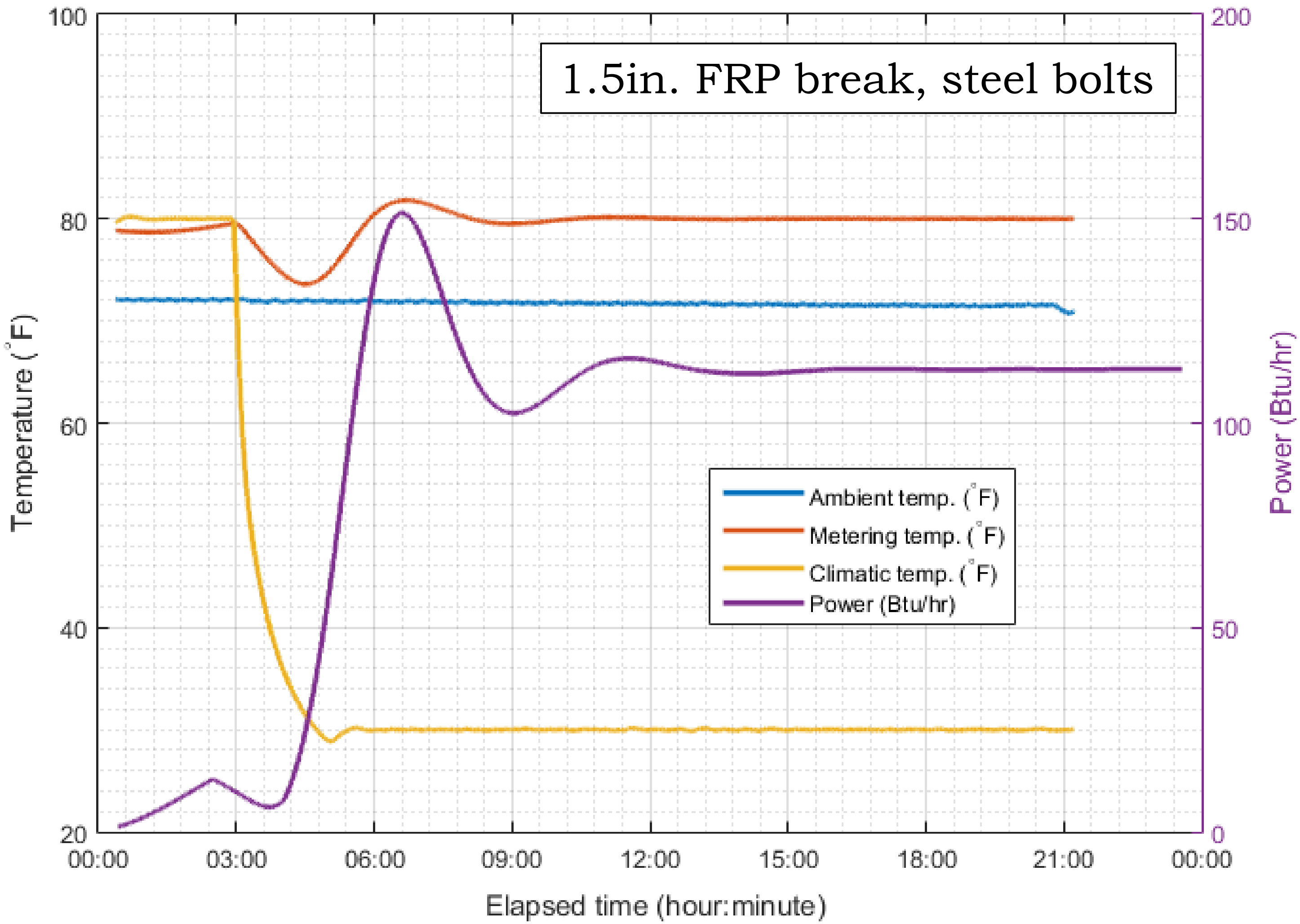
Experimentally measuring heat flow

- Modified ASTM C1363-11: "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus"
- Calibrated hot box:



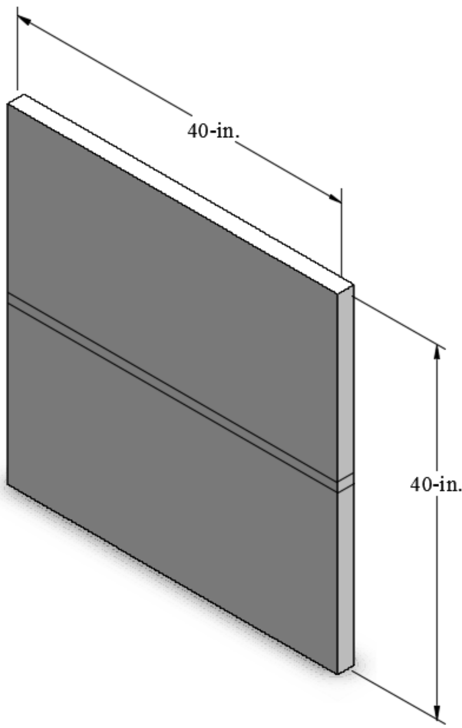
Calibrated hot box

PID control

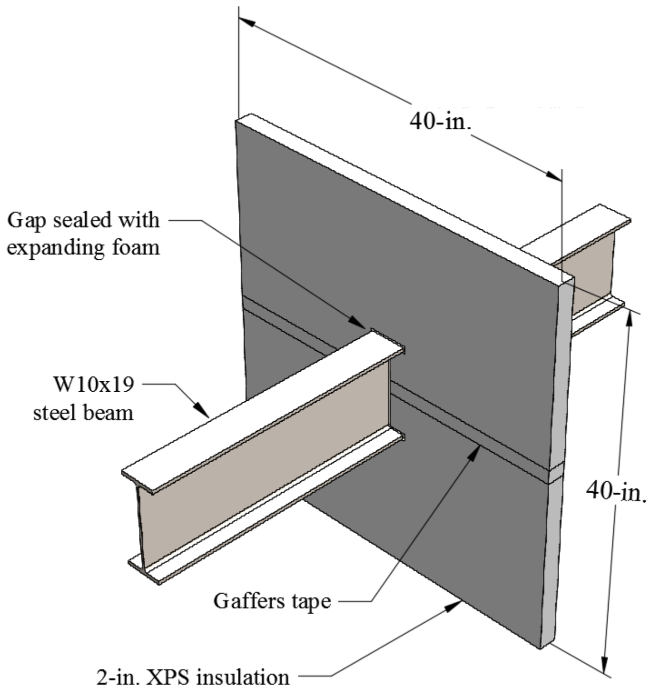

1.5in. FRP break, steel bolts
Temperature (°F)
Power (Btu/hr)
Elapsed time (hour:minute)
Ambient temp. (°F)
Metering temp. (°F)
Climatic temp. (°F)
Power (Btu/hr)
100
80
60
40
20
200
150
100
50
0
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

Calibrated hot box specimens

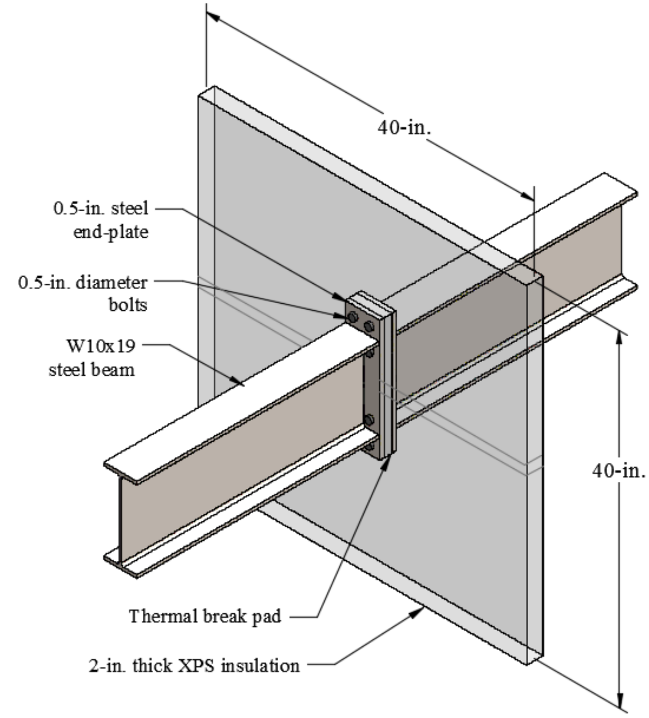
2in. XPS insulation



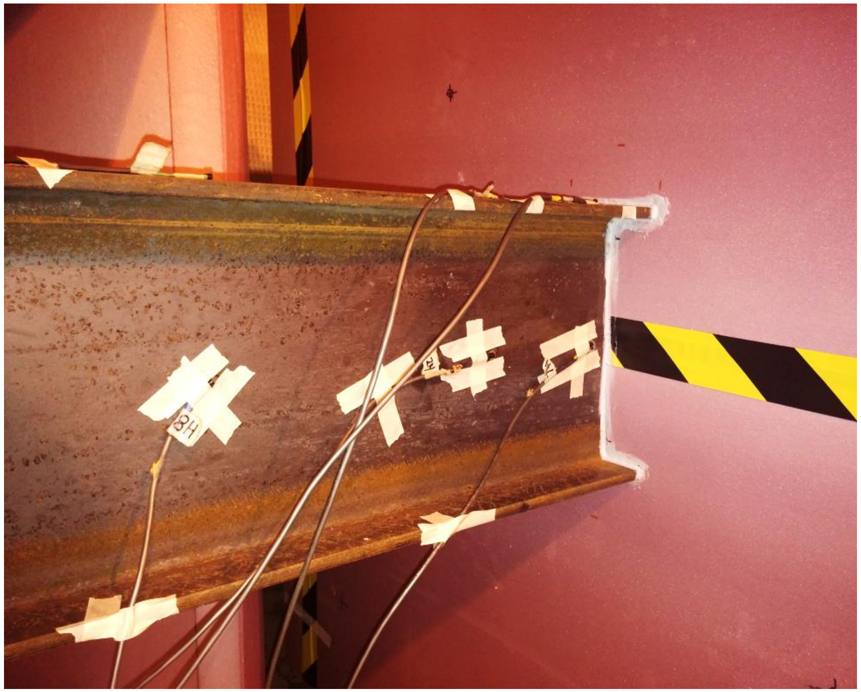
Thermal bridge

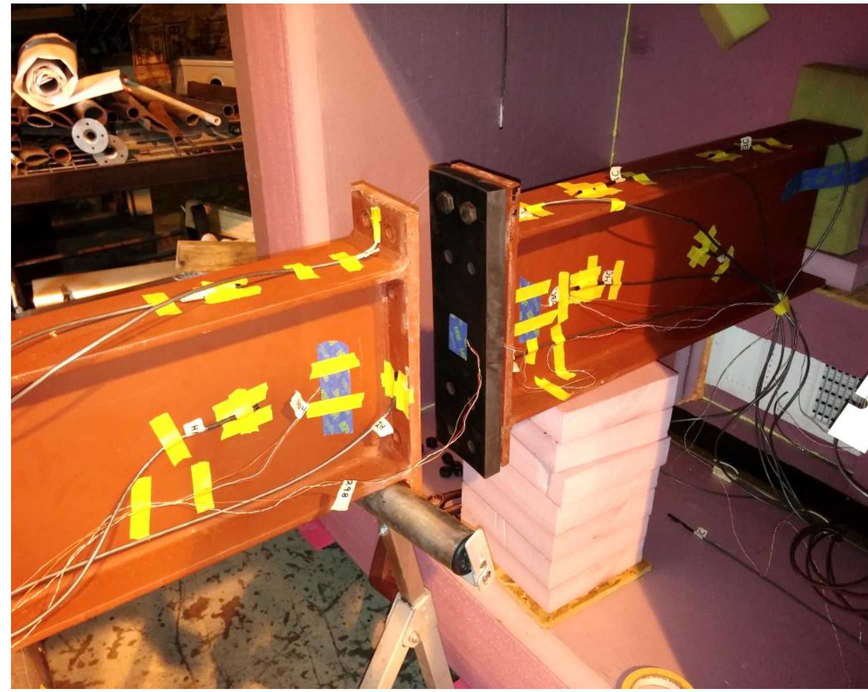


Thermal break



Calibrated hot box specimens

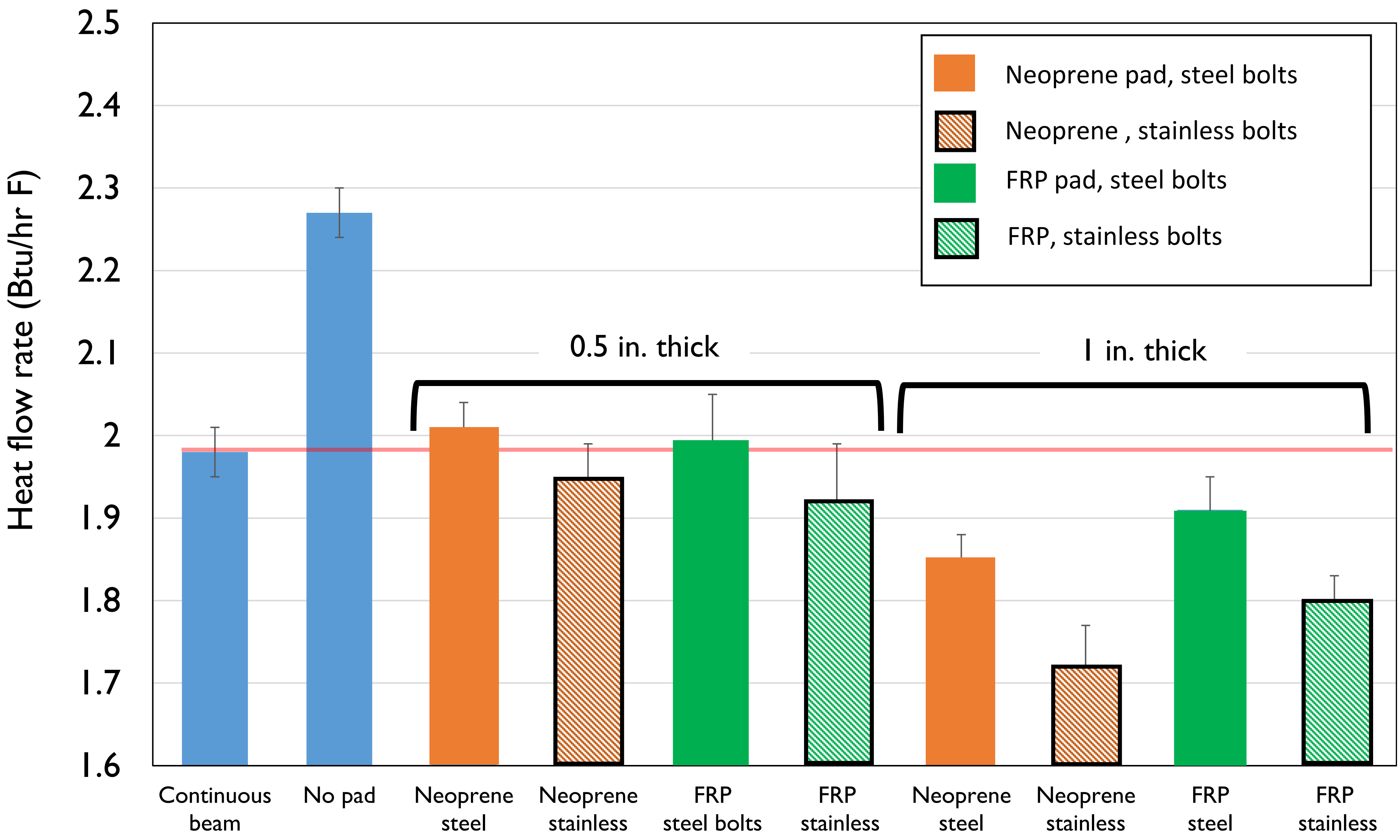




- **Thermal bridge**
  - W10x19 beam through 2-in. XPS

- **Thermal break**
  - Beam to beam end-plate connection
    - Neoprene pad (0.5, 1.0, & 1.5in. thick)
    - Fabreeka pad (0.5, & 1.0in. thick)
    - Steel & stainless-steel bolts

Experimental results

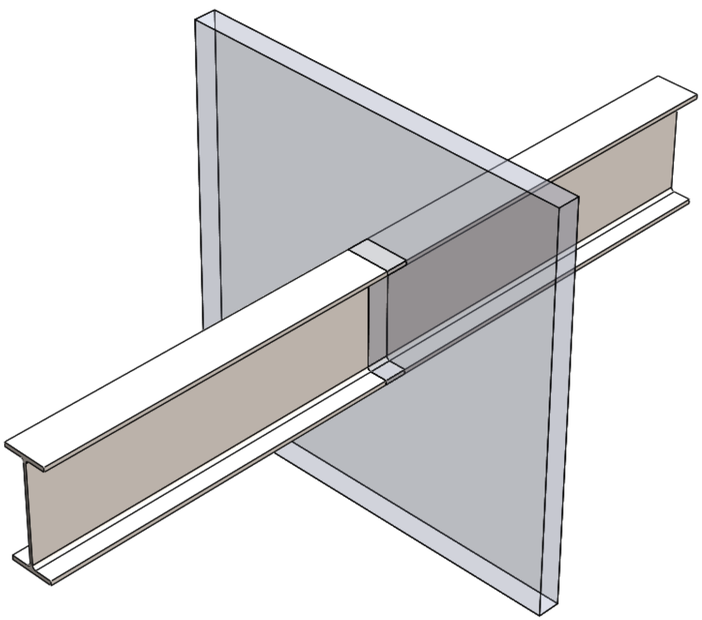


Thermal Finite-Element Modeling

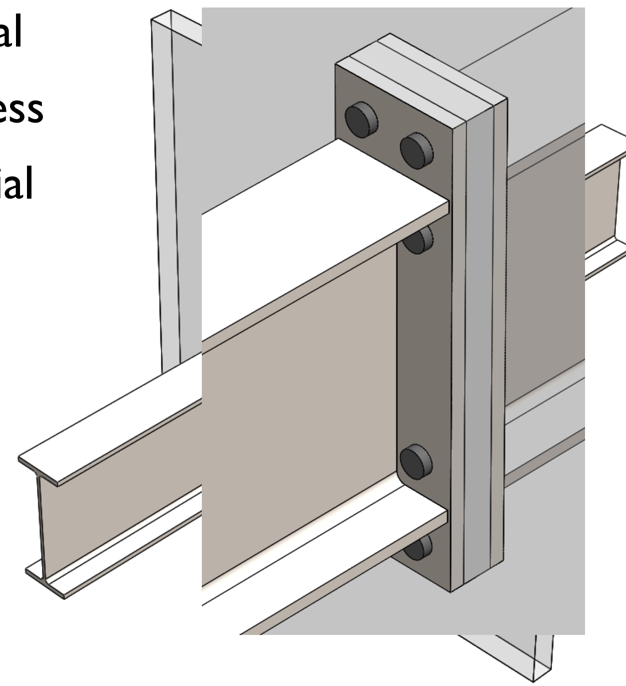
FEA heat transfer model

- Abaqus 6.14/ Standard (& Solidworks)

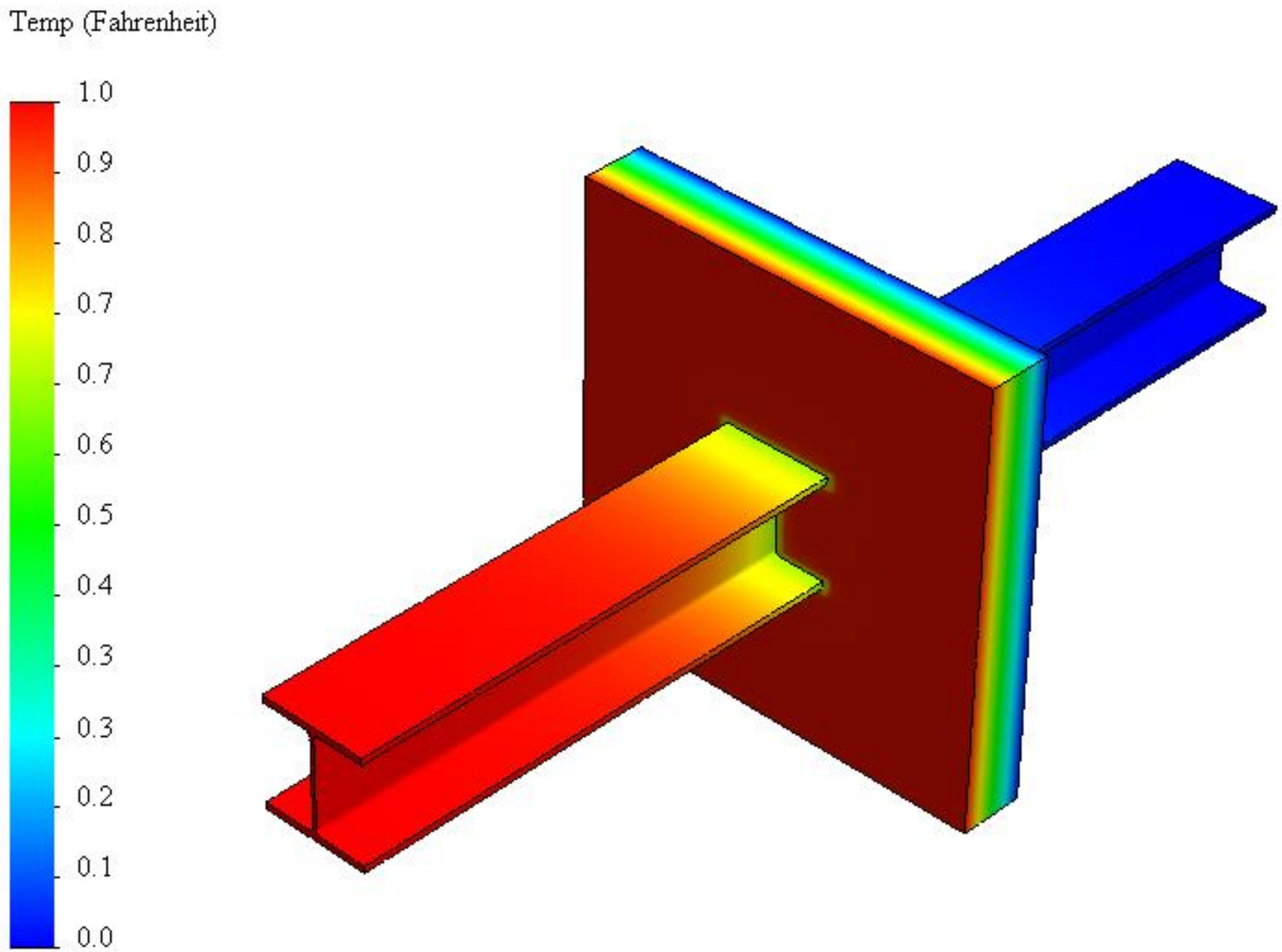
- **Thermal bridge**
  - Parameters:
    - Beam size



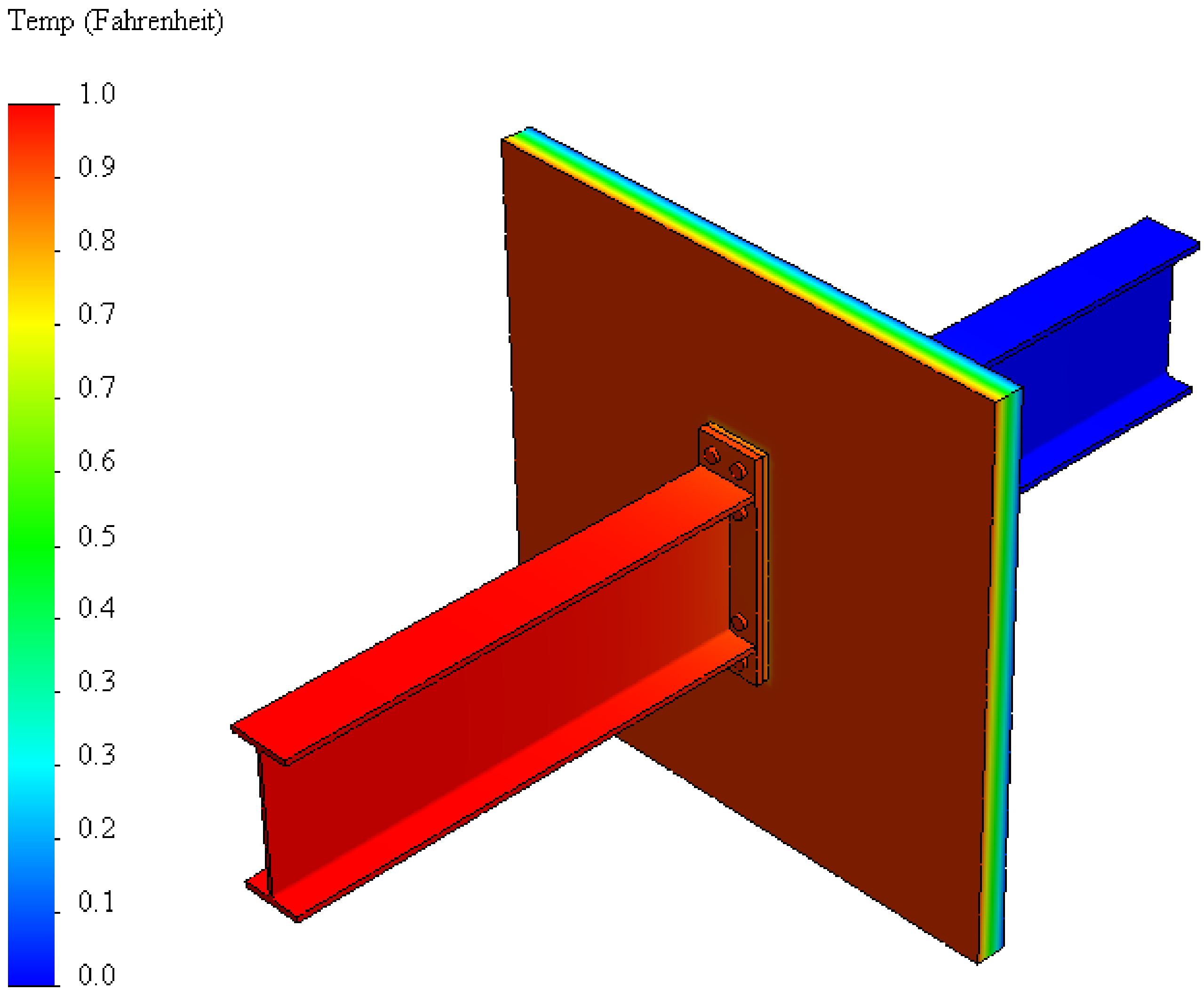
- **Thermal break**
- Parameters:
  - Pad material
  - Pad thickness
  - Bolt material



Continuous beam

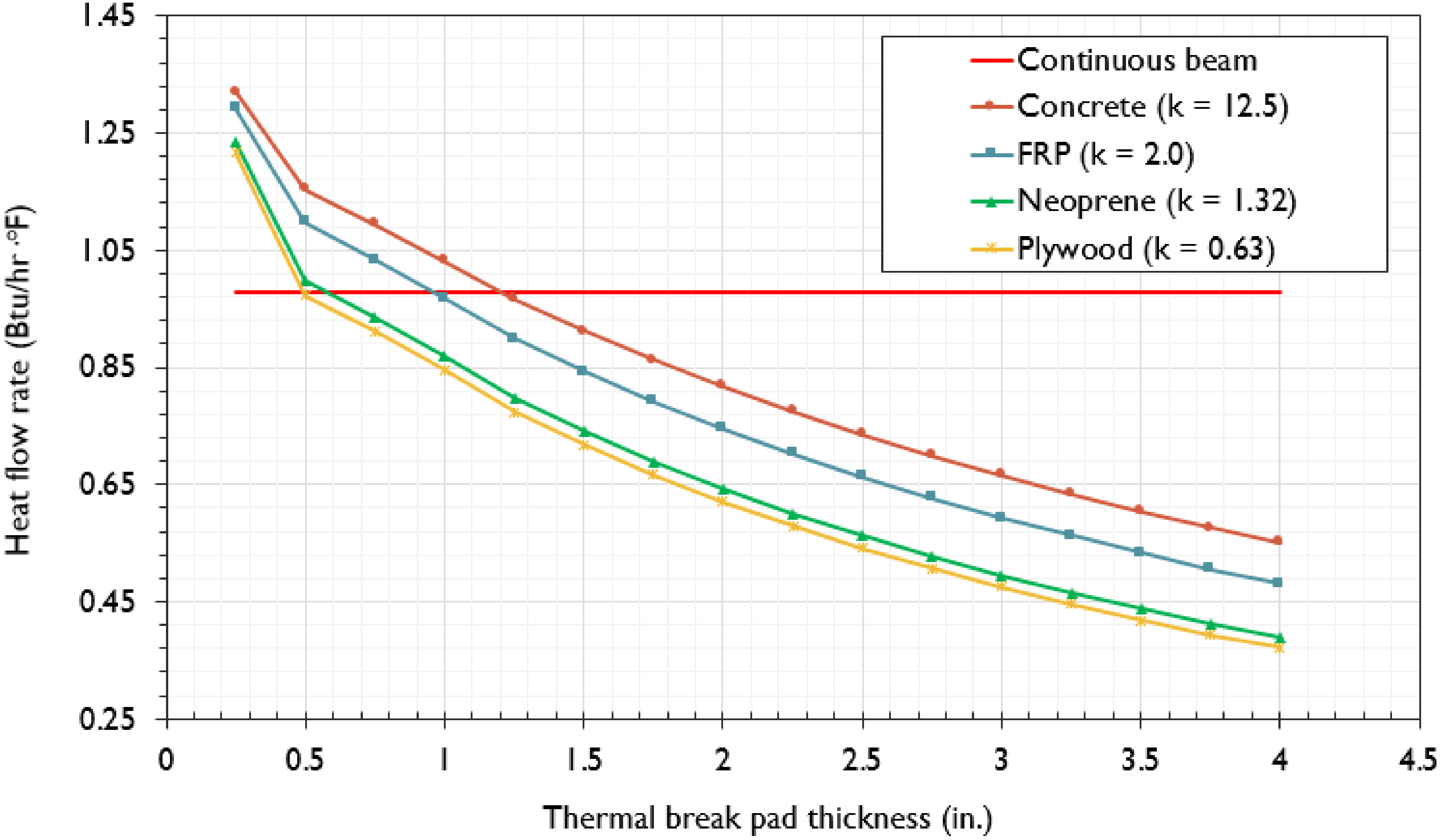


Thermal break results

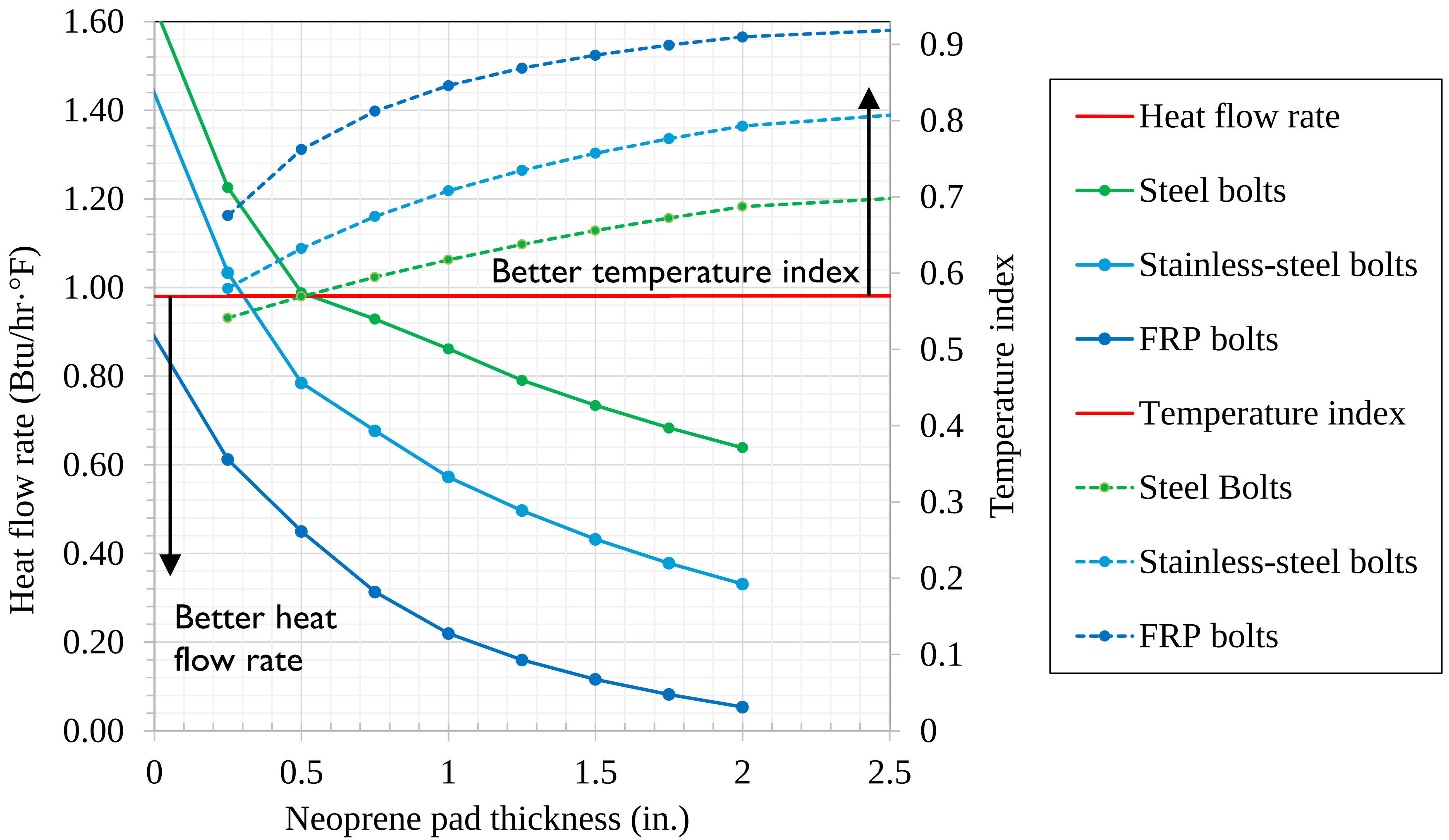


Thermal break pad thickness

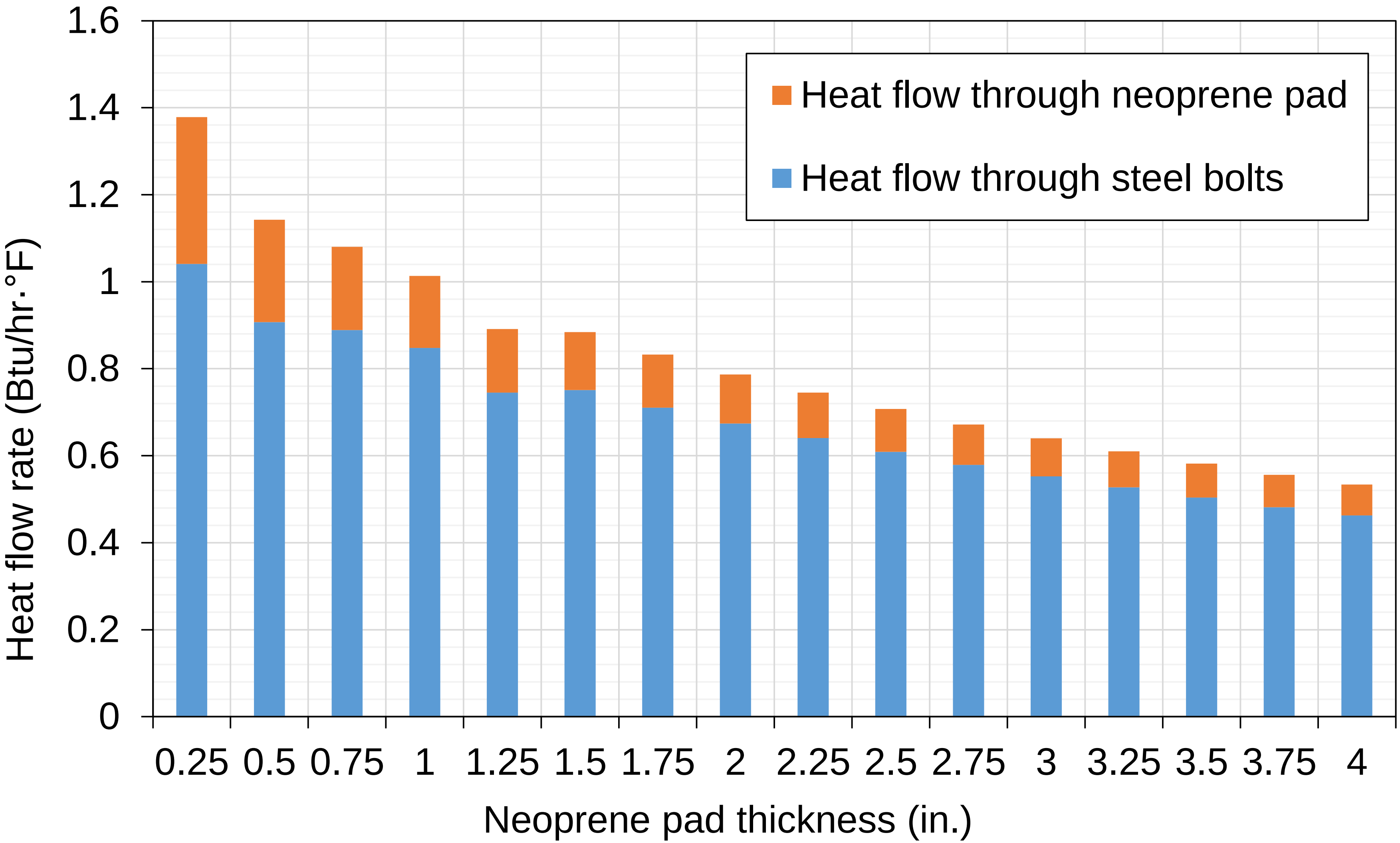
(k in units of Btu ·in/ft² ·hr ·°F)



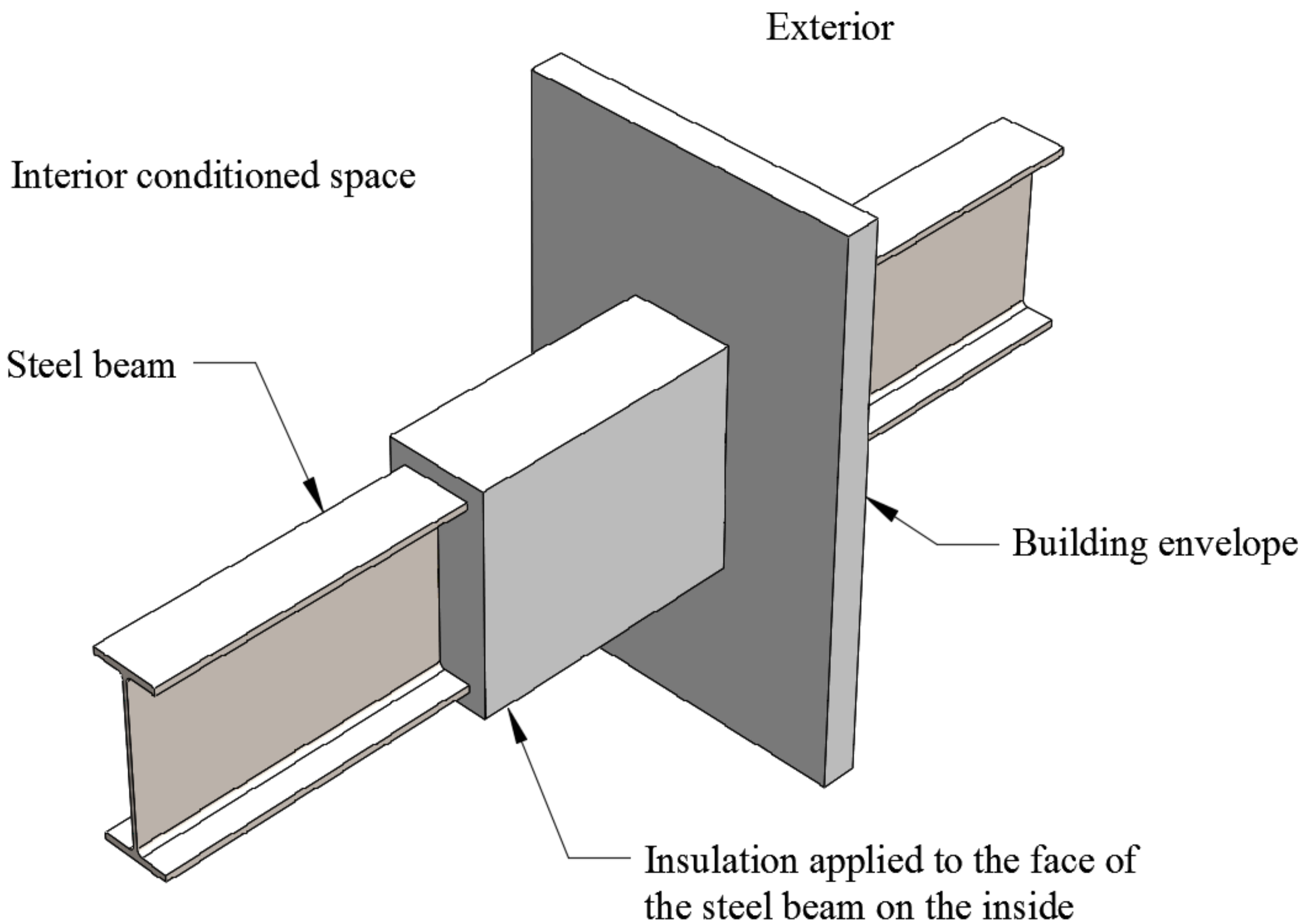
Bolt material



Heat flow - pad vs. bolts

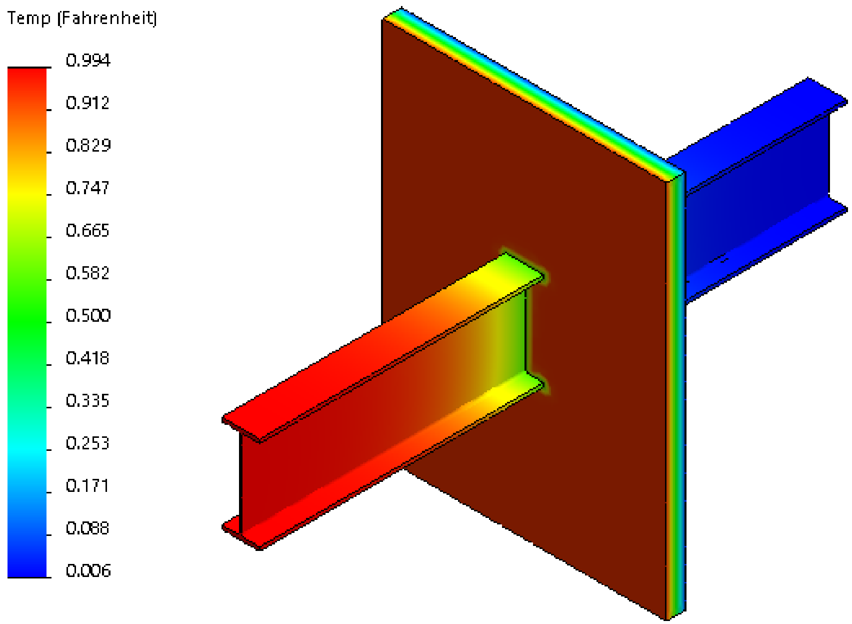


Covering insulation

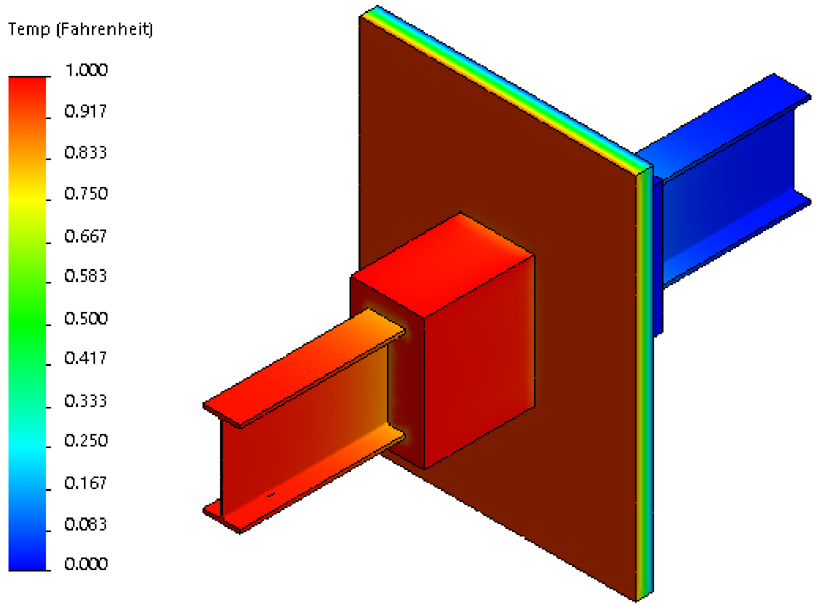


Covering insulation results

Temperature Index = 0.57



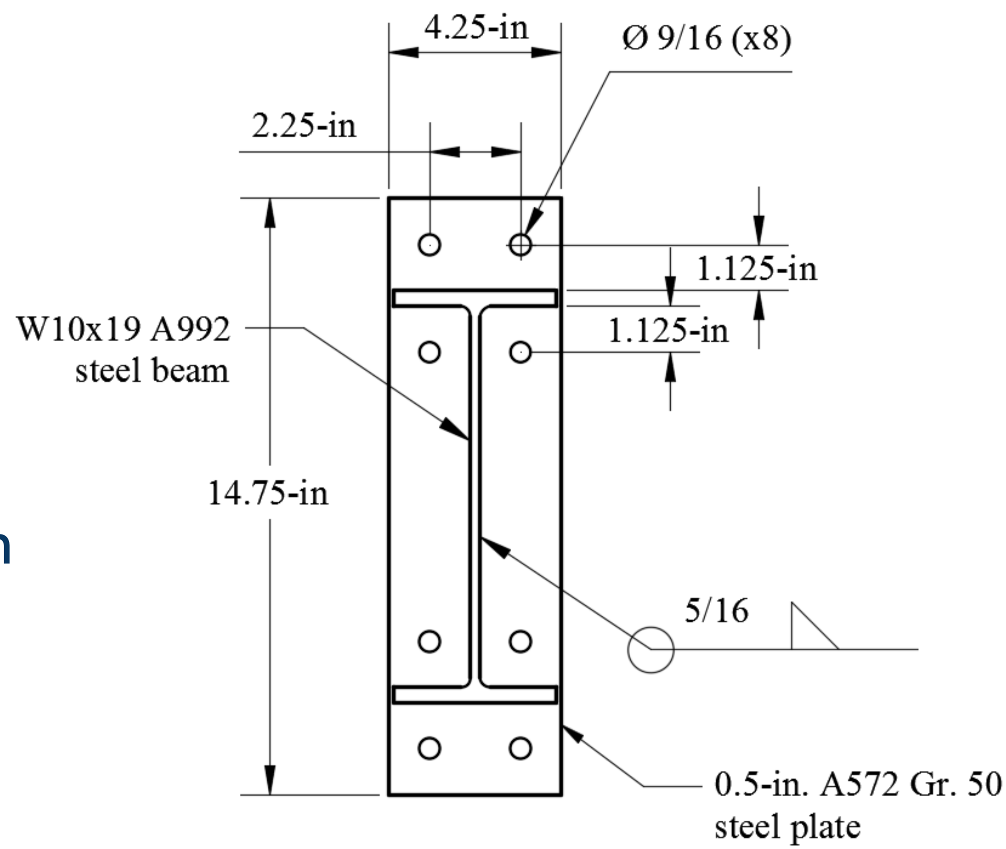
Temperature Index = 0.85



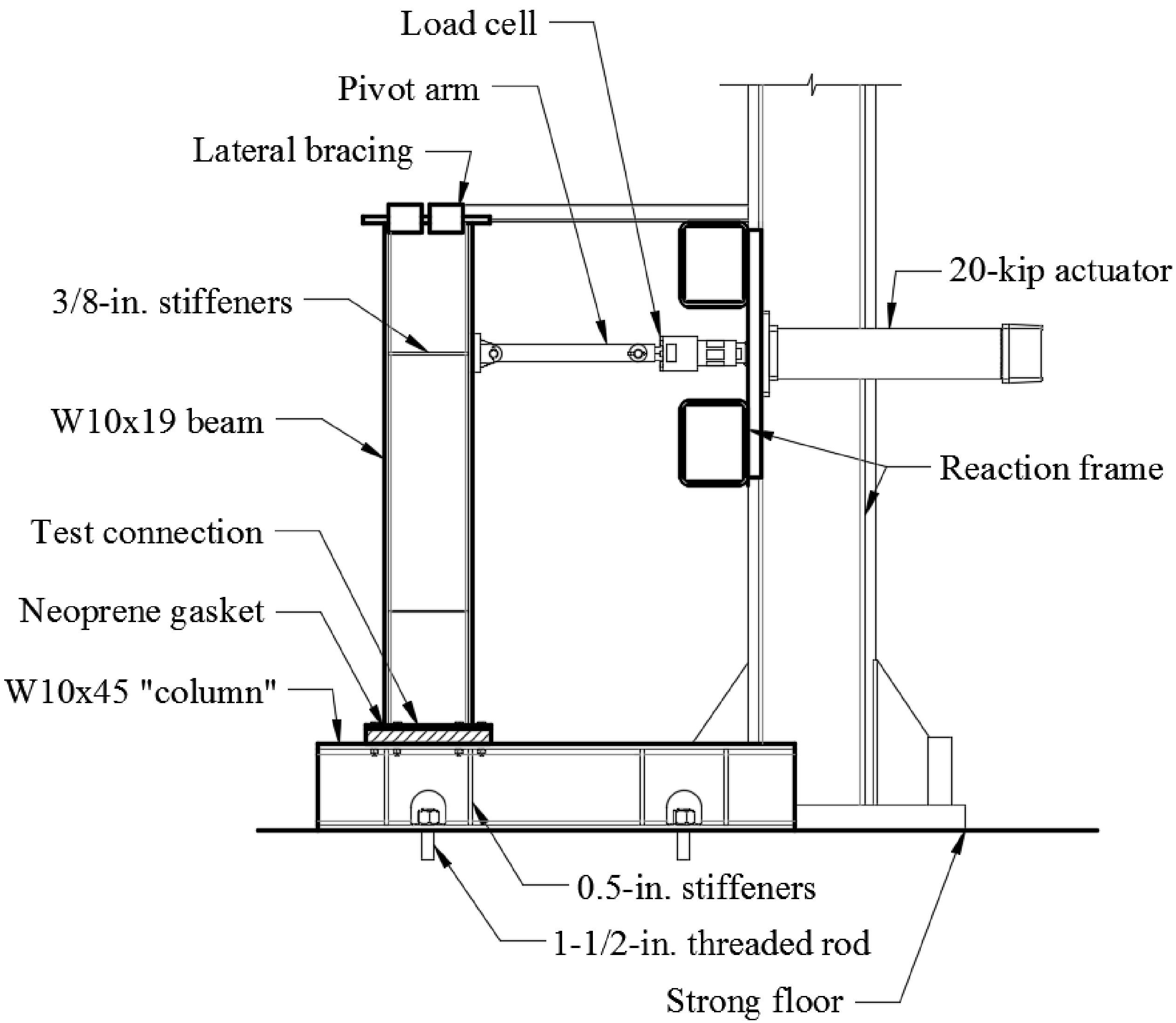
Structural Testing

End-plate thermal break

- End-plate moment connection
- W10x19 A992 steel beam
- A572 Gr. 50 end-plate
- A325 bolts
- Neoprene pad, 0.5”, 1”, 1.5”



Bending tests



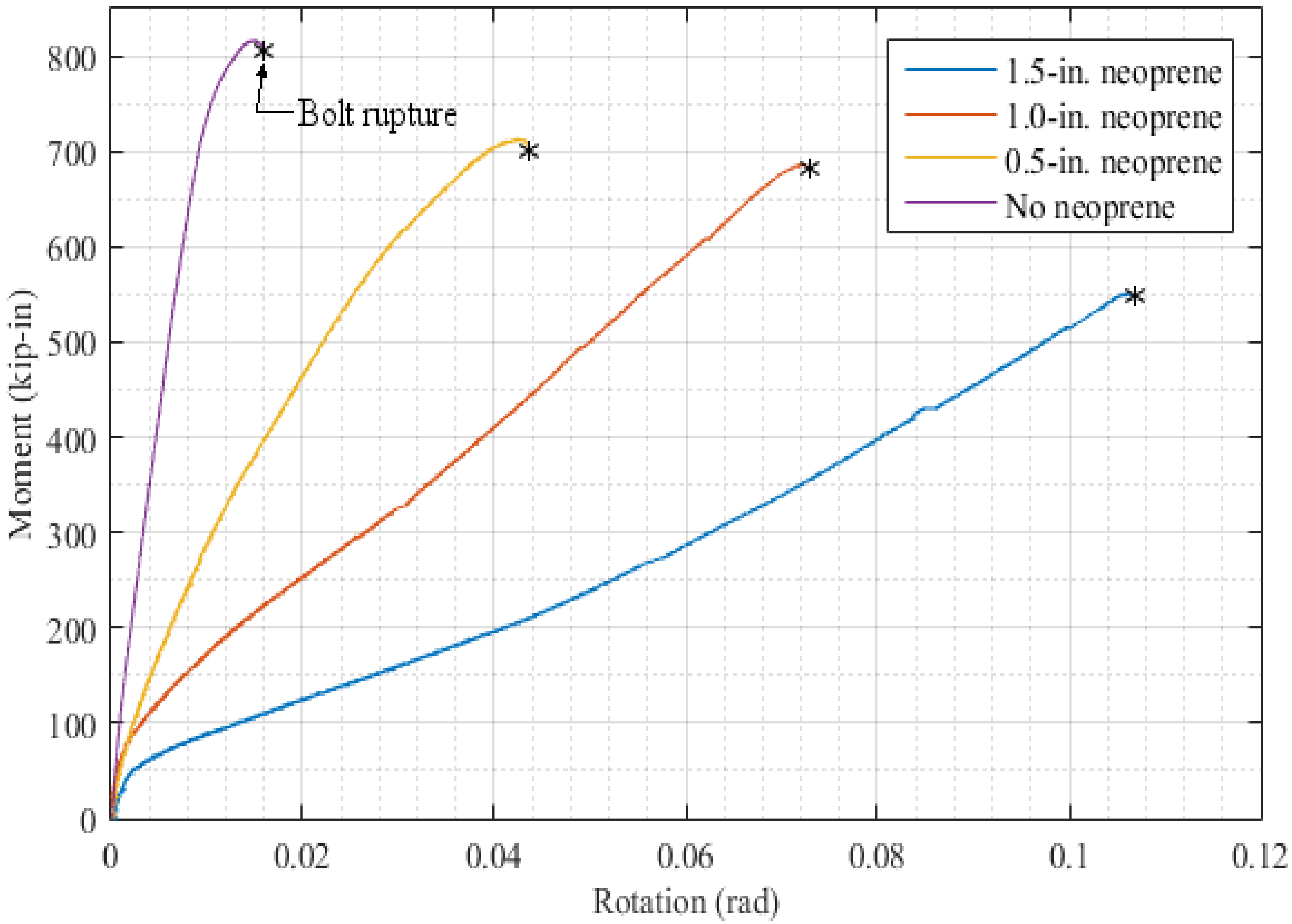
Bending test results

0.5 in. neoprene pad test at failure

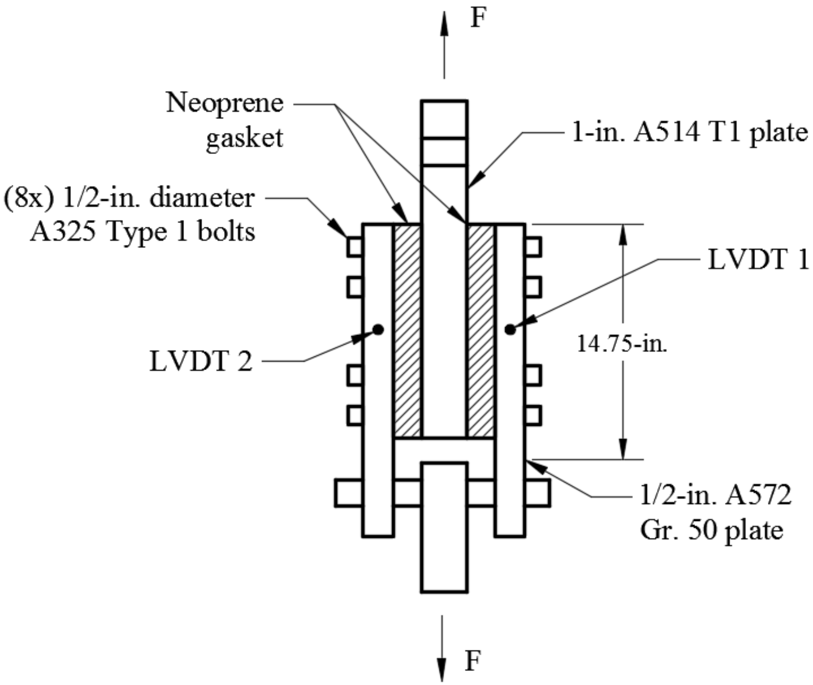
Bending test results

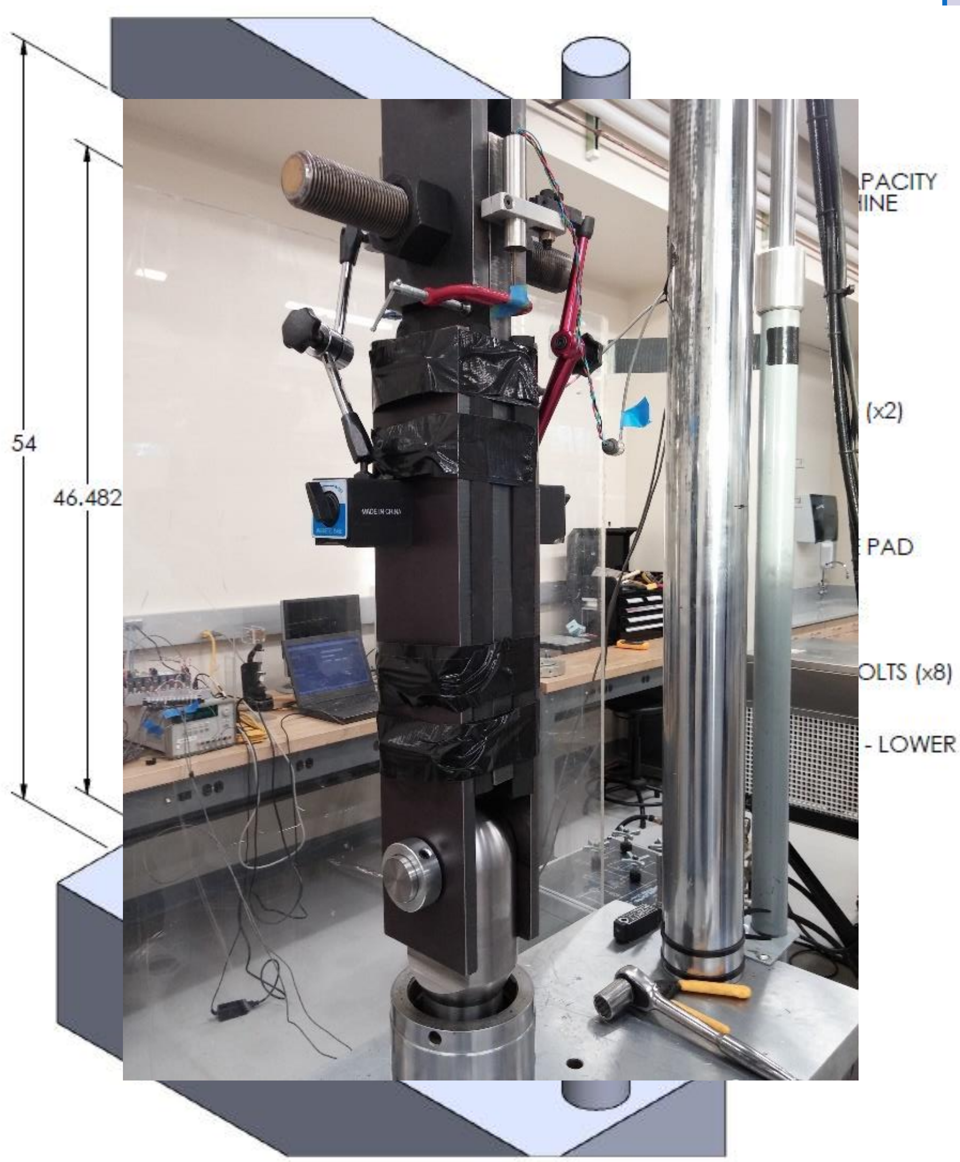
1.5 in. neoprene pad test at failure

Moment-rotation

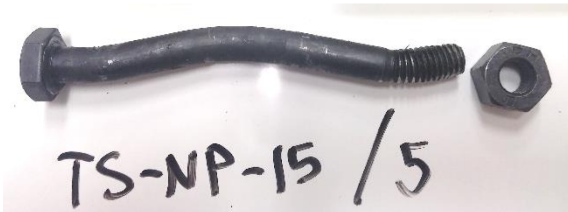


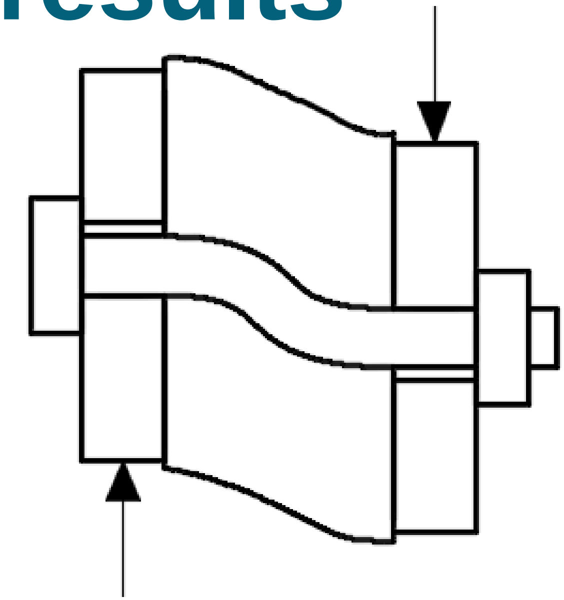
Shea

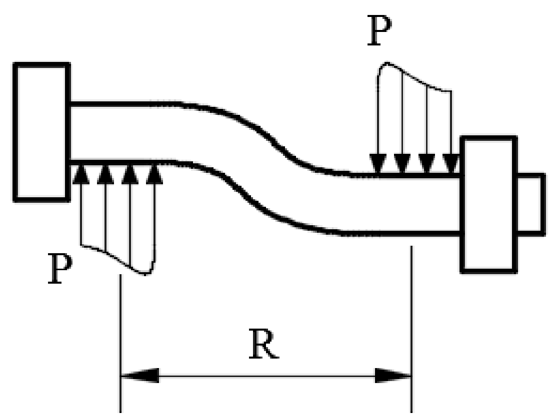

F
Neoprene gasket
1-in. A514 T1 plate
(8x) 1/2-in. diameter A325 Type 1 bolts
LVDT 1
14.75-in.
LVDT 2
1/2-in. A572 Gr. 50 plate
F


54
46.482
PACITY
INE
(x2)
PAD
OLTS (x8)
- LOWER

Shear test results

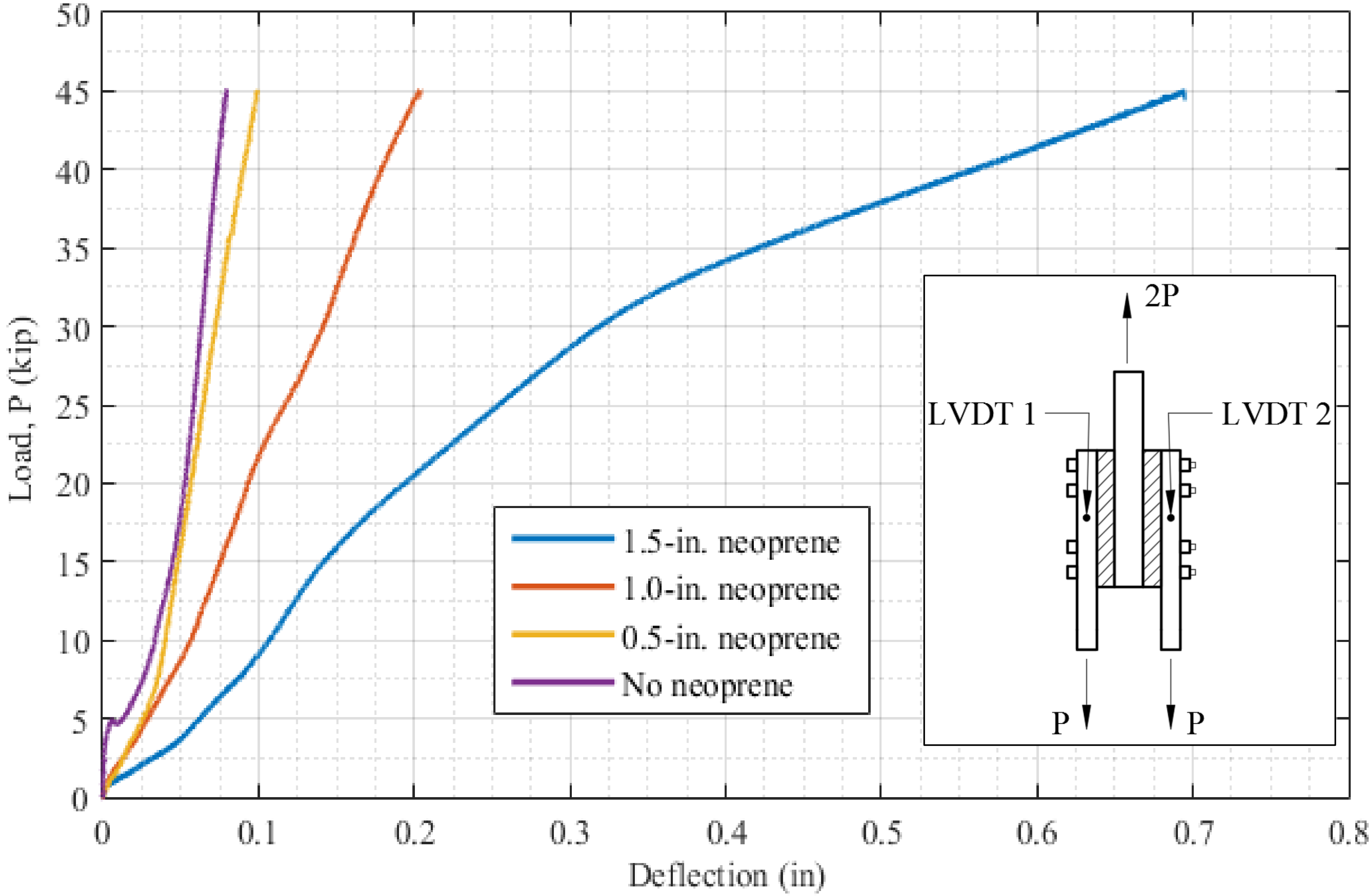






$M = P\,R$

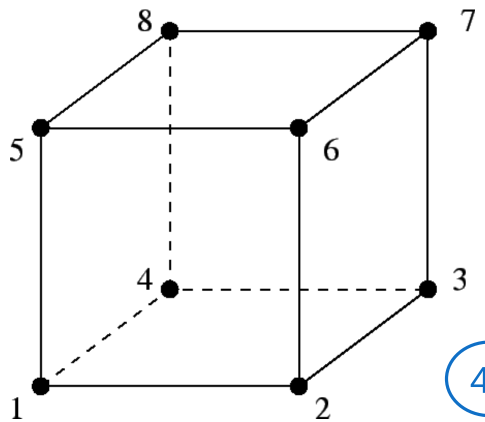
Shear test results



Structural Finite-element Modeling

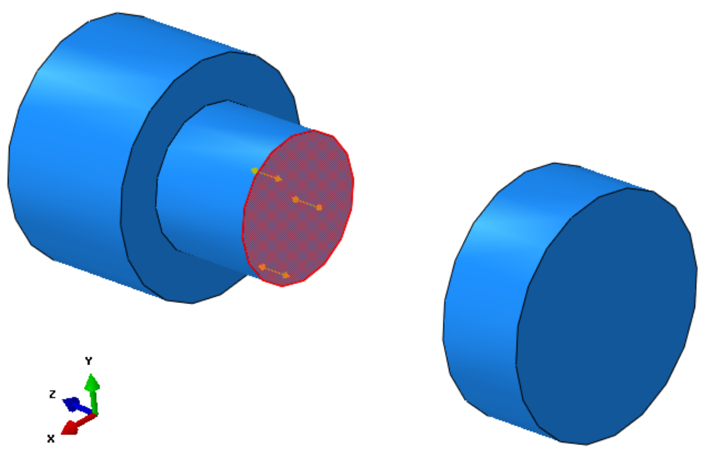
Finite element model

- Abaqus 6.14/ Standard
- 3D deformable elements
- Mesh
  - C3D8RH elements (8-node, linear, hybrid formulation)
- Mesh density
  - 5 elements across any thickness in bending
  - Maintain ~ 1:1 aspect ratio



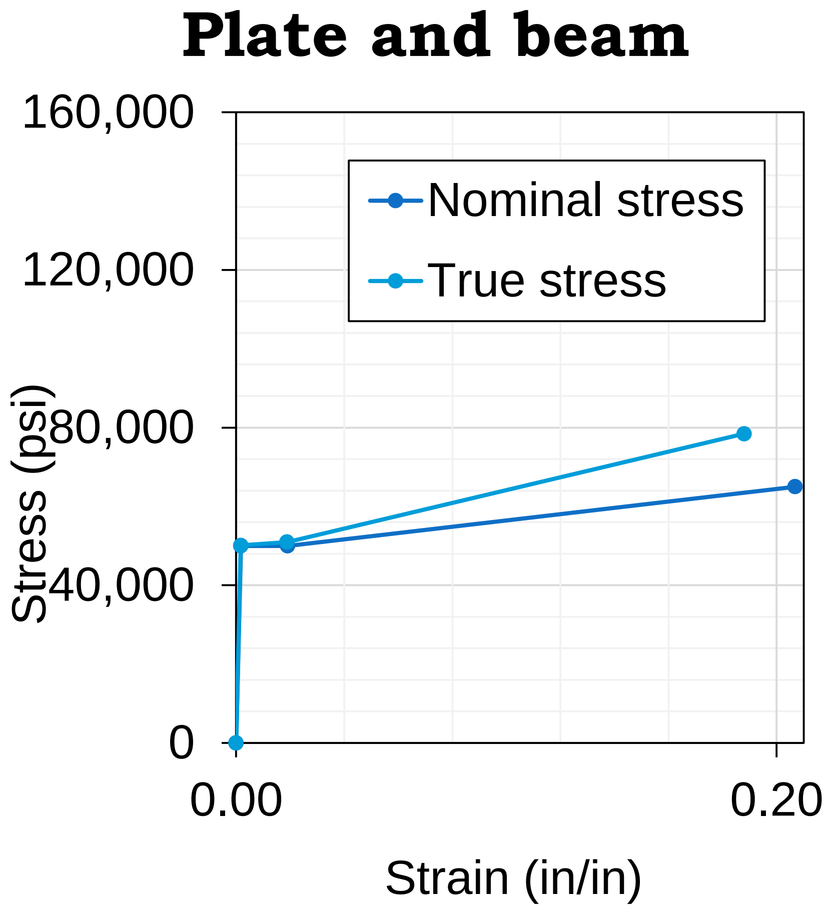
Study properties

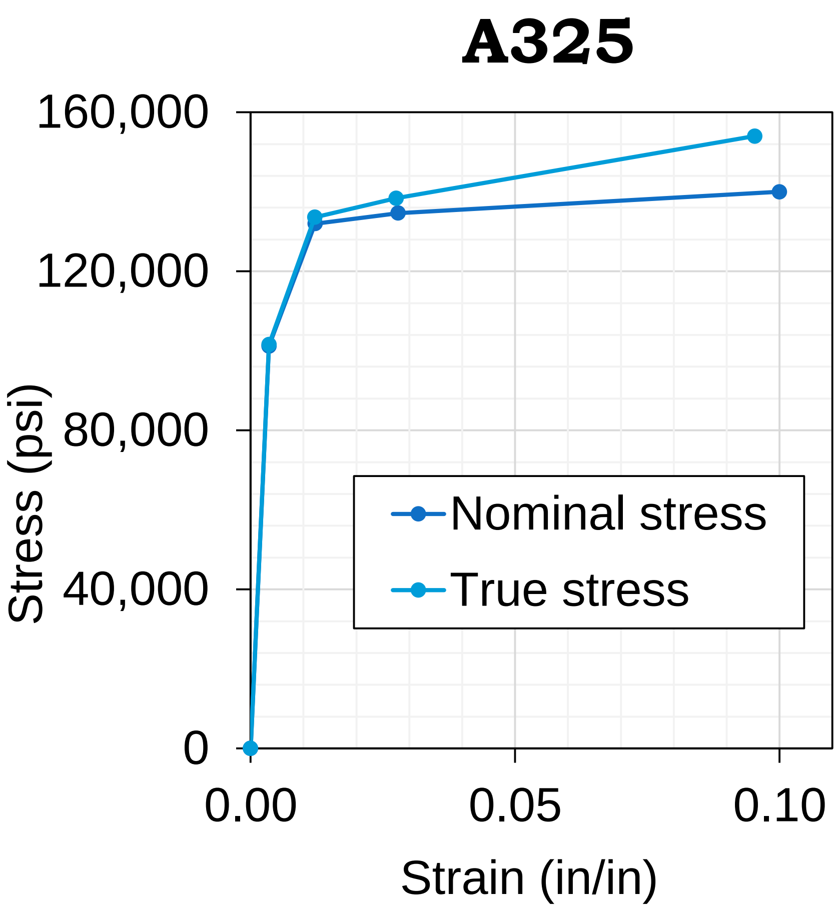
- Steps
  - Step 1: tighten bolts to 2000lb
  - Step 2: apply deflection at 45.9in
- Automatic Incrementation
- Direct solution method
- Full-Newton solution technique



Steel material definition

- Non-linear elastic





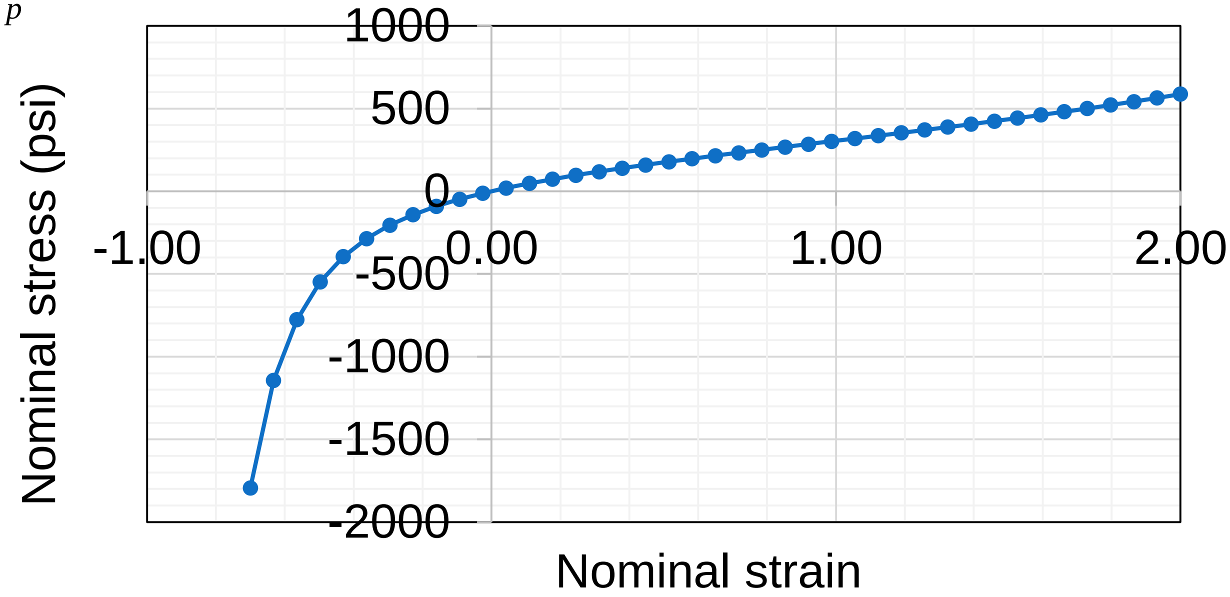
Neoprene Material

- Ogden 2nd order model
  - Function that fits complex incompressible materials
  - Expressed in terms of principal stretches

$$W(\lambda_1, \lambda_2, \lambda_3) = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p} \left(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3 \right)$$

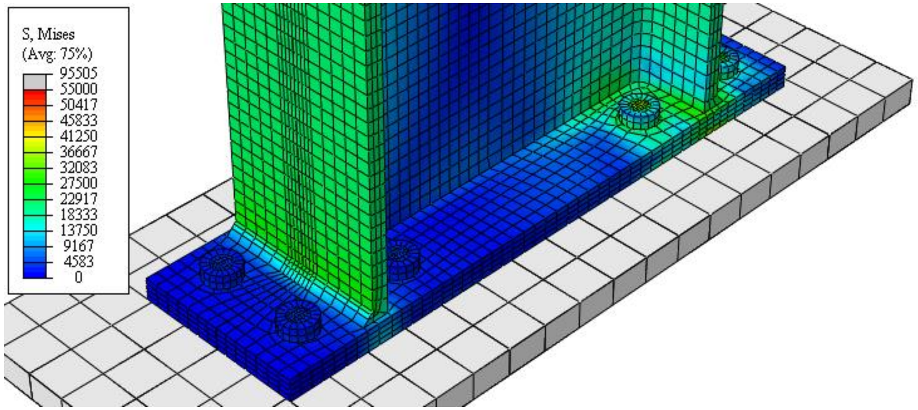
N=2

	1	2
μ_i	0.104347	158.099
α_i	7.78077	2.24987
D	0	0

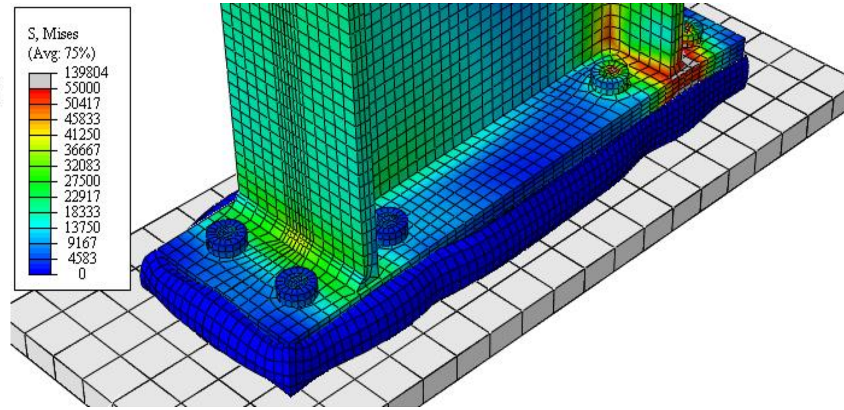


Uniaxial stress-strain curve

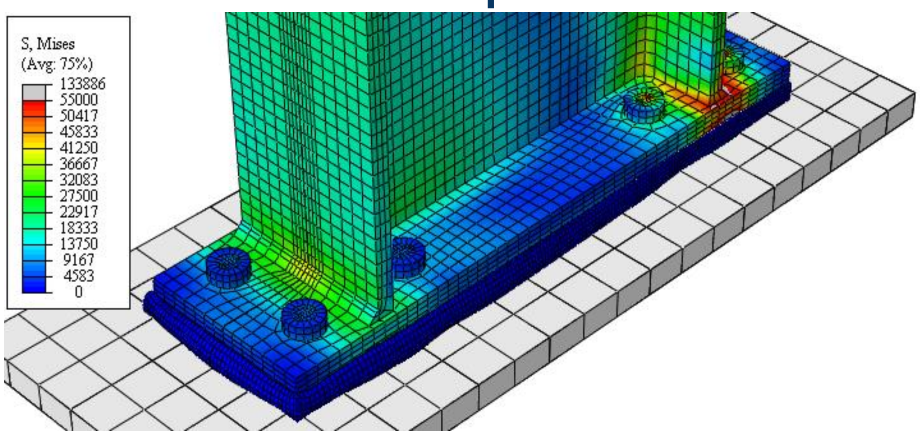
Finite element modeling



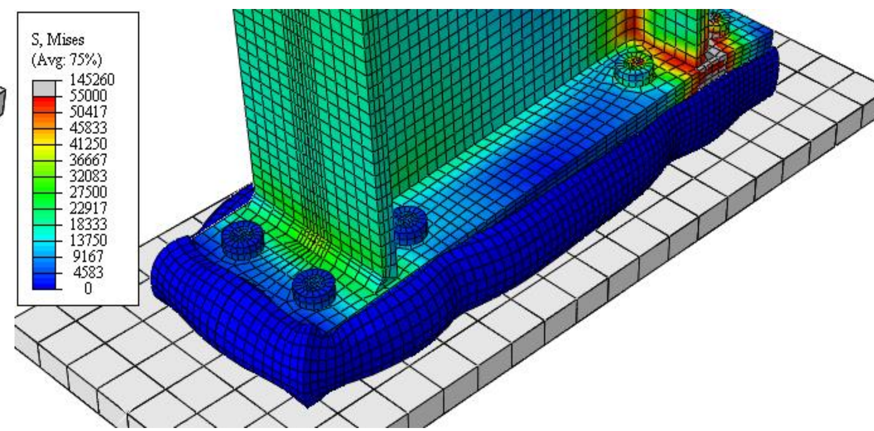
No neoprene



0.5” neoprene



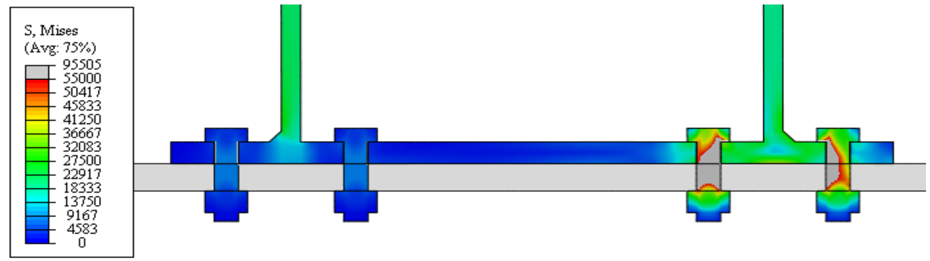
1.0” neoprene



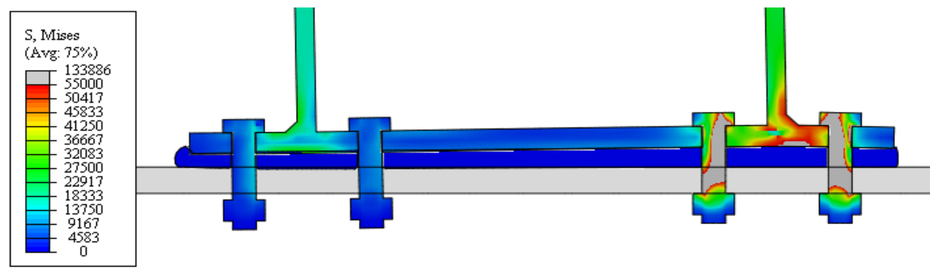
1.5” neoprene

Plate

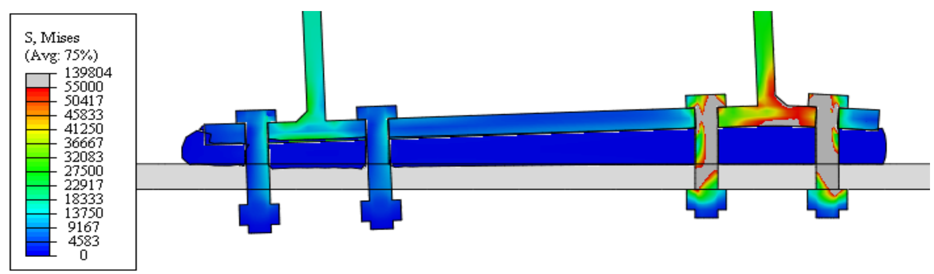
No neoprene



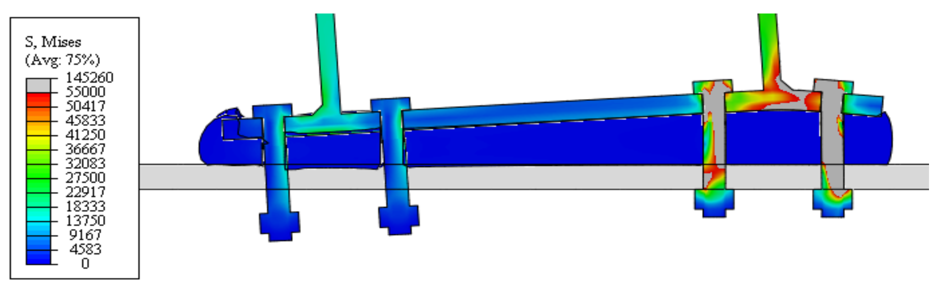
0.5” neoprene



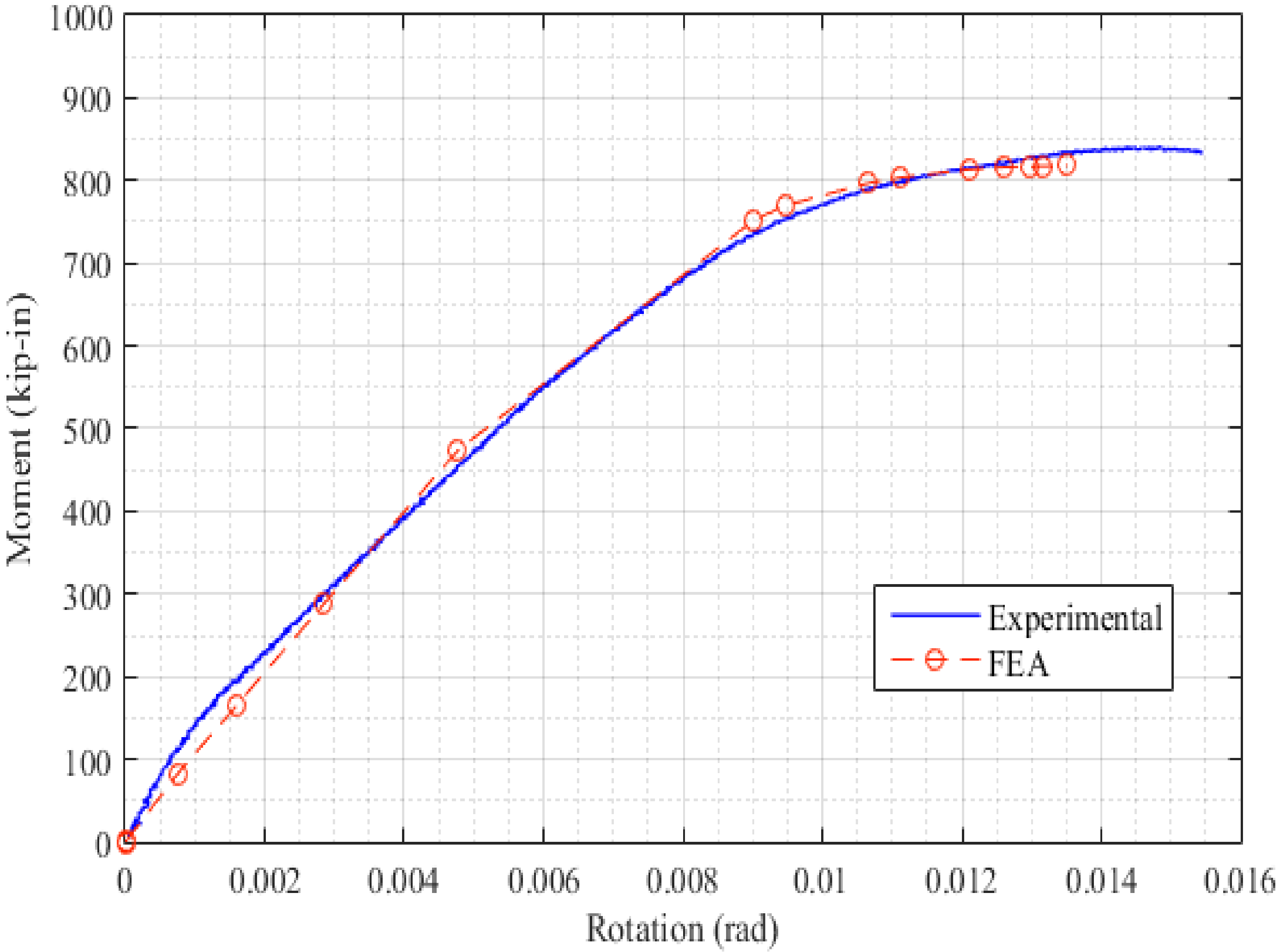
1.0” neoprene



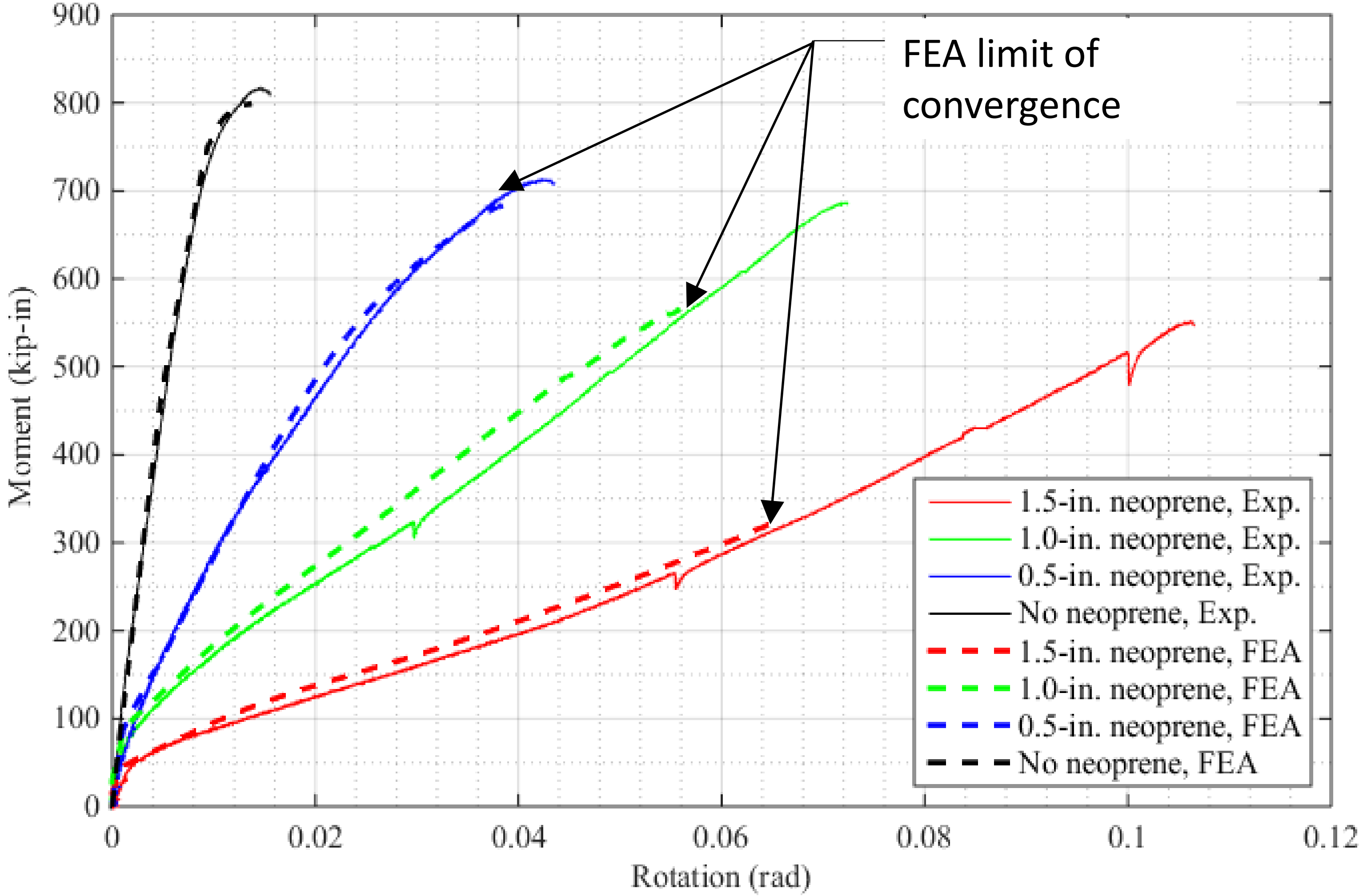
1.5” neoprene



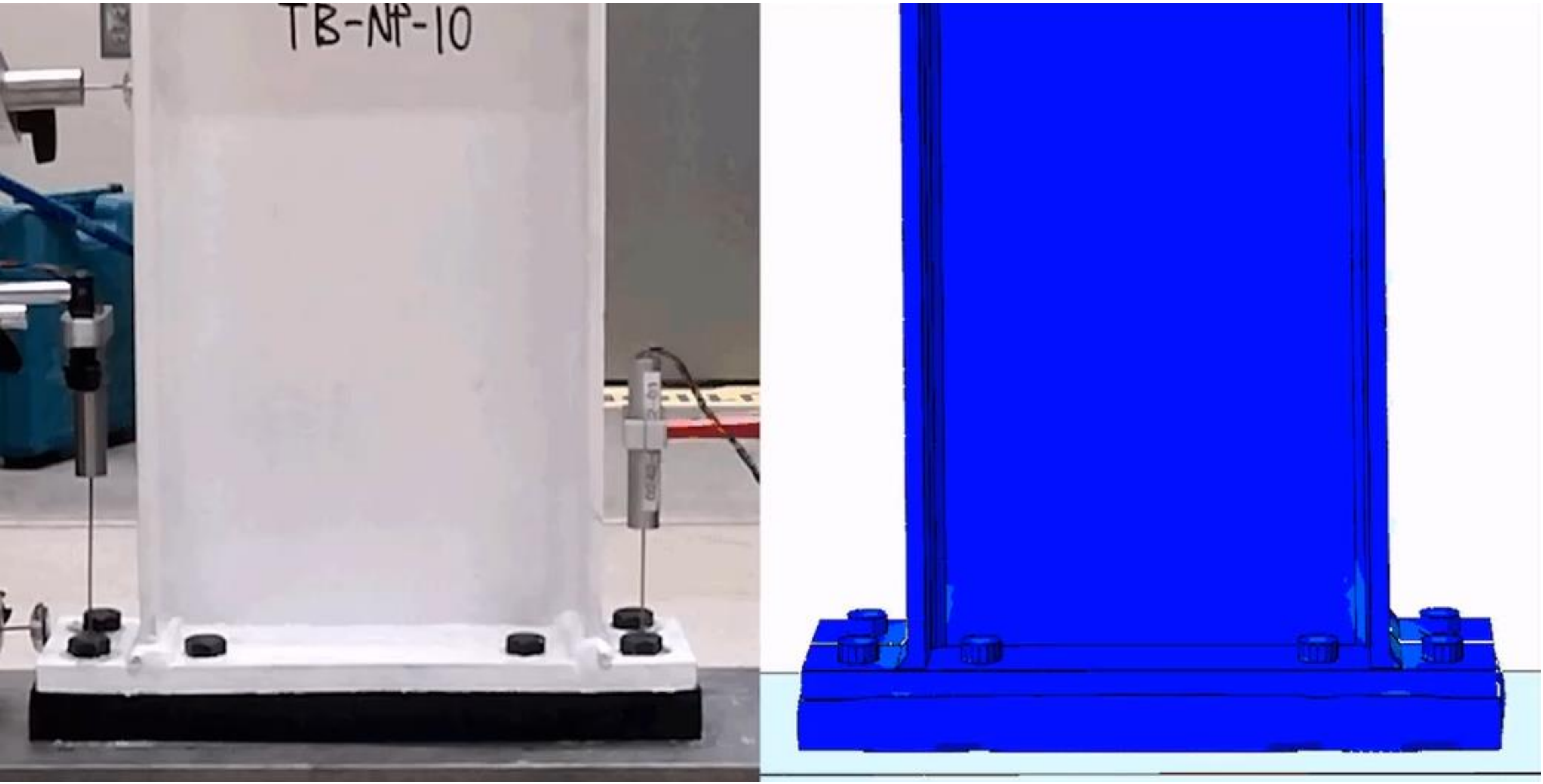
FEA vs. experimental no neoprene



FEA vs. experimental



FEA vs. experimental

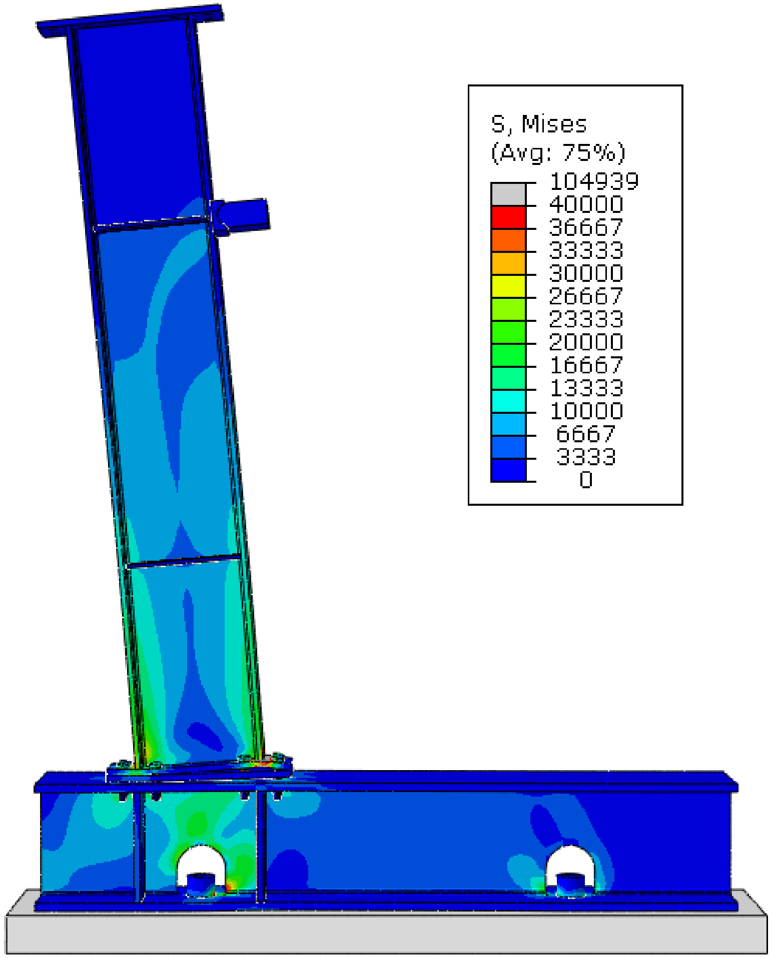


Research Conclusions

- Thermal
  - Thin thermal break pads (<0.5in for neoprene, <1.0in for FRP) increases heat flow greater than continuous beam case
  - Thicker thermal break pads provide reduced heat flow
  - Stainless-steel and FRP bolts reduce heat flow for a 0.5in neoprene pad by 19.4% and 66.3%, respectively, compared to steel bolts
- Structural
  - Rotational stiffness is reduced approximately linearly for increasing neoprene pad thickness
  - Bolt rupture occurred at a lower applied moment for neoprene pad connections
  - Shear stiffness is reduced exponentially with increased pad stiffness
  - Prying action occurs on bolts in connections with a neoprene pad

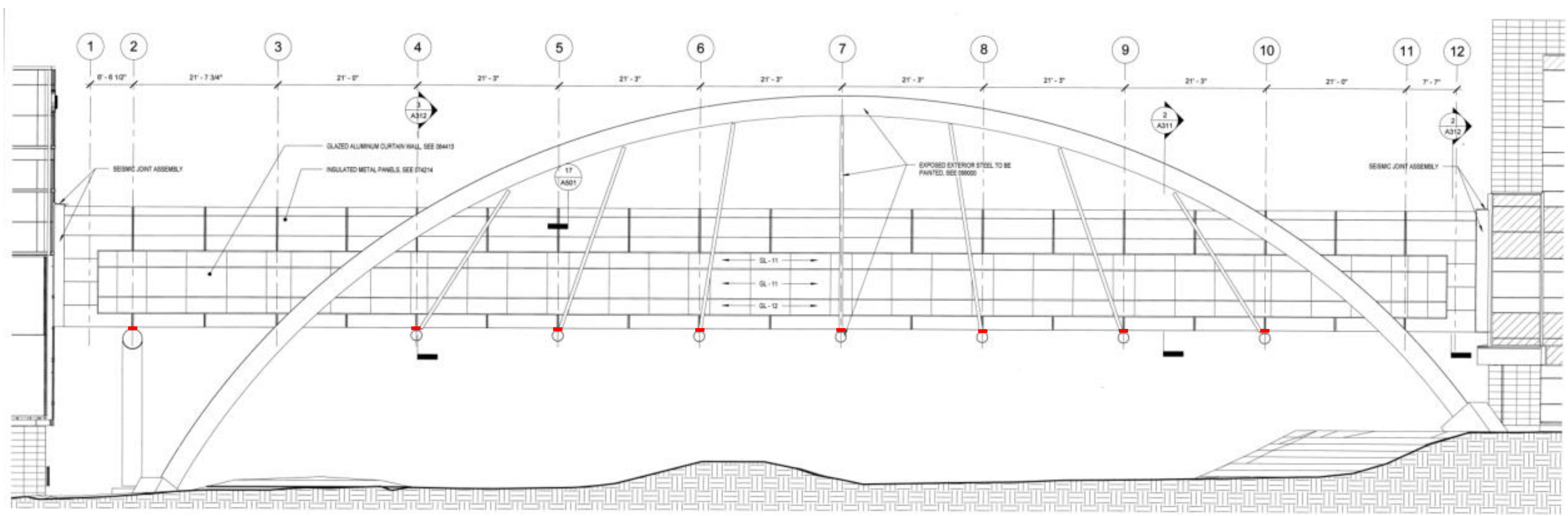
Practical Conclusions

- Thin neoprene pads
  - Bad for heat flow
  - Good for temperature index
  - Good structural behavior
- Thick neoprene pads
  - Good for heat flow
  - Good for temperature index
  - Bad for stiffness in bending
- Thick FRP pads (Northeastern University)
  - Good for heat flow
  - Good for temperature index
  - Good for stiffness in bending?

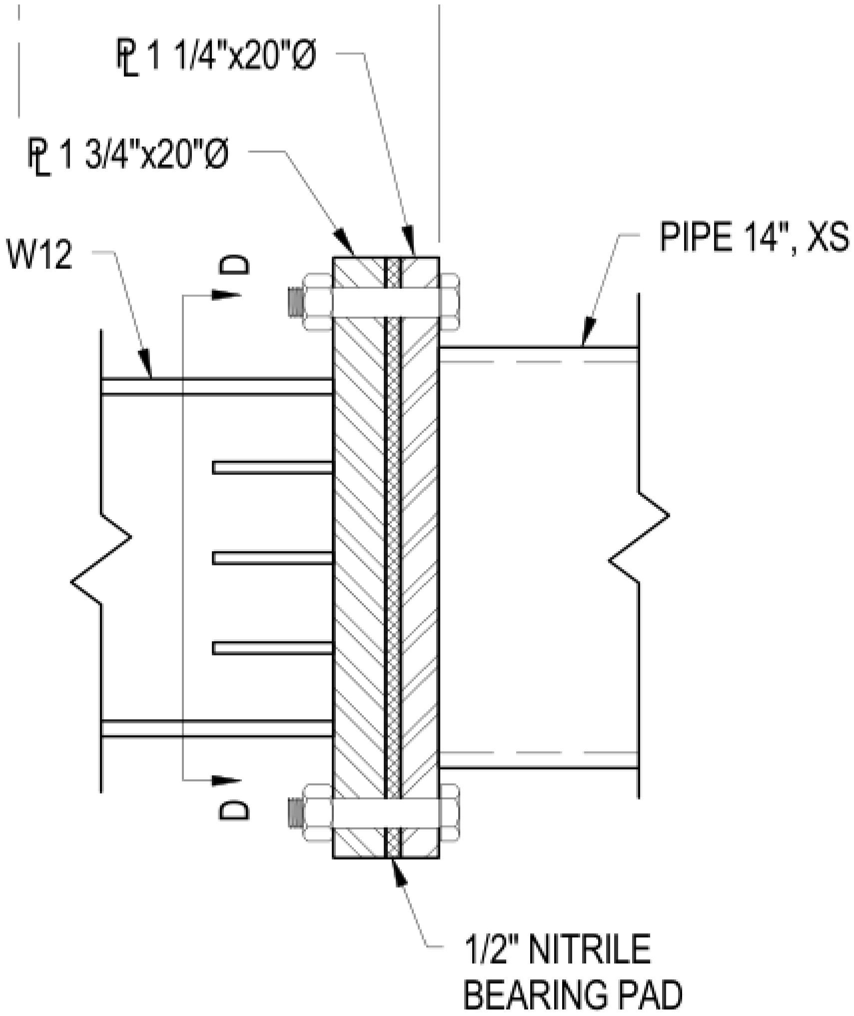


UAA Engineering Industry Building Bridge

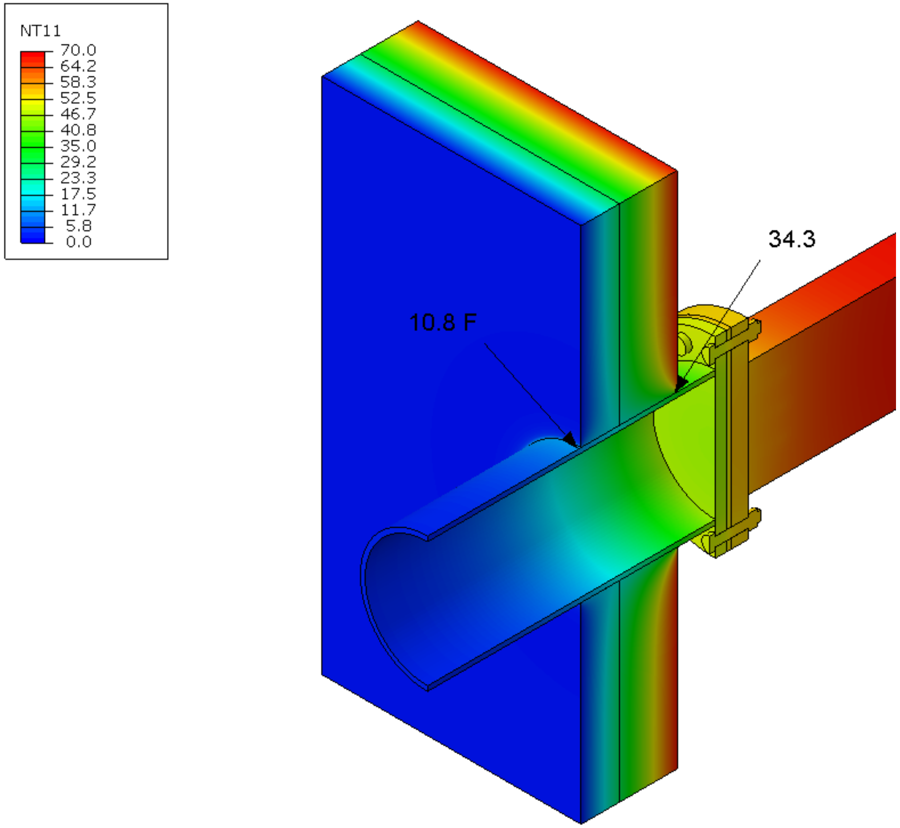
Thermal Break Supports

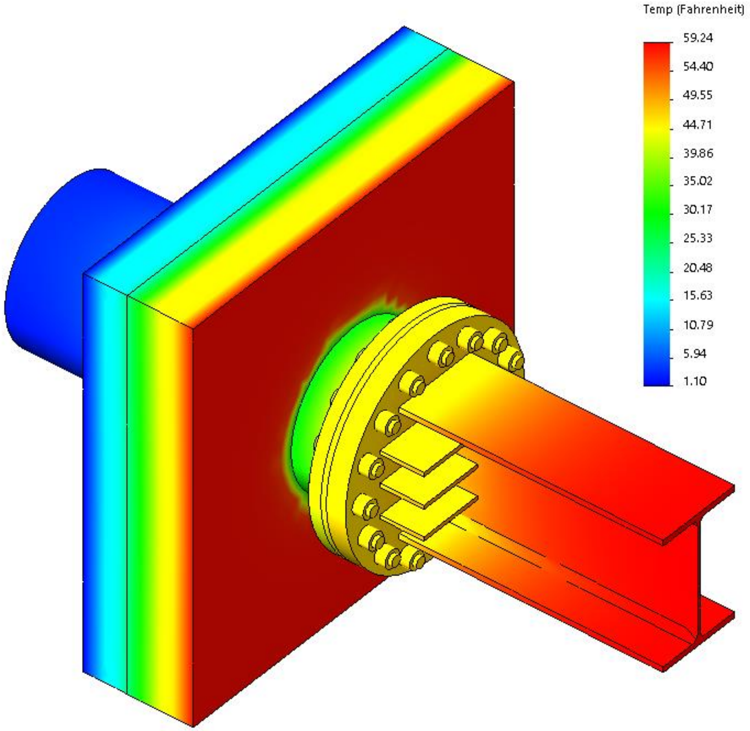


Roof Connection

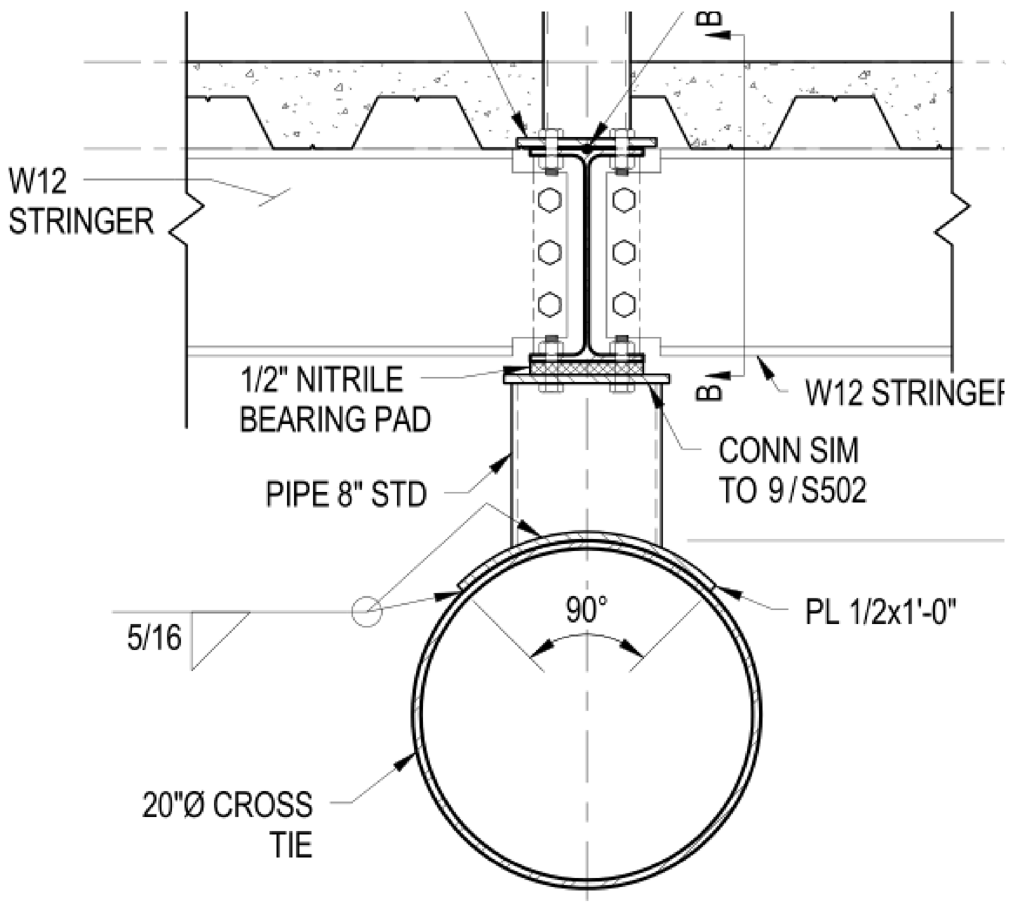


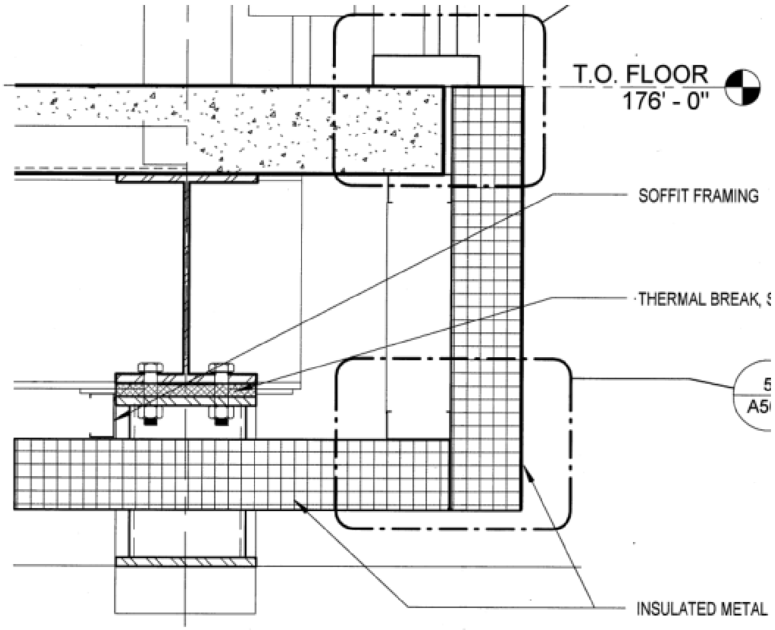
Roof Connection Thermal Model





Floor Connection





Structural Detail

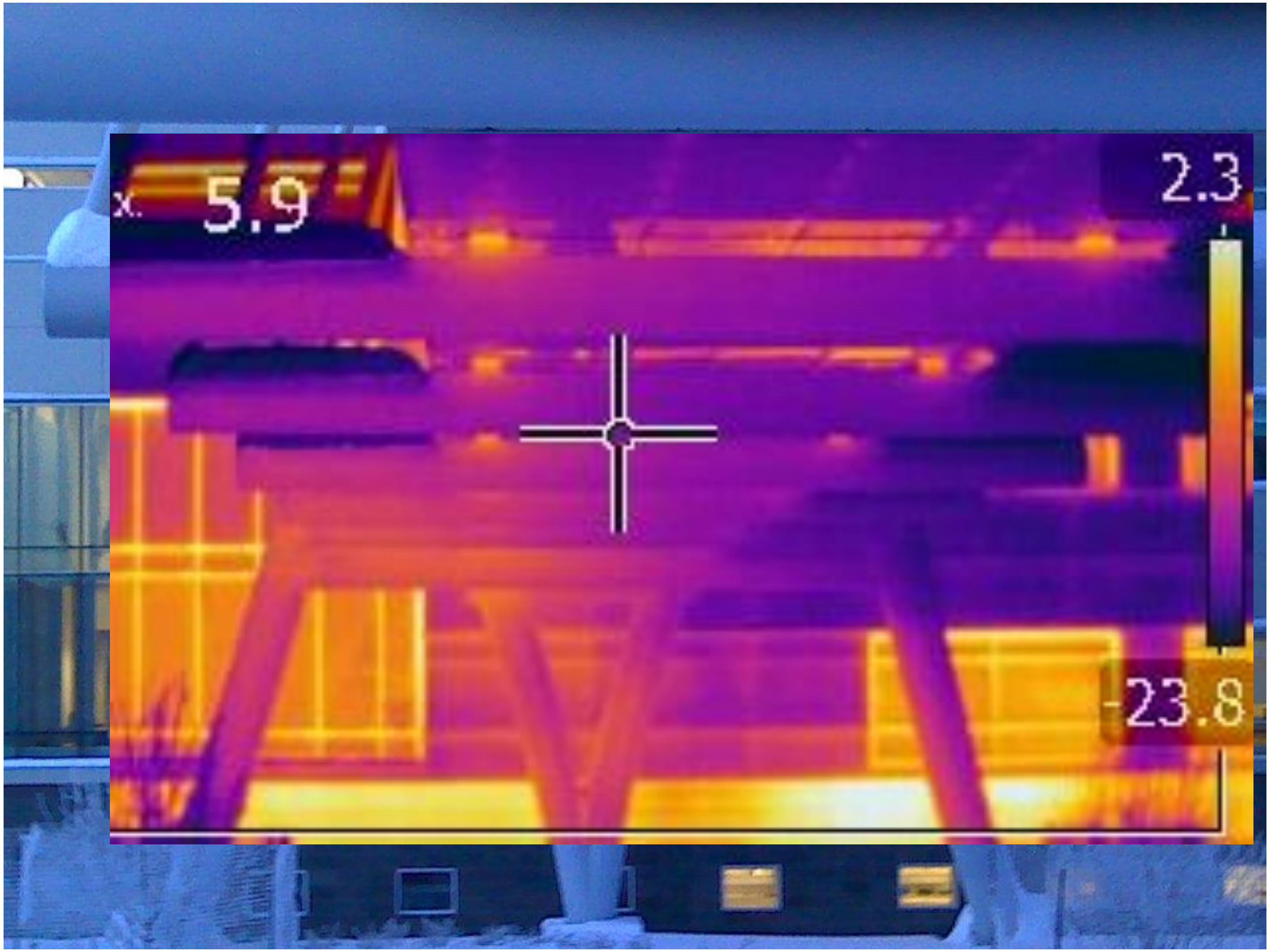
(Looking North)

Structural Detail

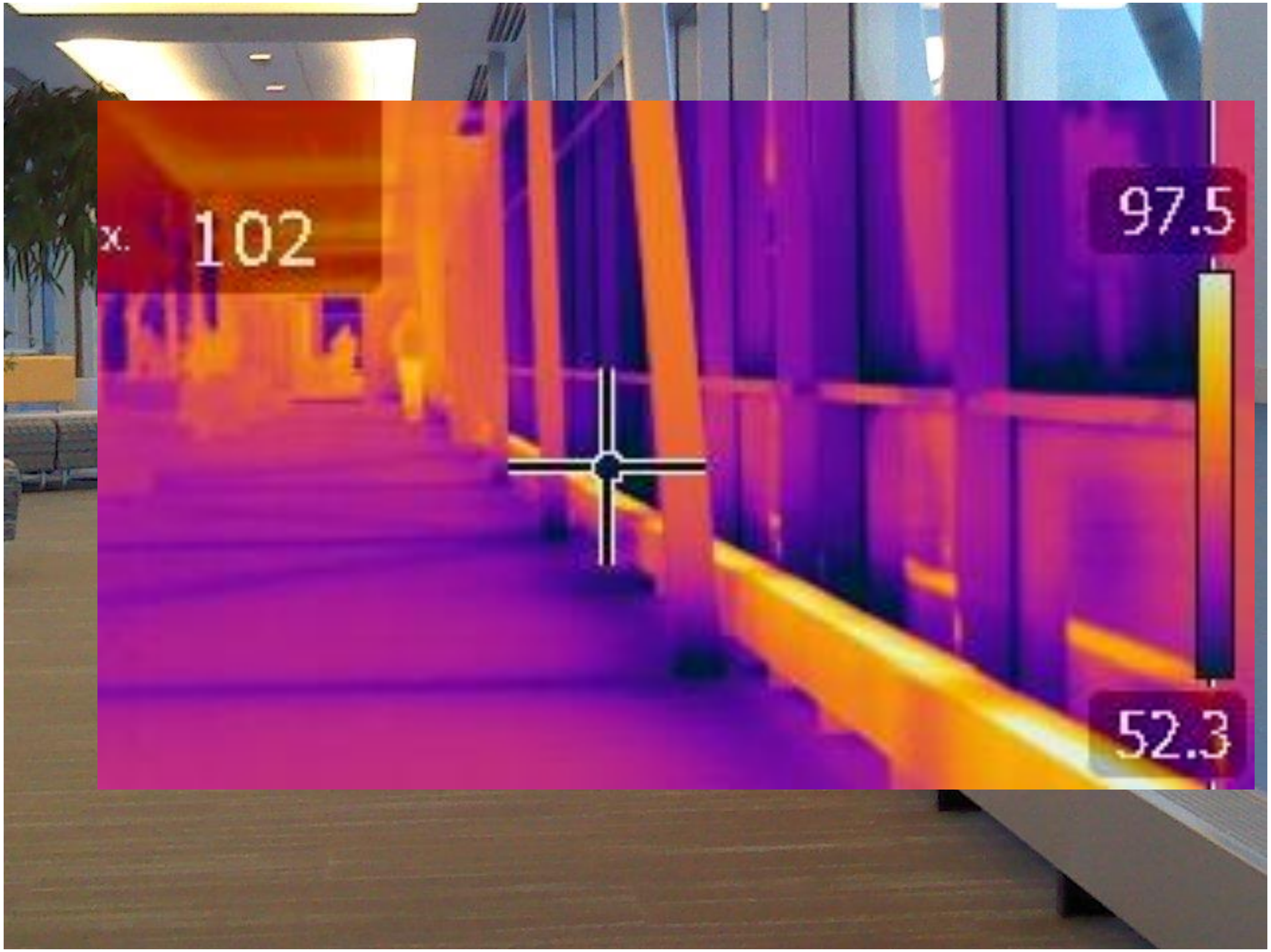
(Looking North)

Instrumented Connection

Results on a Cold Day



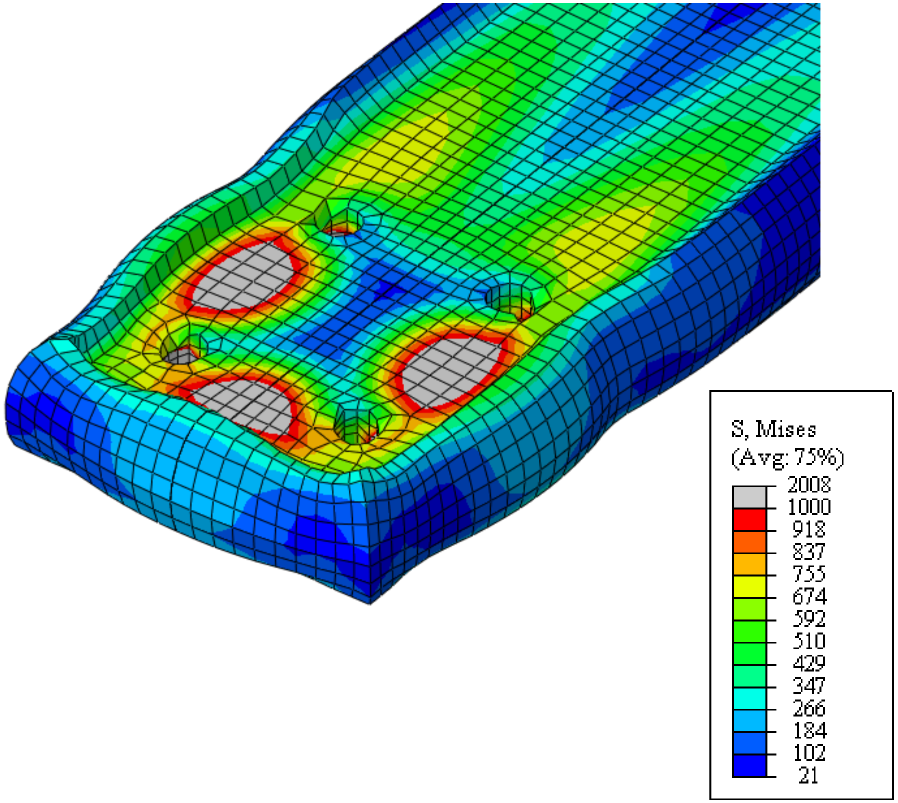
Results on a Cold Day



Acknowledgements

- American Institute of Steel Construction
- Structural Engineers Association of Alaska
- University of Alaska Anchorage, CoEng
- Sava White
- Corbin Rowe
- Nathaniel Cox
- Matheus Bastos Silva

Questions?


S, Mises
(Avg: 75%)
2008
1000
918
837
755
674
592
510
429
347
266
184
102
21

Contact information

- **Scott Hamel, P.E., Ph.D.**
  - p: (907) 786-1070
  - e: sehamel@alaska.edu

Boundary conditions/ interactions

- Boundary conditions
  - Rigid plate fixed for all DOF
- Constraints
  - Nuts "tied" to bolts
  - Bolt heads tied to -plate
- Interactions
  - Bolts & neoprene (fric = 0.4)
  - Neoprene and end-plate (fric = 0.4)
  - Neoprene and rigid plate (fric = 0.4)
  - Nuts to rigid plate (fric = 0.2)

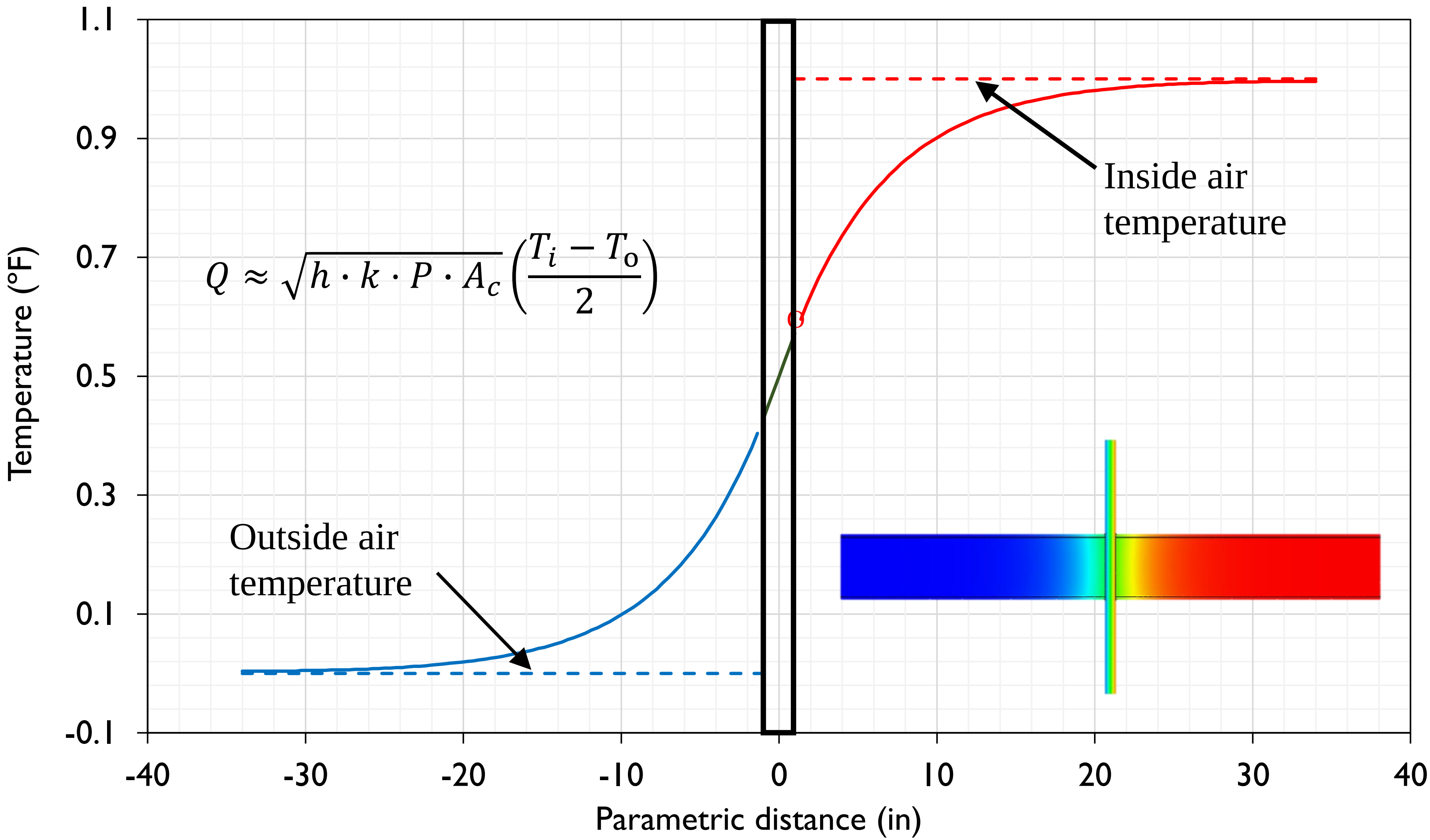
Calculating heat loss in a thermal bridge

- Calculating thermal bridge heat flow:
  - Linear thermal bridge: $$\Psi = \frac{Q - Q_0}{L} = (U - U_0) \cdot \frac{A_{total}}{L}$$
  - Point thermal bridge: $$\chi = Q - Q_0 = (U - U_0) \cdot A_{total}$$
  - Total: $$Q = \Delta T \left(\mathrm{U}_0 \cdot A_{total} + \sum (\Psi_i \cdot L_i) + \sum (\chi_i \cdot n_i) \right)$$

Heat transfer FEA

- Abaqus 6.14/ Standard (& Solidworks)
- Steady-state
- ASHRAE values for:
  - Material thermal conductivity
    - Steel, k = 347 Btu ·in/ft^2 ·hr ·°F
    - Stainless steel, k = 118
    - FRP, k = 2.0
    - Neoprene, k = 1.32
    - XPS insulation, k = 0.2
  - Surface heat transfer coefficient
    - 1.5 Btu/ (hr ·ft^2 ·°F), both sides
    - Sink temperature:
      - Inside: 1°F
      - Outside: 0°F
  - No gap resistance

Continuous beam thermal bridge acts as a cooling fin



Continuous beam heat flow for all W-shapes