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

Presented to the UAA College of Engineering Seminar Series

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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: \( \frac{Btu}{hr\cdot°F} \)

Diagram:
- Conduction
- Convection
- Radiation

Exterior facade
- Insulation layer (building envelope)
- Interior conditioned space
Linear thermal bridge

Exterior

Brick

Brick support angle

Interior conditioned space

Stud wall insulation

Continuous insulation layer

Air space
Point thermal bridge

Exterior

Steel post

Rigid insulation

Rooftop equipment

Roofing membrane

Steel beam

Interior conditioned space
Point thermal bridge

- Exterior facade
- Exterior
- Interior conditioned space
- Stud wall insulation
- Steel beam
- Continuous insulation layer
Thermal bridging in structural steel

\[ k_{\text{steel}} = 347 \frac{\text{Btu} \cdot \text{in}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ \text{F}} \]

\[ k_{\text{XPS insul.}} = 0.2 \frac{\text{Btu} \cdot \text{in}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ \text{F}} \]
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:

\[
TI = \frac{T_s - T_o}{T_i - T_o} = \frac{40.8 - 0}{70 - 0} = 0.58 < 0.70, \text{not good}
\]

\[T_s = 40.8^\circ F\]

\[T_o = 0^\circ F\]

\[T_i = 70^\circ F\]
Industry survey & results
Industry survey

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

Map of survey respondents
Survey results

Most Common Details:

<table>
<thead>
<tr>
<th>#</th>
<th>Answer</th>
<th>Response</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cantilever levels/beams</td>
<td>113</td>
<td>74%</td>
</tr>
<tr>
<td>2</td>
<td>Facade elements</td>
<td>113</td>
<td>74%</td>
</tr>
<tr>
<td>3</td>
<td>Roof protrusions</td>
<td>96</td>
<td>63%</td>
</tr>
<tr>
<td>4</td>
<td>Foundation penetrations</td>
<td>30</td>
<td>20%</td>
</tr>
<tr>
<td>5</td>
<td>External braces</td>
<td>22</td>
<td>14%</td>
</tr>
<tr>
<td>6</td>
<td>Other</td>
<td>10</td>
<td>7%</td>
</tr>
</tbody>
</table>
### How is Thermal-Bridging Addressed?

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

#### What Materials are used for Gasket?

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

Experimental Thermal Performance
Experimentally measuring heat flow

- Calibrated hot box:
Calibrated hot box
PID control

1.5in. FRP break, steel bolts
Calibrated hot box specimens

2in. XPS insulation

Thermal bridge

Thermal break

- Gap sealed with expanding foam
- W10x19 steel beam
- Gaffers tape
- 2-in. XPS insulation

- 0.5-in. steel end-plate
- 0.5-in. diameter bolts
- W10x19 steel beam
- Thermal break pad
- 2-in. thick XPS insulation
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

Heat flow rate (Btu/hr °F)

0.5 in. thick

1 in. thick

Continuous beam
No pad
Neoprene steel
Neoprene stainless
FRP steel bolts
FRP stainless
Neoprene steel
Neoprene stainless
FRP steel
FRP stainless

Neoprene pad, steel bolts
Neoprene, stainless bolts
FRP pad, steel bolts
FRP, stainless bolts
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

$(k \text{ in units of } \text{Btu} \cdot \text{in}/\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{F})$
Bolt material

Heat flow rate (Btu/hr·°F) vs. Neoprene pad thickness (in.)

- Better heat flow rate
- Better temperature index

Heat flow rate:
- Steel bolts
- Stainless-steel bolts
- FRP bolts

Temperature index:
- Steel Bolts
- Stainless-steel bolts
- FRP bolts
Heat flow - pad vs. bolts

Heat flow through neoprene pad
Heat flow through steel bolts

[Graph showing heat flow rate in Btu/hr·°F vs. neoprene pad thickness in inches.]
Covering insulation

- Interior conditioned space
- Steel beam
- Building envelope
- Insulation applied to the face of the steel beam on the inside

Exterior
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

- Load cell
- Pivot arm
- Lateral bracing
- 3/8-in. stiffeners
- W10x19 beam
- Test connection
- Neoprene gasket
- W10x45 "column"
- 20-kip actuator
- Reaction frame
- 0.5-in. stiffeners
- 1-1/2-in. threaded rod
- Strong floor
Bending test results

0.5 in. neoprene pad test at failure
Bending test results

1.5 in. neoprene pad test at failure
Moment-rotation

![Graph showing moment-rotation relationship for different neoprene thicknesses and a no neoprene condition. The graph includes a marked point for bolt rupture.]
Shear tests

1-in. A514 T1 plate

LVDT 1

LVDT 2

1/2-in. A572 Gr. 50 plate

(8x) 1/2-in. diameter A325 Type 1 bolts

Neoprene gasket

F

F

54

46.482

14.75-in.
Shear test results

TS-NP-15/5
TS-NP-10/5
TS-NP-05/5
TS-NP-00/5

M = P R
Shear test results

![Graph showing shear test results with load vs. deflection for different neoprene thicknesses. The graph includes a legend indicating 1.5-in. neoprene, 1.0-in. neoprene, 0.5-in. neoprene, and No neoprene. Inset diagram illustrates the testing setup with LVDT 1 and LVDT 2.](image)
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

**Plate and beam**

- Nominal stress
- True stress

**A325**

- Nominal stress
- True stress
Neoprene Material

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

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

\[ N=2 \]

\begin{tabular}{|c|c|c|}
  \hline
  \( \mu_1 \) & 0.104347 & 158.099 \\
  \( a_1 \) & 7.78077 & 2.24987 \\
  \( D \) & 0 & 0 \\
  \hline
\end{tabular}

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

![Graph showing FEA vs. experimental data without neoprene]
FEA vs. experimental

FEA limit of convergence
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

PIPE 14", XS

R 1 1/4"x20"Ø
R 1 3/4"x20"Ø
W12

1/2" NITRILE BEARING PAD
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
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Questions?
Contact information

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  - 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: \[ Q = \Delta T \left( U_0 \cdot A_{total} + \sum (\Psi_i \cdot L_i) + \sum (\chi_i \cdot n_i) \right) \]
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

\[ Q \approx h \cdot k \cdot P \cdot A_c \left( \frac{T_i - T_o}{2} \right) \]

Temperature (°F)

Inside air temperature

Outside air temperature
Continuous beam heat flow for all W-shapes

\[ Q \approx \sqrt{h \cdot k \cdot P \cdot A_c \left( \frac{T_i - T_o}{2} \right)} \]