A Finite Element Analysis of Substation Aluminum Busbars

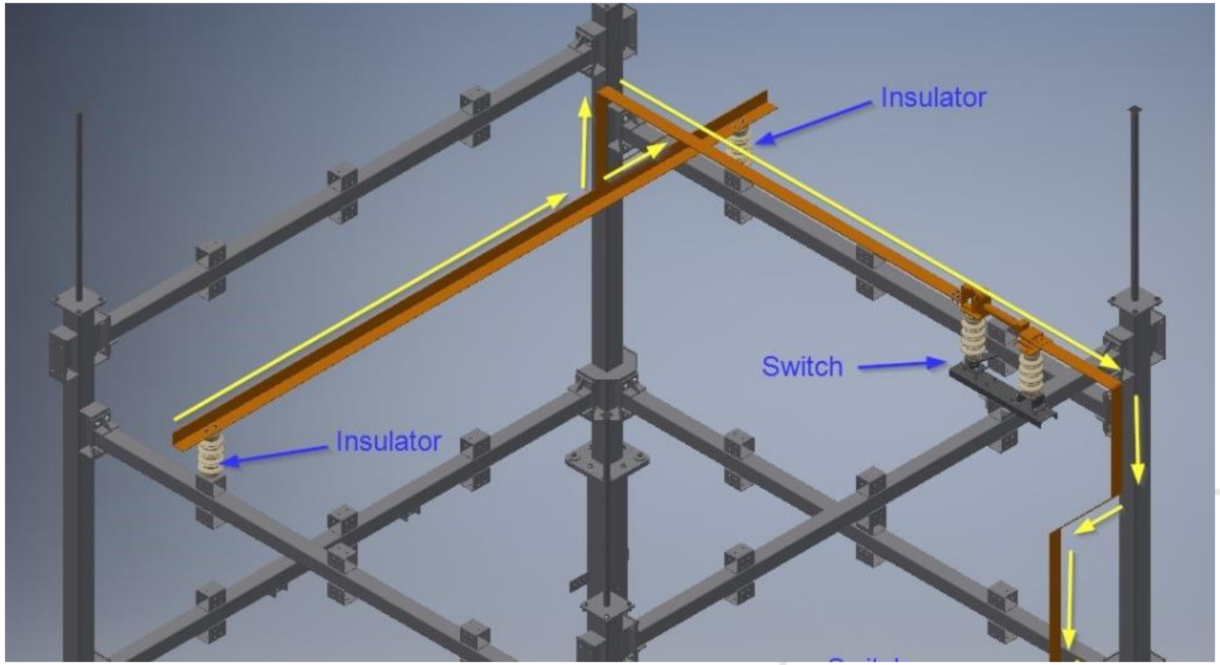
Ryan Grajewski, Grey Williams, & Sameer Zaheer
5/4/2022

Georgia Tech

Introduction

- Substations provide ability to transform voltages, segment grid, and monitor power flow
- Rigid aluminum conductors used to transmit electricity throughout facility
- Conductors held in place w/ porcelain insulators

Credit: https://spotlight.guc.com/2018/09/electric-substation-now-online



Introduction

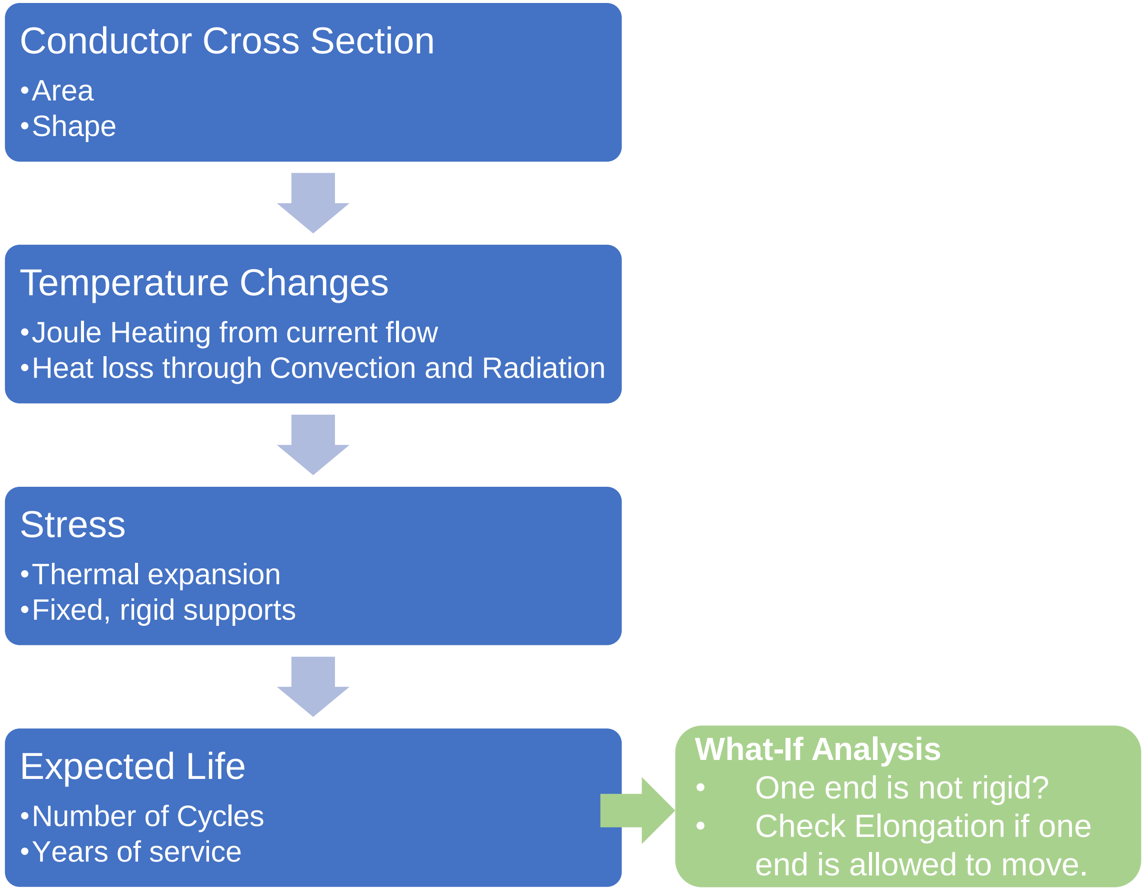
- Conductors available in a variety of shapes
  - Flat bar
  - Angle (UABC)
  - Tubing
  - Integral web (IWCB)

- Shape affects electrical resistance, fatigue, and expected life

- Ampacity and strength are perhaps the most important considerations to be made when selecting a conductor.

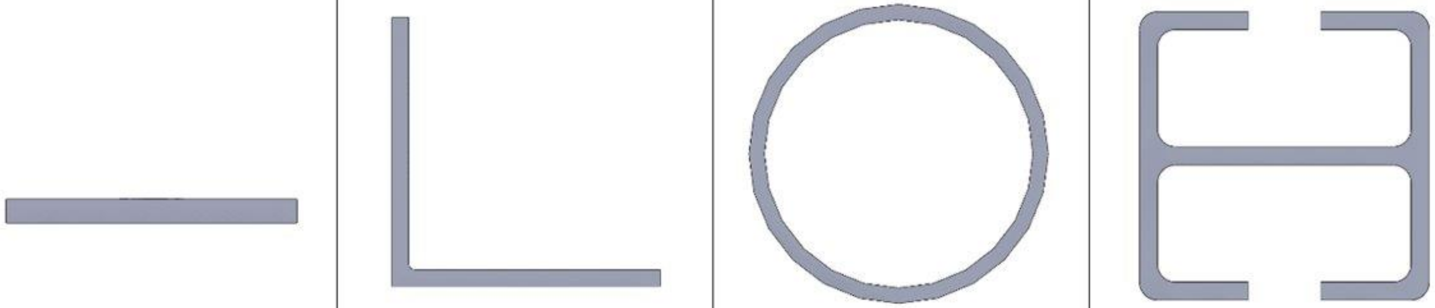
Objectives

- Compare efficacy of common rigid aluminum bus conductors
- Apply high demand current, and stagnant air natural convection.
- Obtain temperature change and internal stresses
- Determine expected life of each conductor undergoing cyclic thermal stress
- Validate results analytically
- Compare results to Southern Company design criteria



Modeling

- All conductors made of 6061-T6 aluminum
- Conductors modeled as 10ft long



Flat Bar	Angle (UABC)	Tubing	Integral Web (IWCB)
Dimensions [in]			
⅜” x 4”	4” x 4”x ¼”	4” NPS Sch. 40 Tube (4.5” OD, 4.03” ID)	4” x 4”x ¼”
Cross-Sectional Area [in^2]			
1.5	1.9375	3.1487	3.781
Area Moment of Inertia [in^4]			
0.018	3.039	7.181	9.213
Linear Resistance [μΩ/ft]			
12.566	9.729	5.987	4.985

Georgia Tech

Material Properties

- Al 6061-T6 aluminum is preferred for
  - High strength-to-weight ratio
  - Excellent corrosion resistance
  - low resistivity.

Property	Value
Density	2713 [lb/in^3]
Tensile Yield Strength	37594 [psi]
Tensile Ultimate Strength	45411 [psi]
Electrical Resistance	18.85 [μΩ/in^2/ft]
Specific Heat Capacity	0.214 [Btu/lb*°F]
Radiation Heat Emissivity	0.11
Young's Modulus	Temperature Dependent
Thermal Conductivity	Temperature Dependent
Coefficient of Thermal Expansion	Temperature Dependent

Georgia Tech

Loading Conditions

- Choosing conditions for worst case scenario
- At installation
  - Uniform internal temperatures of 32°F
- At operation
  - Ambient temperature was assumed to be 120°F
- Considering high electricity demand,
  - a current of 2000 Amps

Condition	Value
Installation Temperature	32 [°F]
Operation Ambient Temperature	120 [°F]
Current Load	2000 [Amps]

General Analysis

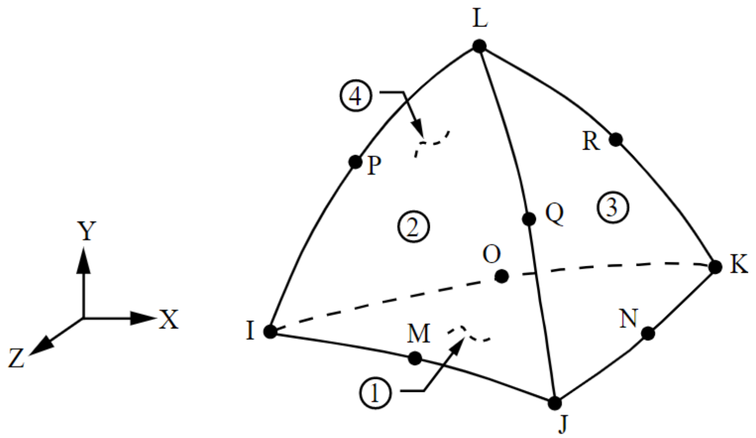
- Thermal-Electric analysis with a Structural analysis is performed
  - Fatigue study is performed on the bus conductors after the structural analysis.

General Analysis (Continued)

- Inputs for the Thermal-Electric analysis include:
  - Ambient temperature
  - Voltage difference across the busbar
  - Emissivity of 6061 Aluminum
- The Static Structural analysis computes stress and deformation of the busbar by using:
  - The initial installation temperature at 32°F
  - The temperature data obtained from the Thermal-Electric analysis
- The fatigue life is calculated by modeling a zero-based loading cycle
  - Full load conditions are the output of the Static Structural Analysis.

Element Selection

- Element SOLID187 was chosen as the element type.
- According to the ANSYS element reference:
  - 'SOLID187 element is a higher order 3-D, 10-node element. SOLID187 has a quadratic displacement behavior and is well suited to modeling irregular meshes (such as those produced from various CAD/CAM systems).'
- The element is defined by 10 nodes having 3 degrees of freedom at each node.
- The element considers bending loads, axial and perpendicular loads and thus allows for a lower resolution mesh.
- This suits the requirements of our 3D analysis.



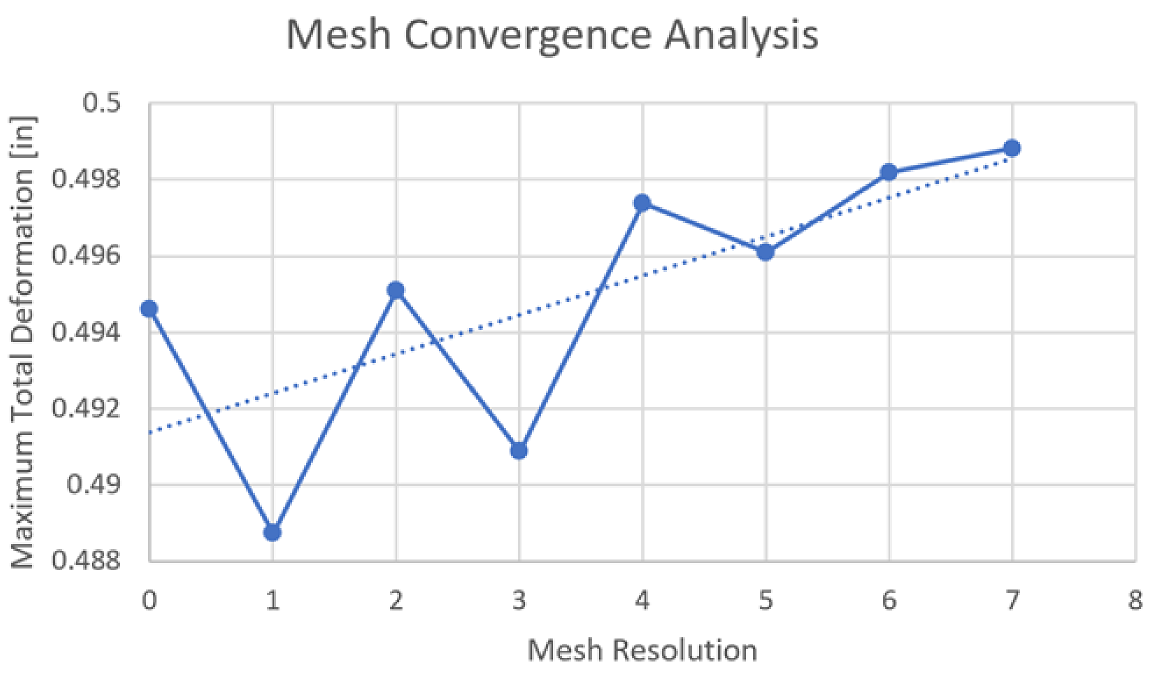
Georgia Tech

Boundary Conditions

- Thermal and Mechanical boundary conditions are applied to models.
- Boundary conditions chosen as worst case scenarios like load conditions
- Convection was considered at exposed surfaces of the busbars
  - With a temperature varying convection coefficient.
  - Coefficient data was preloaded from an ANSYS library considering simplified convection with stagnant air.
- Radiation boundary conditions are applied to all surfaces of the busbars exposed to the ambient environment
  - The emissivity of the material is 0.011 as shown in material properties
- Mechanically all busbars have fixed support boundary conditions applied at the mounting holes.

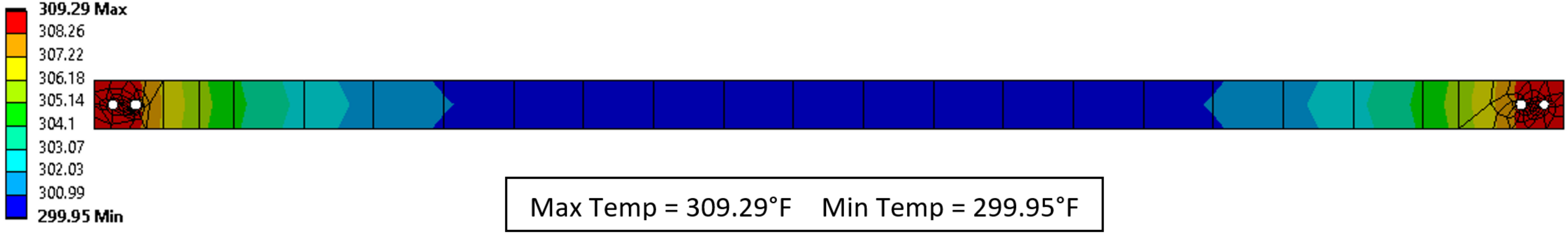
Mesh Convergence Study

- The Mesh Convergence study is shown to the right.
- As we increase the Mesh Resolution little change is seen in maximum deformation.
- Shows that low mesh resolution already shows a converged result.



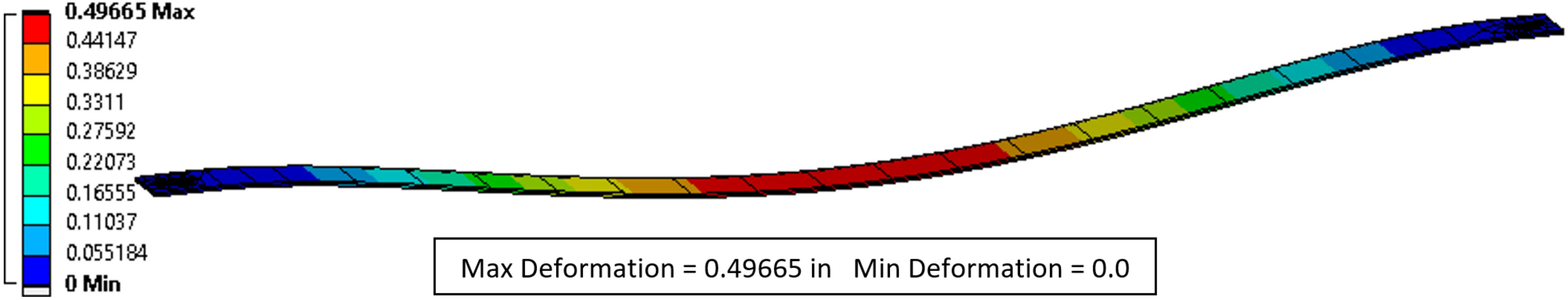
Results – Rectangle Bar

Surface Temperature Distribution [°F]



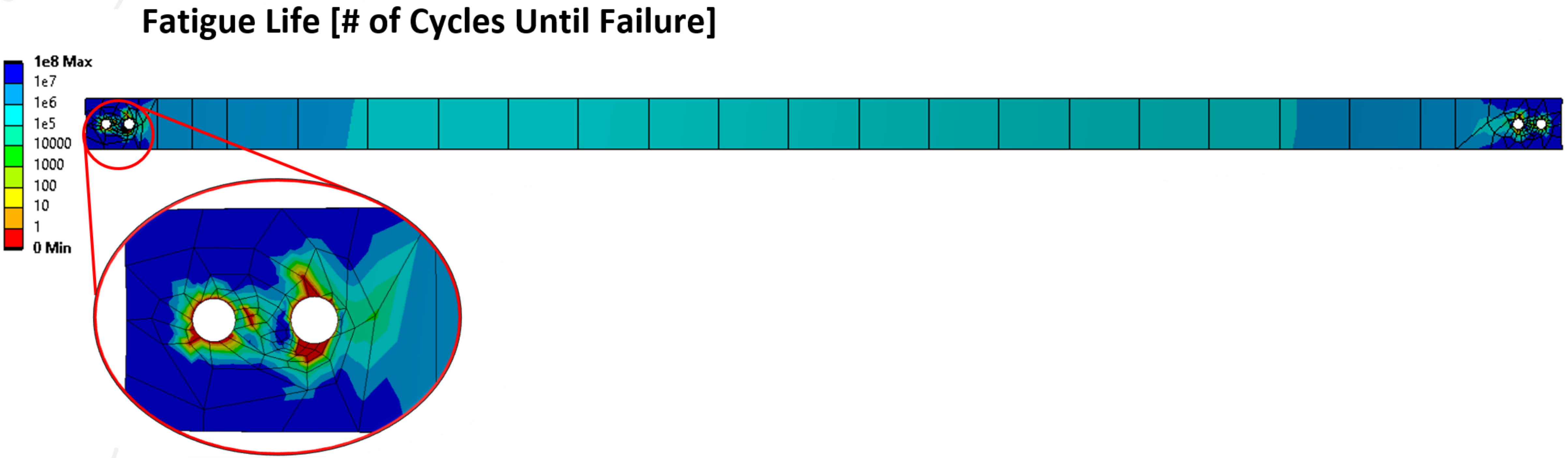
Max Temp = 309.29°F Min Temp = 299.95°F

Total Deformation [in]



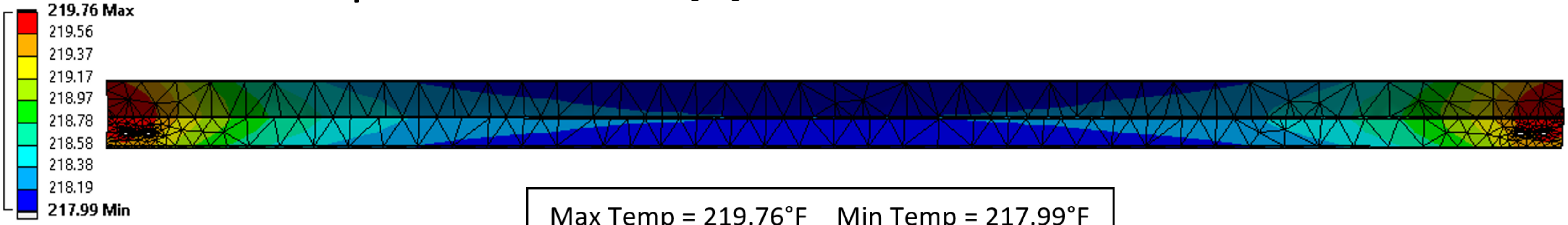
Max Deformation = 0.49665 in Min Deformation = 0.0

Results – Rectangle Bar



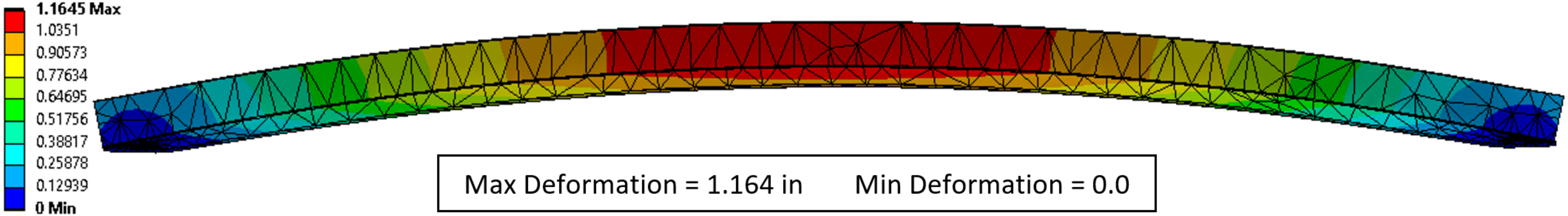
Results – Angle (UABC)

Surface Temperature Distribution [°F]



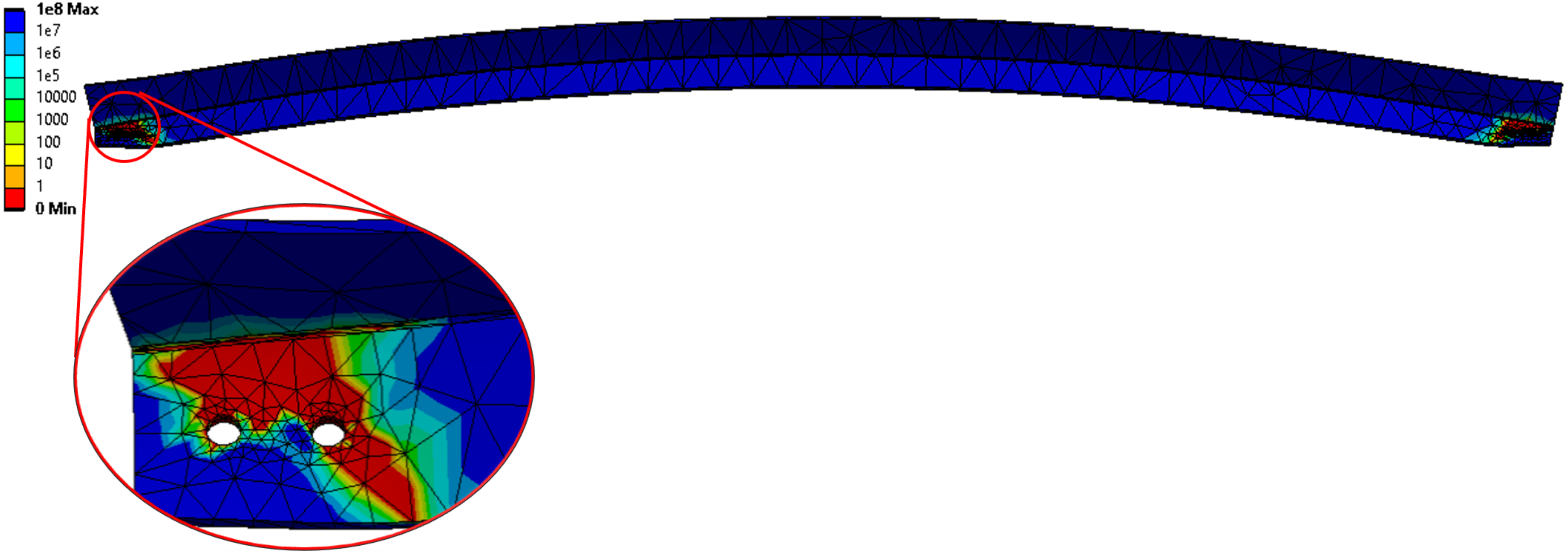
Max Temp = 219.76°F   Min Temp = 217.99°F

Total Deformation [in]



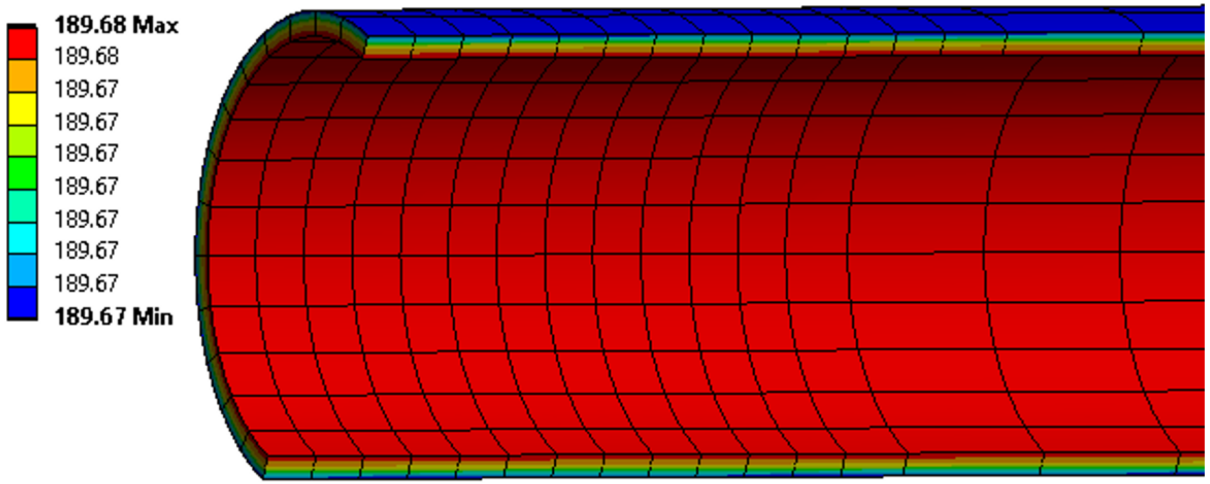
Max Deformation = 1.164 in   Min Deformation = 0.0

Results – Angle (UABC)



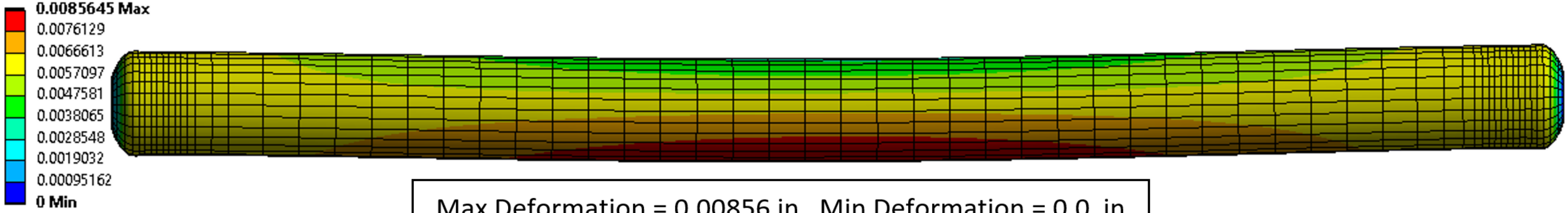
Results – Tube

Surface Temperature Distribution [°F]



Max Temp = 189.68°F   Min Temp = 189.67°F

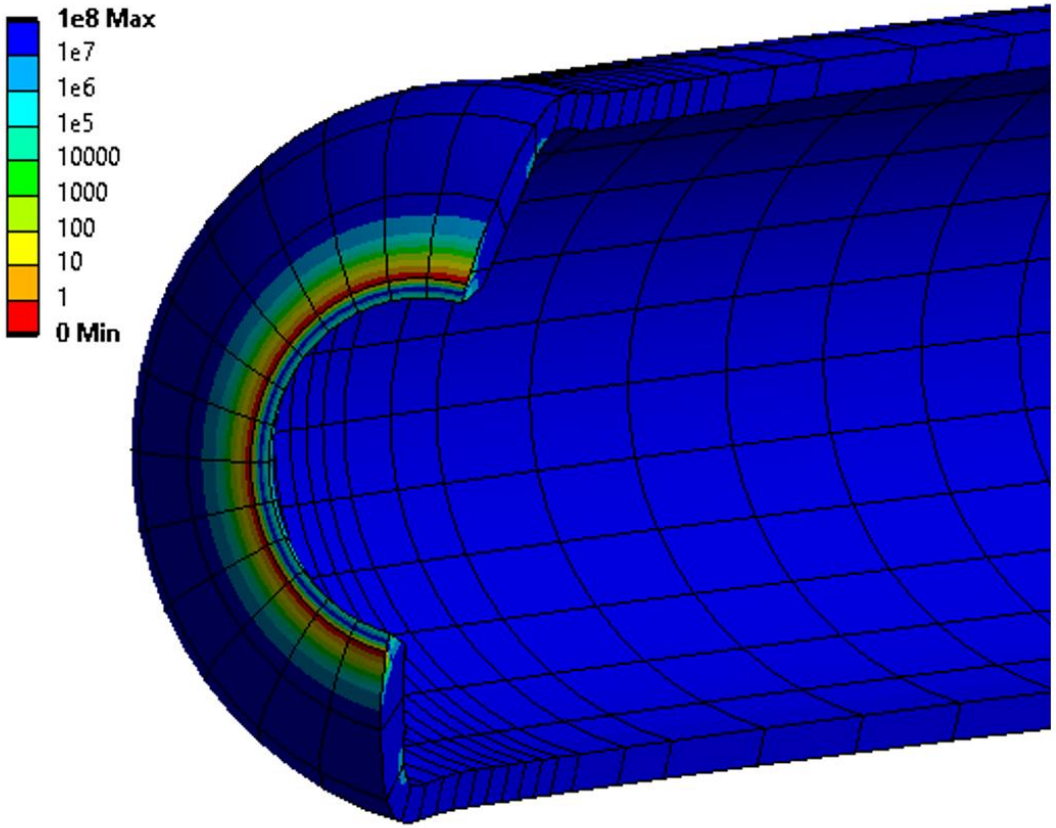
Total Deformation [in]



Max Deformation = 0.00856 in   Min Deformation = 0.0 in

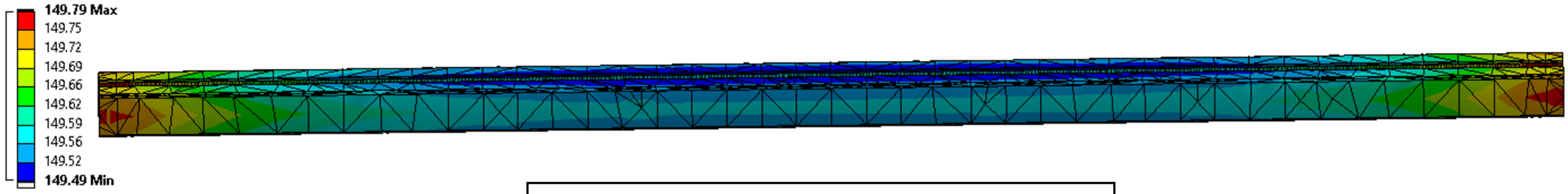
Results – Tube

Fatigue Life [# of Cycles Until Failure]



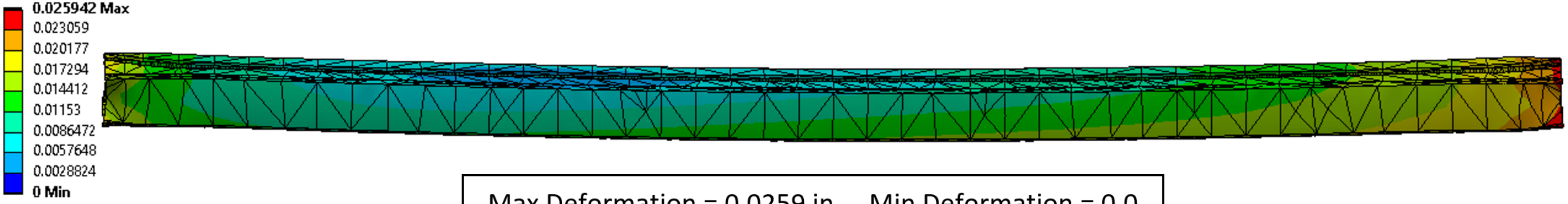
Results – Integral Web (IWCB)

Surface Temperature Distribution [°F]



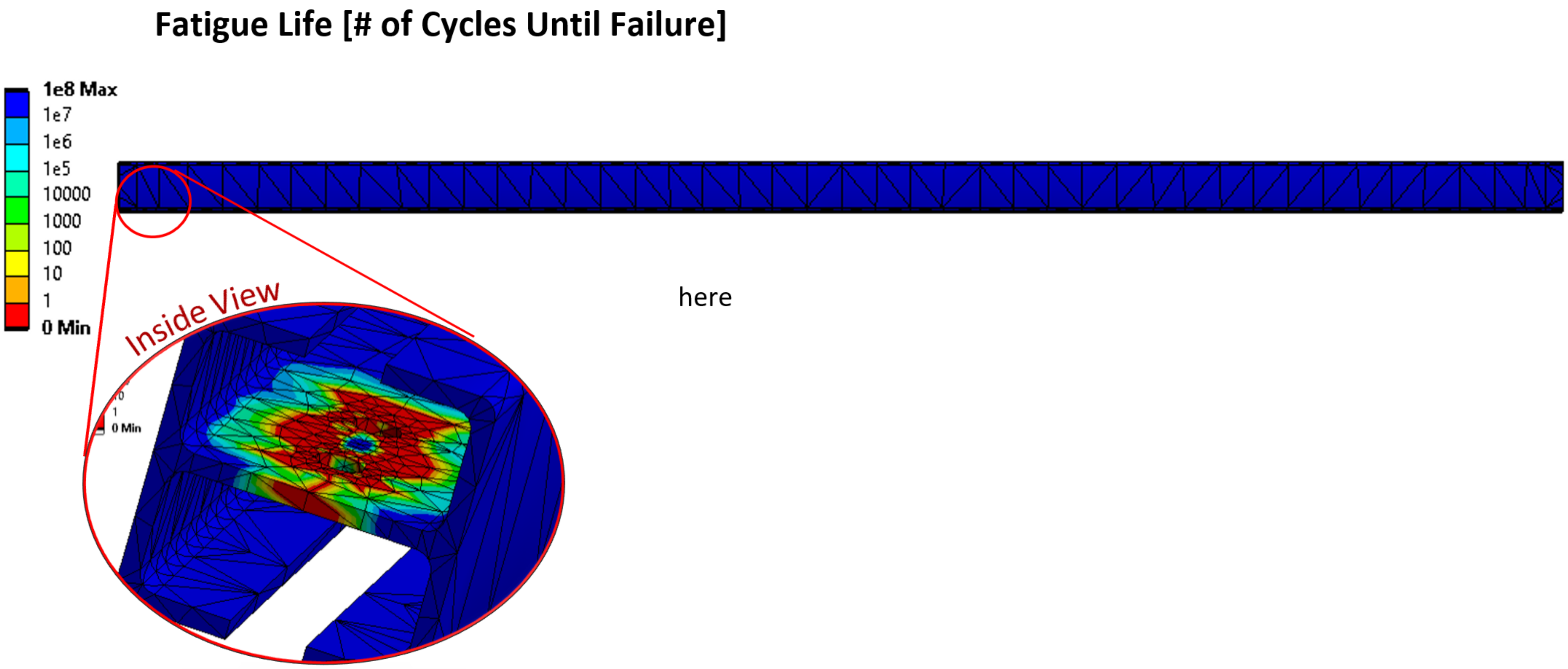
Max Temp = 149.79°F   Min Temp = 149.49°F

Total Deformation [in]



Max Deformation = 0.0259 in   Min Deformation = 0.0

Results – Integral Web (IWCB)



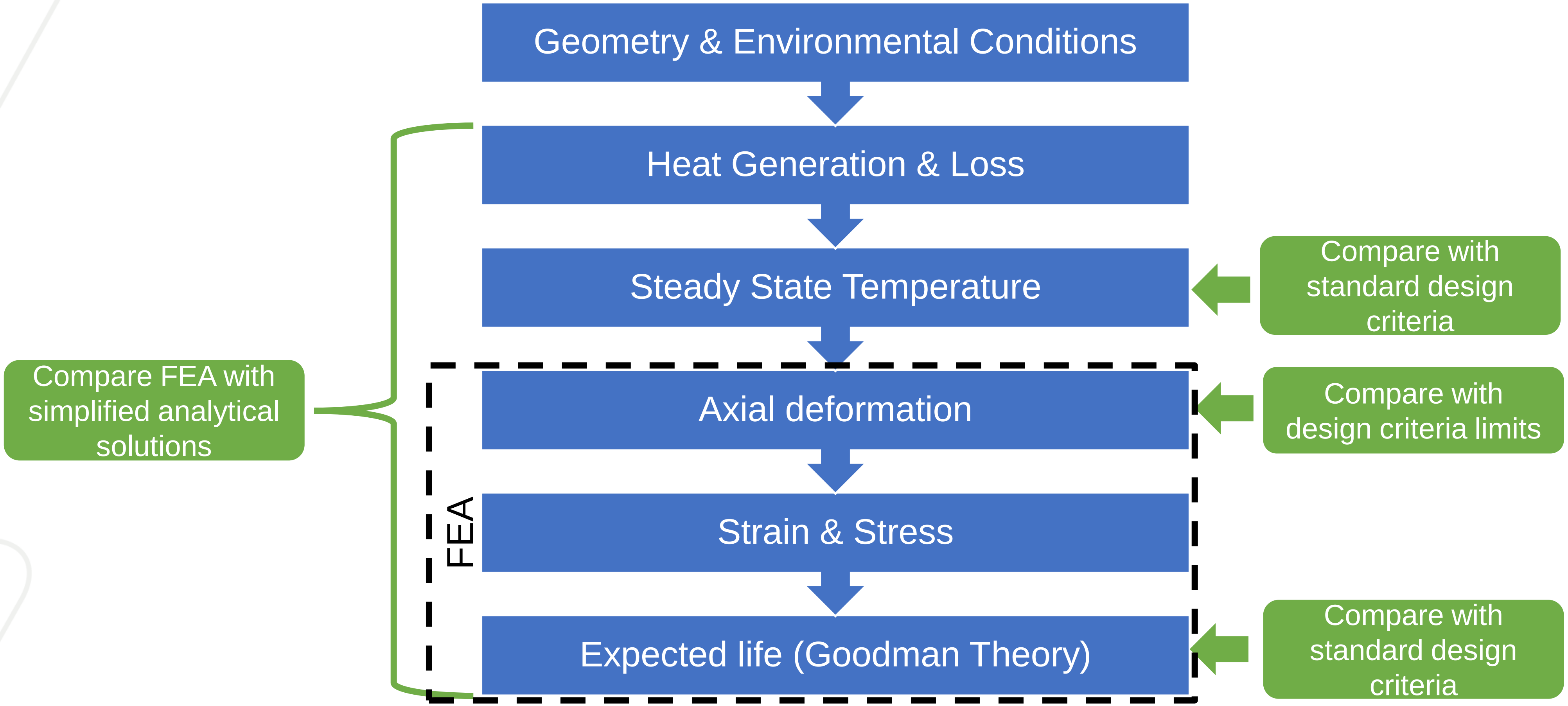
here

Discussion

- Table compares various values for different Busbars
- Clear trend of decrease in maximum temperature seen and as the shape type is changed
  - Largely due to cross-sectional area differences
- Deformation is shape dependent
  - Angle bar highest
  - Tubing is lowest
- Fatigue life is considered infinite for all shapes except

Busbar	Maximum Temperature [°F]	Maximum Total Deformation [in]	Average Fatigue Life [Cycles]
Rectangular Bar	309.29	0.4966	1e7
Angle Bar	219.74	1.1645	1e8
Tubing	189.68	0.0085	1e8
Integral Web	149.79	0.0259	1e8

Validation



Georgia Tech

Validation

- Steady state temperature
  - Analytical solution calculated for simple cases of bar and tubing
  - Results closely match FEA

Busbar	Steady State Temperature	% Difference from FEA
⅜” x 4” Rectangular Bar	302.87 °F	-2.07%
4” NPS, Sch. 80 Tubing	195.94 °F	3.30%

- Comparison to industry standards
  - Bar was over-loaded and failed

Busbar	Southern Company Temperature Limit	FEA Steady State Temperature	Southern Company Ampacity Limits	FEA Applied Current
⅜” x 4” Rectangular Bar	245°F	309.29°F	1780 A	2000 A
4” x 4”x ¼” UABC		219.76°F	2564 A	
4” NPS, Sch. 80 Tubing		189.68°F	3248 A	
4” x 4”x ¼” IWCB		149.79°F	4041 A	

Additional Studies

- Simulating the busbars being mounted on slots that allow the busbars to move in the axial direction, along their length.
- Reduces the risk of injury during maintenance when the tension or compression in the busbars is released.
- Deformation in the axial direction is required to be less than 3/8” to avoid collision
- Boundary conditions were modified from original study.
  - Fixed support boundary conditions are still applied to one side of the busbar
  - The other side is restricted in all degrees of freedom expect movement along the axial direction.
- All other boundary and load conditions are held constant with respect to the previous study.

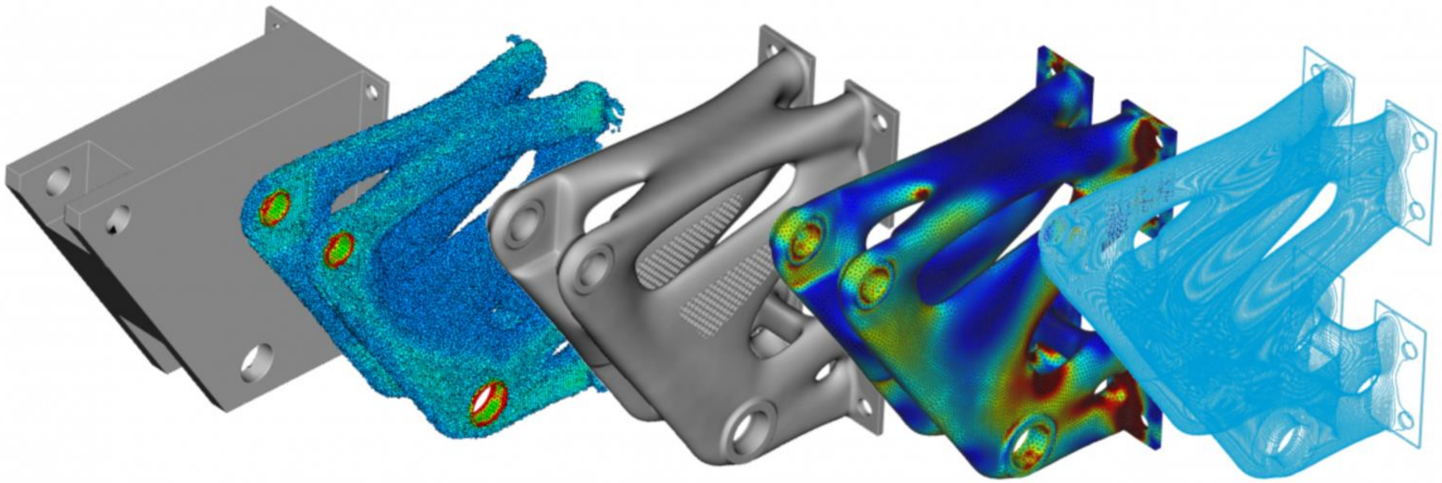
Results of Additional Studies

- Results show rectangular bar exceeds limit
- While angle bar has the lowest resolution
- These are result for 10-foot span
  - deformation is a function of span
- Thus, results can be used to infer deformation of the busbars relative to one another

Busbar	Deformation in Busbar Axial Direction [in]
Rectangular Bar	2.8535
Angle Bar	0.001134
Tubing	0.29803
Integral Web	0.1841

Possible Future Work

- Topology optimization to obtain shape that minimizes the temperature change
- While load conditions and boundary conditions are held constant.



Conclusions

- Validation of stresses needs to be performed
- Each bar demonstrated infinite life under these loading conditions
  - Deformations were key takeaways

Thank You

Ryan Grajewski, Grey Williams, & Sameer Zaheer
5/4/2022

Georgia Tech