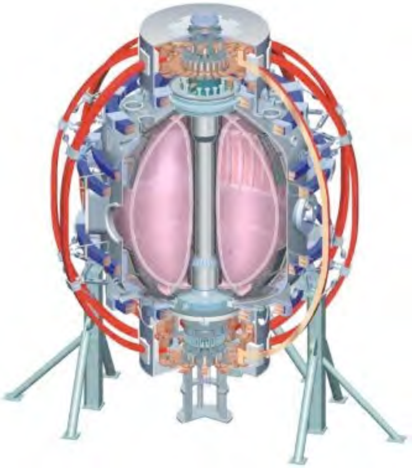
TF Flex Joint and TF Bundle Stub

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Tom Willard

NSTX Center Stack Upgrade Peer Review
LSB, B318
August 13, 2009



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
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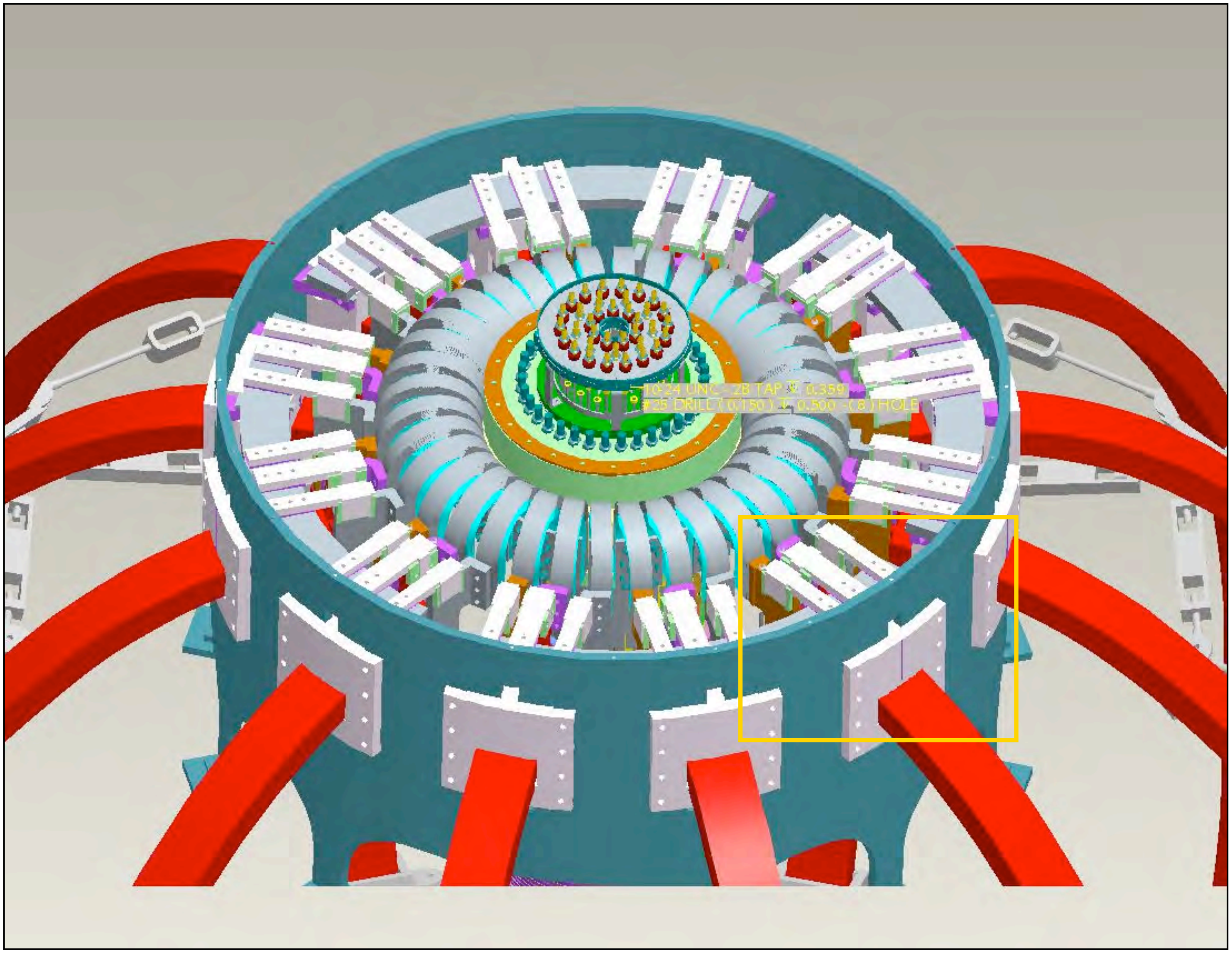
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Study Goals

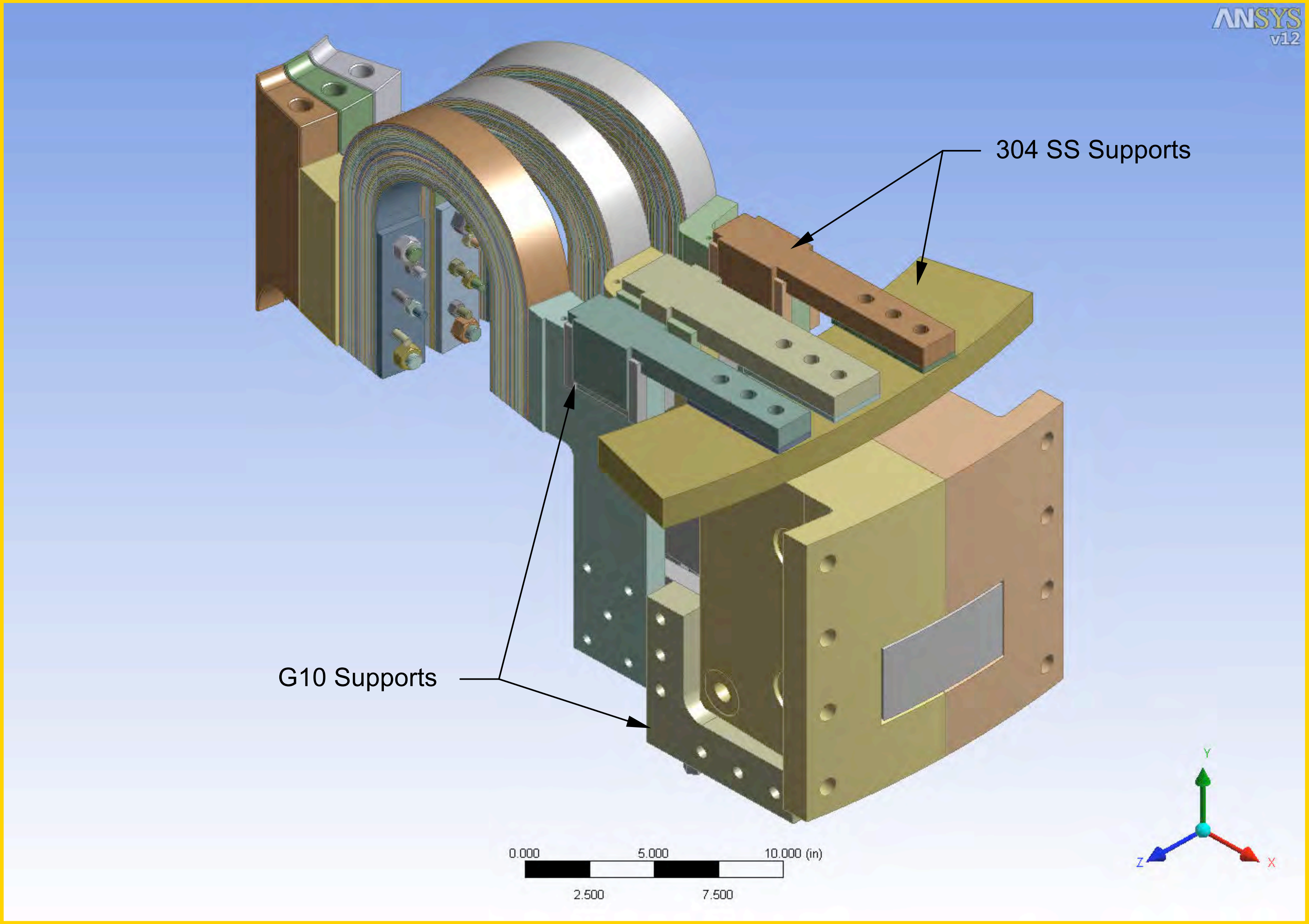
- Purpose:

  To determine if the baseline TF flex joint and bundle stub design are adequate to meet the requirements of the NSTX Structural Design Criteria, specifically, the fatigue requirements of Section I-4.2 for 3000 full power and 30,000 two-thirds full power pulses without failure.
  - Laminations
    - Stresses
    - Buckling
  - Joints
    - Thread shear stress
    - Contact pressure

NSTX Upper Umbrella Assembly Upgrade Design

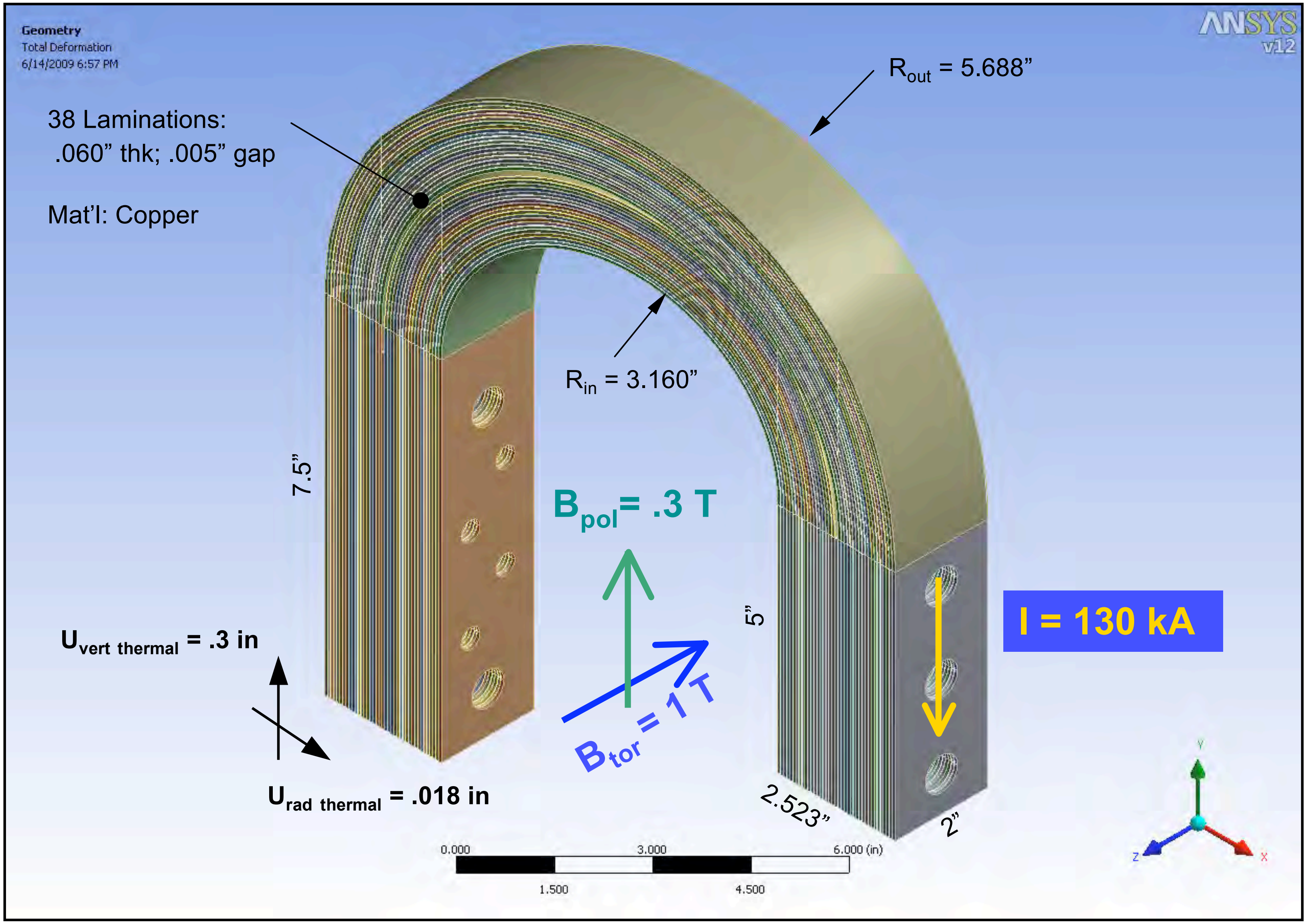


Single Segment 3-Strap Assembly with Supports: Version 3.0



Laminated Strap Assembly with Applied Fields and Current

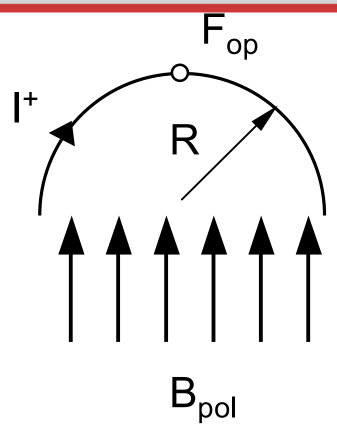
Version 3.0



Calculated Worst-Case EMAG Loads

(Assuming uniform current distribution)

Out-of-Plane Load (z-direction)

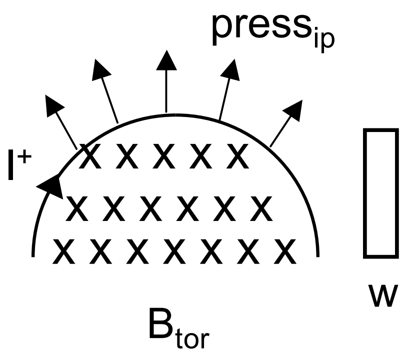


F_{op} = 2*I*B_{pol}*R

F_{op} = 2 x 130,000 A/ 38 x .3 T x 5.688/39.37 m

F_{op} = 296.4 N = 66.6 lbf [Outer lamination]

In-Plane Load (y-direction)



F_{ip}/ L = I*B_{tor}

F_{ip}/ L = 130,000 A/ 38 x 1 T [Outer lamination]

F_{ip}/ L = 3,421 N/ m x .2248 lbf/ N x 1 m/ 39.37 in

F_{ip}/ L = 19.53 lbf/ in

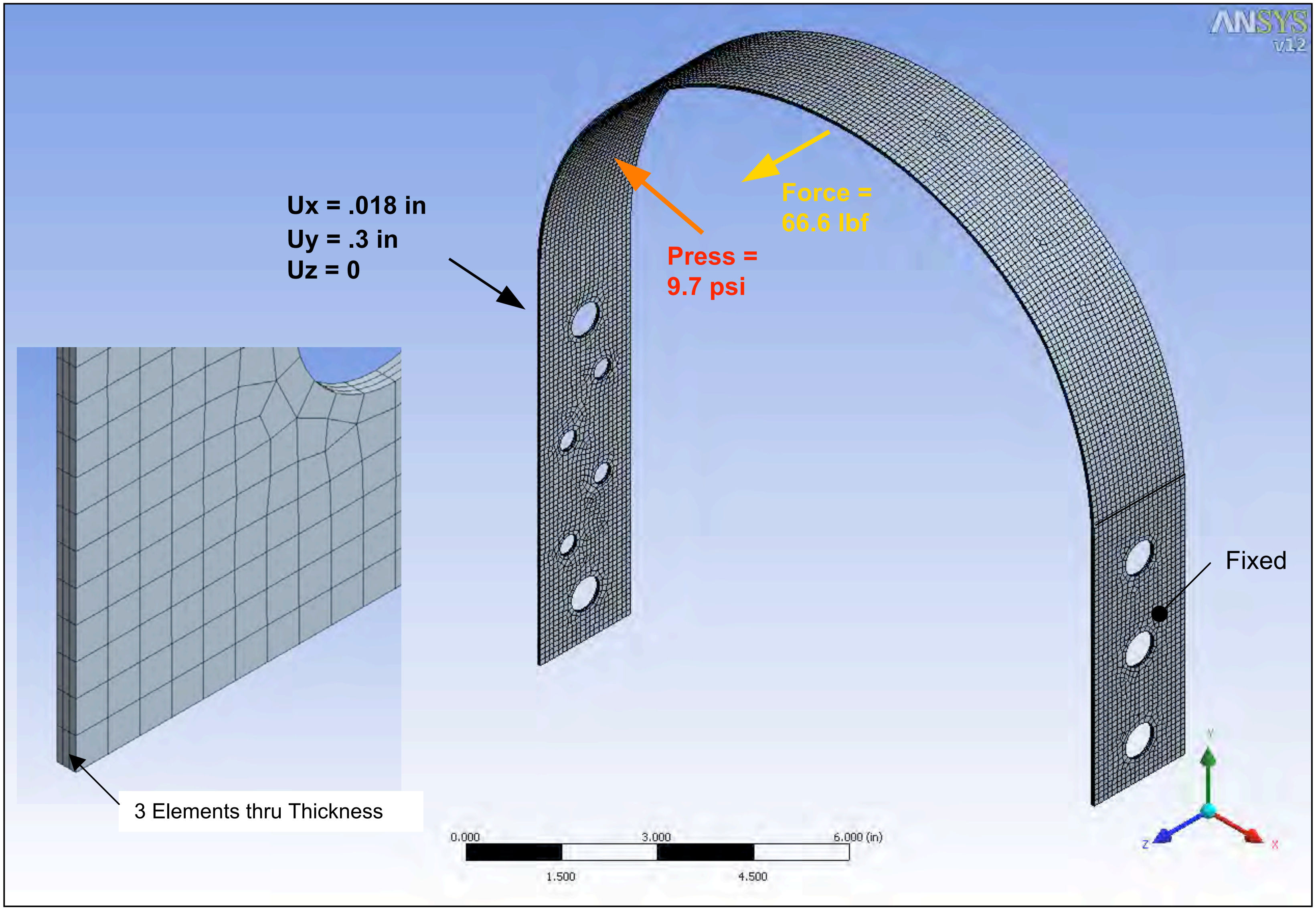
$press_{ip}$ = (F_{ip}/ L)/ w

$press_{ip}$ = 19.53 lbf/in / 2 in

$press_{ip}$ = 9.77 lbf/ in^2 (applied to inside cylindrical face)

Single Lamination FEA Model: Mesh and Boundary Conditions

(Outer-most lamination)



Ux = .018 in
Uy = .3 in
Uz = 0

Force = 66.6 lbf

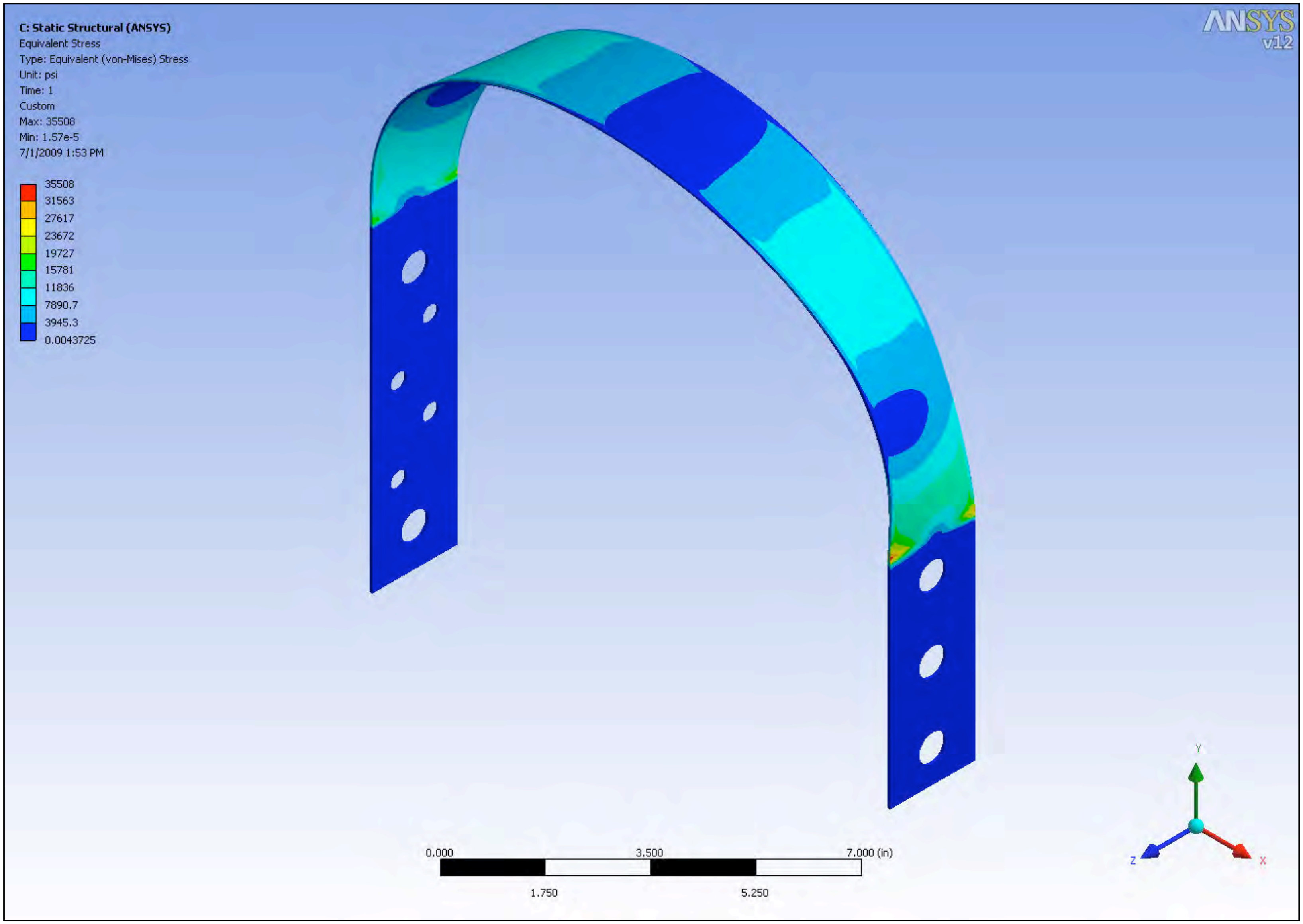
Press = 9.7 psi

Fixed

3 Elements thru Thickness

Single Lamination Linear Results: von Mises Stress

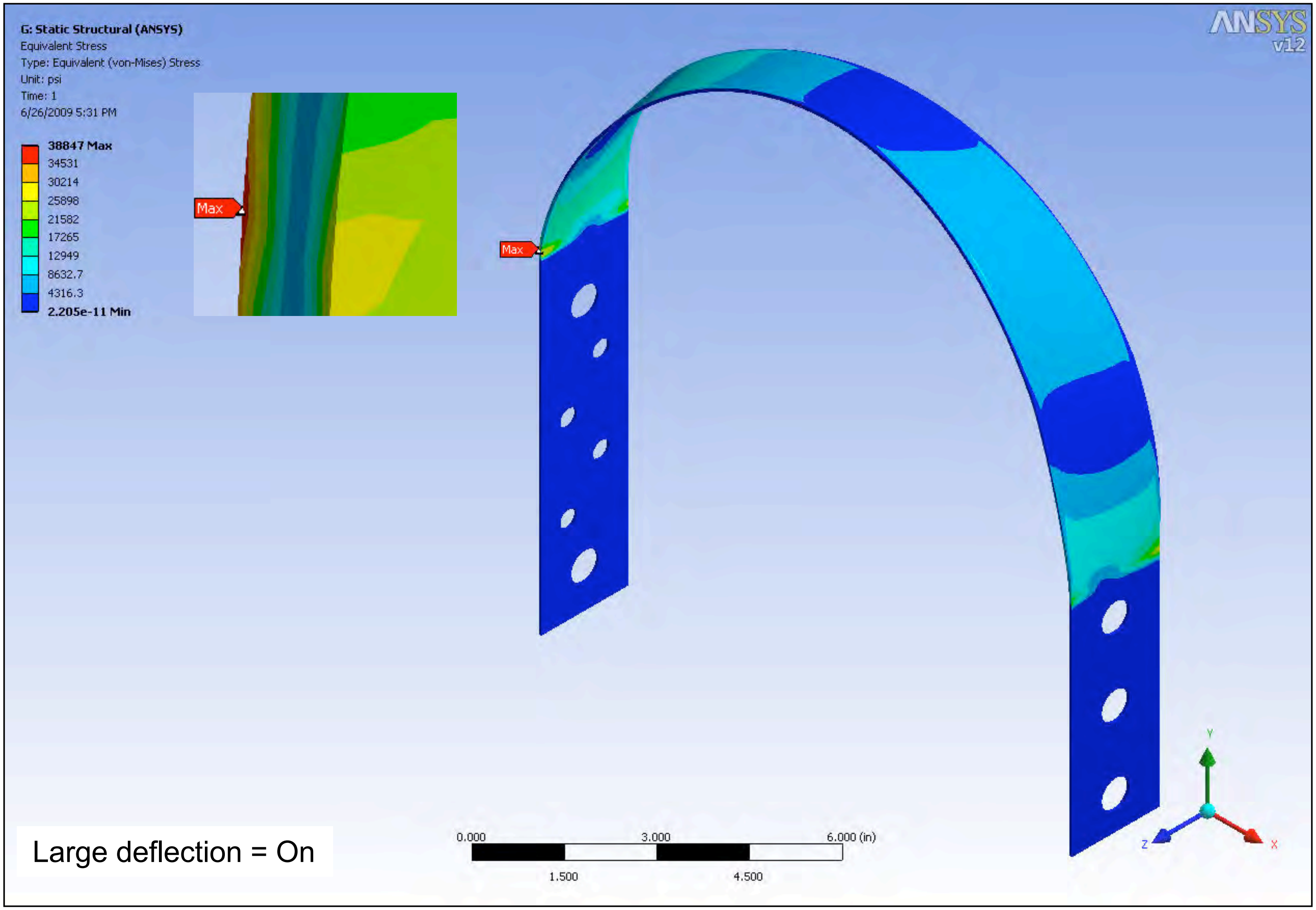
(Loads: Combined Thermal Displacements, Emag Press. (In Plane) and Forces (OOP))



C: Static Structural (ANSYS)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 35508
Min: 1.57e-5
7/1/2009 1:53 PM

Single Lamination Nonlinear Results: von Mises Stress

(Loads: Combined Thermal Displacements, Emag Press. (In Plane) and Forces (OOP))

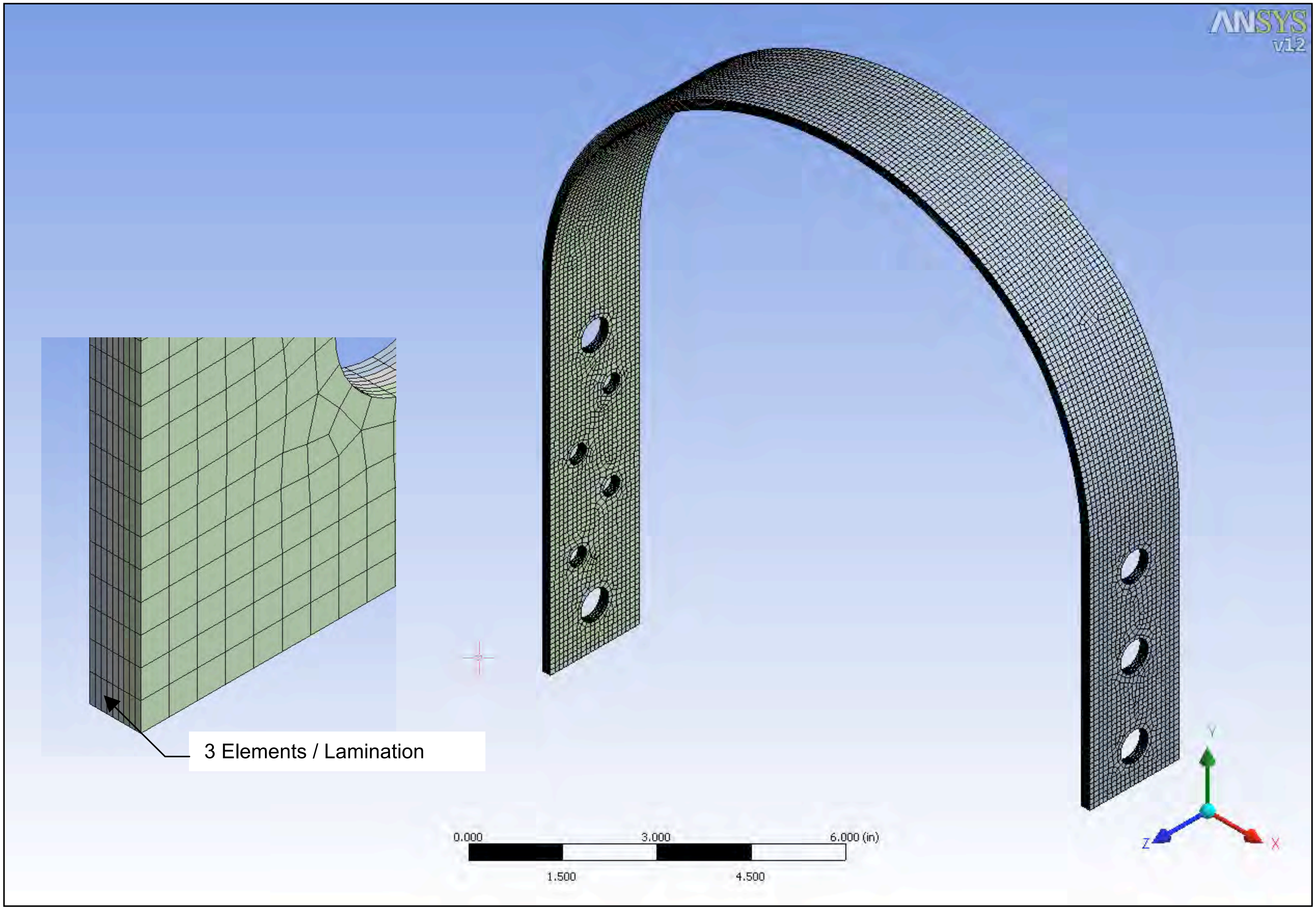


G: Static Structural (ANSYS)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
6/26/2009 5:31 PM

Large deflection = On

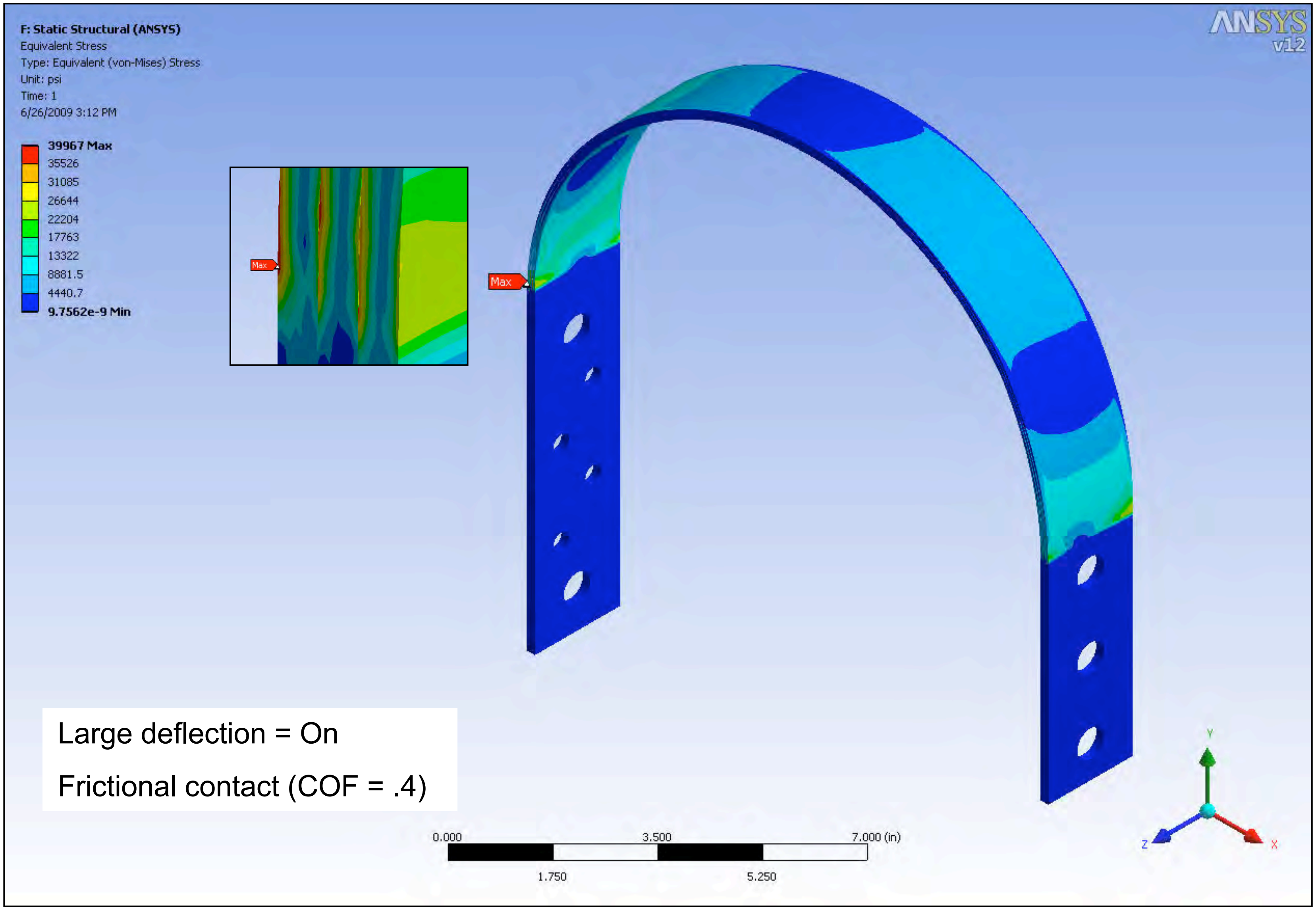
3 Lamination FEA Model: Mesh and Boundary Conditions

(Outer-most laminations)



3 Lamination Nonlinear Results: von Mises Stress

(Loads: Combined Thermal Displacements, Emag Press. (In Plane) and Forces (OOP))

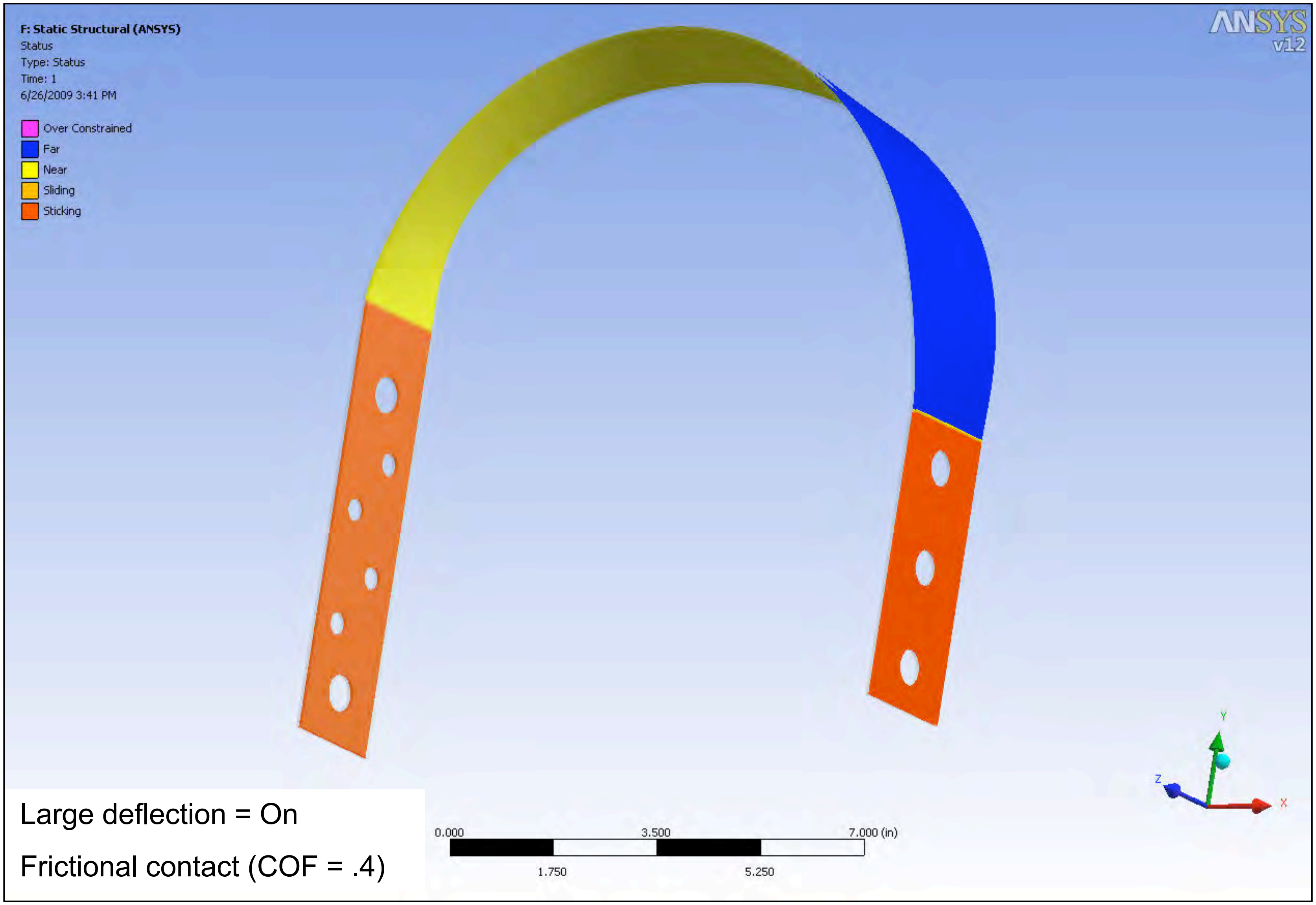


Large deflection = On

Frictional contact (COF = .4)

3 Lamination Nonlinear Results: Contact Status

(Loads: Combined Thermal Displacements, Emag Press. (In Plane) and Forces (OOP))

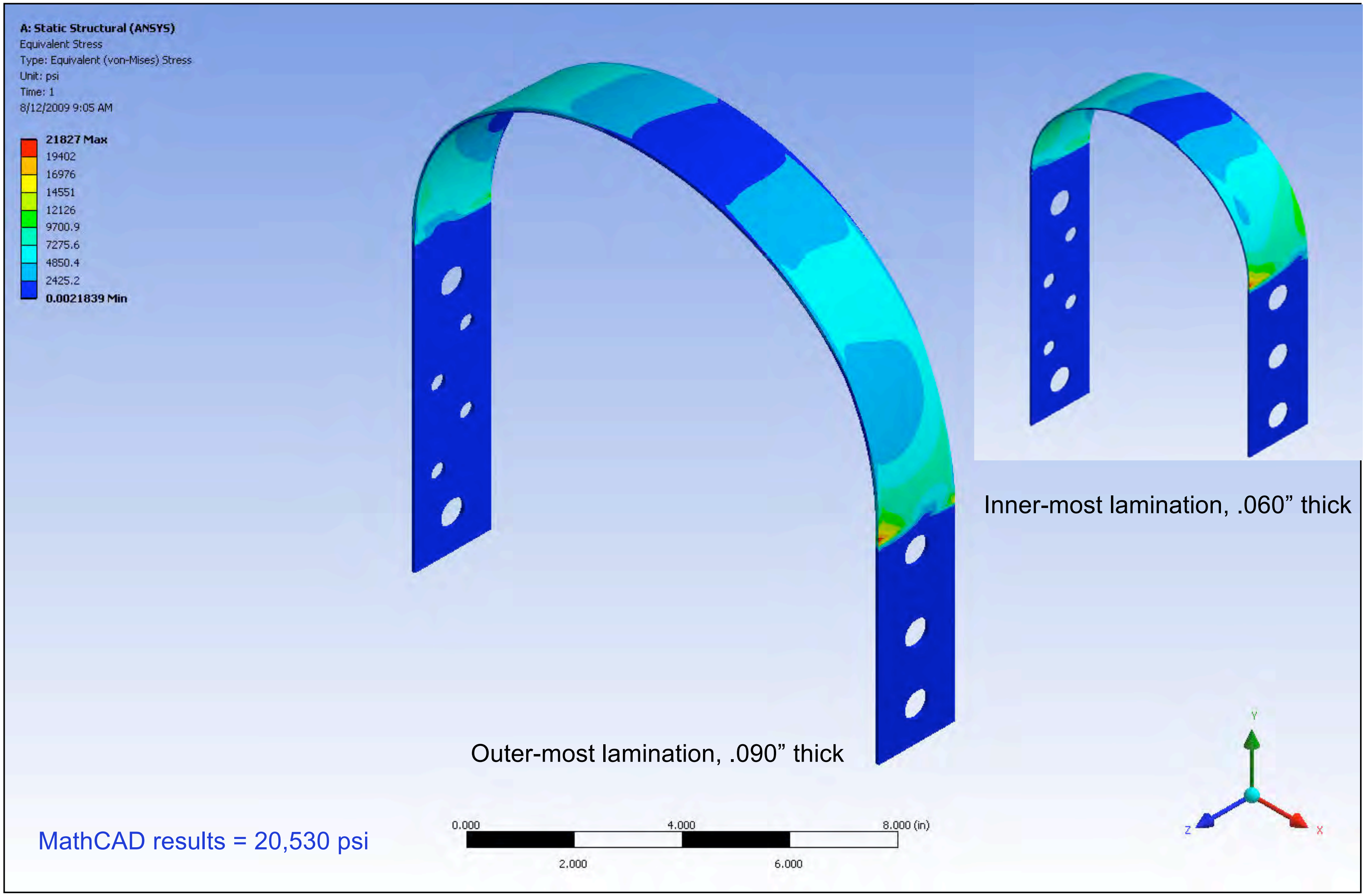


Large deflection = On

Frictional contact (COF = .4)

Optimized Laminations Linear Results: von Mises Stress

(Non-uniform current distribution; combined loads including torsional displacement)



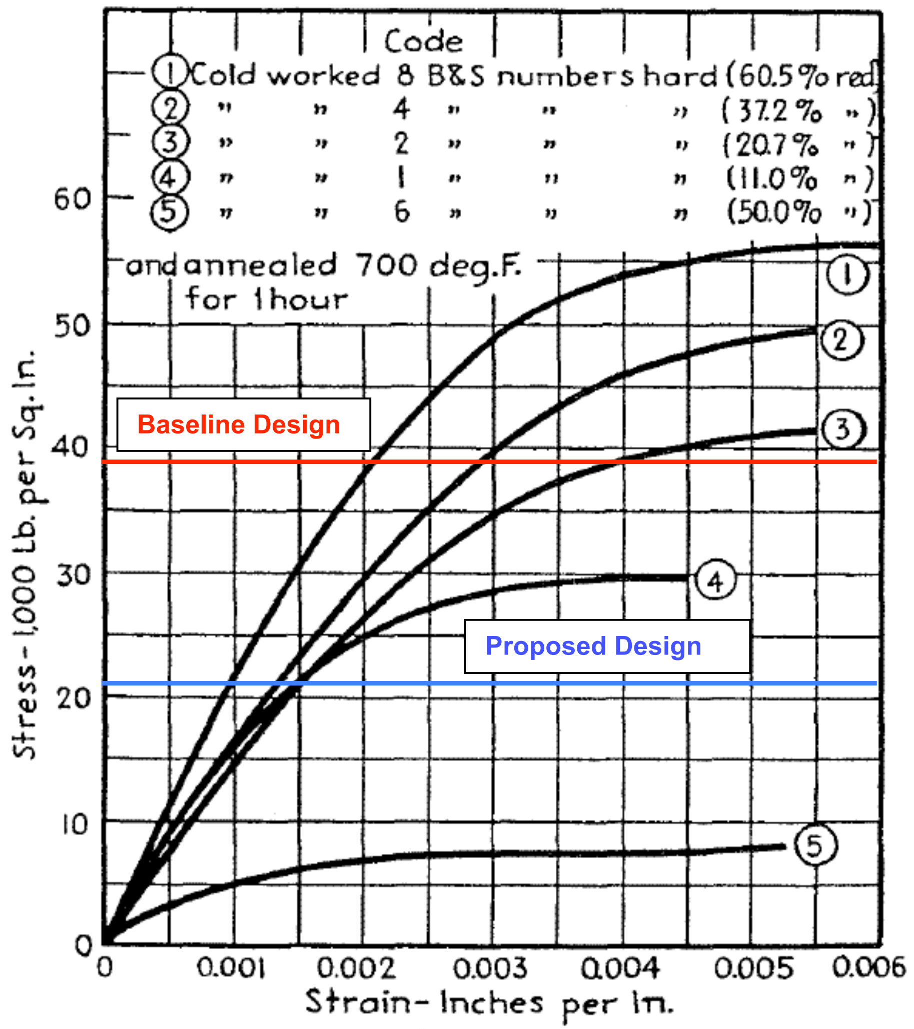
A: Static Structural (ANSYS)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
8/12/2009 9:05 AM

Inner-most lamination, .060” thick

Outer-most lamination, .090” thick

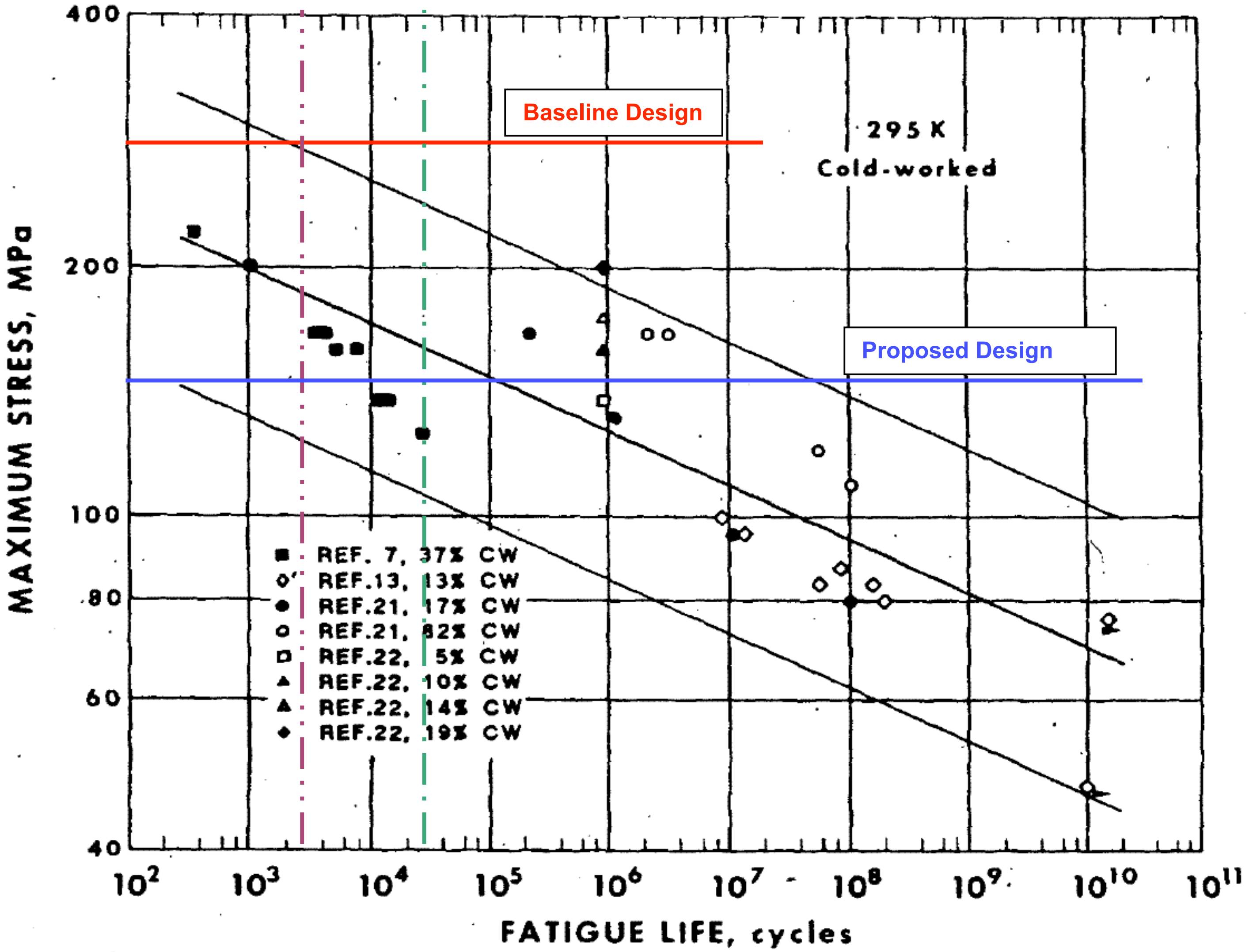
MathCAD results = 20,530 psi

C11000 Copper Stress-Strain Curves versus % Cold Work



ASM International, “Atlas of Stress-Strain Curves”, Electrolytic Tough-Pitch Copper (C11000)

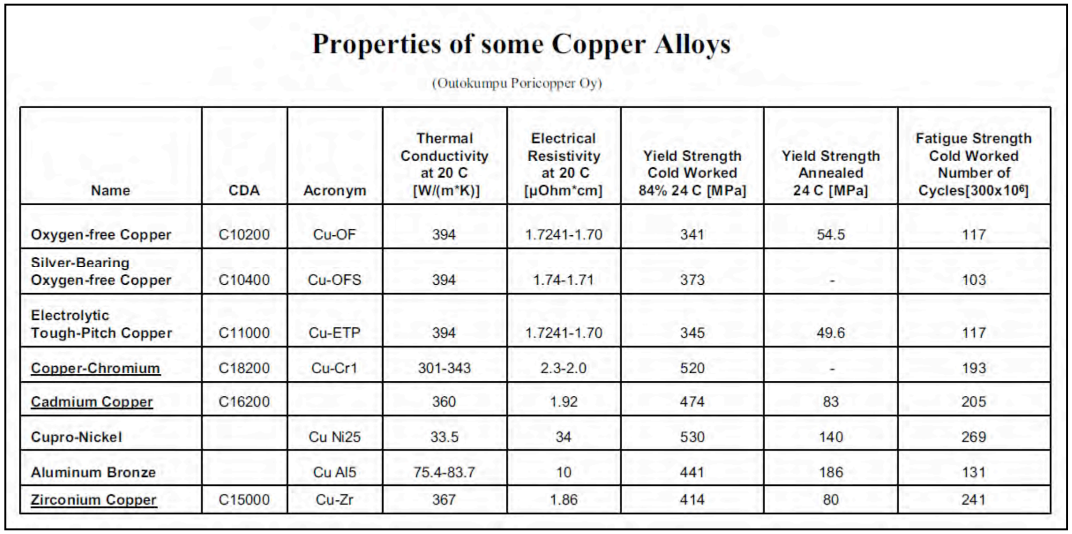
C110000 Copper Fatigue S-N Curves versus % Cold Work



NIST Monograph 177, "Properties of Copper and Copper Alloys at Cryogenic Temperatures"

Copper Alloy Material Properties

(Outokumpu Poricopper Oy)

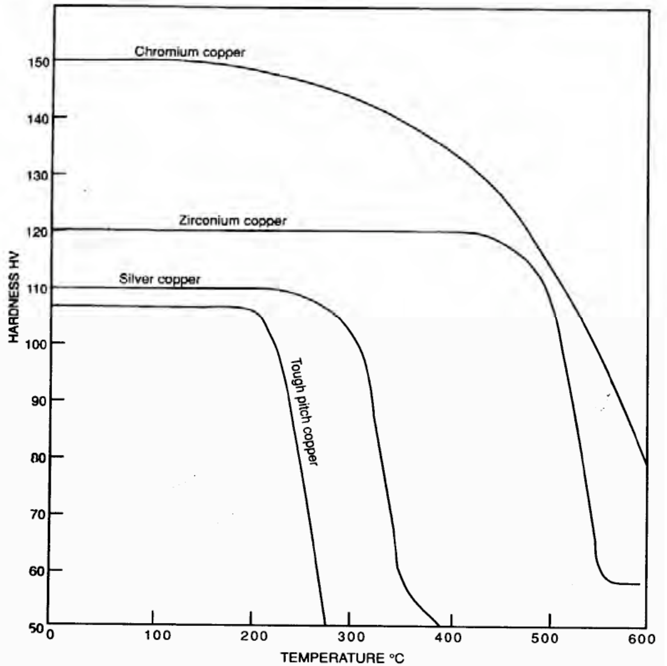


Properties of some Copper Alloys

(Outokumpu Poricopper Oy)

Name	CDA	Acronym	Thermal Conductivity at 20 C [W/(m*K)]	Electrical Resistivity at 20 C [µOhm*cm]	Yield Strength Cold Worked 84% 24 C [MPa]	Yield Strength Annealed 24 C [MPa]	Fatigue Strength Cold Worked Number of Cycles[300x10^6]
Oxygen-free Copper	C10200	Cu-OF	394	1.7241-1.70	341	54.5	117
Silver-Bearing Oxygen-free Copper	C10400	Cu-OFS	394	1.74-1.71	373	-	103
Electrolytic Tough-Pitch Copper	C11000	Cu-ETP	394	1.7241-1.70	345	49.6	117
Copper-Chromium	C18200	Cu-Cr1	301-343	2.3-2.0	520	-	193
Cadmium Copper	C16200		360	1.92	474	83	205
Cupro-Nickel		Cu Ni25	33.5	34	530	140	269
Aluminum Bronze		Cu Al5	75.4-83.7	10	441	186	131
Zirconium Copper	C15000	Cu-Zr	367	1.86	414	80	241

Effect of temperature on the softening of copper alloys



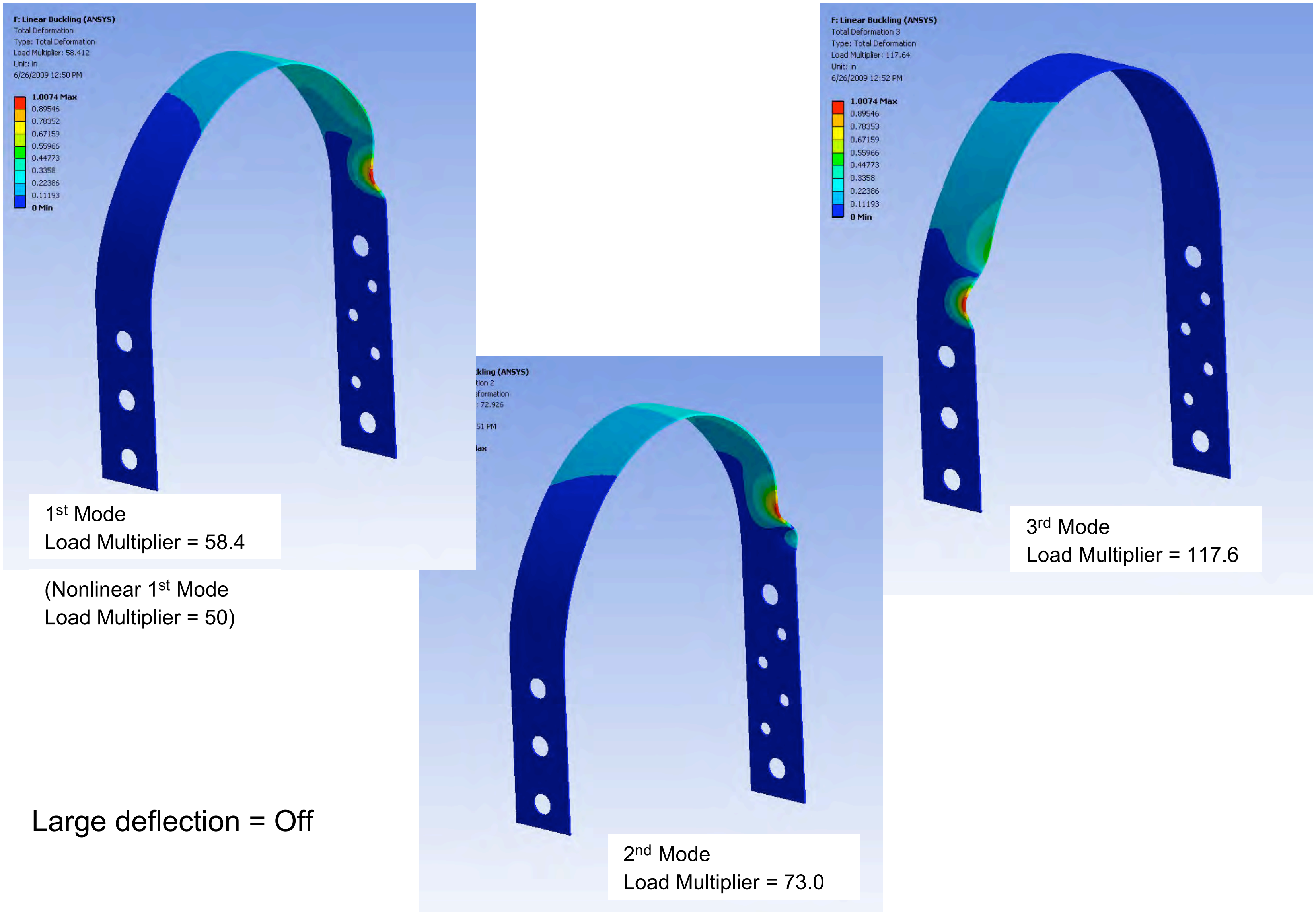
Hardness values as influenced by softening temperatures of typical tough pitch high conductivity copper, silver copper, chromium copper and zirconium copper

ANSYS and MathCAD Lamination Stress Analysis: Conclusions and Recommendations

- Good agreement between MathCAD and ANSYS results.
  - MathCAD model, corrected for non-uniform current distribution, was used to optimize lamination design.
- ~3/4 overall in-plane bending stiffness due to Inner Strap Assy.
- OOP torsional stress dominates in Outer Strap Assy.
- Thermal displacement bending dominates in Inner Strap Assy.
- Deflection force inversely proportional to radius.
- Maximum lamination stress of 38 kpsi exceeds the NSTX Structural Design Criteria fatigue limit requirement of 2x stress level or 20x number of cycles for 3000 full-power cycles and 30,000 half power cycles using C10700 copper.
- Proposed Design:
  - Outer Flex Strap Assembly: 12X .090” thick, 2.0” wide laminations
  - Inner Flex Strap Assembly: 19X .060” thick, 2.0” wide laminations
  - Mat’l: Fully-hardened C15000 Cu-Zr or better.

Single Lamination Pre-Stressed Linear Buckling Results

Load multiplier factor LMF applies to all Emag loads and thermal displacements



F: Linear Buckling (ANSYS)
Total Deformation
Type: Total Deformation
Load Multiplier: 58.412
Unit: in
6/26/2009 12:50 PM

1st Mode
Load Multiplier = 58.4

(Nonlinear 1st Mode
Load Multiplier = 50)

ckling (ANSYS)
tion 2
eformation
: 72.926
51 PM

2nd Mode
Load Multiplier = 73.0

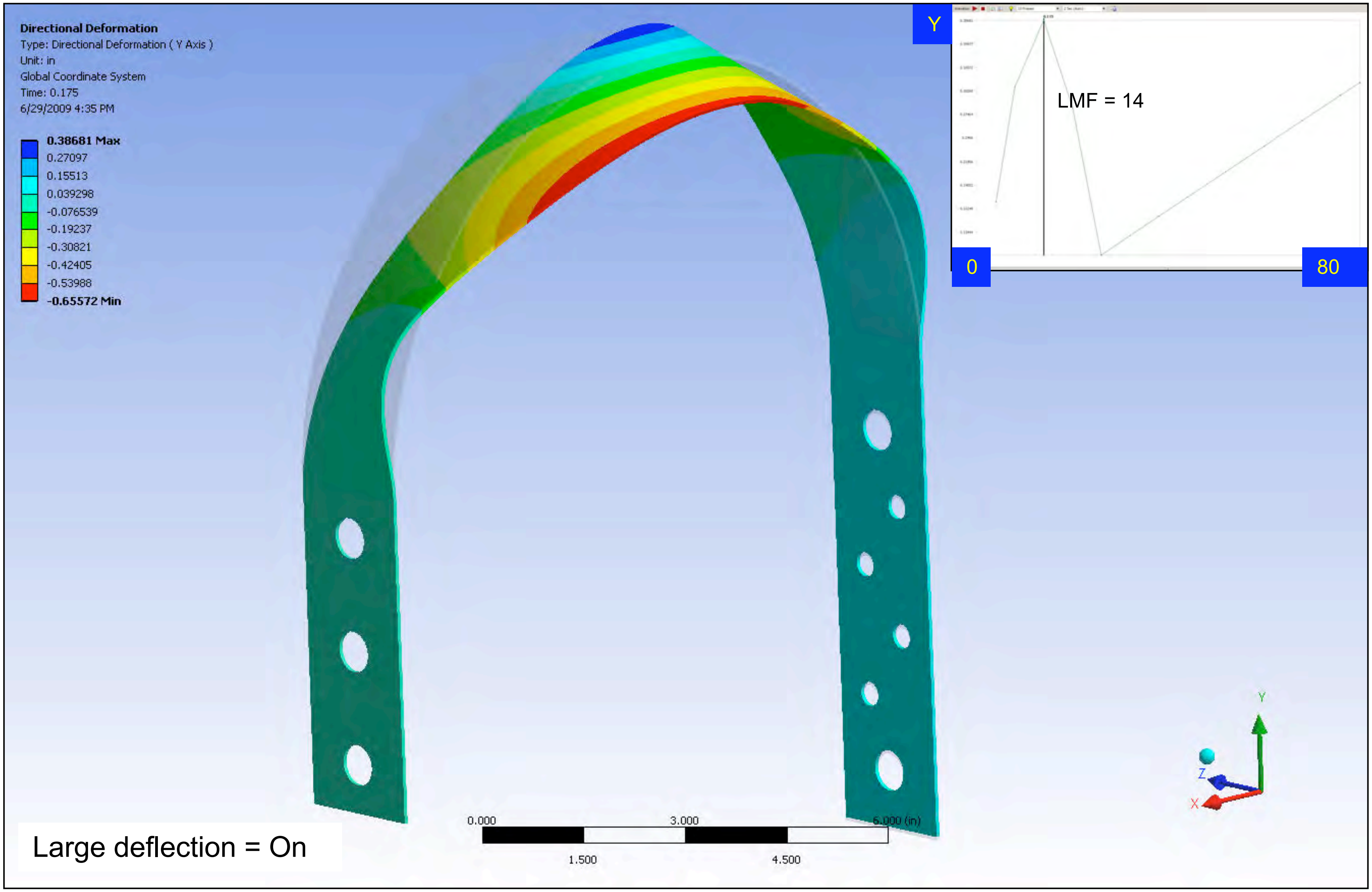
F: Linear Buckling (ANSYS)
Total Deformation 3
Type: Total Deformation
Load Multiplier: 117.64
Unit: in
6/26/2009 12:52 PM

3rd Mode
Load Multiplier = 117.6

Large deflection = Off

Single Lamination Nonlinear Buckling: Y-Deformation at Onset (1)

Load multiplier factor LMF applies only to Out-of-Plane Emag load



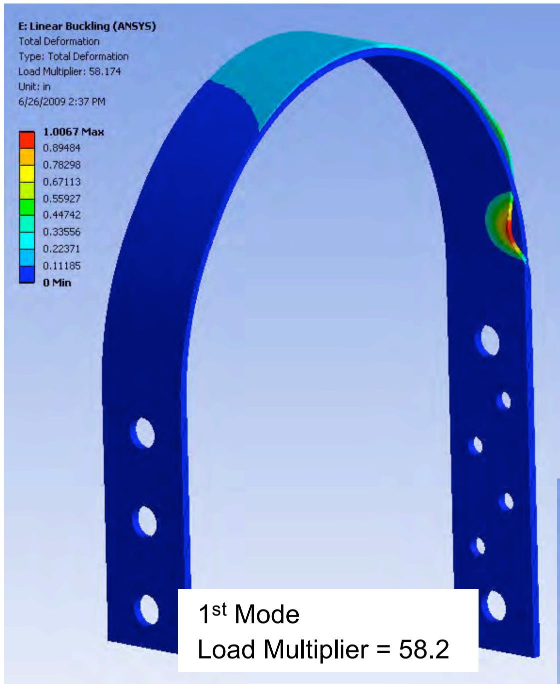
Directional Deformation
Type: Directional Deformation (Y Axis)
Unit: in
Global Coordinate System
Time: 0.175
6/29/2009 4:35 PM

LMF = 14

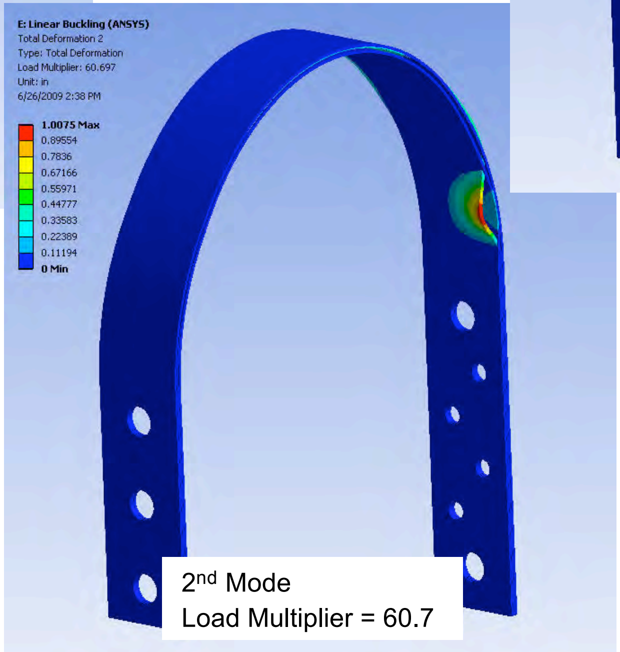
Large deflection = On

3 Lamination Results: Linear Buckling Mode Multiplier

Load Multiplier factor LMF applies to all Emag loads and thermal displacements



1st Mode
Load Multiplier = 58.2



2nd Mode
Load Multiplier = 60.7

3rd Mode
Load Multiplier = 61.8

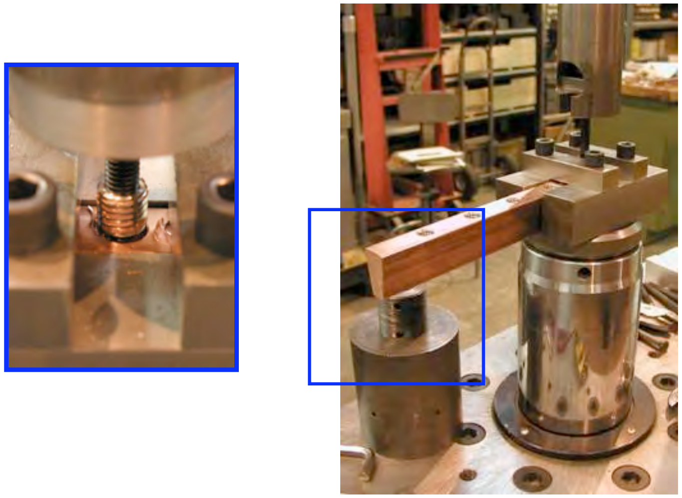
Large deflection = Off

Frictional contact (COF = .4)

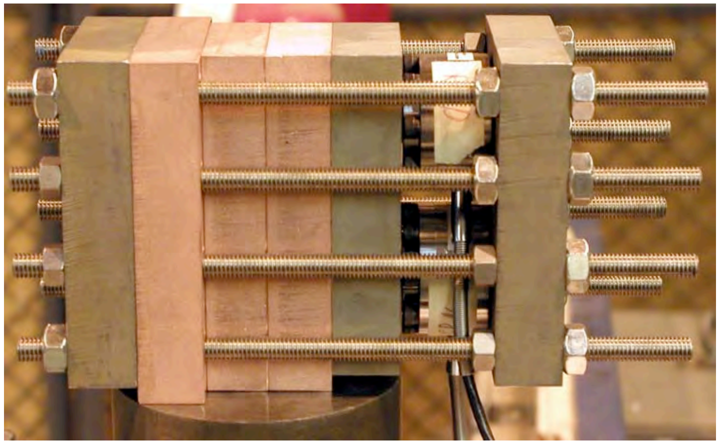
Buckling Analysis Conclusions

- Buckling due mostly to out-of-plane load. In-plane load (pressure outward) reduces buckling; thermal displacements slightly increase buckling.
- Good agreement between linear and nonlinear buckling results with load multiplier factor applied to both Emag loads and to thermal displacements.
- Load multiplier factor over 14 for nonlinear analysis with constant in-plane load and increasing out-of-plane load (conservative) exceeds nonlinear buckling factor of 2 specified in NSTX Structural Design Critieria.

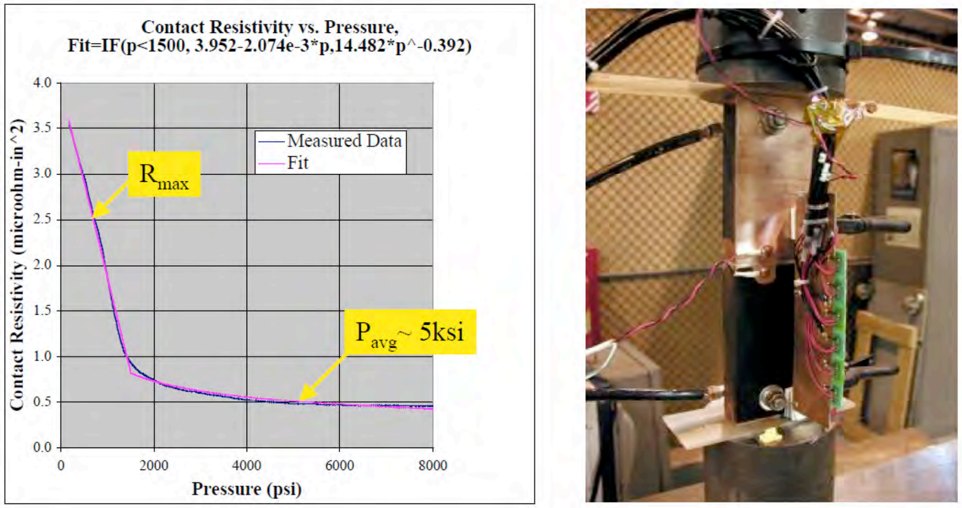
Previous Joint Design: Development Tests



Cyclic Thread Pull-out Test



Coefficient of Friction Test



Contact Resistivity vs Pressure Test

Previous Joint Design: Tap-Lok Threaded Insert Design

- Tap-Lok 3/8-16 medium-length insert used.
  - OD = .562”, length = .562”
- Loading:
  - The stud preload of 5,000 lbf results in an average shear stress of 10,069 psi in the copper threads based on Tap-Lok effective shear area = .497 in^2.
  - Thermal + Mechanical loading adds a cyclic load of ~1,800 psi
- Material: C10700 Silver Bearing Copper , Hard Drawn (50% Cold Worked).
  - Per the inspection certification, the Cu tensile strength = 38 kpsi and yield strength = 36 kpsi.
- Values of 34 kpsi used for yield to account for observation of slight degradation in hardness after thermal cycling.

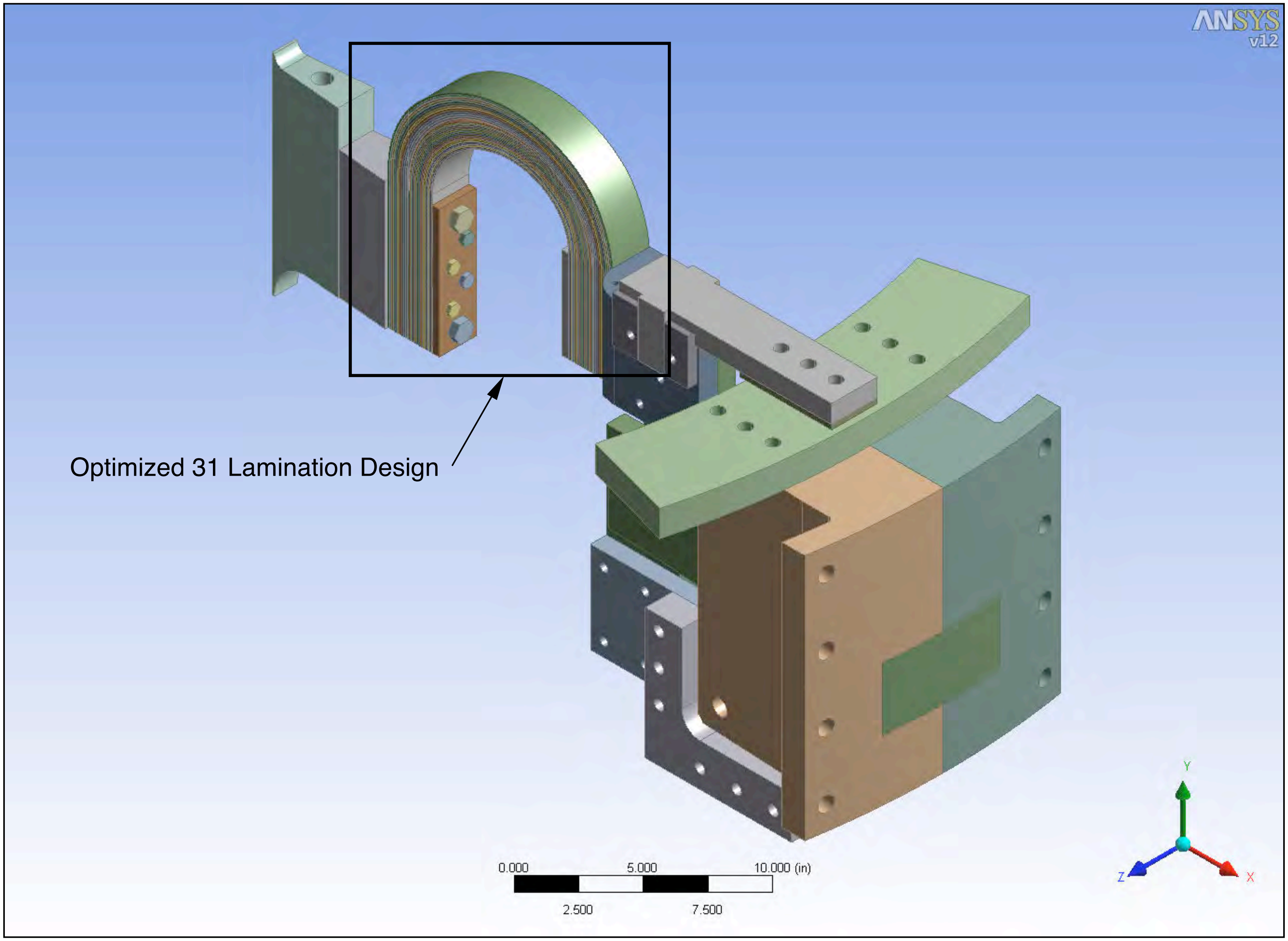
Previous Joint Design: Tap-Lok Cyclic Pull Tests

- Samples heated to 100 C during cycling.
- Six medium-length insert test pieces were cycled from 5,000 to 6,000 lbf for 50,000 cycles or greater.
  - Test levels reflect the 1,000 cycle thermal loading case.
  - Cycled with 1 Hz Sine Wave.
  - No failures during cycling.
- Two samples were cycled at 5,000 to 7,360 lbf to test at the 2x stress at design life condition.
  - No failures during cycling.
- After cycling, static pull tests determined if pull out strength had degraded.
  - No degradation in pull strength after cycling.

Previous Joint Design: Leverage Successful Experience

- Flag Material: C10700 H002, Silver Bearing Copper, Half Hard or better.
  - Keep copper average thread shear stress below 10,069 psi to reduce need for retesting.
- Tap-lok inserts.
  - Use longest insert possible: insert allows load sharing between threads.
- Bolt Material: Inconel 718.
  - Pretension stress much less than .75 yield strength (copper thread shear stress dominates). Bolt should extend full length of insert.
- Use Belleville washers.
  - As Direct Tension Indicating (DTI) washers to monitor bolt pretension, to reduce cyclic stress amplitude, and to maintain bolt tension with thermal cycling and creep.
- Load bolts in tension only.
  - Separate shear load and compression load functions.
    - Rely on friction or separate feature to take shear load.
  - Prevent bending.
- Monitor joint electrical contact resistance.
  - Minimum average contact pressure in previous design = 3850 psi.

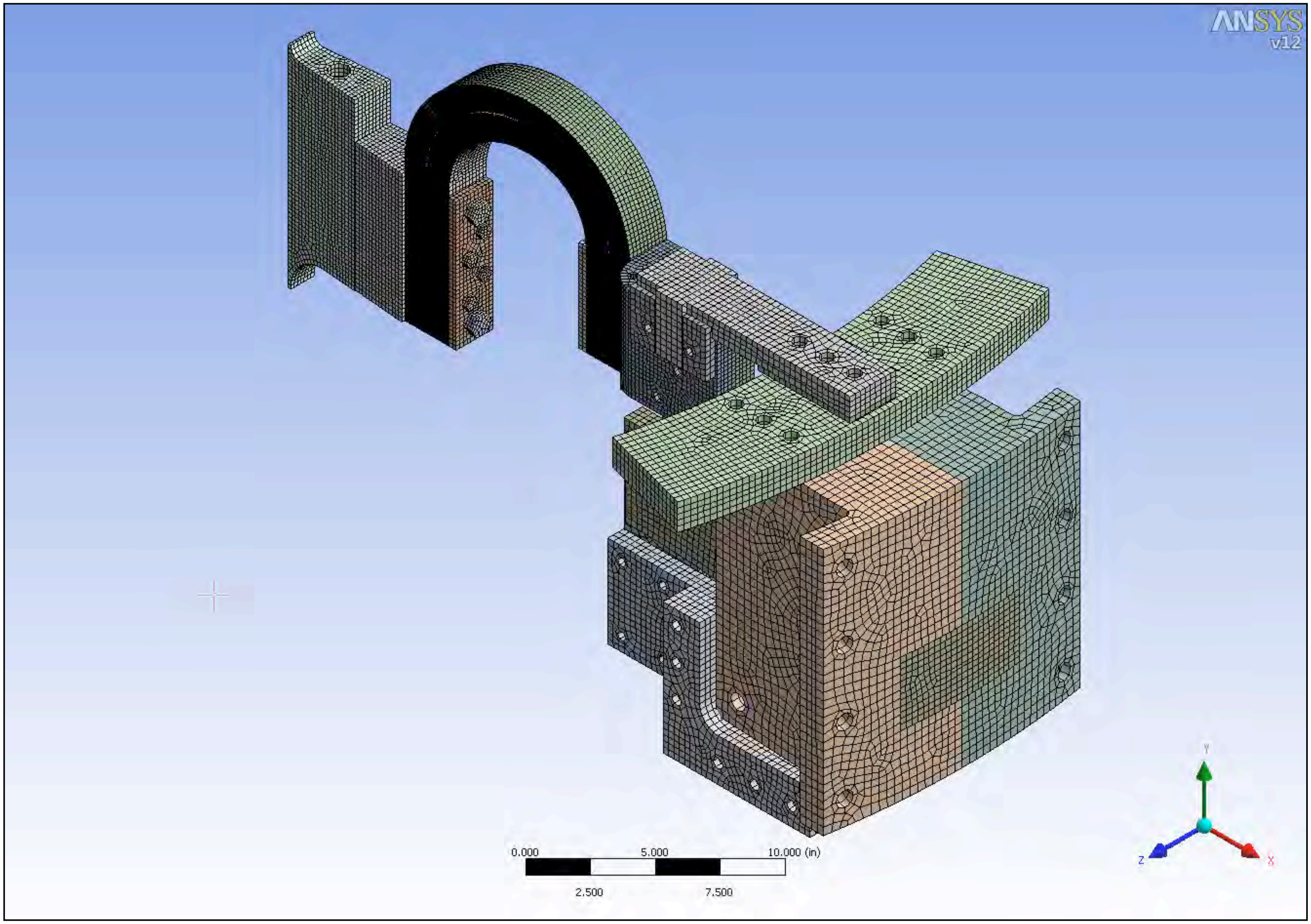
Single Segment with Center Strap Only: Version 3.1



Optimized 31 Lamination Design

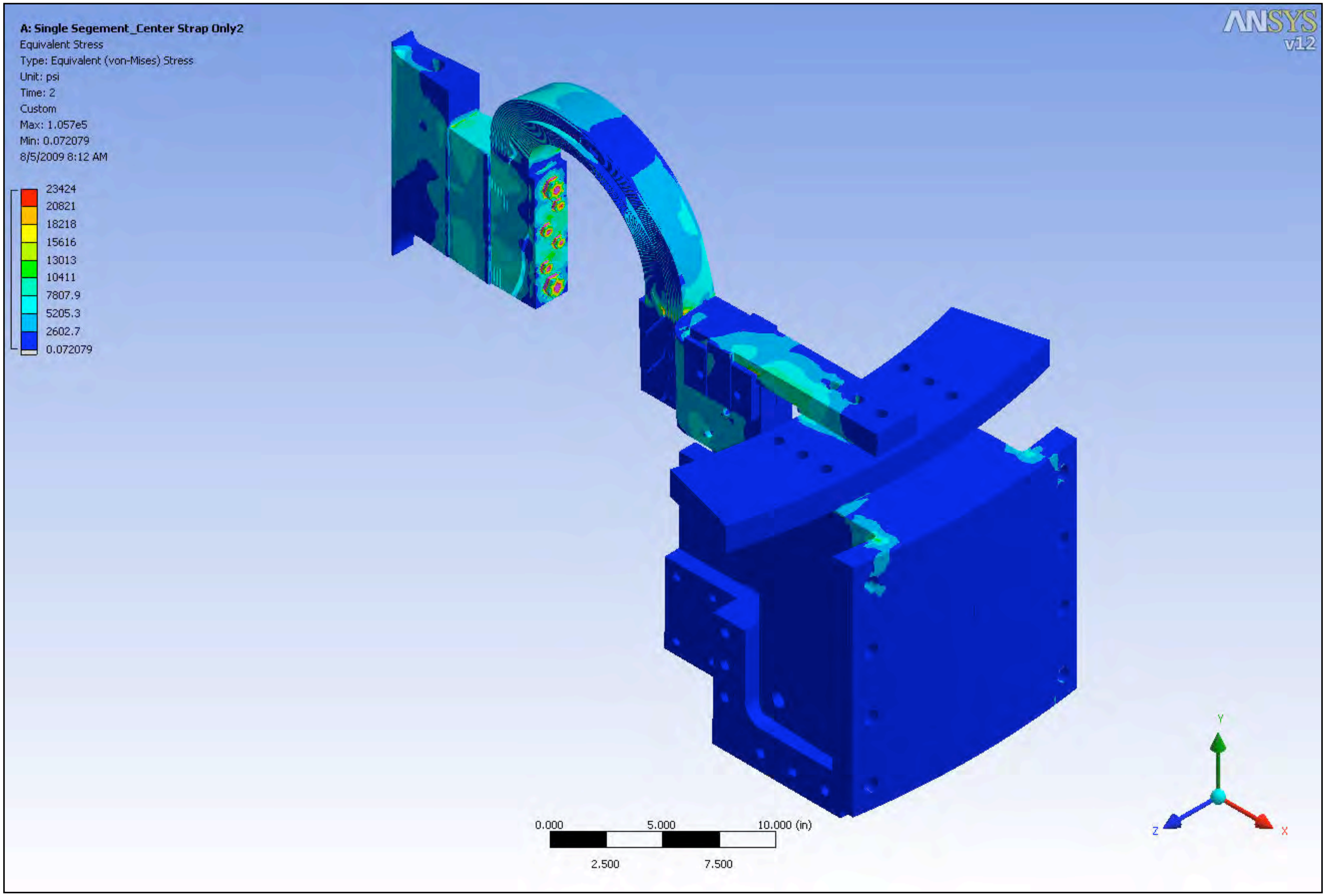
Single Segment Center Strap-Only FEA Model: Mesh

Version 3.1



Single Segment Center Strap-Only Results: von Mises Stress

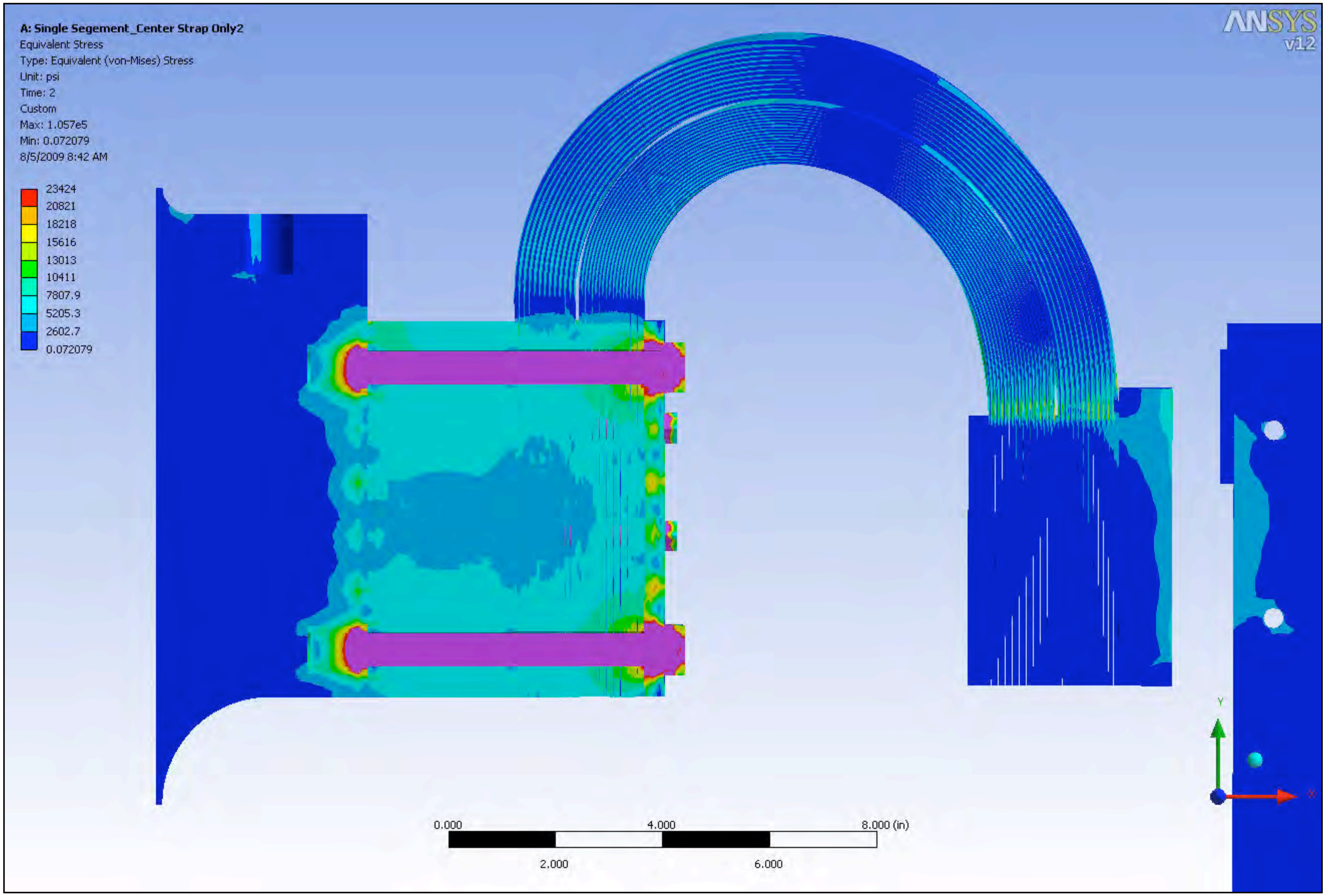
(Assumes non-uniform current distribution)



A: Single Segement_Center Strap Only2
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 2
Custom
Max: 1.057e5
Min: 0.072079
8/5/2009 8:12 AM

Single Segment Center Strap-Only Results: von Mises Stress (2)

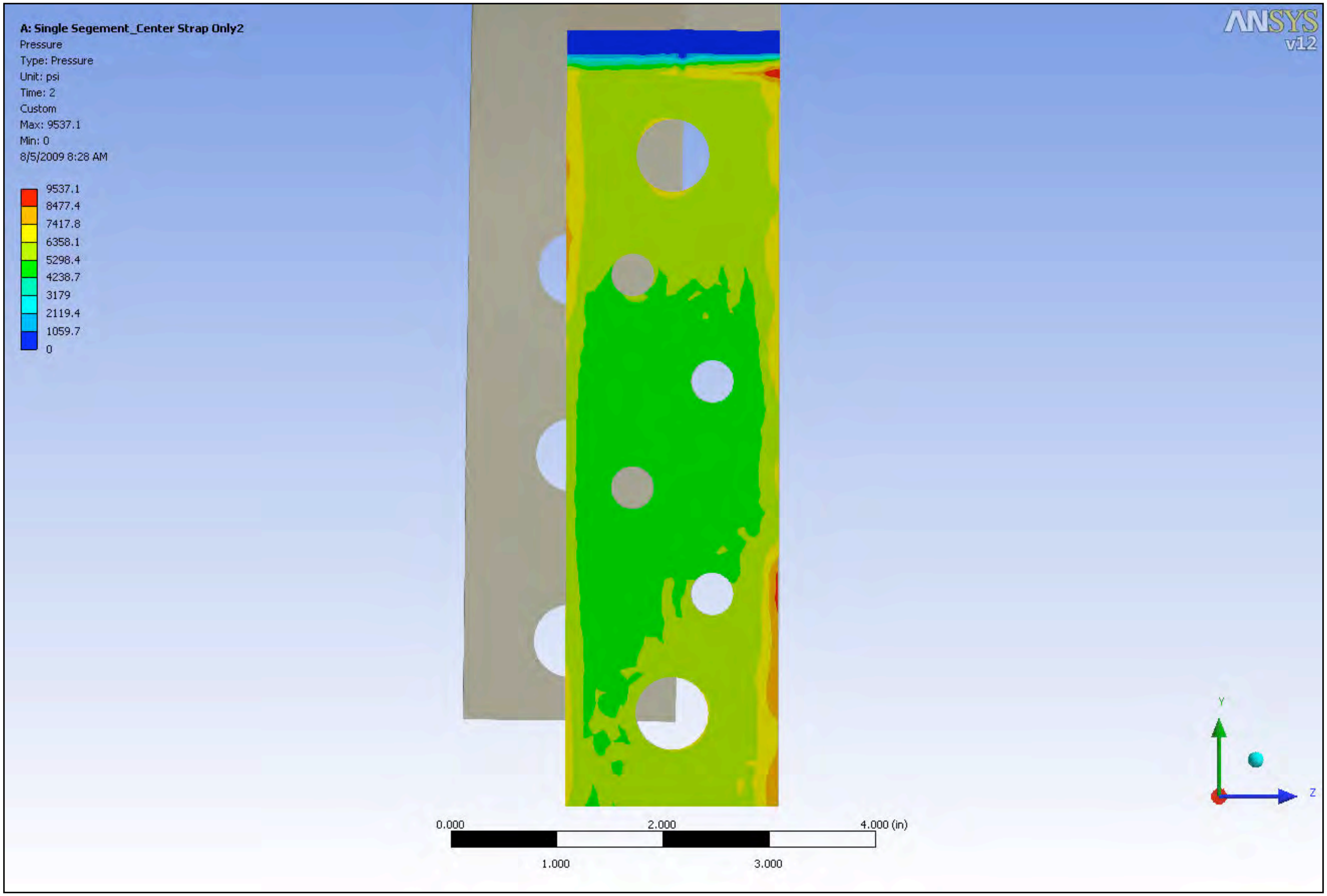
Version 3.1



A: Single Segement_Center Strap Only2
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 2
Custom
Max: 1.057e5
Min: 0.072079
8/5/2009 8:42 AM

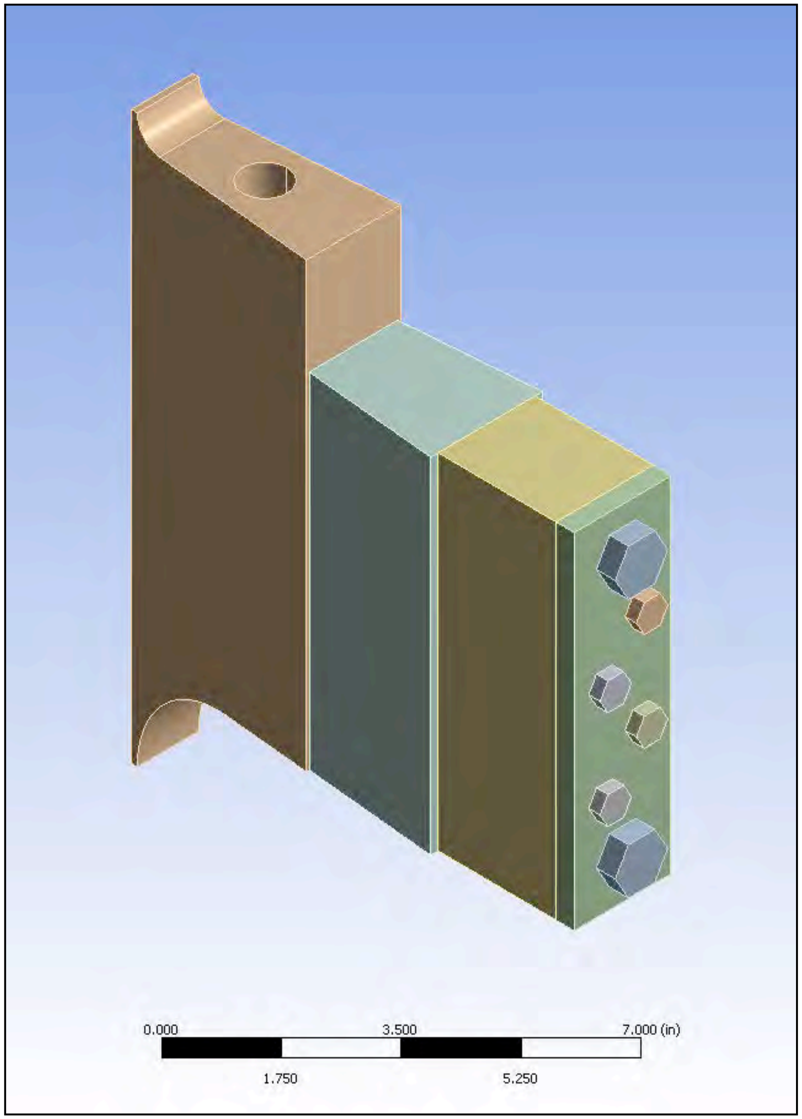
Single Segment Center Strap-Only Results: Contact Pressure

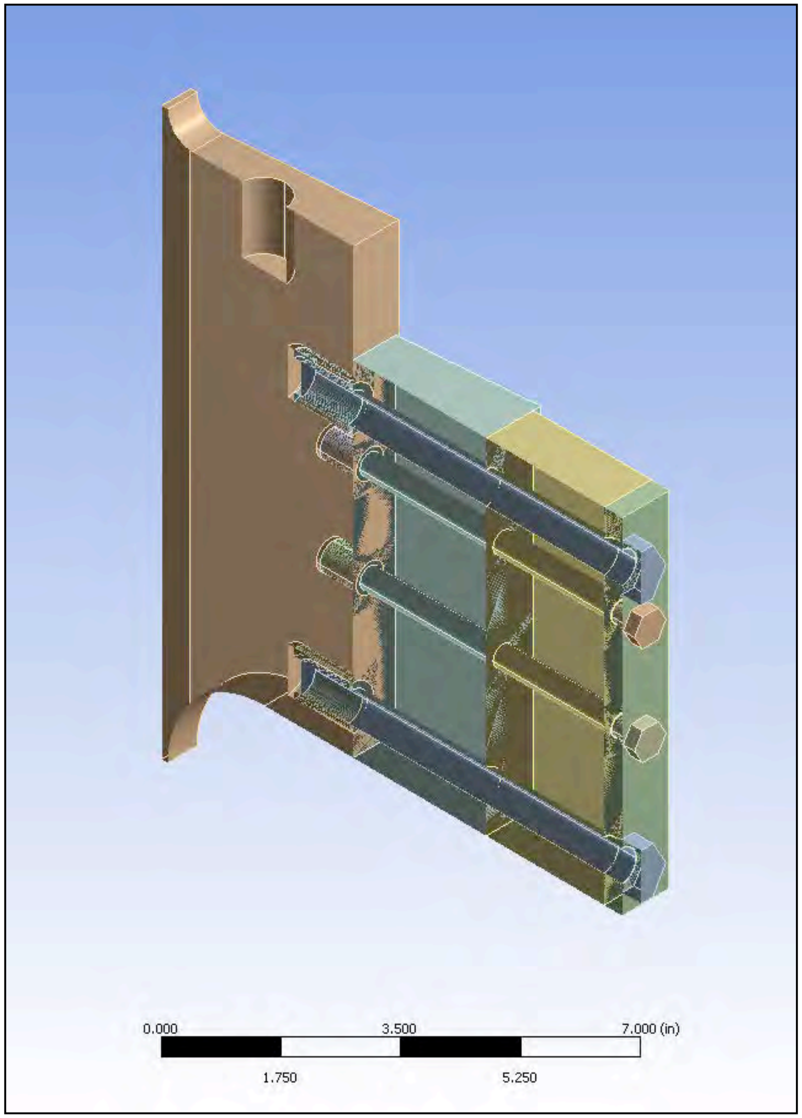
Version 3.1



A: Single Segement_Center Strap Only2
Pressure
Type: Pressure
Unit: psi
Time: 2
Custom
Max: 9537.1
Min: 0
8/5/2009 8:28 AM

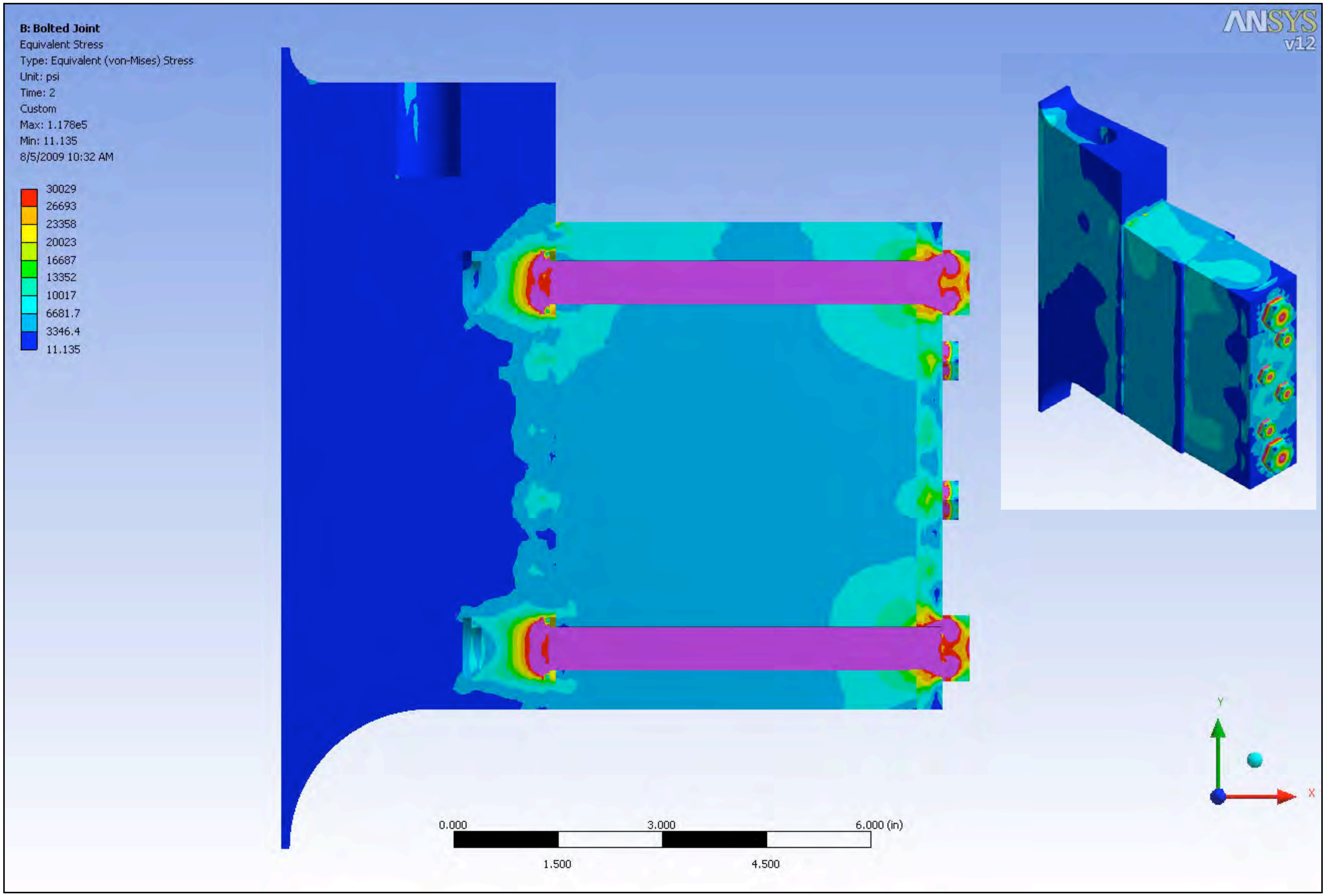
Strap-to-Stub Joint Sub-model: Solid Model





Strap-to-Stub Joint Sub-model Results: von Mises Stress

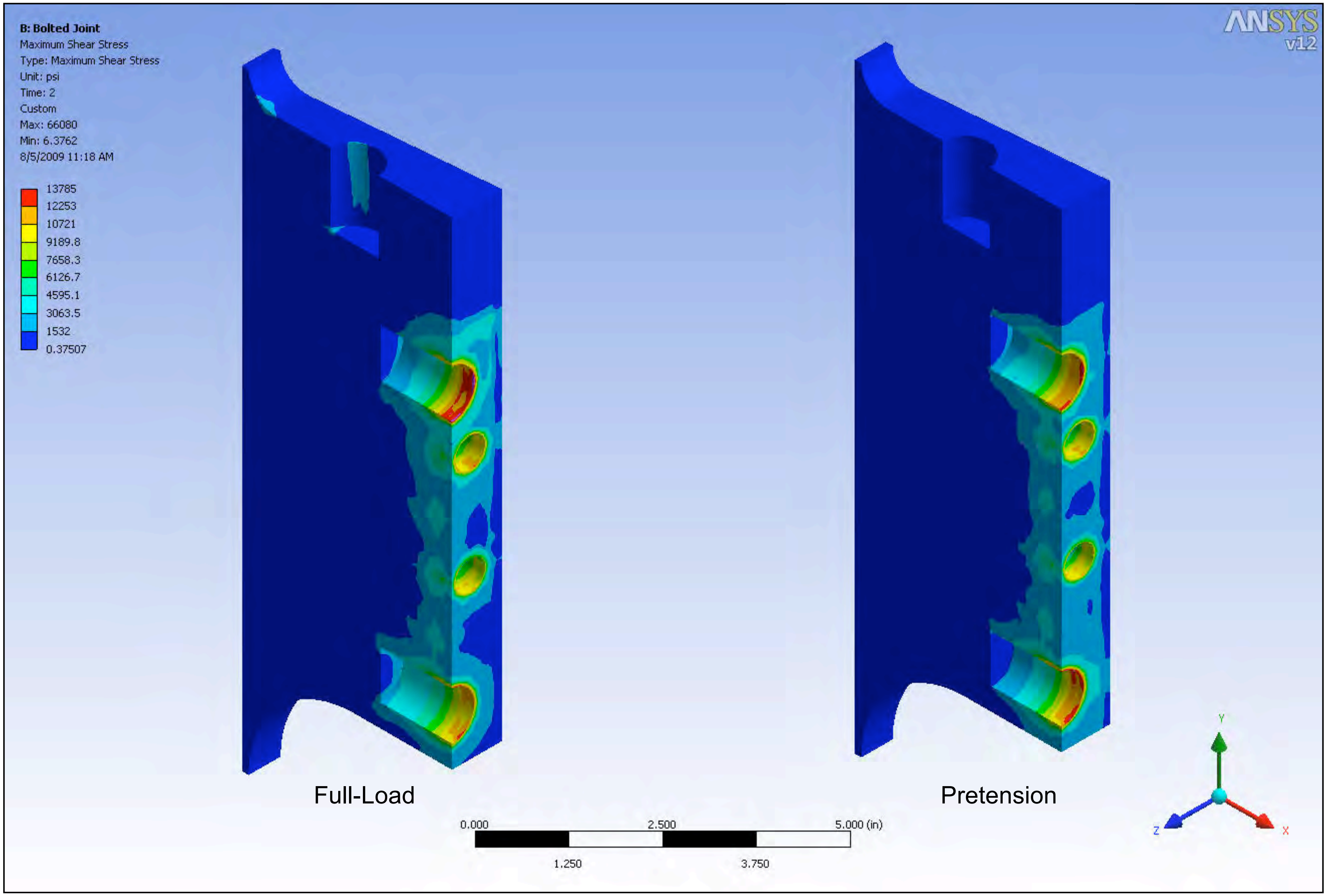
Loads from Single Segment Center Strap-Only Results



B: Bolted Joint
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 2
Custom
Max: 1.178e5
Min: 11.135
8/5/2009 10:32 AM

Strap-to-Stub Joint Sub-model Results: Max. Shear Stress

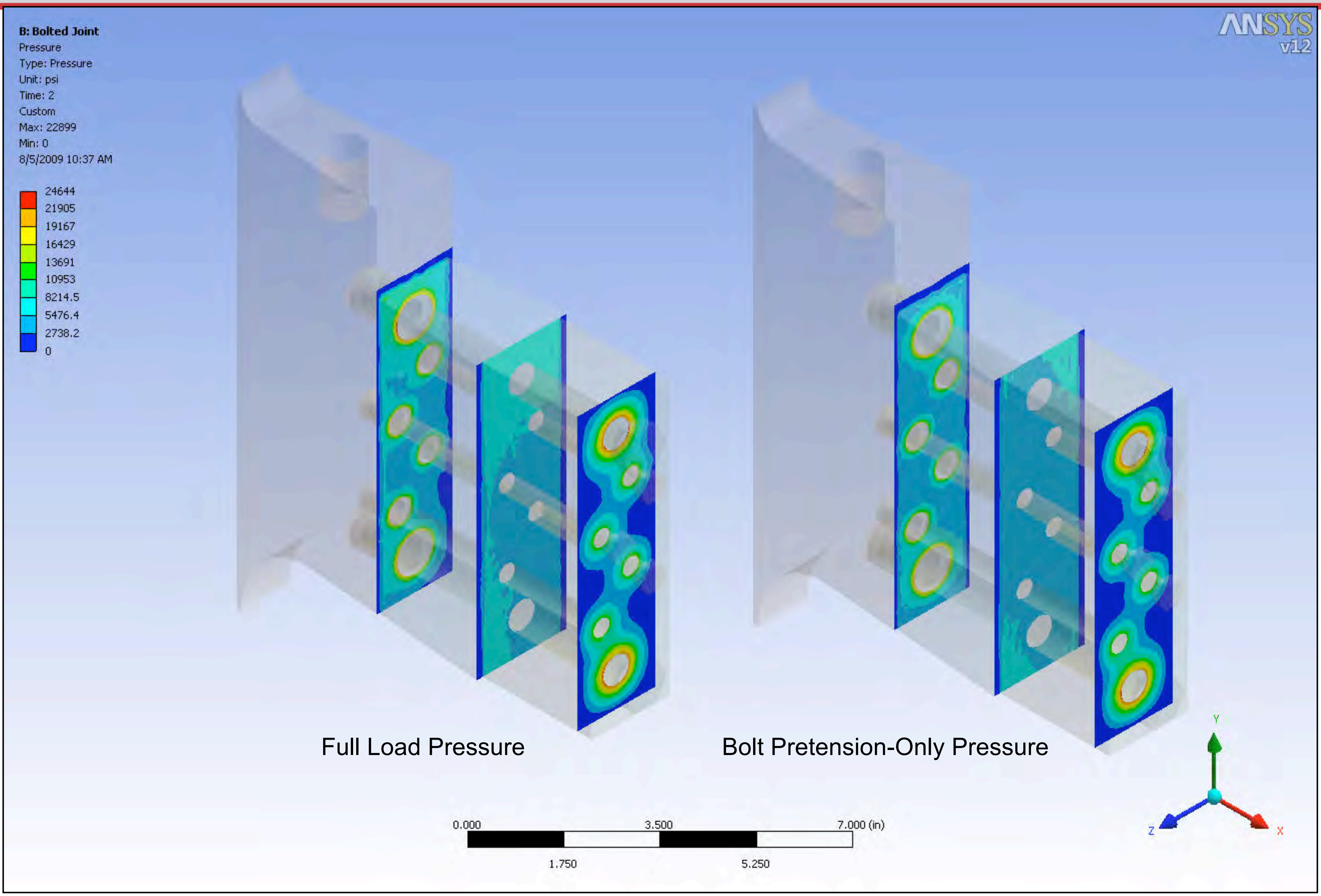
Loads from Single Segment Center Strap-Only Results



B: Bolted Joint
Maximum Shear Stress
Type: Maximum Shear Stress
Unit: psi
Time: 2
Custom
Max: 66080
Min: 6.3762
8/5/2009 11:18 AM

Strap-to-Stub Joint Sub-model Results: Contact Pressure

Loads from Single Segment Center Strap-Only Results

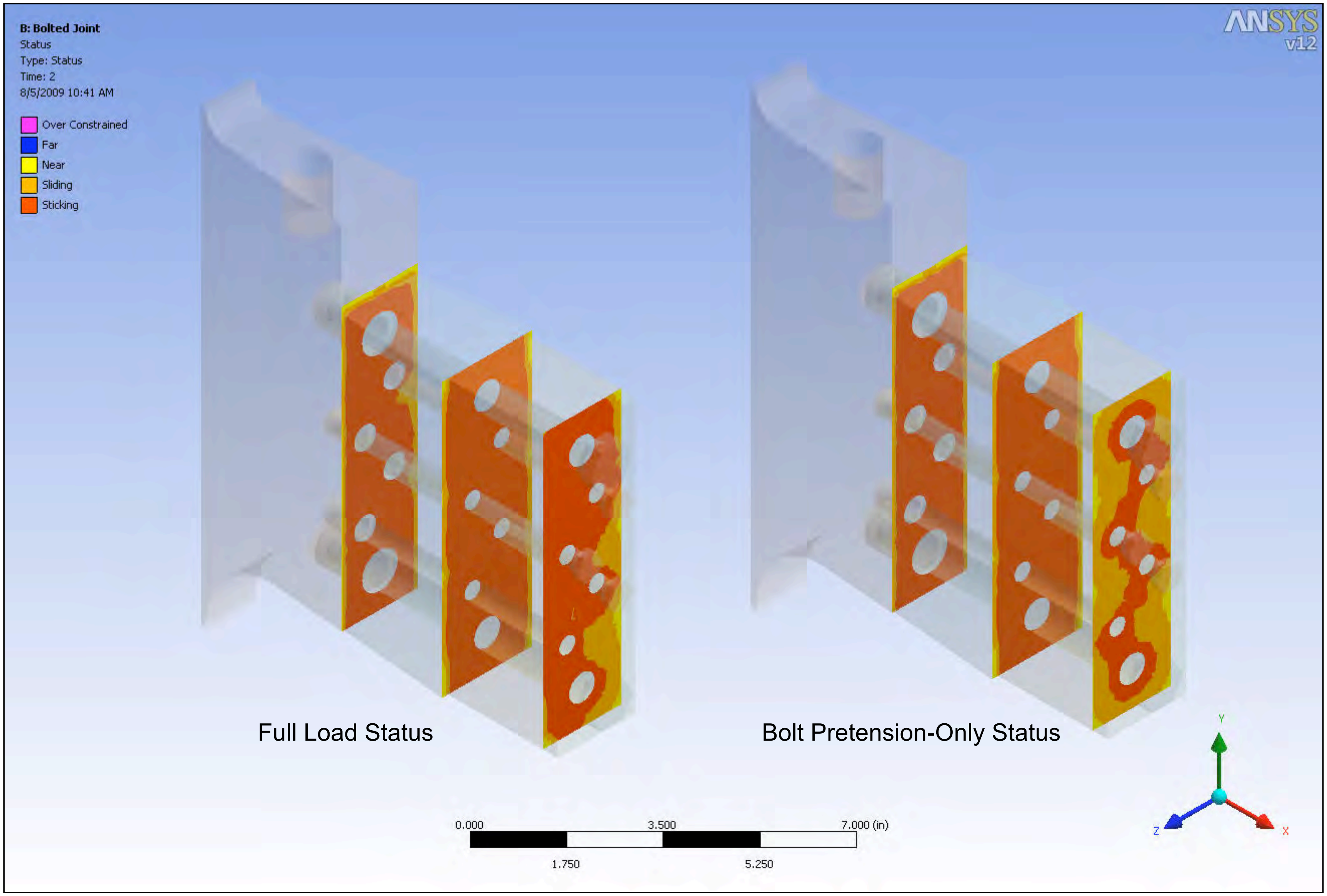


Full Load Pressure

Bolt Pretension-Only Pressure

Strap-to-Stub Joint Sub-model Results: Contact Status

Loads from Single Segment Center Strap-Only Results

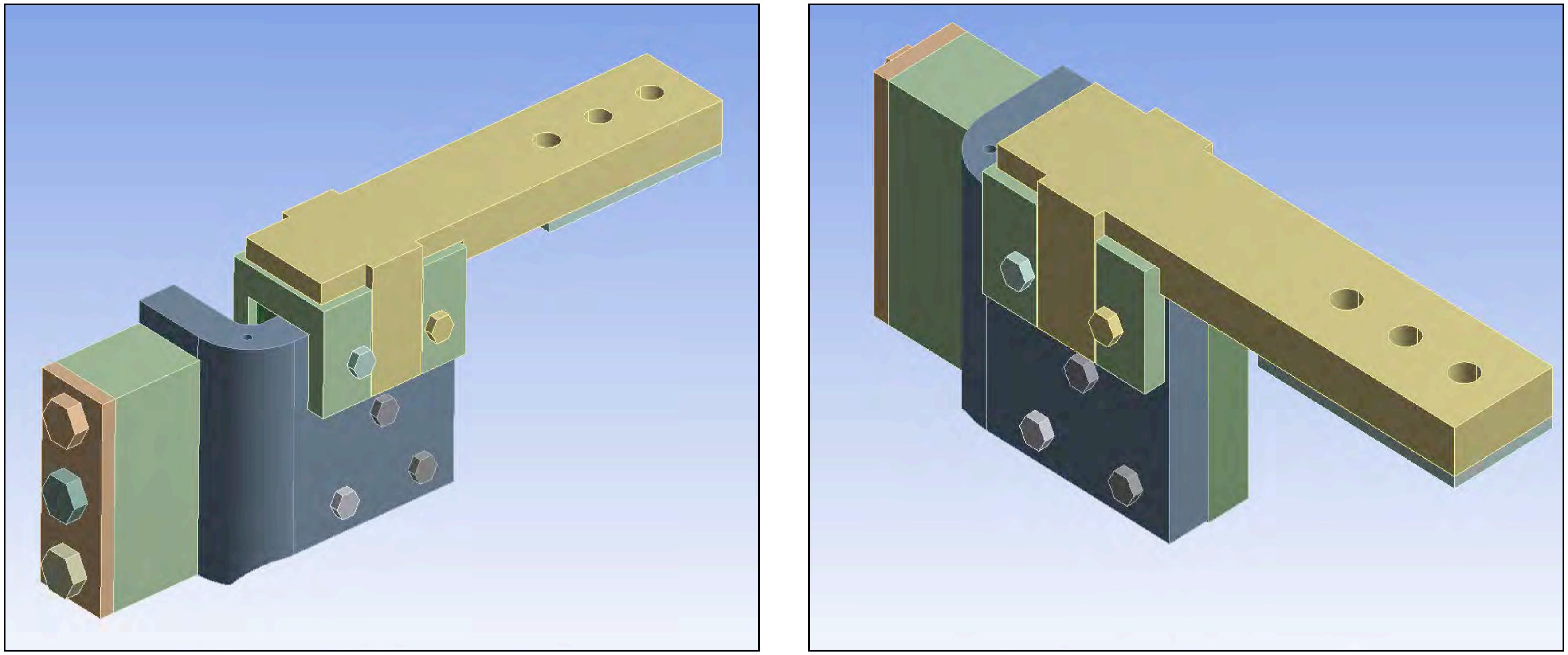


B: Bolted Joint
Status
Type: Status
Time: 2
8/5/2009 10:41 AM

Full Load Status

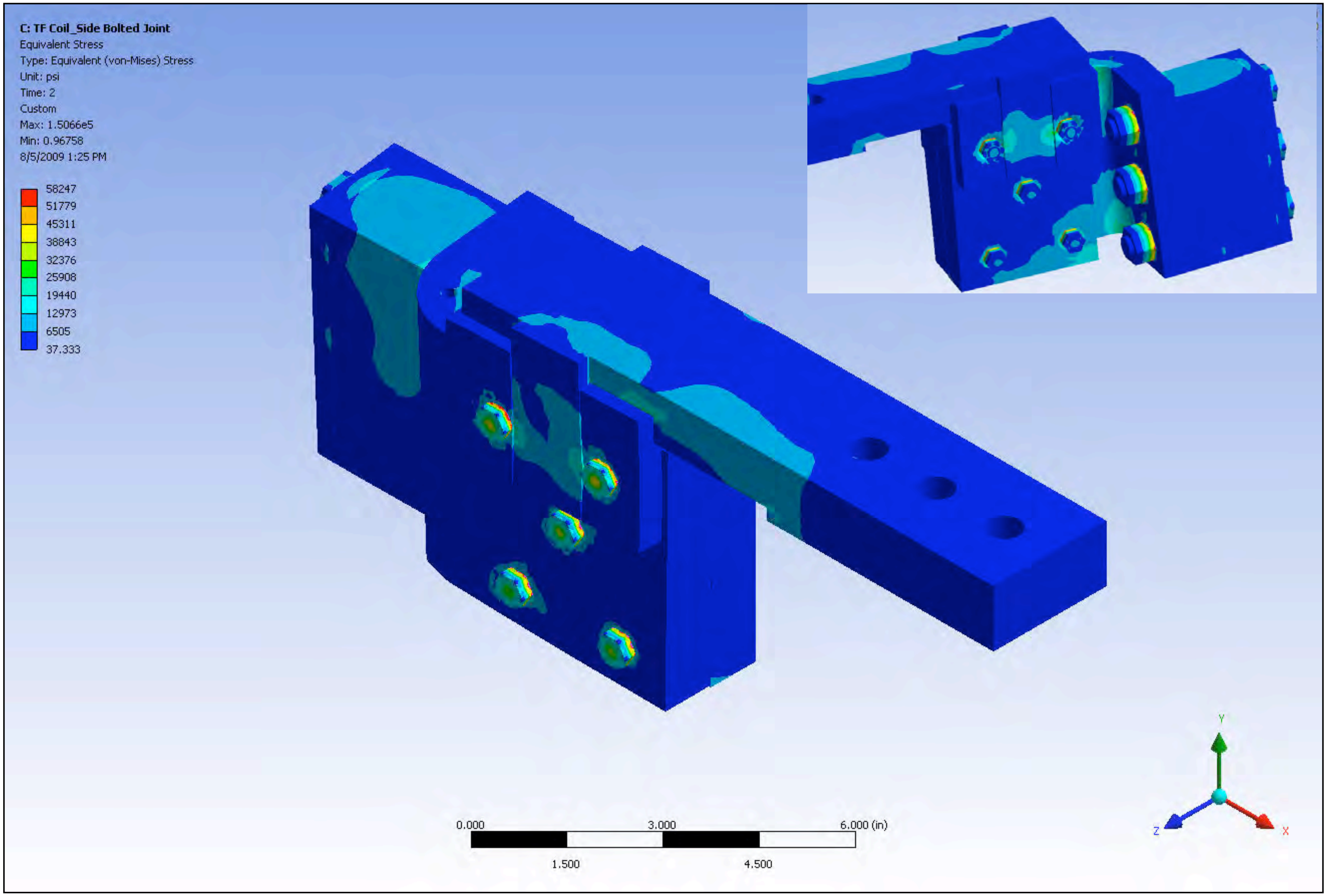
Bolt Pretension-Only Status

Figure 10A – Strap-to-TF Coil Outer Leg Joint: Solid Model



Strap-to-Flag Joint Sub-model Results: von Mises Stress

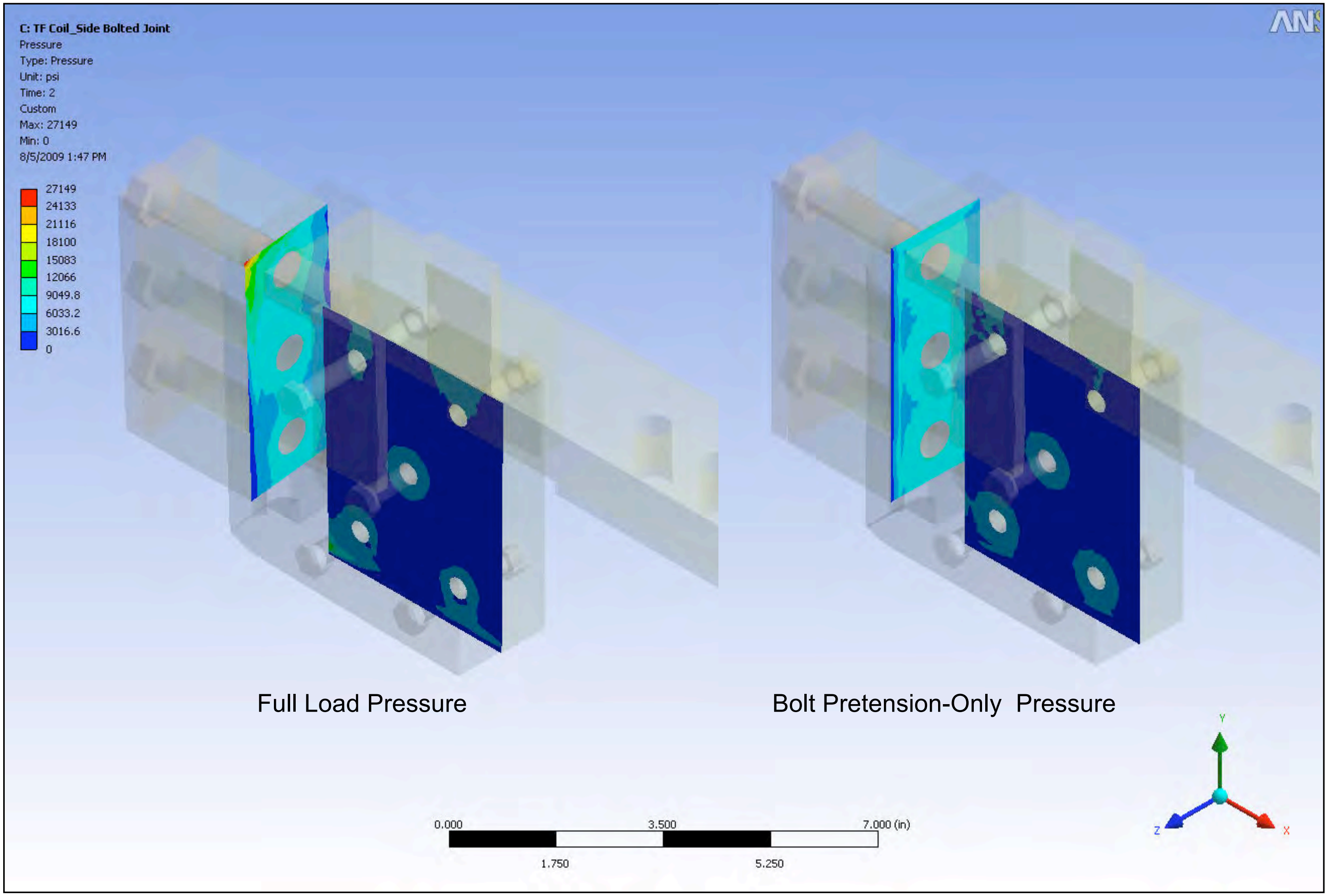
Loads from Single Segment Center Strap-Only Results



C: TF Coil_Side Bolted Joint
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 2
Custom
Max: 1.5066e5
Min: 0.96758
8/5/2009 1:25 PM

Strap-to-Flag Joints Sub-model Results: Contact Pressure

Loads from Single Segment Center Strap-Only Results



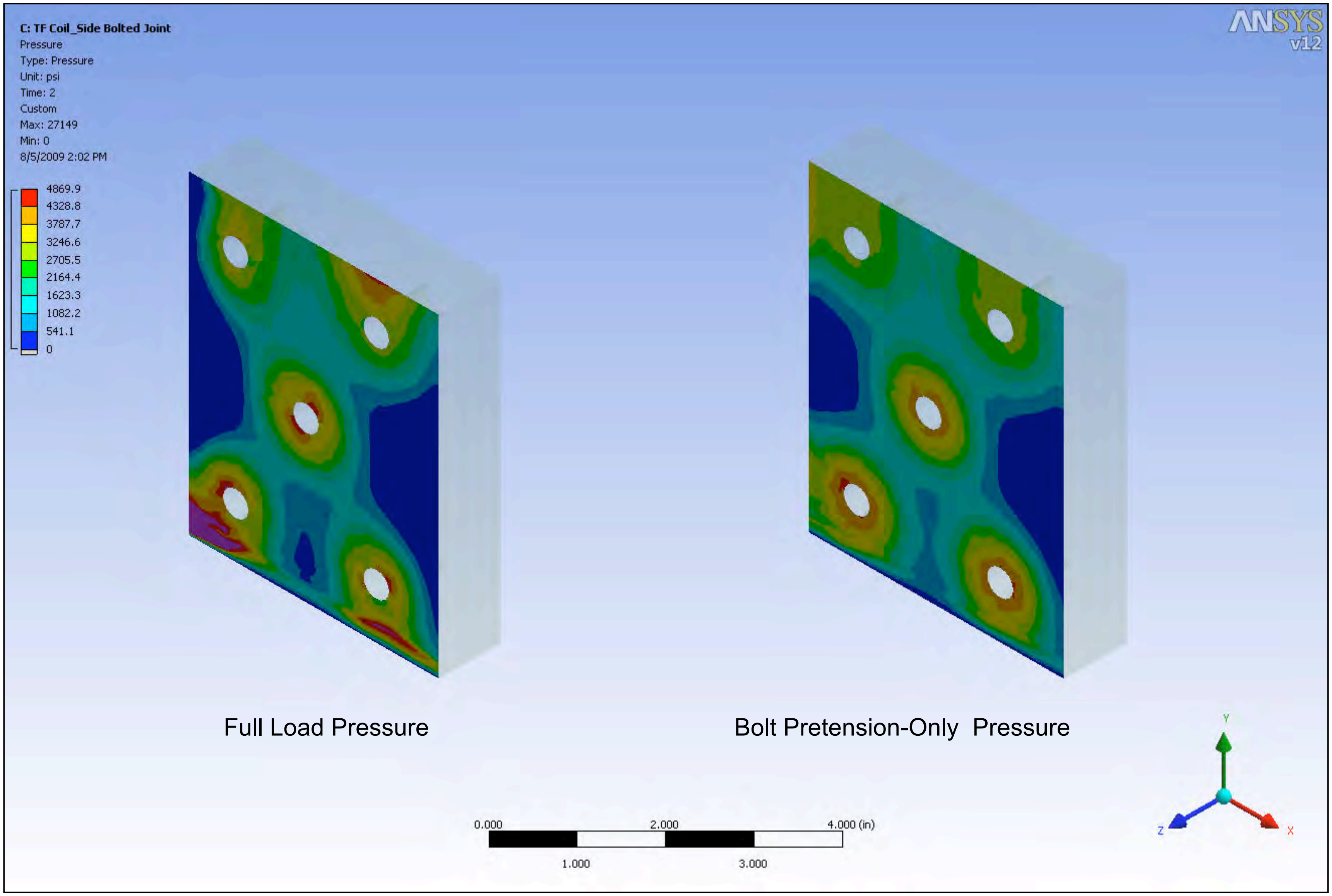
C: TF Coil_Side Bolted Joint
Pressure
Type: Pressure
Unit: psi
Time: 2
Custom
Max: 27149
Min: 0
8/5/2009 1:47 PM

Full Load Pressure

Bolt Pretension-Only Pressure

TF Coil Outer Leg Joint Sub-model Results: Contact Pressure

Loads from Single Segment Center Strap-Only Model Results



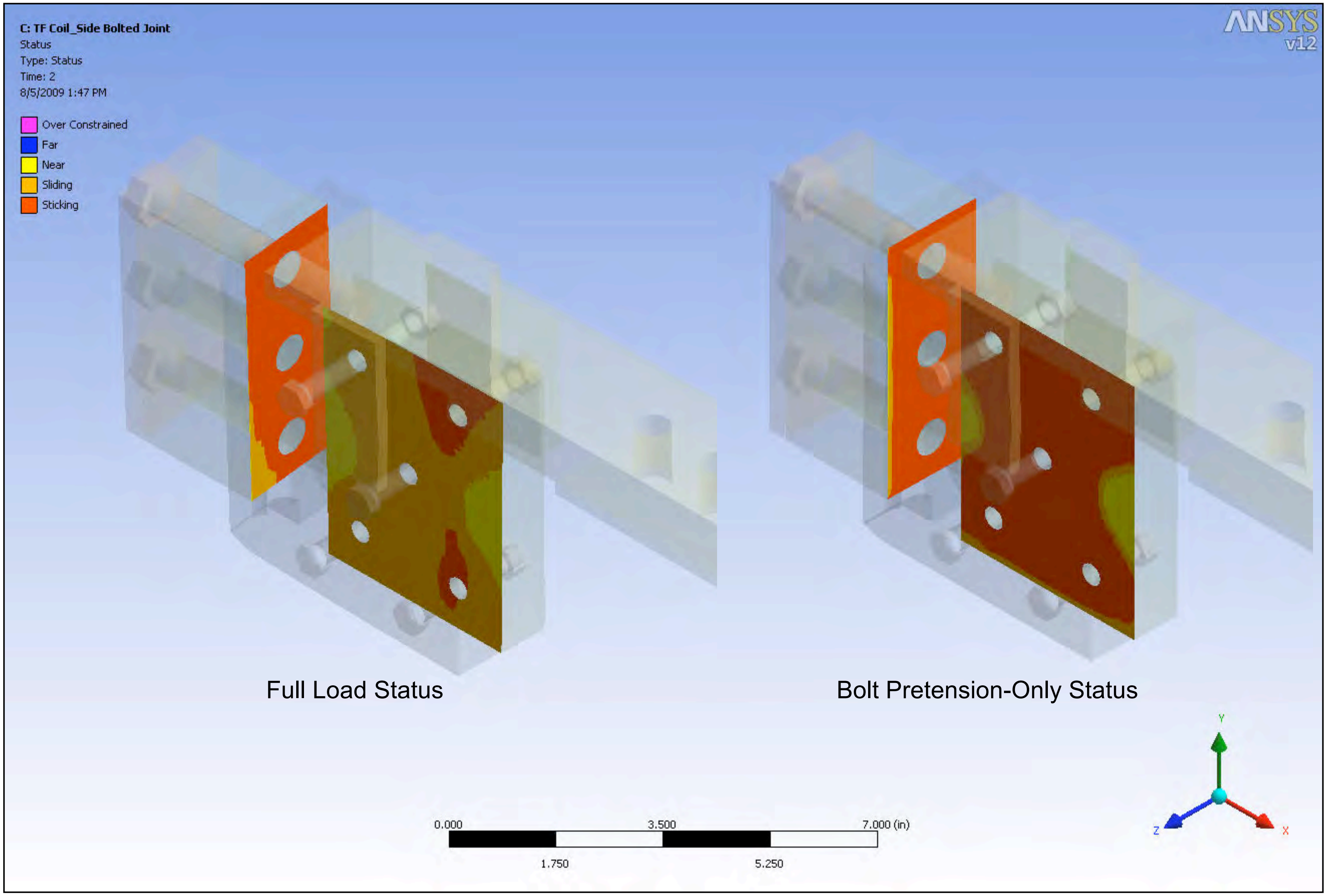
C: TF Coil_Side Bolted Joint
Pressure
Type: Pressure
Unit: psi
Time: 2
Custom
Max: 27149
Min: 0
8/5/2009 2:02 PM

Full Load Pressure

Bolt Pretension-Only Pressure

Strap-to-Flag Joints Sub-model Results: Contact Status

Loads from Single Segment Center Strap-Only Model Results

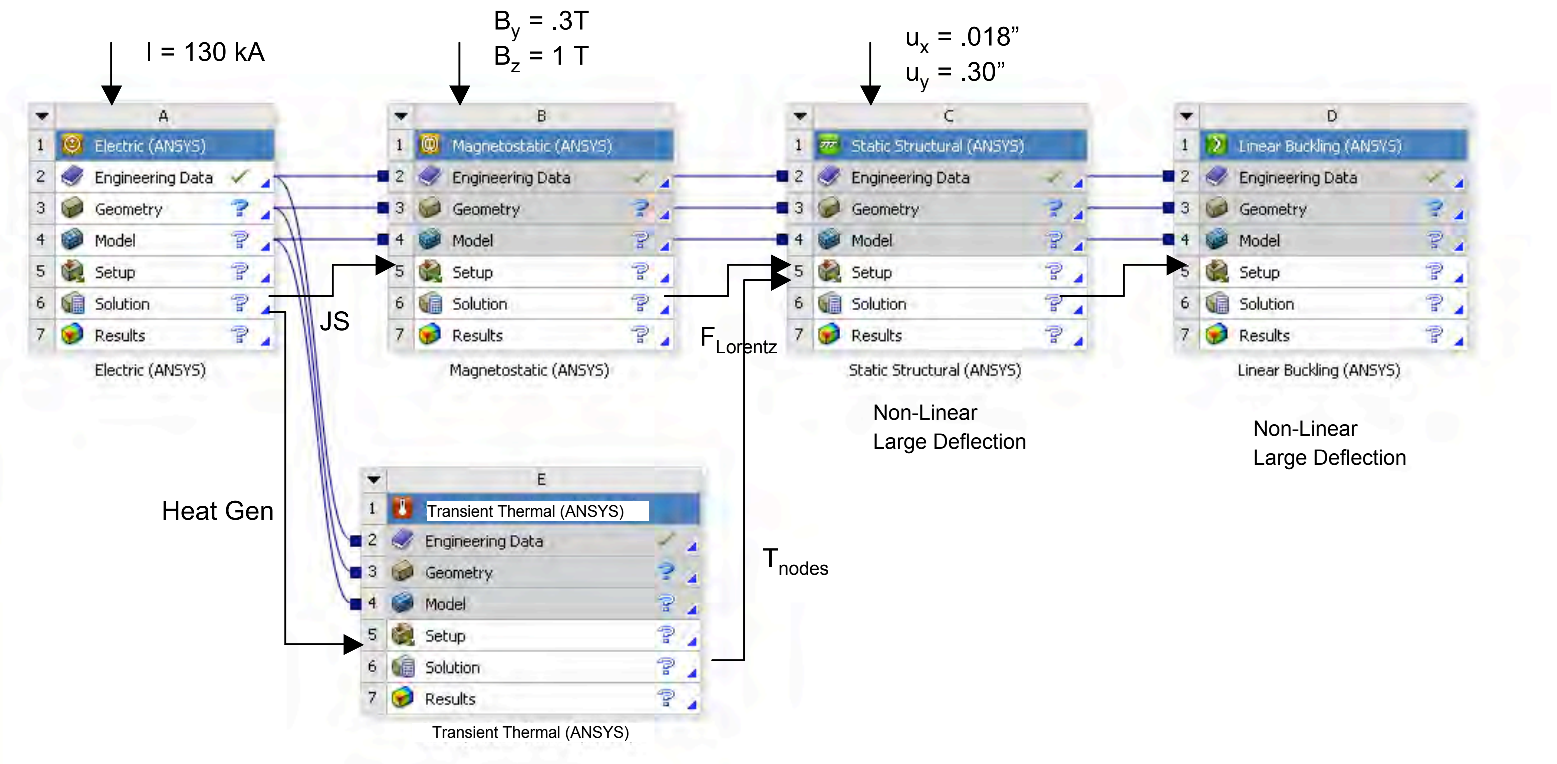


C: TF Coil_Side Bolted Joint
Status
Type: Status
Time: 2
8/5/2009 1:47 PM

Full Load Status

Bolt Pretension-Only Status

ANSYS Full Multiphysics Analysis Flow Diagram



I = 130 kA

B_y = .3T
B_z = 1 T

u_x = .018”
u_y = .30”

JS

$F_{Lorentz}$

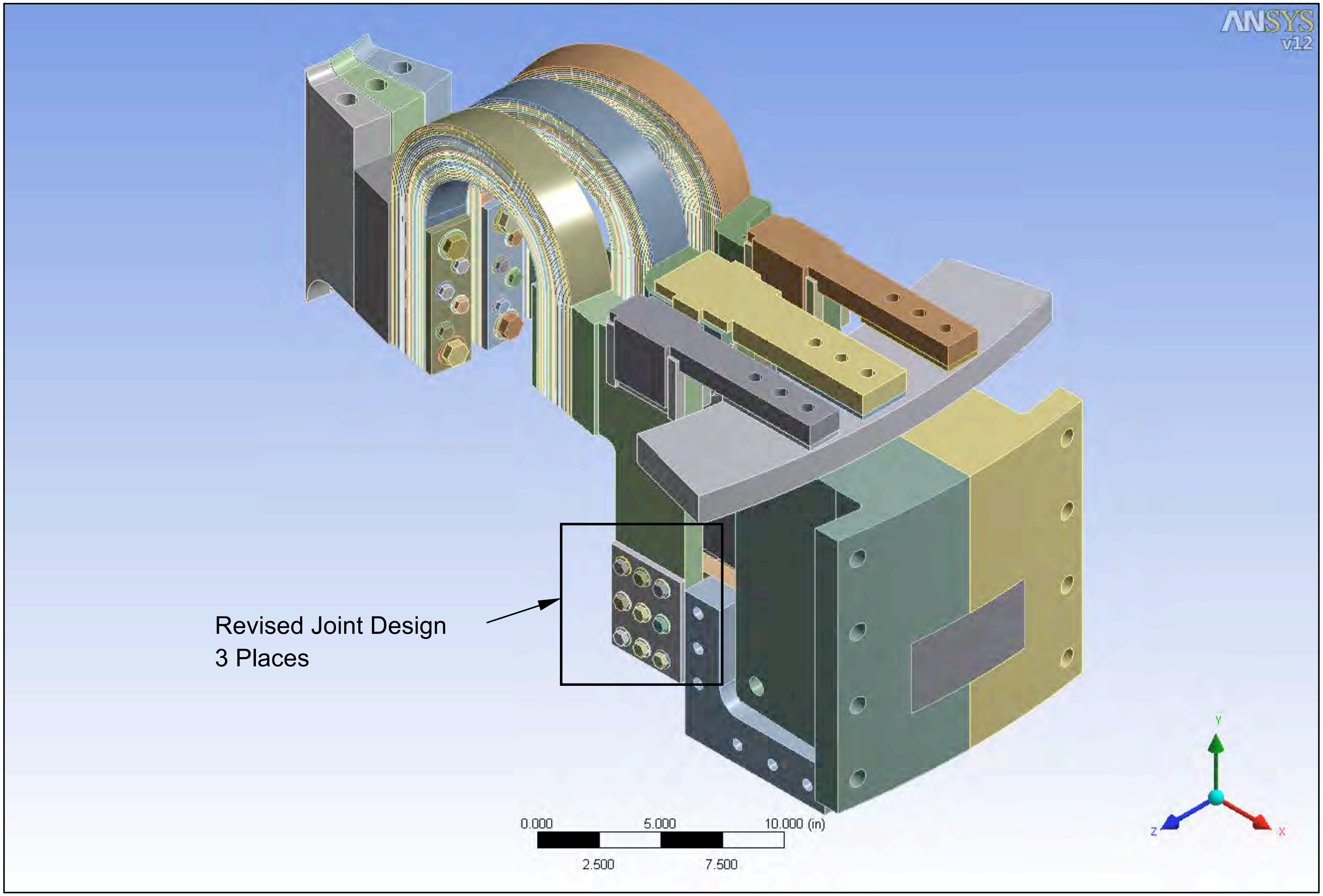
Heat Gen

T_{nodes}

Non-Linear
Large Deflection

Non-Linear
Large Deflection

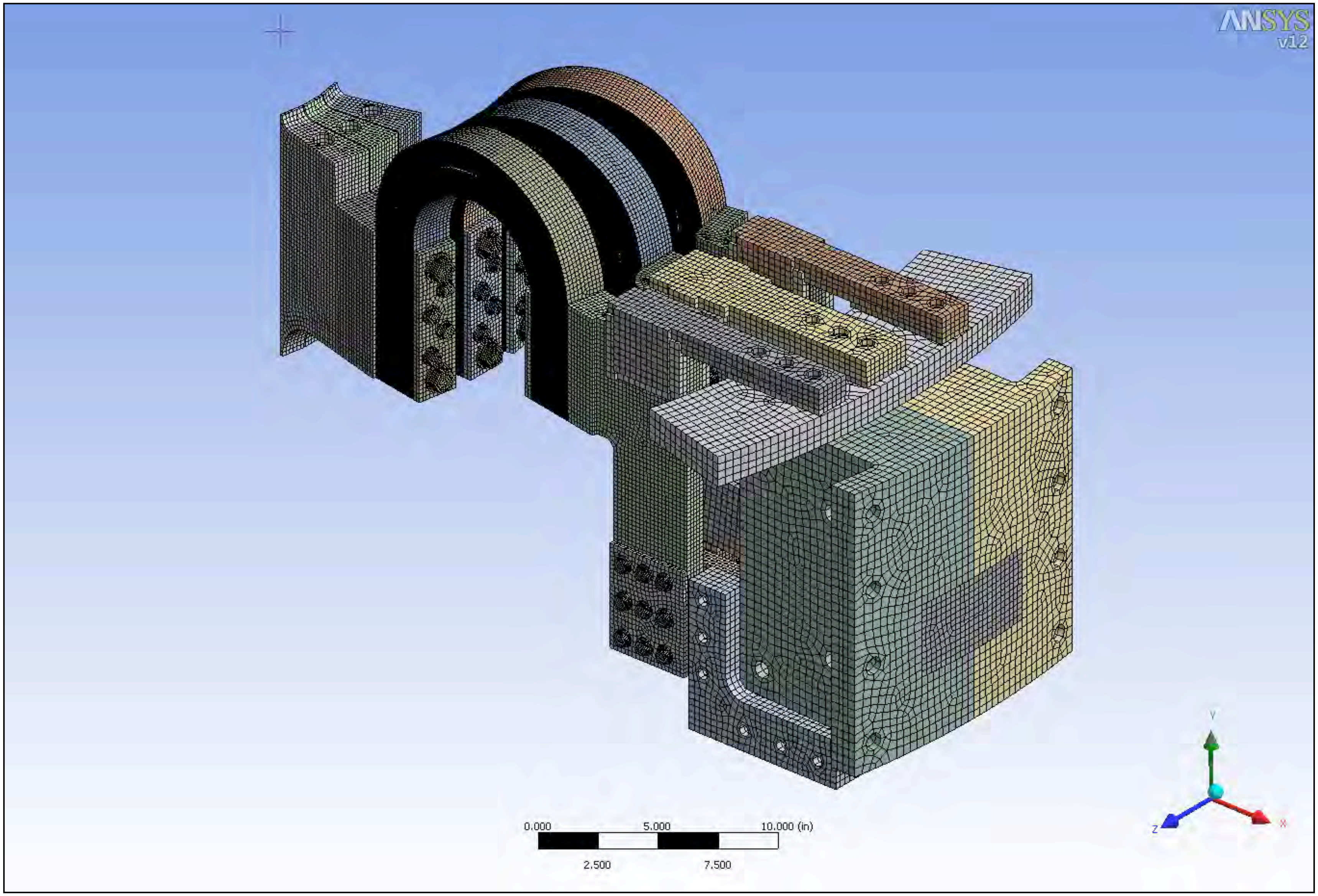
Single Segment 3-Strap Assembly: Version 3.2



Revised Joint Design
3 Places

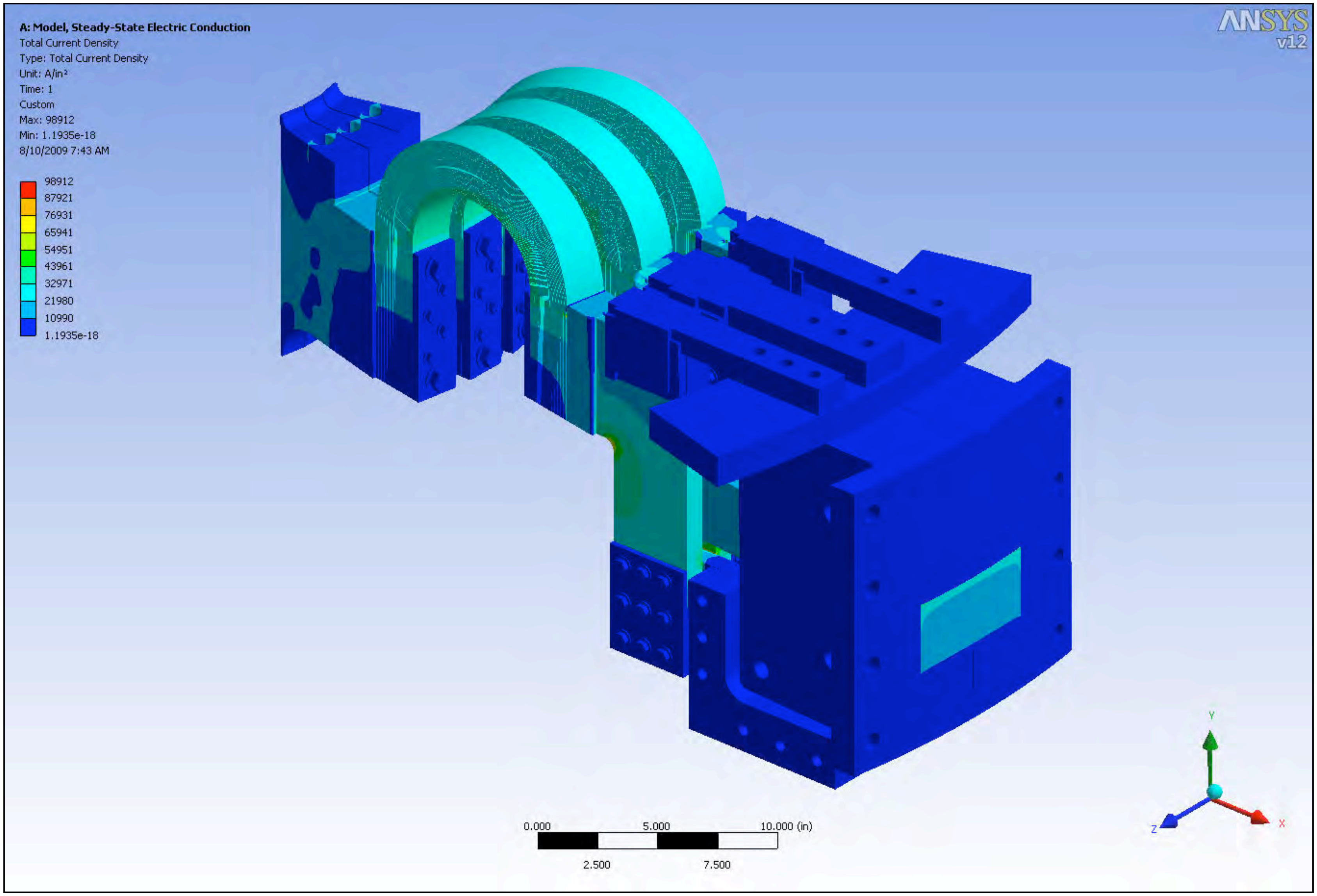
Single Segment 3-Strap Assembly FEA Model: Mesh

Version 3.2



Single Segment 3-Strap Model Results: Total Current Density

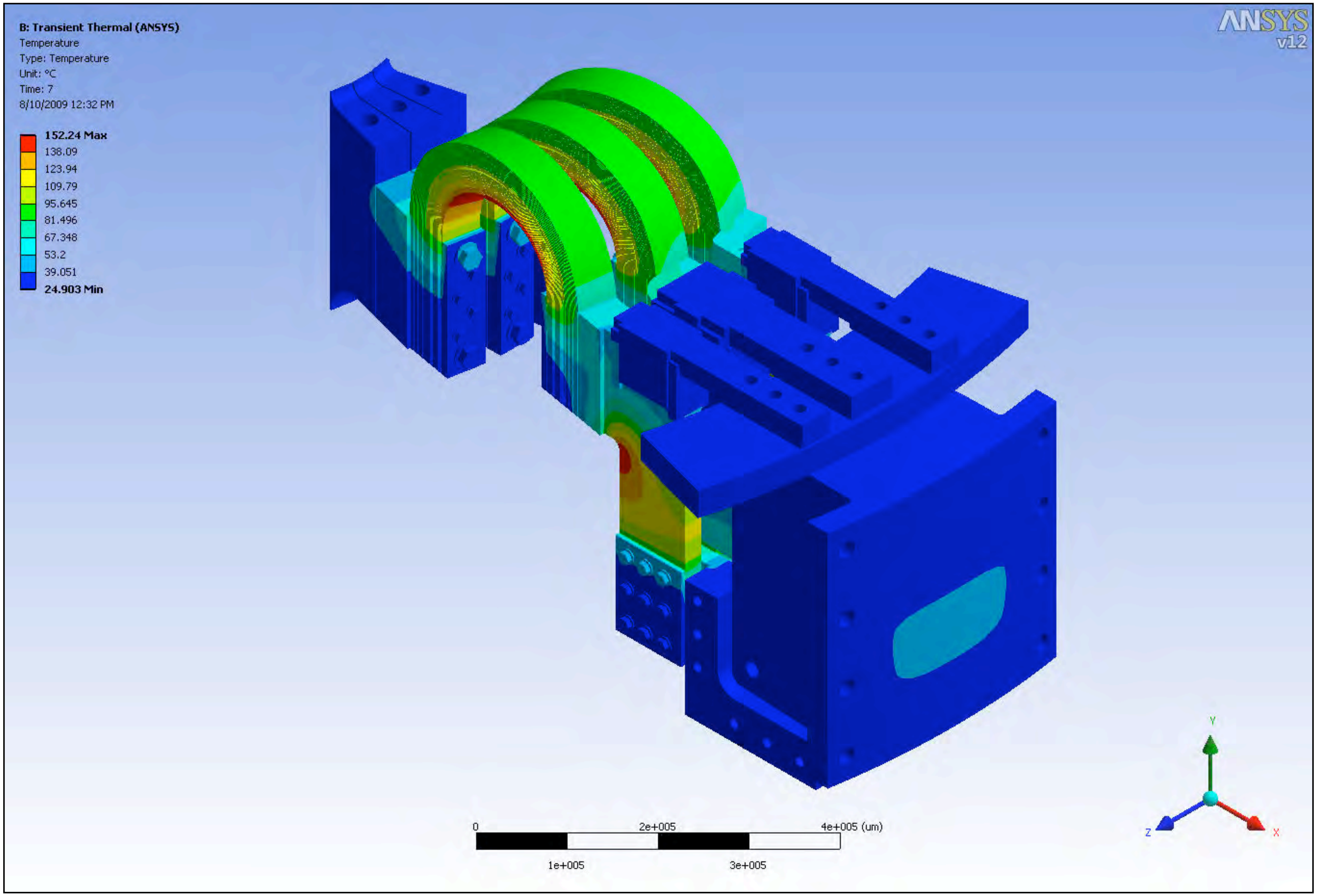
Version 3.2



A: Model, Steady-State Electric Conduction
Total Current Density
Type: Total Current Density
Unit: A/in²
Time: 1
Custom
Max: 98912
Min: 1.1935e-18
8/10/2009 7:43 AM

Single Segment 3-Strap Model Results: Temperature Profile

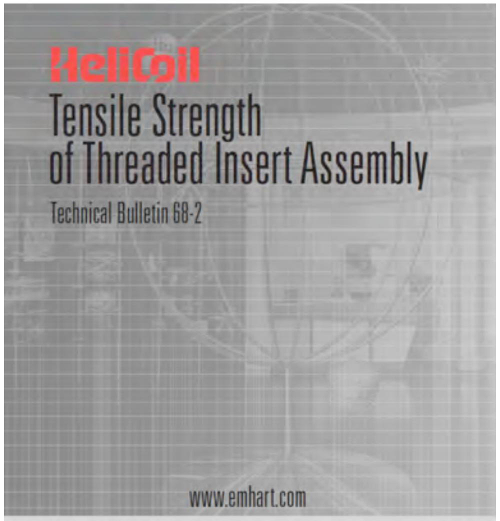
Version 3.2



Next Steps

- Complete full-multiphysics analysis.
  - Version 3.1Single Segment 3-Strap Assembly design.
- Investigate alternatives to C10700 copper.
  - Candidates are: C15000 Cu-Zr, with twice the high temperature fatigue strength of C10700; and C18150 Cu-Cr-Zr.
  - Perform stir weldability tests of candidate materials.
  - Repeat subset of cyclic pull-out tests of candidate materials.
- Optimize design.
  - Reduce number of joints if possible.

Appendix A –Assembly Strength vs Helicoil Insert Length



HeliCoil

Tensile Strength of Threaded Insert Assembly

Technical Bulletin 68-2

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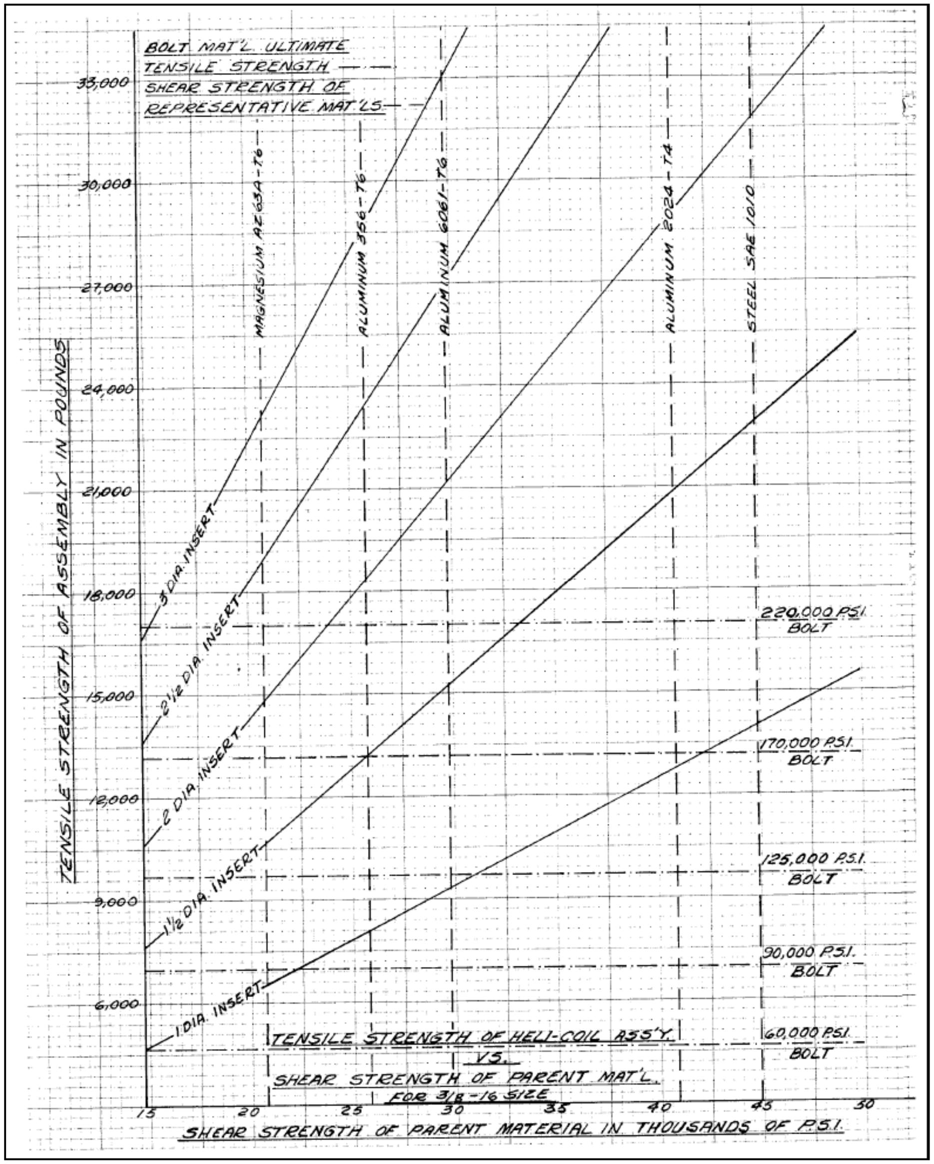
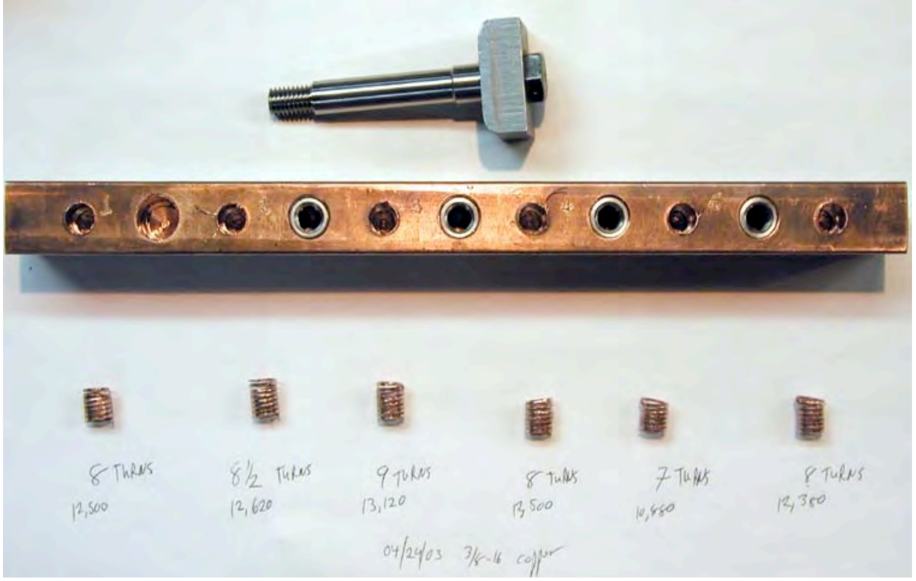


Appendix B- Shear Key Copper Threads, Static Results

- Correlation between pull out force and the number of threads pulled explains scatter
- By design shear key bolt will catch 8-9 threads



A-1 12,500lbs peak, 8 Threads
A-2 12,620lbs peak, 8.5 Threads
A-3 13,120lbs peak, 9 Threads
A-4 12,500lbs peak, 8 Threads
A-5 10,880lbs peak, 7 Threads
A-6 12,380lbs peak, 8 Threads