NSTX Upgrade

TF Flex Joint and TF Bundle Stub

NSTXU-CALC-132-06-01

Rev 1

February 2, 2011

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Jim Chrzanowski, NSTX Cognizant Engineer

PPPL Calculation Form

Calculation # NSTX-CALC-132-06 Revision # 01 ___ WP #, if any (ENG-032) ________

Purpose of Calculation: (Define why the calculation is being performed.)

To determine if the upgrade TF flex joint and bundle stub design is adequate to meet the requirements of the NSTX Structural Design Criteria, specifically, the fatigue requirements of Section I-4.2 for 60,000 full power cycles without failure.

References (List any source of design information including computer program titles and revision levels.)

[1] NSTX Structural Design Criteria Document, I. Zatz
[2] NSTX Design point, June 2010
[3] ANSYS v13.0
[4] Maxwell v14.0

Assumptions (Identify all assumptions made as part of this calculation.)

1.) Because it results in the largest background field at the radial center of the flex strap, Current Scenario #81 was assumed worst-case for this analysis.
2.) A one-way coupled electromagnetic-structural analysis was used, based on the assumption that the bolted joints do not separate. This assumption was proven valid by checking the contact status of the joints after the analysis was completed.

Calculation (Calculation is either documented here or attached)

See attached.

Conclusions (Specify whether or not the purpose of the calculation was accomplished.)

1.The maximum stress in the lamellae is 19 ksi, below the NSTX Design Criteria allowable to meet the fatigue requirements for 60,000 full-power cycles;
2.) The HeliCoil and SuperBolt stresses are below the maximum allowable to meet the fatigue requirement ;
3.) The bolted joints were shown not to separate, and the minimum contact pressure is well above the design goal of 1500 psi.
4.) The dynamic load factor was calculated for the flex strap alone. A full transient electromagnetic disruption analysis using the worst-case combination of current and plasma disruption scenarios should be performed to fully qualify the joint and flex strap designs.

Cognizant Engineer's printed name, signature, and date

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

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NSTXU-CALC-132-06-01

TF Flex Joint and TF Bundle Stub

02-03-11

Study Goals

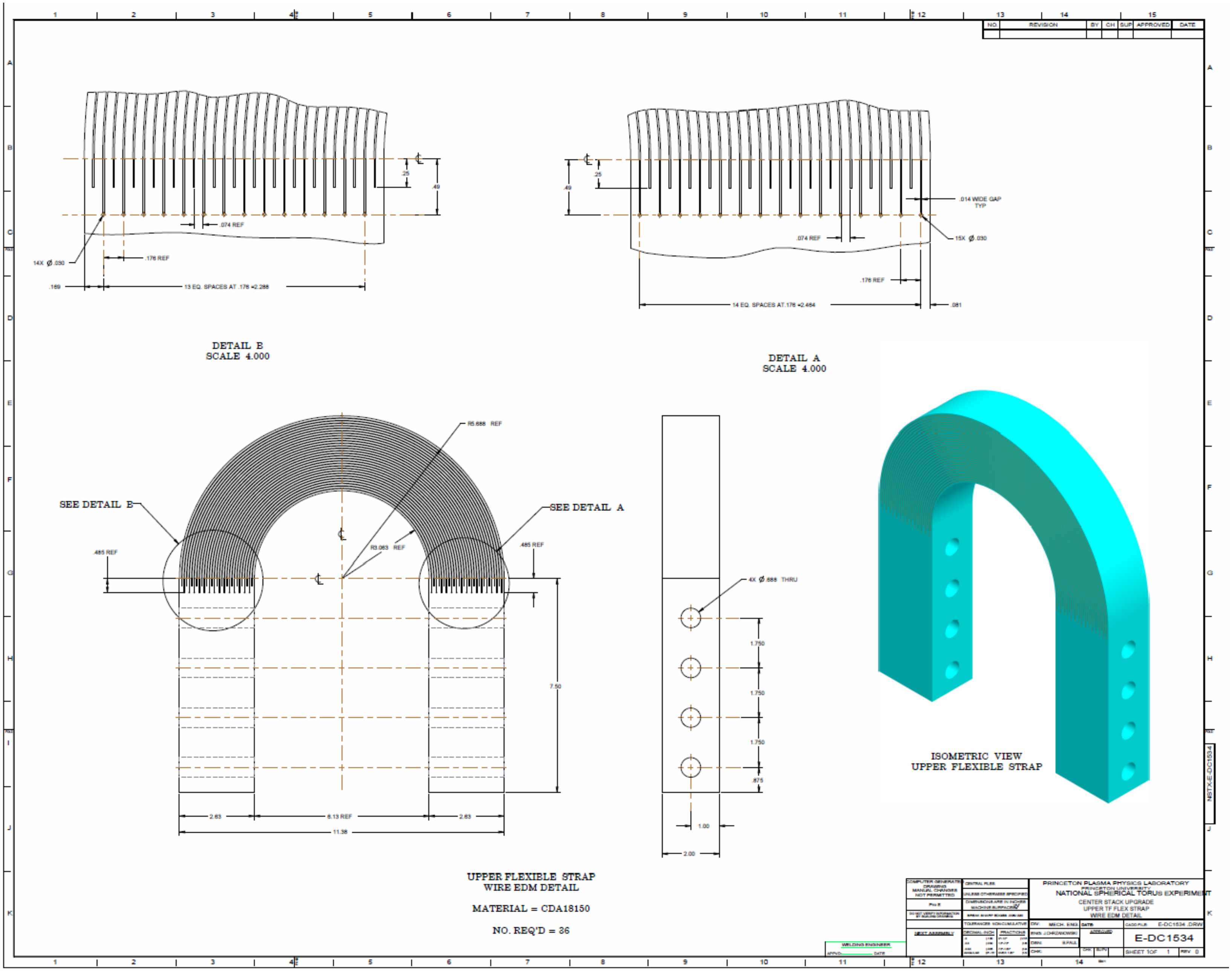
- Purpose:

  To determine if the upgrade TF flex joint and bundle stub design is adequate to meet the requirements of the NSTX Structural Design Criteria, specifically, the fatigue requirements of Section I-4.2 for 60,000 full power cycles without failure.

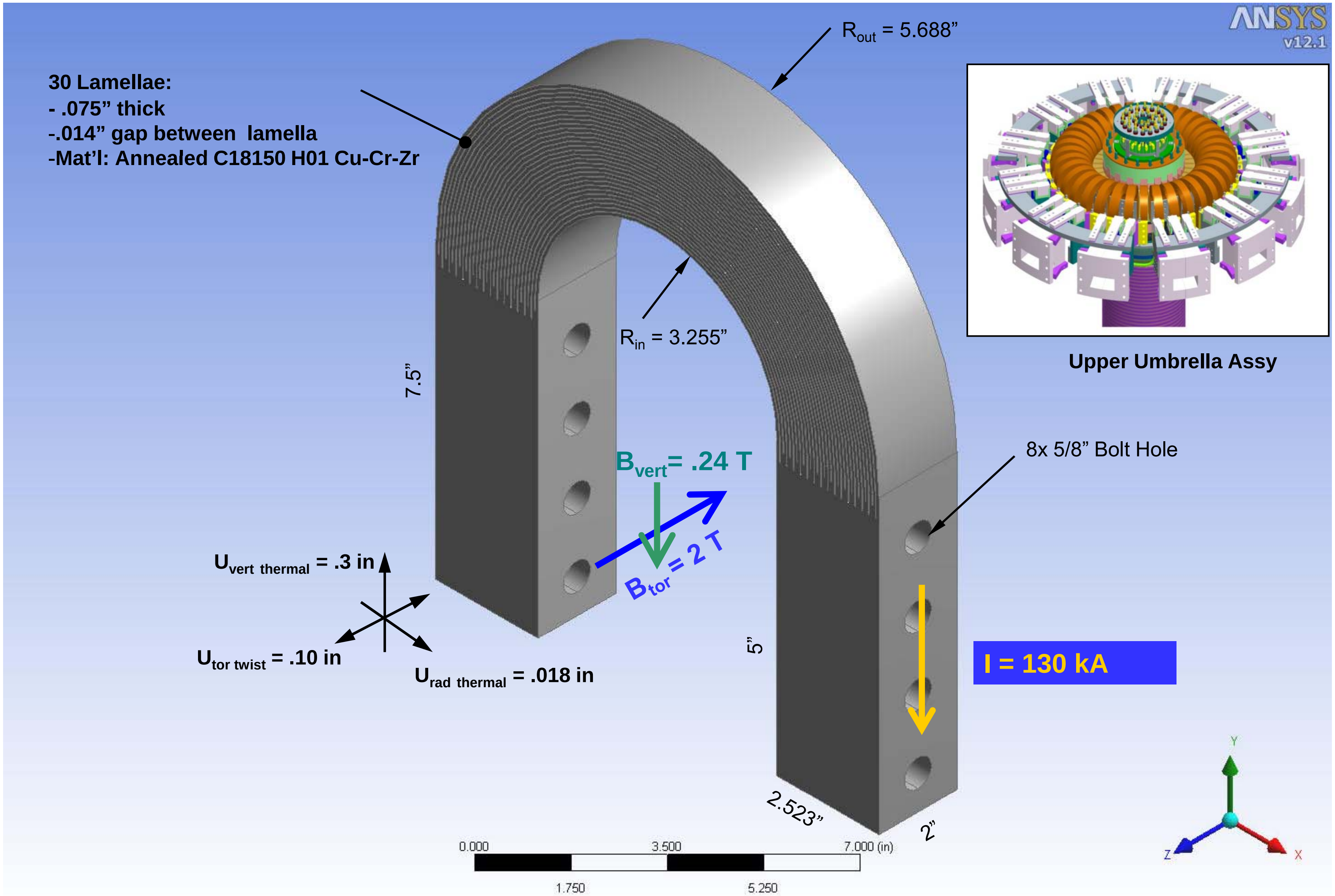
  – Strap Lamellae
    - Stresses
    - Buckling
  – Bolted Joints
    - Thread shear stress
    - Contact status and pressure

Outline

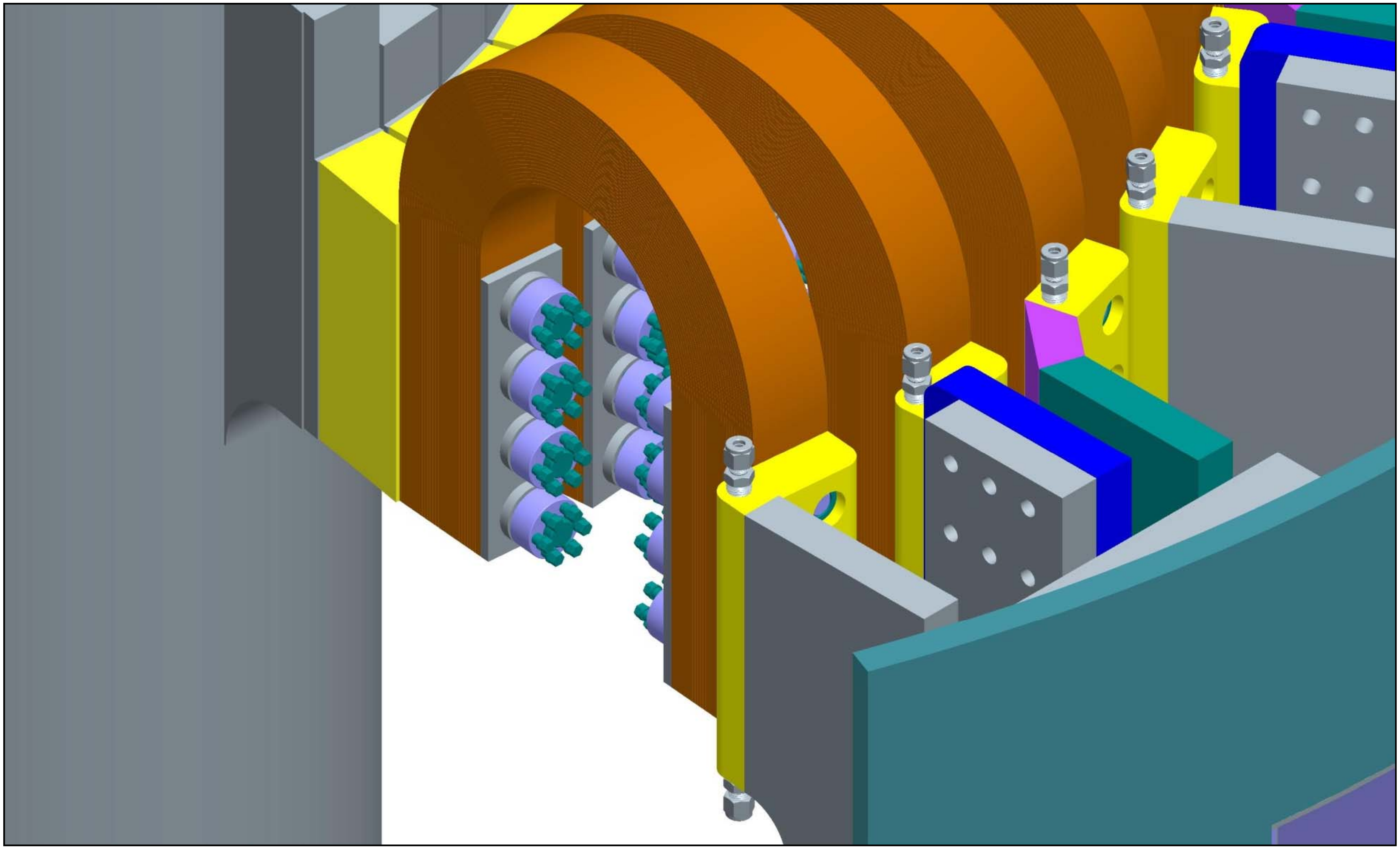
- Wire EDM Flex Strap and Joint Design
  - Flex Strap
  - *Superbolt* Jack-screw Tensioned Nut
- Analysis
  - Magnetostatic
    - Magnetic Flux Density
    - Current Density
  - Transient Thermal
    - Temperature
  - Static Structural
    - Conductor Stress
    - Lamella Stress
    - Thread and Bolt Stress
    - Contact Pressure
- Development Tests
- Conclusion


DETAIL B
SCALE 4.000
DETAIL A
SCALE 4.000
14X Ø .030
.176 REF
.074 REF
13 EQ. SPACES AT .176 =2.288
.169
.014 WIDE GAP TYP
15X Ø .030
14 EQ. SPACES AT .176 =2.464
.081
SEE DETAIL B
SEE DETAIL A
R5.688 REF
R3.063 REF
.485 REF
4X Ø .688 THRU
1.750
.875
7.50
2.63
6.13 REF
11.38
1.00
2.00
ISOMETRIC VIEW
UPPER FLEXIBLE STRAP
UPPER FLEXIBLE STRAP
WIRE EDM DETAIL
MATERIAL = CDA18150
NO. REQ'D = 36
PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
NATIONAL SPHERICAL TORUS EXPERIMENT
CENTER STACK UPGRADE
UPPER TF FLEX STRAP
WIRE EDM DETAIL
E-DC1534

NSTX CSU Flex Strap with Applied Boundary Conditions

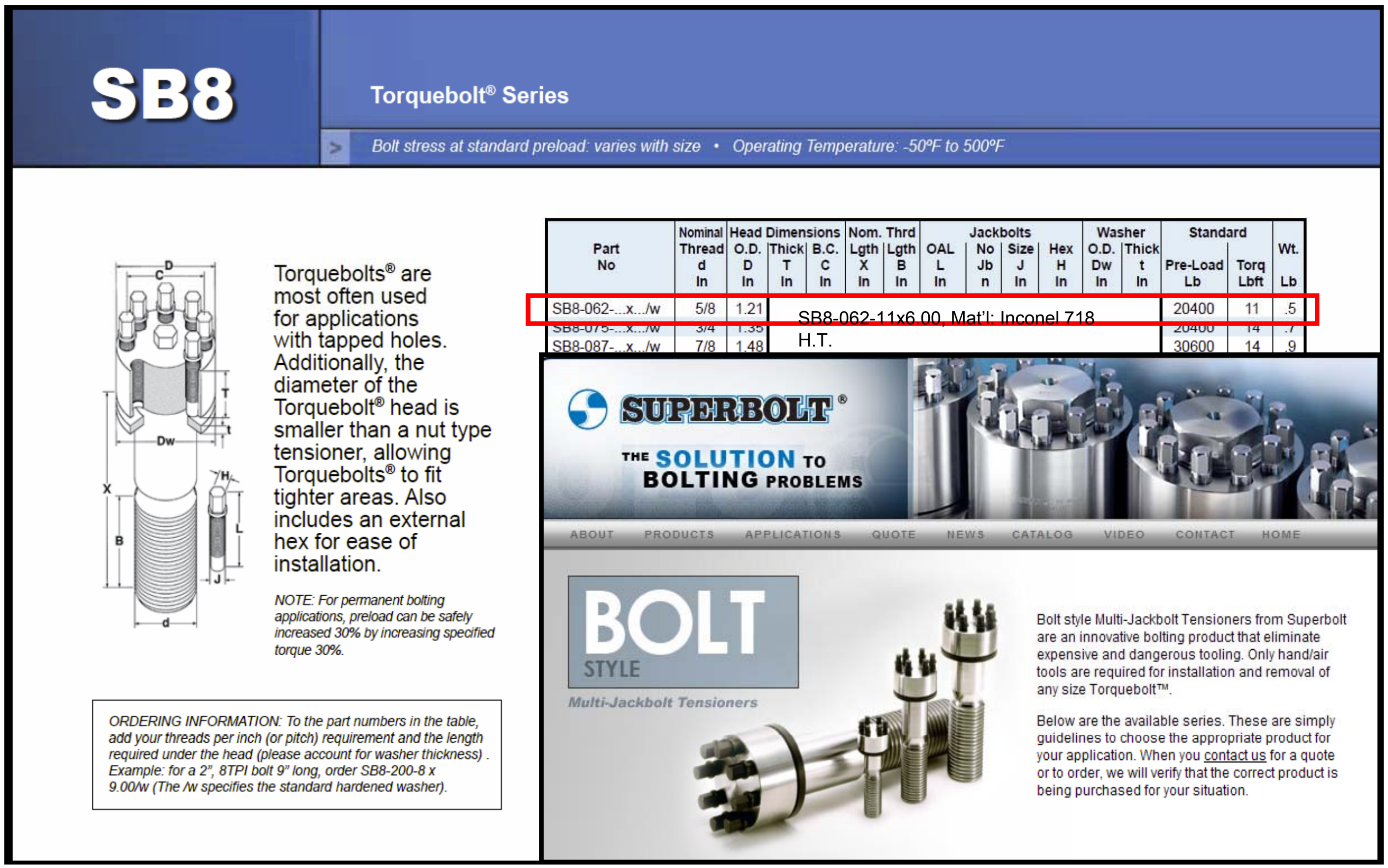


Flex Joint Design using *Superbolt* Jack-Screw Tensioned Nuts

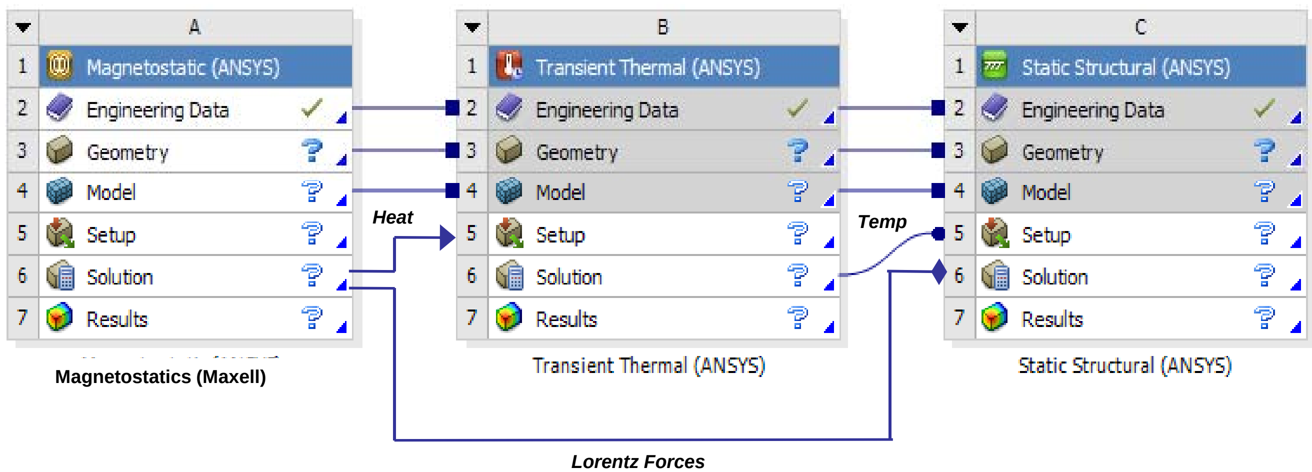


Superbolt Jack-Screw Tensioned Nut

- Advantages of using *Superbolts*
  - Easy Installation and removal of individual flex assemblies
  - Low torque required: ~ 11 ft-lbf
  - Smaller inner-radius of flex strap required, allows use of more laminations, reducing the maximum lamination stress

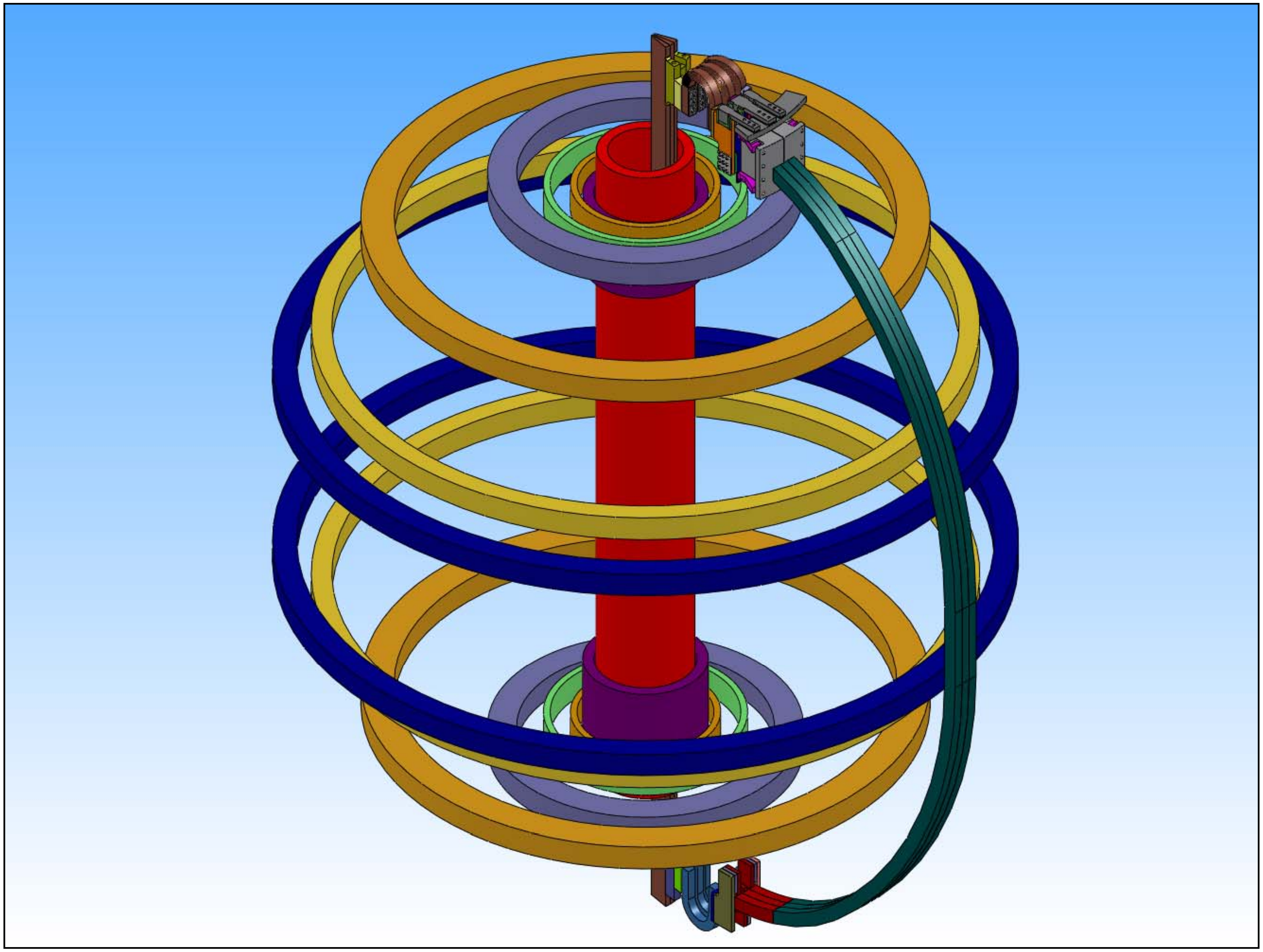


Coupled *Maxwell* Magnetostatic and *ANSYS* Transient Thermal/ Static Structural Analysis Block Diagram



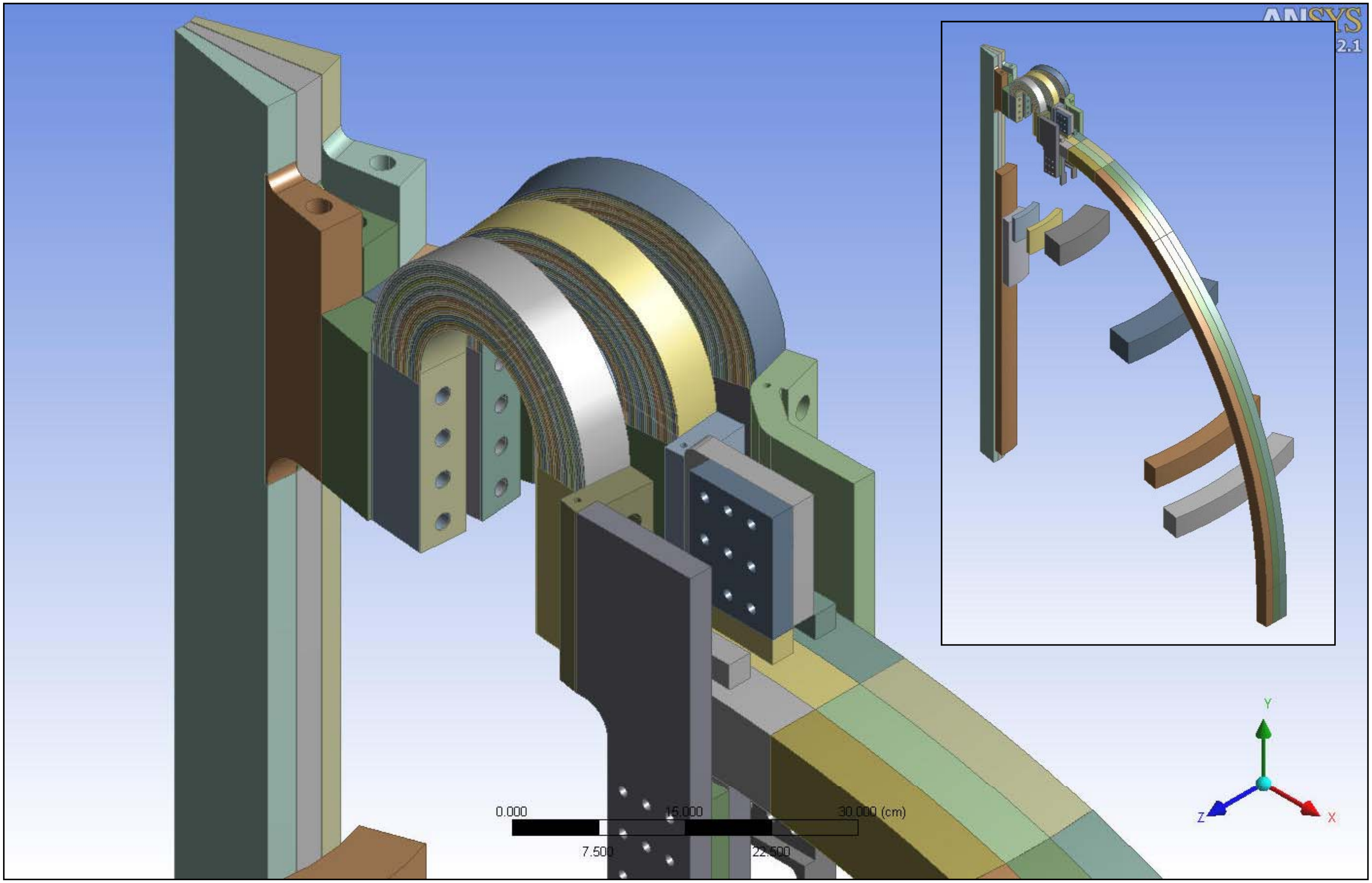
Note: This sequential, one-way coupled analysis is only valid if the bolted joints do not separate, and if the electrical and thermal contact resistances are a weak function of contact pressure, which is true in this case if the minimum local contact pressure is above 1500 psi.

SolidWorks Model of 3 Strap Assembly with Simplified OH, PF, and TF Coils



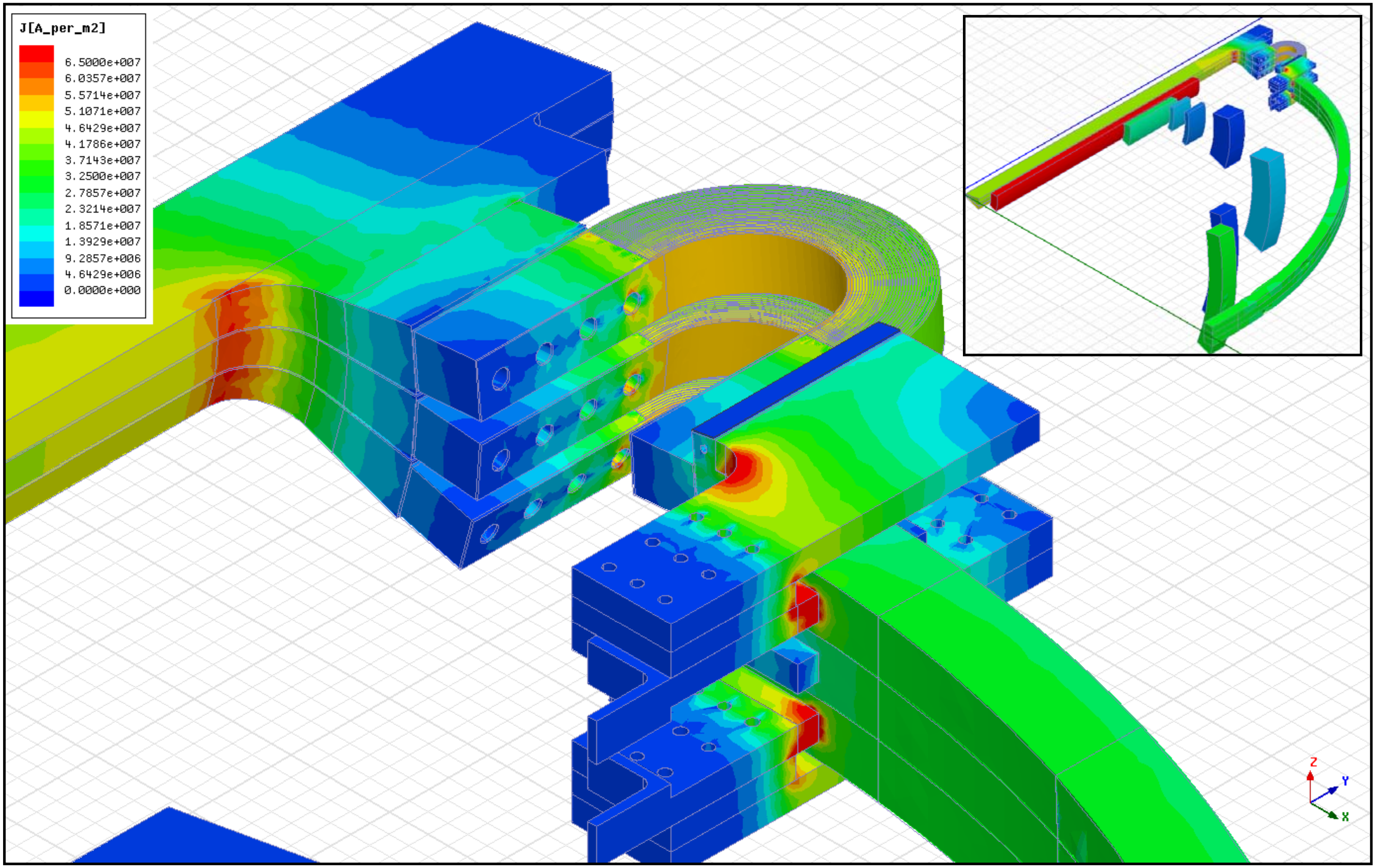
Maxwell Magnetostatic Analysis: DM Solid Model

310 Laminations/ Strap



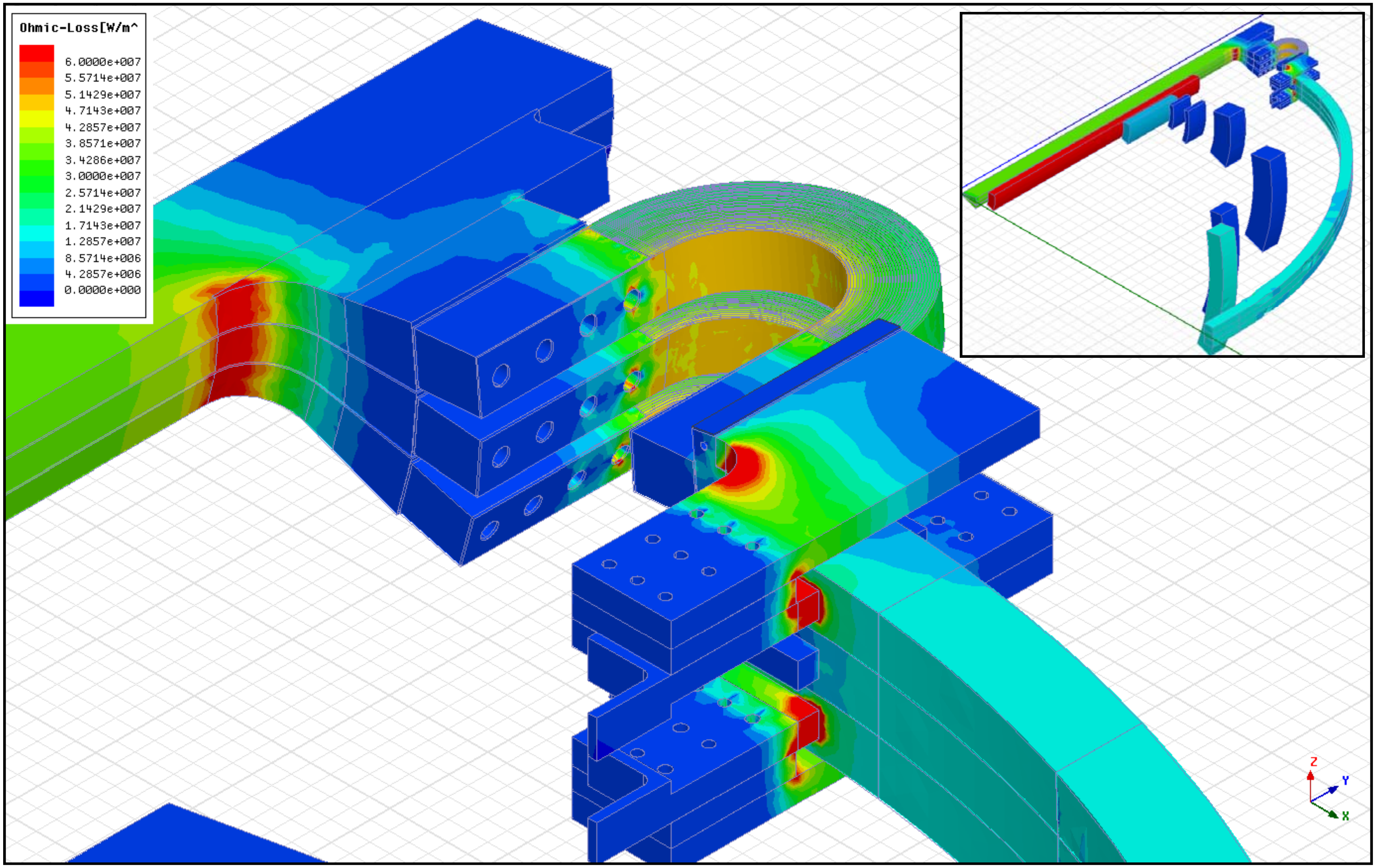
Maxwell Magnetostatic Results: Current Density

Current Scenario #82, 30 Laminations/ Strap



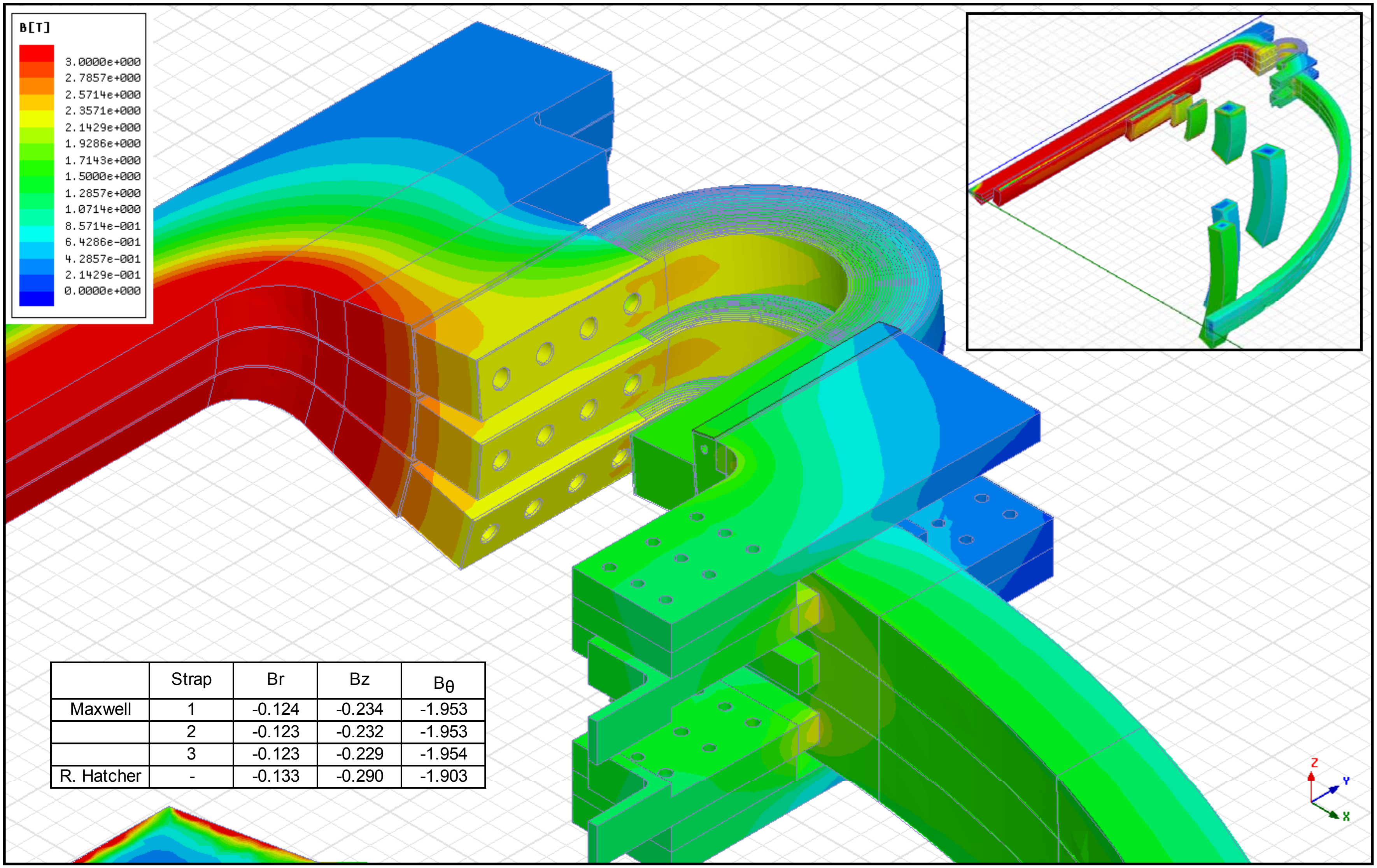
Maxwell Magnetostatic Results: Ohmic Loss

Current Scenario #82, 30 Laminations/ Strap



Maxwell Magnetostatic Results: Magnetic Flux Density

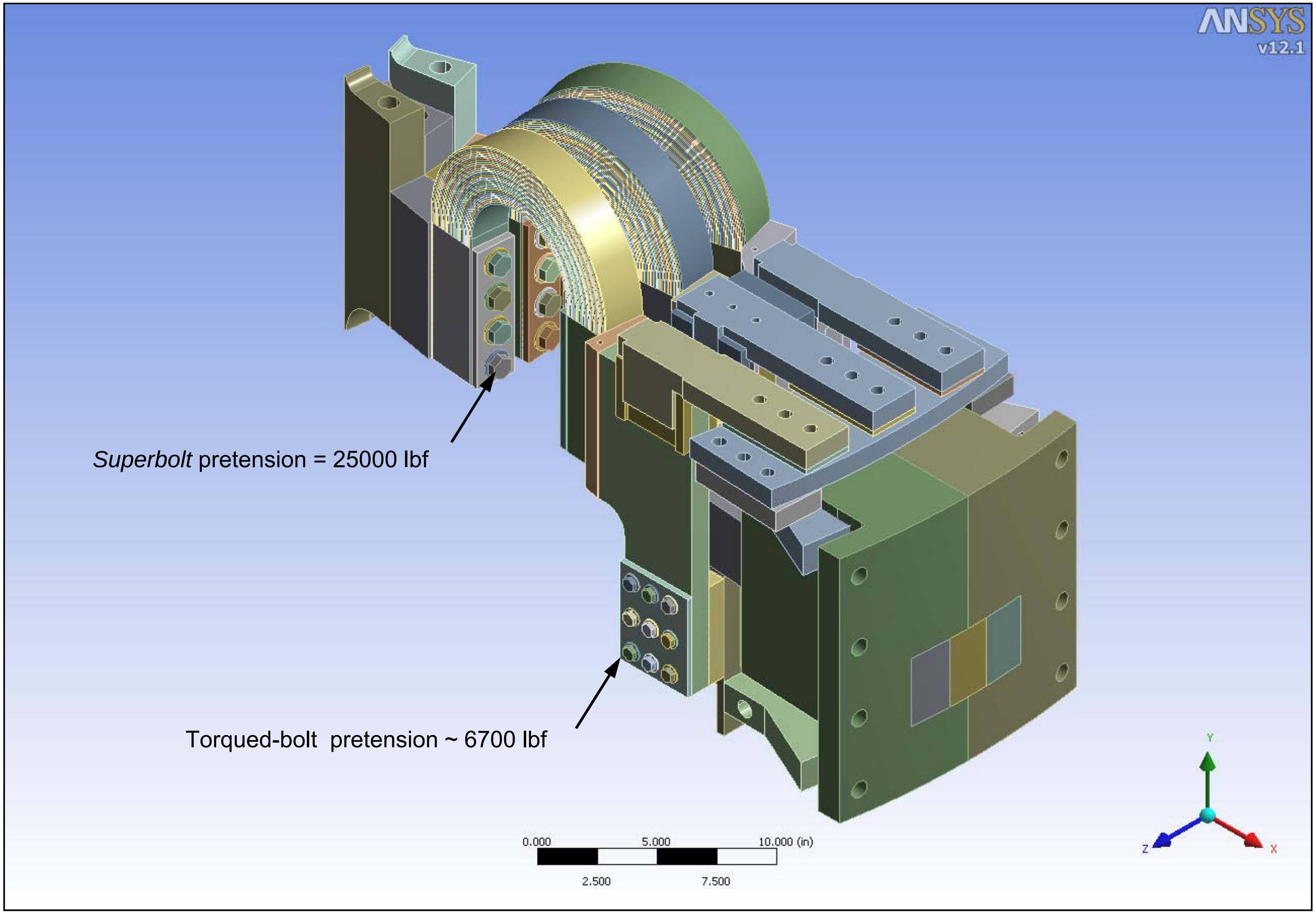
Current Scenario #82, 30 Laminations/ Strap



	Strap	Br	Bz	B_θ
Maxwell	1	-0.124	-0.234	-1.953
	2	-0.123	-0.232	-1.953
	3	-0.123	-0.229	-1.954
R. Hatcher	-	-0.133	-0.290	-1.903

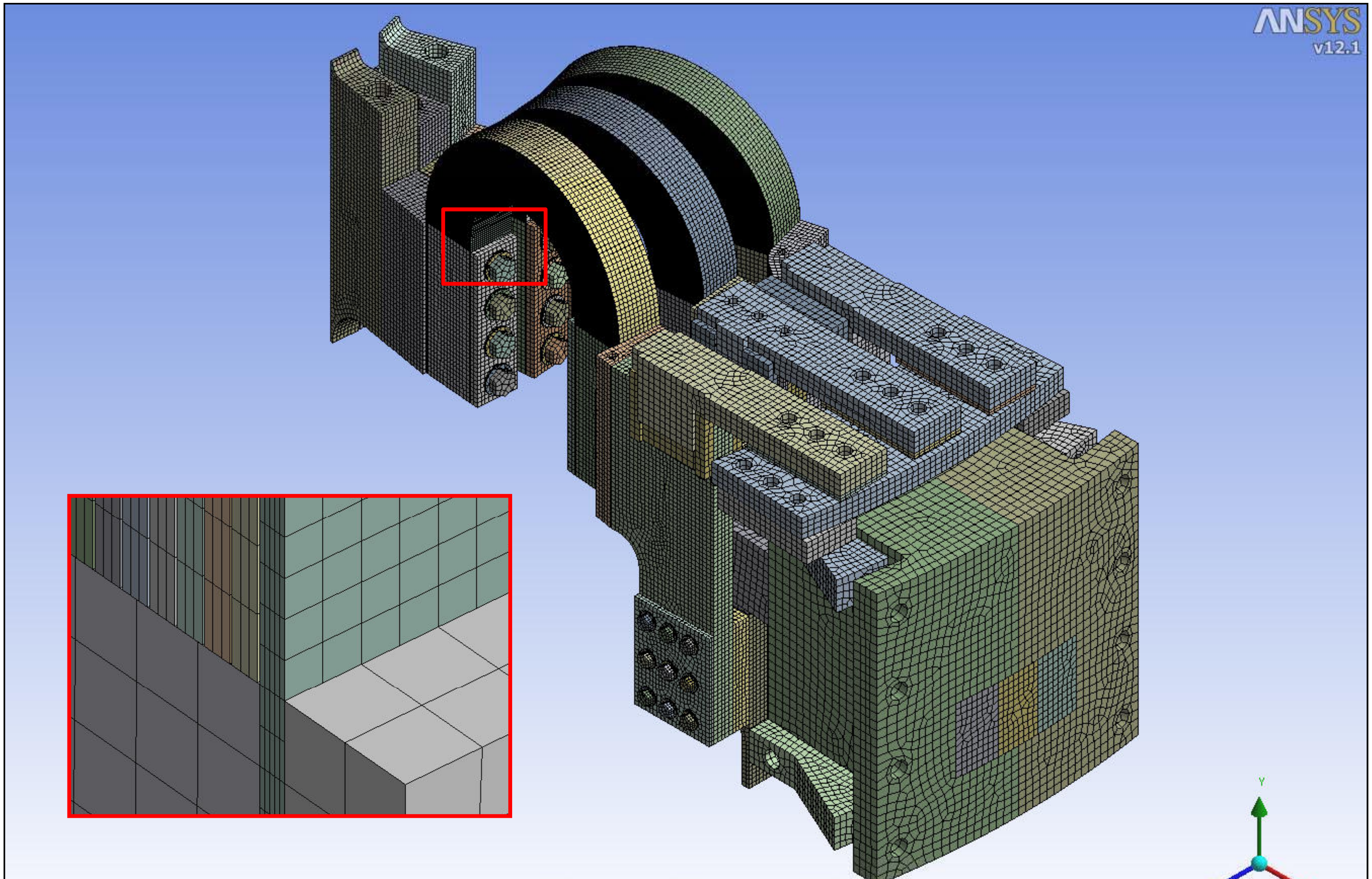
ANSYS Thermal and Structural Analysis Solid Model

30 Laminations/ Strap



ANSYS Thermal and Structural Analysis Mesh

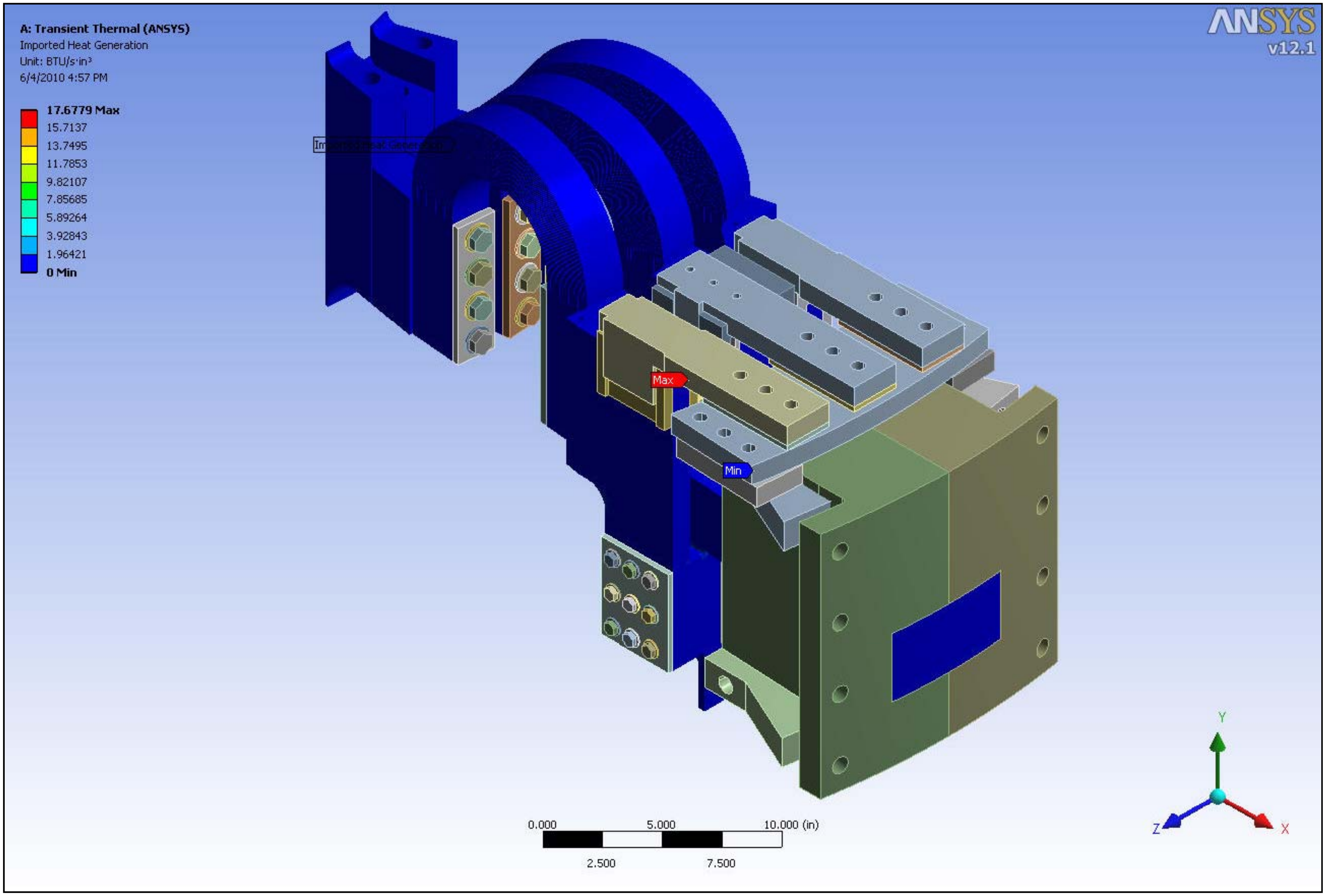
30 Laminations/ Strap



Nodes = 2,468,759
Elements = 518,097

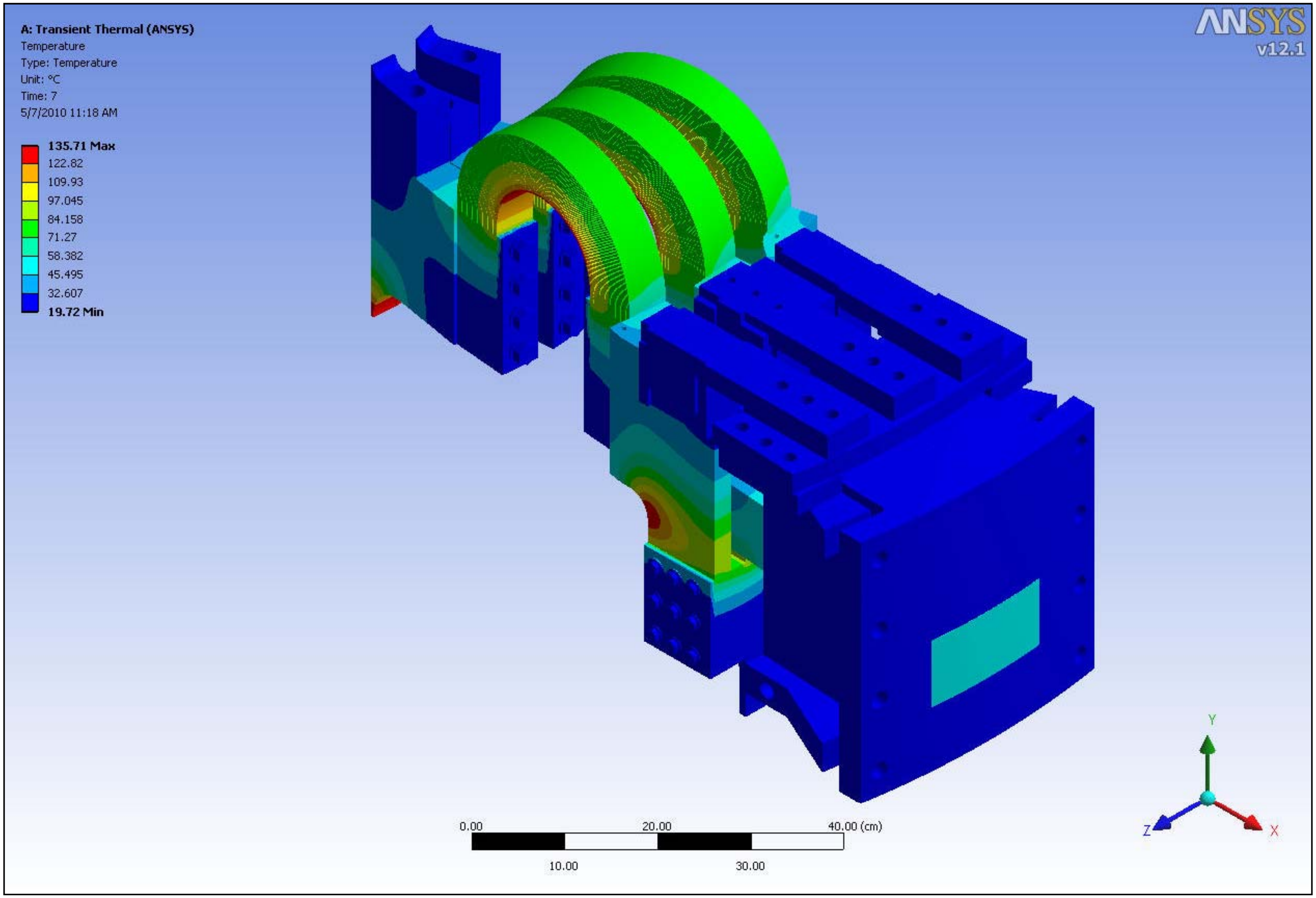
Parts Common Between *Maxwell* and *ANSYS* Analysis

30 Laminations/ Strap



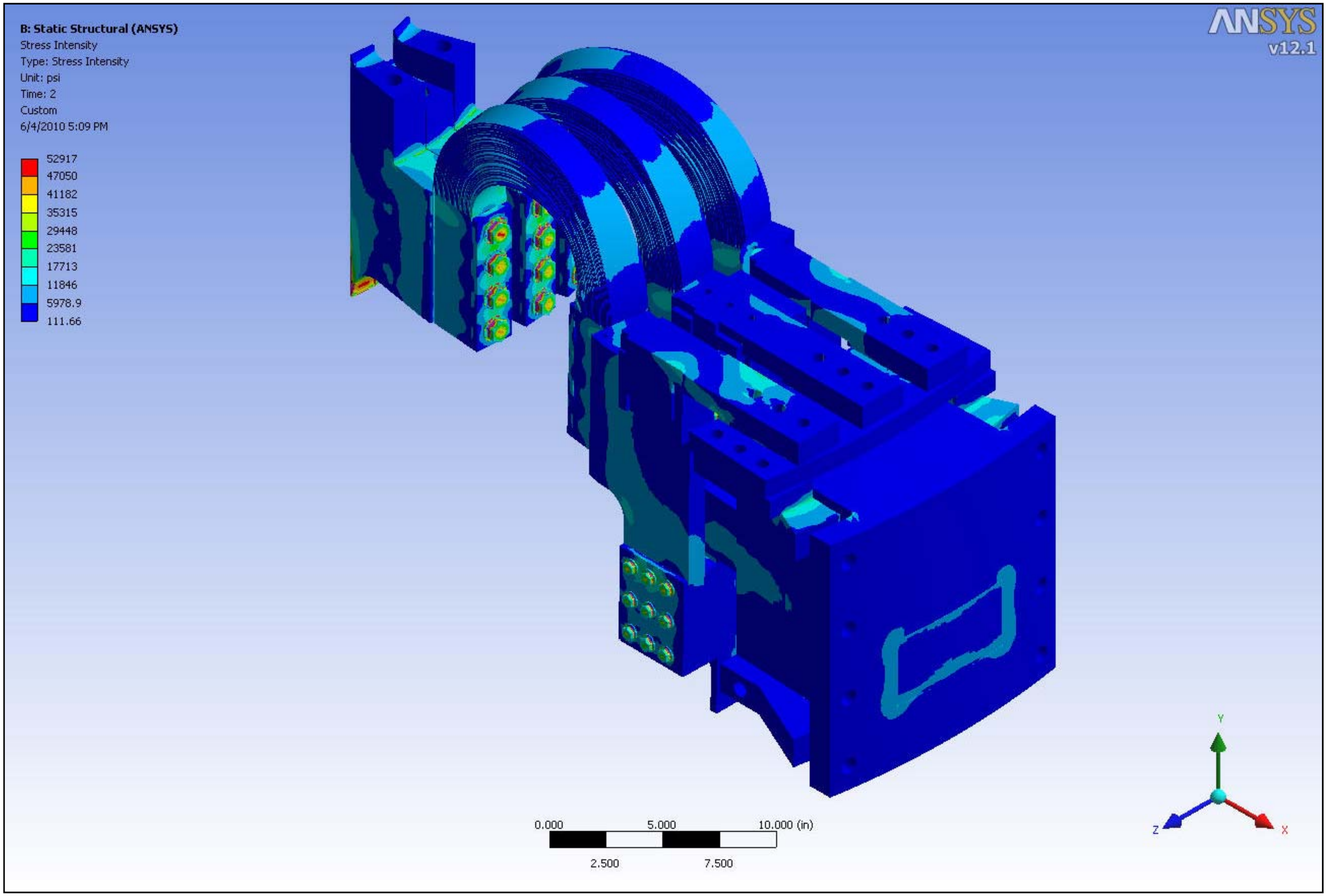
ANSYS Transient Thermal Results: Temperature

Current Scenario #82, 30 Laminations



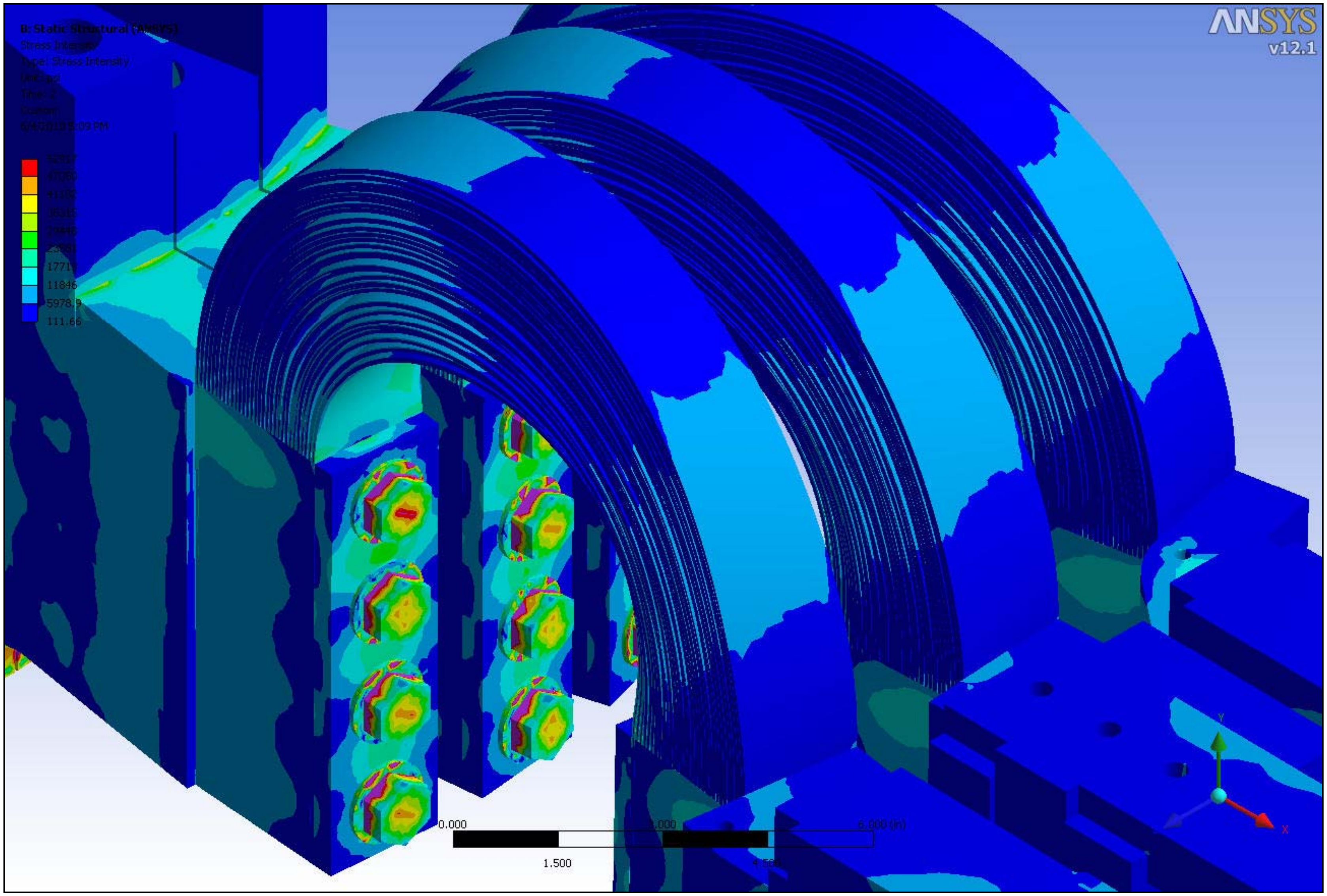
ANSYS Static Structural Results: Tresca Stress 1

Current Scenario #82, 30 Laminations/ Strap



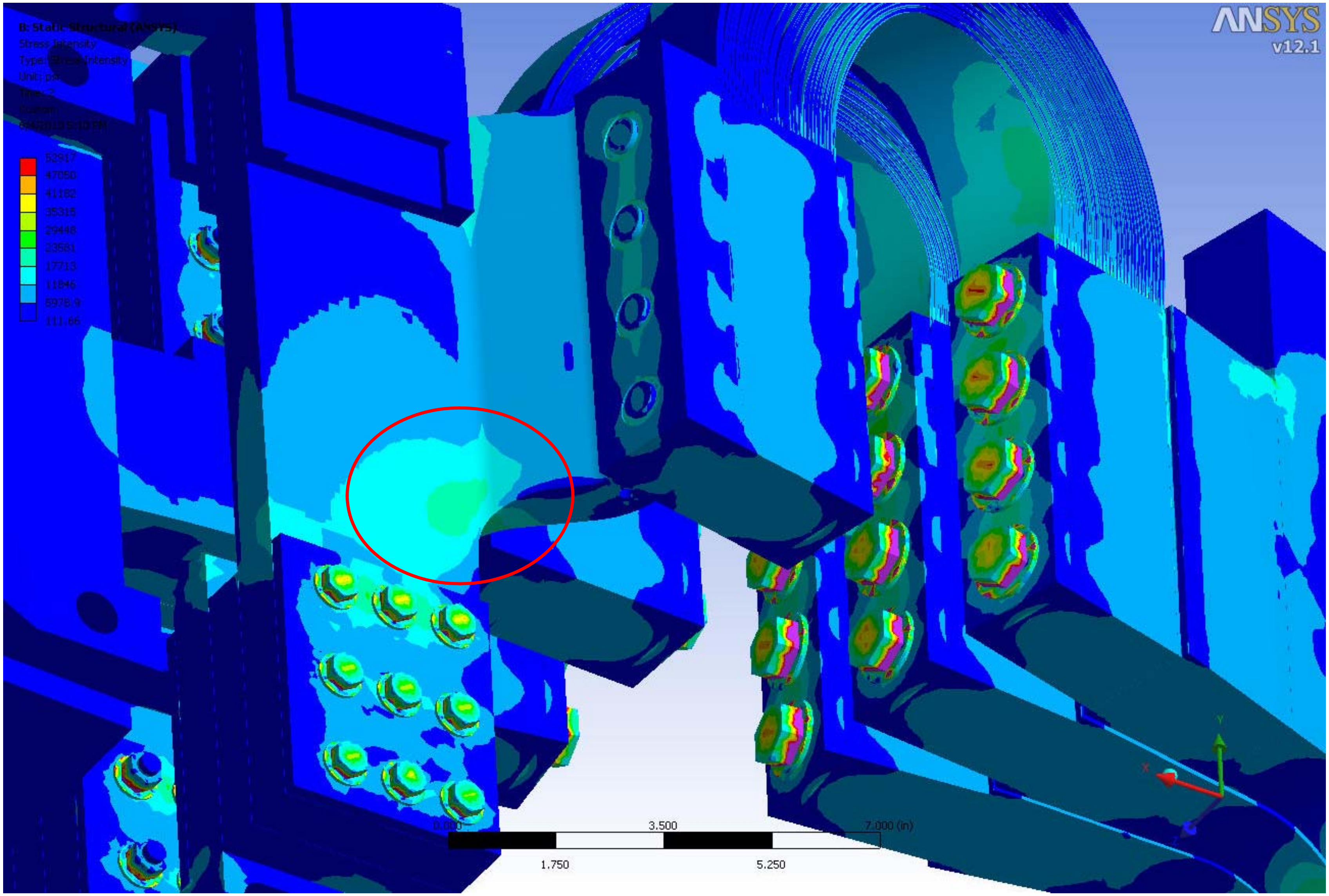
ANSYS Static Structural Results: Tresca Stress 2

Current Scenario #82, 30 Laminations/ Strap



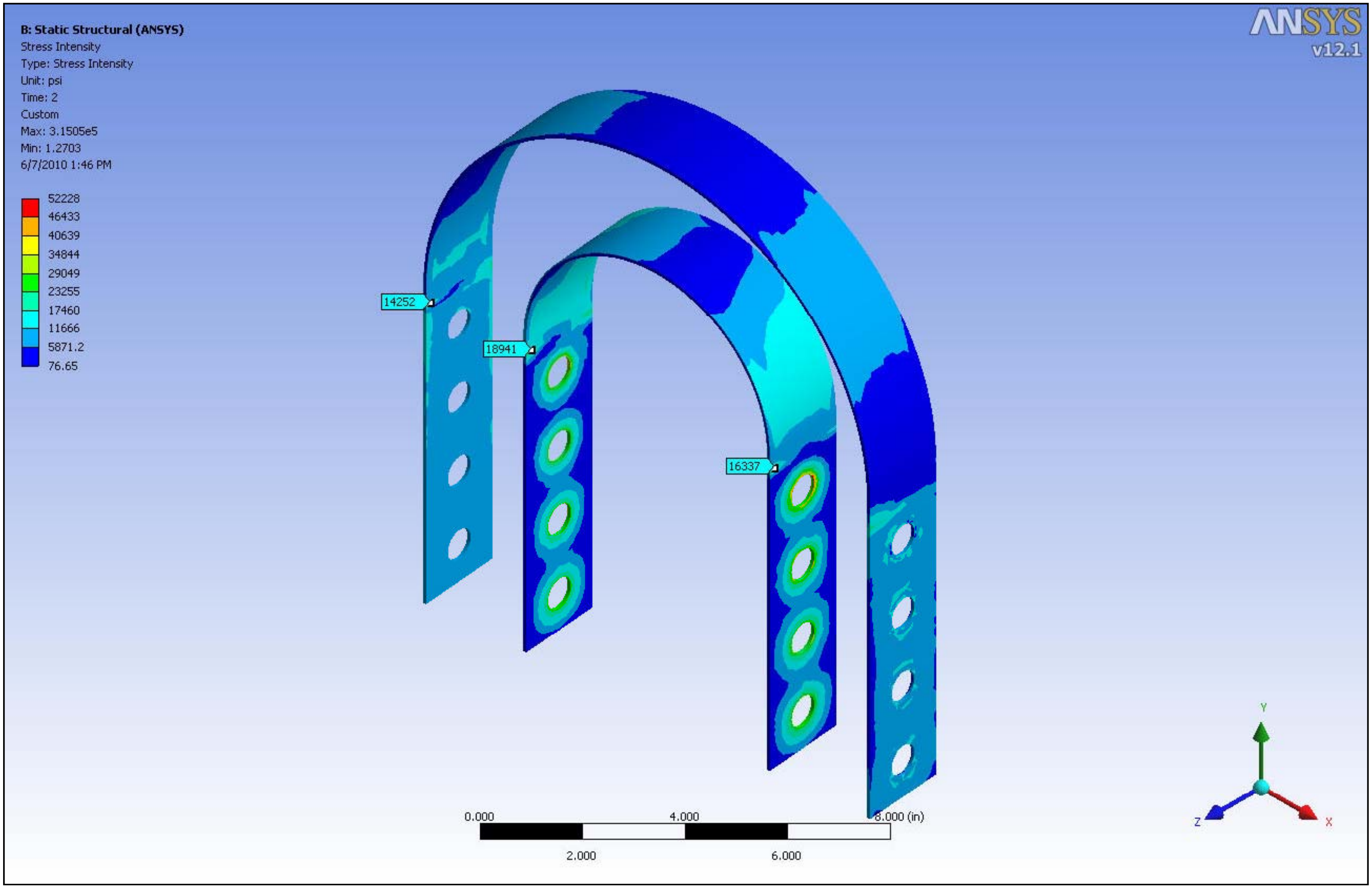
ANSYS Static Structural Results: Tresca Stress 4

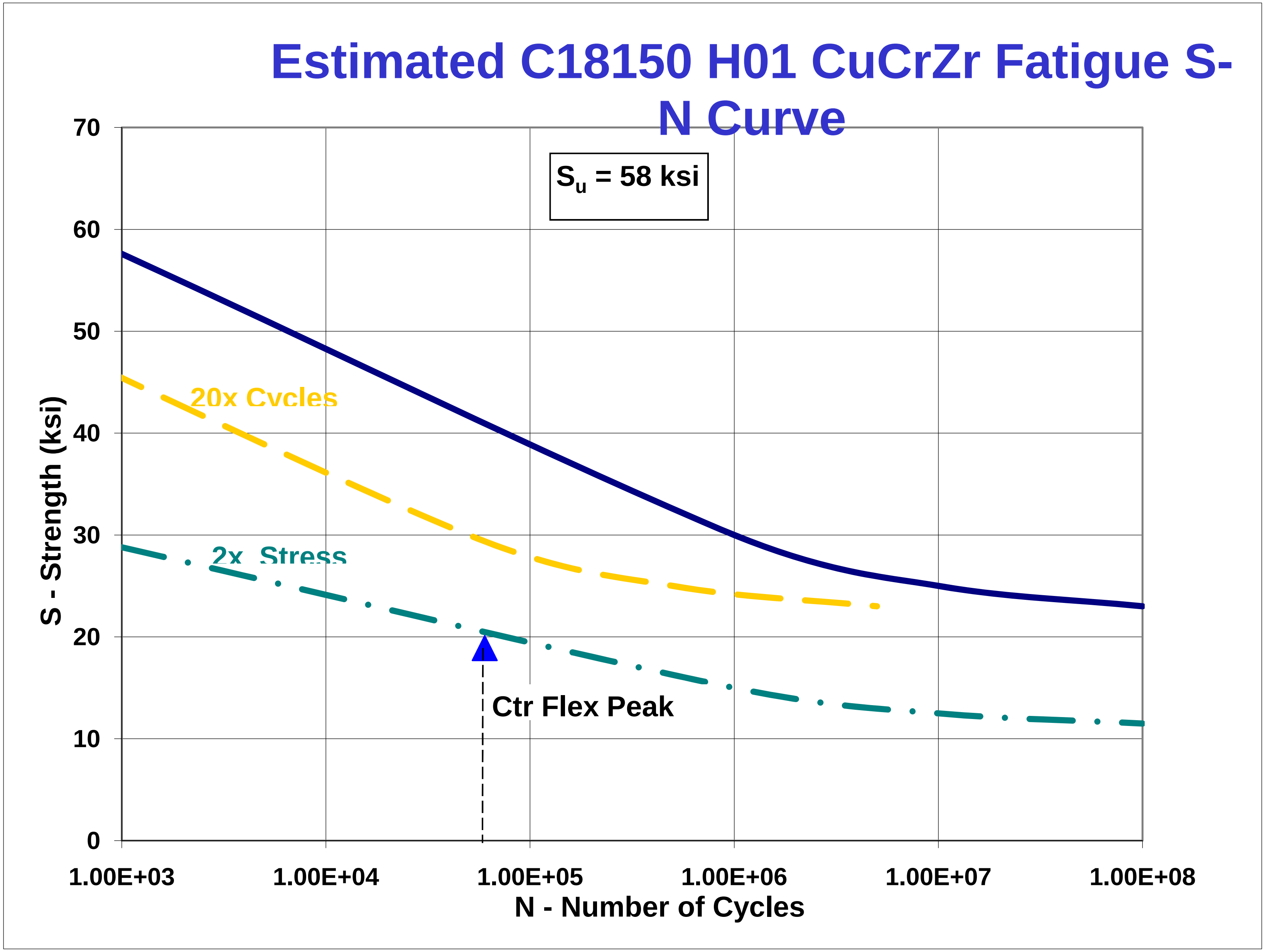
Current Scenario #82, 30 Laminations/ Strap



ANSYS Static Structural Results: Lamination Tresca Stress

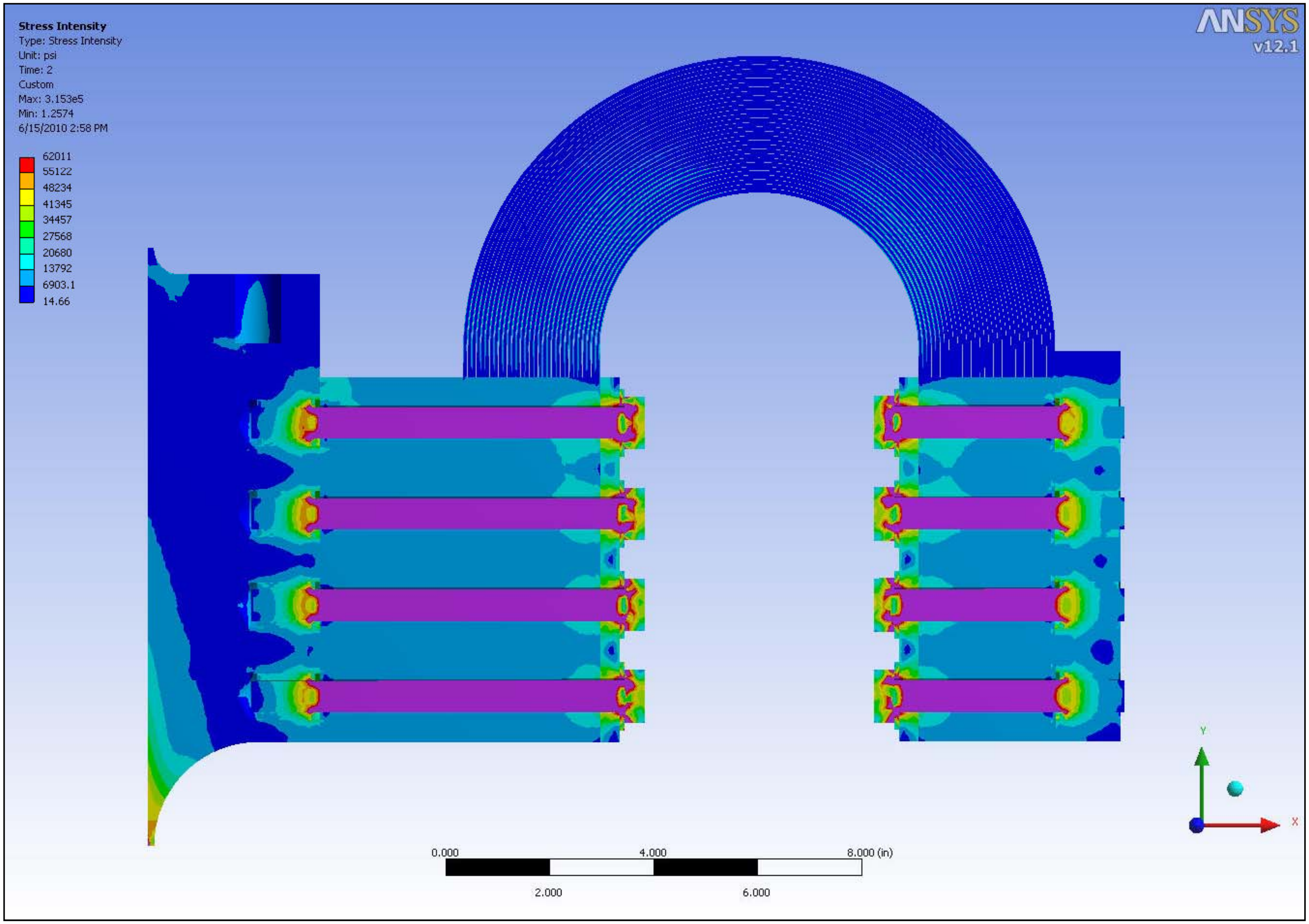
Current Scenario #82, 30 Laminations/ Strap, Center Strap

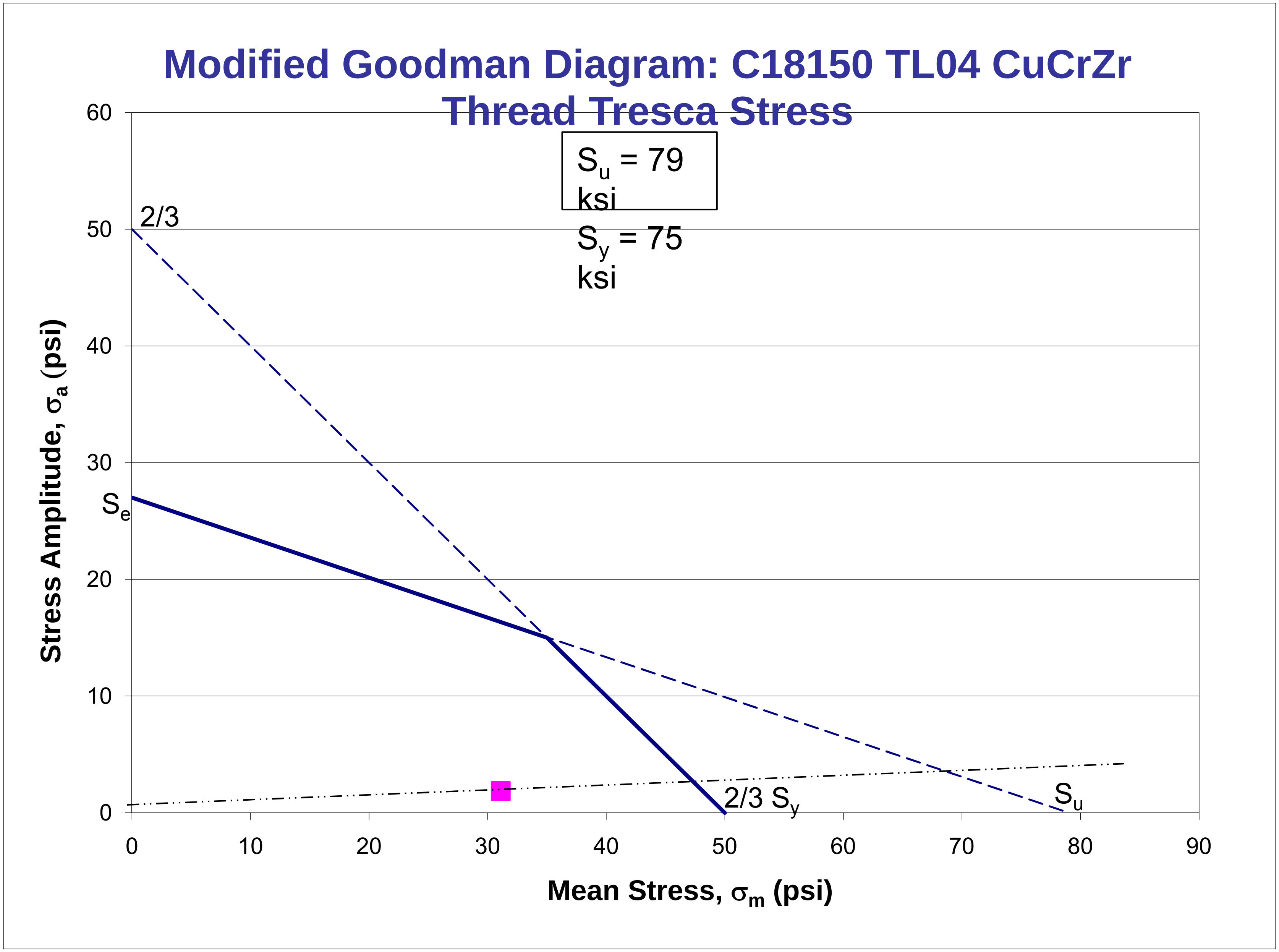



Estimated C18150 H01 CuCrZr Fatigue S-N Curve
S_u = 58 ksi
20x Cycles
2x Stress
Ctr Flex Peak
S - Strength (ksi)
N - Number of Cycles
70
60
50
40
30
20
10
0
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07
1.00E+08

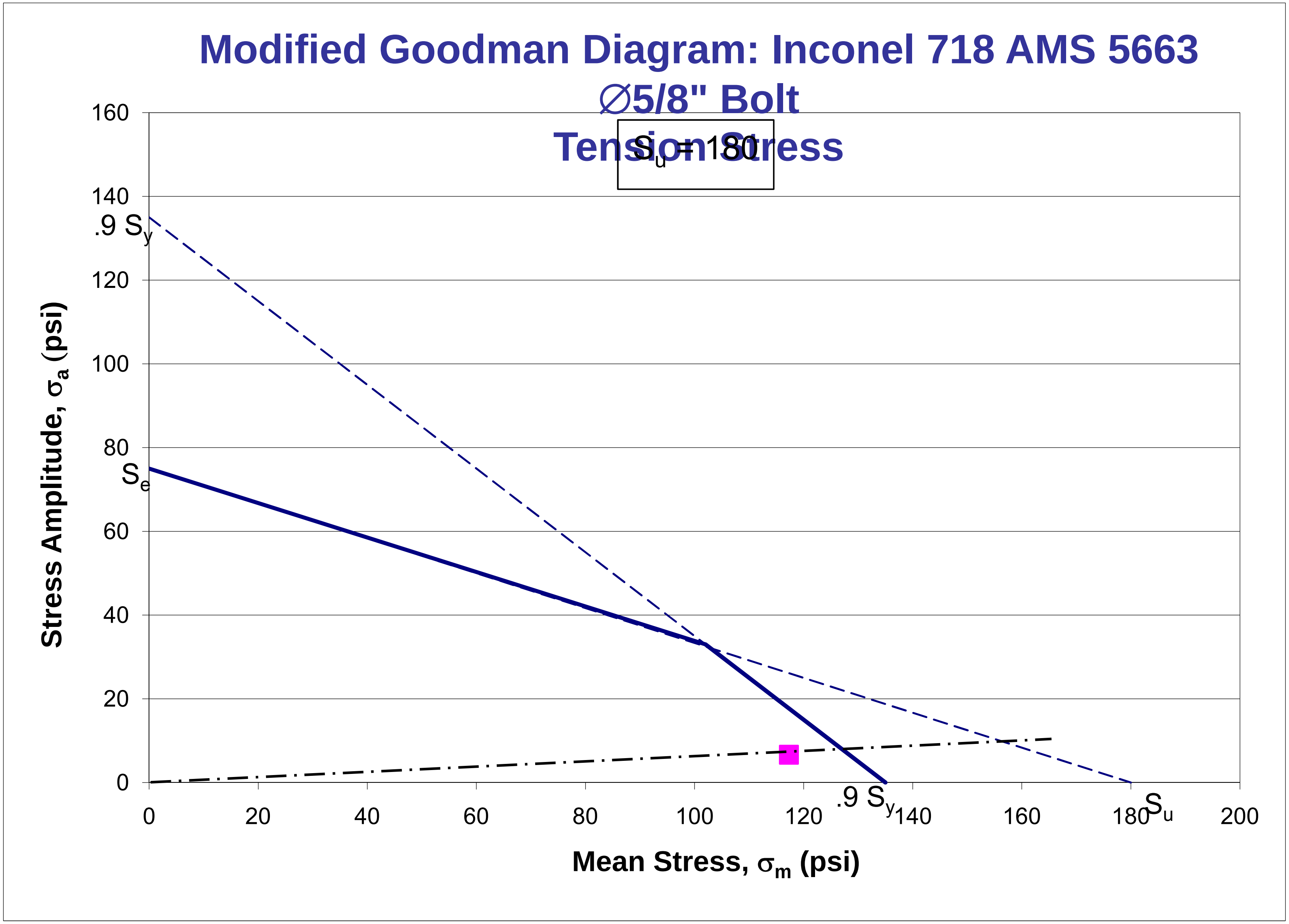
ANSYS Static Structural Results: Joint Tresca Stress

Current Scenario #82, 30 Laminations/ Strap



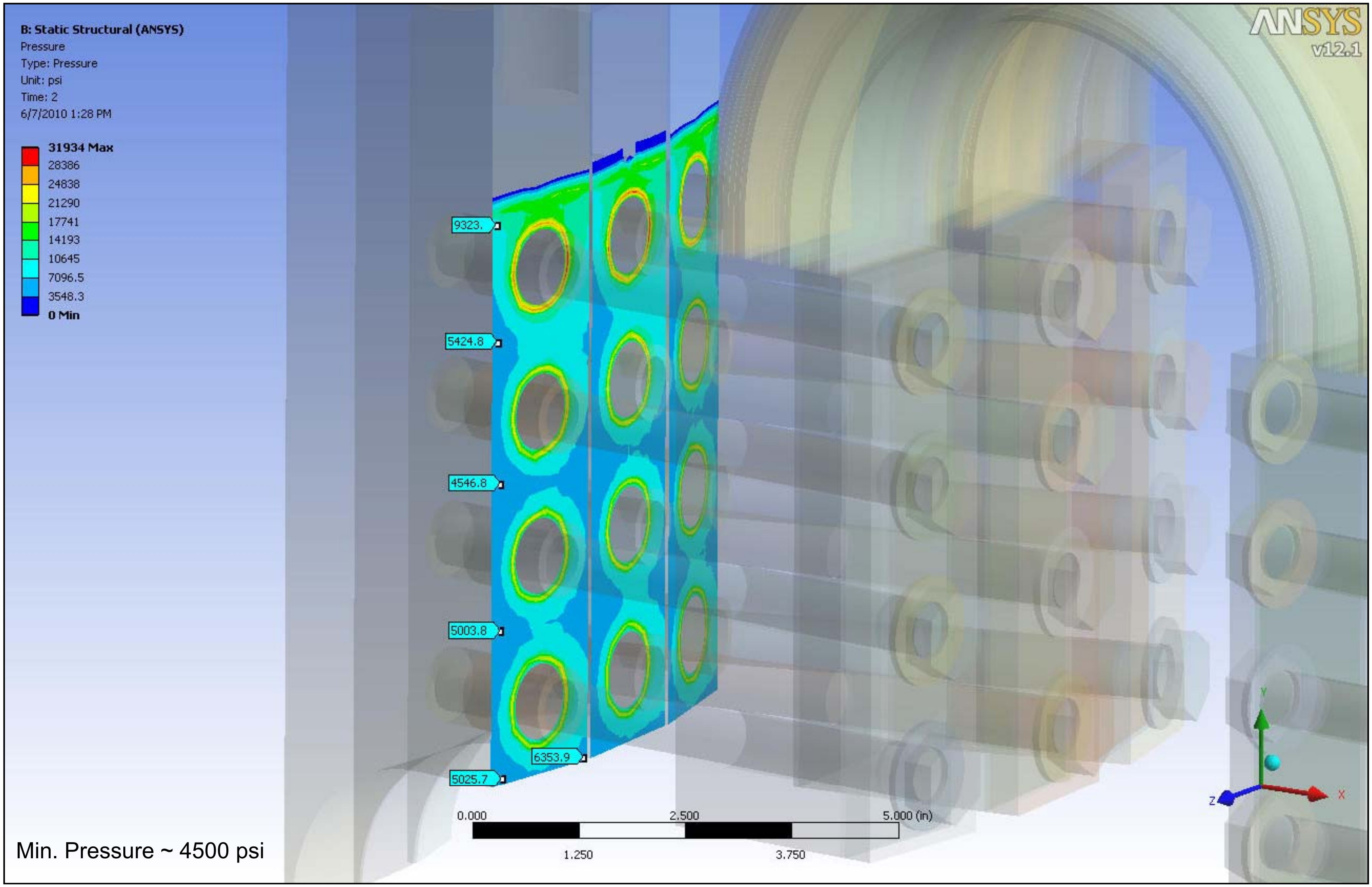


Modified Goodman Diagram: C18150 TL04 CuCrZr
Thread Tresca Stress
S_u = 79 ksi
S_y = 75 ksi
2/3
S_e
2/3 S_y
S_u
Stress Amplitude, σ_a (psi)
Mean Stress, σ_m (psi)
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90


Modified Goodman Diagram: Inconel 718 AMS 5663
∅5/8" Bolt
Tension Stress
Su = 180
.9 Sy
Se
.9 Sy
Su
Stress Amplitude, σa (psi)
Mean Stress, σm (psi)
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
120
140
160
180
200

ANSYS Static Structural Results: 5/8” Bolted Contact Pressure

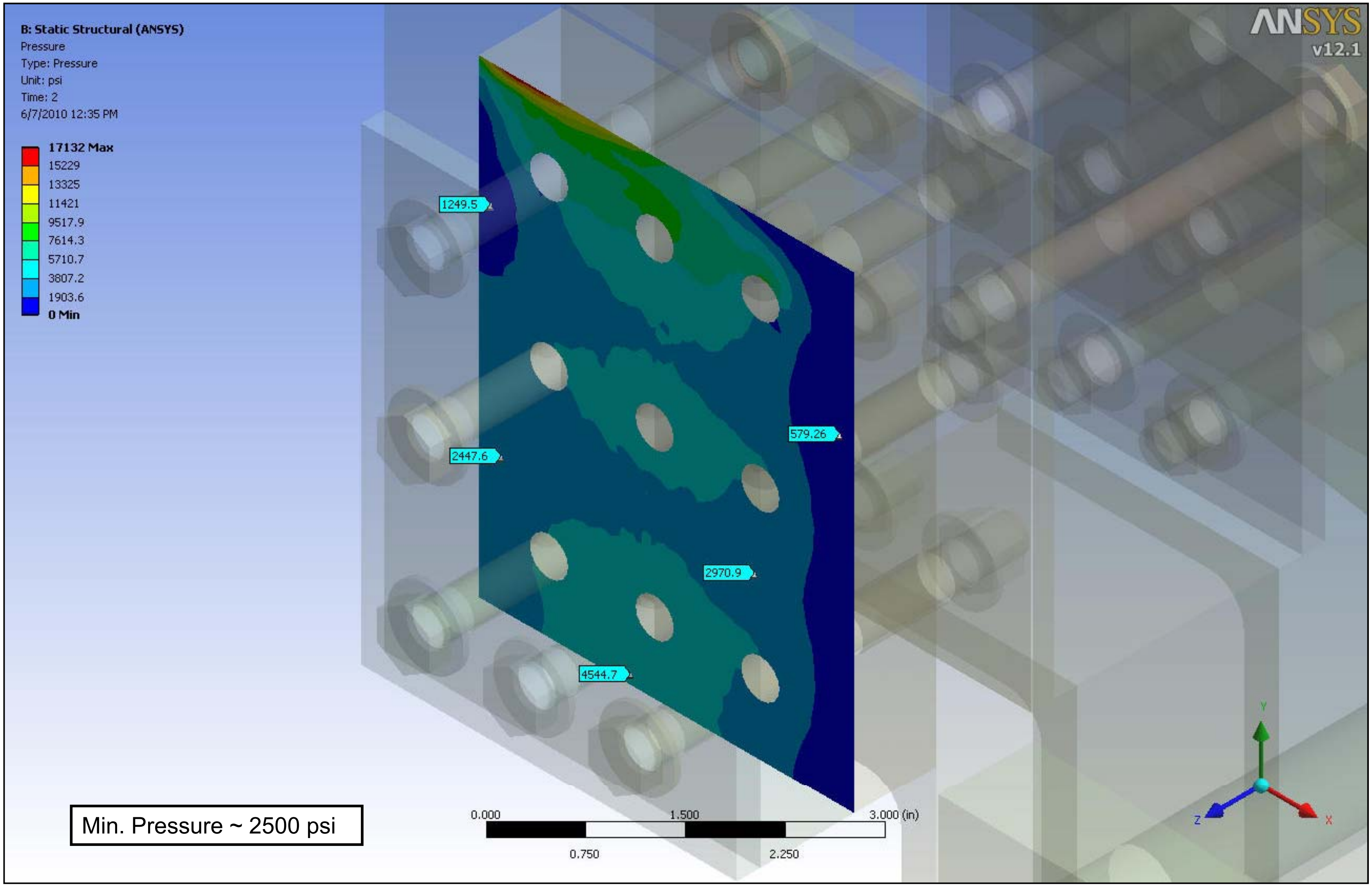
Current Scenario #82, 30 Laminations/ Strap



Min. Pressure ~ 4500 psi

ANSYS Static Structural Results: 3/8” Bolted Contact Pressure

Current Scenario #82, 30 Laminations/ Strap



Flex Strap and Bolted Joint Design Verification Tests

- Tests Performed at 3 Different Levels
  - Material Level
    - C18150 H01 fatigue strength (R0)
  - Stub Joint Level
    - HeliCoil insert pull-out strength in C18150 copper stub, static and fatigue
    - Inconel 718 custom *Superbolt* nut/ stud fatigue strength
  - Flex Strap Assembly Level
    - Manufacturability
    - In-plane bending stiffness
    - Cyclic, simulated maximum combined loads
    - Contact pressure distribution
      - Bolt pretension only
      - Bolt pretension + simulated maximum combined-load
    - *Superbolt* nut tensioned in umbrella segment mock-up

Conclusions

1. Lamination Stress:

Excluding singularities, the maximum Tresca stress in the laminations is 18.9 ksi. To satisfy the requires of the NSTX Structural Design Criteria, the fatigue strength at 60 K cycles must be greater than twice this stress, or the fatigue strength at 1.2 E06 cycles (20x N) must be equal to or greater than this stress, whichever is the more severe requirement.

– The fatigue S-N curve for C18150 copper-zirconium, with the maximum lamination Tresca stress plotted at N = 60 K cycles, is shown above. The lamination stress is slightly below the 2x stress level and meets all the requirement of the Design Criteria.

2. Copper Flag Thread Stress:

The average shear stress in the copper threads is 34.8 ksi. To satisfy the Design Criteria, the shear stress must be less than 0.6 Sm = .4 Sy = 37.5 ksi.

– The Modified Goodman diagram for C18150 copper-chromium-zirconium, with thread Tresca stress plotted, is shown above. The thread stress meets all the requirements of the Design Criteria.

3. Contact Status/ Pressure:

Results show that none of the joints separate, and that the minimum local contact pressure is approximately 2600 psi, which is 1100 psi above the minimum requirement.

– Initial assumptions are correct, sequential one-way coupled model is valid.

4. Lamination Buckling Load Multiplier Factor (LMF):

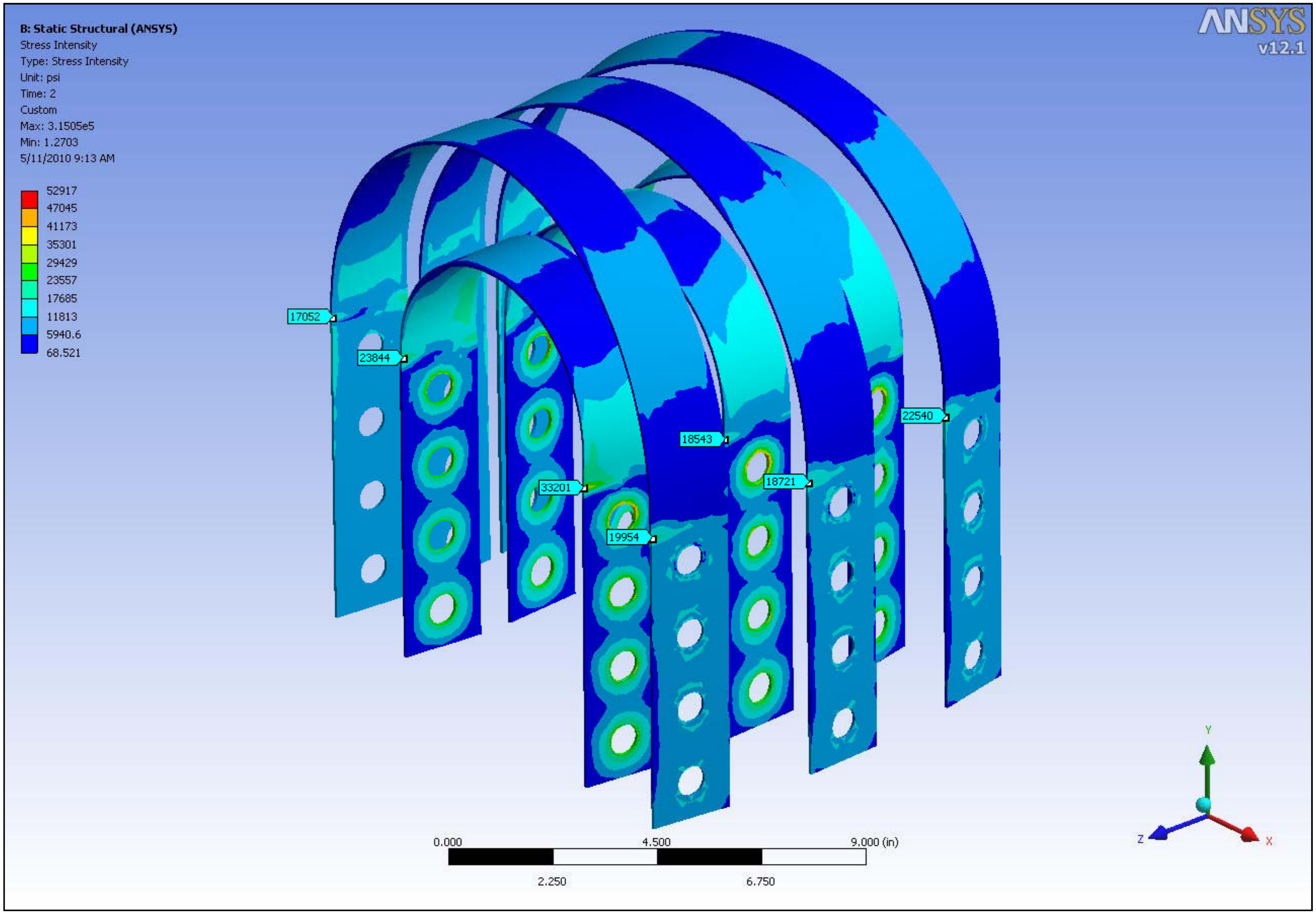
The 1st mode LMF is 58 (see Appendix), well above the Design Criteria linear buckling requirement of 5.

Appendix A

Lamella Stress Linearization

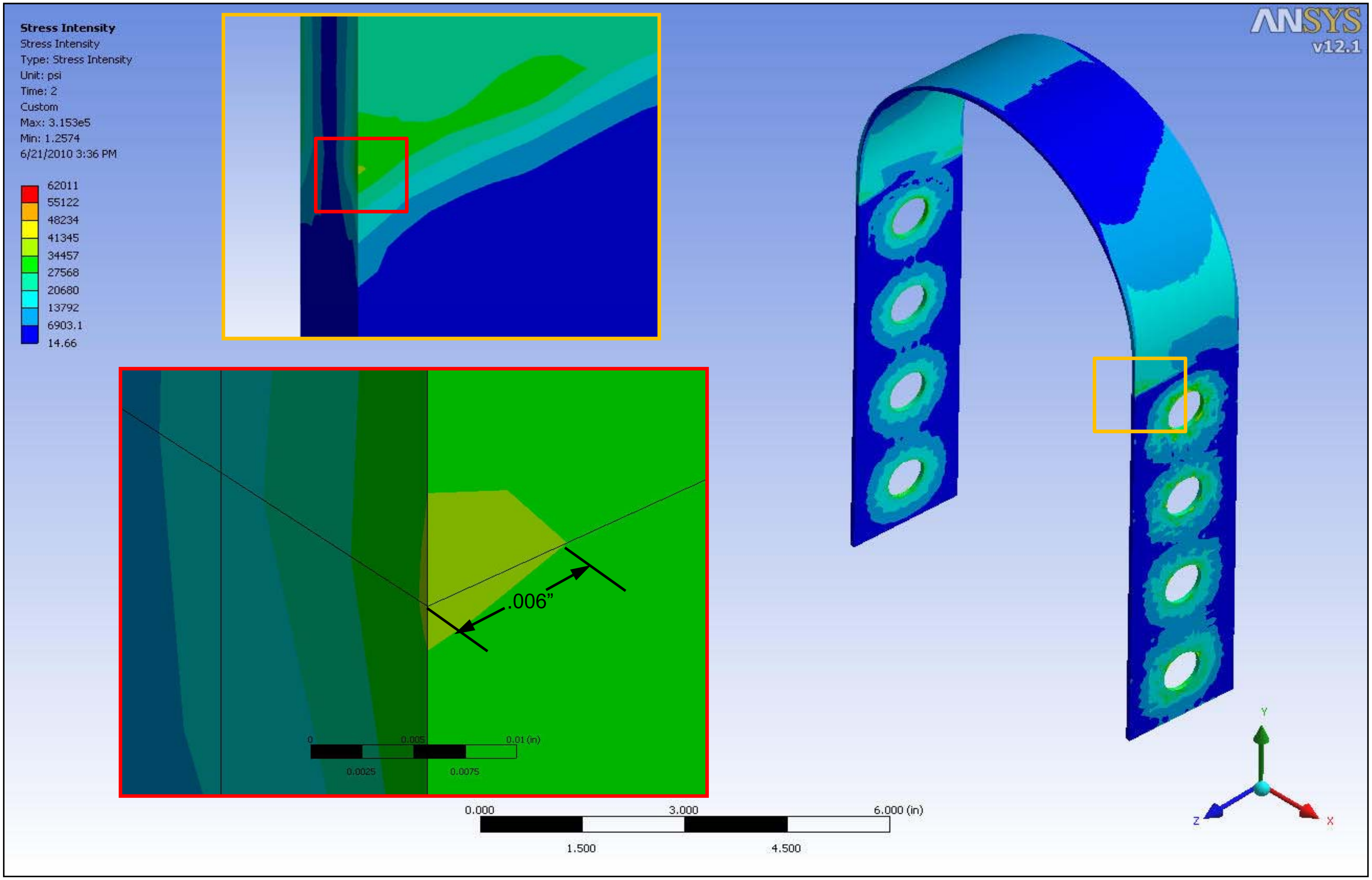
ANSYS Static Structural Results: Lamination Tresca Stress

Current Scenario #82, 30 Laminations/ Strap



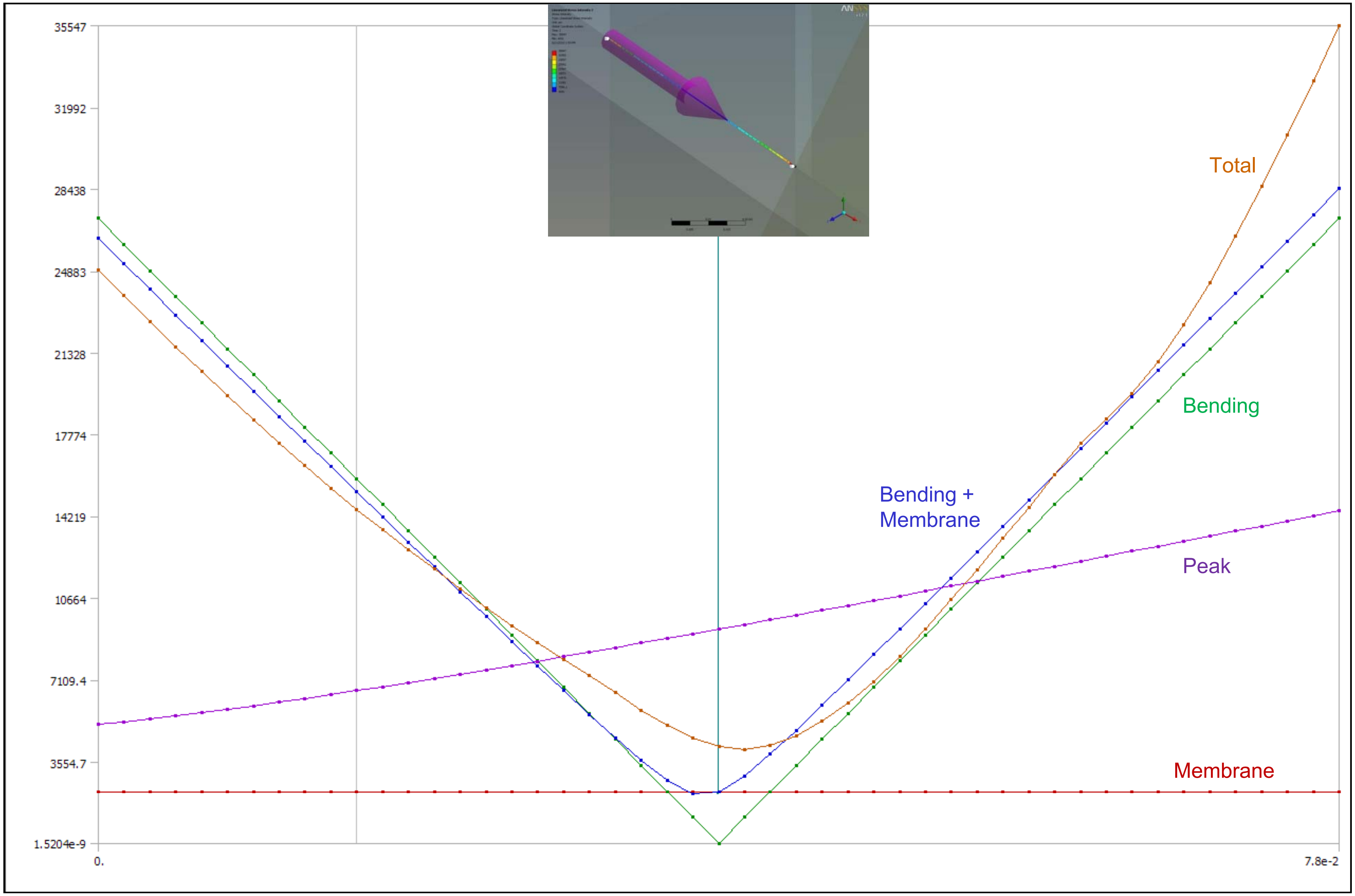
ANSYS Static Structural Results: Lamination Stress Singularity

Current Scenario #82, 30 Laminations/ Strap, Center Strap



ANSYS Static Structural Results: Stress Linearization

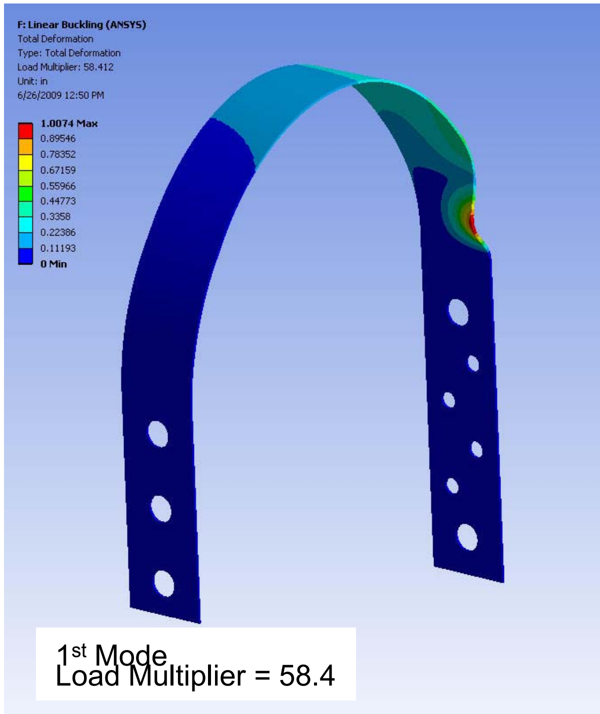
Current Scenario #82, 30 Laminations/ Strap, Worst-Case Lamination



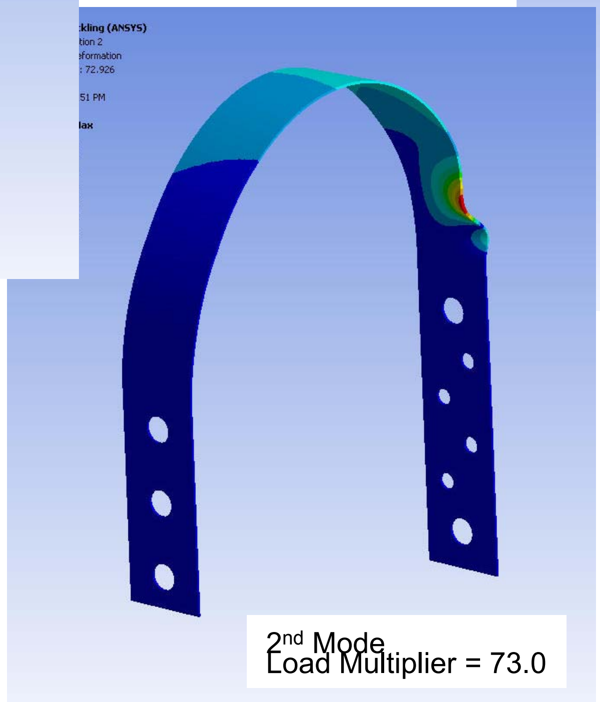
Appendix B

Lamella Buckling Analysis

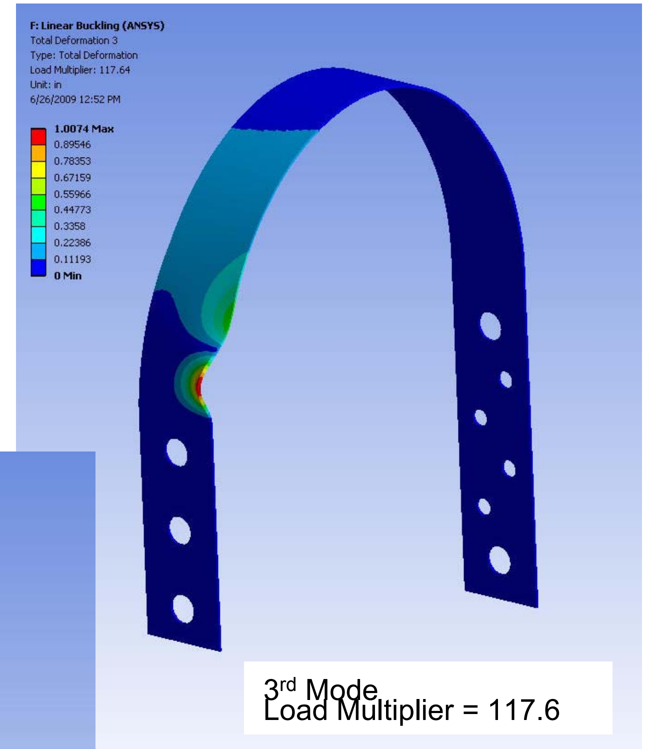
Single Lamination Linear Buckling Model Results



1st Mode
Load Multiplier = 58.4



2nd Mode
Load Multiplier = 73.0



3rd Mode
Load Multiplier = 117.6

Appendix C

Flex Strap Dynamic Load Factor

HALF-SINE PULSE

Consider the "half-sine" acceleration pulse (Fig. 31.20*A*) of amplitude $\ddot{u}_m$ and duration τ:

$$\ddot{u} = \ddot{u}_m \sin \frac{\pi t}{\tau} \qquad [0 \le t \le \tau]$$
$$\ddot{u} = 0 \qquad [t > \tau] \tag{31.34}$$

From Eq. (31.28), the effective duration is

$$\tau_r = \frac{2}{\pi}\,\tau \tag{31.35}$$

VERSED SINE PULSE

The versed sine pulse (Fig. 31.20*B*) is described by

$$\ddot{u} = \frac{\ddot{u}_m}{2}\left(1 - \cos \frac{2\pi t}{\tau}\right) = \ddot{u}_m \sin^2 \frac{\pi t}{\tau} \qquad [0 \le t \le \tau]$$
$$\ddot{u} = 0 \qquad [t > \tau] \tag{31.36}$$

The effective duration τ_r given by Eq. (31.28) is

$$\tau_r = (\tfrac{1}{2})\tau \tag{31.37}$$

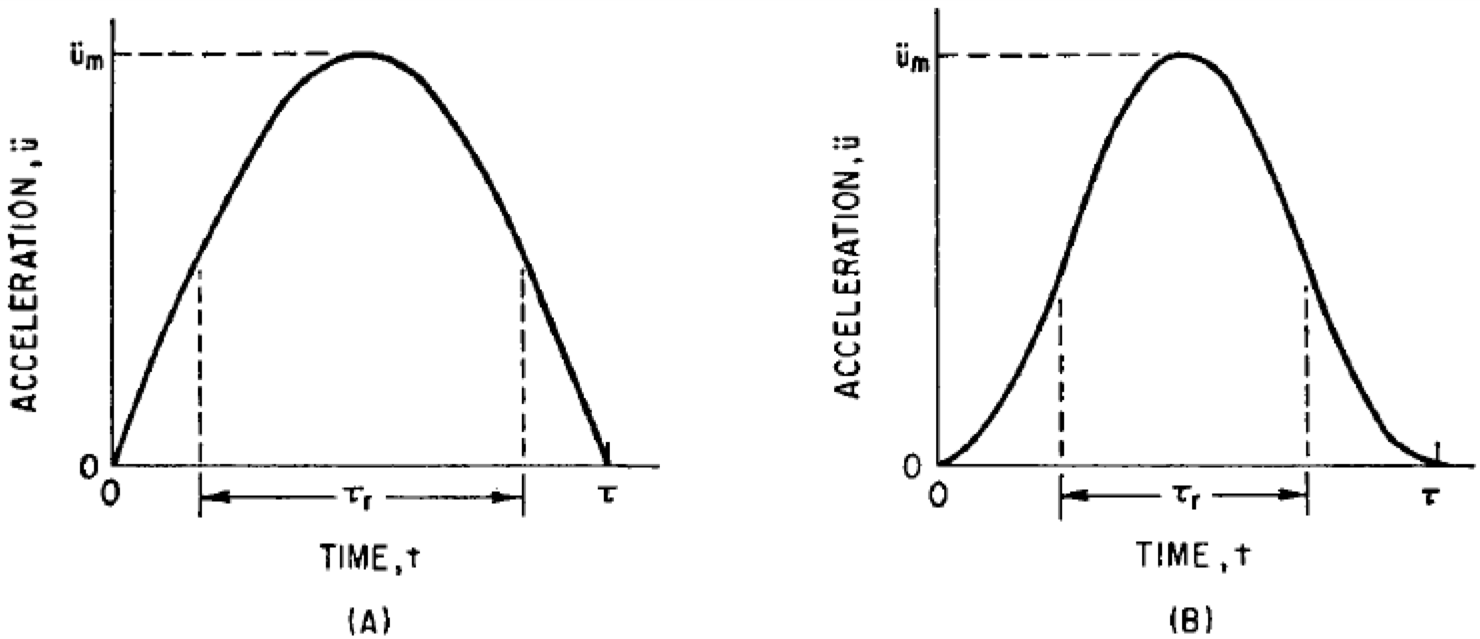


FIGURE 31.20 Half-sine acceleration pulse (*A*) and versed sine acceleration pulse (*B*).

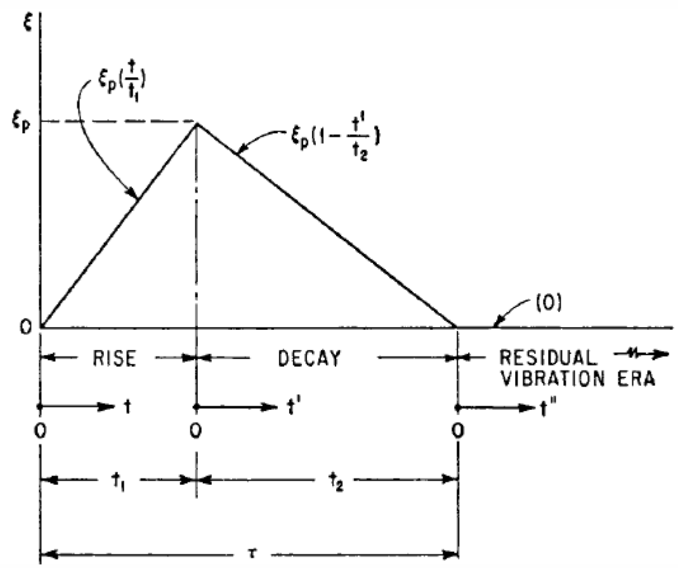


FIGURE 8.21 General triangular pulse.

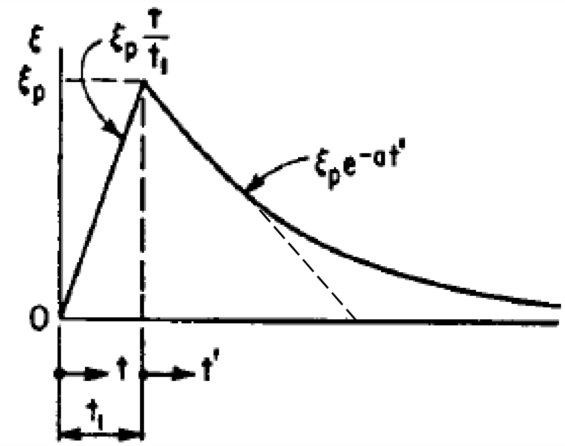
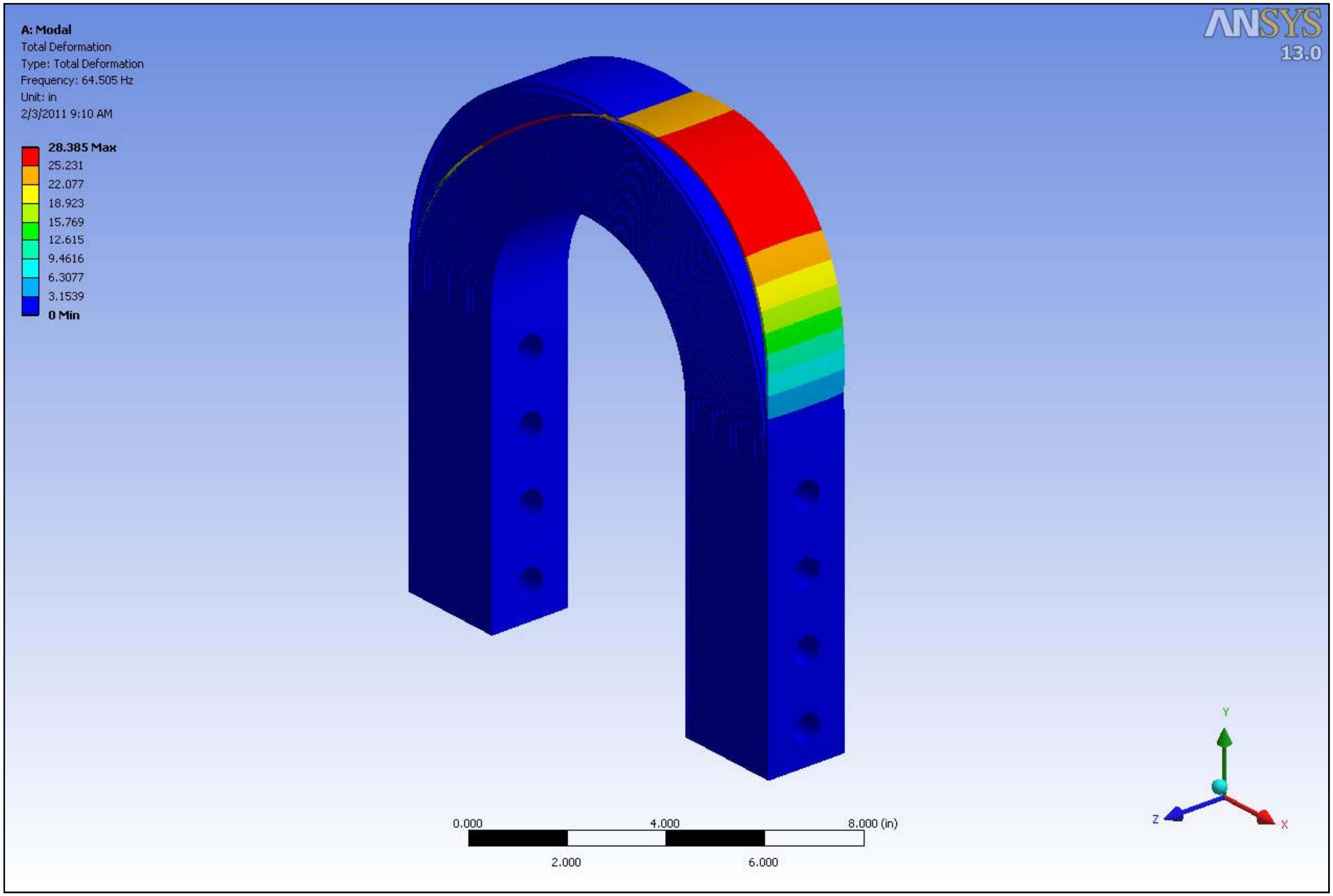


FIGURE 8.35 Pulse formed by a straight-line rise followed by an exponential decay asymptotic to the time axis.

t_r ~ 6 ms

Centered Plasma Disruption: Effective Pulse Duration



Modal Analysis Results: Flex Strap Mode 1 = 65 Hz

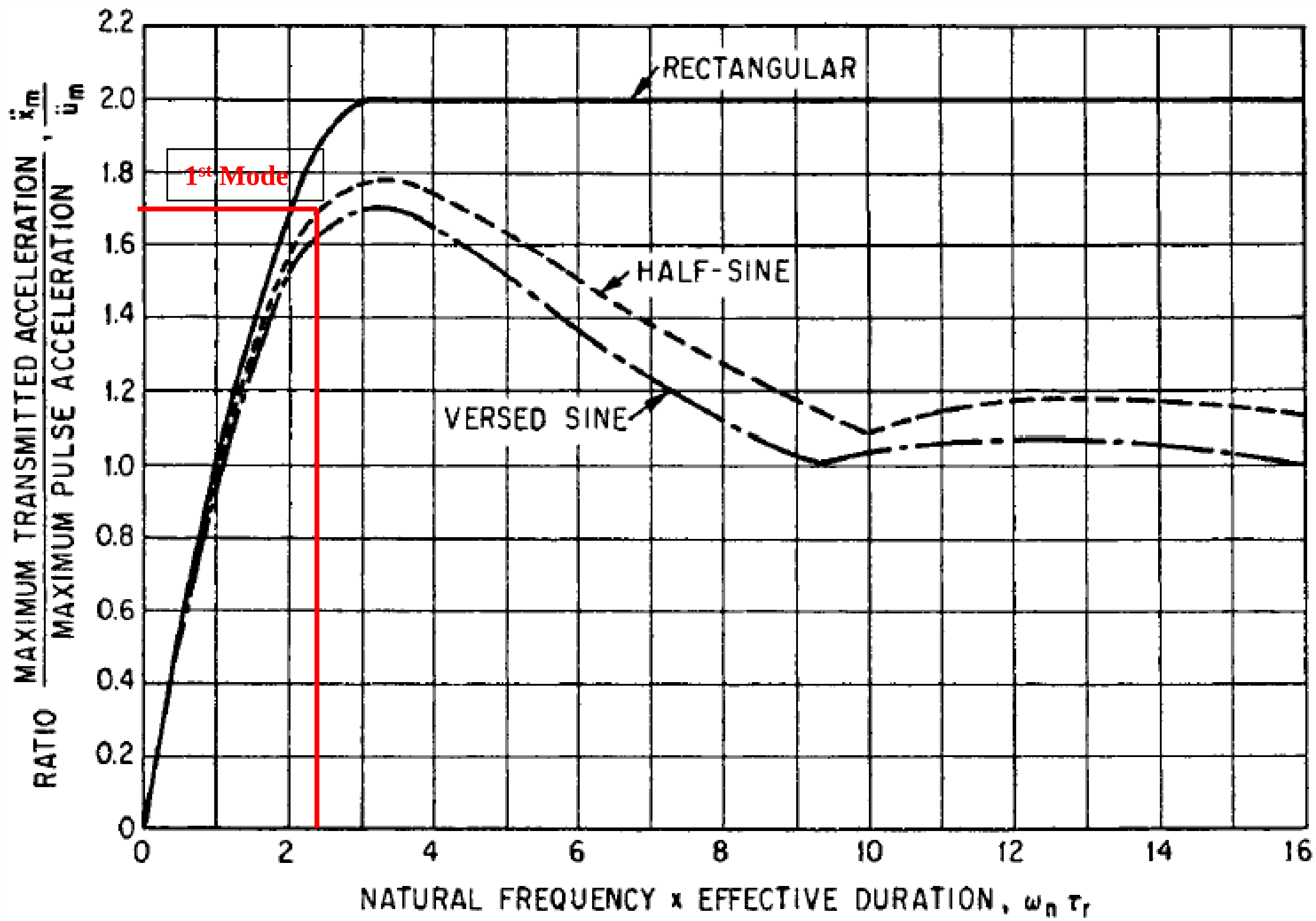


FIGURE 31.22 Shock transmissibility for the undamped linear system of Fig. 31.6 as a function of angular natural frequency ω_n and effective pulse duration τ_r.