NSTX

Ring Bolted Joint

NSTX-CALC-132-11

Rev 0

March 2011

Prepared By:

Peter Rogoff Digitally signed by Peter Rogoff
DN: cn=Peter Rogoff, o=Princeton Plasma Physics Lab, ou=Mechanical Engineering, email=progoff@pppl.gov, c=US
Date: 2011.04.12 10:58:22 -04'00'

Peter Rogoff, PPPL Mechanical Engineering

Reviewed By:

Irving Zatz Digitally signed by Irving Zatz
DN: cn=Irving Zatz, o=PPPL, ou, email=zatz@pppl.gov, c=US
Date: 2011.04.12 12:28:54 -04'00'

Irv Zatz, PPPL Mechanical Engineer

Reviewed By:

Mark Smith Digitally signed by Mark Smith
DN: cn=Mark Smith, o=PPPL, ou=FOM, email=msmith@pppl.gov, c=US
Date: 2011.04.21 08:58:47 -04'00'

Mark Smith, PPPL Mechanical Engineer

PPPL Calculation Form

Calculation # **NSTXU-132-11-00** Revision #**00** WP # **1677**
(ENG-032)

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

In order to support the principal magnetic coils of the NSTX device, two substantial rings are required to restrain the applied TF and PF forces. Each ring consists of twelve assemblies which are connected through a stepped lap joint with four stainless steel bolts. These bolts, must provide sufficient compressive force, through combined preload, to resist the joint separation for all mechanical load applications.
This analysis is performed in order to check and design the joint integrity by selecting and specifying the necessary bolts. The actual joint geometry is presented in the calculation section.

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

The complete joint FEA simulation is accomplished via FEA 2010.1r.2 Nastran code.
Required displacements, forces and moments were extracted from various ANSYS code Global Models simulations. Present calculations are based on the latest Global model data which was produced on 3/19/2011. This complete data is listed in the BoltJoint3-7-2011.ppt.
Results are checked using classical bolt design equations as recommended by various bolt manufacturers. These equations are listed in the calculation section.

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

Joint integrity greatly depends on the shear flow resistance between contacting surfaces. If any motion takes place, the geometry of the Coil-Rings supports configuration will change. This would influence and redistribute forces, displacements and moments. Therefore, a sufficient bolt preload is required with reasonable coefficient of friction which will keep the surfaces in proper contact.
Based on the existing PPPL test data (see appendix A of the calculations), a reasonable coefficient of friction “mu= .3” is and can be used.
In this case, the selected bolts must provide the necessary preload forces which will resist the combined shear forces at the contact surfaces.

Calculation (Calculation is either documented here or attached)

All the existing calculations are provided by the:

BoltJoint3-7-2011.ppt

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

Selection of one inch diameter 316 stainless steel cold finished bolts and mu=.3, the joint can withstand successfully the shear Fs=26,000 lbs., including various moments. This is outlined by the referenced Global model data.
The complete coil rings support configuration is being updated and other ANSYS simulations are in the works. This will require repeating/rechecking the calculation when this new data becomes available.

Therefore, for the present, the bolts should be as follows:

316 one inch diameter,
Cold finished: Yield = 100ksi, Tensile Strength = 125ksi, Shear 25ksi (no threads)
Bolt is good for 2/3 Yield NSTX stress requirement.
2.0 inch diameter washer is required.
Bolt preload = 44,000.Lbs.
Required torque = 8,844. Lb-in.

Preparing Engineer's printed name, signature, and date

Peter Rogoff 3/21/2011 Peter Rogoff

Digitally signed by Peter Rogoff
DN: cn=Peter Rogoff, o=Princeton Plasma Physics Lab, ou=Mechanical Engineering, email=progoff@pppl.gov, c=US
Date: 2011.04.12 10:59:26 -04'00'

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

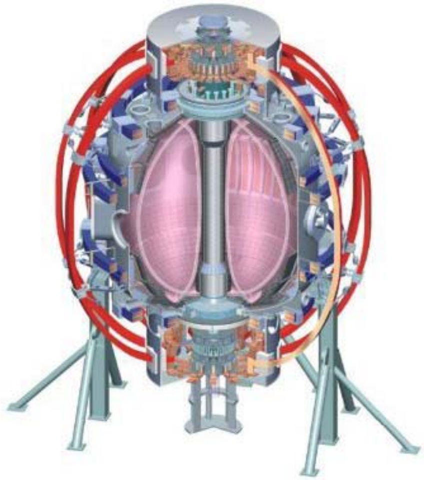
Checker's printed name, signature, and date

Irving Zatz Irving Zatz

Digitally signed by Irving Zatz
DN: cn=Irving Zatz, o=PPPL, ou, email=zatz@pppl.gov, c=US
Date: 2011.04.12 12:29:14 -04'00'

BoltJoin3-7-2011.ppt

P. Rogoff
3/24/2011



Update Ring Bolted Joint

Design and Recommend the Joint Geometry using bolts with necessary pre loads to keep the contact surfaces from sliding using the NSTX Global model extracted loads.

Ti=Fp(KD)- torque
K is the "nut factor" and dimensionless

This is done via Nastran FEA and hand calculations.

Explanation: Bolt preloads apply a compressive force "Fn" between the contact surfaces which must have a reasonable coefficient of friction in order to create a sufficient shear force "Fs" to resist the tensile force created by the applied loads.

Fp=UTS x As – tension P.L.

As=.785(D-(.9743/n))^2

n = # of threads per inch.

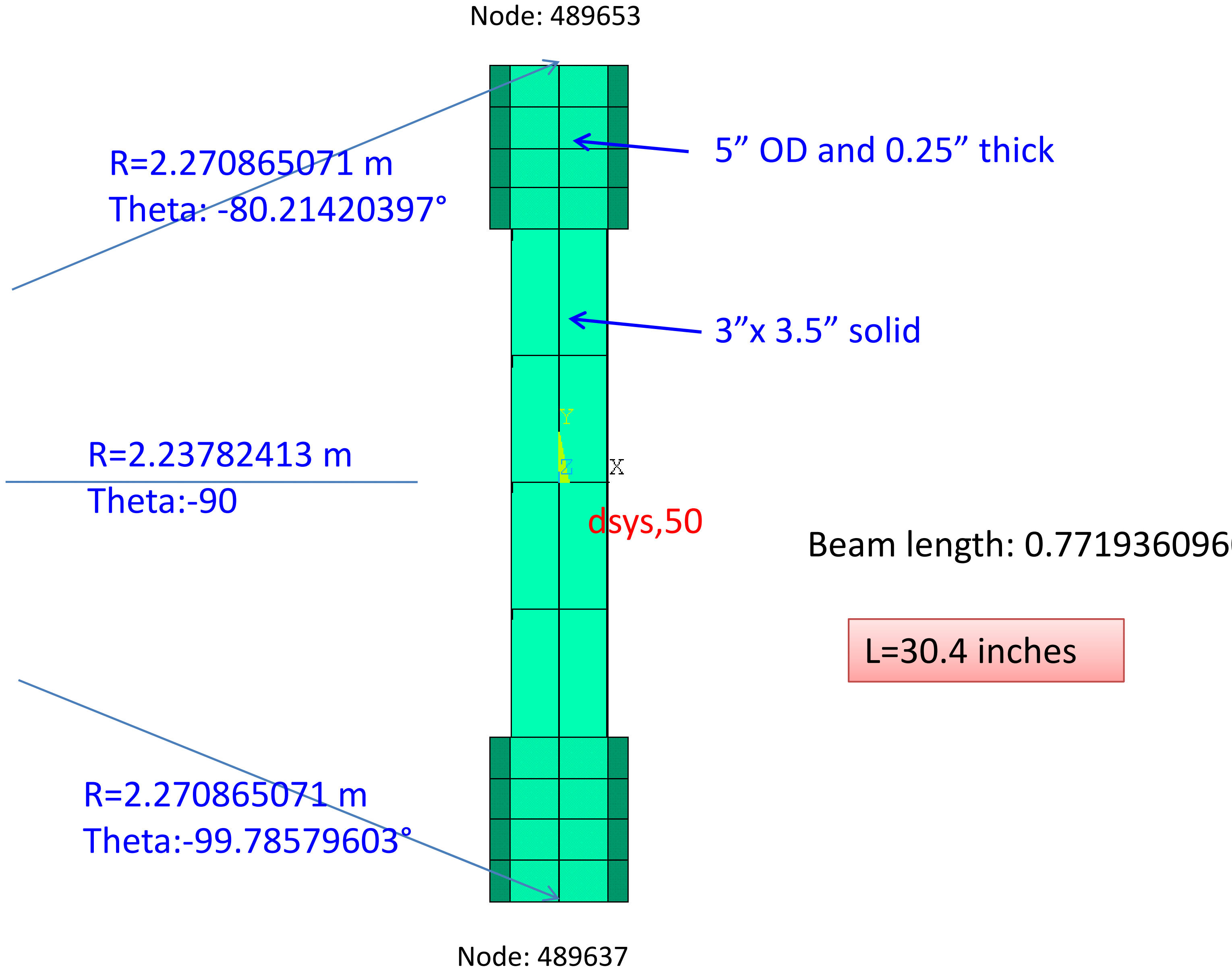
Selection of the Friction coefficient value "Mu" critical.

316 cold finished: Yield strength =100. ksi, Tensile (uts)= 125. ksi, Shear = 25. ksi

P. R.
3/9/2011

Beam model

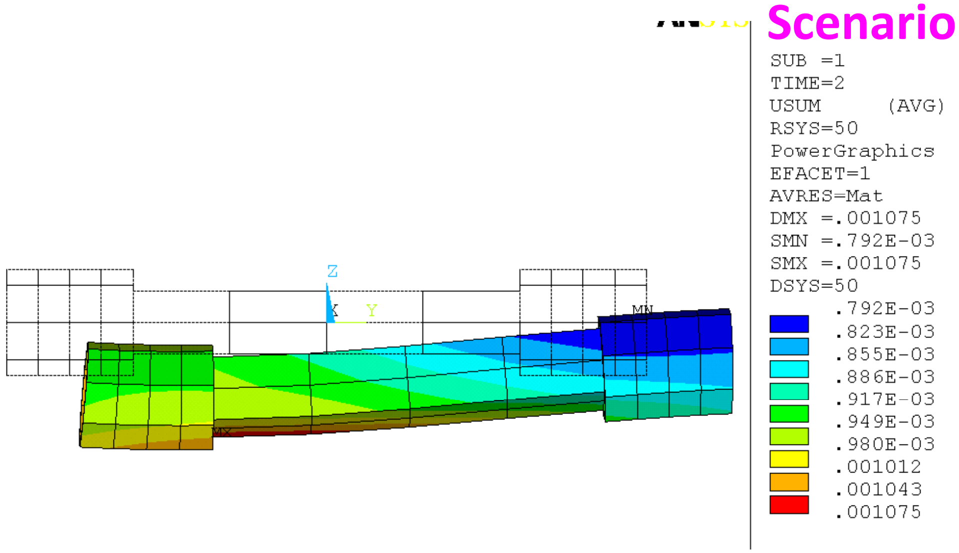
Data Received from the Global ANSYS model 3/19/2011

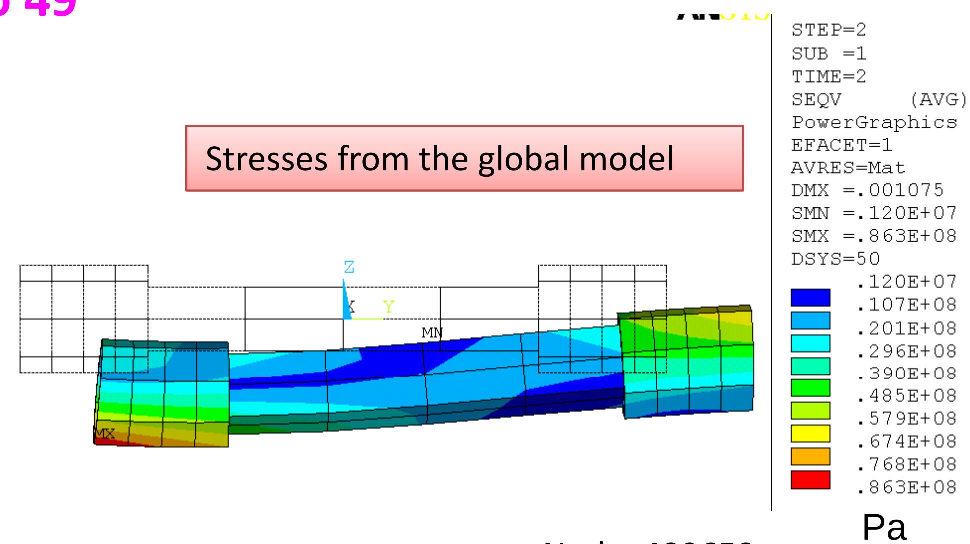


Beam length: 0.7719360960 m

L=30.4 inches

Scenario 49





Node: 489653

Node: 489637

Node: 489637

Node: 489653

THE FOLLOWING DEGREE OF FREEDOM RESULTS ARE IN COORDINATE SYSTEM 50

unit: m

NODE	UX	UY	UZ	USUM
489637	0.29608E-03	0.68516E-03	-0.64286E-03	0.98507E-03
489653	0.18566E-03	0.74549E-03	-0.34586E-03	0.84252E-03

THE FOLLOWING X,Y,Z SOLUTIONS ARE IN COORDINATE SYSTEM 50

Unit: N

NODE	FX	FY	FZ
489637	-3440.5	-64444.	-8651.6
489653	3440.5	64444.	8651.6

THE FOLLOWING DEGREE OF FREEDOM RESULTS ARE IN COORDINATE SYSTEM 50

unit: m

NODE	ROTX	ROTY	ROTZ	RSUM
489637	-0.54201E-03	-0.17193E-02	0.37961E-03	0.18423E-02
489653	0.21024E-03	-0.19470E-02	0.31508E-03	0.19835E-02

THE FOLLOWING X,Y,Z SOLUTIONS ARE IN COORDINATE SYSTEM 50

Unit: N-m

NODE	MX	MY	MZ
489637	-4080.7	171.36	1405.3
489653	-2597.8	-171.36	1250.5

Data from the ANSYS Global model 3/19/2011

Conversion of the ANSYS **Global data** into Pounds and Inches

Convesion factor m=39.37 in				39.37	
Nastran Node	ANSYS Node	Ux	Uy	Uz	
47432	489637	0.000296	0.000685	-0.00064	m
47432	489637	0.011654	0.026968	-0.0252	inches
47431	489653	0.000186	0.00075	-0.00035	m
47431	489653	0.007323	0.029528	-0.01378	inches
		RotX	RotY	RotZ	
47432	489637	-0.00054	-0.0017	0.00038	m
47432	489637	-0.02126	-0.06693	0.014961	inches
47431	489653	0.00021	-0.00195	0.00032	m
47431	489653	0.008268	-0.07677	0.012598	inches

Conversion Factor for Force Lbs = 4.448 N					4.448
Nastran Node	ANSYS Node	Fx	Fy	Fz	
47432	489637	-3440.5	-64444.1	-8651.6	N
47432	489637	-773.49	-14488.3	-1945.05	Lbs
47431	489653	3440.5	64444.1	8651.6	N
47431	489653	773.49	14488.33	1945.05	Lbs
Conversion Factor Moments 8.85 Lbf-in = 1 n-m					8.85
		Mx	My	Mz	
47432	489637	-4080.7	171.4	1405.3	
47432	489637	-36114.2	1516.89	12436.91	
47431	489653	-2597.8	-171.4	1250.5	
47431	489653	-22990.5	-1516.89	11066.93	

<u>Note</u>: Data in the green fields used in the Nastran Loads. Other combinations can be used if desired

distribution will probably be even more irregular than suggested in the drawing.

The contact pressure between nut or bolt head and the joint can have an important influence on the way in which a loaded fastener retains the potential energy stored in it during assembly (see Chapter 1). Excessive pressure will allow the head or nut to embed itself gradually in the joint surfaces, allowing the fastener to relax, to shed some of its stored energy. These contact

Typical Bolt load distribution

For demonstration purposes only

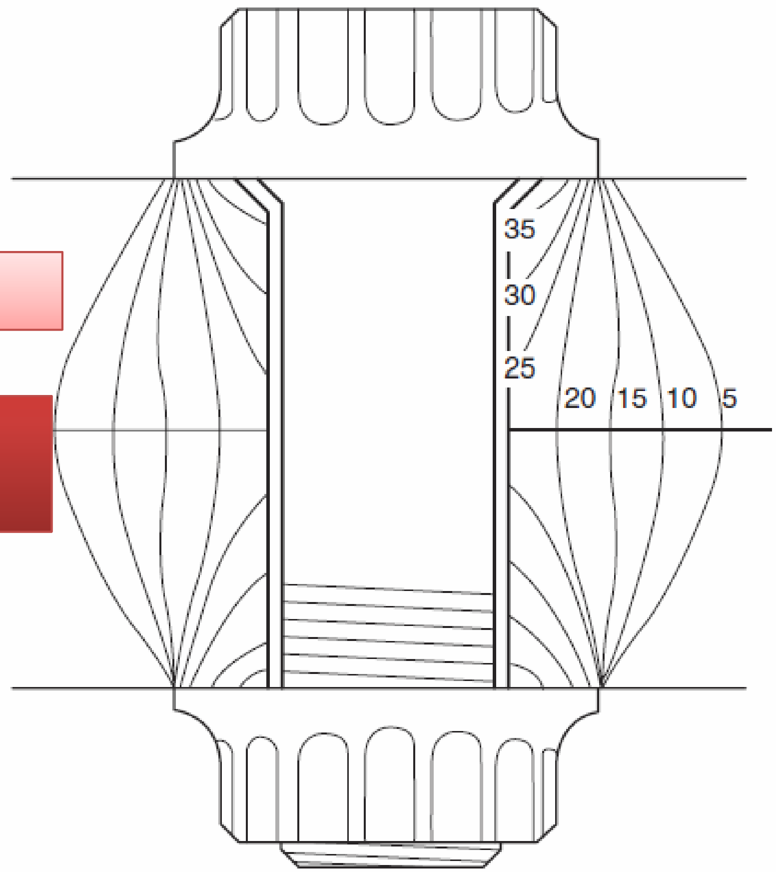
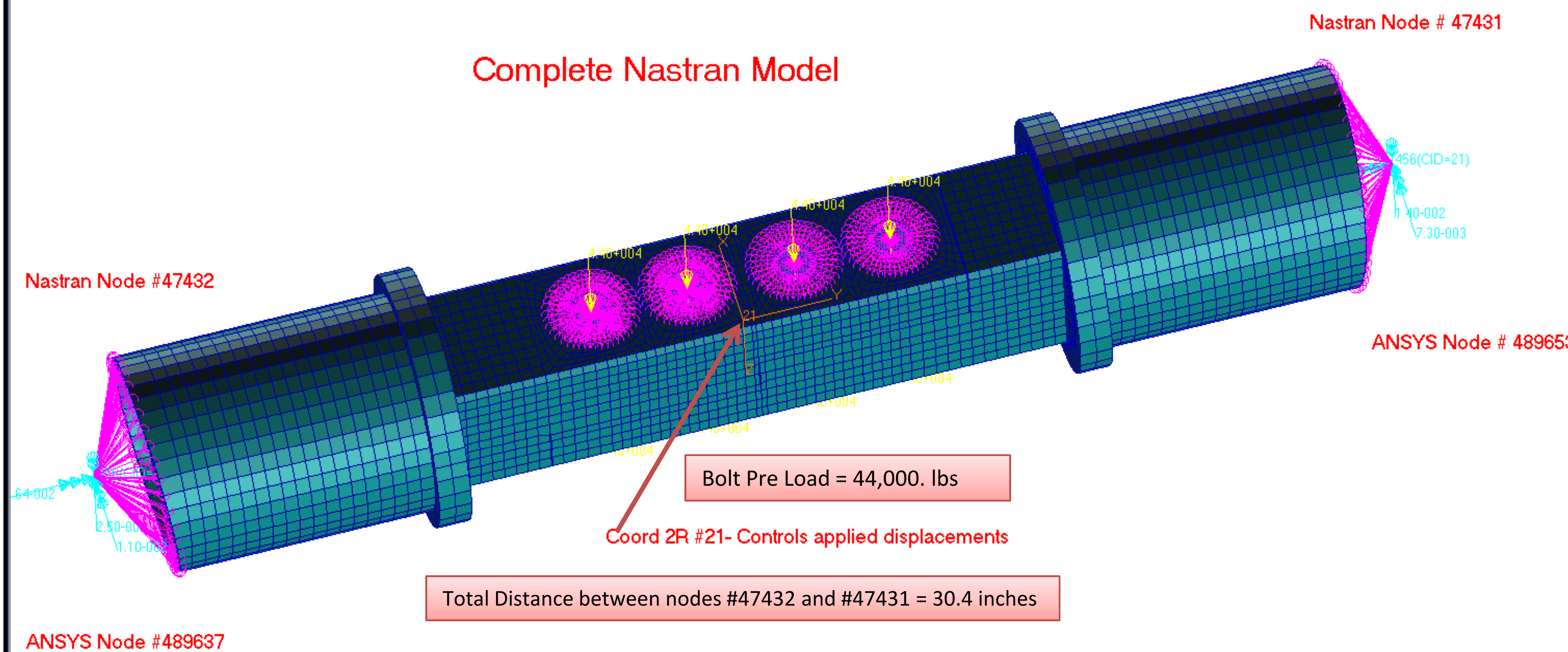


FIGURE 3.13 Lines of equal compressive stress in joint members when the bolt is loaded to 100 kips. Values given are in ksi.



Calculations based on standard equations, See above

See next slide

Problem: 1.0 in. dia. Bolt , As= .663 in^2, Yield = 100.ksi, Based on 2/3 yield = 66.7 ksi.

Fp = 66.7ksi x .663in^2 = 44.22 Kips per bolt, If mu = .3, Fs = 44.22 Kips X .3 = 13,266 lbs/bolt

Typical "nut factor" see the torque equation

For two bolts Fs= 26532. lbs And required torque = 44,220 lbs. x .2 x 1.0 in.= 8,844 lb-in

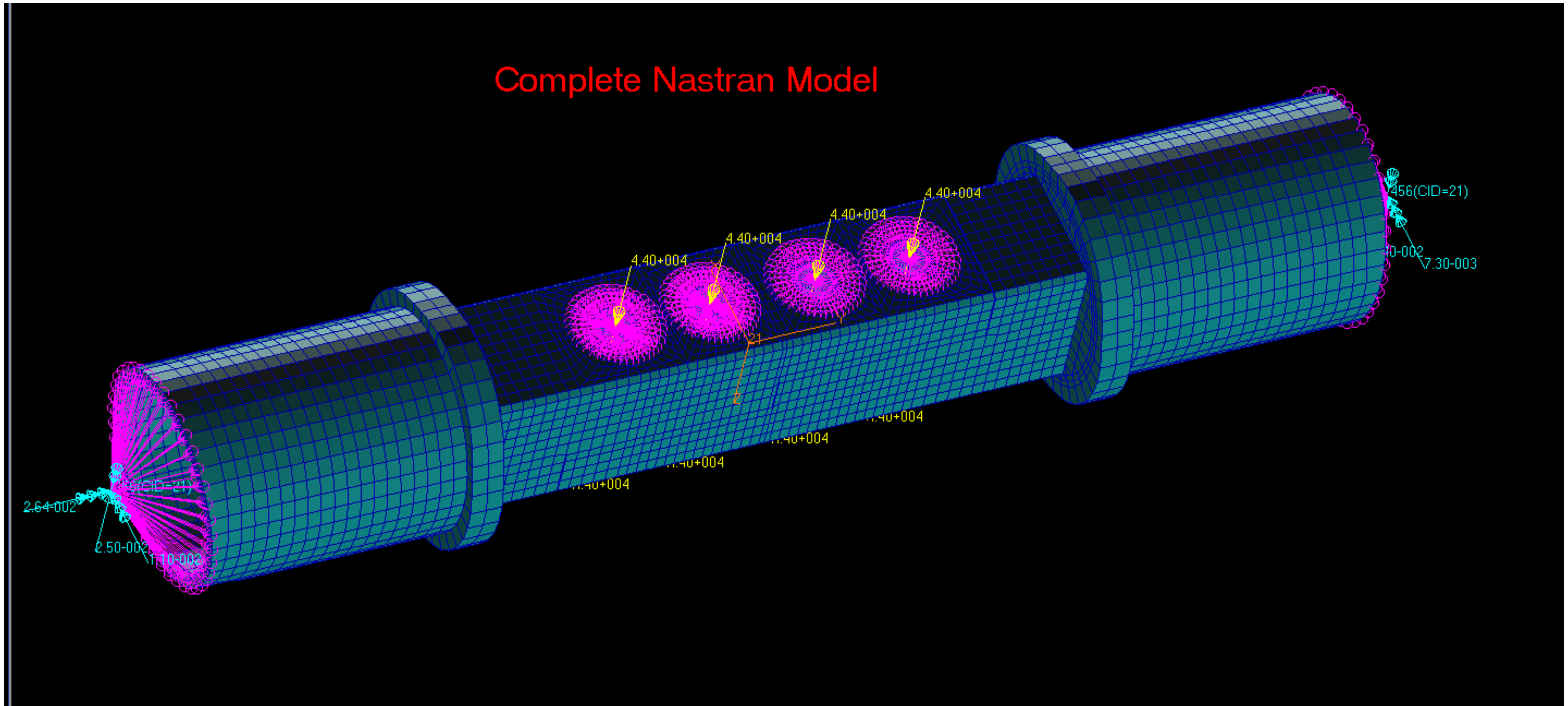
Additional Explanations and Justifications

Based on the NSTX Structural Design Criteria document "NSTX-CRIT-0001-01" Section #2.4.1.4.3, Bolt Preload shell not exceed 0.75Sy.
For the above calculations, 2/3Sy was used which is considered conservative, and, it demonstrates that a significant margin exists in case loads need to be increased.

Coefficient of friction "mu = .3" was used for the above calculations assuming standard material finish for steel products. This seems to be reasonable. Appendix A page #3 presents test data for certain plates (finish unknown) in the range up to m=.26 and only for four tests. Based on the present Global model loads even this value would produce conservative results.

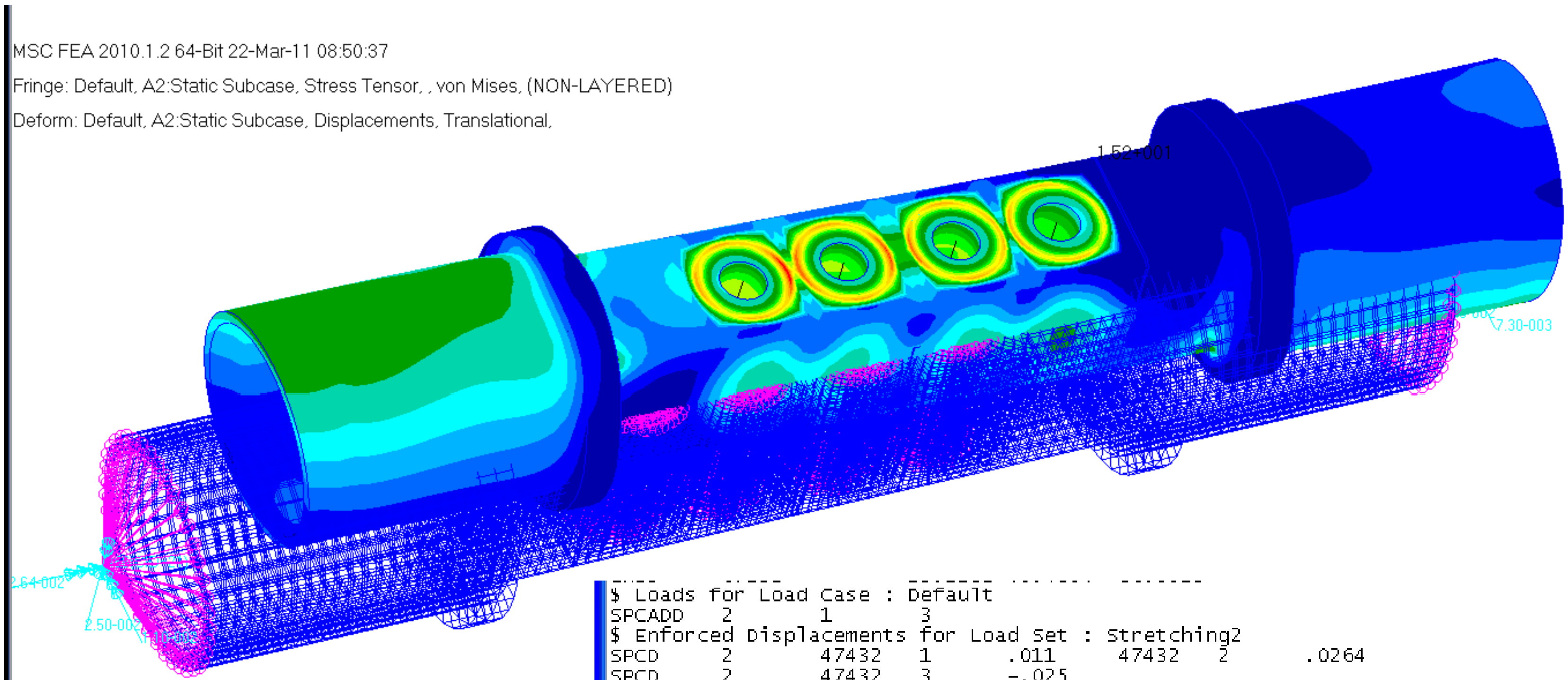
As = .663 in^2 was used. This is based un the "Designer Handbook Stainless Steel Fasteners" page#9, Table 5, 1.0 inch bolt Fine Thread (12 threads per inch).
"n" in the As equation represents number of threads per inch.

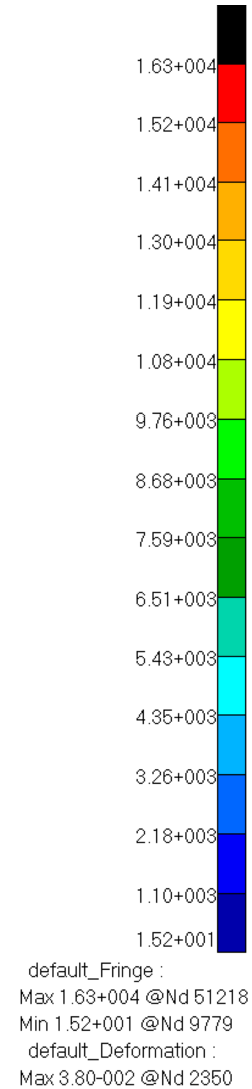
"K" -nut factor- value is the average recommended by manufacturers.
see: Taylor & Francis Group.LLC publication, Section 7.4.




```
     SOL 101
     CEND
1    MSC.NASTRAN JOB CREATED ON 08-MAR-11 AT 12:07:44                    MARCH  22, 2011  MSC.NASTRAN  6/19/08   PAGE     3

0
0                                        C A S E    C O N T R O L    E C H O
                 COMMAND
                 COUNT
                  1      $ DIRECT TEXT INPUT FOR GLOBAL CASE CONTROL DATA
                  2      TITLE = MSC.NASTRAN JOB CREATED ON 08-MAR-11 AT 12:07:44
                  3      ECHO = NONE
                  4      SUBCASE 1
                  5         TITLE=THIS IS A DEFAULT SUBCASE.
                  6         SPC = 2
                  7         LOAD = 2
                  8         DISPLACEMENT(SORT1,REAL)=ALL
                  9         SPCFORCES(SORT1,REAL)=ALL
                 10         STRESS(SORT1,REAL,VONMISES,BILIN)=ALL
                 11      $ DIRECT TEXT INPUT FOR THIS SUBCASE
                 12      BEGIN BULK
0                            INPUT BULK DATA ENTRY COUNT =    73833
0                       TOTAL COUNT=     73815


                                       M O D E L   S U M M A R Y

                                   NUMBER OF GRID     POINTS    =    30053

                                   NUMBER OF CBAR     ELEMENTS =       48
                                   NUMBER OF CHEXA    ELEMENTS =    21176
                                   NUMBER OF CPENTA   ELEMENTS =     1024

                                   NUMBER OF RBE2     ELEMENTS =       10
1    MSC.NASTRAN JOB CREATED ON 08-MAR-11 AT 12:07:44                    MARCH  22, 2011  MSC.NASTRAN  6/19/08   PAGE     4
```

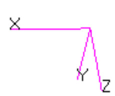
Model Solution Sequence and Statistics

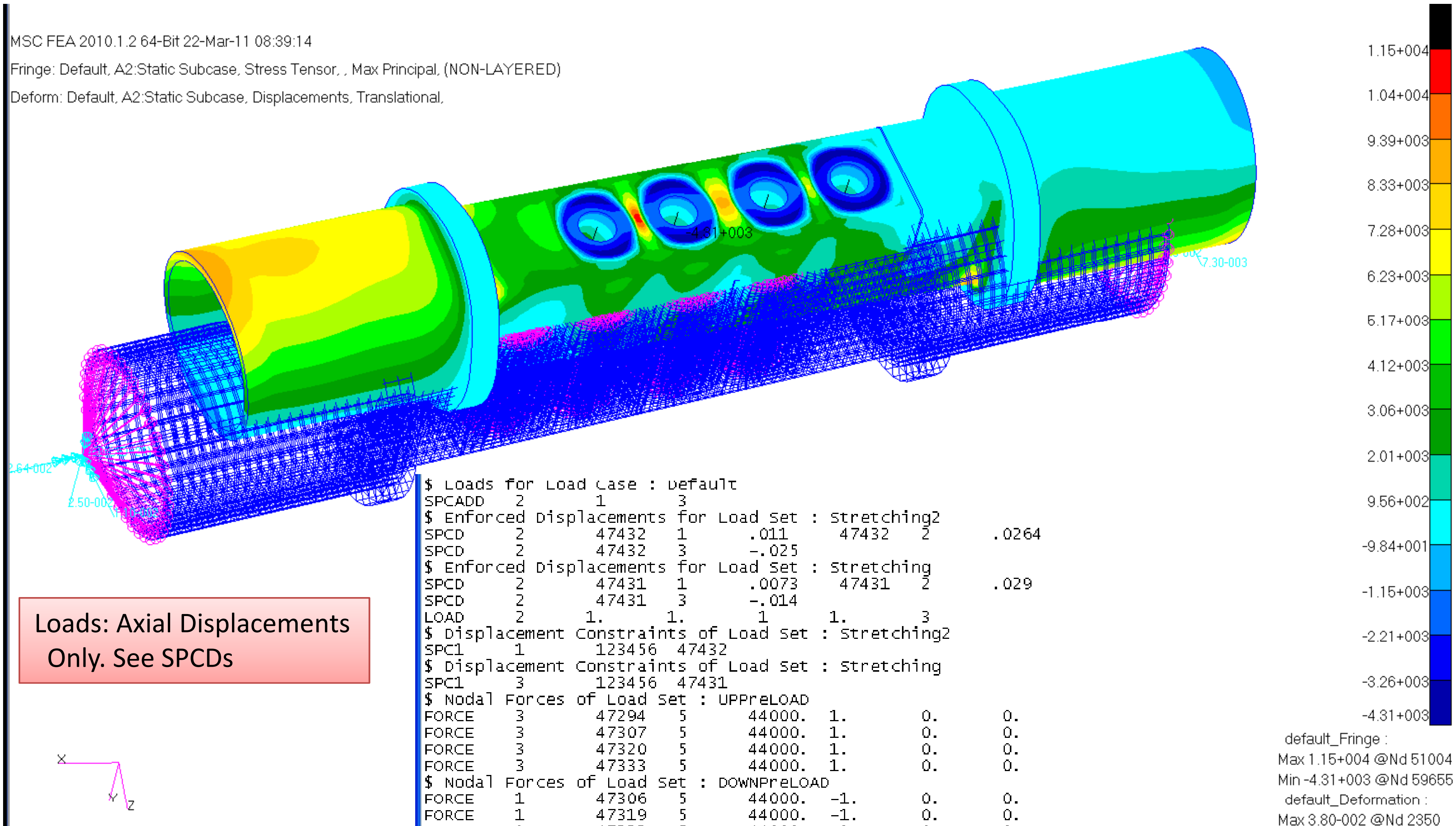





```
$ Loads for Load Case : Default
SPCADD   2       1       3
$ Enforced Displacements for Load Set : Stretching2
SPCD     2       47432   1       .011    47432   2       .0264
SPCD     2       47432   3       -.025
$ Enforced Displacements for Load Set : Stretching
SPCD     2       47431   1       .0073   47431   2       .029
SPCD     2       47431   3       -.014
LOAD     2       1.      1.      1       1.      3
$ Displacement Constraints of Load Set : Stretching2
SPC1     1       123456  47432
$ Displacement Constraints of Load Set : Stretching
SPC1     3       123456  47431
$ Nodal Forces of Load Set : UPPreLOAD
FORCE    3       47294   5       44000.  1.      0.      0.
FORCE    3       47307   5       44000.  1.      0.      0.
FORCE    3       47320   5       44000.  1.      0.      0.
FORCE    3       47333   5       44000.  1.      0.      0.
$ Nodal Forces of Load Set : DOWNPreLOAD
FORCE    1       47306   5       44000.  -1.     0.      0.
FORCE    1       47319   5       44000.  -1.     0.      0.
FORCE    1       47332   5       44000.  -1.     0.      0.
FORCE    1       47345   5       44000.  -1.     0.      0.
$ Referenced Coordinate Frames
CORD2R   5               29.8001 45.0852 -83.68784.01658 46.1807 12.5327
         29.5188 -54.5299-82.629
CORD2R   10              19.5362 44.76   -86.434419.8165 144.032 -87.4893
         -6.1586345.8515 9.4541
CORD2C   16              36.4143 45.0927 -81.916427.6557 145.057 -81.8895
         65.0164 47.6246 -178.068
CORD2C   17              9.42231 45.0925 -89.148116.9968 145.058 -84.7788
         32.724  47.5916 -186.72
CORD2R   21              22.9182 45.085  -85.531723.1987 144.445 -86.5875
         48.6339 43.9926 -181.506
ENDDATA 74f0c776
```

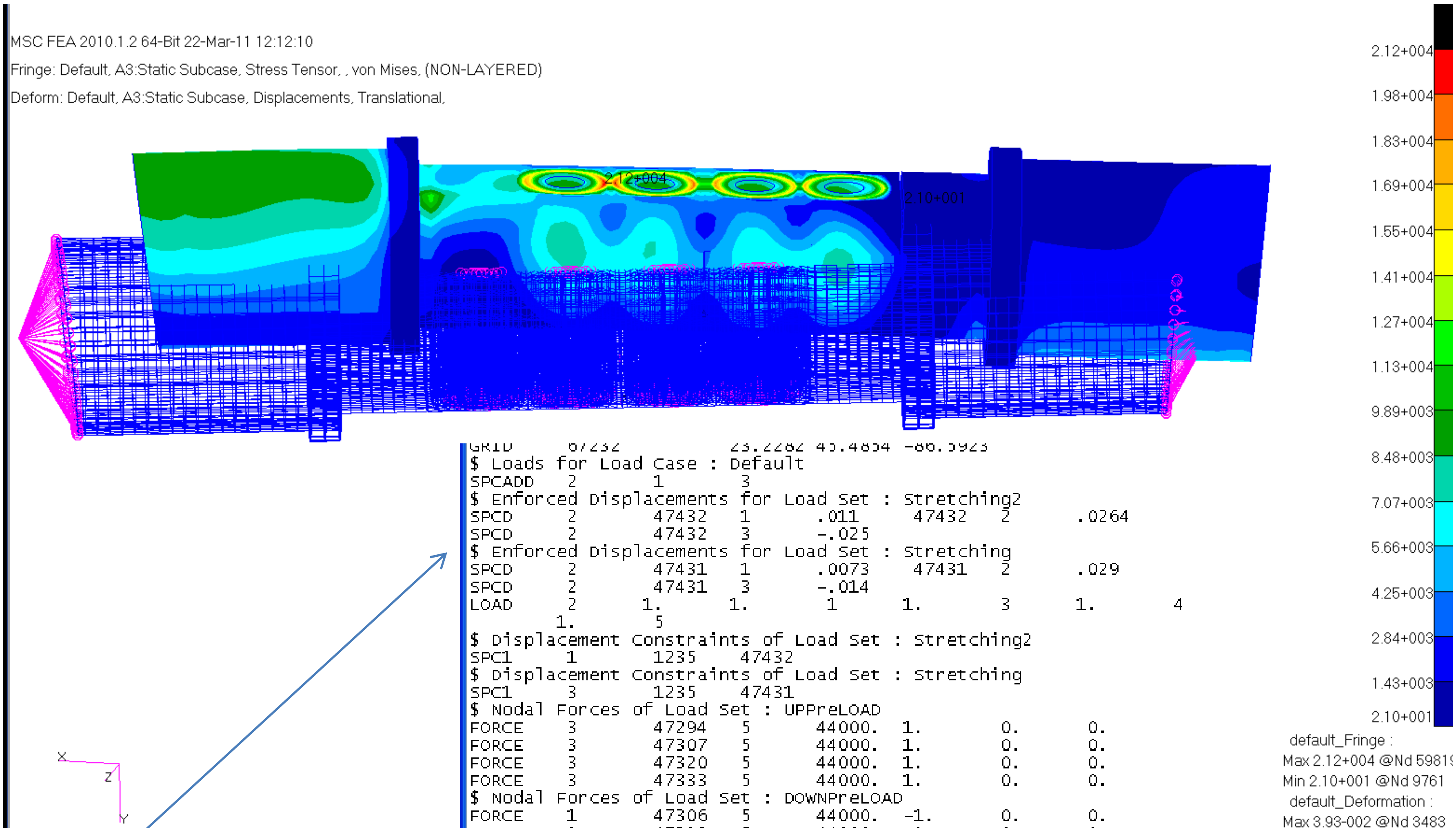
Loads: Axial Displacements Only , See SPCDs





Loads: Axial Displacements Only. See SPCDs

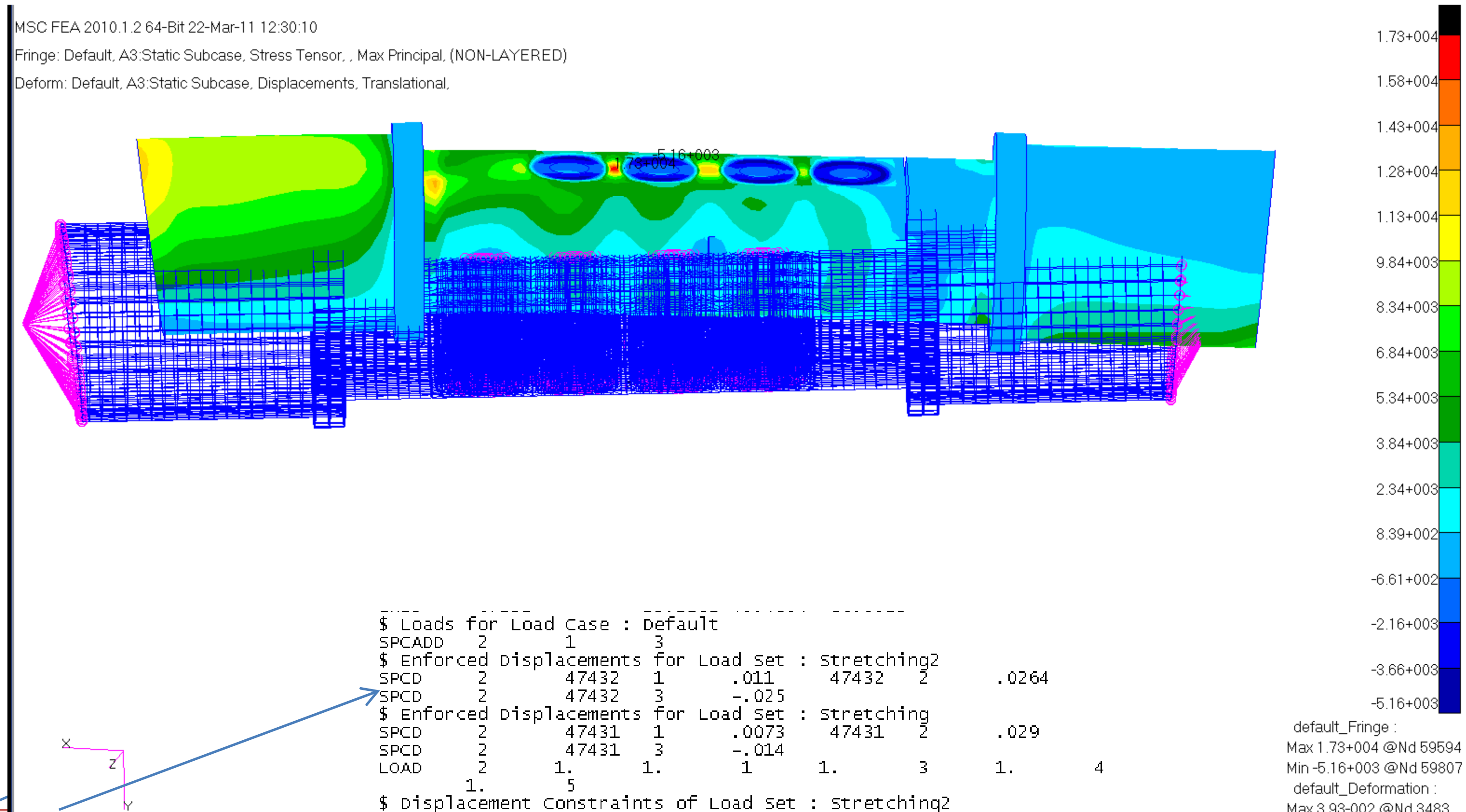
```
$ Loads for Load Case : Default
SPCADD   2       1       3
$ Enforced Displacements for Load Set : Stretching2
SPCD     2       47432   1       .011    47432   2       .0264
SPCD     2       47432   3       -.025
$ Enforced Displacements for Load Set : Stretching
SPCD     2       47431   1       .0073   47431   2       .029
SPCD     2       47431   3       -.014
LOAD     2       1.      1.      1       1.      3
$ Displacement Constraints of Load Set : Stretching2
SPC1     1       123456  47432
$ Displacement Constraints of Load Set : Stretching
SPC1     3       123456  47431
$ Nodal Forces of Load Set : UPPreLOAD
FORCE    3       47294   5       44000.  1.      0.      0.
FORCE    3       47307   5       44000.  1.      0.      0.
FORCE    3       47320   5       44000.  1.      0.      0.
FORCE    3       47333   5       44000.  1.      0.      0.
$ Nodal Forces of Load Set : DOWNPreLOAD
FORCE    1       47306   5       44000.  -1.     0.      0.
FORCE    1       47319   5       44000.  -1.     0.      0.
FORCE    1       47332   5       44000.  -1.     0.      0.
FORCE    1       47345   5       44000.  -1.     0.      0.
$ Referenced Coordinate Frames
CORD2R   5               29.8001 45.0852 -83.68784.01658 46.1807 12.5327
         29.5188 -54.5299-82.629
CORD2R   10              19.5362 44.76   -86.434419.8165 144.032 -87.4893
         -6.1586345.8515 9.4541
CORD2C   16              36.4143 45.0927 -81.916427.6557 145.057 -81.8895
         65.0164 47.6246 -178.068
CORD2C   17              9.42231 45.0925 -89.148116.9968 145.058 -84.7788
         32.724  47.5916 -186.72
CORD2R   21              22.9182 45.085  -85.531723.1987 144.445 -86.5875
         48.6339 43.9926 -181.506
ENDDATA 74f0c776
```




```
GRID     67232          23.2282 43.4834 -86.5923
$ Loads for Load Case : Default
SPCADD   2       1       3
$ Enforced Displacements for Load Set : Stretching2
SPCD     2       47432   1       .011    47432   2       .0264
SPCD     2       47432   3       -.025
$ Enforced Displacements for Load Set : Stretching
SPCD     2       47431   1       .0073   47431   2       .029
SPCD     2       47431   3       -.014
LOAD     2       1.      1.      1       1.      3       1.      4
         1.      5
$ Displacement Constraints of Load Set : Stretching2
SPC1     1       1235    47432
$ Displacement Constraints of Load Set : Stretching
SPC1     3       1235    47431
$ Nodal Forces of Load Set : UPPreLOAD
FORCE    3       47294   5       44000.  1.      0.      0.
FORCE    3       47307   5       44000.  1.      0.      0.
FORCE    3       47320   5       44000.  1.      0.      0.
FORCE    3       47333   5       44000.  1.      0.      0.
$ Nodal Forces of Load Set : DOWNPreLOAD
FORCE    1       47306   5       44000.  -1.     0.      0.
FORCE    1       47319   5       44000.  -1.     0.      0.
FORCE    1       47332   5       44000.  -1.     0.      0.
FORCE    1       47345   5       44000.  -1.     0.      0.
$ Nodal Forces of Load Set : Right Force
MOMENT   5       47431   21      25506.6 -.901061 0.     .433692
$ Nodal Forces of Load Set : Left Force
MOMENT   4       47432   21      38188.9 -.94551 0.      .325592
$ Referenced Coordinate Frames
CORD2R   5               29.8001 45.0852 -83.68784.01658 46.1807 12.5327
         29.5188 -54.5299-82.629
CORD2R   10              19.5362 44.76   -86.434419.8165 144.032 -87.4893
         -6.1586345.8515 9.4541
CORD2C   16              36.4143 45.0927 -81.916427.6557 145.057 -81.8895
         65.0164 47.6246 -178.068
CORD2C   17              9.42231 45.0925 -89.148116.9968 145.058 -84.7788
         32.724  47.5916 -186.72
CORD2R   21              22.9182 45.085  -85.531723.1987 144.445 -86.5875
         48.6339 43.9926 -181.506
ENDDATA 3359329b
```

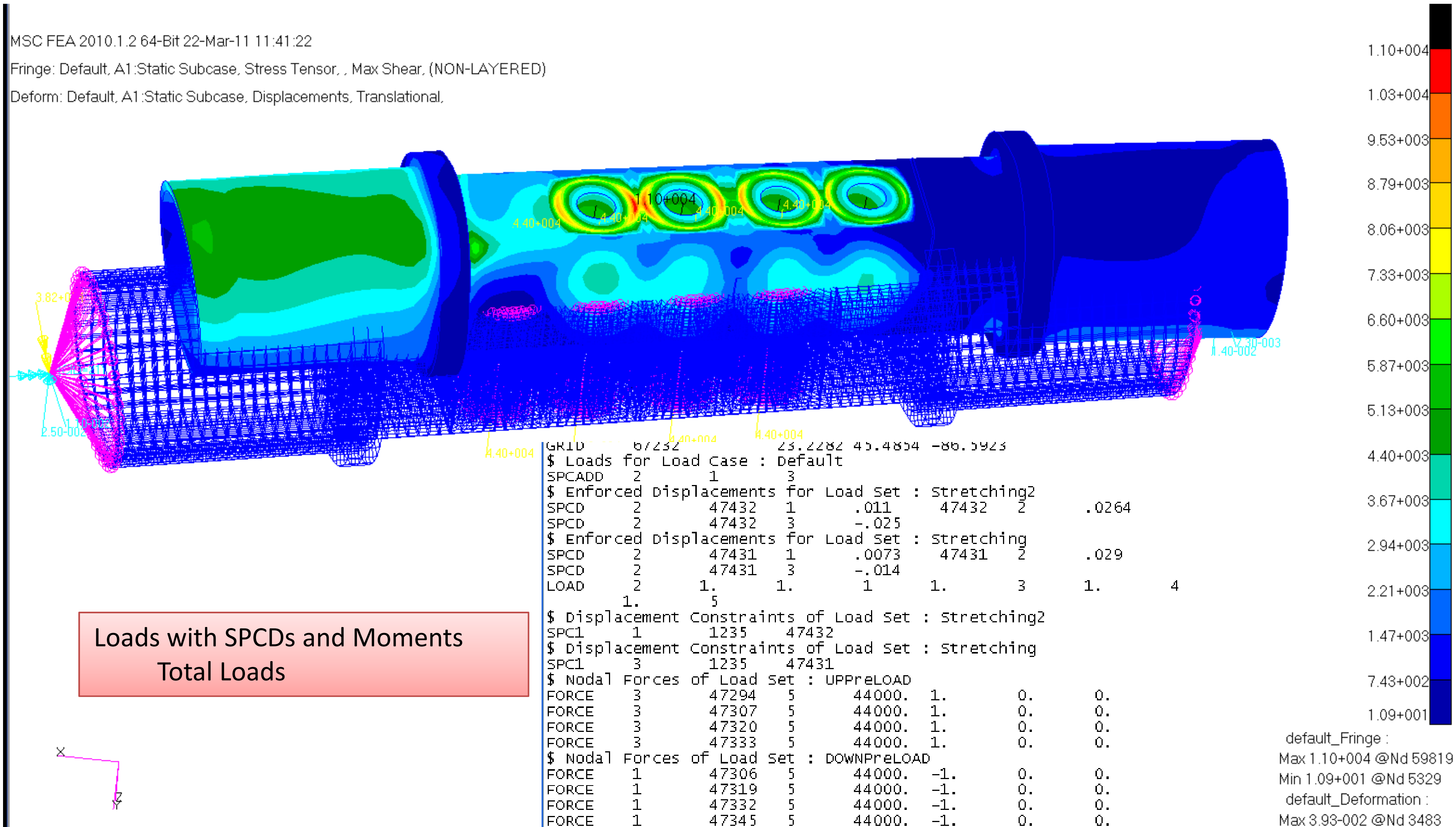
Loads with SPCDs and Moments

Total Load




```
$ Loads for Load Case : Default
SPCADD   2       1       3
$ Enforced Displacements for Load Set : Stretching2
SPCD     2       47432   1       .011    47432   2       .0264
SPCD     2       47432   3       -.025
$ Enforced Displacements for Load Set : Stretching
SPCD     2       47431   1       .0073   47431   2       .029
SPCD     2       47431   3       -.014
LOAD     2       1.      1.      1       1.      3       1.      4
         1.      5
$ Displacement Constraints of Load Set : Stretching2
SPC1     1       1235    47432
$ Displacement Constraints of Load Set : Stretching
SPC1     3       1235    47431
$ Nodal Forces of Load Set : UPPreLOAD
FORCE    3       47294   5       44000.  1.      0.      0.
FORCE    3       47307   5       44000.  1.      0.      0.
FORCE    3       47320   5       44000.  1.      0.      0.
FORCE    3       47333   5       44000.  1.      0.      0.
$ Nodal Forces of Load Set : DOWNPreLOAD
FORCE    1       47306   5       44000.  -1.     0.      0.
FORCE    1       47319   5       44000.  -1.     0.      0.
FORCE    1       47332   5       44000.  -1.     0.      0.
FORCE    1       47345   5       44000.  -1.     0.      0.
$ Nodal Forces of Load Set : Right Force
MOMENT   5       47431   21      25506.6 -.901061 0.     .433692
$ Nodal Forces of Load Set : Left Force
MOMENT   4       47432   21      38188.9 -.94551  0.     .325592
$ Referenced Coordinate Frames
CORD2R   5               29.8001 45.0852 -83.68784.01658 46.1807 12.5327
         29.5188 -54.5299-82.629
CORD2R   10              19.5362 44.76   -86.434419.8165 144.032 -87.4893
         -6.1586345.8515 9.4541
CORD2C   16              36.4143 45.0927 -81.916427.6557 145.057 -81.8895
         65.0164 47.6246 -178.068
CORD2C   17              9.42231 45.0925 -89.148116.9968 145.058 -84.7788
         32.724  47.5916 -186.72
CORD2R   21              22.9182 45.085  -85.531723.1987 144.445 -86.5875
         48.6339 43.9926 -181.506
ENDDATA 3359329b
```

Loads with SPCDs and Moments
Total Loads

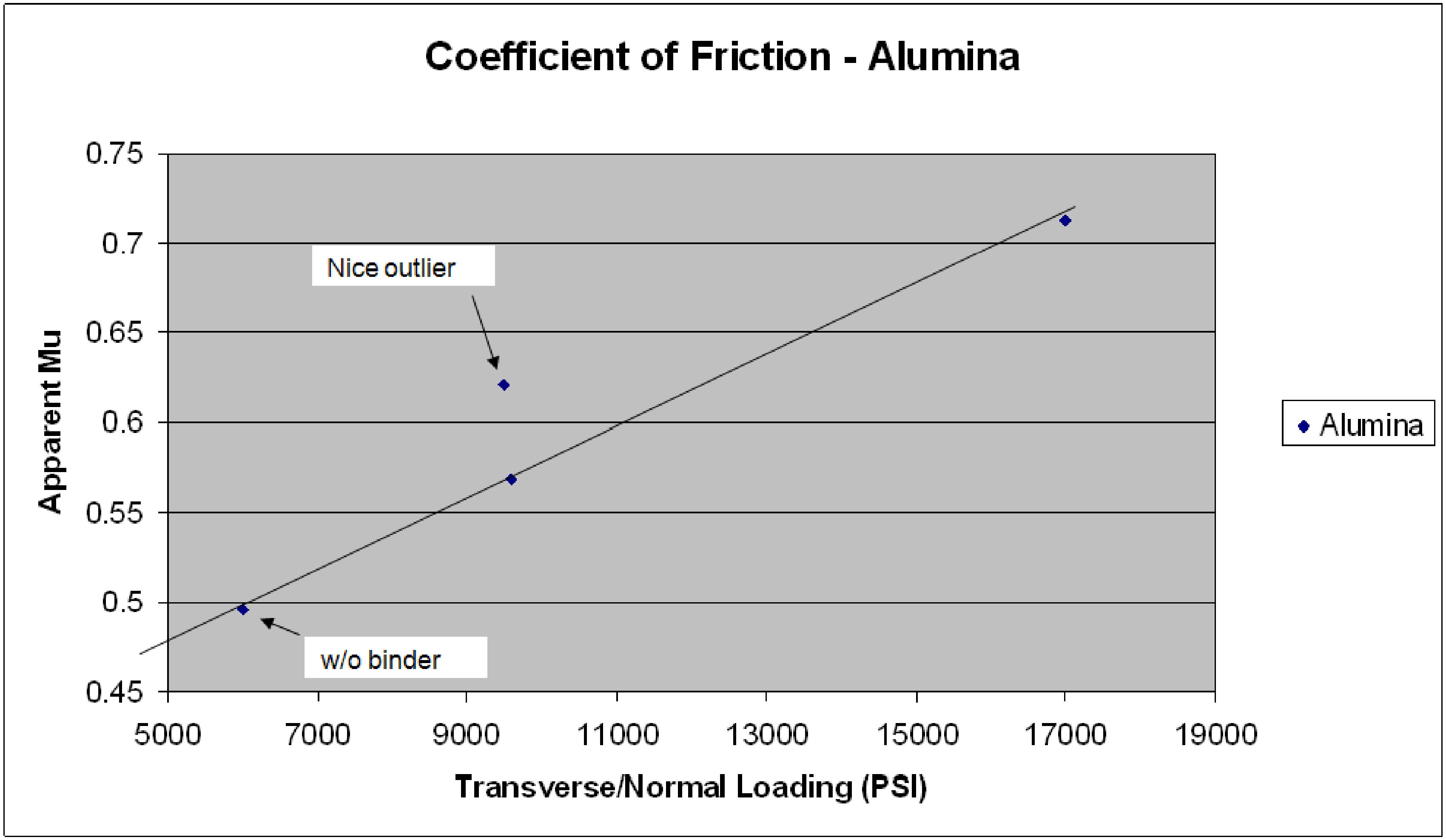


Loads with SPCDs and Moments
Total Loads

```
GRID     67232          23.2282 45.4854 -86.5923
$ Loads for Load Case : Default
SPCADD   2       1       3
$ Enforced Displacements for Load Set : Stretching2
SPCD     2       47432   1       .011     47432   2       .0264
SPCD     2       47432   3       -.025
$ Enforced Displacements for Load Set : Stretching
SPCD     2       47431   1       .0073    47431   2       .029
SPCD     2       47431   3       -.014
LOAD     2      1.      1.       1       1.       3       1.      4
        1.       5
$ Displacement Constraints of Load Set : Stretching2
SPC1     1       1235    47432
$ Displacement Constraints of Load Set : Stretching
SPC1     3       1235    47431
$ Nodal Forces of Load Set : UPPreLOAD
FORCE    3       47294   5       44000.  1.      0.      0.
FORCE    3       47307   5       44000.  1.      0.      0.
FORCE    3       47320   5       44000.  1.      0.      0.
FORCE    3       47333   5       44000.  1.      0.      0.
$ Nodal Forces of Load Set : DOWNPreLOAD
FORCE    1       47306   5       44000.  -1.     0.      0.
FORCE    1       47319   5       44000.  -1.     0.      0.
FORCE    1       47332   5       44000.  -1.     0.      0.
FORCE    1       47345   5       44000.  -1.     0.      0.
$ Nodal Forces of Load Set : Right Force
MOMENT   5       47431   21      25506.6 -.901061 0.     .433692
$ Nodal Forces of Load Set : Left Force
MOMENT   4       47432   21      38188.9 -.94551  0.     .325592
$ Referenced Coordinate Frames
CORD2R   5               29.8001 45.0852 -83.68784.01658 46.1807 12.5327
        29.5188 -54.5299-82.629
CORD2R   10              19.5362 44.76   -86.434419.8165 144.032 -87.4893
        -6.1586345.8515 9.4541
CORD2C   16              36.4143 45.0927 -81.916427.6557 145.057 -81.8895
        65.0164 47.6246 -178.068
CORD2C   17              9.42231 45.0925 -89.148116.9968 145.058 -84.7788
        32.724  47.5916 -186.72
CORD2R   21              22.9182 45.085  -85.531723.1987 144.445 -86.5875
        48.6339 43.9926 -181.506
ENDDATA 3359329b
```

Alumina - Linear Relationship?

NCSX



Ref.: From NCSX "Friction Coating Peer Review", and "FrictionPeer(3).ppt"

Really Better Solution

NCSX

- Plasma-sprayed alumina emerged as the big winner
  - 1) Mu's from 0.50 to 0.71 at pressures from 6 ksi to 17 ksi
  - 2) Infinite electrical isolation to 45 ksi compressive loading (at 9 volts)
  - 3) The ability to "give" as the test set-up (always imperfect) aligns itself while the slip load is applied to failure
  - 4) The ability to maintain its peak mu (and load) during slip to failure. The diamond solutions fall in load capacity after slipping starts.

Ref.: From NCSX "Friction Coating Peer Review", and "FrictionPeer(3).ppt"

APPENDIX A

Early Test Observations

NCSX

- File 070129Summary.xls lists the outcomes of 21 trials
  - G-10 on SS (ambient,1trial) m=0.18
  - SS on SS (amb/cold, 4 trials) m=0.21-0.26
  - SS/diamond/SS (amb/cold, 16 trials) mavg=0.53
    - Many combinations
- The fundamental failure in the diamond-assisted trials was the tearing of the seated diamonds along/through the surface of the stainless
  - The tear-outs look like aerial views of perfectly plowed fields
  - This may be the functional limit of the material

Ref.: From NCSX "Friction Coating Peer Review", and "FrictionPeer(3).ppt"