National Spherical Torus eXperiment - Upgrade

NSTX-U

Local pin-lockbar stress analysis for IBDH and IBDV tile designs

NSTXU-CALC-11-30-00

Sep. 24, 2018

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Approved By – R. Ellis (TA Mechanical)

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	9/24/18	Initial Release	

Calculation No: NSTXU-CALC-11-30-00 **Revision No: 0**

Local pin-lockbar stress analysis for IBDH and IBDV tile designs

Purpose of Calculation: Evaluate stress and performance of pin and lock-bar features of the IBDH and IBDV HHF designs.

Codes and versions:

None

References:

R. Roark and W. Young, "Formulas for Stress and Strain", 5th Edition, McGraw-Hill Book Company, New York, NY.
Drawing C-ED1394 (Locking Post Prototype)
Drawing E-ED1393 (Locking Rod Prototype)
A. Khodak, et al., "High Heat Flux Plasma Facing Components Preliminary Design Review; Inboard Divertor Horizontal", HHF Preliminary Design Review meeting, Princeton Plasma Physics Laboratory, Plainsboro, NJ. Nov. 2017.

Assumptions:

Maximum design preload during engaging the pin-lockbar is 840N (indicated in HHF PDR)
Worst-case tolerances indicated in drawings C-ED1394 and E-ED1393

Calculation:

See attached sheets

Conclusion:

Pin and lock-bar stresses far from the contact elements are well within acceptable levels for Inconel 718. Local stress does not exceed structural design criteria.

Cognizant Individual (or designee) printed name, signature, and date

Michael Jaworski

Preparer's printed name, signature and date:

Michael Jaworski

Michael Jaworski

Digitally signed by Michael Jaworski
Date: 2018.09.26 09:37:53 -04'00'

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

Checker's printed name, signature, and dat

Jason Cook

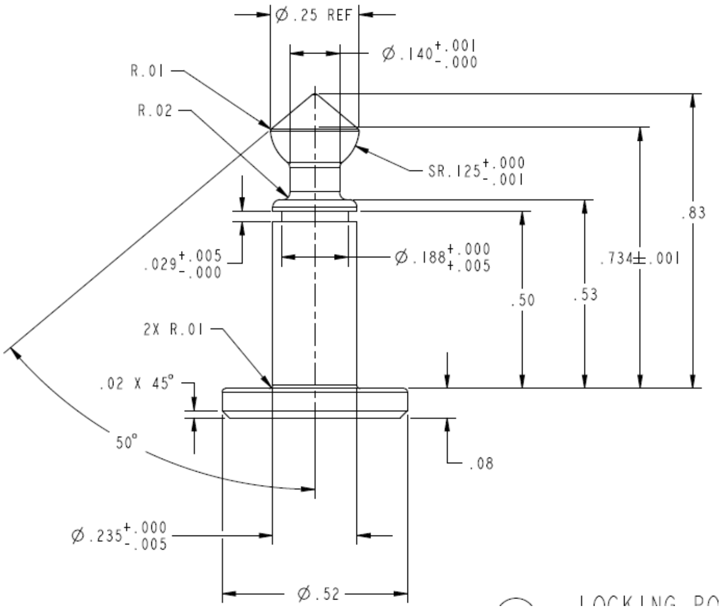
Jason T. Cook

Digitally signed by Jason T. Cook
Date: 2018.09.26 09:42:36 -04'00'

Analytical evaluations of pin and lock-bar

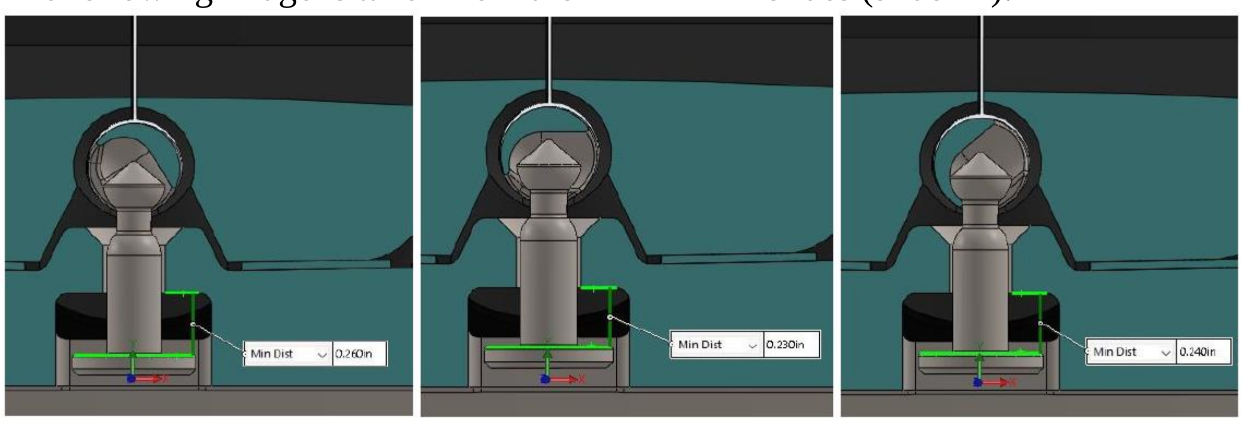
Stress allowables for Inconel 718 are taken from PFC-180919-MAJ-03 which references ASTM specifications. Allowable stress is 100 ksi (689 MPa).

The pin head geometry has not changed since the prototype process:



This image is taken from the C-ED1393 drawing showing a spherical radius of 0.125+0.000/-0.001". The thinnest portion of the pin has a diameter of 0.140+0.001/-0.000".

The following image is taken from the IBDH PDR slides (slide 12):



Initial Position
640N load

Intermediate Position
Maximum compression of the Belleville washers
840N load

Position during operation
750N load

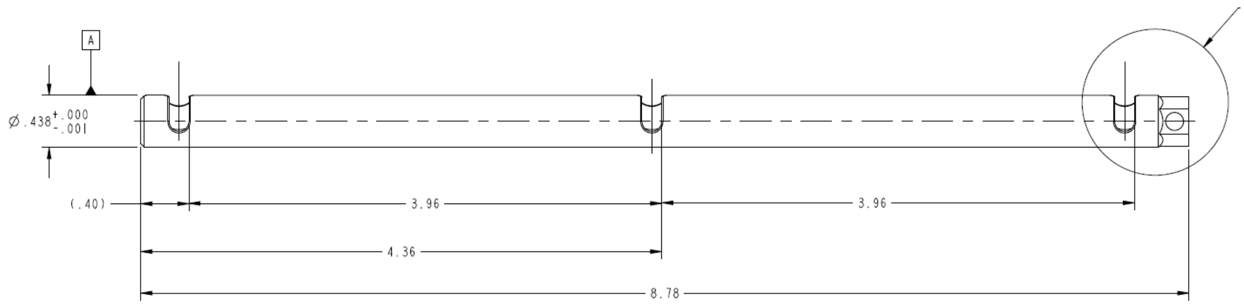
Indicating the design load is 750N with a maximum load of 840N during actuation. 840 N is equal to 188.84 lbf.

The stress in the stem of the pin is therefore:

$$\sigma = \frac{P}{\pi R_{stem}^2} = \frac{189\ lbf}{0.0154\ in\text{^}2} = 12.3ksi\ (84.6\ MPa)$$

The allowable stress for Inconel 718 is 100 ksi (689 MPa).

The locking bar has geometry reported in E-ED1393 showing below. The main points are the minimum diameter of the bar and the distance between pins. These are 0.438+0.000/-0.001" and 3.96" respectively



A simple stress estimate is made assuming a bar in bending with a symmetry point half-way between lock pins. The moment applied is 3.96/2" with the full load of 189 lbf resulting in 373.9 lbf-in.

The section modulus is S = pi*d^3/32 and the maximum stress for a symmetric cross-section beam is:

$$\sigma = \frac{M}{S} = \frac{Pd/2}{\pi d^3/32} = \frac{373.9\ lbf - in.}{0.008193\ in.^3} = 45.6\ ksi\ (315\ MPa)$$

Local stresses are estimated using sphere-in-socket relations found in Roark's formulas for stress and strain. These will be modified by estimates for the effective contact area in an attempt to account for the non-spherical features in the design.

Roark's lists the maximum stress in the contact point as:

$$\sigma_c = 1.5\frac{P}{\pi a^2} = 0.616\sqrt[3]{\frac{PE^2}{K_D^2}}$$

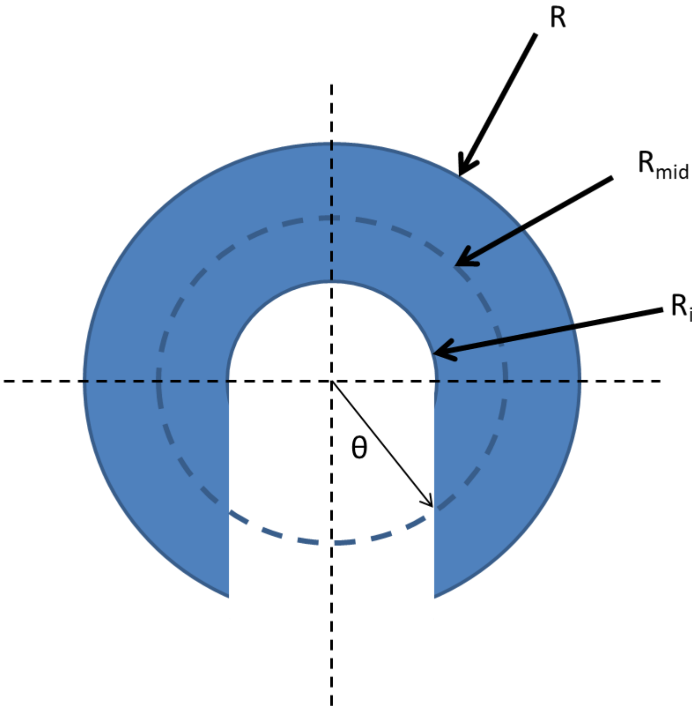
In cases where the elastic modulus, E, is equal between the two contacting elements and Poisson's ratio is about 0.3. The geometric factor KD is given as:

$$K_D = \frac{D_1 D_2}{D_1 - D_2} = \frac{0.252 \times 0.248}{0.252 - 0.248} = 15.624$$

Which assumes worst-case sizes based on the tolerances in the relevant drawings.

For a load of 840N, corresponding to 189 lbf, elastic modulus of 29,000 ksi, the resulting maximum compressive stress is 53.4 ksi (368 MPa).

Estimates are made to account for the reduced contact area between the components. This accounts for the one-sided "slot" feature in the lock-bar and the presence of the "stem" in the pin.



The maximum radius for contact is R (0.125") and the cut-out feature corresponds to features in the lock-bar with a R_i=0.083". One estimate for the contact line may be at the mid-point between R_i and R which corresponds to R_{mid}=0.104". The half-angle of the cut is given as:

$$sin\theta = \frac{R_i}{R} \rightarrow 53°$$

The effective contact line length is the ratio of angles which is:

$$\sigma_{eff} = f_{line} \times \sigma_c = \frac{360°}{106°} 53.4\ ksi = 1.42 \times 53.4\ ksi = 75.6\ ksi\ (521\ MPa)$$

Another estimation method for the value of *f* is with an area ratio method which removes the cut-feature from the contacting surfaces:

$$f_{area} = \frac{A_{sphere}}{A_{sphere} - A_{cut}} = \frac{2\pi R^2}{2\pi R^2 - \left(\frac{1}{2}\pi R_i^2 + 2R_i\left(\frac{\pi}{4}\right) R\right)} = \frac{0.0982\ in.^2}{0.05476\ in.\text{^}2} = 1.79$$

With this scaling factor for effective area, the resulting effective stress is found to be:

$$\sigma_{eff} = 1.79 \times 53.4\ ksi = 95.7\ ksi\ (659.8\ MPa)$$

In both cases, the contact stress is found to be within the acceptable level for primary stresses (100 ksi/689 MPa) and well within the Structural Design Criteria allowable for local primary stresses (150 ksi/1034 MPa).

Checks for Calculation No: NSTXU-CALC-11-30-00# **Revision No: 0 #**

Local pin-lockbar stress analysis for IBDH and IBDV tile designs

Component was checked against latest design

All required load cases are included and current

Discuss method used in the calculation

Analytical methods are used to estimate the primary stress of the pin model and lockbar components. An analytical method is used to estimate local contact stresses at the spherical contact point with factors to account for reduced contact areas.

Discuss how the calculation was checked (*)

An independent analysis was carried out with ANSYS 19.0 using a non-linear elastic simulation on a local model of the pin-lockbar contact region. The material model used is elastic-plastic to determine the behavior if any yielding occurs.

Local stresses in the lockbar show peak equivalent stresses of 681 MPa, which is within the allowable stress for Inconel 718 and well below the yield strength so no plastic deformation occurs. Local stress in the pin head reaches 461 MPa. All stresses are well under the allowable *local* primary stresses of the material which is 1034 MPa.

See attached sheets.

List issue identified and how they were resolved

No issues were identified. All calculations show the components meet structural design criteria.

Checker's name: Jason Cook (ORNL)

Technical Authority: Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.10.01 10:10:13 -04'00' ______________________(sign and date)

(*) independent calculations can be appended

Pin-Lockbar sub-model

Jason Cook

9/20/18

Analysis Justification

- Justification: linear-elastic modeling shows large stresses at contact points. Hand calculations indicate compressive stresses are manageable, but FEA shows large local stresses. NSTX-U Structural Design Criteria document makes allowances for local bearing stresses. Full integrated modelling is not necessary to understand behavior of local contact.

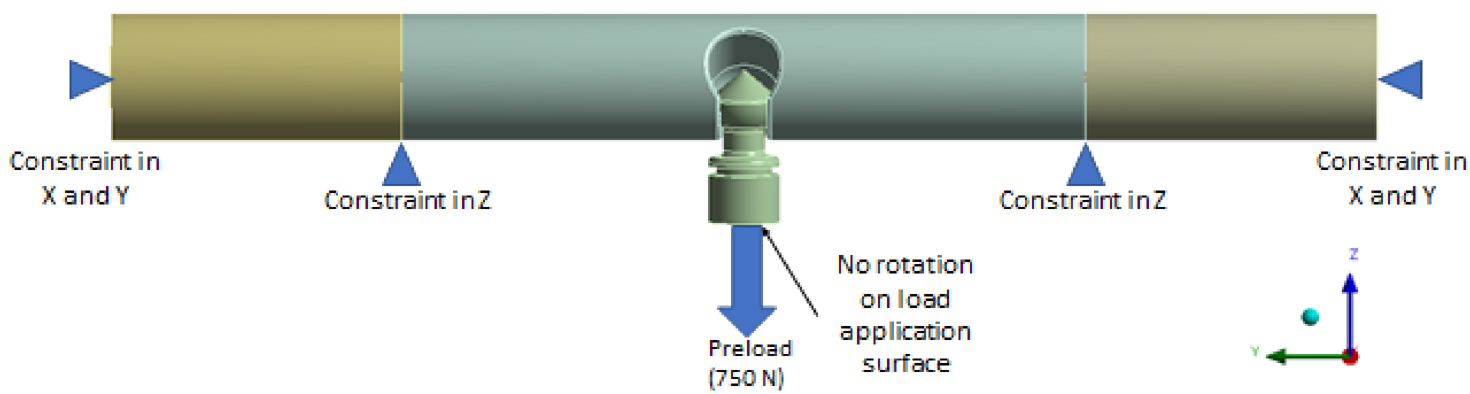
Analysis Procedure

- 4 sub models were analyzed
  - Linear Elastic Coarse mesh
  - Linear Elastic Refined mesh
  - Non-linear Elastic Coarse mesh
  - Non-linear Elastic Refined mesh

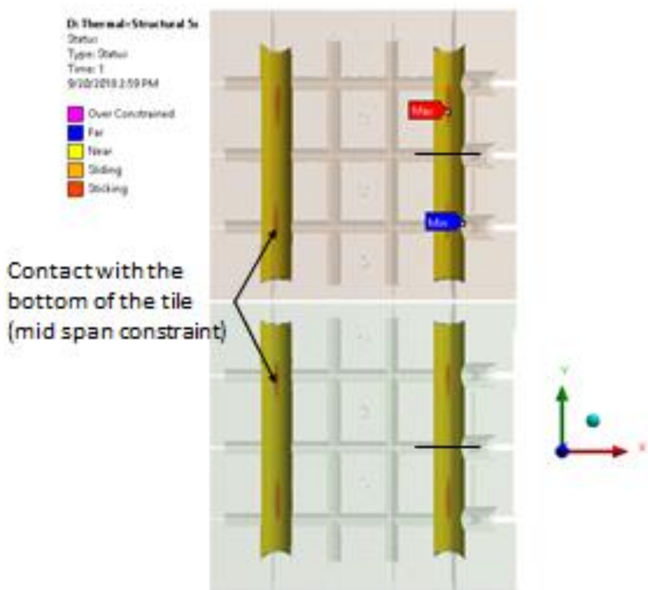
- The original goal of the study was to look at non-linear Elastic-plastic analysis assuming a material with a bilinear stress-strain curve. Basically, once the yield of the material is reached in an area of the model, the modulus of elasticity of the area is reduced. However, modeling plasticity was not necessary because conducting a non-linear analysis reduced the stresses in the model to well below the yield strength of the material.

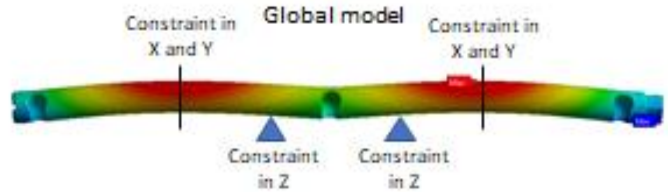
Model Boundary Conditions

- An effort was made to try and recreate stresses and deformation within the sub-model to match the global model. The boundary conditions that produced similar behavior are shown in the figure below.



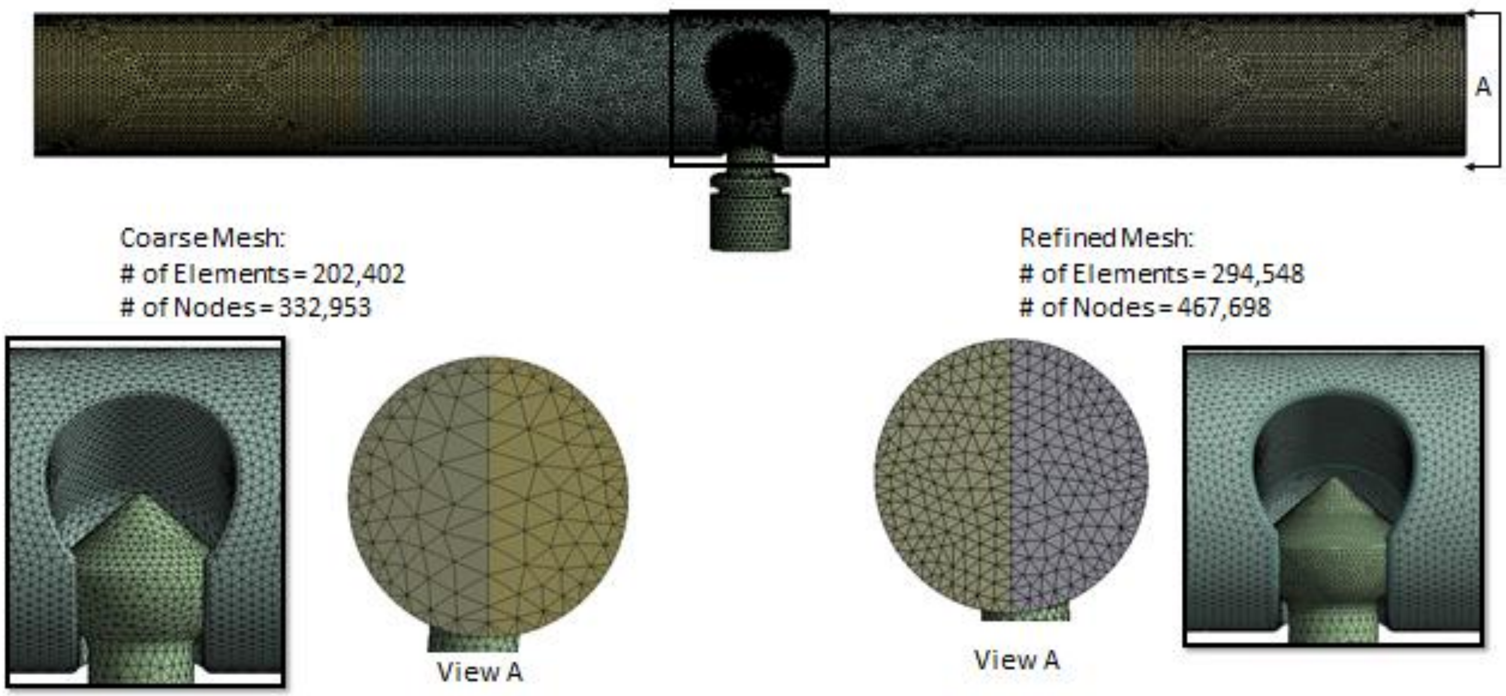
Boundary Conditions



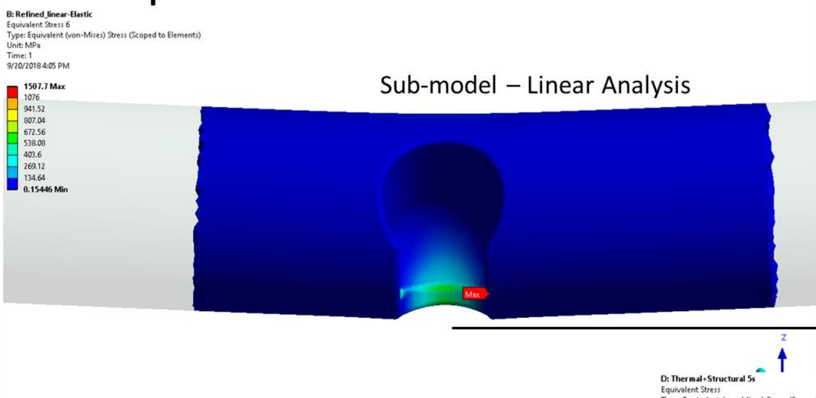


Attempt to mimic behavior of rod in global model

Mesh Description

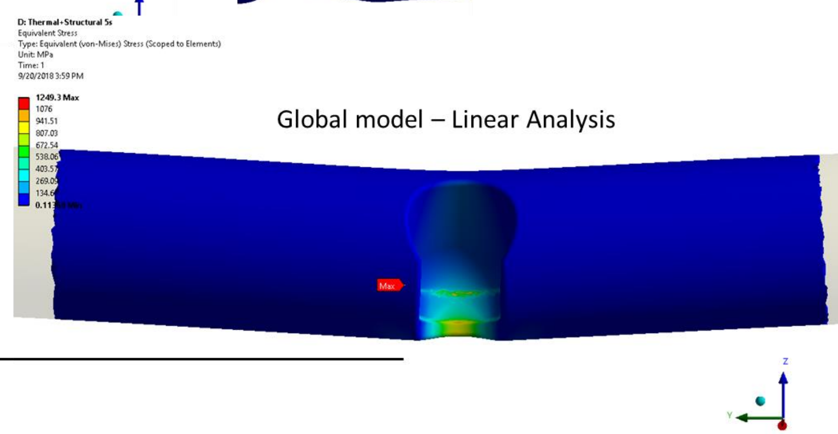


Comparison between Global and Submodel

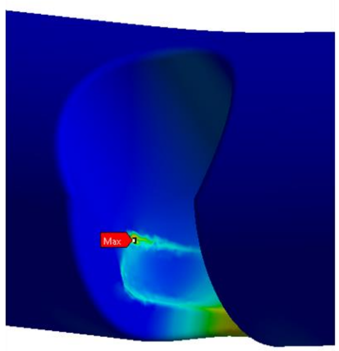


Sub-model – Linear Analysis

Peak stress are not in the same spot. Magnitudes are within 20%. However both models exceed the yield strength of the material.

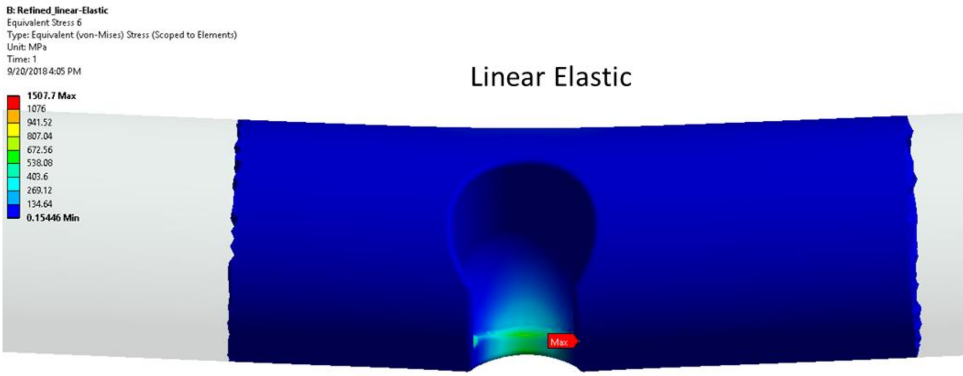


Global model – Linear Analysis



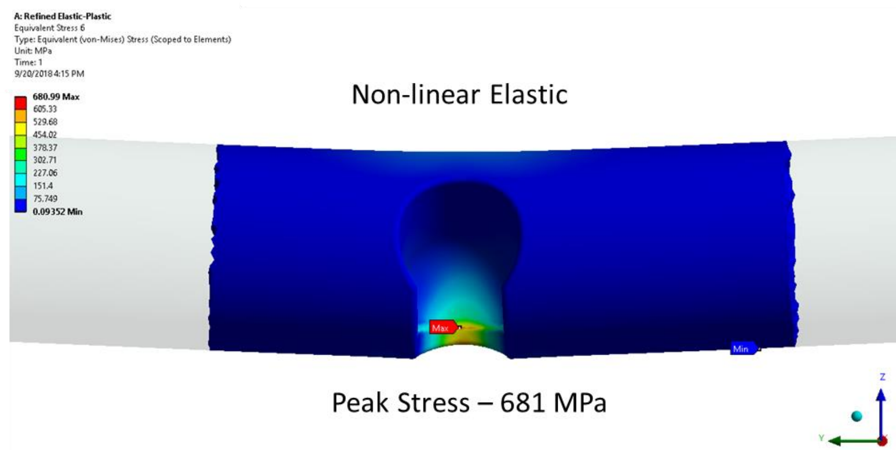
Peak Stresses in pins and Rods (Refined Mesh)

Linear Elastic



Peak Stress – 1508 MPa

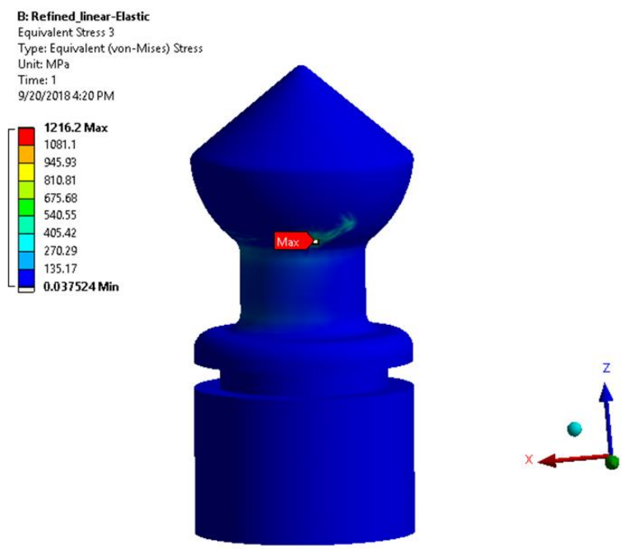
Non-linear Elastic



Peak Stress – 681 MPa

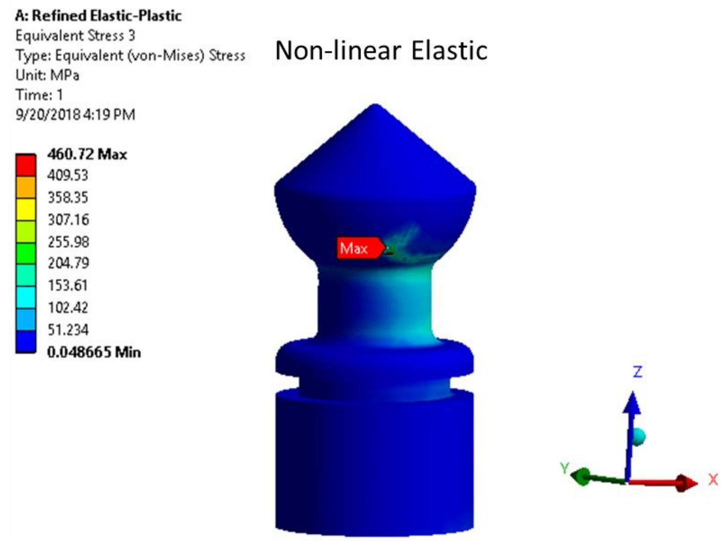
Peak Stresses in pins and Rods (Refined Mesh)

Linear Elastic



Peak Stress – 1216 MPa

Non-linear Elastic



Peak Stress – 461 MPa

Preliminary Conclusions

- All results presented were from the refined mesh. The stress decreased from 1508 MPa to 681 MPa in the rods by changing between a linear elastic solution method to a non-linear elastic solution method. There was no need to run this with bilinear properties because the model under non-linear conditions does not exceed the yield stress of 718.

1. **Minimum Requirements for Checking Calculations**

2. Assure that inputs were correctly selected and incorporated into the design.

3. Calculation considers, as appropriate:

   - Performance Requirements (capacity, rating, system output)
   - Design Conditions (pressure, temperature, voltage, etc.)
   - Load Conditions (Electromagnetic (Lorentz Force), seismic, wind, thermal, dynamic)
   - Environmental Conditions (radiation zone, hazardous material, etc.)
   - Material Requirements
   - Structural Requirements (foundations, pipe supports, etc.)
   - Hydraulic Requirements (NPSH, pressure drops, etc.)
   - Chemistry Requirements
   - Electrical Requirements (power source, volts, raceway, and insulation)
   - Equipment Reliability (FMEA)
   - Failure Effects on Surrounding Equipment
   - Tolerance Buildup

4. Assumptions necessary to perform the design activity are adequately described and reasonable.

5. An appropriate calculation method was used.

6. The results are reasonable compared to the inputs.

7. Error bars (range) for inputs used, results / conclusions, assumptions, have been considered and are acceptable.

8. NOTE: IT IS THE RESPONSIBILITY OF THE CHECKER TO USE METHODS THAT WILL SUBSTANTIATE TO HIS/HER PROFESSIONAL SATISFACTION THAT THE CALCULATION IS CORRECT.

BY SIGNING CALCULATION, CHECKER ACKNOWLEDGES THAT THE CALCULATION HAS BEEN APPROPRIATELY CHECKED AND THAT THE APPLICABLE ITEMS LISTED ABOVE HAVE BEEN INCLUDED AS PART OF THE CHECK.