Problem Statement

- Objective of analysis: To verify strength of Bend Limiter of Apache Julimar under listed loading condition

  A) Subsea Termination - Bend Limiter

    - Bending moment of 60 kN*m
    - Axial load of 1.5 tonnef (14.715 kN)
    - Shear load of 7.69 kN

  B) Pulling Head Side - Bend Limiter

    - Bending moment of 60 kN*m
    - Axial load of 15 tonnef (147.15 kN)
    - Shear load of 25 kN

Problem Statement, cont..

- Design criteria: as per ASME - BPVC 2010, Section VIII, Division 2
- Geometry Inputs:
  - Subsea Termination – Bend Limiter
    - Main Body: *D-0573608, Rev A*
    - Connecting Cap: *D-0573607, Rev A*
  - Pulling Head Side – Bend Limiter
    - Main Body: *D-0569157 , Rev A*
    - Connecting Cap: *D-0569155 , Rev A*
- Material of Construction
  - Main Body & Connection Cap : Medium Carbon Steel BS EN 10225 Grade S335 G10+M

Material Properties

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
S335 G10+M[1]	335	470

- The true Stress-Strain Curve Modeling for these materials as per ASME 2010, Section VIII, Division 2, Annexure 3.D
- *Material properties are same for both subsea termination and pulling head side Bend Limiter.*

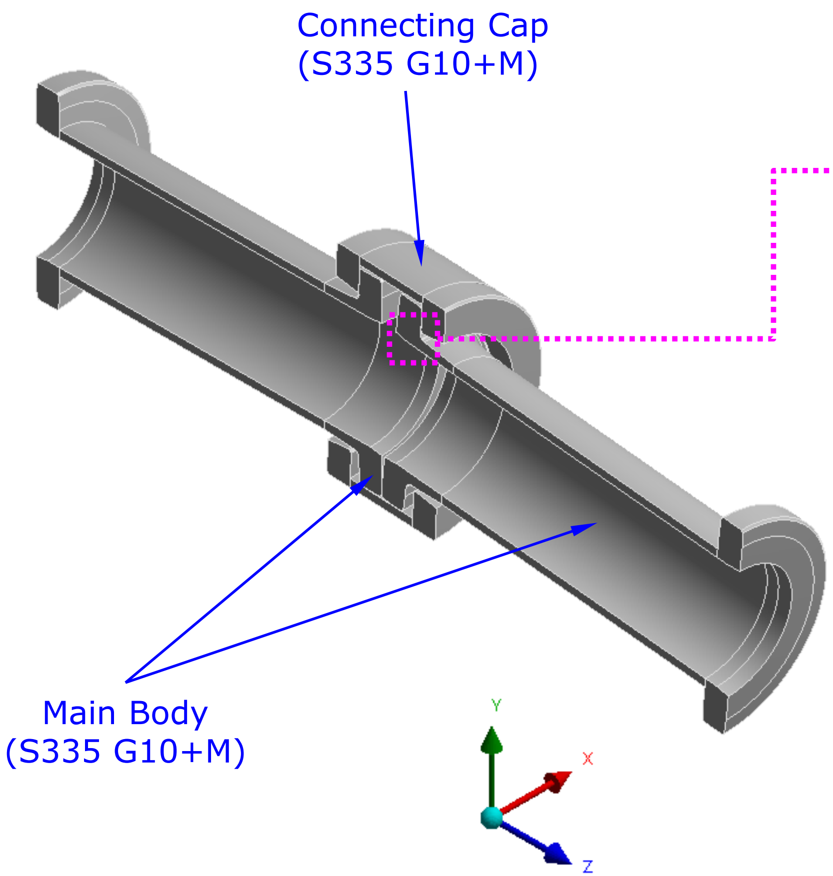
References

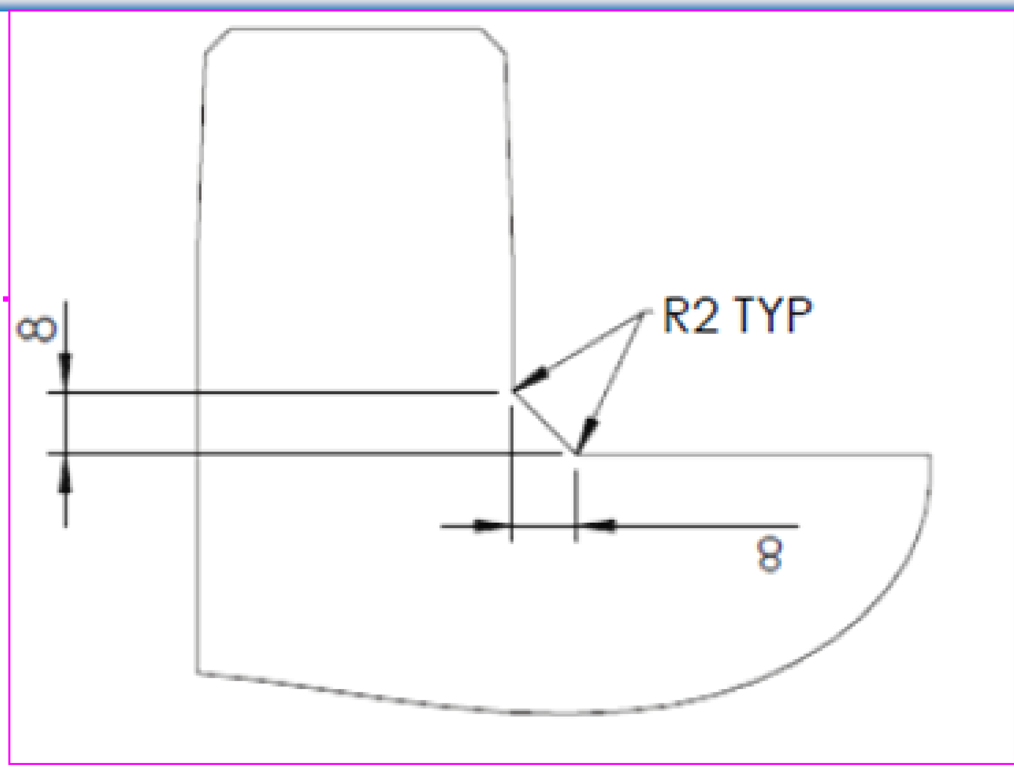
[1] *Material properties as per BS EN 10225 Specification*

Subsea Termination Bend Limiter

Analysis Results

Geometry Details

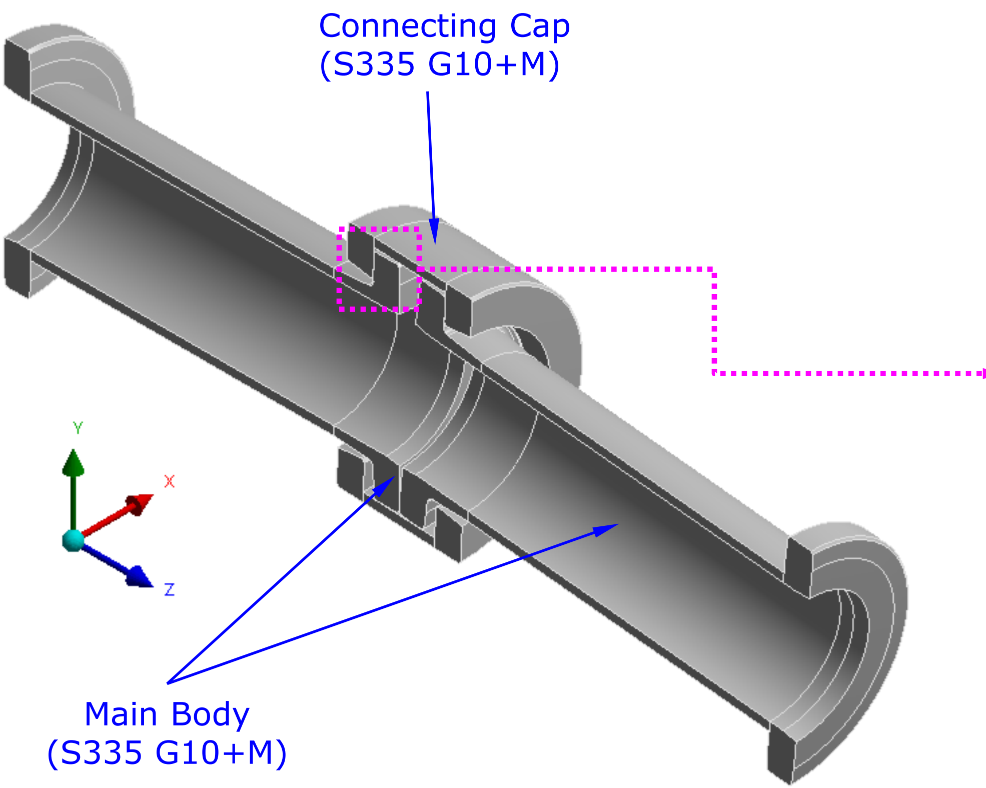


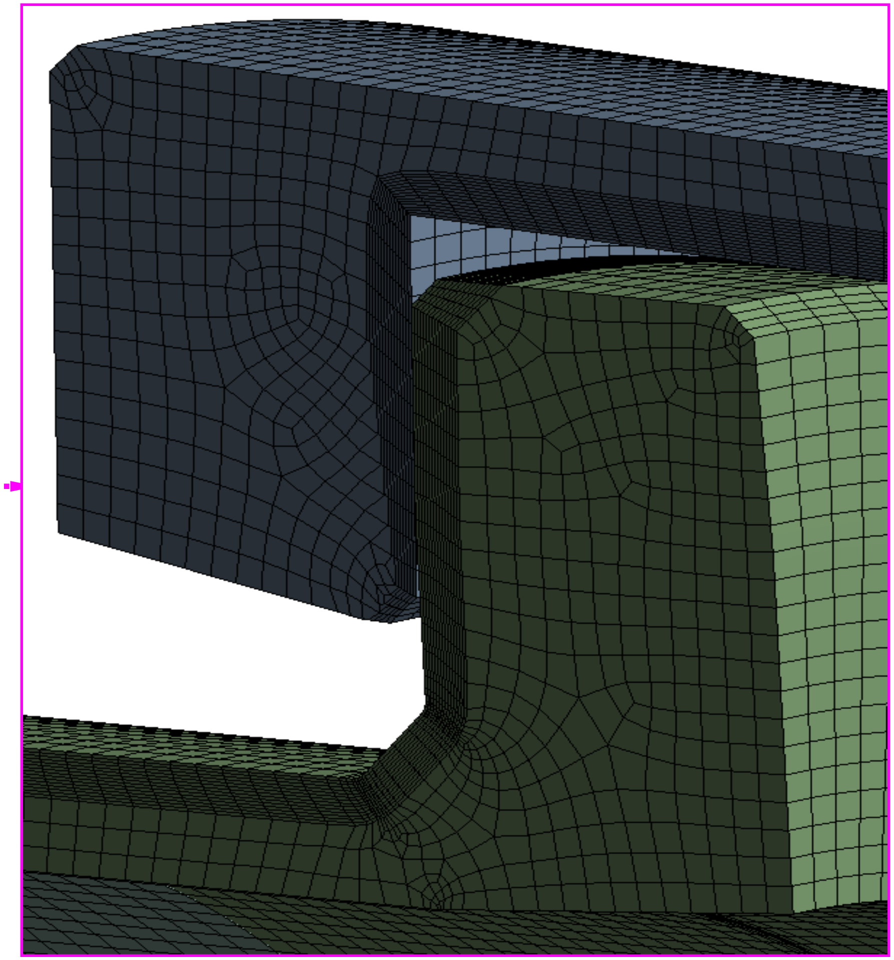


Post Weld Machining Details

FEA Model

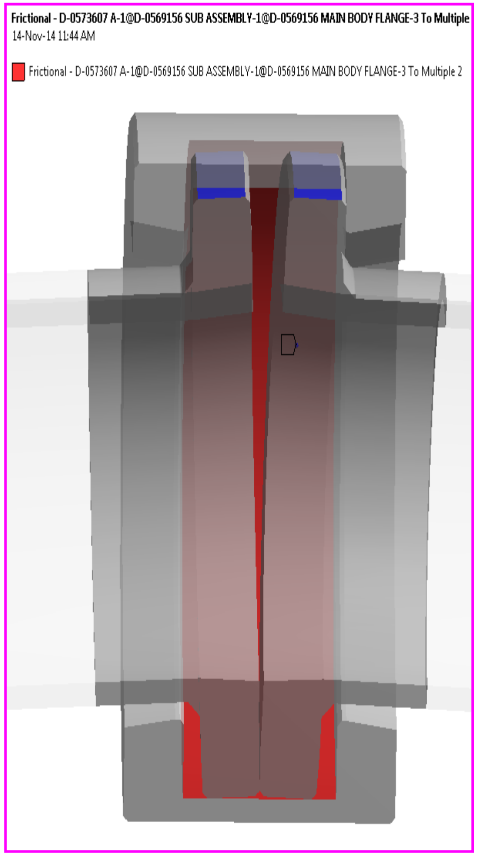
- Half symmetric solid model considered for this analysis
- Brick element SOLID186 used to mesh the FEA model

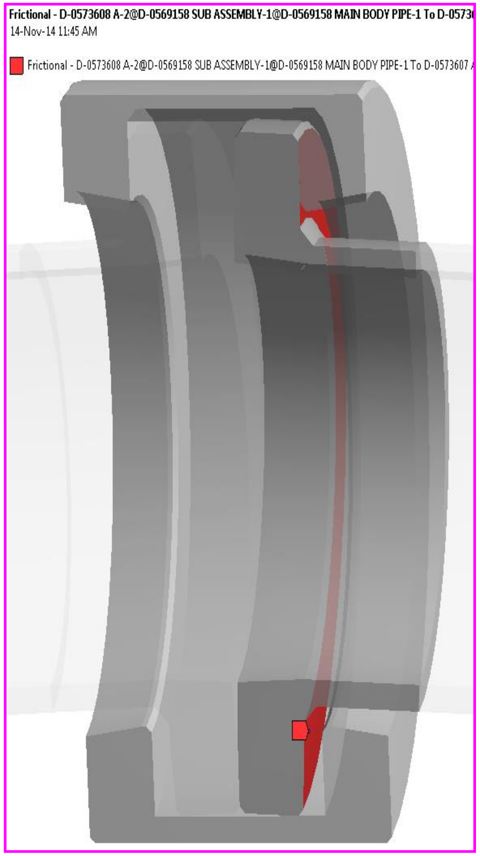


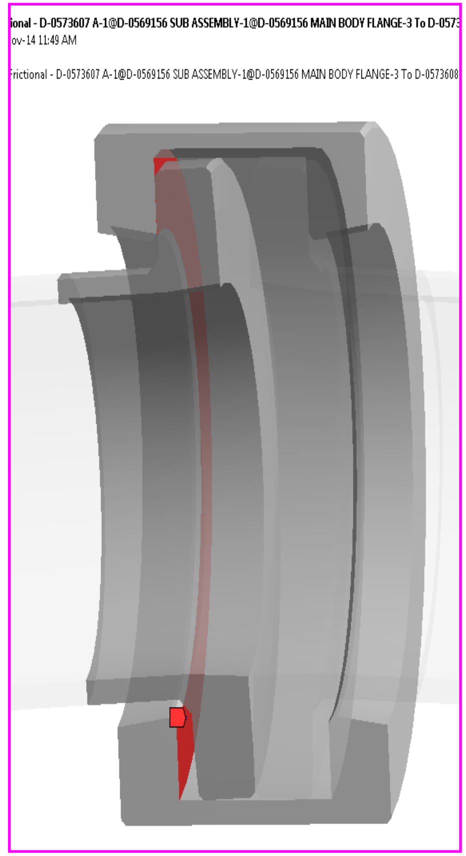


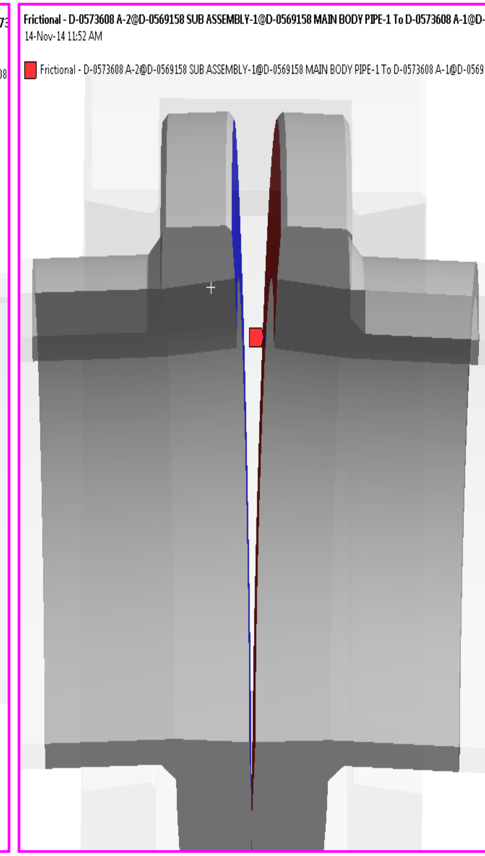
Subsea Termination - Bend Limiter

Frictional Contact Details









Frictional contact – Flanges of main body to Flanges of connecting body#

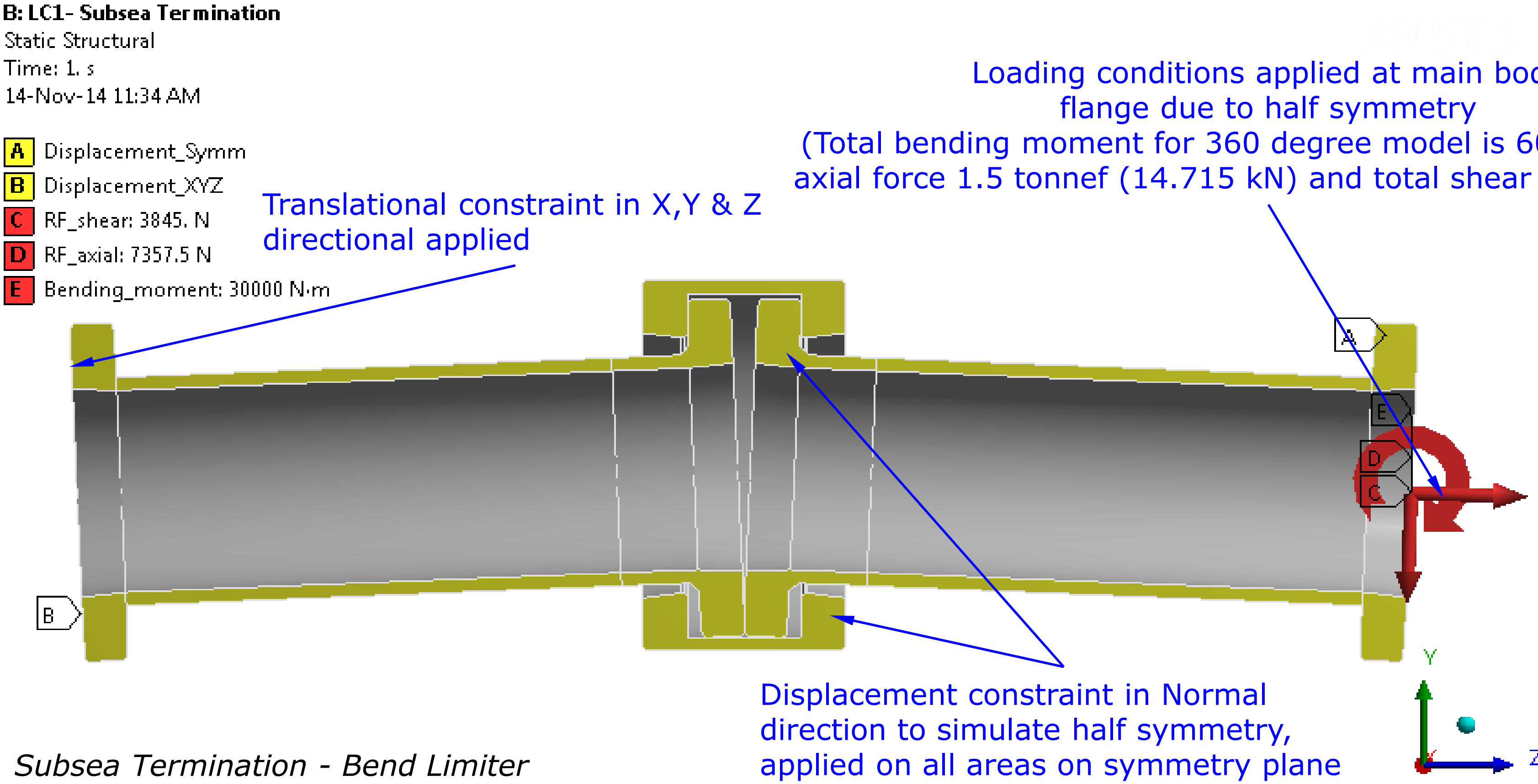
Frictional contact – Flanges of main body to Pipe of connecting body#

Frictional contact – Between two flanges of main body#

#Frictional coefficient between all contacts – 0.15

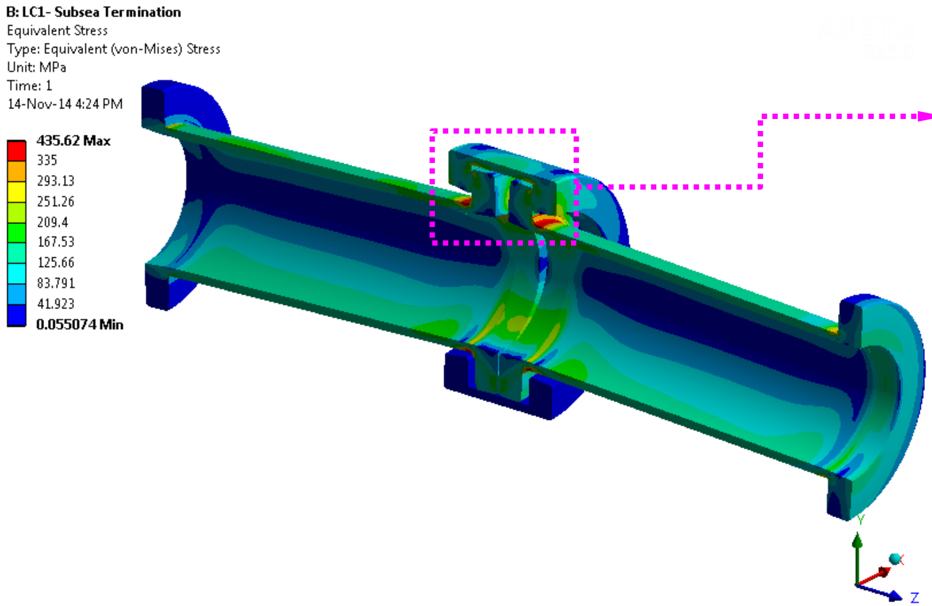
FEA Physics

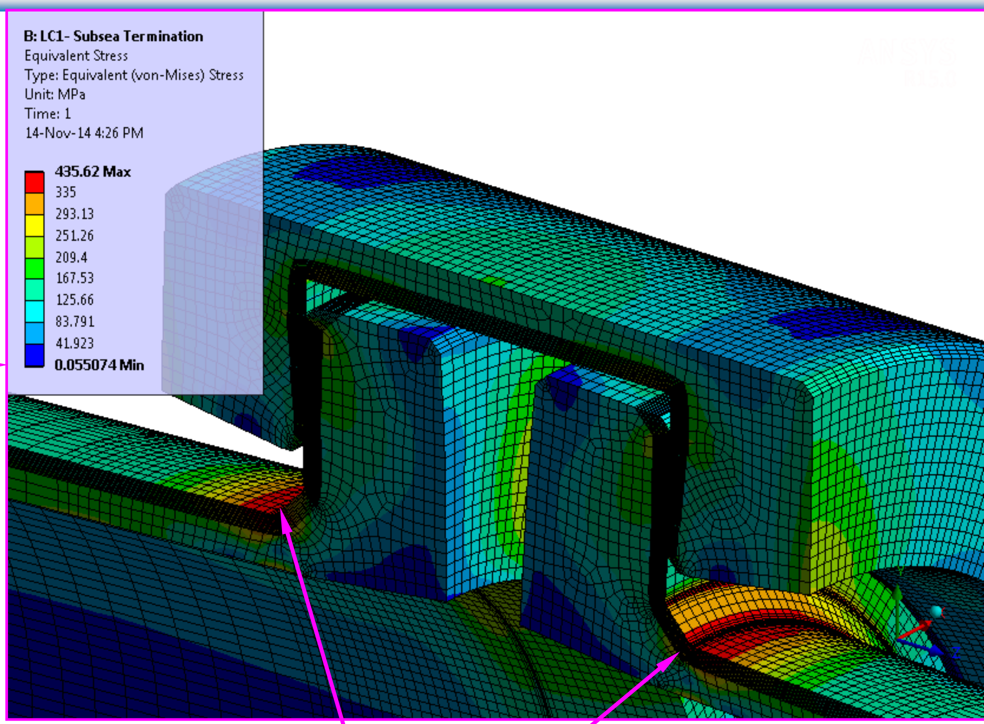
- Frictional contacts with frictional coefficient of 0.15 defined between all the adjoining parts
- Other loading & boundary conditions as stated below



Subsea Termination - Bend Limiter

Stress, von-Mises, Plot-1 (MPa)

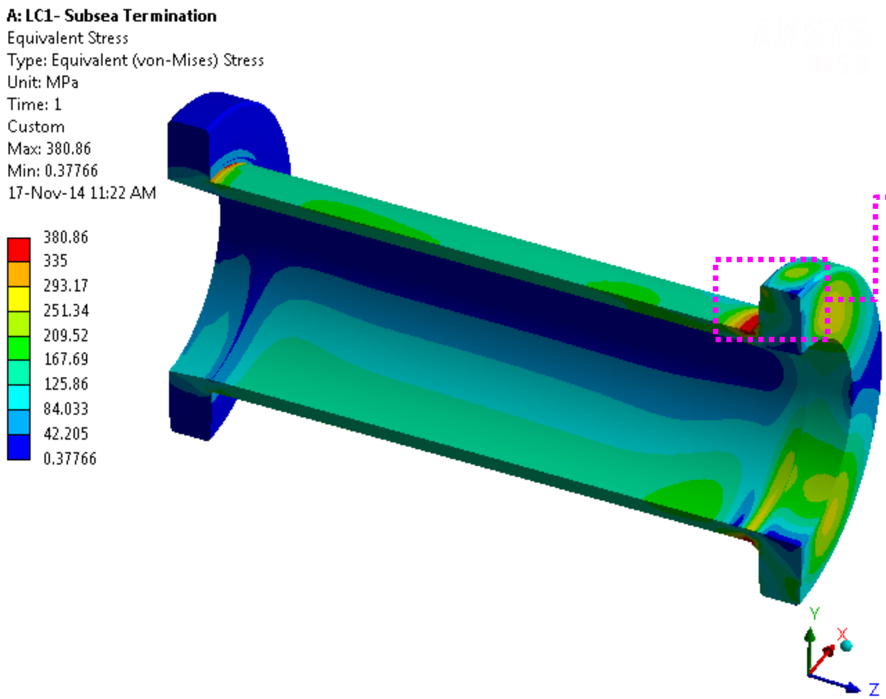


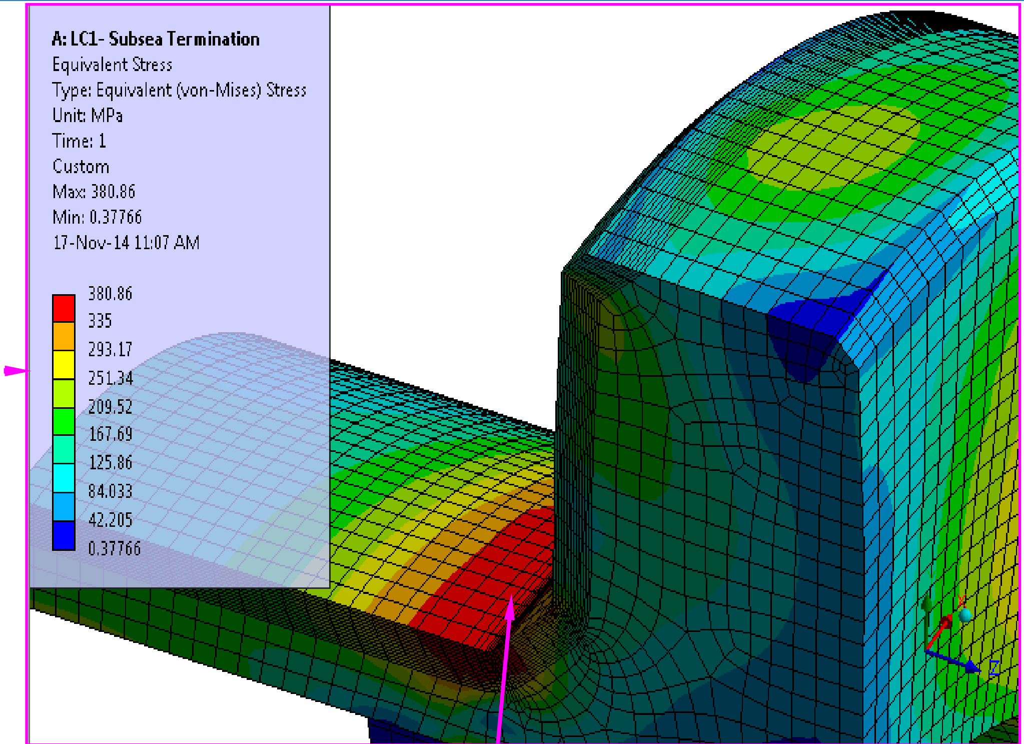


- Stresses above yield strength of material (S335 G10+M – 335 MPa)
- Local plastic deformation observed and verified using Tri-axial Limiting Strain Criteria as per ASME BVPC Div 2 Sec VIII

Subsea Termination - Bend Limiter
Overall Stress Plot

Stress, von-Mises, Plot-2 (MPa)



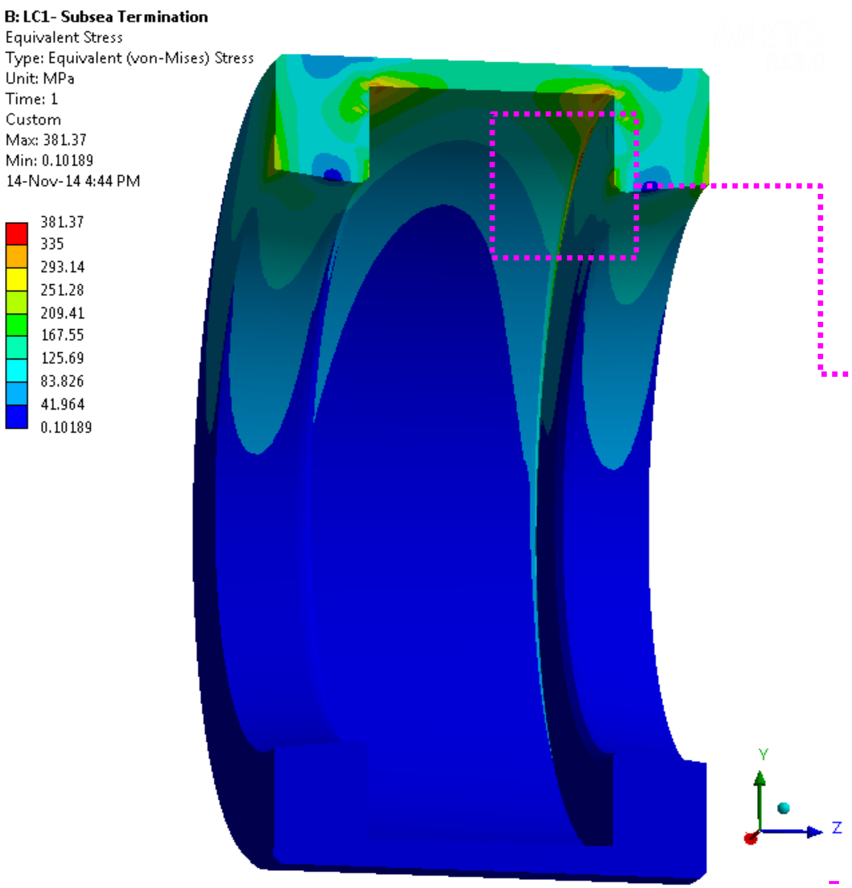


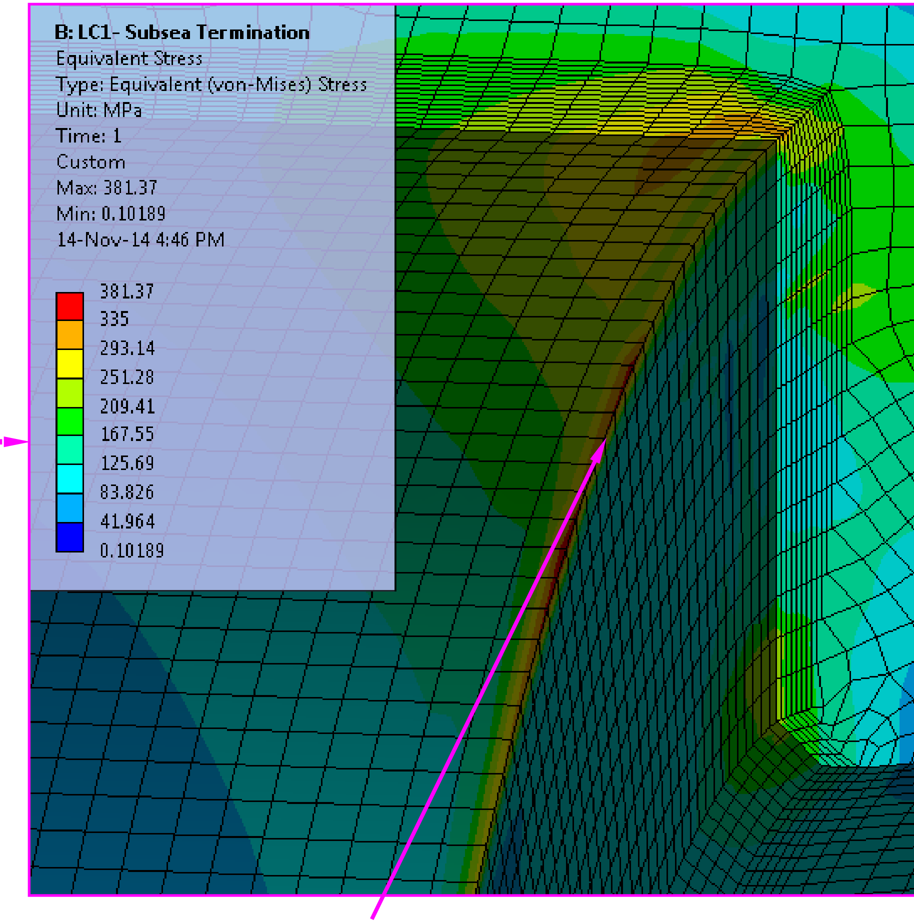
- Maximum von-Mises stress * = 380.86 MPa
(Material Yield strength = 335.00 MPa)
- Local plastic deformation observed and verified using Tri-axial Limiting Strain Criteria as per ASME BVPC Div 2 Sec VIII

* Region of max. plastic strain.

Subsea Termination - Bend Limiter Main Body

Stress, von-Mises, Plot-3 (MPa)

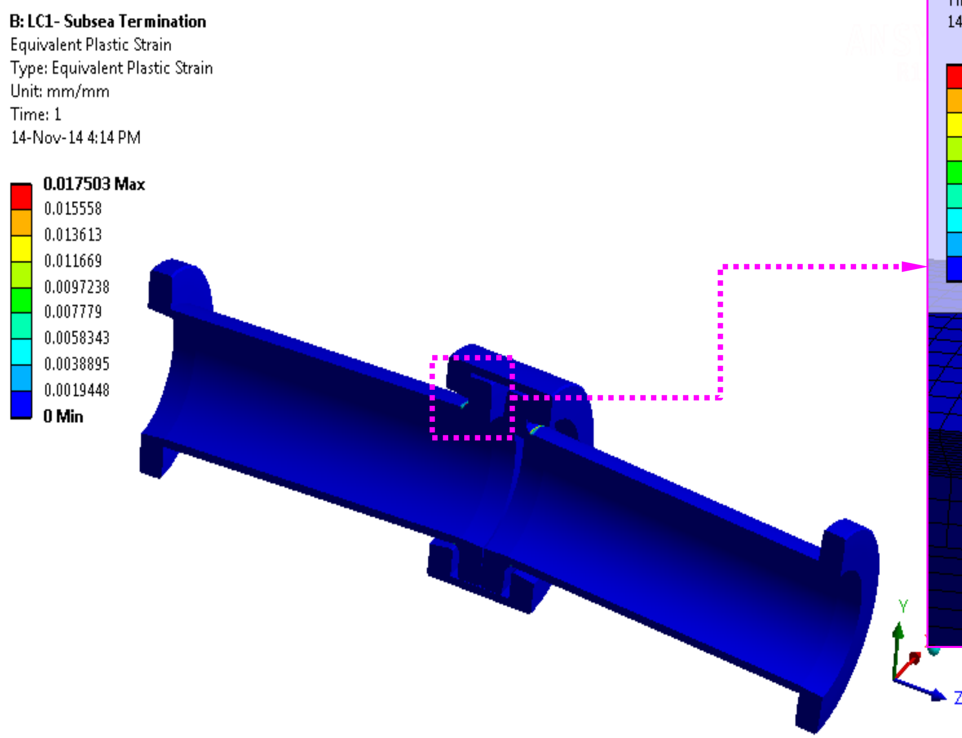


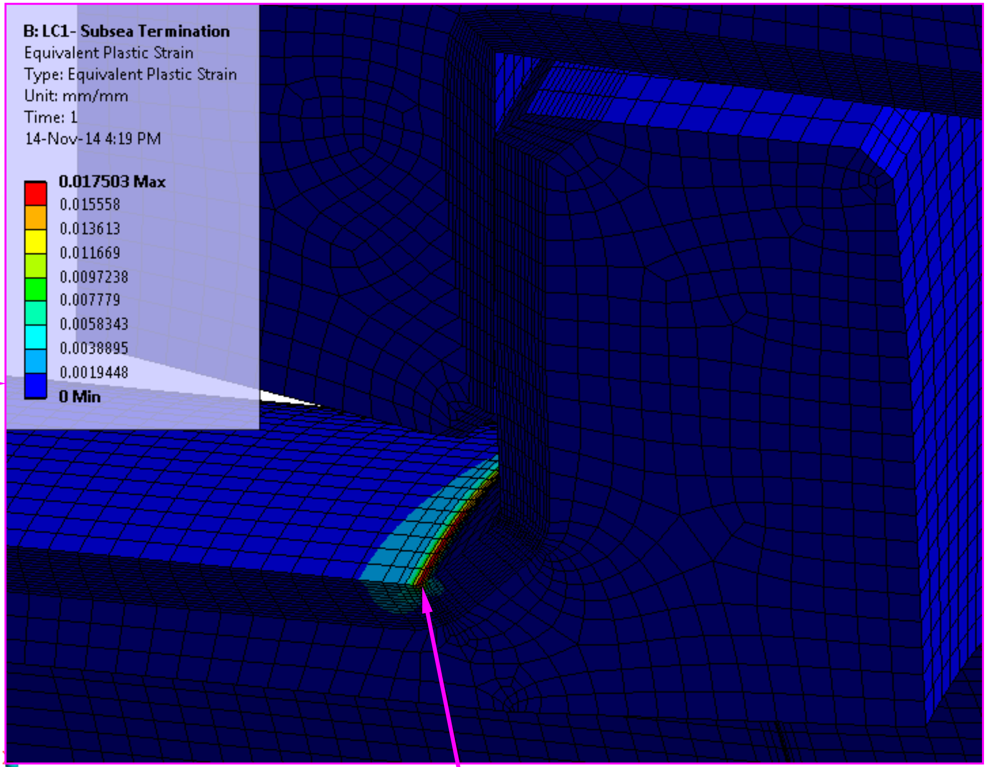


- Maximum von-Mises stress = 381.37 MPa
(Material Yield strength = 335.00 MPa)
- This value of stress is only due to meshing. No yielding will be observed at shown Area.

Subsea Termination - Bend Limiter Connecting Cap

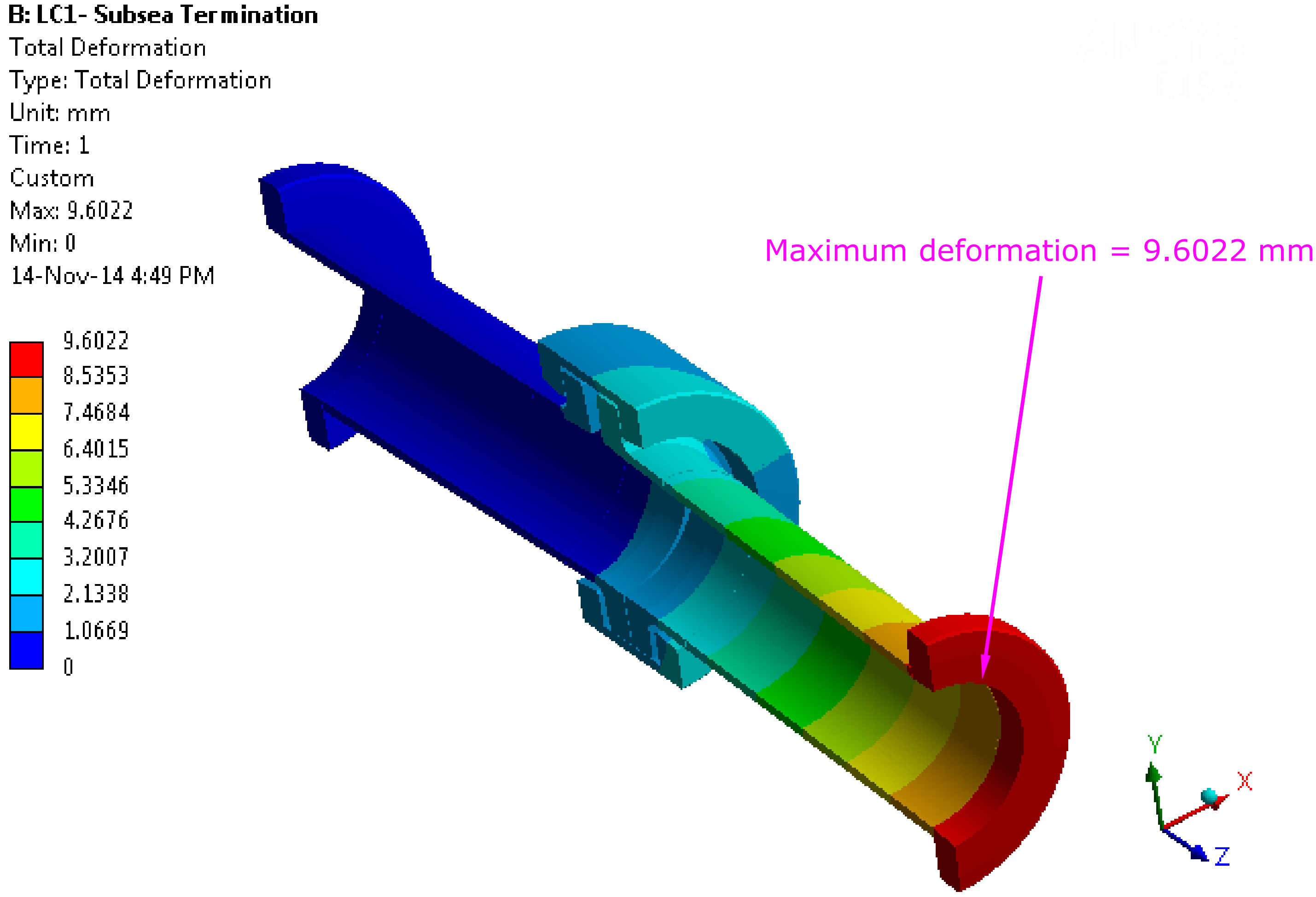
Plastic Strain, Plot - 4 (mm/ mm)





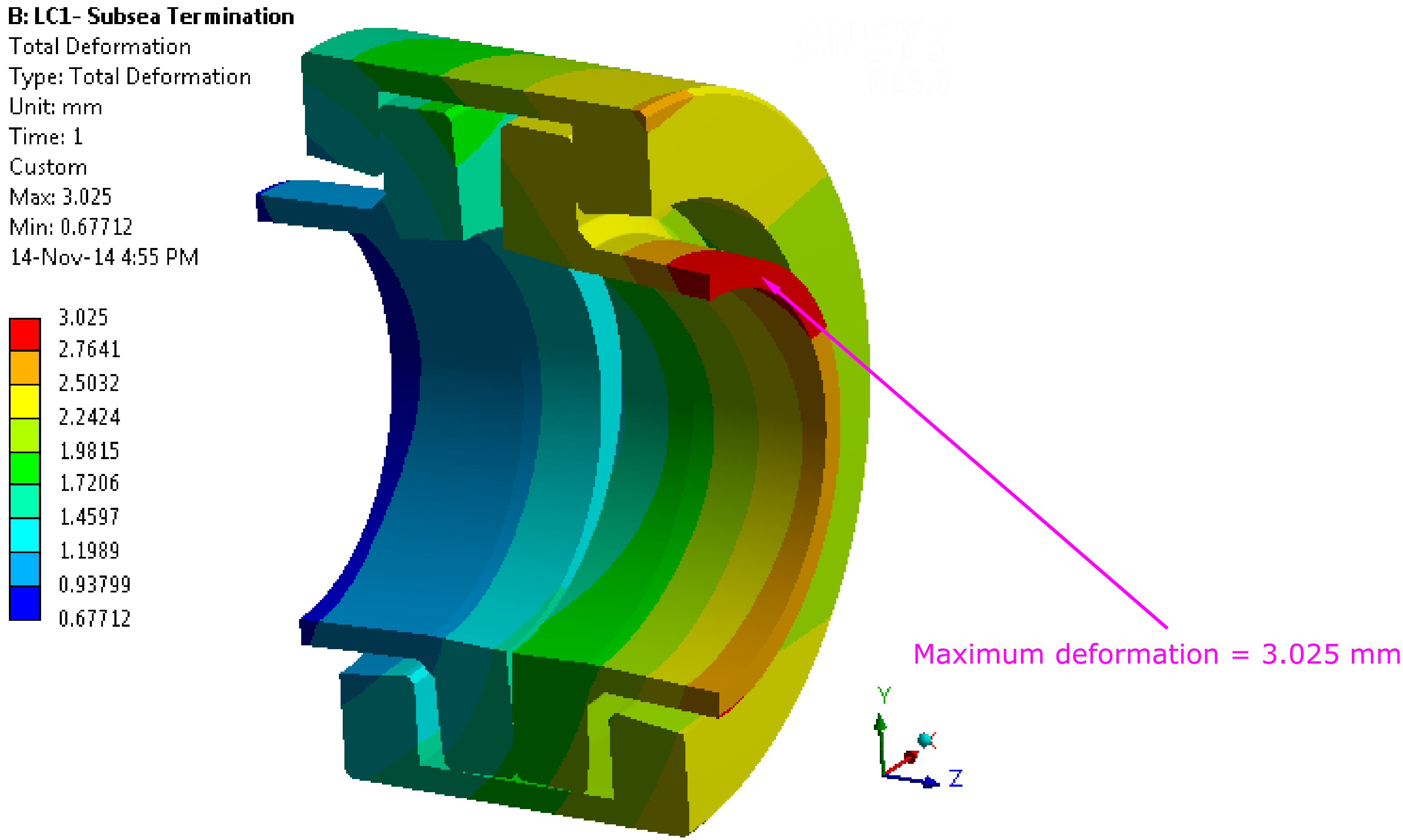
Maximum Plastic Strain = 0.017503 mm/mm
(At +ve principal stress locations)

Total Deformation, Plot-5 (mm)



Subsea Termination - Bend Limiter
Overall Deformation

Total Deformation, Plot-6 (mm)



Subsea Termination - Bend Limiter
Center region

Limiting Tri-axial Strain Calculation

Elastic-Plastic analysis as per ASME 2010, Section VIII, Division 2, Part 5.3.3

Material = BS EN 10225 Grade S355 G10 + M

$\sigma_1 := 453.74\text{MPa}$ — Principal stress in the 1-direction (at maximum equivalent plastic strain location)

$\sigma_2 := 233.23\text{MPa}$ — Principal stress in the 2-direction (at maximum equivalent plastic strain location)

$\sigma_3 := 13.969\text{MPa}$ — Principal stress in the 3-direction (at maximum equivalent plastic strain location)

$E := 200\text{GPa}$ — Modulus of elasticity

$\sigma_{ys} := 335\text{MPa}$

$\sigma_{uts} := 470\text{MPa}$ — Engineering ultimate tensile stress, evaluated at the temperature of interest

$\sigma_e := 380.86\text{MPa}$ — Equivalent stress (from Ansys Resullt)

$\varepsilon_{peq} := 0.017503$ — Total equivalent plastic strain (from Ansys Result)

$\varepsilon_{cf} := 0.00$ — Forming strain

Material_Type := 2 — Type of material (and temperature limit), as per Table 3.D.1

1 = Ferritic Steel [480°C (900°F)]
2 = Stainless Steel and Nickel Base Alloys [480°C (900°F)]
3 = Duplex Stainless Steel [480°C (900°F)]
4 = Precipitation Hardenable Nickel Base [540°C (1000°F)]
5 = Aluminum [120°C (250°F)]
6 = Copper [65°C (150°F)]
7 = Titanium and Zirconium [260°C (500°F)]

$$R := \frac{\sigma_{ys}}{\sigma_{uts}}$$

Ratio of the minimum specified yield strength divided by the minimum specified ultimate tensile strength

$R = 0.713$

$$\alpha_{sl} := \begin{cases} 2.2 & \text{if Material\_Type} = 1 \\ 0.6 & \text{if Material\_Type} = 2 \\ 2.2 & \text{if Material\_Type} = 3 \\ 2.2 & \text{if Material\_Type} = 4 \\ 2.2 & \text{if Material\_Type} = 5 \\ 2.2 & \text{if Material\_Type} = 6 \\ 2.2 & \text{if Material\_Type} = 7 \end{cases}$$

Material factor for the multiaxial strain limitas per Table 5.7.

$\alpha_{sl} = 0.6$

$$m_2 := \begin{cases} [0.60\cdot(1.00 - R)] & \text{if Material\_Type} = 1 \\ [0.75\cdot(1.00 - R)] & \text{if Material\_Type} = 2 \\ [0.70\cdot(0.95 - R)] & \text{if Material\_Type} = 3 \\ [1.90\cdot(0.93 - R)] & \text{if Material\_Type} = 4 \\ [0.52\cdot(0.98 - R)] & \text{if Material\_Type} = 5 \\ [0.50\cdot(1.00 - R)] & \text{if Material\_Type} = 6 \\ [0.50\cdot(0.98 - R)] & \text{if Material\_Type} = 7 \end{cases}$$

Curve fitting exponent for the stress-strain curve equal to the true strain at the true ultimate stress, as per Table 5.7

$m_2 = 0.215$

If the elongation and reduction in area are not specified,then

$\varepsilon_{Lu} := m_2$

$$\varepsilon_L := \varepsilon_{Lu}\cdot e^{\left[-\left[\frac{\alpha_{sl}}{(1+m_2)}\right]\left[\left[\frac{(\sigma_1+\sigma_2+\sigma_3)}{3\sigma_e}\right]-\frac{1}{3}\right]\right]}$$

$\varepsilon_L = 0.188$ — Limiting triaxial strain

$$FOS := \frac{\varepsilon_L}{\varepsilon_{peq}}$$

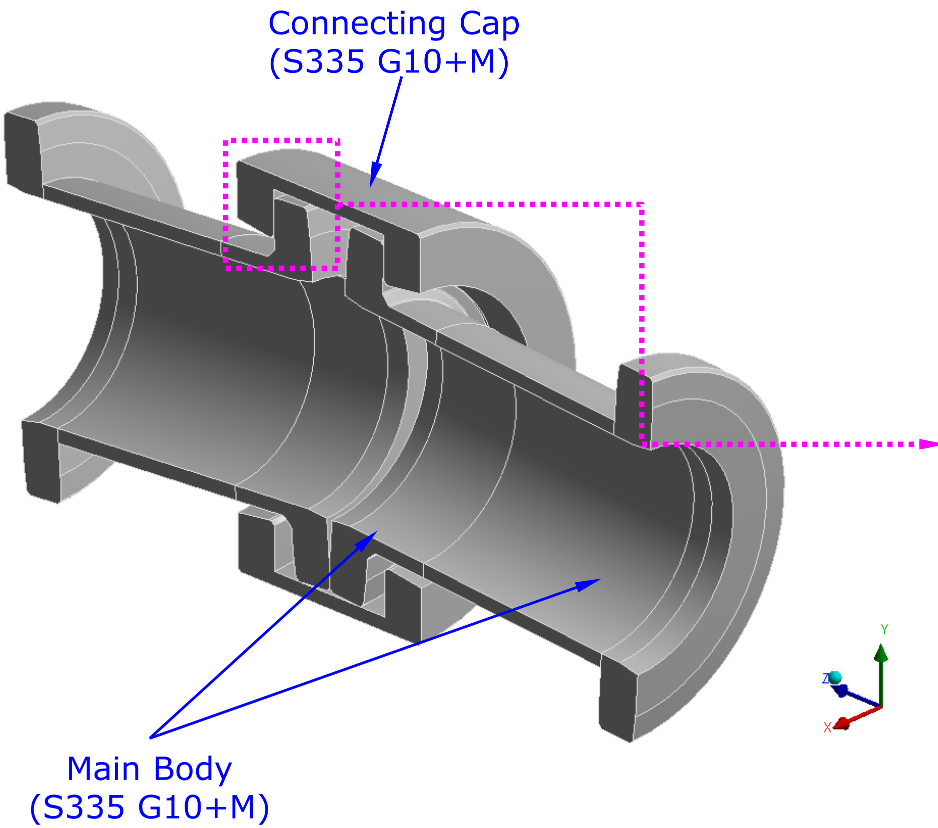
$FOS = 10.718$ — Factor of safety against local failure due to any plastic strain

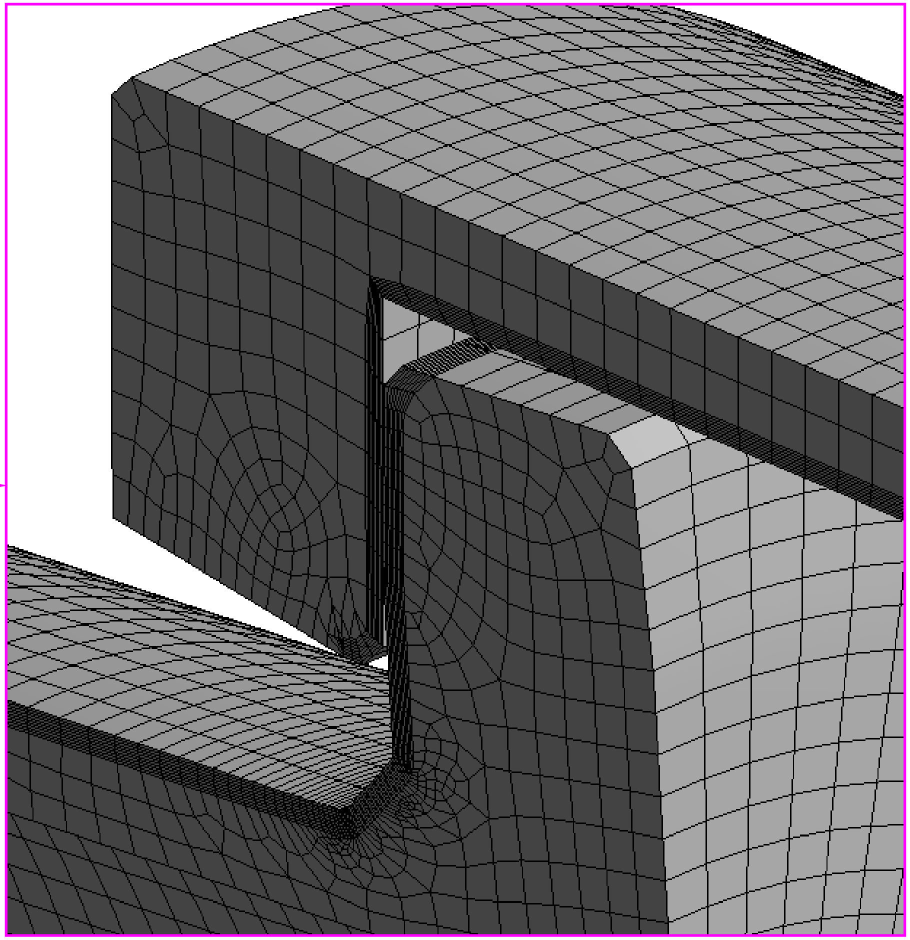
Pulling Head Side Bend Limiter

Analysis Results

FEA Model

- Half symmetric solid model considered for this analysis
- Brick element SOLID186 used to mesh the FEA model

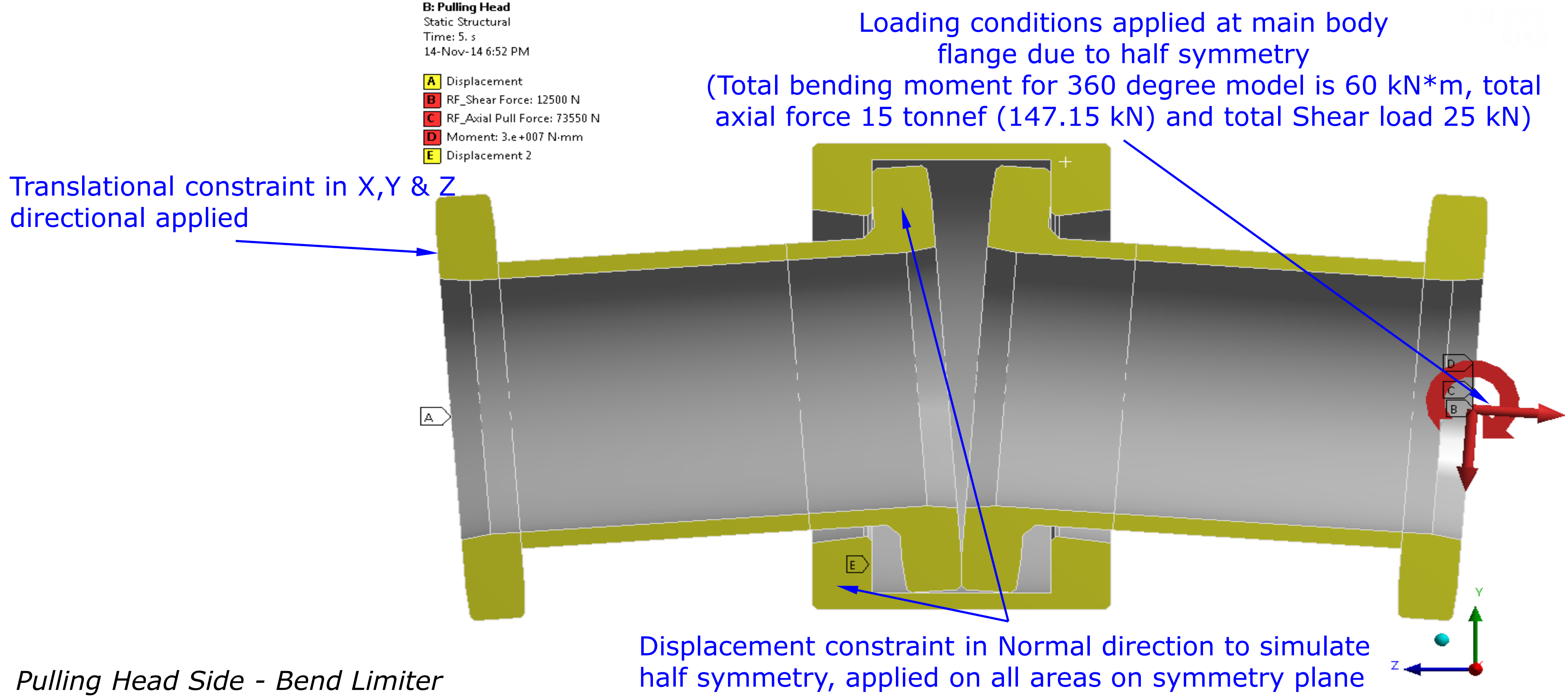




Pulling Head Side - Bend Limiter

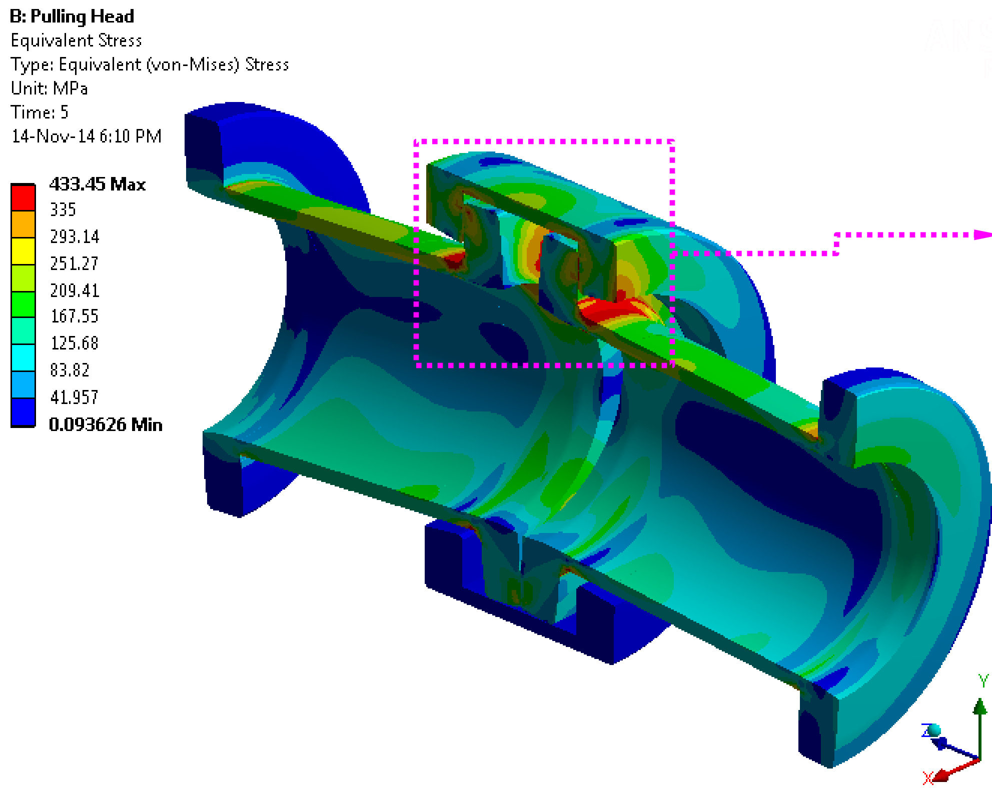
FEA Physics

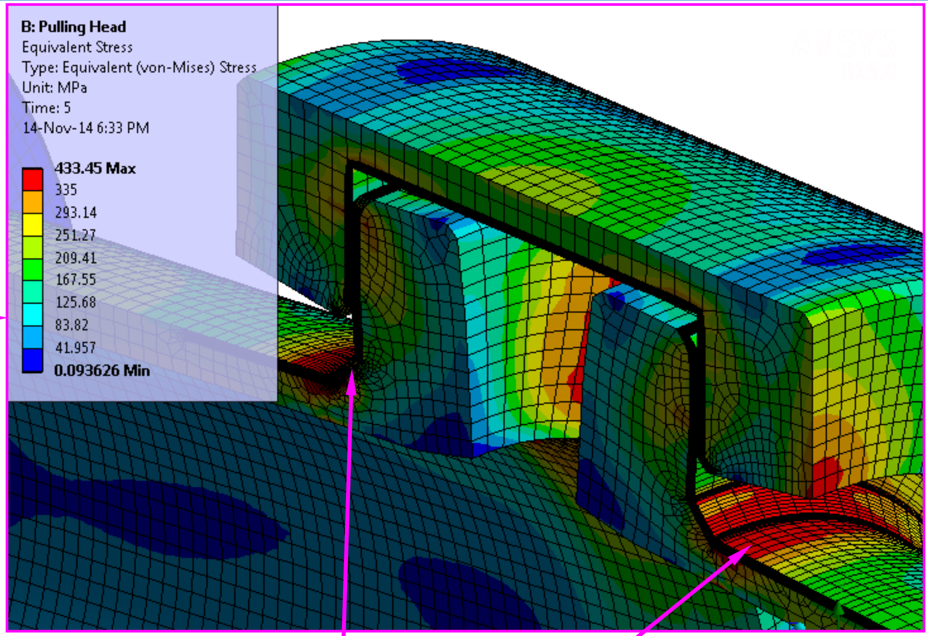
- Frictional contacts with frictional coefficient of 0.15 defined between all the adjoining parts as shown in Slide 8.
- Other loading & boundary conditions as stated below



Pulling Head Side - Bend Limiter

Stress, von-Mises, Plot-1 (MPa)

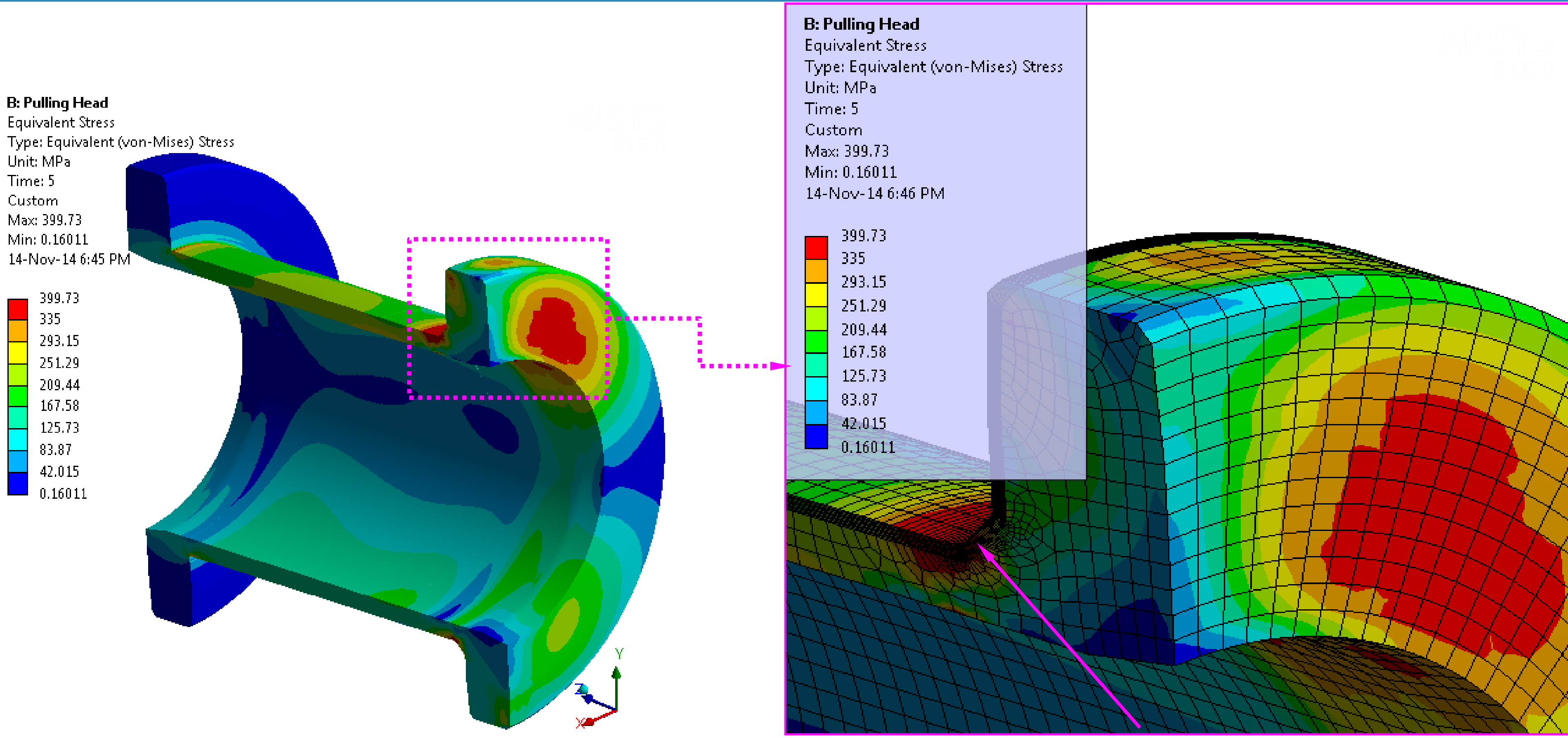




- Stresses above yield strength of material (S335 G10+M – 335 MPa)
- Local plastic deformation observed and verified using Tri-axial Limiting Strain Criteria as per ASME BVPC Div 2 Sec VIII

Pulling Head Side - Bend Limiter
Overall Stress Plot

Stress, von-Mises, Plot-2 (MPa)

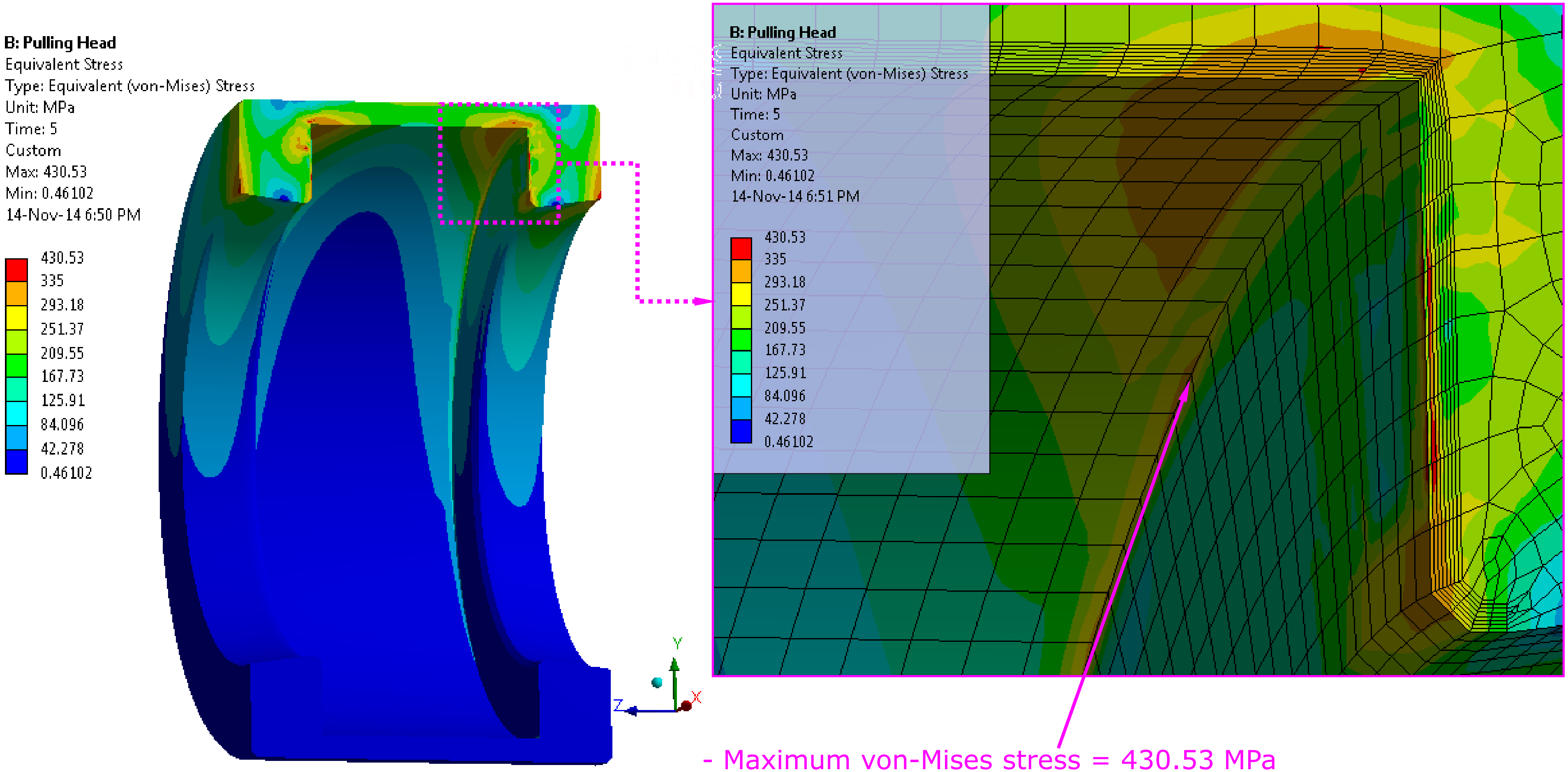


- Maximum von-Mises stress * = 399.73 MPa
  (Material Yield strength = 335 MPa)
- Local plastic deformation observed and verified using Tri-axial Limiting Strain Criteria as per ASME BVPC Div 2 Sec VIII

Pulling Head Side - Bend Limiter
Main Body

* Region of max. plastic strain.

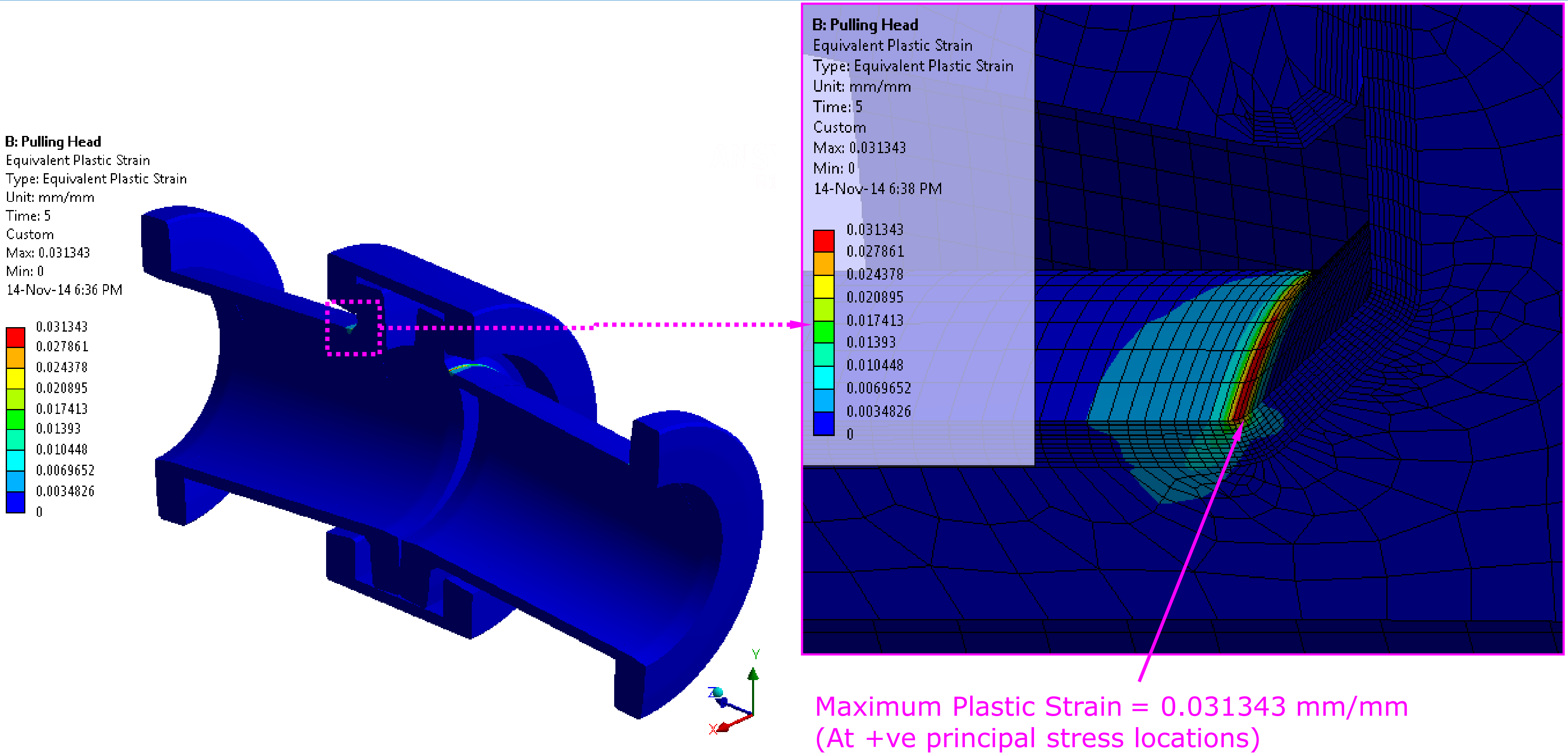
Stress, von-Mises, Plot-3 (MPa)



- Maximum von-Mises stress = 430.53 MPa
(Material Yield strength = 335 MPa)
- This value of stress is only due to meshing. No yielding will be observed at shown Area.

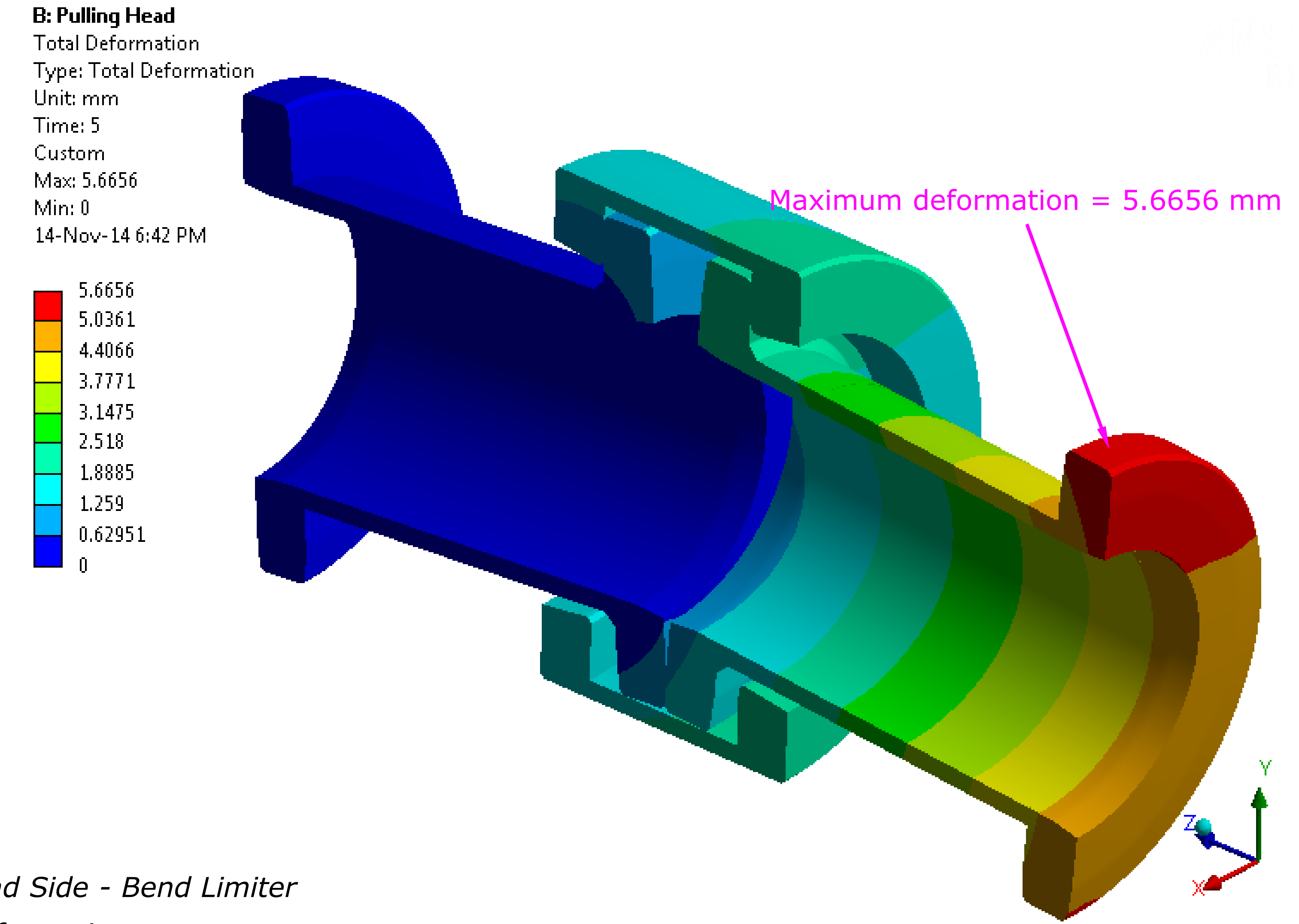
Pulling Head Side - Bend Limiter Connecting Cap

Plastic Strain, Plot – 4 (mm/mm)



Pulling Head Side - Bend Limiter

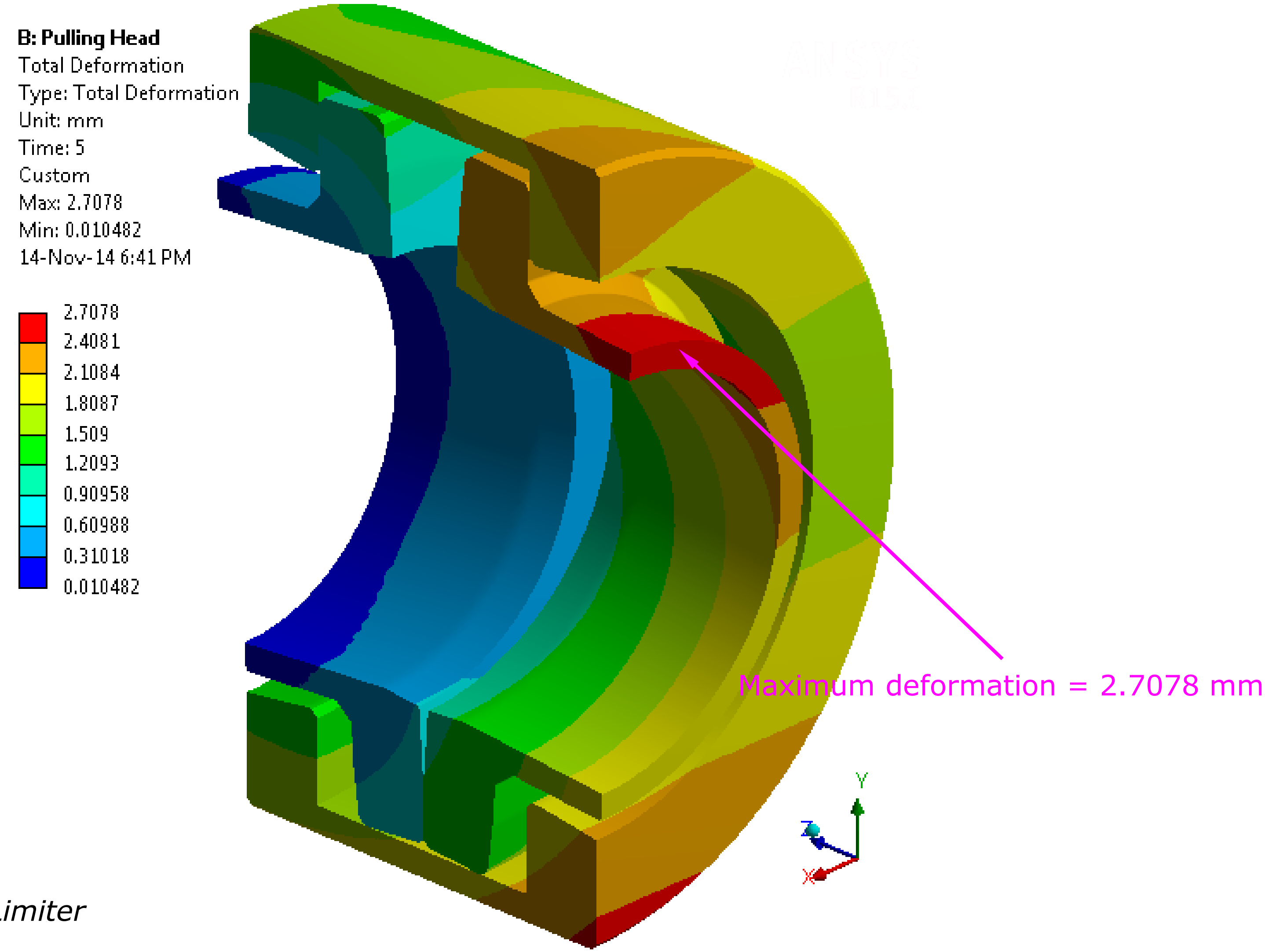
Total Deformation, Plot-5 (mm)



Pulling Head Side - Bend Limiter

Overall Deformation

Total Deformation, Plot-6 (mm)



Pulling Head Side - Bend Limiter

Center Region

Limiting Tri-axial Strain Calculation

Elastic-Plastic analysis as per ASME 2010, Section VIII, Division 2, Part 5.3.3

Material = BS EN 10225 Grade S355 G10 + M

$\sigma_1 := 475.33\text{MPa}$ Principal stress in the 1-direction (at maximum equivalent plastic strain location)

$\sigma_2 := 246.51\text{MPa}$ Principal stress in the 2-direction (at maximum equivalent plastic strain location)

$\sigma_3 := 13.765\text{MPa}$ Principal stress in the 3-direction (at maximum equivalent plastic strain location)

$E := 200\text{GPa}$ Modulus of elasticity

$\sigma_{ys} := 335\text{MPa}$

$\sigma_{uts} := 470\text{MPa}$ Engineering ultimate tensile stress, evaluated at the temperature of interest

$\sigma_e := 399.73\text{MPa}$ Equivalent stress (from Ansys Resullt)

$\varepsilon_{peq} := 0.031343$ Total equivalent plastic strain (from Ansys Result)

$\varepsilon_{cf} := 0.00$ Forming strain

Material_Type := 2 Type of material (and temperature limit), as per Table 3.D.1
1 = Ferritic Steel [480°C (900°F)]
2 = Stainless Steel and Nickel Base Alloys [480°C (900°F)]
3 = Duplex Stainless Steel [480°C (900°F)]
4 = Precipitation Hardenable Nickel Base [540°C (1000°F)]
5 = Aluminum [120°C (250°F)]
6 = Copper [65°C (150°F)]
7 = Titanium and Zirconium [260°C (500°F)]

$R := \frac{\sigma_{ys}}{\sigma_{uts}}$ Ratio of the minimum specified yield strength divided by the minimum specified ultimate tensile strength

$R = 0.713$

$$\alpha_{sl} := \begin{cases} 2.2 & \text{if Material\_Type} = 1 \\ 0.6 & \text{if Material\_Type} = 2 \\ 2.2 & \text{if Material\_Type} = 3 \\ 2.2 & \text{if Material\_Type} = 4 \\ 2.2 & \text{if Material\_Type} = 5 \\ 2.2 & \text{if Material\_Type} = 6 \\ 2.2 & \text{if Material\_Type} = 7 \end{cases}$$

Material factor for the multiaxial strain limitas per Table 5.7.

$\alpha_{sl} = 0.6$

$$m_2 := \begin{cases} [0.60\cdot(1.00 - R)] & \text{if Material\_Type} = 1 \\ [0.75\cdot(1.00 - R)] & \text{if Material\_Type} = 2 \\ [0.70\cdot(0.95 - R)] & \text{if Material\_Type} = 3 \\ [1.90\cdot(0.93 - R)] & \text{if Material\_Type} = 4 \\ [0.52\cdot(0.98 - R)] & \text{if Material\_Type} = 5 \\ [0.50\cdot(1.00 - R)] & \text{if Material\_Type} = 6 \\ [0.50\cdot(0.98 - R)] & \text{if Material\_Type} = 7 \end{cases}$$

Curve fitting exponent for the stress-strain curve equal to the true strain at the true ultimate stress, as per Table 5.7

$m_2 = 0.215$

If the elongation and reduction in area are not specified,then

$\varepsilon_{Lu} := m_2$

$$\varepsilon_L := \varepsilon_{Lu}\cdot e^{\left[-\left[\left(\frac{\alpha_{sl}}{(1+m_2)}\right)\right]\left[\frac{(\sigma_1+\sigma_2+\sigma_3)}{3\sigma_e}\right]-\frac{1}{3}\right]}$$

$\varepsilon_L = 0.188$ Limiting triaxial strain

$FOS := \frac{\varepsilon_L}{\varepsilon_{peq}}$ $FOS = 5.986$ Factor of safety against local failure due to any plastic strain

Pulling Head Side - Bend Limiter

Analysis Summary

- The subsea termination and Pulling Head side Main body is experiencing local plastic deformation, hence limiting tri-axial strain is derived for main body as per ASME - BPVC 2010
- Local plastic deformation is observed at main body shown in Slide 13 and Slide 23 for subsea termination and Pulling Head side respectively
- The ratio of limit stain (tri-axial limiting strain - as per ASME - BPVC 2010, Section VIII, Division 2) to observed plastic strain is above 1.5
- No local plastic yielding is observed on connection body – both Bend limiter

Conclusions

- Local plastic deformation is observed in pipe of main body at joint of flange and pipe. This is caused by yielding around local geometric stress concentrations and limited to a small percentage of the section thickness.
- The factors of safety in terms of strain are 10.72 (*Subsea termination*) and 5.99 (*Pulling Head*)
- The bend limiters (main body) may observe permanent plastic deformation under analyzed condition. Due to permanent plastic deformation the component/ assembly will observed low cycle fatigue life (life $< 10^3$)

Appendix A:

Non-Linear Material Properties Calculations (BS EN 10225 Grade S335)

Stress-Strain Curve Modeling – BS EN 10225 Grade S335 (slide 1)

Stress Strain Curve Modeling as per ASME 2010, Section VIII, Division 2, Annexure 3.D

Material = BS EN 10225 S335

$\sigma_{ys} := 335\,\text{MPa}$ — Engineering yield stress, evaluated at the temperature of interest as per Document S5490 AB.pdf,Page-7

$\sigma_{ys} = 48.588 \cdot \text{ksi}$

$\sigma_{uts} := 470\,\text{MPa}$ — Engineering ultimate tensile stress, evaluated at the temperature of interest as per Document S5490 AB.pdf,Page-7

$\sigma_{uts} = 68.168 \cdot \text{ksi}$

$E_y := 200\,\text{GPa}$ — Modulus of elasticity, evaluated at the temperature of interest

$E_y = 29007.55 \cdot \text{ksi}$

Material_Type := 2 — Type of material (and temperature limit), as per Table 3.D.1
1 = Ferritic Steel [480°C (900°F)]
2 = Stainless Steel and Nickel Base Alloys [480°C (900°F)]
3 = Duplex Stainless Steel [480°C (900°F)]
4 = Precipitation Hardenable Nickel Base [540°C (1000°F)]
5 = Aluminum [120°C (250°F)]
6 = Copper [65°C (150°F)]
7 = Titanium and Zirconium [260°C (500°F)]

$\varepsilon_{ys} := 0.002$ — 0.2% engineering offset strain, as per Equation 3.D.11

$R := \dfrac{\sigma_{ys}}{\sigma_{uts}}$ — Engineering yield to engineering tensile ratio, as per Equation 3.D.10

$R = 0.713$

$K := 1.5 \cdot R^{1.5} - 0.5 \cdot R^{2.5} - R^{3.5}$ — Material parameter for stress-strain curve model, as per Equation 3.D.12

$K = 0.382$

$$m_2 := \begin{cases} [0.60 \cdot (1.00 - R)] & \text{if Material\_Type} = 1 \\ [0.75 \cdot (1.00 - R)] & \text{if Material\_Type} = 2 \\ [0.70 \cdot (0.95 - R)] & \text{if Material\_Type} = 3 \\ [1.90 \cdot (0.93 - R)] & \text{if Material\_Type} = 4 \\ [0.52 \cdot (0.98 - R)] & \text{if Material\_Type} = 5 \\ [0.50 \cdot (1.00 - R)] & \text{if Material\_Type} = 6 \\ [0.50 \cdot (0.98 - R)] & \text{if Material\_Type} = 7 \end{cases}$$

Curve fitting exponent for the stress-strain curve equal to the true strain at the true ultimate stress, as per Table 3.D.1

$m_2 = 0.215$

$$\varepsilon_p := \begin{cases} 5.0 \times 10^{-6} & \text{if } 5 \le \text{Material\_Type} \le 6 \\ 2.0 \times 10^{-5} & \text{otherwise} \end{cases}$$

Stress-strain curve fitting parameter, as per Table 3.D.1

$\varepsilon_p = 2 \times 10^{-5}$

$$m_1 := \frac{\ln(R) + \varepsilon_p - \varepsilon_{ys}}{\ln\left(\dfrac{\ln(1+\varepsilon_p)}{\ln(1+\varepsilon_{ys})}\right)}$$

Curve fitting exponent for the stress-strain curve equal to the true strain at the proportional limit and the strain hardening coefficient in the large strain region, as per Equation 3.D.6

$m_1 = 0.074$

$\sigma_{uts\_t} := \sigma_{uts} \cdot \exp(m_2)$ — True ultimate tensile stress evaluated at the true ultimate tensile strain, as per Equation 3.D.13

$\sigma_{uts\_t} = 582.983 \cdot \text{MPa}$

$\sigma_{uts\_t} = 84.555 \cdot \text{ksi}$

True stress at which the true strain will be evaluated

$$\sigma_t := \begin{bmatrix} 0\,\text{MPa} \\ \sigma_{ys} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{1}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{2}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{3}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{4}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{5}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{6}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{7}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{8}{10} \\ \sigma_{ys} + (\sigma_{uts\_t} - \sigma_{ys}) \cdot \frac{9}{10} \\ \sigma_{uts\_t} \end{bmatrix}$$

$$\sigma_t = \begin{pmatrix} 0 \\ 335 \\ 359.798 \\ 384.597 \\ 409.395 \\ 434.193 \\ 458.992 \\ 483.79 \\ 508.588 \\ 533.386 \\ 558.185 \\ 582.983 \end{pmatrix} \cdot \text{MPa} \qquad \sigma_t = \begin{pmatrix} 0 \\ 48.588 \\ 52.184 \\ 55.781 \\ 59.378 \\ 62.974 \\ 66.571 \\ 70.168 \\ 73.764 \\ 77.361 \\ 80.958 \\ 84.555 \end{pmatrix} \cdot \text{ksi}$$

Stress-Strain Curve Modeling –BS EN 10225 Grade S335 (slide 2)

$$A_1 := \frac{\sigma_{ys} \cdot (1+\varepsilon_{ys})}{\left(\ln(1+\varepsilon_{ys})\right)^{m_1}}$$

Curve fitting constant for the elastic region of the stress-strain curve, as per Equation 3.D.5

$A_1 = 531.611 \cdot MPa$

$A_1 = 77.104 \cdot ksi$

$$\varepsilon_1 := \left(\frac{\sigma_t}{A_1}\right)^{\frac{1}{m_1}} \qquad \varepsilon_1 = \begin{pmatrix} 0 \\ 0.0019 \\ 0.0051 \\ 0.0126 \\ 0.0293 \\ 0.0648 \\ 0.1373 \\ 0.2796 \\ 0.5496 \\ 1.0461 \\ 1.9337 \\ 3.48 \end{pmatrix}$$

True plastic strain in the micro-strain region of the stress-strain curve, as per Equation 3.D.4

$$A_2 := \frac{\sigma_{uts} \cdot \exp(m_2)}{{m_2}^{m_2}}$$

Curve fitting constant for the plastic region of the stress-strain curve, as per Equation 3.D.8

$A_2 = 811.486 \cdot MPa$

$A_2 = 117.696 \cdot ksi$

$$\varepsilon_2 := \left(\frac{\sigma_t}{A_2}\right)^{\frac{1}{m_2}} \qquad \varepsilon_2 = \begin{pmatrix} 0 \\ 0.0165 \\ 0.0229 \\ 0.0312 \\ 0.0418 \\ 0.0549 \\ 0.071 \\ 0.0906 \\ 0.1143 \\ 0.1426 \\ 0.1761 \\ 0.2154 \end{pmatrix}$$

True plastic strain in the macro-strain region of the stress-strain curve, as per Equation 3.D.7

$$H := \frac{2 \cdot \left[\sigma_t - \left[\sigma_{ys} + K \cdot (\sigma_{uts} - \sigma_{ys})\right]\right]}{K \cdot (\sigma_{uts} - \sigma_{ys})} \qquad H = \begin{pmatrix} -14.9763 \\ -2 \\ -1.0394 \\ -0.0789 \\ 0.8817 \\ 1.8423 \\ 2.8028 \\ 3.7634 \\ 4.724 \\ 5.6845 \\ 6.6451 \\ 7.6056 \end{pmatrix}$$

Stress-strain curve fitting parameter, as per Equation 3.D.9

$$\gamma_1 := \overrightarrow{\left[\frac{\varepsilon_1}{2} \cdot (1 - \tanh(H))\right]} \qquad \gamma_1 = \begin{pmatrix} 0 \\ 0.00190978 \\ 0.00453894 \\ 0.00678143 \\ 0.00428295 \\ 0.00158722 \\ 0.000503 \\ 0.00015049 \\ 0.00004334 \\ 0.00001208 \\ 0.00000327 \\ 8.6179388 \times 10^{-7} \end{pmatrix}$$

True strain in the micro-strain region of the stress-strain curve, as per Equation 3.D.2

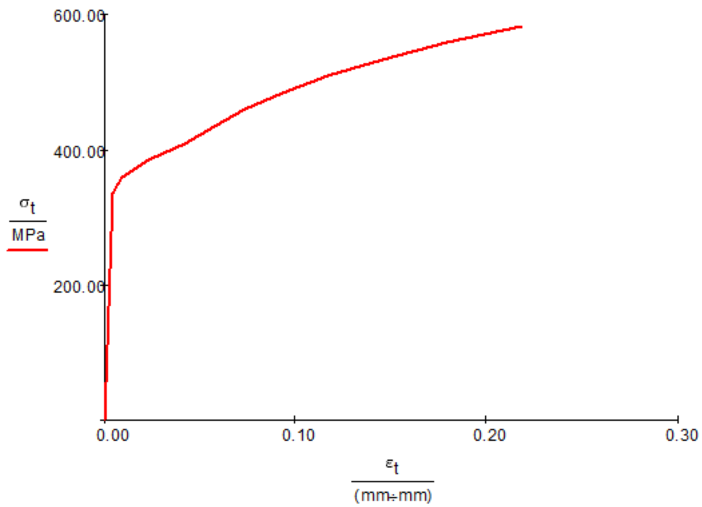
$$\gamma_2 := \overrightarrow{\left[\frac{\varepsilon_2}{2} \cdot (1 + \tanh(H))\right]} \qquad \gamma_2 = \begin{pmatrix} 0 \\ 0.00029602 \\ 0.00254877 \\ 0.01439095 \\ 0.03564204 \\ 0.05351554 \\ 0.07073398 \\ 0.09058725 \\ 0.11429877 \\ 0.14257622 \\ 0.1760619 \\ 0.21542548 \end{pmatrix}$$

True strain in the macro-strain region of the stress-strain curve, as per Equation 3.D.3

Stress-Strain Curve Modeling –BS EN 10225 Grade S335 (slide 3)

$\varepsilon_t := \frac{\sigma_t}{E_y} + \gamma_1 + \gamma_2$ Total true strain, as per Equation 3.D.1

$$\varepsilon_t = \begin{pmatrix} 0 \\ 0.003880803 \\ 0.0088867078 \\ 0.0230953611 \\ 0.0419719687 \\ 0.0572737255 \\ 0.0735319396 \\ 0.0931566906 \\ 0.1168850447 \\ 0.1452552314 \\ 0.1788560919 \\ 0.2183412559 \end{pmatrix} \qquad \sigma_t = \begin{pmatrix} 0 \\ 335 \\ 359.79831 \\ 384.59662 \\ 409.39494 \\ 434.19325 \\ 458.99156 \\ 483.78987 \\ 508.58818 \\ 533.38649 \\ 558.18481 \\ 582.98312 \end{pmatrix} \cdot \mathrm{MPa}$$



Plastic Strain & corresponding Strength (Inputs in Ansys)

$$\xi_p := \begin{pmatrix} \varepsilon_{t_1} - \varepsilon_{t_1} \\ \varepsilon_{t_2} - \varepsilon_{t_1} \\ \varepsilon_{t_3} - \varepsilon_{t_1} \\ \varepsilon_{t_4} - \varepsilon_{t_1} \\ \varepsilon_{t_5} - \varepsilon_{t_1} \\ \varepsilon_{t_6} - \varepsilon_{t_1} \\ \varepsilon_{t_7} - \varepsilon_{t_1} \\ \varepsilon_{t_8} - \varepsilon_{t_1} \\ \varepsilon_{t_9} - \varepsilon_{t_1} \\ \varepsilon_{t_{10}} - \varepsilon_{t_1} \\ \varepsilon_{t_{11}} - \varepsilon_{t_1} \end{pmatrix} \qquad \sigma_p := \begin{pmatrix} \sigma_{t_1} \\ \sigma_{t_2} \\ \sigma_{t_3} \\ \sigma_{t_4} \\ \sigma_{t_5} \\ \sigma_{t_6} \\ \sigma_{t_7} \\ \sigma_{t_8} \\ \sigma_{t_9} \\ \sigma_{t_{10}} \\ \sigma_{t_{11}} \end{pmatrix}$$

$\xi_p =$

0
$5.0059 \cdot 10^{-3}$
0.0192
0.0381
0.0534
0.0697
0.0893
0.113
0.1414
0.175
0.2145

$\sigma_p =$ ·MPa

335
359.7983
384.5966
409.3949
434.1932
458.9916
483.7899
508.5882
533.3865
558.1848
582.9831