NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

August 15, 2011

MATERIALS LABORATORY STUDY REPORT Report No. 11-075

A. ACCIDENT INFORMATION

Place	:	San Bruno, California
Date	:	September 9, 2010
Vehicle	:	Natural Gas Transmission Pipeline
NTSB No.	:	DCA10MP008
Investigator	:	Ravi Chhatre

B. TOPICS ADDRESSED

Finite element modeling to examine stresses and strains in sections of pipe.

C. DETAILS OF THE STUDY

Six finite element models were constructed to examine stresses and strains in sections of pipe with different angular alignments, and different notch widths. Model 1 was based on the observed geometry of pup 1.[1] Model 2 was based on the observed geometry of pup 3.[1,2] The main difference between pup 1 and pup 3 was a seam weld misalignment of 14.5° for pup 1 and a seam weld misalignment between 7° and 10° for pup 3 (figures 1a and 1b). Model 3 was an idealized geometry with a perfectly circular cross section for both the inner and outer walls, except for the incomplete seam weld at the top of the pipe. Models 4, 5, and 6 had geometries identical to Models 1, 2, and 3, respectively, except that the notch radius at the incomplete weld was reduced from 0.004 inch to 0.001 inch.

The finite element modeling was carried out using ABAQUS Standard 6.10, which employs an implicit solution methodology. The finite element models were two-dimensional, using an assumption of plane strain. All dimensions are in inches. Nonlinear material properties were included in the models, and nonlinear geometric effects were permitted in the solution. Loads were applied quasistatically. No material softening or crack propagation was considered for this study.

[1] Materials Laboratory Factual Report 10-119, National Transportation Safety Board, Washington, DC, 2011.
[2] Materials Laboratory Factual Report 11-056, National Transportation Safety Board, Washington, DC, 2011.

1. Geometry

a. *Model 1 – Pup 1 seam weld with incomplete penetration and an angular misalignment of 14.5°*

The overall geometry for Model 1 is shown in figure 2 and was taken from a previous NTSB report.[3] A detailed view of the weld cross section is shown in figure 3.

b. *Model 2 - Pup 3 seam weld with incomplete penetration and an angular misalignment of 10°*

For Model 2, both the inner and outer walls had identical diameters as in Model 1 (29.260 inch and 30.000 inch respectively), which resulted in an identical wall thickness of 0.370 inch. The seam weld was also placed at the top of the pipe, with the notch radius in line with the centerline of the pipe. The length of the uncracked ligament remained the same as Model 1, 0.160 inch. The notch was modeled as a semicircle with a radius of 0.004 inch. This model had angular misalignment at the seam weld of 10°. The angular misalignment was modeled such that straight sections on the left and right sides of the longitudinal seam transitioned to the circular section of pipe at tangent points on the outer and inner surfaces of the pipe. A short arc length connected the two straight sections on the outer surface of the pipe across the seam. The length of this arc was such that it extended for 0.5 inch to the right of the centerline and 0.3 inch to the left. The highest point of the connecting radius was placed on the centerline of the pipe. A detailed view of the notched section is shown in figure 4.

c. *Model 3 - Pipe with seam weld with incomplete penetration and perfectly circular geometry*

For Model 3, both the inner and outer walls had identical diameters (29.260 inch and 30.000 inch respectively) as in the previous two models, which resulted in an identical wall thickness of 0.370 inch. Again, the seam weld was placed at the top of the pipe, in line with the center line of the pipe. However, this model had idealized geometry where both walls were perfectly circular and concentric, with no deviations near the welds as in the previous two models. The length for the uncracked ligament, and radius for the unwelded notch were identical to the previous two models. A detailed view of the notched section is shown in figure 5.

[3] Materials Laboratory Study Report 11-058, National Transportation Safety Board, Washington, DC, 2011.

d. Models 4, 5, and 6

The geometries for Models 4, 5, and 6 were nearly the same as Models 1, 2, and 3, respectively. The only change was that the notch radius was reduced from 0.004 inch to 0.001 inch. The center of the notch was kept in line with the center of the pipe.

2. Material properties

The material properties used for these models are identical to the properties used in the models in a previous NTSB report.[4]

3. Loads and boundary conditions

For all models, the only load applied was pressure at the inner surface of the pipe, with zero pressure applied at the exterior of the pipe. The pressure was also applied on the inner surface of the notch where the weld metal did not penetrate the joint. The pressure was linearly applied to 350 psi in 10 increments, and then to 375 psi in a single increment.

As noted above, the weld was located at the top of the pipe in each model. In order to prevent rigid-body motions, the pipe was held fixed (no displacement or rotation) at a single node at the bottom of the pipe, opposite the weld in each model.

4. Mesh

The models were meshed with linear plane strain elements, using primarily quadrilateral elements, but with some triangular elements allowed to facilitate mesh-size transitions. The element sizes were biased to be smaller near the areas of stress and strain gradients which occur at the notch formed by the lack of weld metal in the seam. The bias was such that the smallest elements at the seam had sides that were on the order of 0.0001 inch long, and the largest elements on the bottom of the pipe, opposite the seam, had sides that were on the order of 0.1 inch long. No formal mesh convergence study was performed for any model[5].

5. Output

Figures 6 through 11 show the contours of the Mises stress for Models 1 through 3 at 375 psi. The contour levels are in psi and are the same for all figures. For each model, the figures are shown in pairs, with the top figure showing an overall view of the notched area, and the bottom figure showing a magnified view. All figures are on the same visual scale, with the bottom figures being magnified 5 times relative to the top. Tables 1 through 3 show the peak values for the Mises stress (S_{Mises}) as functions of the applied pressure for all models.

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[4] Materials Laboratory Study Report 11-058, National Transportation Safety Board, Washington, DC, 2011.

[5] Mesh convergence refers to the smallness of the elements that are required to ensure that the results of an analysis are not affected by a change in the size of the mesh.

Figures 12 through 14 show the magnitude of the plastic strain for Models 1 through 3 at 375 psi. The contour levels are the same for all of the figures. Again, the visual scale is the same for all of the figures and is identical to that of the bottom figures showing the Mises stresses. Tables 1 through 3 show the peak values for the magnitude of the plastic strain ($\varepsilon_{plastic}$) as functions of the applied pressure for all models.

William Young
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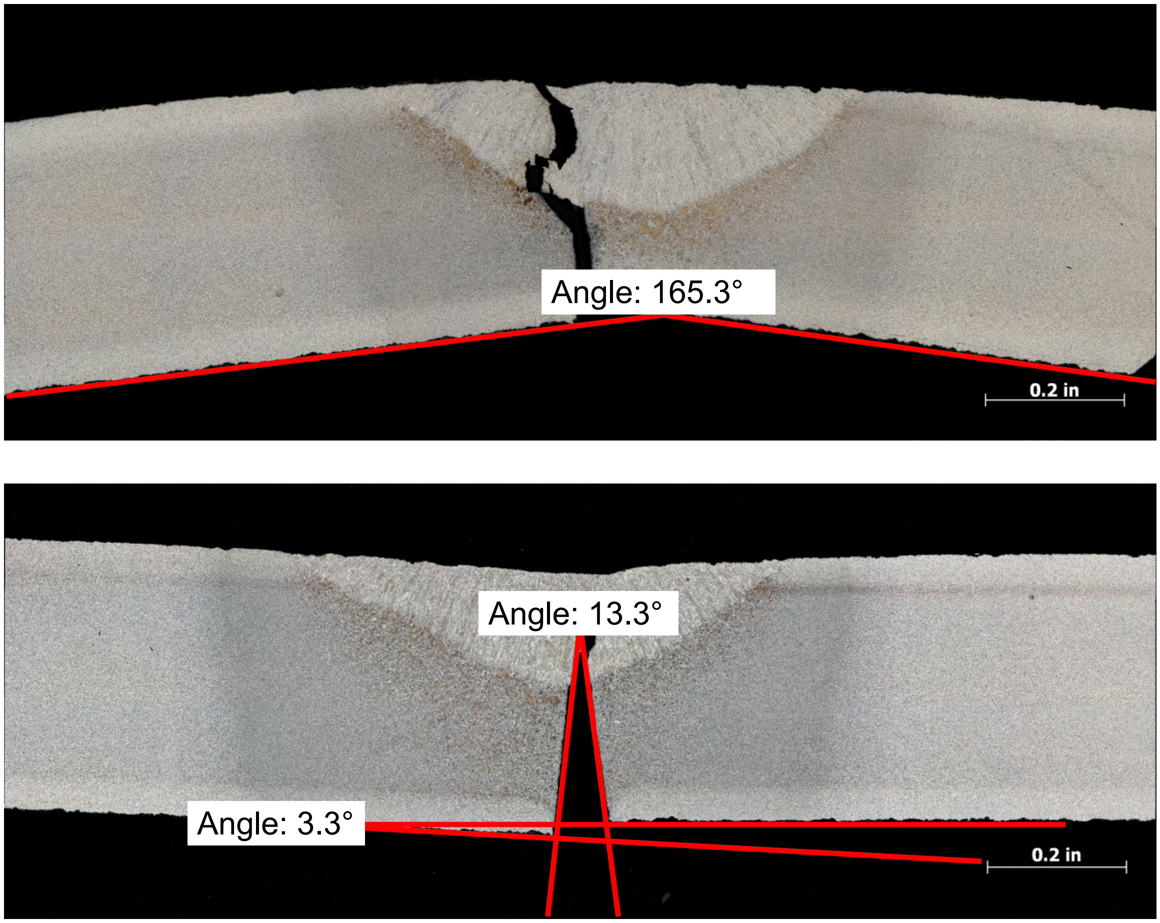
a)
b)


Figure 1 Metallographic cross sections of; a) pup 1 longitudinal seam weld and b) pup 3 longitudinal seam weld.

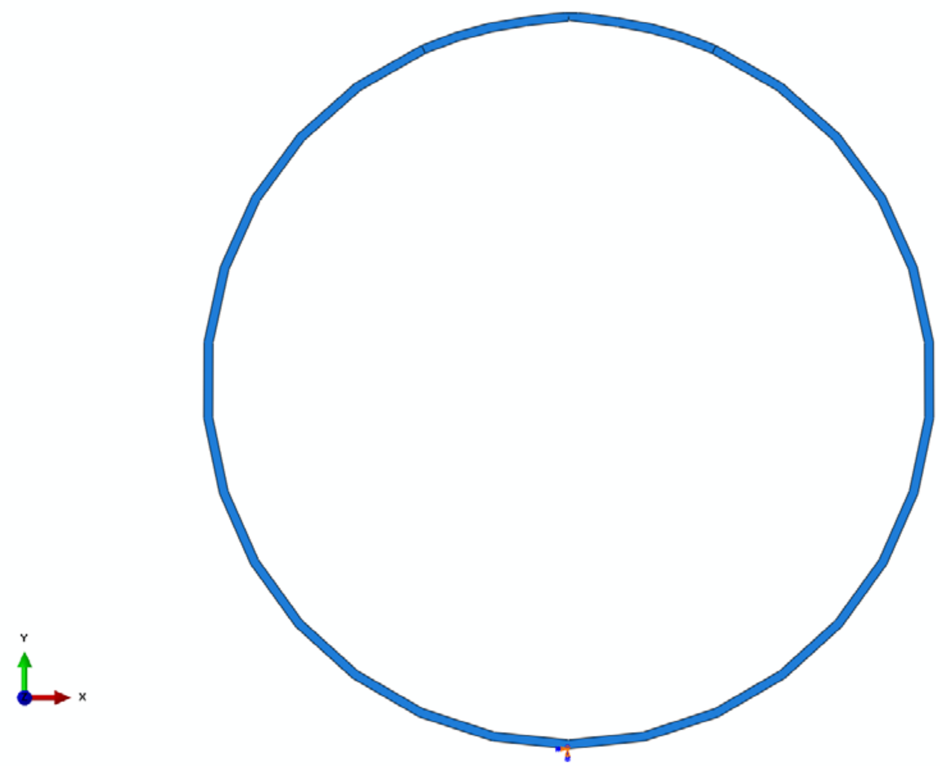


Figure 2 Overview of Model 1, the pipe with a seam weld of incomplete penetration at the top, and an angular misalignment of 14.5°. The highlighted point at the bottom is used for constraining the model to prevent of rigid body motions.

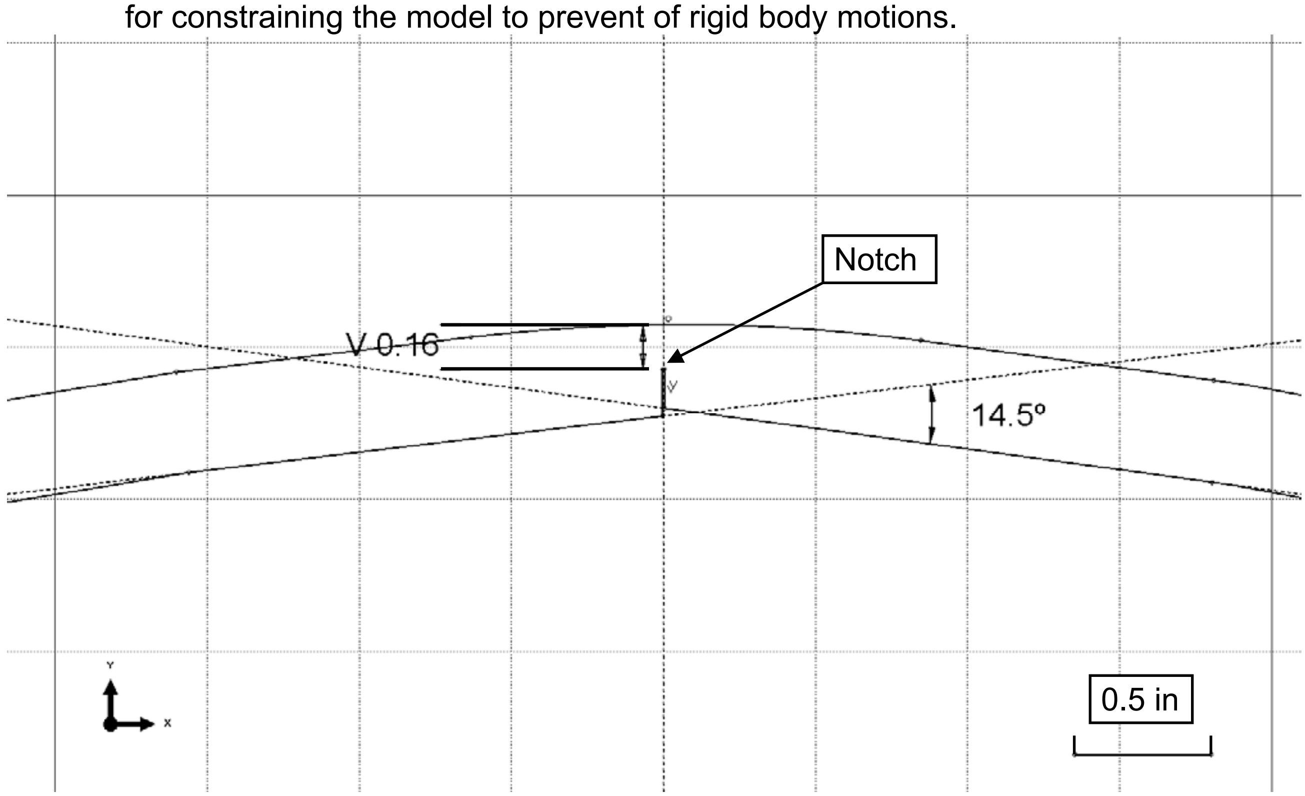


Figure 3 - Detailed view of the weld area for Model 1.

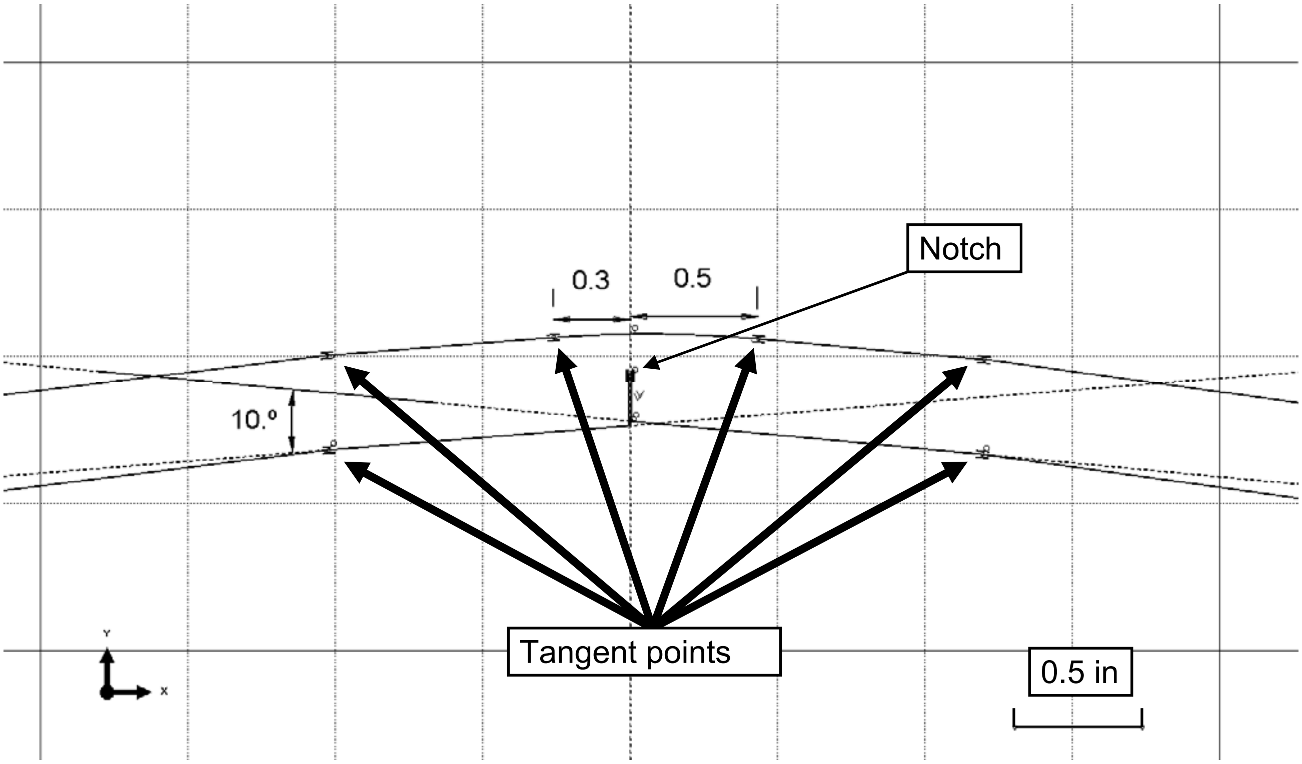


Figure 4 Detailed view of the weld area for Model 2.

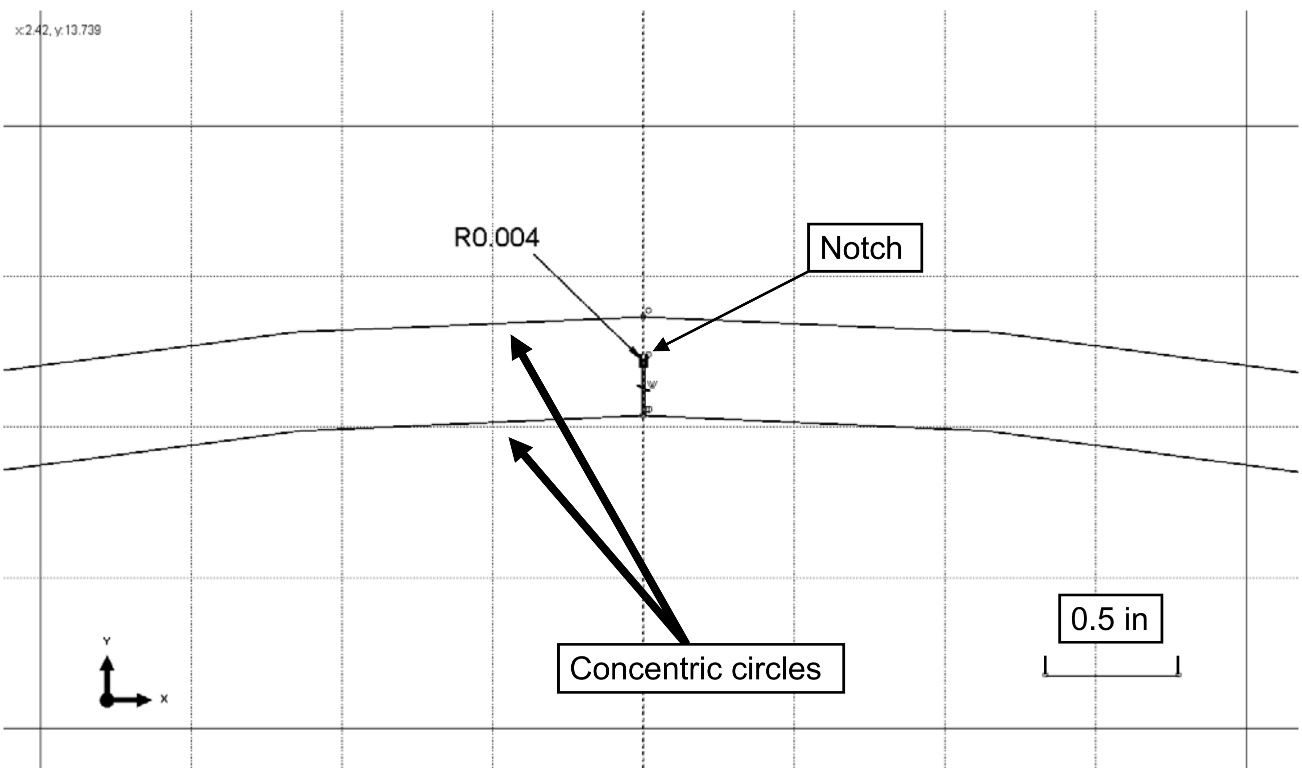


Figure 5 Detailed view of the weld area for Model 3.

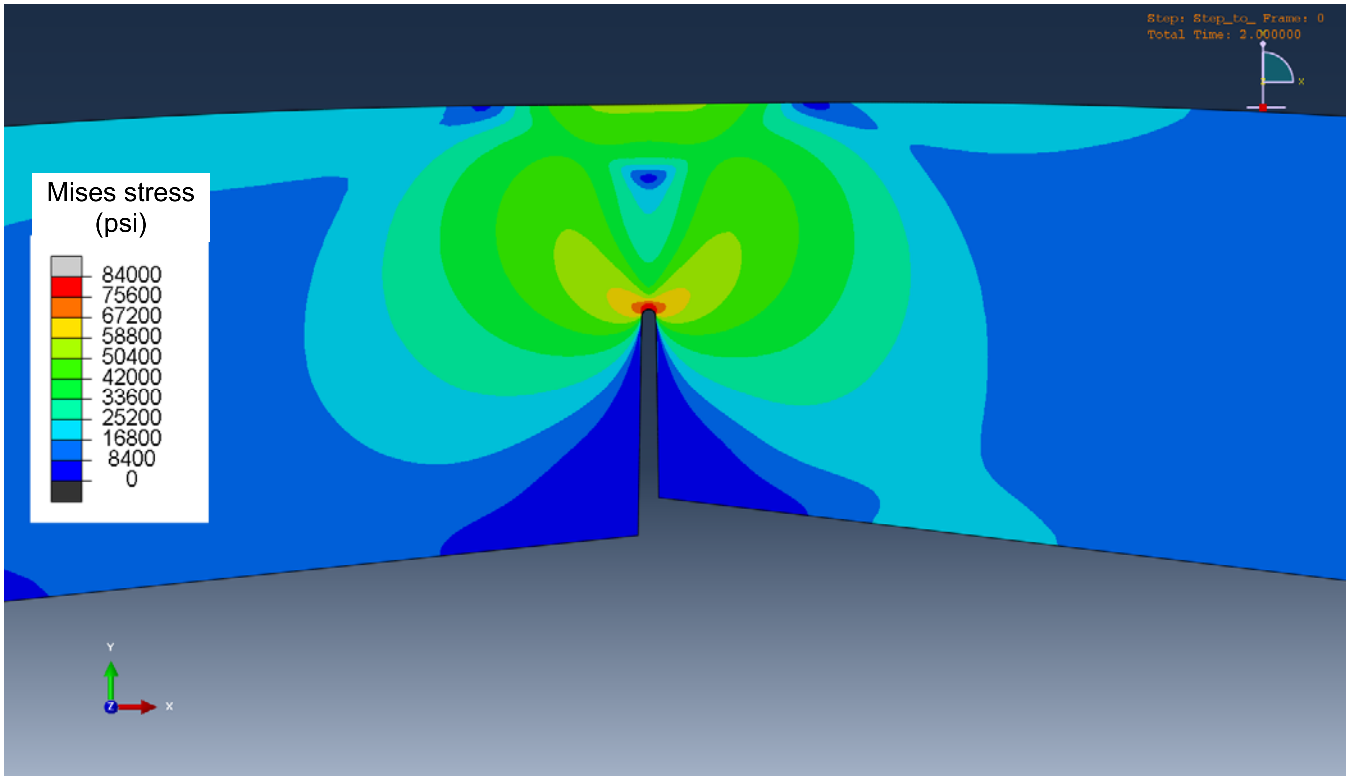


Figure 6 Contours of Mises stress of Model 1 at the seam weld at a pressure of 375 psi.

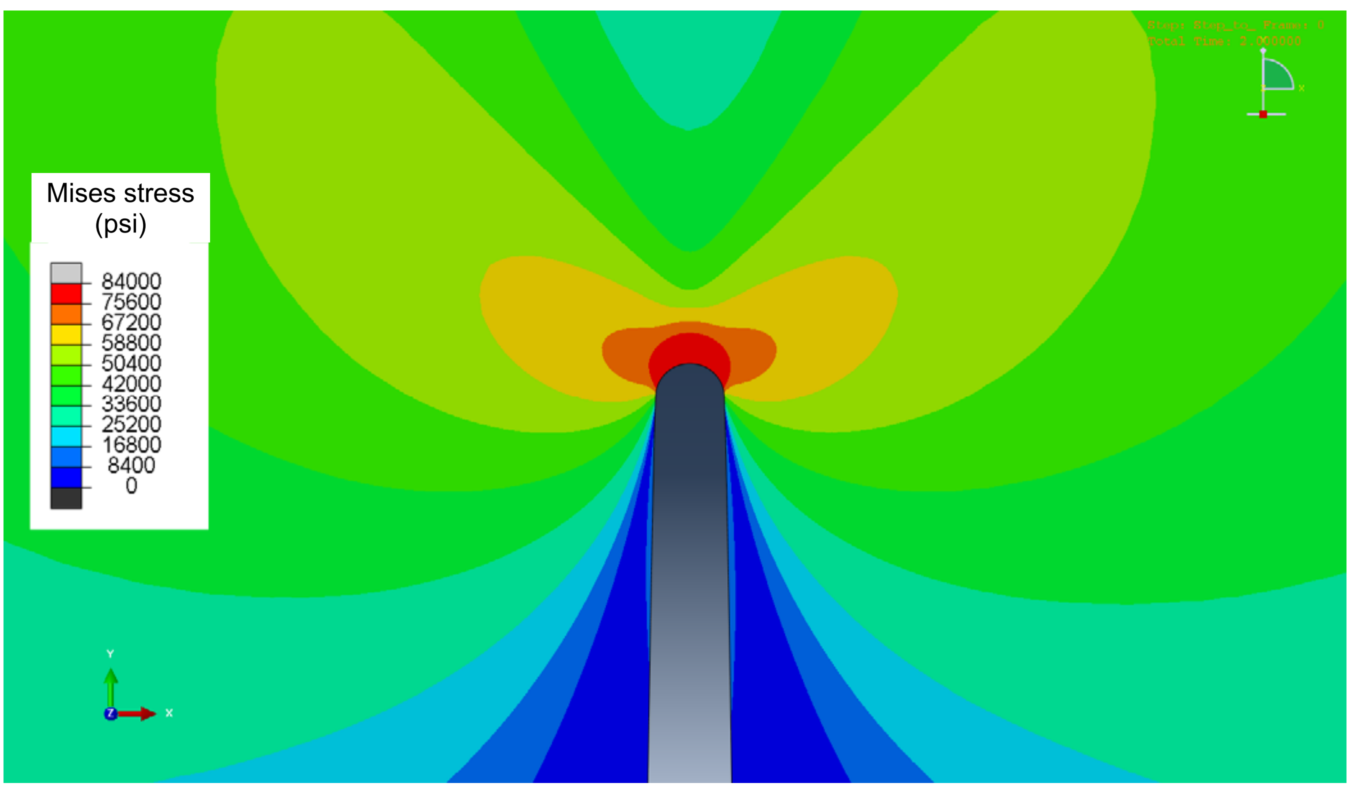


Figure 7 Contours of Mises stress of Model 1 at the seam weld at a pressure of 375 psi, magnified 5 times relative to figure 6.

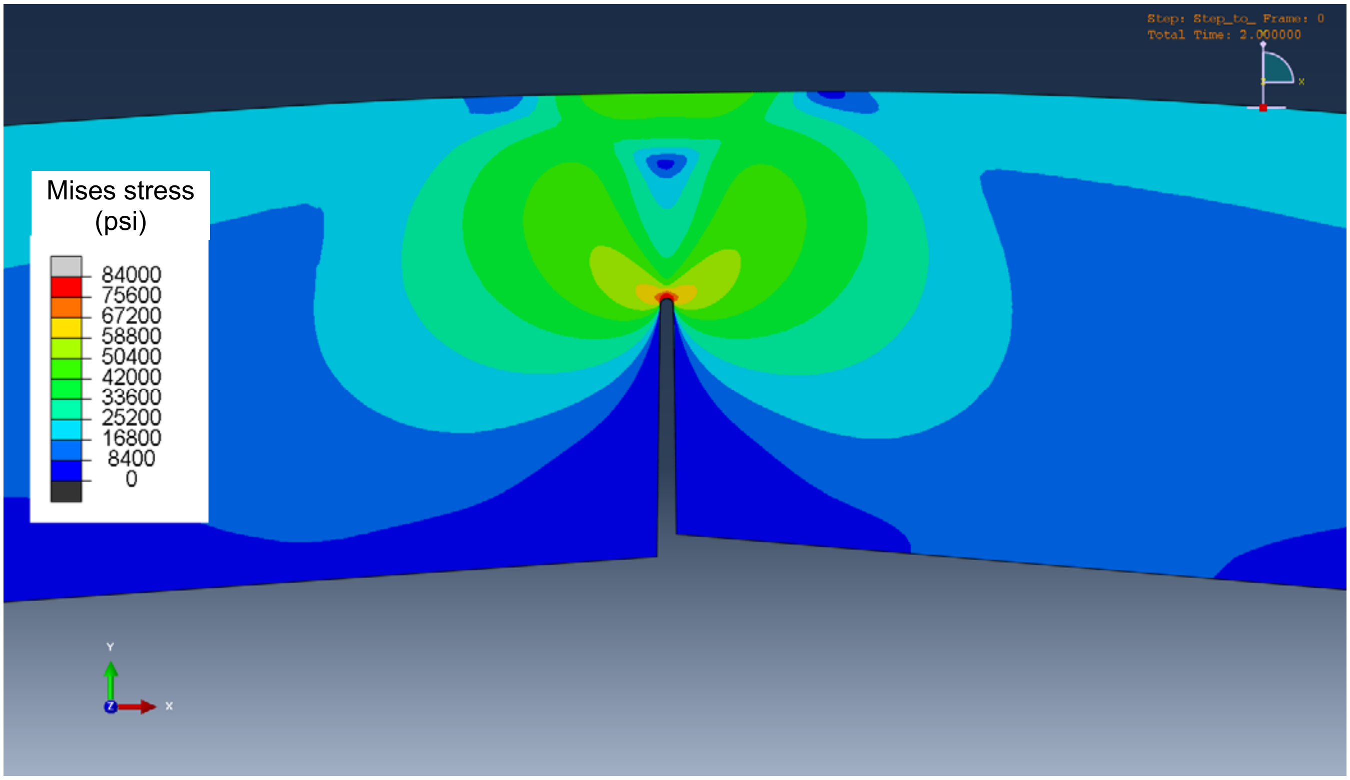


Figure 8 Contours of Mises stress of Model 2 at the seam weld at a pressure of 375 psi.

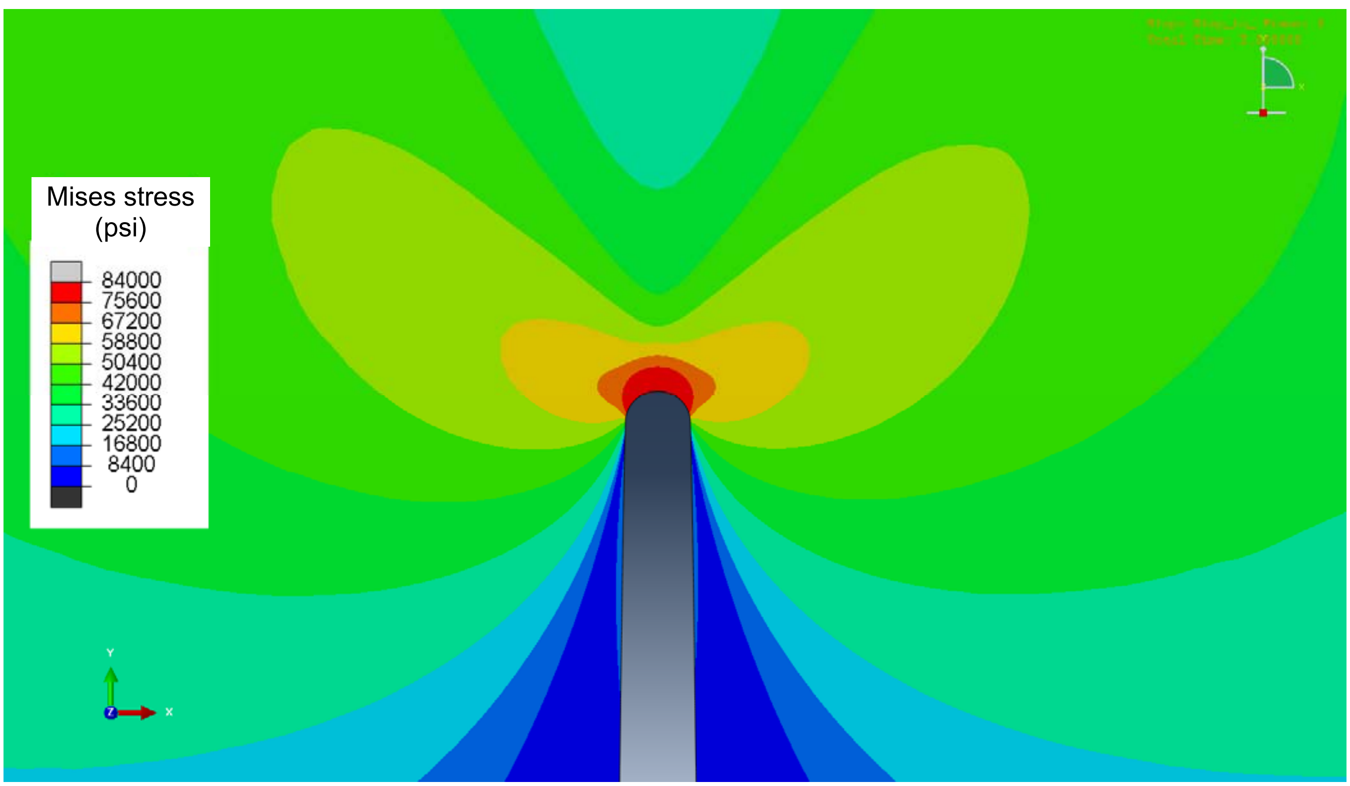


Figure 9 Contours of Mises stress of Model 2 at the seam weld at a pressure of 375 psi, magnified 5 times relative to figure 8.

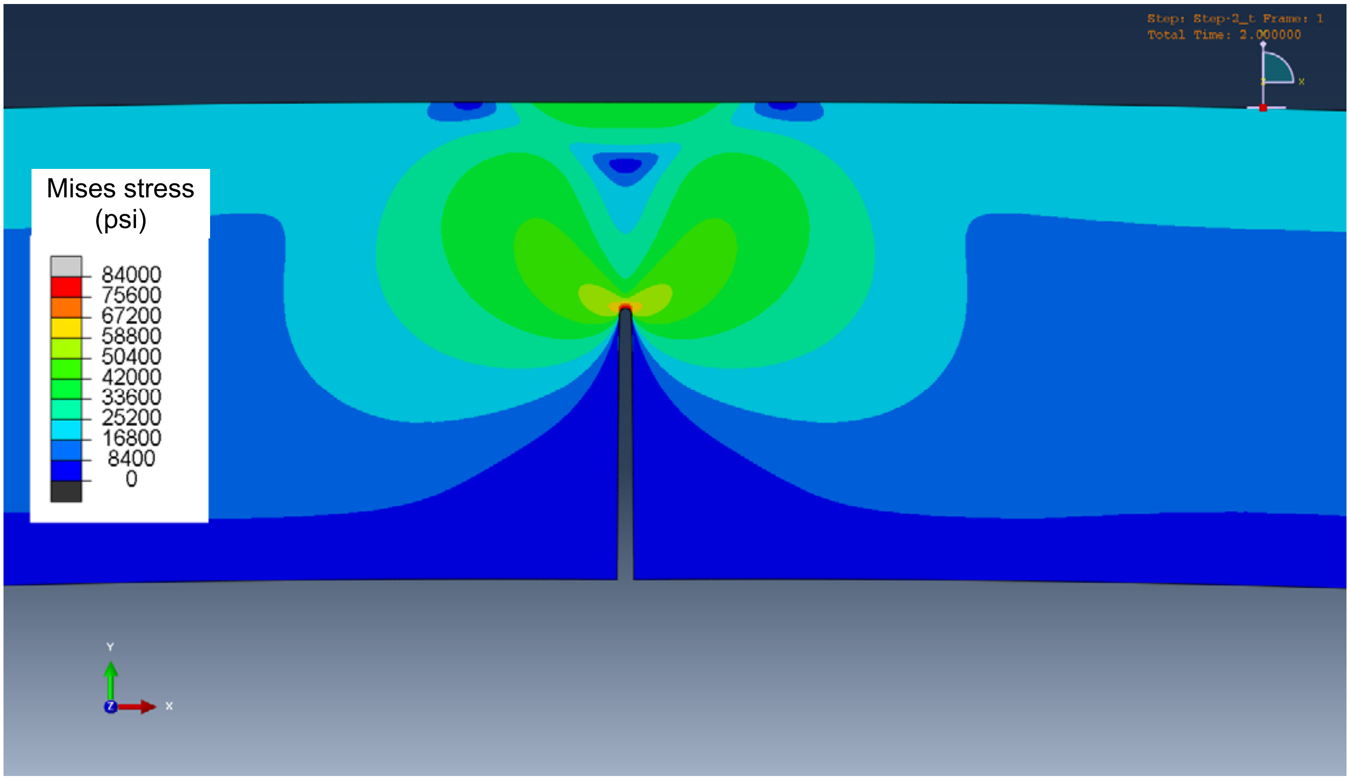


Figure 10 Contours of Mises stress of Model 3 at the seam weld at a pressure of 375 psi.

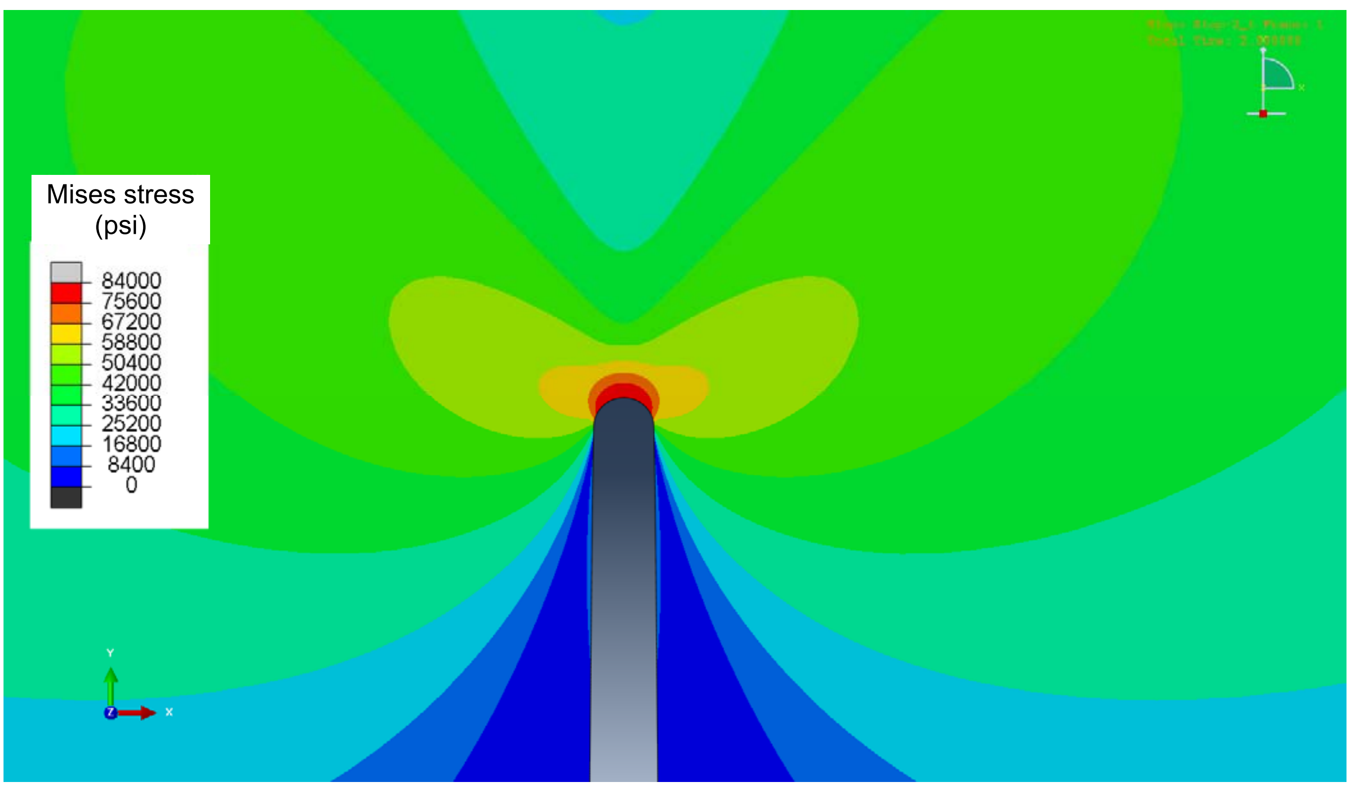


Figure 11 Contours of Mises stress of Model 3 at the seam weld at a pressure of 375 psi, magnified 5 times relative to Figure 10.

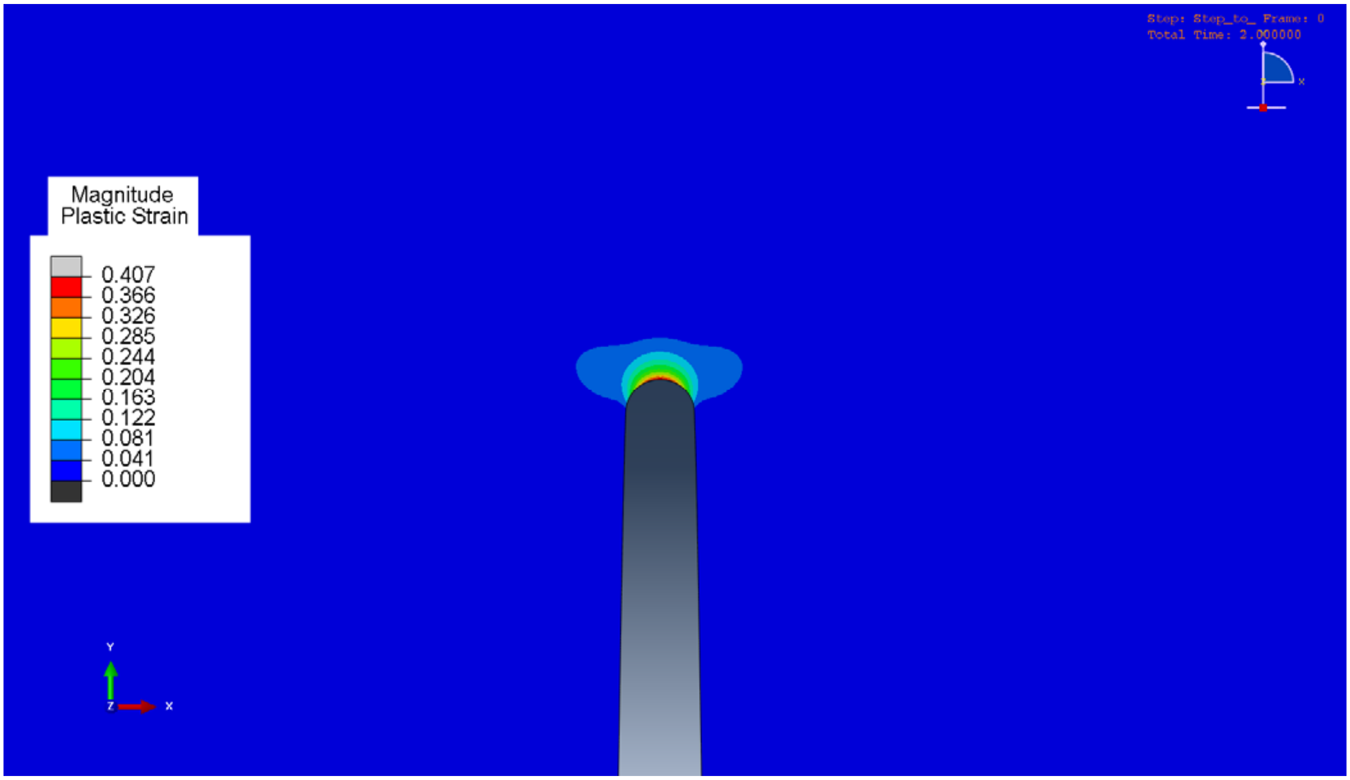


Figure 12 Contours of the magnitude of plastic strain in Model 1 at a pressure of 375 psi.

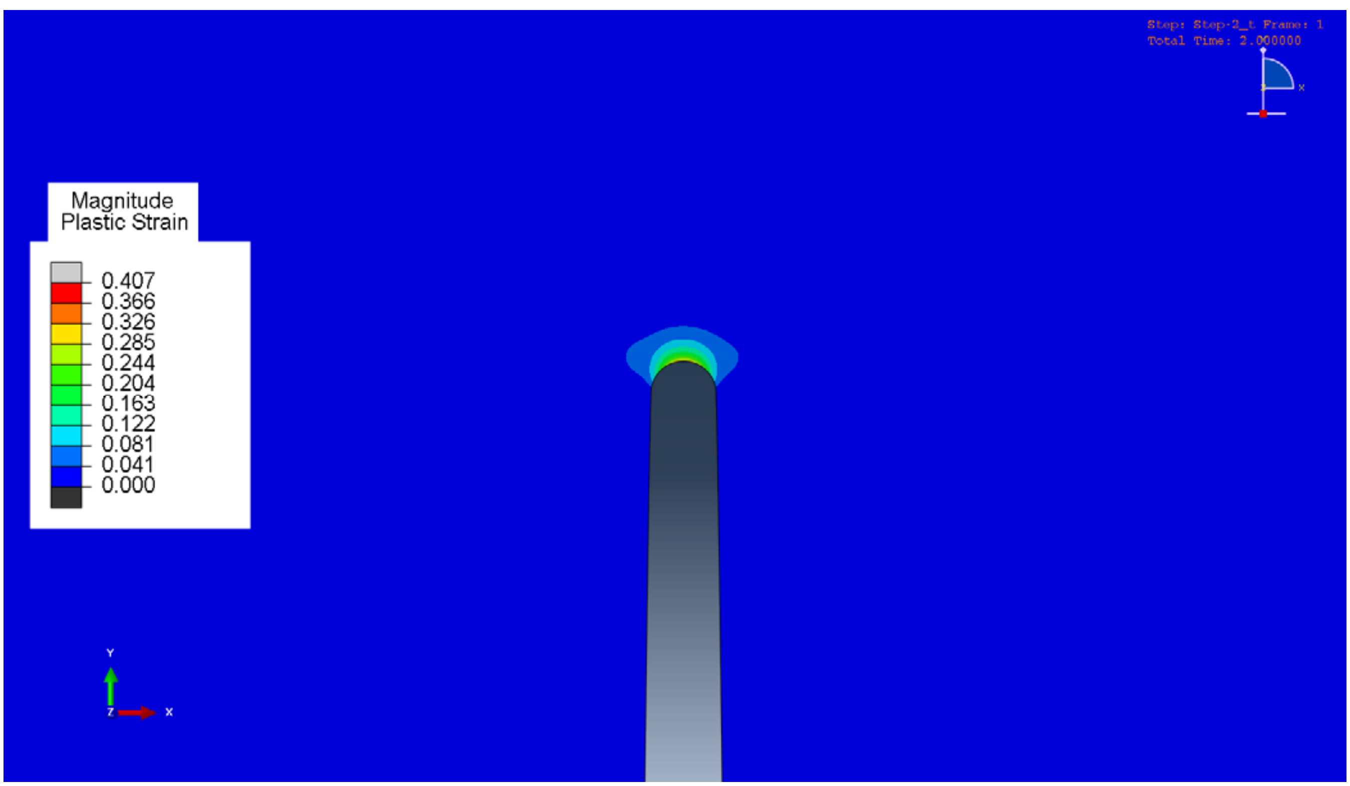


Figure 13 Contours of the magnitude of plastic strain in Model 2 at a pressure of 375 psi.

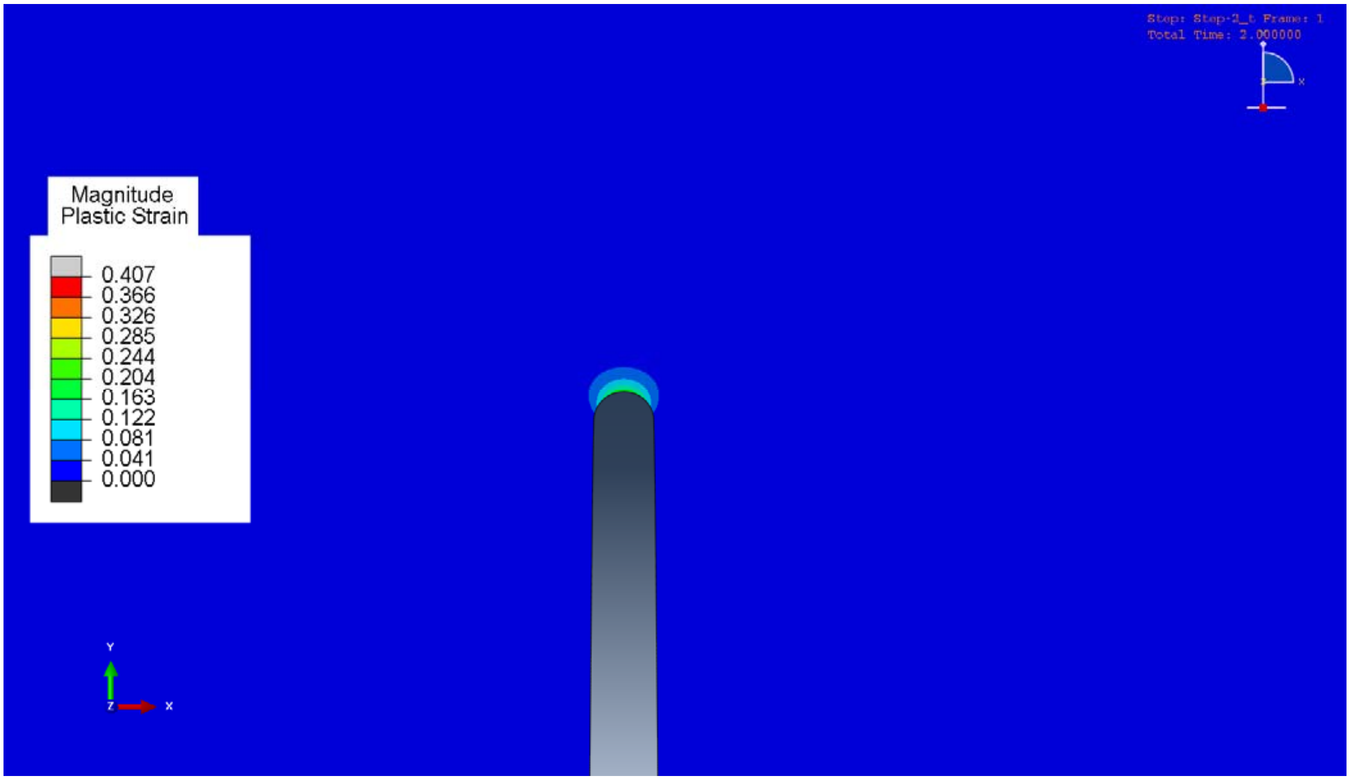


Figure 14 Contours of the magnitude of plastic strain in Model 3 at a pressure of 375 psi.

Table 1 Maximum Mises stress and magnitude of plastic strain for Model 1 and 4 (14.5° misalignment).

	Model 1		Model 4	
Pressure (psi)	S_{Mises} **(ksi)**	$\varepsilon_{plastic}$	S_{Mises} **(ksi)**	$\varepsilon_{plastic}$
35	43.2	0.004	53.7	0.012
140	70.3	0.050	83.9	0.136
210	82.7	0.122	84.0	0.341
350	84.0	0.355	84.0	0.982
375	84.0	0.407	84.0	1.117

Table 2 Maximum Mises stress and magnitude of plastic strain for Model 2 and 5 (10° misalignment).

	Model 2		Model 5	
Pressure (psi)	S_{Mises} **(ksi)**	$\varepsilon_{plastic}$	S_{Mises} **(ksi)**	$\varepsilon_{plastic}$
35	40.7	0.003	51.1	0.010
140	66.0	0.037	81.0	0.103
210	79.0	0.087	84.0	0.249
350	84.0	0.272	84.0	0.787
375	84.0	0.314	84.0	0.900

Table 3 Maximum Mises stress and magnitude of plastic strain for Model 3 and 6 (idealized geometry).

	Model 3		Model 6	
Pressure (psi)	S_{Mises} **(ksi)**	$\varepsilon_{plastic}$	S_{Mises} **(ksi)**	$\varepsilon_{plastic}$
35	37.0	0.002	47.7	0.006
140	60.6	0.023	74.7	0.067
210	70.9	0.052	84.0	0.147
350	84.0	0.168	84.0	0.489
375	84.0	0.197	84.0	0.574