Fermilab

SDC SOLENOID DESIGN NOTE #157

TITLE: Stress Analysis of the SDC Vacuum Shell and Vertical Chimney Penetration

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Stress Analysis of the SDC Vacuum Shell and Vertical Chimney Penetration (Task 2)

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1.0 Introduction

This report presents results from static stress analyses of the SDC structure in the region where the vertical chimney penetrates the outer vacuum shell. Material properties, modelling details, and analysis results are presented in the following six sections.

Section 2.0 discusses the finite element model used to perform the static stress analyses. Material properties, model geometry, applied loading, and boundary conditions are presented in detail.

Section 3.0 presents analysis results when loading consists of external lateral pressure only. This load case provides a base-line reference against which results due to pressure and chimney loads can be compared.

Sections 4.0 through 6.0 discuss structural deformation and stresses resulting from pressure and chimney loading consisting of a punch force and 1) a +X directed lateral force, 2) a +Z directed longitudinal force, and 3) a -Z directed longitudinal force, respectively.

Finally, section 7.0 presents a summary of the results and collects the principal stress values for all analyses.

2.0 Finite Element Modelling of the Vacuum Shell and Vertical Chimney

2.1 Material Properties

The vacuum shell structure is considered made from aluminum 2219-T851. Properties for this material are taken from MIL-HDBK-5C [1] and are given in Table 2-1 below.

Table 2-1. Properties for Al 2219-T851 (Room Temperature)

Young' Modulus	10.5×10^6 psi
Poisson's Ratio	0.33
Weight Density	0.102 lb/in^3
Tensile Ultimate Strength	62,000 psi
Tensile Yield Stress	47,000 psi
Allowable Stress	15,500 psi

The allowable stress value given above is determined from the ASME Pressure Vessel Code rule (cf. [2], Appendix P):

allowable stress = MIN (0.25 * ultimate strength, 0.67 * yield stress)

Material properties for the chimney pipe were chosen from typical values for aluminum: Young's modulus = 10.2×10^6 psi and Poisson's ratio = 0.33.

2.2 Model Geometry

Basic geometry for the vacuum shell and chimney pipe was specified by Fermilab as presented in Table 2-2 below.

Table 2-2. Vacuum Shell and Chimney Pipe Geometry

Shell Diameter	160.0 in
Shell Length	360.0 in
Chimney Diameter	12.75 in
Chimney Length	30.00 in
Chimney Thickness	0.180 in

The current Isogrid design geometry is given below. See my report for Task 1 [3] for a discussion of the dimensionless parameters and computation of section details.

Table 2-3. Isogrid Geometry

Node Spacing	a	6.9930 in
Web Width	b	0.1500 in
Flange Depth	c	0.2900 in
Web Depth	d	1.8000 in
Triangle Height	h	6.0561 in
Flange Width	w	1.0000 in
Skin Thickness	t	0.1100 in

Table 2-4. Isogrid Dimensionless Parameters

$\alpha = bd/ht$	0.4053
β	49.917
$\delta = d/t$	16.364
$\tau = c/t$	2.6264
$\mu = wc/ht$	0.4353

Table 2-5. Isogrid Section Parameters

Effective Area	A	0.2025 in^2/in
Flange Fiber Distance	Cf	1.4617 in
Skin Fiber Distance	Cs	0.7383 in
Shell Modulus	E*	7.13×10^5 psi
Bending Rigidity	D	1.77×10^6 in-lb
Moment of Inertia	I	0.1502 in^4/in
Extension Stiffness	K	2.39×10^6 lb/in
Weight Thickness	t_{bar}	0.3874 in
Effective Thickness	t_{eff}	0.2025 in
Shell Thickness	t*	2.9832 in

The SDC vacuum shell and chimney pipe were modelled using a three-dimensional finite element representation, see Figure 2.1. The origin of the global coordinate system is located at the chimney-end of the shell, with the X-axis horizontal, the Y-axis vertical, and the longitudinal Z-axis increasing away from the shell. A close-up view of the shell-chimney penetration region is shown in Figure 2.2, and element numbers for the shell-chimney collar are given in Figure 2.3.

Stress values will be given referring to the element numbers shown in Figure 2.3. Elements in the shell-chimney collar are divided into six areas, labelled "A" through "F". Each area has a local element coordinate system as shown in the figure. Also shown as an insert in Figure 2.3 is the Isogrid pattern and rib identifiers, where rib (1) is the circumferential rib.

The finite element model consists of 800 shell elements, 24 beam elements, and 1139 nodes. The outer shell consists of 584 shell elements while the chimney pipe consists of 216 shell and 24 beam elements. The beam elements were used to model a one-inch square aluminum rim around the top edge of the chimney. This

rim provided a reinforcement where chimney loads could be applied, and also prevented the pipe from experiencing excessive deformations in the loading region.

2.3 Applied Loading

Four loading conditions were considered. The first load case used an external lateral pressure of 15 psi applied to the vacuum shell and chimney pipe. This case provides a reference against which the three chimney punch/shear load cases can be compared.

The next three load cases considered a 2,000 pound downward punch load and a 1,00 pound horizontal shear load applied at the chimney-bellows rim. The punch load was applied uniformly to the 24 nodes around the chimney rim (i.e., at each rim node a load Fy = -83.3333 pounds was applied). Similarly, the shear load was applied uniformly to the 24 nodes around the chimney rim (i.e., at each rim node a load of 41.6667 pounds was applied). These three cases considered the shear load applied in the global +X direction, +Z direction, and -Z direction, respectively.

2.4 Boundary Conditions

Based on results from my report for Task 1 [3], the Isogrid shell can be considered clamped at the chimney-end bulk head. Since shell bending resultants decay rapidly from the fixed end, only half the shell length was modelled using longitudinal symmetric boundary conditions at the -Z end of the vacuum shell.

3.0 Results for Pressure Loading

Presented in this section are results for deformation, chimney stresses, and shell-chimney collar region internal loads and stresses due only to lateral pressure loading.

Figure 3.1 shows the deformed structure relative to the undeformed configuration. (Note that the scale is greatly exaggerated.) The maximum displacement is 0.0652 inches and occurs at the chimney-bellows rim. As can be seen from the figure, virtually all of the chimney motion results from the deflection and rotation of the Isogrid shell.

Stress contour plots for the chimney are shown in Figures 3.2 through 3.4. Stress component values are given in the chimney element coordinate system were "x" is in the axial direction and "y" is in the hoop direction. Stress component values from these figures are collected in Table 3-1 shown below.

Table 3-1 Chimney Stress Components (Pressure)

Direction	Minimum	Maximum
Axial	-1,225	729
Hoop	-2,546	868
von Mises	40	2,436

As seen from these figures, the region of peak stress occurs at the base of the chimney at the interface with Isogrid elements 162 and 163. The chimney peak von Mises stress value of 2,436 psi is well below the allowable stress value for aluminum.

Results for the internal load resultants and stresses in the Isogrid shell-chimney collar region are given below in Table 3-2 and Table 3-3, respectively. Values in these tables refer to element numbers and element coordinate directions shown in Figure 2.3.

Table 3-2 Isogrid Element Resultants (Pressure)

	Minimum	Maximum
Mx	-180 (191)	726 (65)
My	-240 (139)	828 (3)
Mxy	-217 (61)	217 (64)
Nx	-1,270 (162)	363 (65)
Ny	-853 (157)	239 (33)
Nxy	-578 (181)	386 (161)

Table 3-3 Isogrid Element Stresses (Pressure)

		Minimum	Maximum
Skin	Sx	-6,234 (173)	5,361 (65)
Skin	Sy	-4,557 (189)	4,375 (33)
Skin	Sxy	-2,236 (161)	3,334 (181)
Skin	Sv	309 (71)	6,714 (189)
Flange	S1	-6,717 (162)	1,686 (160)
Flange	S2	-6,298 (36)	1,997 (168)
Flange	S3	-5,544 (81)	2,144 (77)

The interesting values in these tables are the skin von Mises stress value of 6,714 psi and the hoop flange stress value of -6717 psi. These can be compared to the allowable stress of 15,500 psi.

4.0 Results for Pressure, Punch and +X Shear Loading

Presented in this section are results for deformation, chimney stresses, and shell-chimney collar region internal loads and stresses due to external pressure, punch load, and a +X directed shear load.

Figure 4.1 shows the deformed structure relative to the undeformed configuration. The maximum displacement of 0.0905 inches occurs at the chimney-bellows rim. This deflection is 38.8 percent larger than the pressure loading case. Figures 4.2 and 4.3 show the longitudinal and an oblique view, respectively.

Stress contour plots for the chimney pipe are shown in Figures 4.4 through 4.6. Stress component values are given in the chimney element coordinate system were "x" is in the axial direction and "y" is in the hoop direction. Stress component values from these figures are collected in Table 4-1 shown below.

As seen from these figures, peak axial and hoop compressive stresses occur near the base of the chimney at the interface with elements 162 and 163. The peak von Mises stress in this region has a value of 2,628 psi, only 7.9 percent greater than the pressure case, and well below the allowable stress value for aluminum.

Table 4-1 Chimney Stress Components (+X Shear)

Direction	Minimum	Maximum
Axial	-2,181	2,094
Hoop	-2,924	1,362
von Mises	79	2,628

Results for the internal load resultants and stresses for the Isogrid shell-chimney collar region are given below in Table 4-2 and Table 4-3, respectively. Values in these tables refer to element numbers and element coordinate directions shown in Figure 2.3.

Table 4-2 Isogrid Element Resultants (+X Shear)

	Minimum	Maximum
Mx	-579 (179)	1,090 (65)
My	-259 (197)	1,450 (52)
Mxy	-261 (161)	503 (64)
Nx	-1,350 (162)	439 (65)
Ny	-885 (157)	264 (33)
Nxy	-613 (153)	437 (161)

Table 4-3 Isogrid Element Stresses (+X Shear)

	Minimum	Maximum
Skin Sx	-7,507 (163)	7,526 (65)
Skin Sy	-4,999 (189)	7,705 (52)
Skin Sxy	-3,441 (161)	3,816 (160)
Skin Sv	447 (41)	7,607 (161)
Flange S1	-6,976 (173)	5,976 (180)
Flange S2	-9,239 (52)	3,887 (177)
Flange S3	-8,805 (52)	5,237 (77)

The peak skin von Mises stress value is 7,607 psi, an increase of 13.3 percent compared to the pressure case. The peak flange stress is -9,239 psi, or 37.6 percent greater than the pressure case. These can be compared to the allowable stress of 15,500 psi.

5.0 Results for Pressure, Punch and +Z Shear Loading

This section presents results for deformation, chimney stresses, and shell-chimney collar region internal loads and stresses due to external pressure, punch load, and a +Z directed shear load.

Figure 5.1 shows the deformed structure relative to the undeformed configuration. The maximum deformation (0.0545 in) is the radial displacement of the vacuum shell.

Stress contour plots for the chimney pipe are shown in Figures 5.2 through 5.4. Stress component values are given in the chimney element coordinate system were "x" is in the axial direction and "y" is in the hoop direction. Stress component values from these figures are collected in Table 5-1 shown below.

Table 5-1 Chimney Stress Components (+Z Shear)

Direction	Minimum	Maximum
Axial	-2,085	1,132
Hoop	-2,600	879
von Mises	41	2,326

As seen from these figures, peak axial and hoop compressive stresses occur near the base of the chimney at the interface with elements 62 and 63, and 162 and 163, respectively. The peak von Mises stress occurs at the chimney interface with elements 162 and 163 and has a value of 2,326 psi; -4.5 percent less than the pressure case.

Results for the internal load resultants and stresses for the Isogrid shell-chimney collar region are given in Table 5-2 and Table 5-3, respectively. Values in these tables refer to element numbers and element coordinate directions shown in Figure 2.3.

Table 5-2 Isogrid Element Resultants (+Z Shear)

	Minimum	Maximum
Mx	-184 (157)	674 (65)
My	-244 (202)	1,060 (50)
Mxy	-169 (79)	124 (33)
Nx	-1,220 (229)	279 (65)
Ny	-774 (157)	162 (33)
Nxy	-542 (181)	350 (161)

Table 5-3 Isogrid Element Stresses (+Z Shear)

	Minimum	Maximum
Skin Sx	-6,059 (232)	4,691 (65)
Skin Sy	-4,338 (189)	5,110 (49)
Skin Sxy	-1,795 (161)	3,160 (185)
Skin Sv	689 (148)	6,594 (189)
Flange S1	-9,173 (162)	1,847 (160)
Flange S2	-7,547 (50)	2,863 (148)
Flange S3	-7,547 (51)	2,213 (169)

The peak skin von Mises stress value is 6,594 psi, a -1.8 percent decrease compared to the pressure case. The peak flange stress is -9,173 psi, or 36.6 percent greater than the pressure case. These can be compared to the allowable stress of 15,500 psi.

6.0 Results for Pressure, Punch and -Z Shear Loading

This section presents results for deformation, chimney stresses, and shell-chimney collar region internal loads and stresses due to external pressure, punch load, and a -Z directed shear load.

Figure 6.1 shows the deformed structure relative to the undeformed configuration. The maximum displacement is 0.1316 inches and occurs at the chimney rim. This deflection is 101.8 percent larger than the pressure loading case. Clearly, half of the total deflection results from the 1,000 pound shear load.

Stress contour plots for the chimney pipe are shown in Figures 6.2 through 6.4.

Stress component values are given in the chimney element coordinate system were "x" is in the axial direction and "y" is in the hoop direction. Stress component values from these figures are collected in Table 6-1 shown below.

Table 6-1 Chimney Stress Components (-Z Shear)

Direction	Minimum	Maximum
Axial	-3,659	2,146
Hoop	-4,584	1,136
von Mises	60	4,199

As seen from these figures, peak axial and hoop compressive stresses occur near the base of the chimney at the interface with elements 162 and 163. The peak von Mises stress, occurring near the chimney interface with elements 162 and 163, has a value of 4,199 psi, 72.4 percent greater than the pressure case.

Results for the internal load resultants and stresses for the Isogrid shell-chimney collar region are given below in Table 6-2 and Table 6-3, respectively. Values in these tables refer to element numbers and element coordinate directions shown in Figure 2.3.

Table 6-2 Isogrid Element Resultants (-Z Shear)

	Minimum	Maximum
Mx	-589 (162)	1,010 (65)
My	-525 (160)	918 (81)
Mxy	-462 (61)	482 (36)
Nx	-1,530 (162)	557 (65)
Ny	-1,040 (157)	416 (33)
Nxy	-666 (181)	469 (161)

Table 6-3 Isogrid Element Stresses (-Z Shear)

		Minimum	Maximum
Skin	Sx	-10,451 (162)	7,715 (65)
Skin	Sy	-7,519 (160)	6,355 (33)
Skin	Sxy	-3,009 (161)	4,349 (178)
Skin	Sv	1,189 (72)	9,488 (160)
Flange	S1	-8,941 (77)	4,256 (179)
Flange	S2	-11,525 (36)	2,440 (61)
Flange	S3	-7,203 (61)	5,052 (77)

The peak skin von Mises stress value is 9,488 psi, a 41.3 percent increase compared to the pressure case. The peak flange stress is -11,525 psi, or 71.6 percent greater than the pressure case. These can be compared to the allowable stress of 15,500 psi.

7.0 Discussion of Results

Stress values for the four load cases discussed in this report are collected in Figure 7-1. The table columns for chimney and Isogrid skin stress values contain von Mises stress results. The column labelled "Flange" is the peak bending stress in one of the Isogrid rib flanges.

Table 7-1 Peak Stress Component Values

Load Case	Chimney	Skin	Flange
Pressure	2,436	6,714 (189)	-6,717 (162)
+X Shear	2,628	7,607 (161)	-9,239 (52)
+Z Shear	2,326	6,594 (189)	-9,173 (162)
-Z Shear	4,199	9,488 (160)	-11,525 (36)

Clearly the worst case condition results when the chimney-bellows shear load is directed along the vacuum shell longitudinal -Z axis. The skin and flange peak stresses occur at the edge of the vacuum shell-chimney interface. No special reinforcements around the shell-chimney joint were considered in these analyses, consequently, additional material in this area will reduce the stress values given above.

References

[1] MIL-HDBK-5C, Military Standardization Handbook, Metallic Materials and Elements for Aerospace Vehicle Structures. September 15, 1976.

[2] ASME Boiler and Pressure Vessel Code, Section VIII Rules for Construction of Pressure Vessels, Division I. 1989 Edition, July 1, 1989.

[3] L.W. Swenson, Jr, "Buckling and Stress Analysis of the SDC Vacuum Shell (Task 1)", Fermilab Report, August 30, 1991.

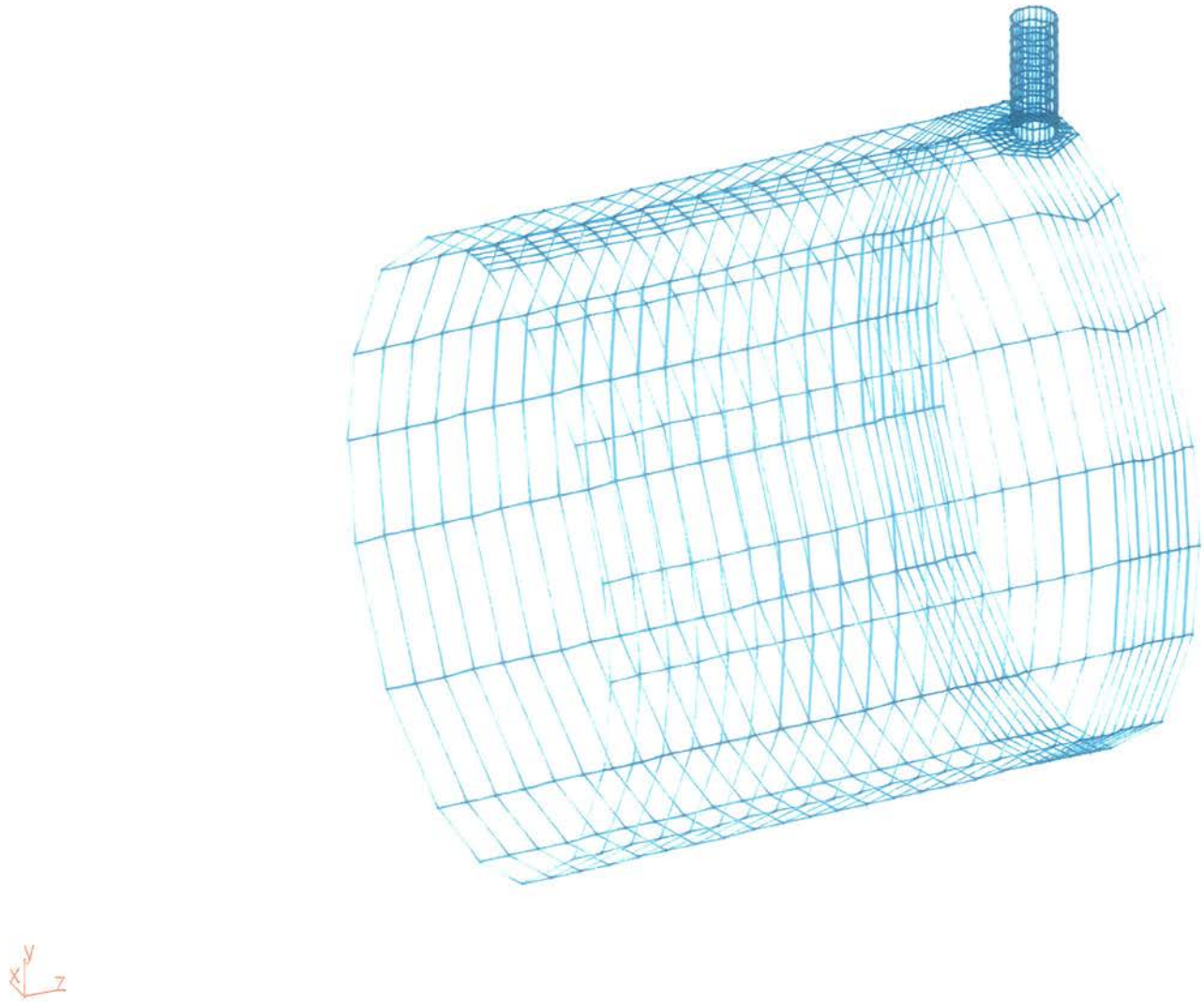

Figure 2.1 Finite Element Model of SDC Vacuum Shell and Chimney Pipe

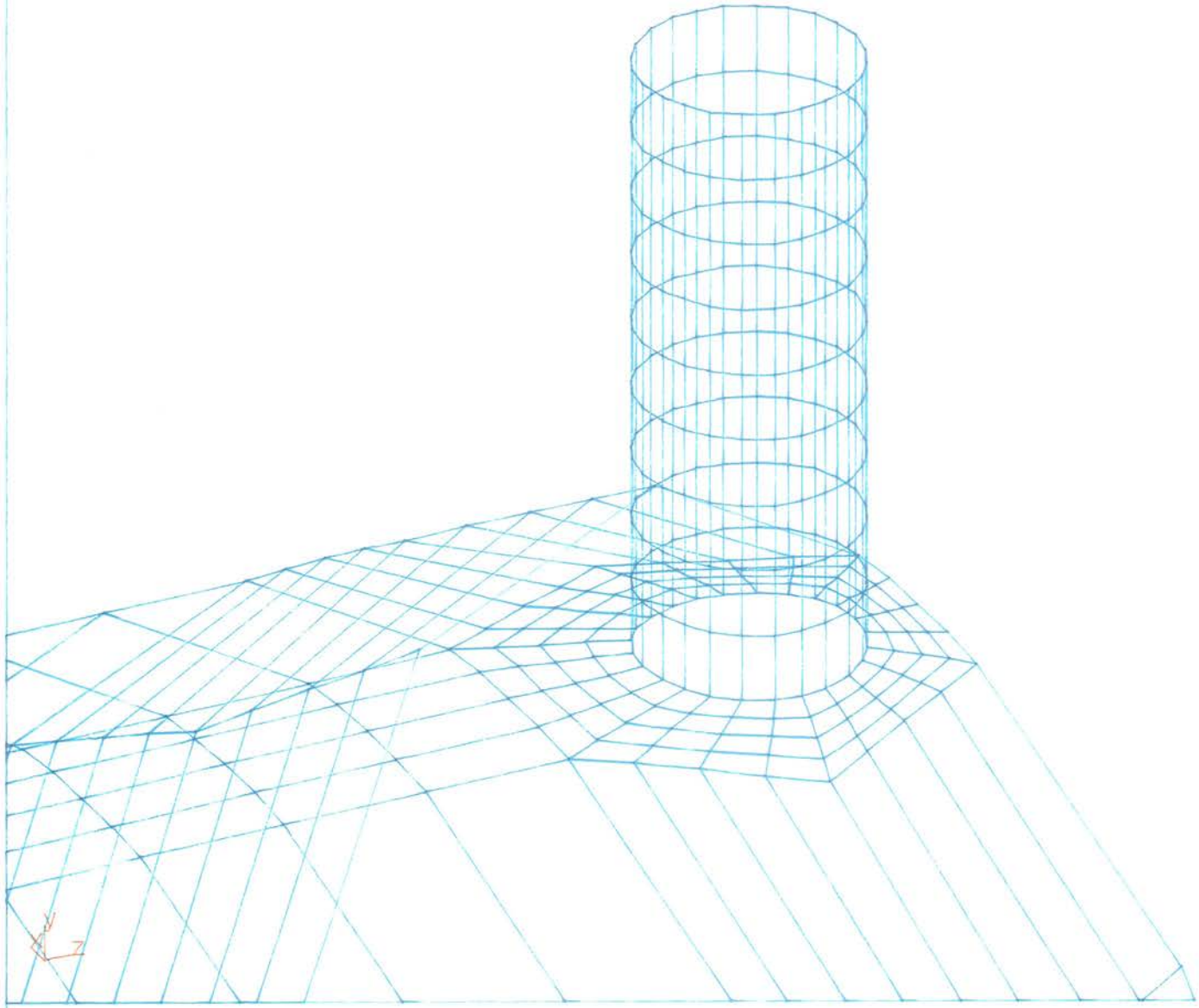

Figure 2.2 Vacuum Shell-Chimney Collar Region

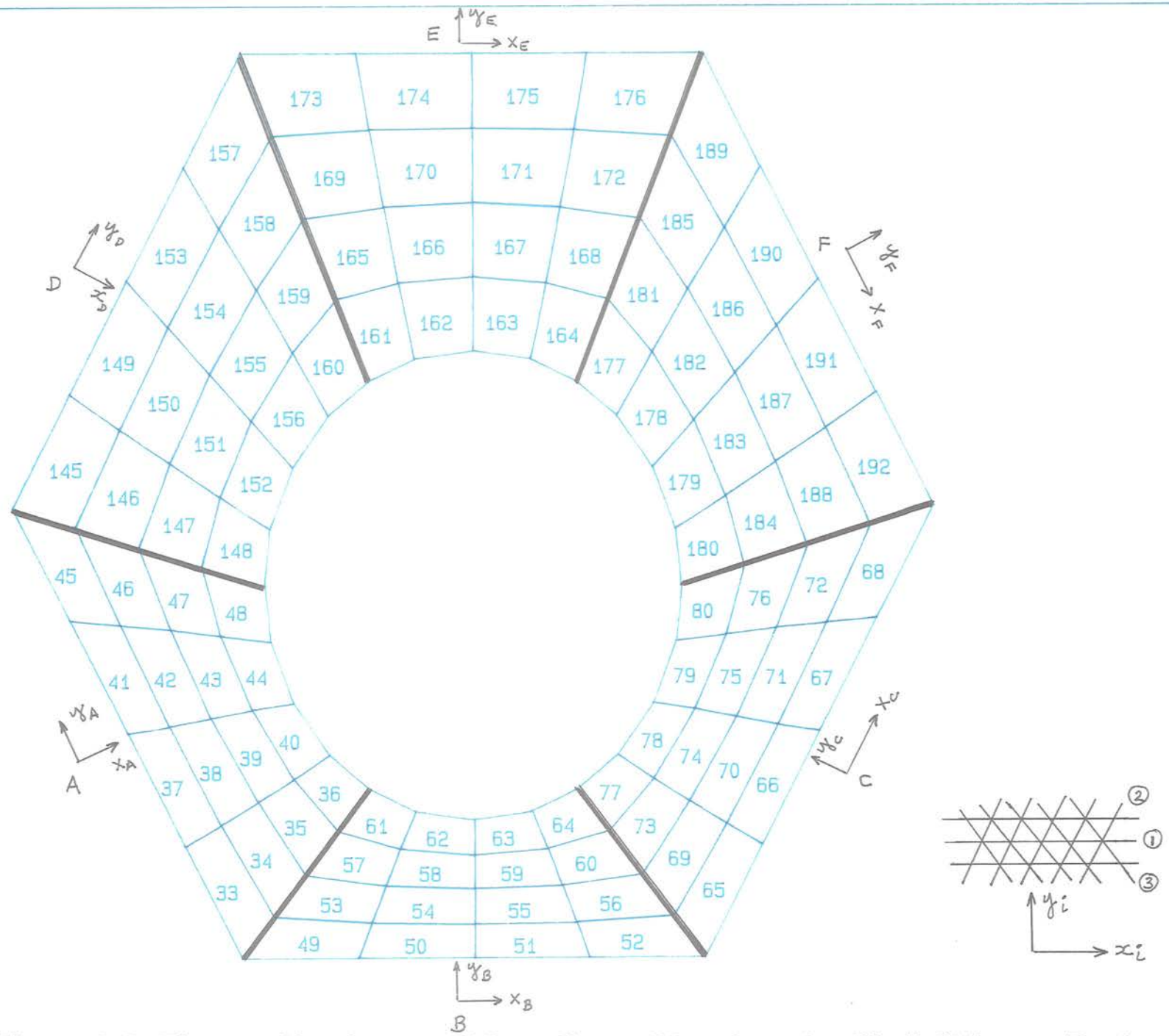

Figure 2.3 Element Numbers and Coordinate Directions for Shell-Chimney Region

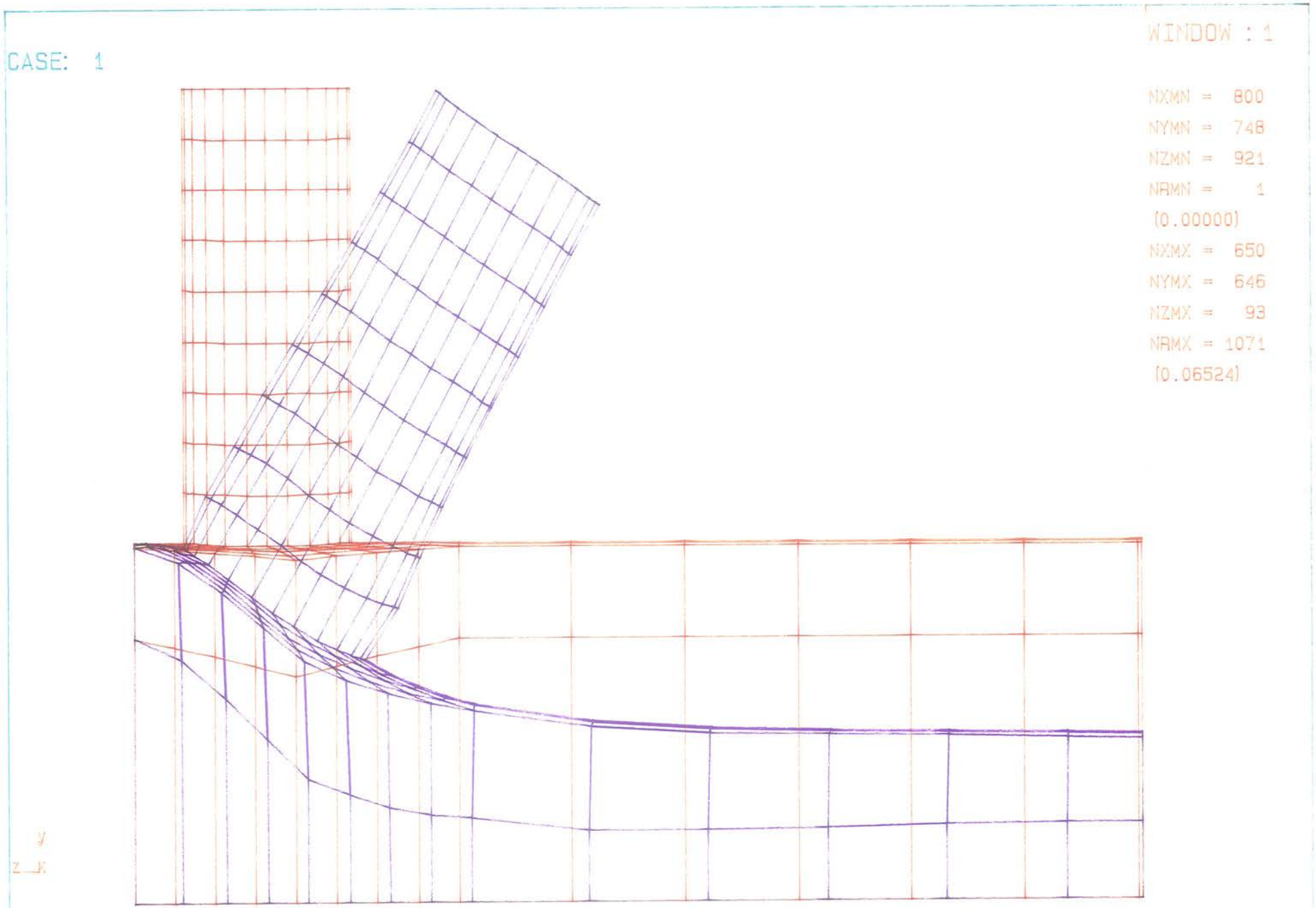

Figure 3.1 Deformation of Vacuum Shell-Chimney Pipe (Pressure Loading)

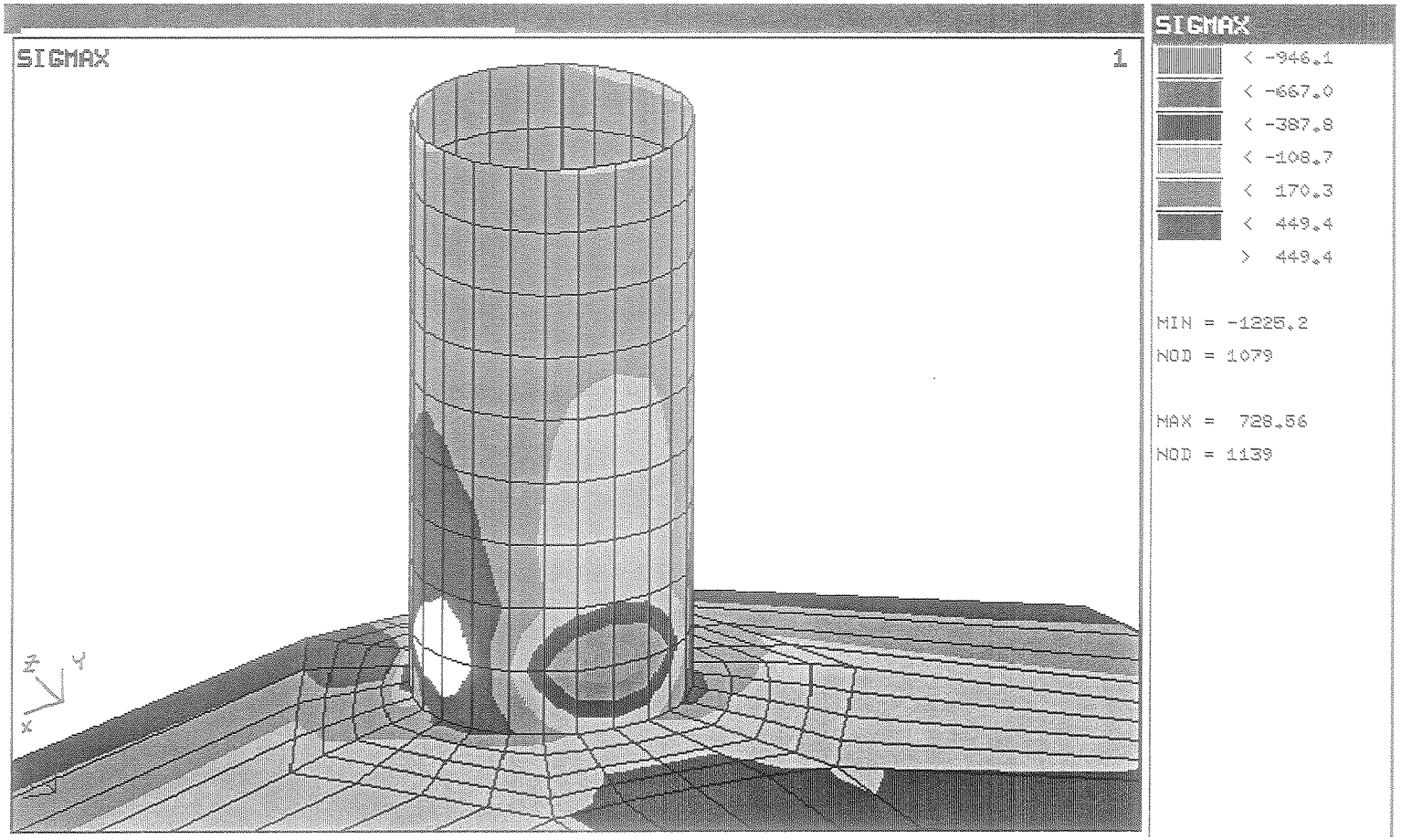

Figure 3.2 Chimney Pipe Axial Stress Contours

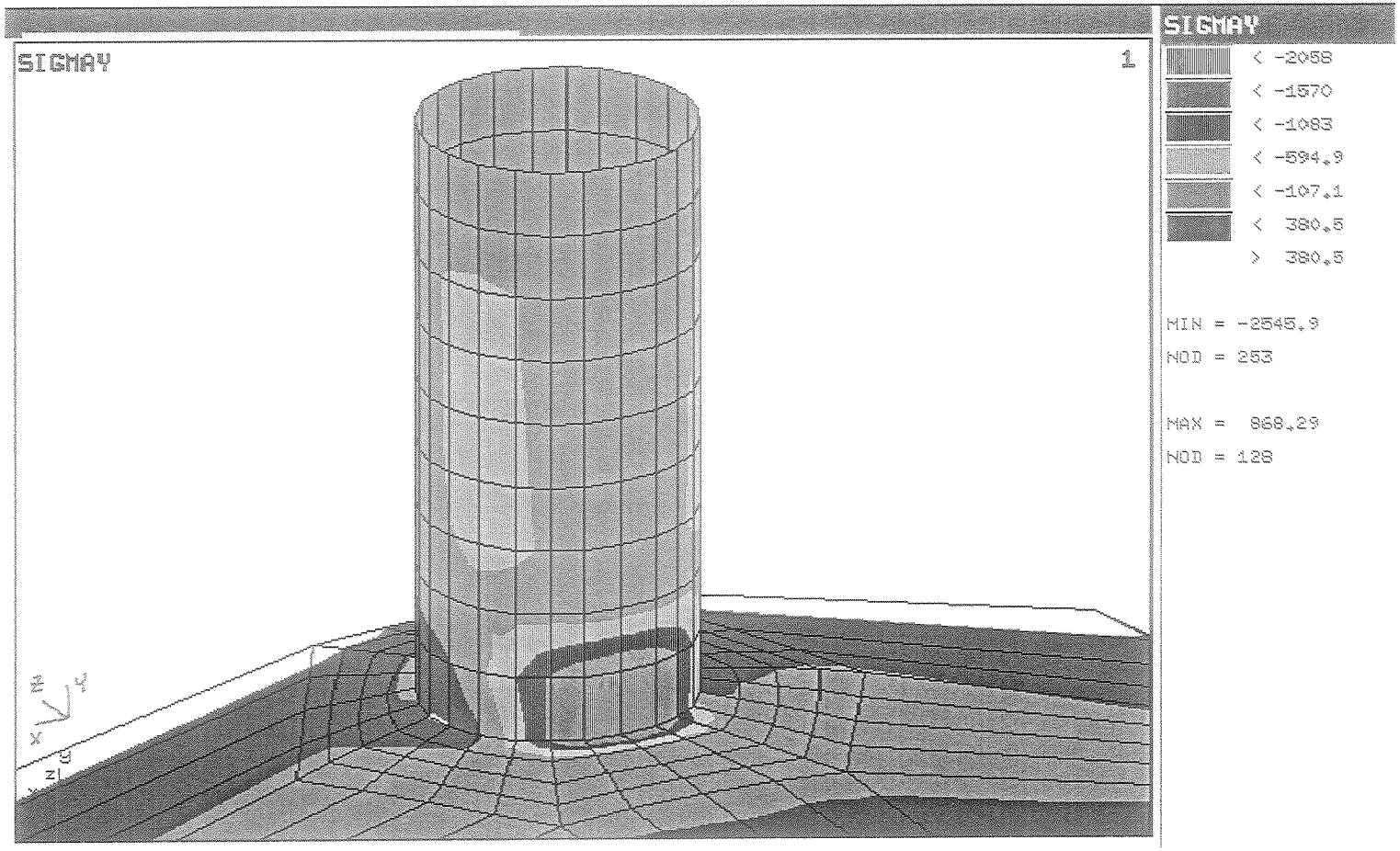

Figure 3.3 Chimney Pipe Circumferential Stress Contours (Pressure)

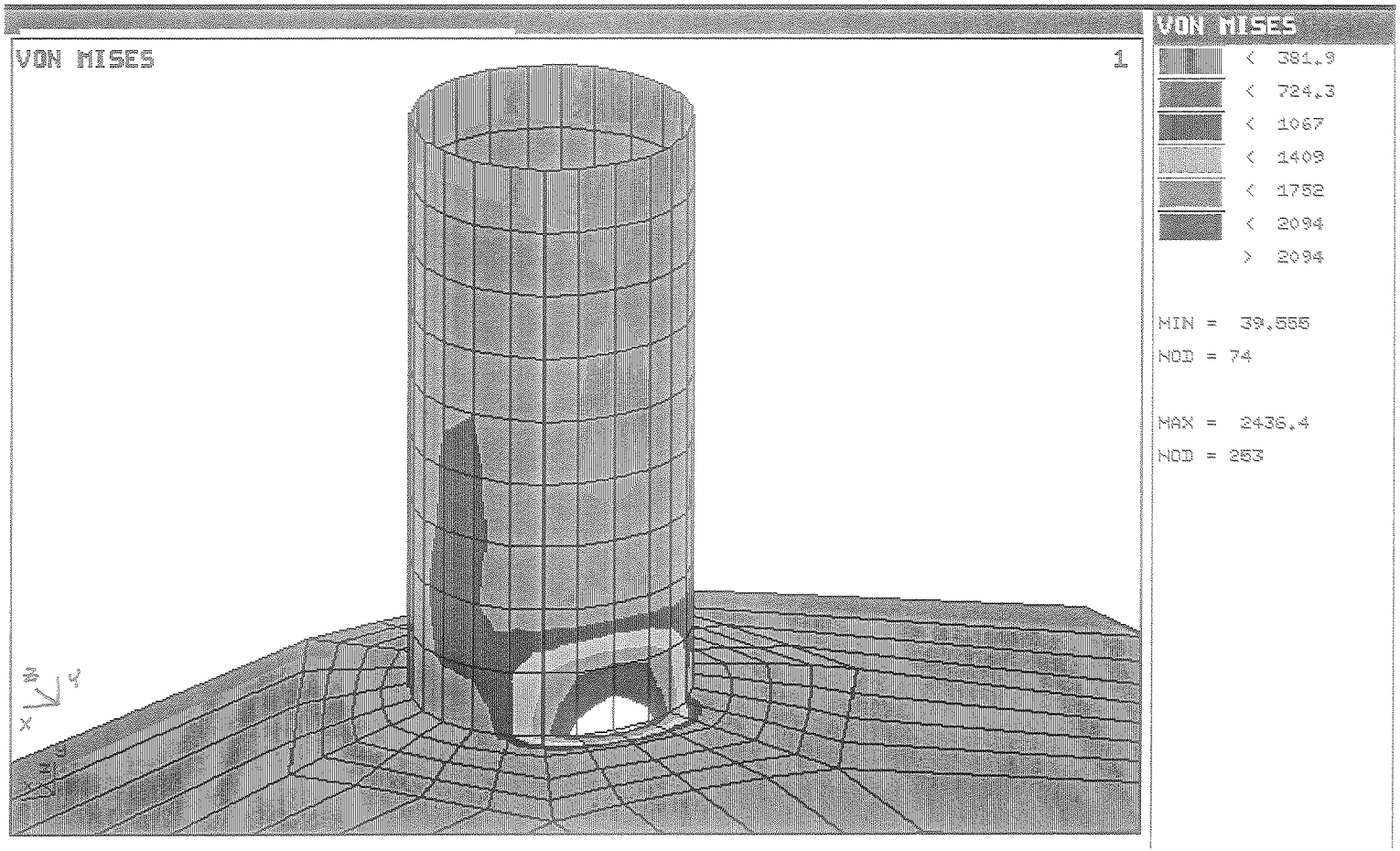

Figure 3.4 Chimney Pipe von Mises Stress (Pressure)

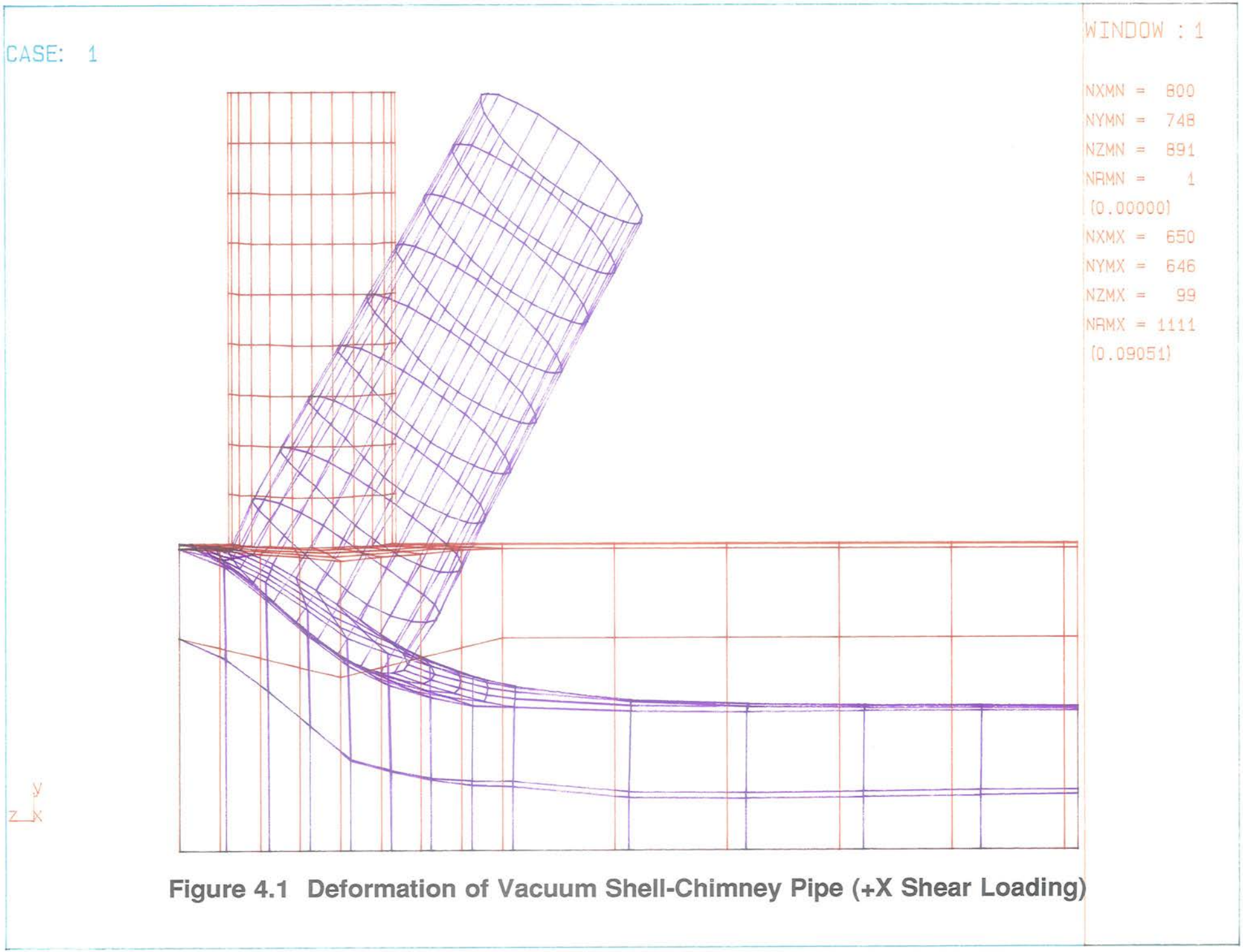

Figure 4.1 Deformation of Vacuum Shell-Chimney Pipe (+X Shear Loading)

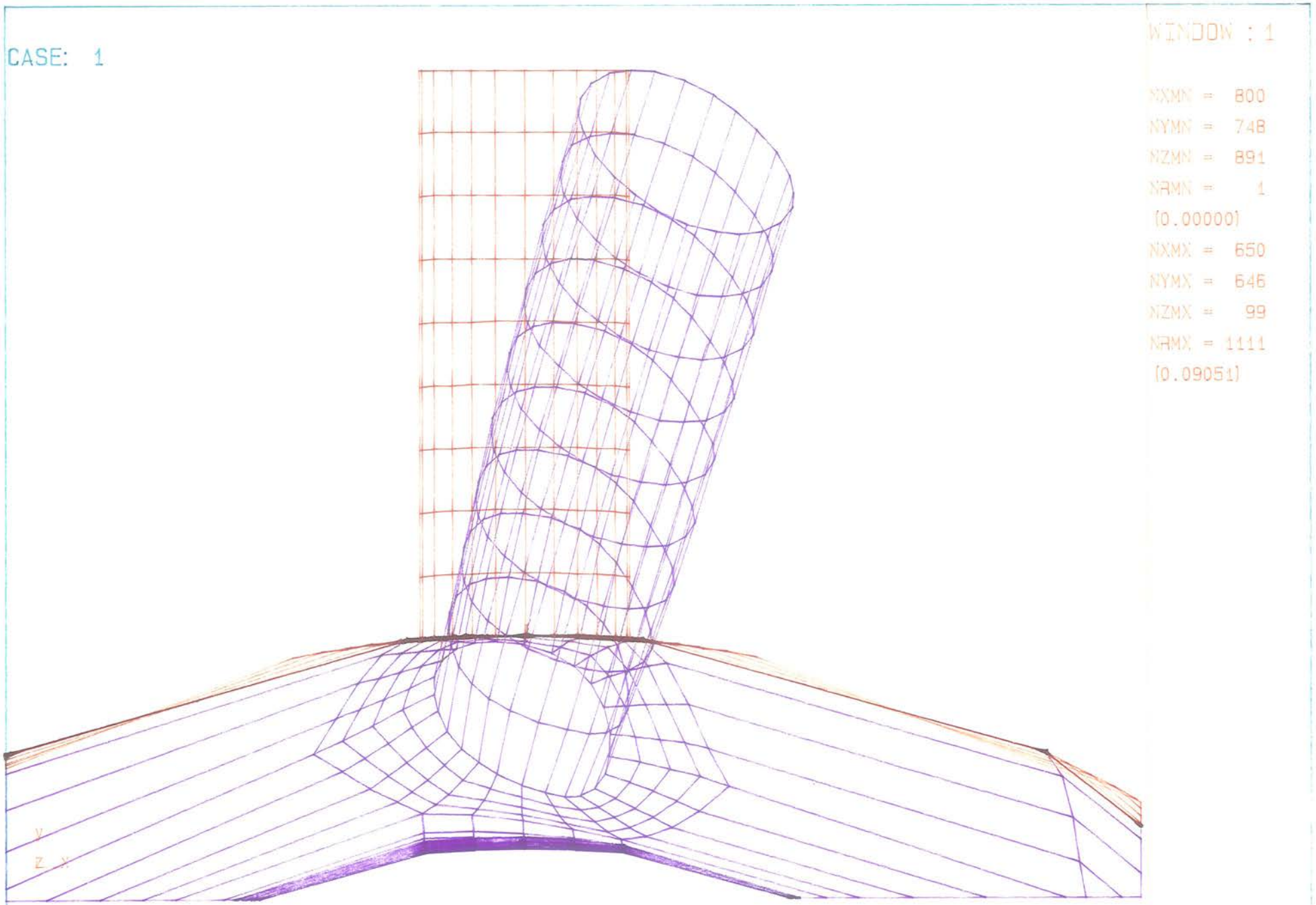

Figure 4.2 Longitudinal View of Shell-Chimney Deformation (+X Shear)

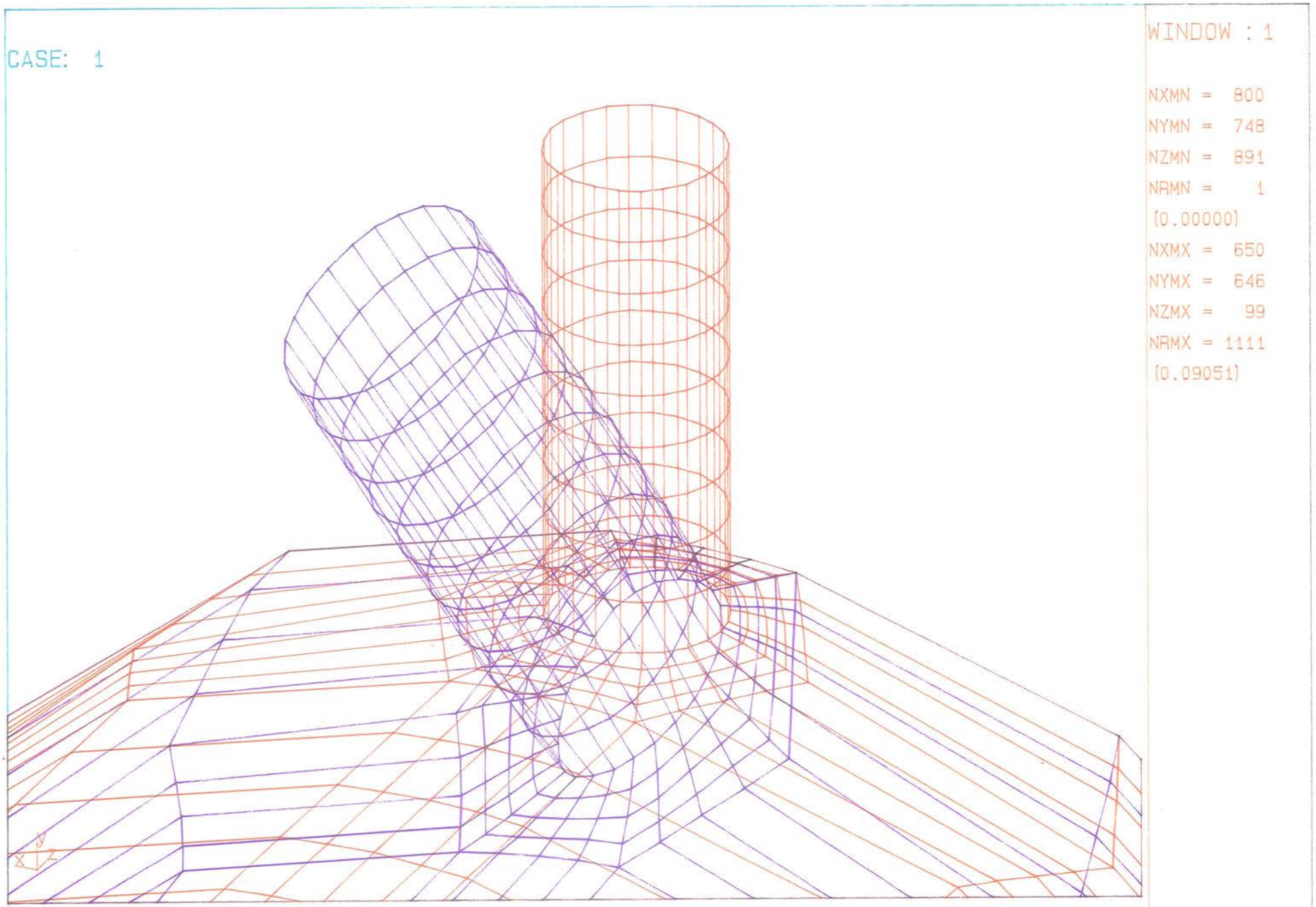

Figure 4.3 Oblique View of Shell-Chimney Deformation (+X Shear)

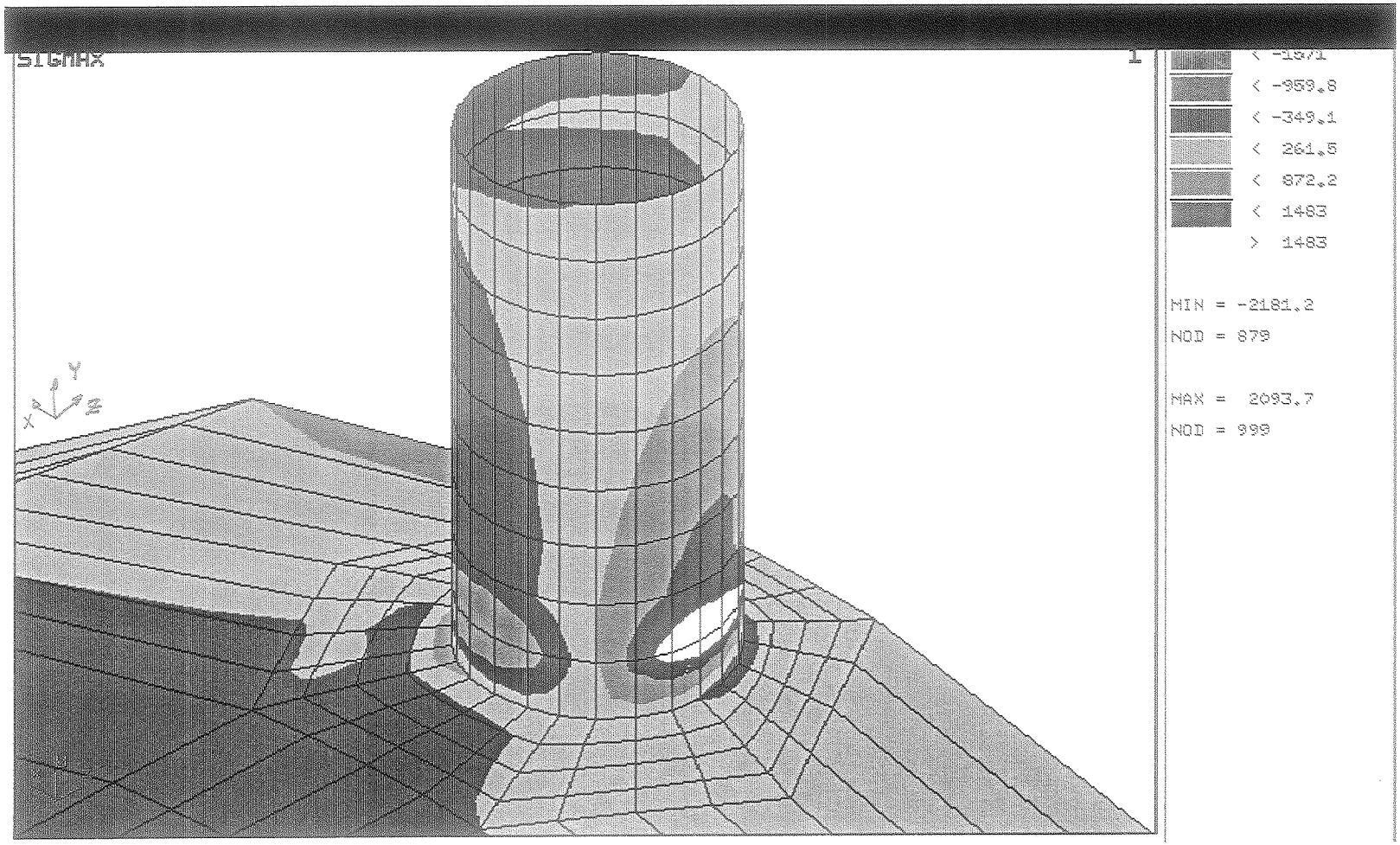

Figure 4.4 Chimney Pipe Axial Stress Contours (+X Shear)

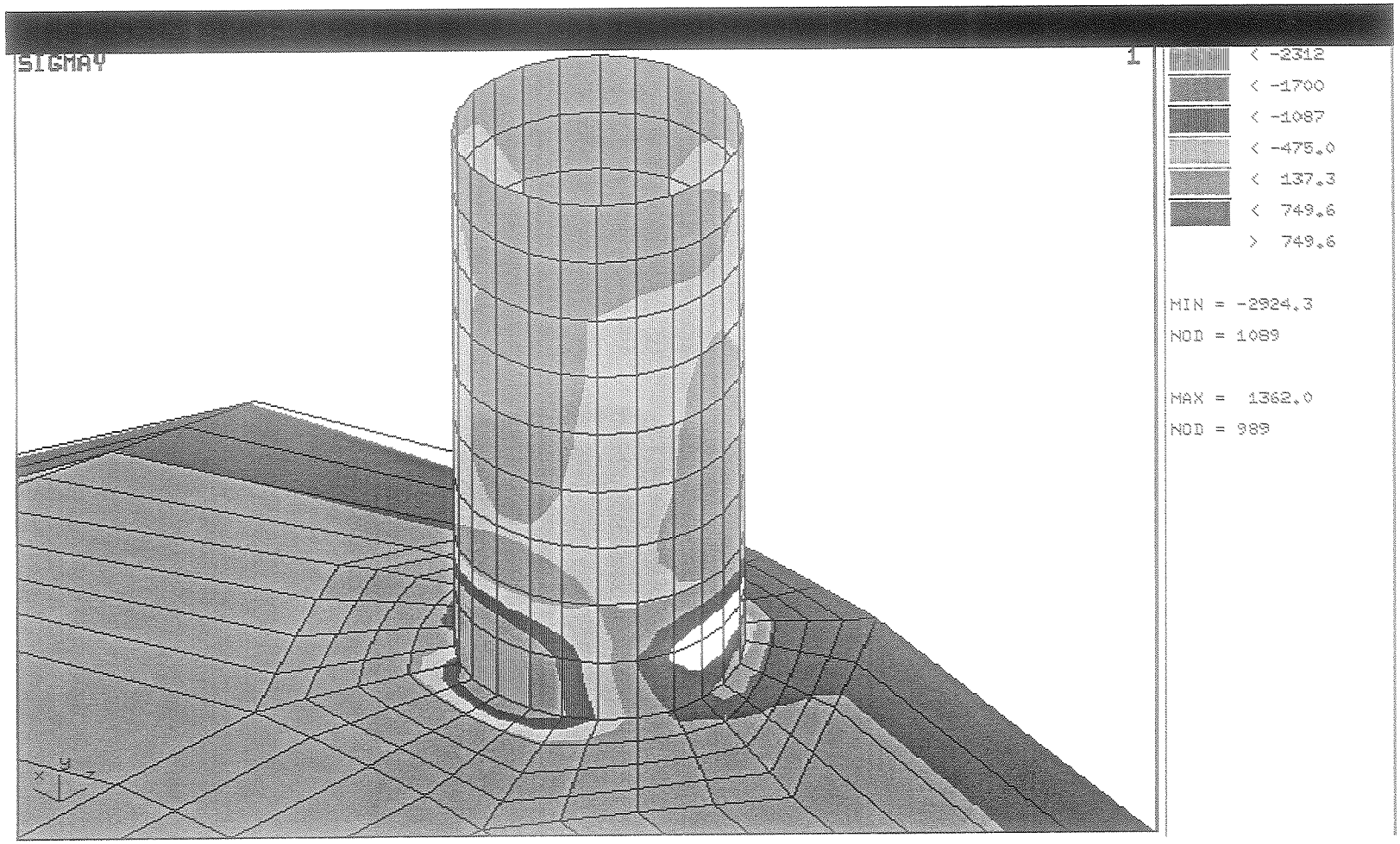

Figure 4.5 Chimney Pipe Circumferential Stress Contours (+X Shear)

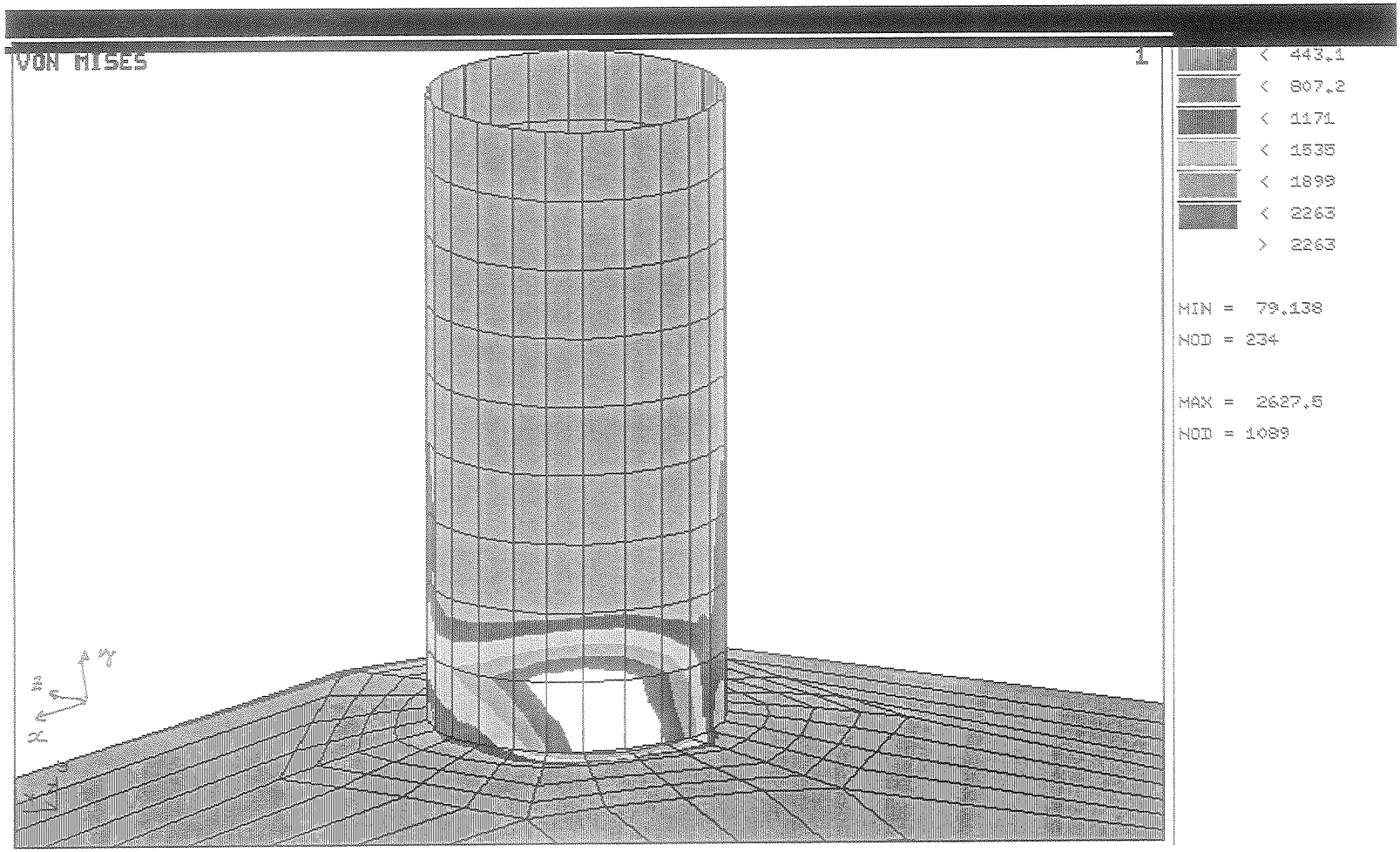

Figure 4.6 Chimney Pipe von Mises Stress (+X Shear)

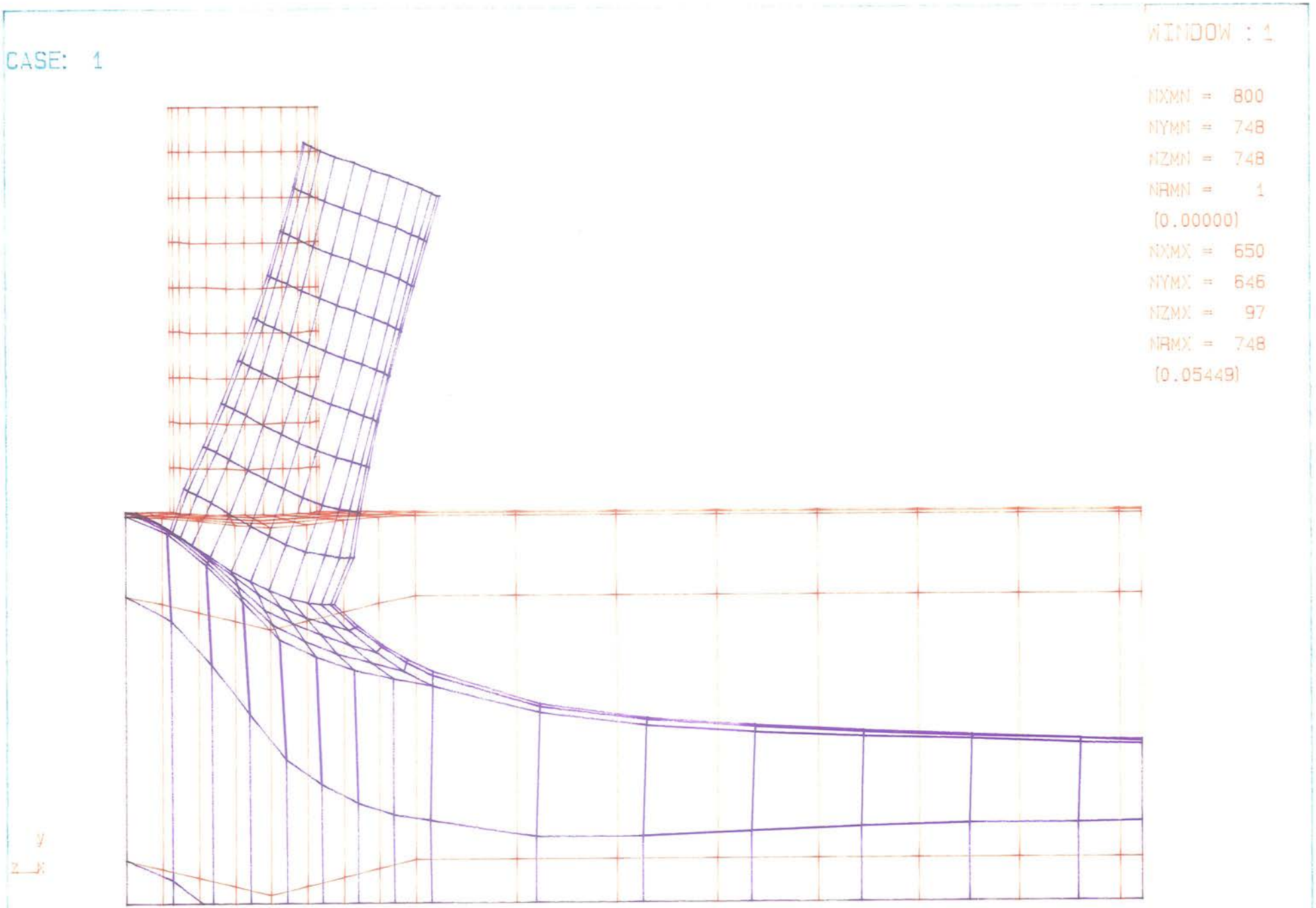

Figure 5.1 Deformation of Vacuum Shell-Chimney Pipe (+Z Shear Loading)

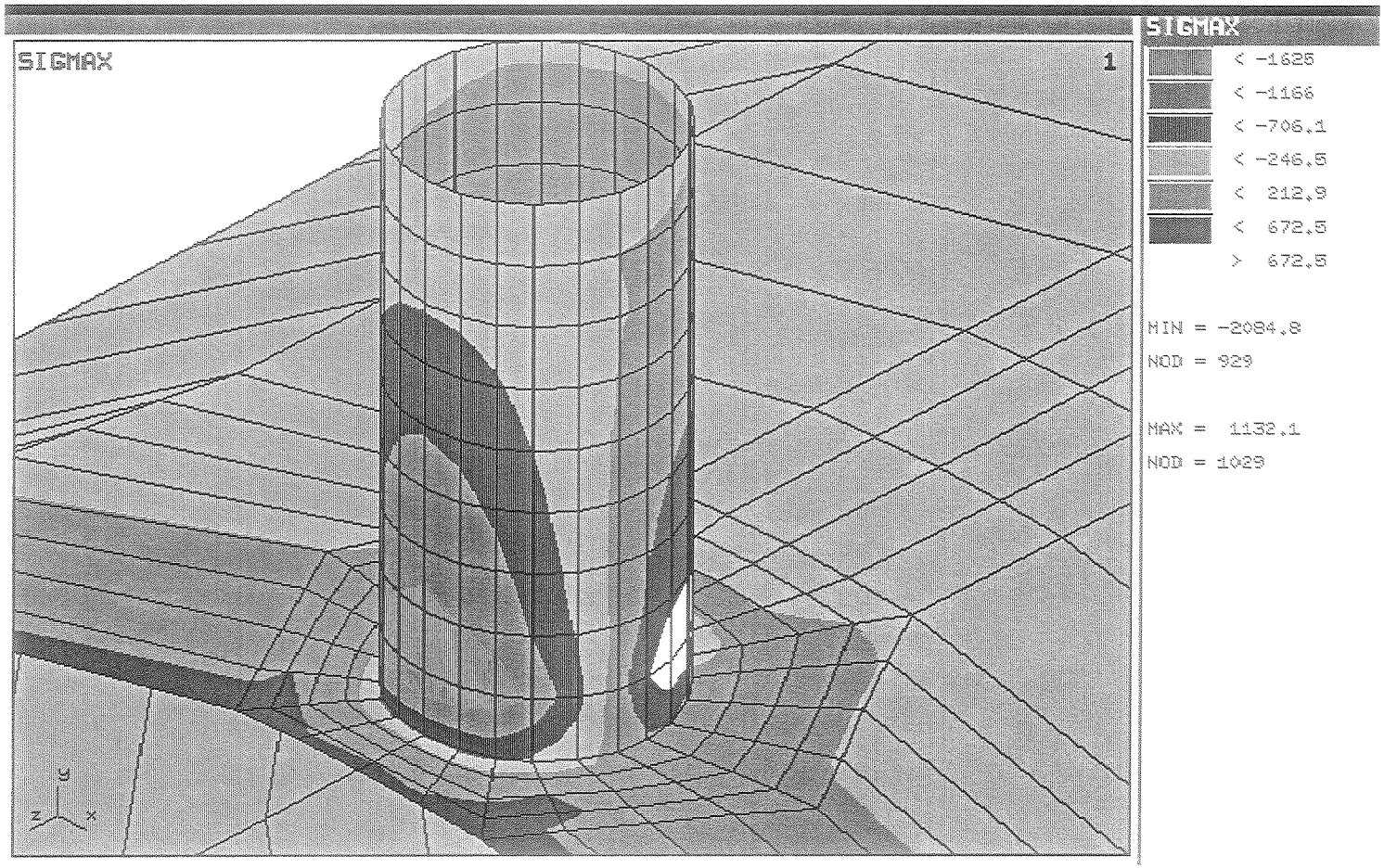

Figure 5.2 Chimney Pipe Axial Stress Contours (+Z Shear)

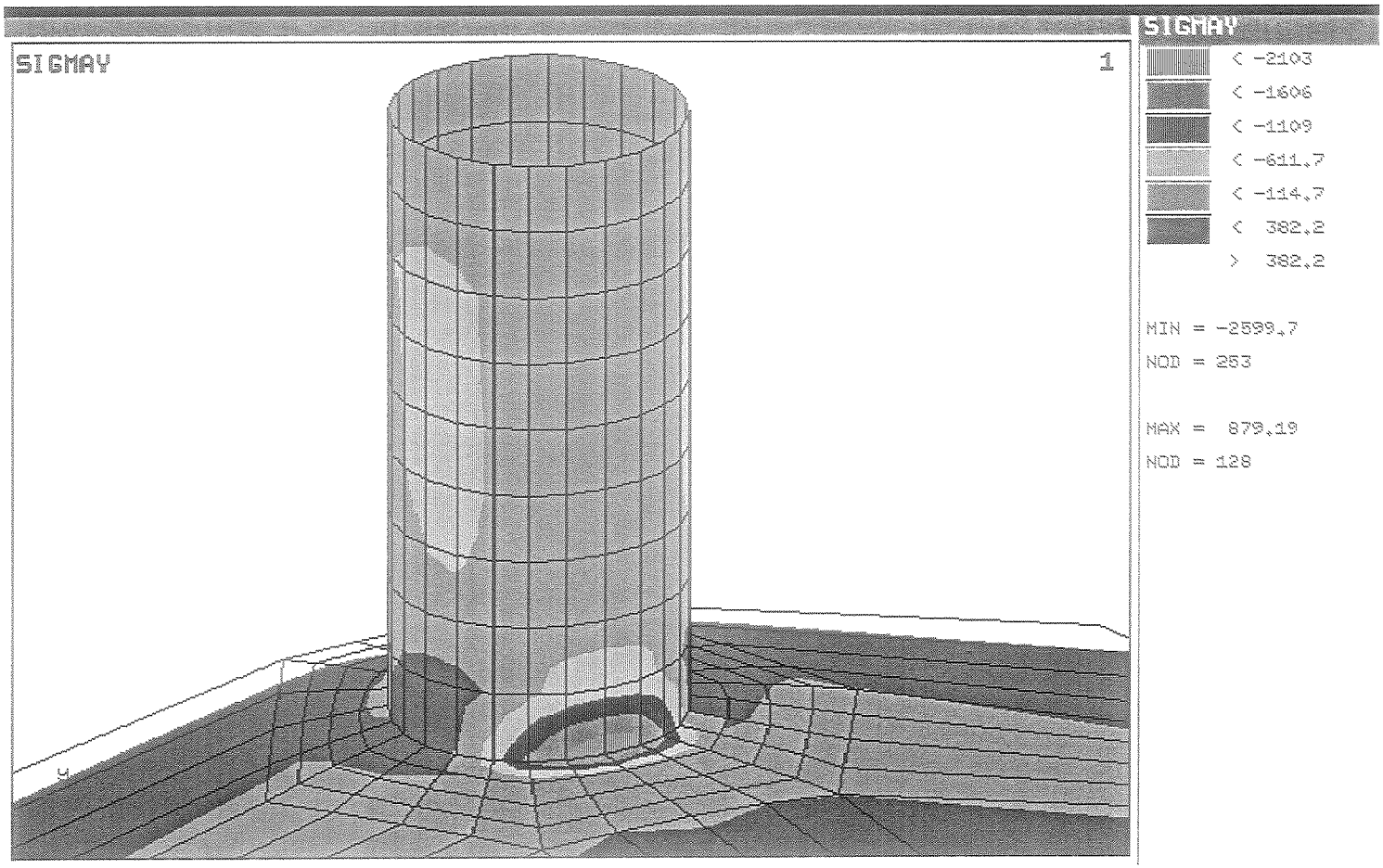

Figure 5.3 Chimney Pipe Circumferential Stress Contours (+Z Shear)

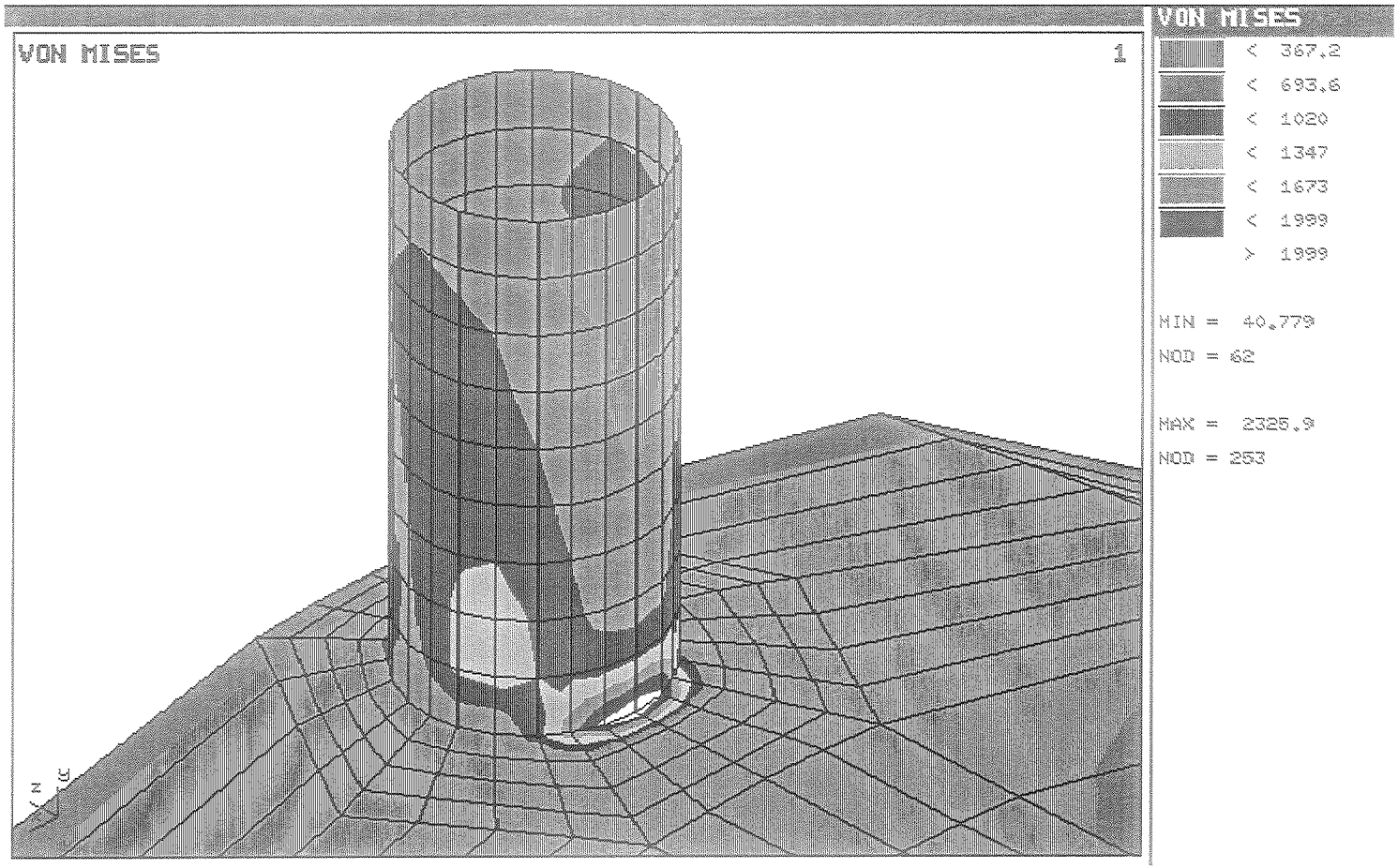

Figure 5.4 Chimney Pipe von Mises Stress (+Z Shear)

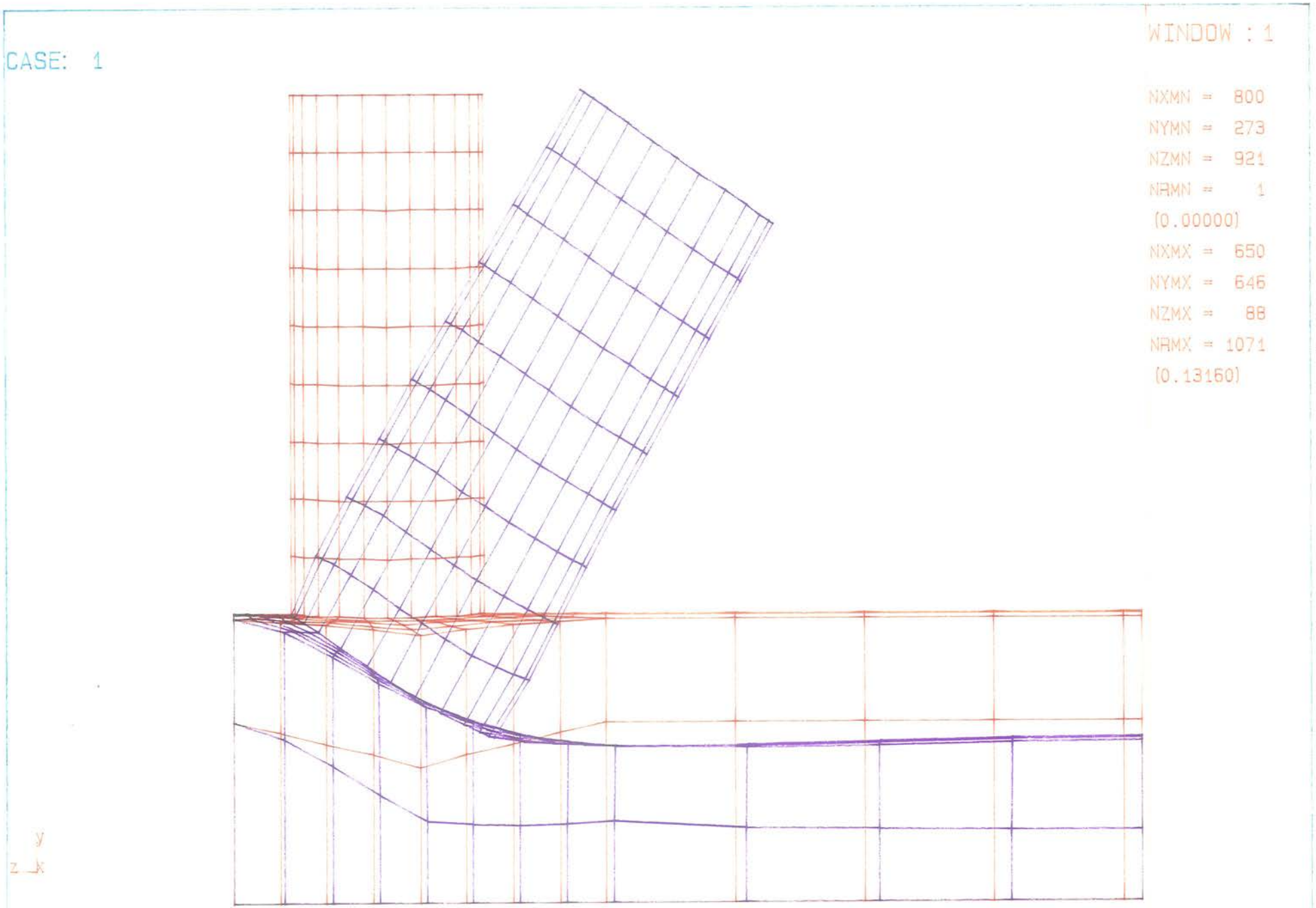

Figure 6.1 Deformation of Vacuum Shell-Chimney Pipe (-Z Shear Loading)

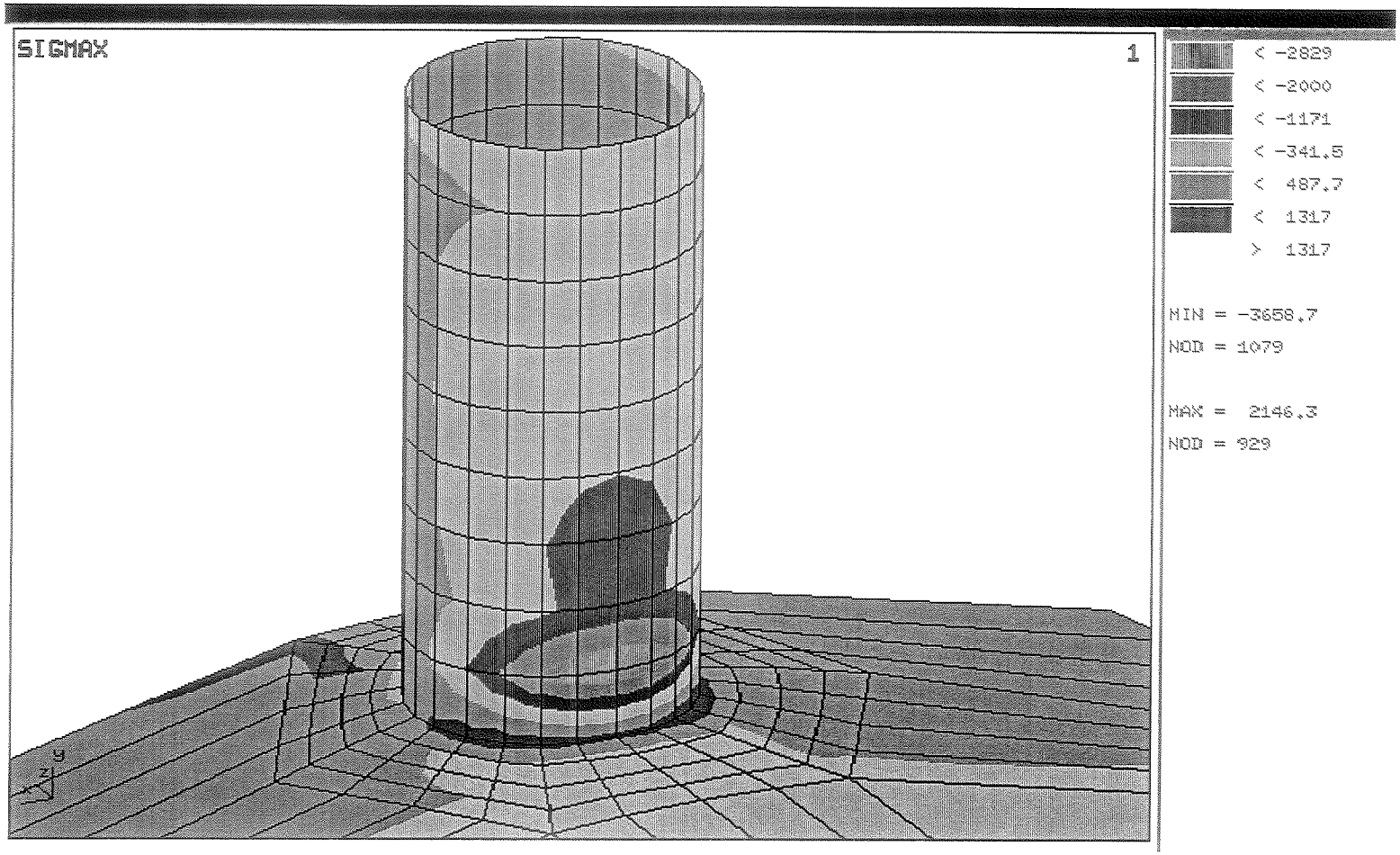

Figure 6.2 Chimney Pipe Axial Stress Contours (-Z Shear)

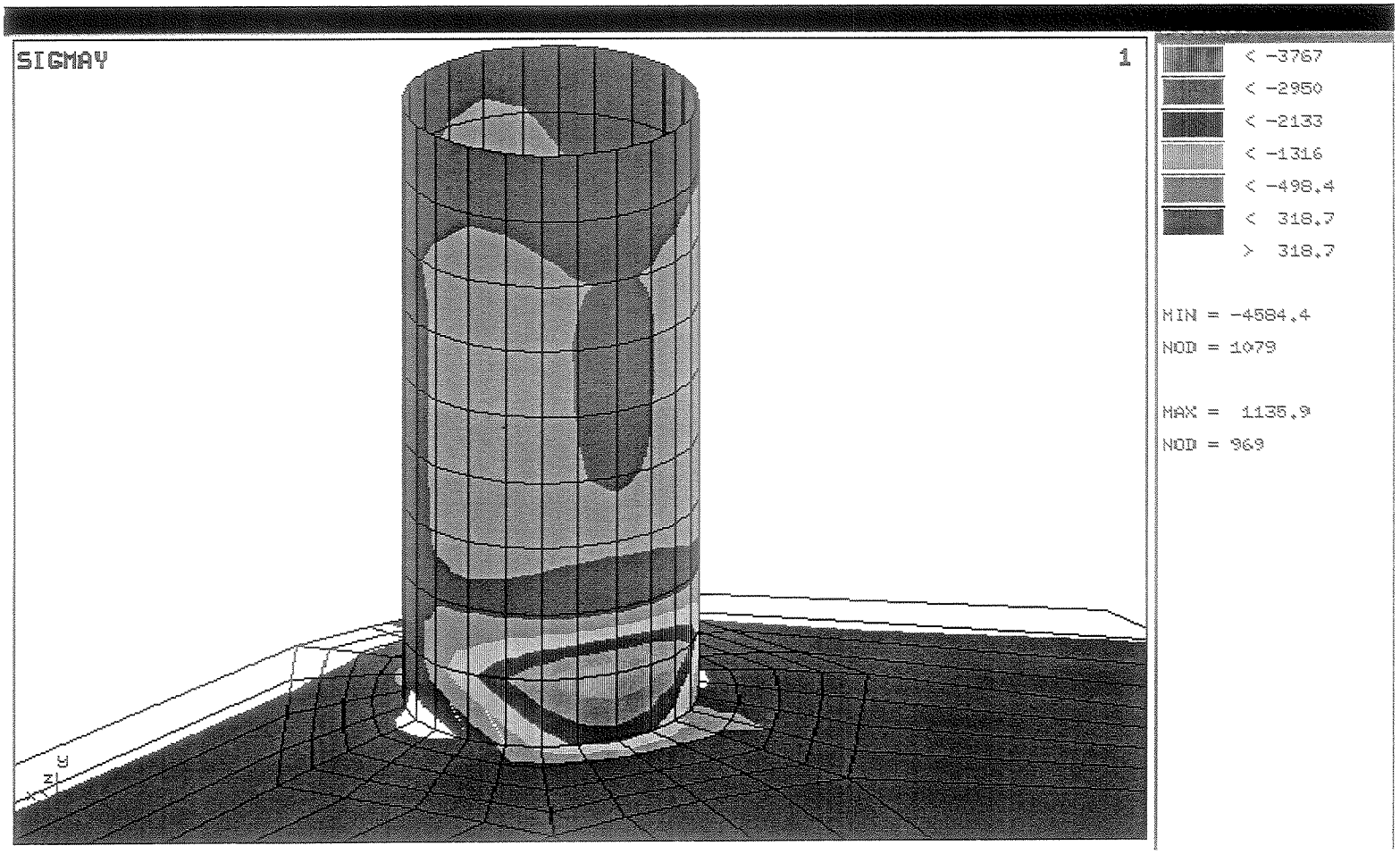

Figure 6.3 Chimney Pipe Circumferential Stress Contours (-Z Shear)

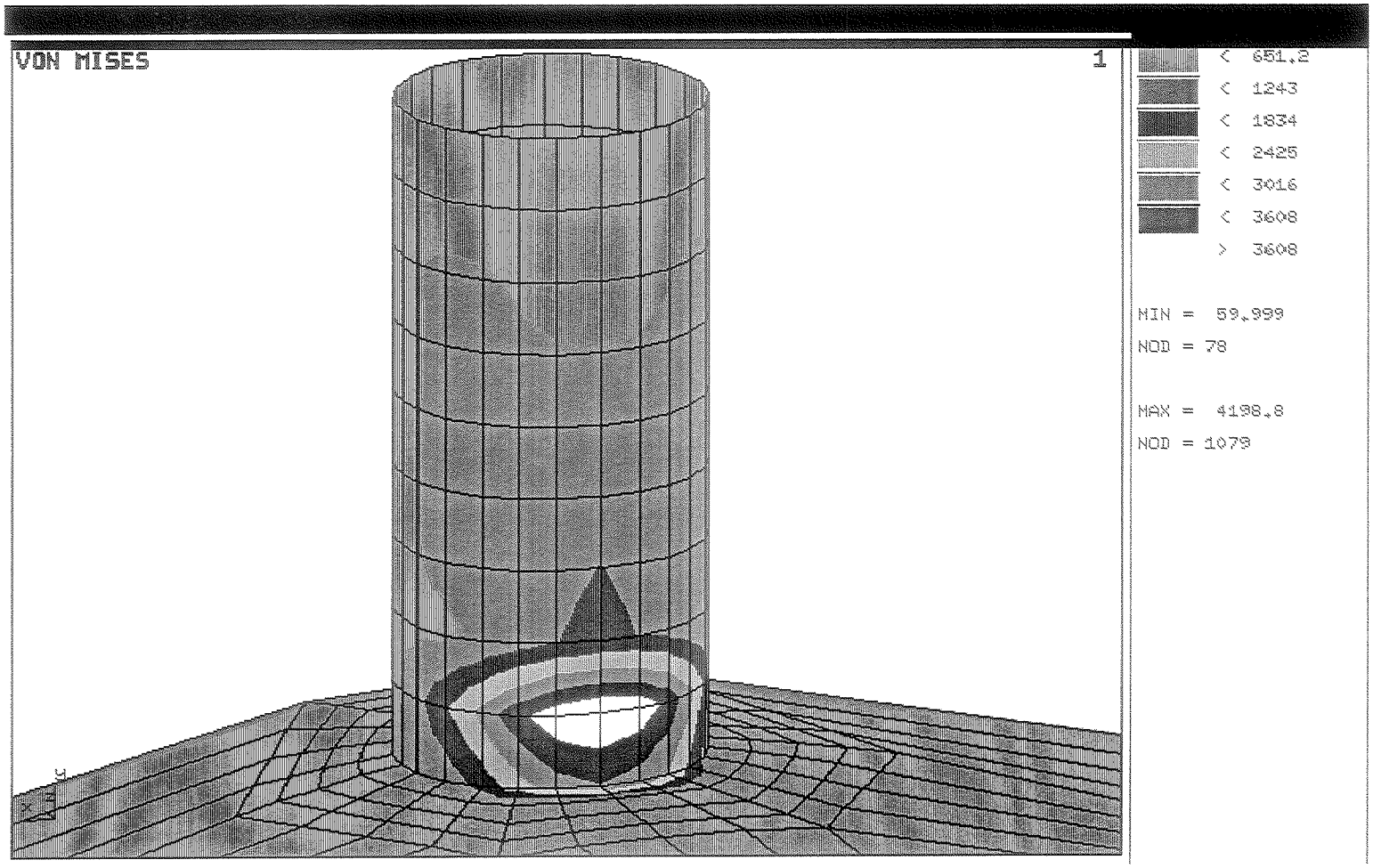

Figure 6.4 Chimney Pipe von Mises Stress (-Z Shear)