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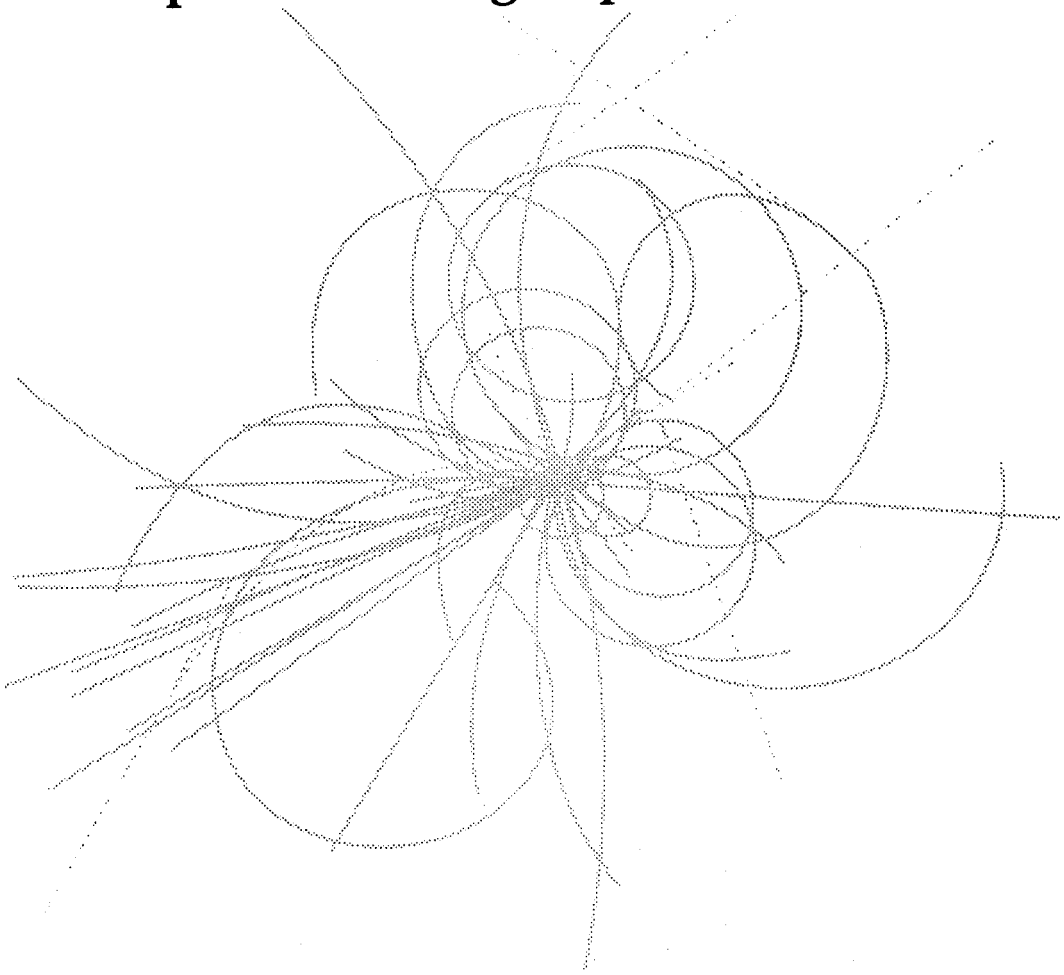

Accelerator System String Test (A.S.S.T.) Interconnect Region Cold Mass Connection Analysis

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Abstract

Two-dimensional axisymmetric linear and nonlinear ANSYS finite element models of the A.S.S.T. Interconnect Region cold mass connection piping sleeve and flange and their adjoining weld (Drawings M30-000499A and M30-000573A) have been developed. These models indicate that a strong, highly localized stress concentration occurs at the interface region of the weld and sleeve parent metal (heat affected zone), at the inner diameter of the sleeve. Therefore, fatigue crack propagation has also been studied. For loading characteristics of 177 N/rad (250 lb total) axial force and 2.533 MPa (25 atm) internal pressure, an initial circumferential crack of 0.15 mm or less will not propagate through the 2 mm thickness of the sleeve within the 150 cycle design lifetime.

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1.0 INTRODUCTION

The A.S.S.T. Interconnect Region cold mass piping system serves as the means for refrigeration of the cold mass, and is normally subject to an internal pressure of 405 300 Pa (4 atm). However, during quenches this system may undergo a design maximum axial loading of 177 N/rad (250 lb total) and an internal pressure of 2.533 MPa (25 atm). ANSYS 4.4A+ finite element models have been created to analyze the effects of this loading.

Linear and nonlinear two-dimensional axisymmetric models of the pipe sleeve and flange (Drawings M30-000499A and M30-000513A), and their adjoining weld, have been created using STIF42 2-D 4-Noded Isoparametric Solid elements and STIF82 2-D 8-Noded Isoparametric Solid elements. A sketch of these models is included in Figure 1. Material properties defined for these models are extrapolated from data for stainless steels SSTL304 and SSTL316L at 4 K cryogenic temperature.[1,2,3] These properties are shown in Figure 2.

2.0 LINEAR MODELS

The primary linear model includes 2576 nodes and 2336 elements, and serves as a general model for locating any regions of interest. While stresses throughout this model are generally one order of magnitude below the yield value of the materials at room temperature, a Von Mises (SIGE) stress concentration (max. 129 MPa) is located at the interface of the weld and parent model as shown in Figure 3.

Further analysis of this weld region has been done using a number of increasingly smaller, more detailed submodels of the primary linear model. These submodels range in dimension from 6 mm × 4.05 mm to 1 mm × 1.05 mm, centered on the interface region between the outer diameter of the flange and inner diameter of the sleeve, and include 1680 to 3280 elements each. Each submodel has a different concentration of elements at the region of interest; consequently, maximum SIGE stress levels at the heat affected zone range from 208 MPa (30.2 ksi) to 572 MPa (83.0 ksi), although the region and shape of the stress concentration do not fluctuate considerably. Figure 4 shows a typical analysis result.

The submodels have been created in several series in which consecutive submodels are smaller, more detailed versions of previous submodels. However, there do not appear to be any strong stress value convergence patterns among submodels within a series, indicating a singularity in the model and a strong possibility for plastic yielding in the heat affected zone. Therefore, a nonlinear model has been developed to more accurately depict the stress concentration effects, and is described in the following section.

Other linear models have been created which include gravity effects, small dimension changes, and other analysis methods such as adaptive meshing. These models resulted in similar stress concentrations and negligible effects upon stress values away from the weld region.

3.0 NONLINEAR MODEL

The nonlinear model has been created with 5836 STIF82 elements and 18 001 nodes, and has the nonlinear material properties described in Section 1.0. Loading has been applied as follows:

1. Axial loading is applied throughout the nonlinear run.
2. Internal pressure is applied in 0.05 MPa load step increments, starting just under yield at 1.05 MPa up to 2.533 MPa (25 atm) design loading. ANSYS default convergence criteria and a maximum of ten iterations per load step were used.

Results for the nonlinear model are similar to that of the comparable linear models. Figure 5 shows SIGE stress levels for the weldment, and Figure 6 shows SIGE stress levels for the adjoining flange and sleeve. The model indicates a maximum SIGE stress of 333 MPa (48.3 ksi) at the inner diameter of the sleeve. Figures 7 and 8 are magnified displays of these SIGE stresses.

Stress components σ_y (SY) and σ_{xy} (SXY) are included in Figures 9 through 12 as follows:

Figure 9: SY in weldment

Figure 10: SY in parent metal, max. 403 MPa (58.4 ksi)

Figure 11: SXY in weldment

Figure 12: SXY in parent metal, max. -180 MPa (26.1 ksi)

While stress values begin to level off with increasing pressure. a stress concentration is still present. The nonlinear model shows a plastic zone of less than 50 micrometers length (Figures 7, 8), so the possibility of fatigue crack propagation has been considered, and is discussed in the following section.

4.0 FATIGUE CRACK STUDY

A fatigue crack study has been included to ensure that there will not be a leakage problem in the cold mass connection piping at the weld region. The primary assumption used is that a crack initiated by the stress concentration plastic zone could be modelled as a one-sided crack through the thickness of a narrow axially-loaded plate. This would be similar to a complete circumferential crack at the inner diameter of the sleeve. This model is used because it is conservative in comparison to a partial-thickness crack (one that does not exist along the entire circumference of the sleeve).

The applicable equation for the fatigue crack growth is the following:[4]

$$\Delta K = \Delta S(a)^{0.5}Y,$$

where

ΔK = Stress Intensity Factor Range, MPa-m$^{0.5}$

ΔS = Nominal Stress Range (uncracked), MPa

a = crack length, m

Y = geometry factor, single edge crack in tension

$= 1.99 - 0.41\,(a/width) + 18.7\,(a/width)^2 - 38.48\,(a/width)^3 + 53.85\,(a/width)^4$

width = 2 mm

While the expected worst case would include a maximum stress level of 90 ksi (ultimate stress at room temperature), it may be possible to reach a stress level of 190 ksi (ultimate stress at 4 K temperature), so this case has been considered for the fatigue crack study:

ΔS = ultimate stress at 4 K temperature = 1310 MPa (190 ksi)

Fatigue crack growth rates (da/dN, where a = crack length and N = number of cycles) can be generated from data for ΔK.[5] This crack growth rate is affected by many factors, including cold working, annealing, temperature of operation, irradiation, operation environment, etc. In this study, cryogenic-temperature stress levels were analyzed at room temperature, as this provides for a conservative estimate. Annealed conditions have been applied, and irradiation has been found to have only secondary effects. Table 1 shows the resulting expected cycles to failure. Prestressing has not been considered, which can reduce expected cycles to failure by an additional factor of two in some cases.[4] Thus, as an additional factor of safety, the design lifetime for this fatigue study has been doubled to 300 cycles instead of 150 cycles in choosing a maximum initial crack length for comparison to that indicated by the ANSYS finite element models.

Because of the highly localized nature of the stress concentration indicated by the ANSYS finite element model analysis and the corresponding minimum number of cycles to failure indicated by the fatigue crack study, the possible cracks induced in the piping will not cause a leakage within the design lifetime of the system. Barring defects in manufacturing, assembling, welding, etc., the piping should be able to fully serve its design purpose.

5.0 CONCLUSION AND RECOMMENDATIONS

ANSYS 4.4A+ linear and nonlinear models of the Interconnect Region cold mass connection piping indicate a generally low stress level throughout, with the exception of a highly-localized stress concentration at the interface region between the weld and sleeve at the inner diameter of the sleeve. This stress concentration may induce fatigue cracks through an initial plastic zone of approximately 50 micrometers. A fatigue crack study shows that an initial crack of this length will have a minimum fatigue cycle lifetime of over 1100 cycles, and that a maximum initial crack of 0.15 mm can exist without causing leakage during the design lifetime of 150 cycles.

In order to ensure that cracks of this size do not occur, it is recommended that completed pipe sleeves and flanges be examined, particularly after the welding process has been completed. Also, a piping system test should be done to check for possible loading effects that may not have been considered up to this point.

TABLE 1. MINIMUM CYCLES TO FAILURE.

a (m)	ΔS (MPa)	$a^{0.5}$ ($m^{0.5}$)	Y	ΔK (MPa-$m^{0.5}$)	da/DN (m/cycle)	Min. cycles from level x-1 to x	Minimum cycles to failure
0.00005	1310	0.00707	2.0	18.5	< 1e-7	-	1104
0.00010	1310	0.01000	2.0	26.2	1e-7	500	604
0.00015	1310	0.01225	2.1	33.7	2e-7	250	354
0.0002	1310	0.01414	2.1	38.9	3e-7	167	207
0.0003	1310	0.01732	2.3	52.2	8e-7	125	82
0.0004	1310	0.02000	2.5	65.5	2e-6	50	32
0.0005	1310	0.02236	2.7	79.1	5e-6	20	12
0.0006	1310	0.02449	2.9	93.1	~1e-5	10	2
0.0007	1310	0.02646	3.3	114.4	~1e-4	1	1
0.0008	1310	0.02828	3.7	137.1	Broken	1	0

For an expected lifetime of at least 300 pressure cycles, the maximum allowable crack length would be over 0.15 mm.

6.0 RESULTS

Linear and nonlinear ANSYS finite element models of the Interconnect Region cold mass connection piping have shown that the maximum stresses throughout the piping are an order of magnitude below the yield stress of the material. However, a stress concentration develops at the interface region between the weld and sleeve at the inner diameter of the sleeve. This stress concentration is highly localized, but may induce crack initiation and propagation, with a plastic zone on the order of 50 micrometers. Therefore, a fatigue crack study has been included, which indicates that an initial crack length of this size would have a minimum lifetime of more than 1100 cycles.

In fact, an initial crack of more than 0.15 mm would be required to induce leakage within 300 pressure cycles, twice the true design lifetime of 150 cycles. This 300-cycle lifetime has been considered for this study as an additional factor of safety, since prestressing levels have not been included in the study, but may sometimes cause the fatigue lifetime to be halved.

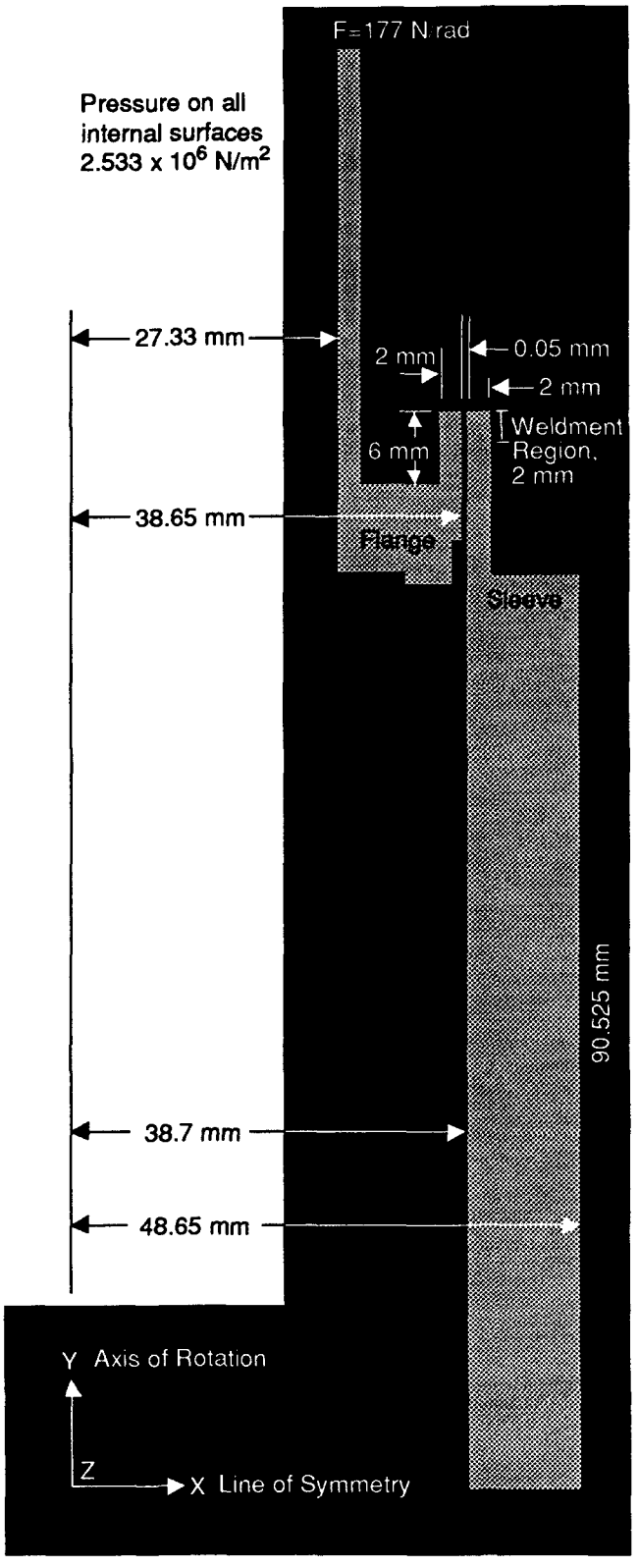
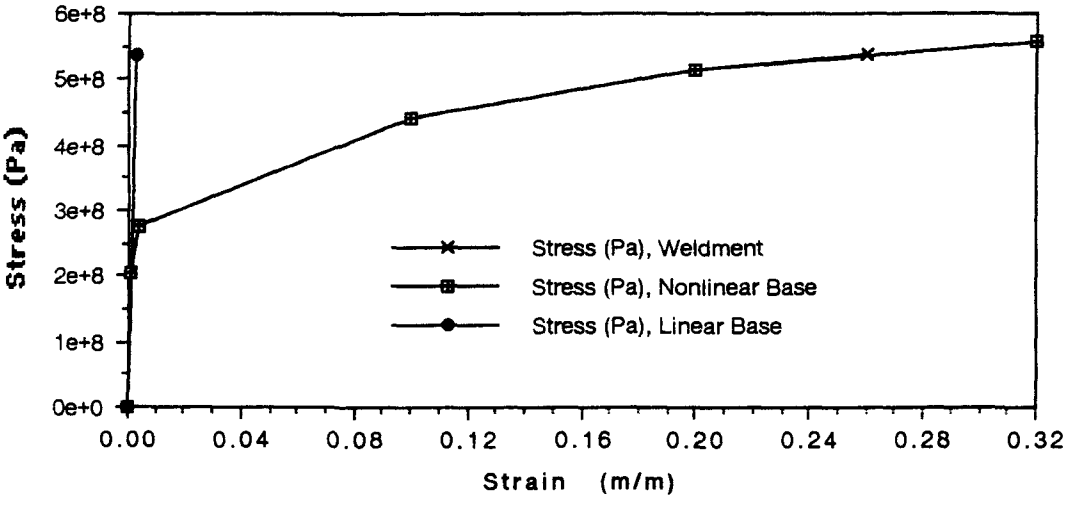


Figure 1. Model Parameters and Loading Conditions.



$E_{linear} = 1.9306 \times 10^{11}$ N/m^2 (28×10^6 psi)
$\nu = 0.3$
σ_{yld} at 300 K (0.2% strain) = 276 MPa (40 ksi)
σ_{ult} at 300 K = 621 MPa (90 ksi)
σ_{ult} at 4 K = 1310 MPa (190 ksi)

Figure 2. Material Properties for Finite Element Models.

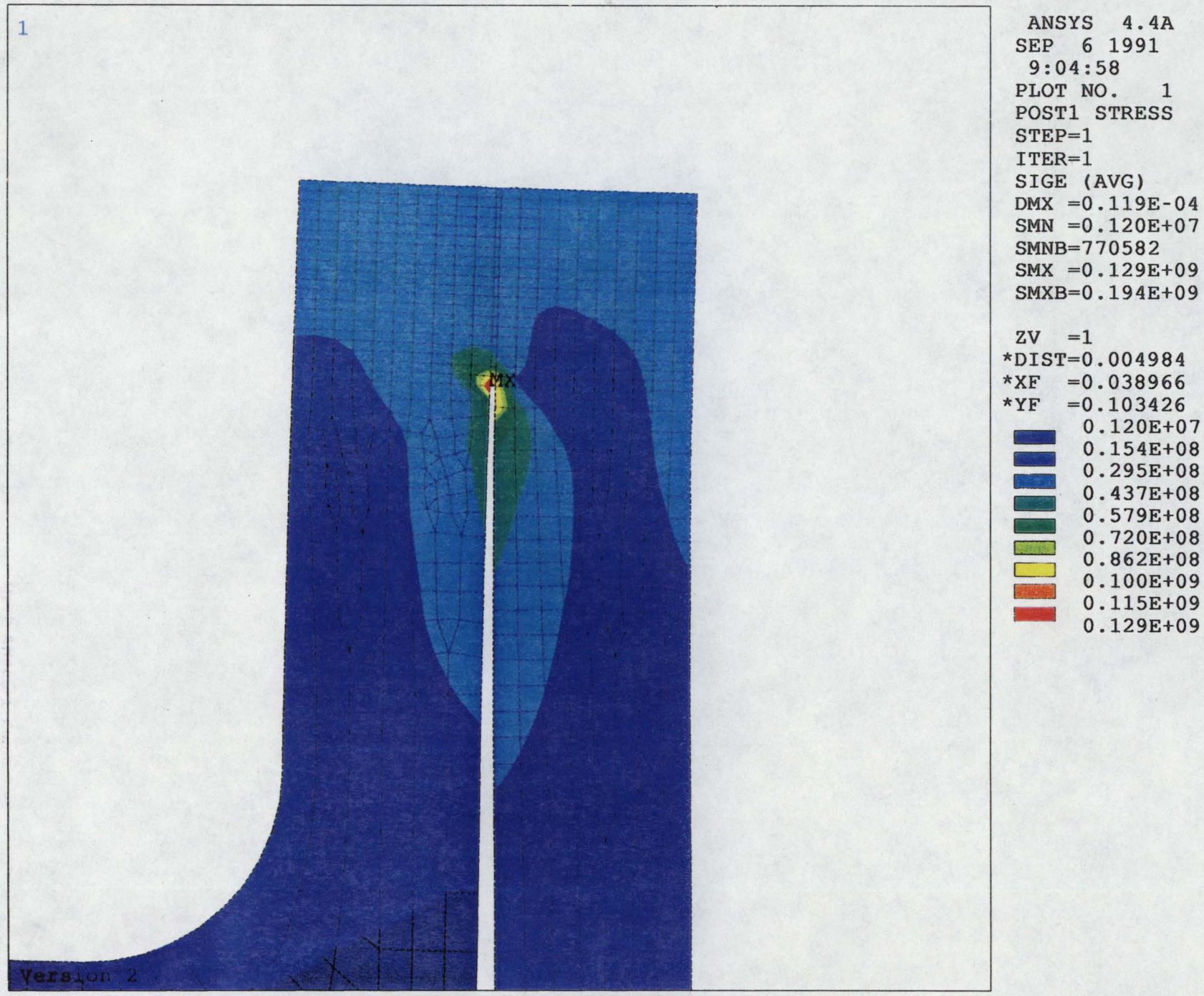


Figure 3. Stress Concentration at Heat Affected Zone.

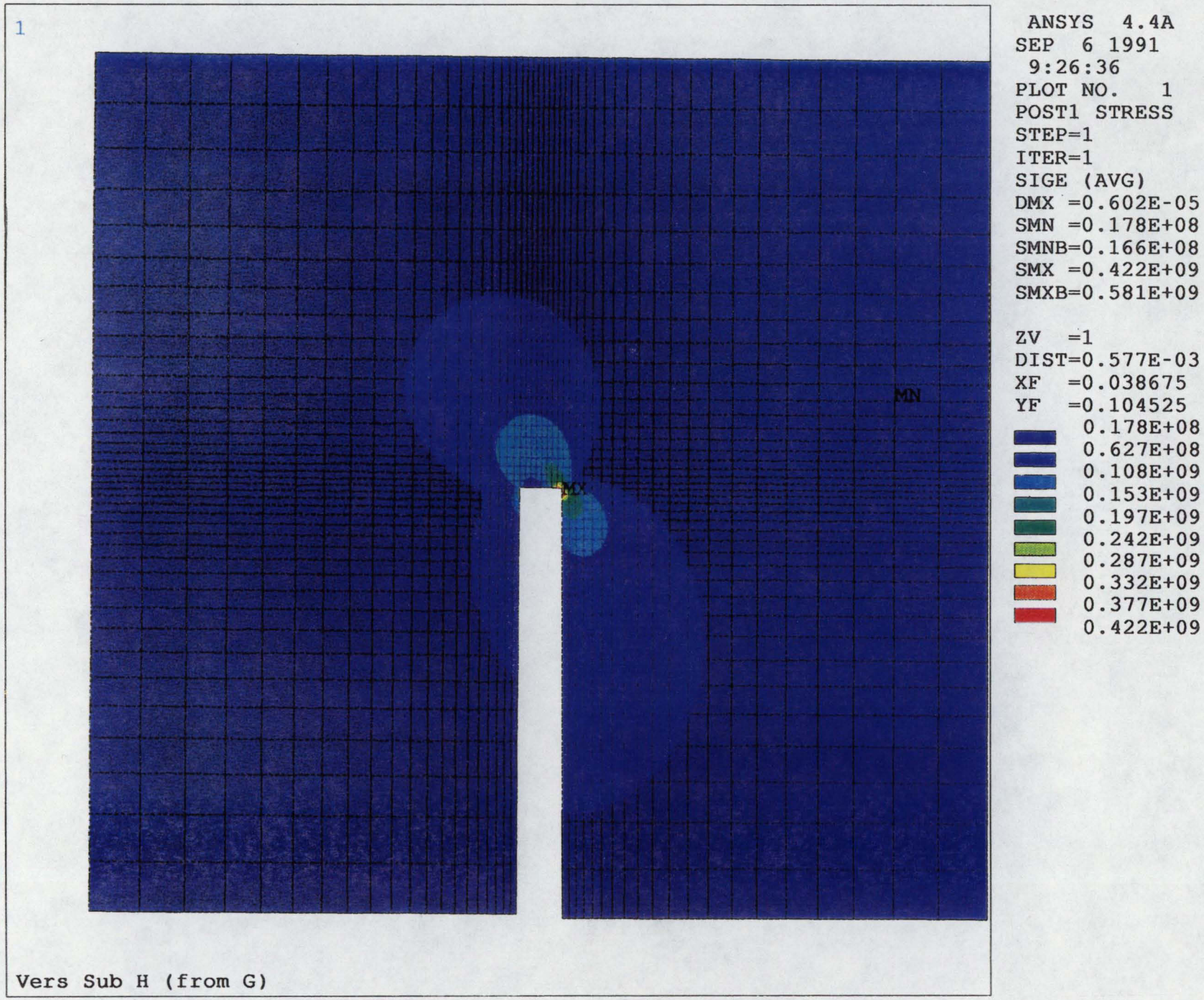


Figure 4. Typical Linear Submodel Analysis Result.

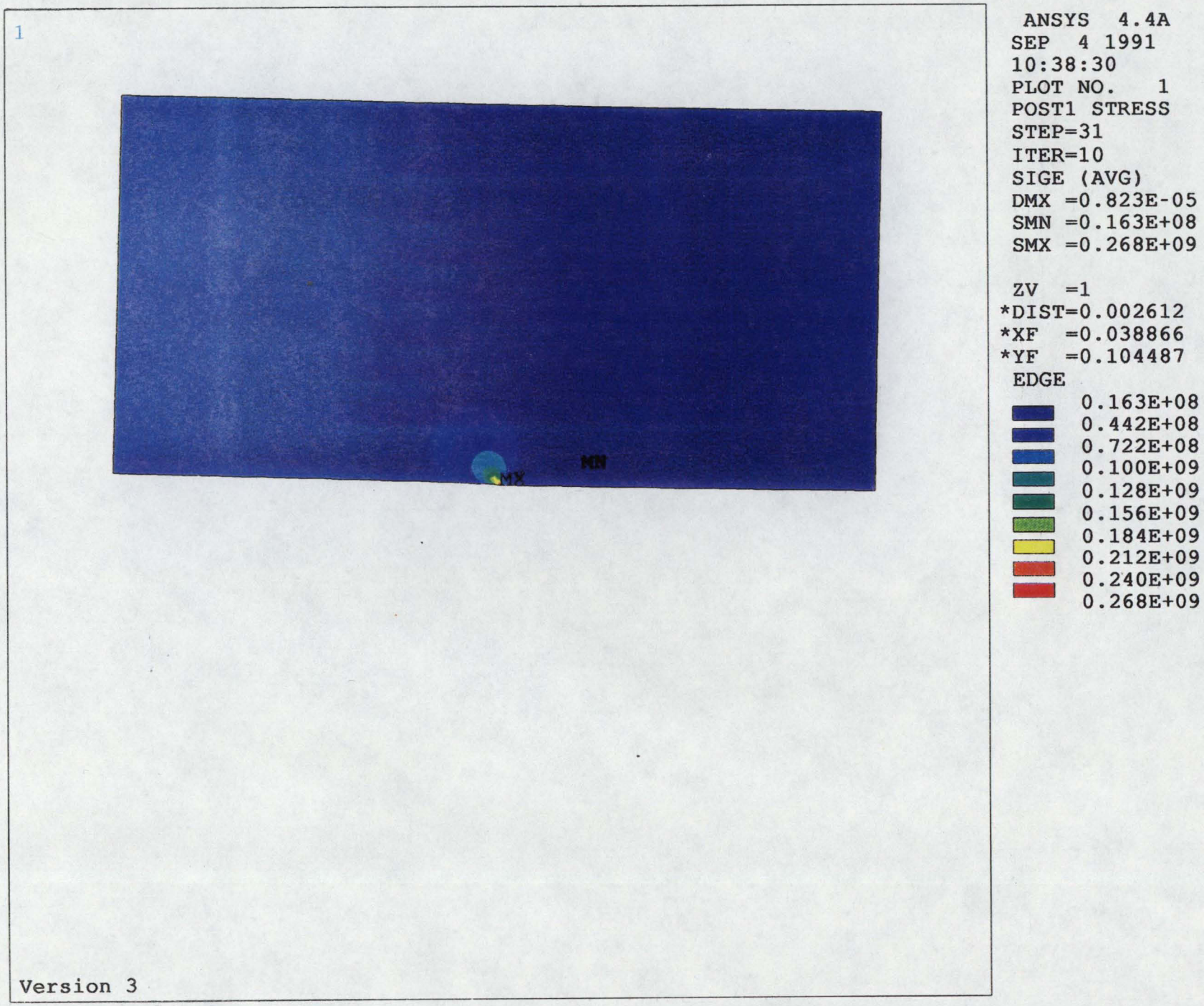


Figure 5. Nonlinear Model SIGE Stress Concentration—Weldment.

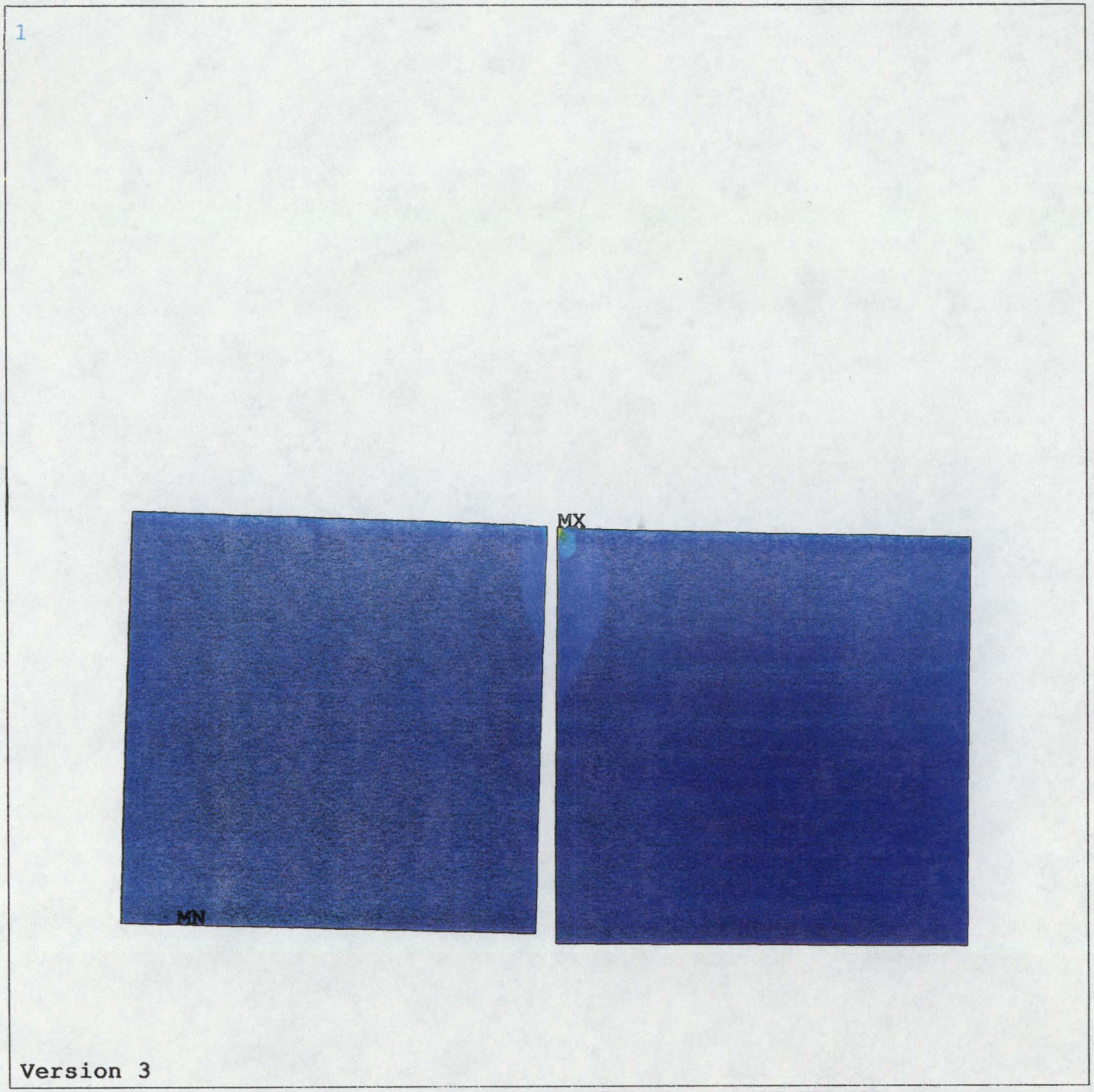


Figure 6. Nonlinear SIGE Stress Concentration—Flange & Sleeve.

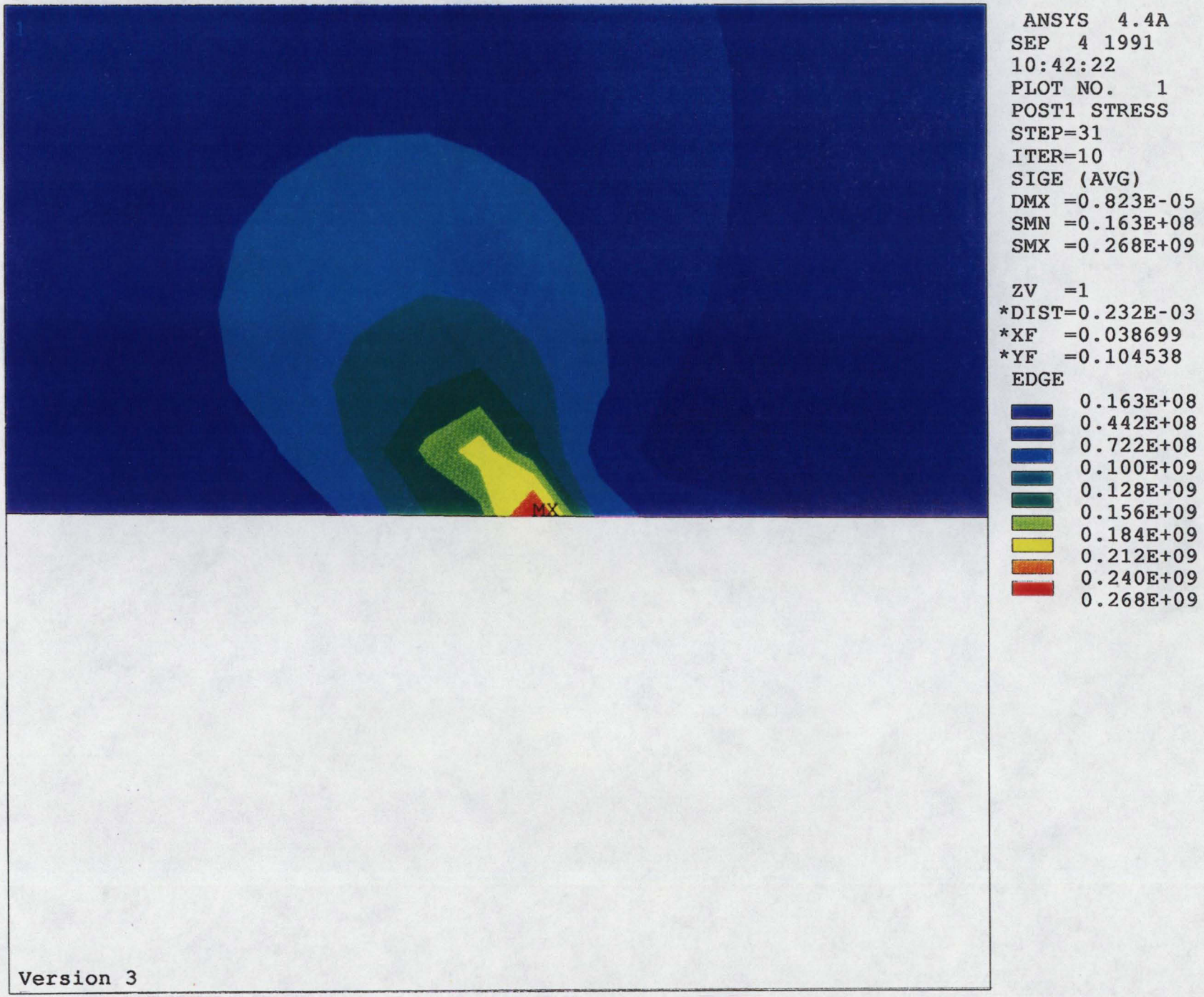


Figure 7. Closeup—Weldment.

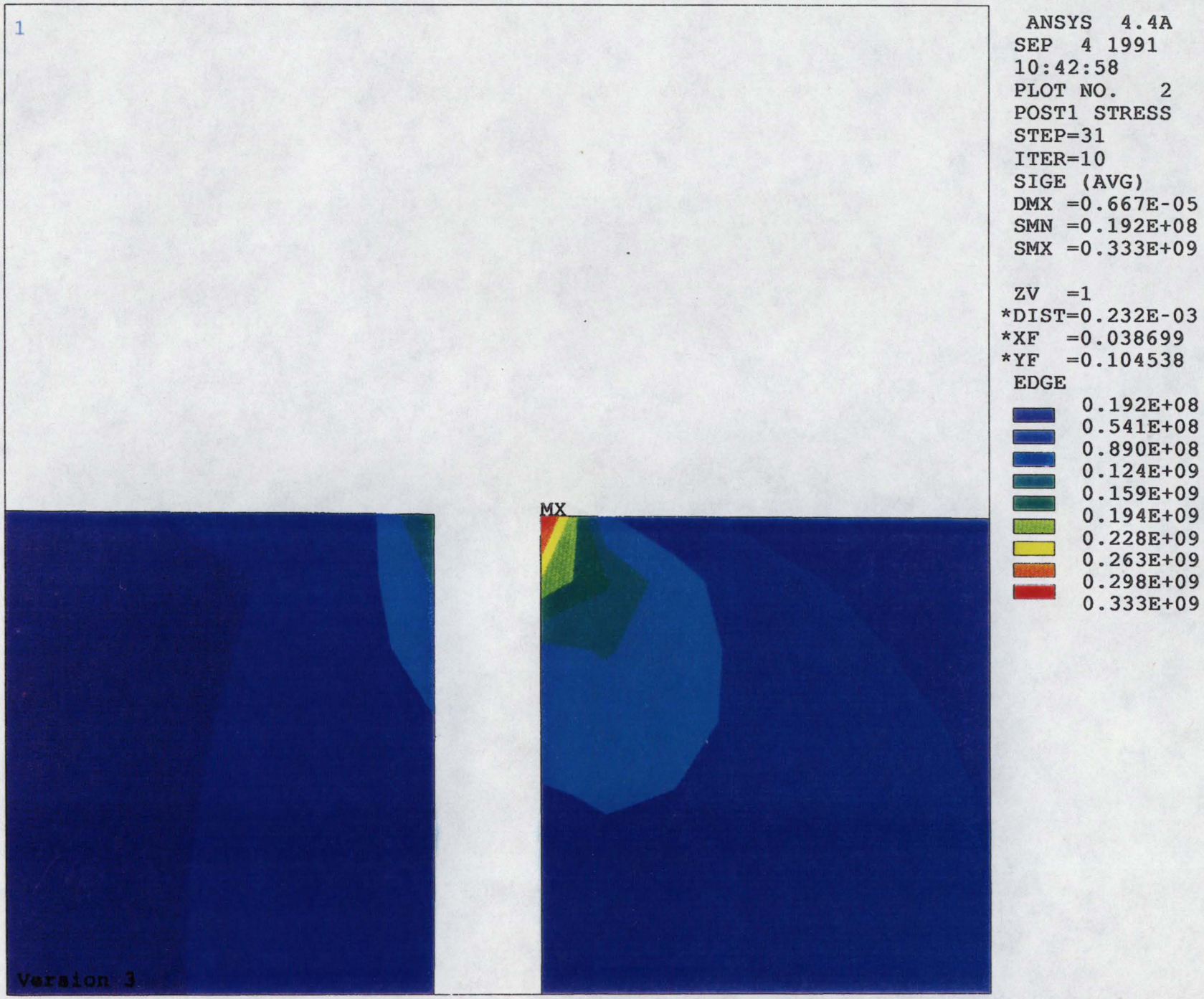


Figure 8. Closeup—Flange & Sleeve.

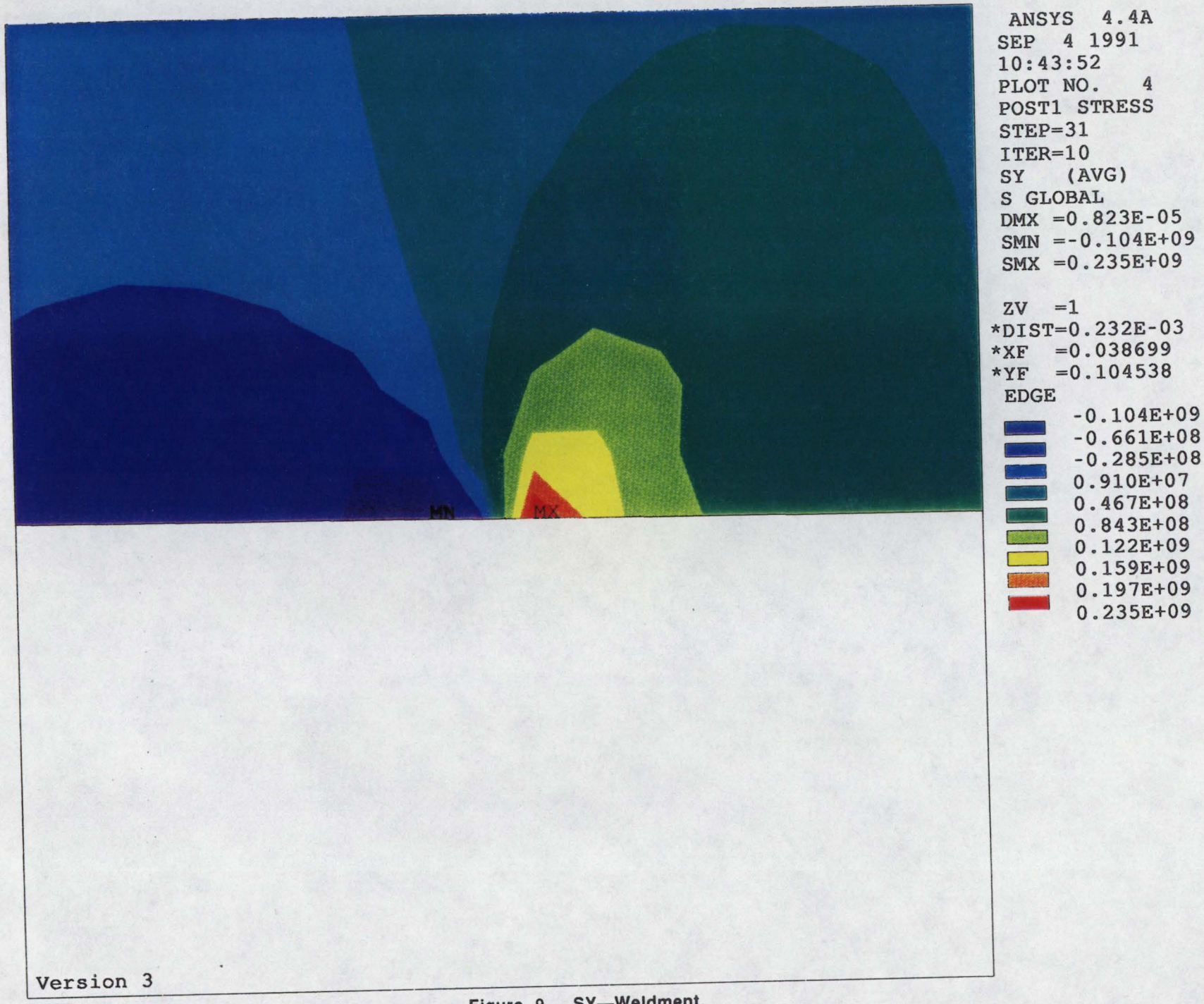


Figure 9. SY—Weldment.

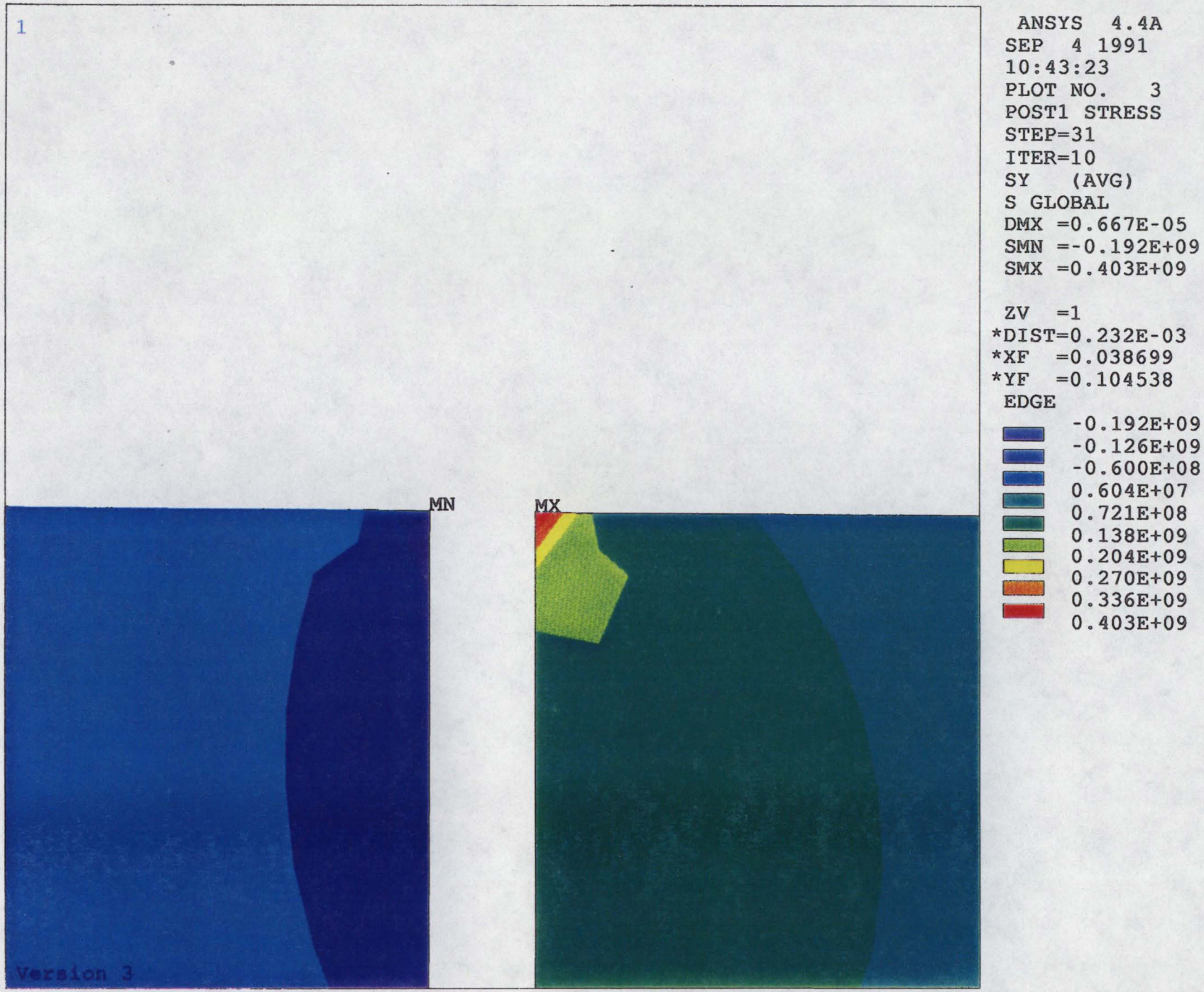


Figure 10. SY—Flange & Sleeve.

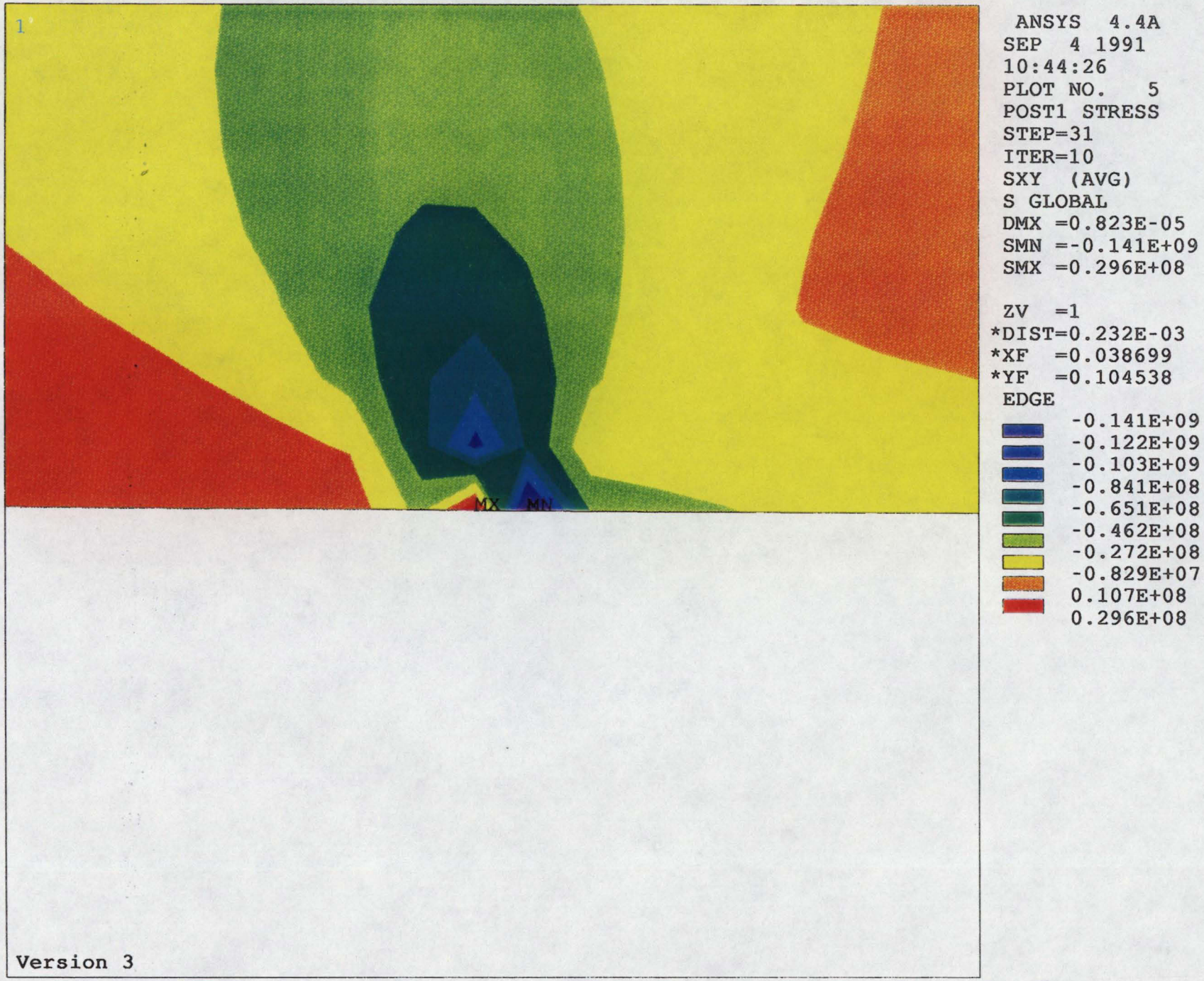


Figure 11. SXY—Weldment.

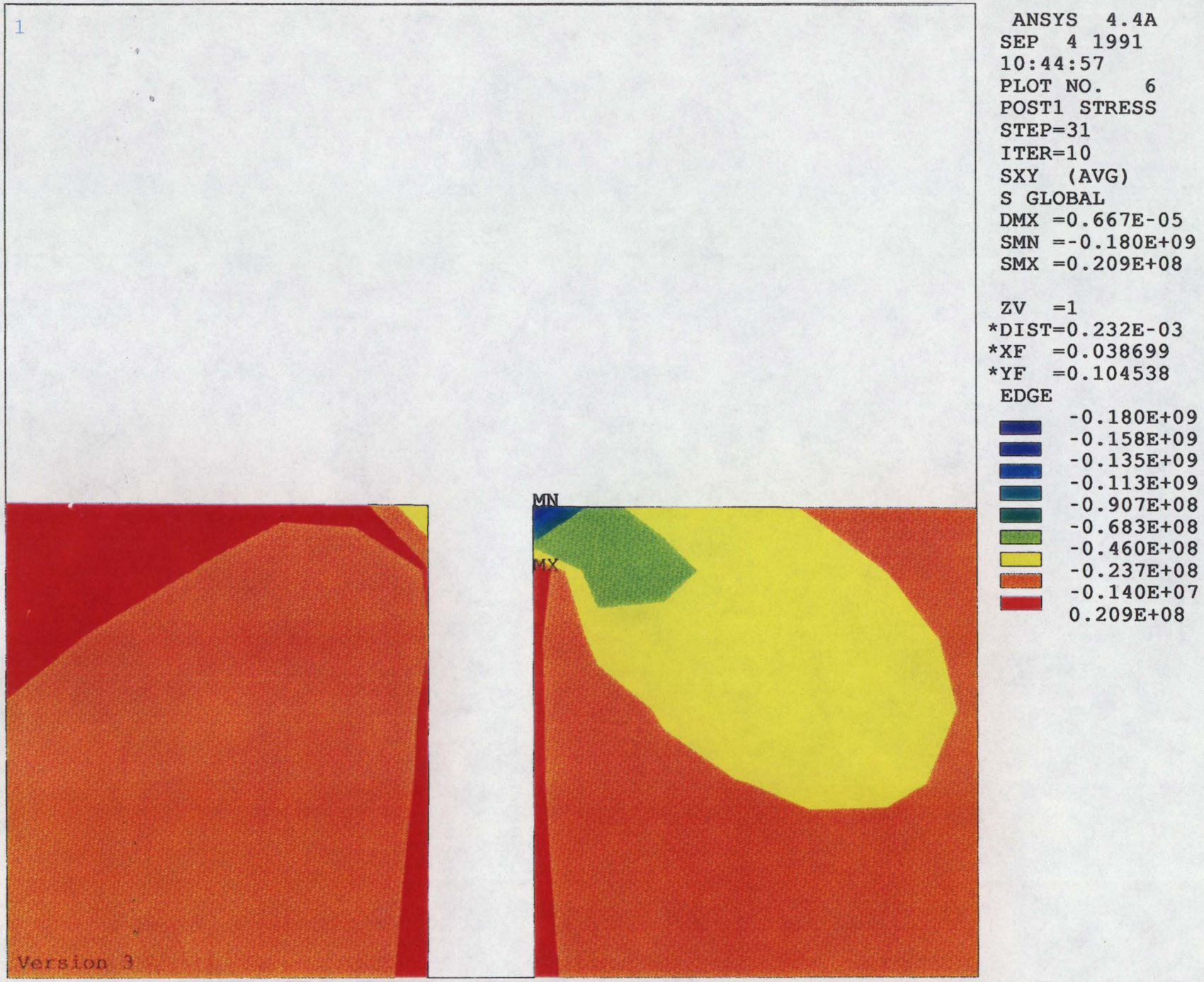


Figure 12. SXY—Flange & Sleeve.

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