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Analysis of Stress Concentration in the Dutton Groove Regions of the Super Lightweight External Tank

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ANALYSIS OF STRESS CONCENTRATION IN THE DUTTON GROOVE REGIONS OF THE SUPER LIGHTWEIGHT EXTERNAL TANK

INTRODUCTION

To enable the space shuttle to reach the space station high-inclination orbits with adequate payload, an effort was made in the early 1990's to reduce the weight of the space shuttle external tank (ET) and/or the solid rocket boosters (SRB's). This culminated in the design of the super lightweight ET (SLWT ET), which will reduce ET weight by at least 8,000 lb. To accomplish this, NASA and Martin Marietta (the prime contractor for the ET) proposed replacing most of the 2219 aluminum used in the current ET with the lighter, stiffer, and stronger 2195 aluminum-lithium (Al-Li) alloy. Design changes were also proposed to take advantage of the increased strength and modulus of the new alloy over 2219. These included using a new weight-saving orthogrid stiffener design in the liquid hydrogen (LH_2) tank barrel sections to provide resistance to the compressive line loads encountered during flight.

This report deals with how analysts reduced stress concentration at the SLWT ET LH_2 tank Dutton groove regions, which are 0.08-in deep grooves machined into the outer skin surface at locations near the weld lands, under the internal proof pressure of 37.8 lb/in^2.

BACKGROUND

In the design of a space vehicle such as the ET, particular attention must be paid to areas of stress concentration. These include holes, weld lands, inserts, fillets, welds, and other areas that tend to create load and stiffness gradients. Such locations have local areas of much higher stress than would be found or expected in larger, more uniform sections. For instance, the maximum stresses around a hole under uniform tension (assuming linear elasticity) are three times the nominal far-field stress, and local plastic yielding will occur wherever the hole stress is greater than or equal to the yield stress. Loads of this magnitude tend to be redistributed to regions farther away from the hole as a result of the plastic behavior of the material, thus relieving the stress and preventing failure as long as the stress and strain of the highest loaded position in the body remain below the ultimate point. In order to accomplish this stress redistribution effectively, the material must have a sufficient area under the plastic regime of the stress-strain curve. This area is governed both by the material's ultimate strain capability and the difference between the ultimate and yield strengths (henceforth referred to as the yield-ultimate delta).

During preliminary design of the SLWT ET, the 2195 Al-Li alloy showed a lower yield-ultimate delta than the 2219 alloy used previously (3 to 5 ksi for 2195 versus 13 ksi for 2219). As a result, ET designers and analysts became concerned that 2195 would not redistribute the load around stress concentrations adequately enough to prevent failure at proof pressure. To examine this behavior more closely, elastic-plastic structural analyses of typical stress concentration configurations were made. Among these were the fillets and notches in and around the Dutton grooves of the ET LH_2 tank barrels, described in more detail later. Since the 2195 material supplier would not guarantee a minimum ultimate strain of greater than 4 percent, ET engineers performed structural analyses to find any areas where strain might approach or exceed 2 percent, for a safety factor of 2 on strain.

In addition to the stress concentration issue, there were concerns over excessive stresses at the weld lands (and hence, the welds) at the edges of each barrel panel. An effort to reduce these weld land stresses to the lowest possible level was also initiated simultaneously with the effort to reduce the stress concentrations.

STRUCTURE DESCRIPTION

General Description of the SLWT ET

The SLWT ET is, as of this writing, the latest generation design for the ET component of the Space Transportation System (STS). The other major elements of the STS are the space shuttle orbiter and the two SRB's. The purposes of the ET are to provide structural continuity between the orbiter and its SRB's and to contain the large quantities of LH_2 and oxygen required by the orbiter's space shuttle main engines (SSME's). Each ET is about 153.8-ft long and about 27.6-ft in diameter. The empty weight of the SLWT ET was not finalized at the time of this writing, but is in the range of 57,000 to 59,000 lb (fig. 1).

The ET consists of three major structural components: the liquid oxygen (lox) tank, the intertank, and the LH_2 tank. As its name implies, the purpose of the intertank is to provide structural continuity between the lox and LH_2 tanks. The lightweight (LWT) version of this tank, which preceded the SLWT ET, was constructed primarily of 2219 aluminum alloy in the lox and LH_2 tanks, while the intertank was made of 2024 and 7075 aluminum alloys. The major differences between the SLWT ET and the previous LWT ET design are as follows:

(1) Substitution of 2195 Al-Li for 2219 aluminum alloy in most structural components of the lox and LH_2 tanks

(2) Substitution of 2090 Al-Li for 2024 and 7075 aluminum alloys in most components of the intertank

(3) Design changes throughout the entire ET structure to take advantage of increased stiffness and strength properties of Al-Li alloys, a major portion of which is the use in the LH_2 tank of machined and contour-formed orthogrid panels instead of the previous skin-stringer construction.

Description of SLWT ET LH_2 Tank Barrels

Since this work was concerned with stress concentration in the LH_2 tank, the LH_2 barrel panel design will be described next. The four LH_2 barrel sections were each constructed from eight machined, curved panels welded together. The four barrels were then welded together to construct a whole LH_2 barrel of 27.6-ft diameter, which, in turn, was welded to the forward and aft domes to create the completed tank. Each orthogrid panel was machined from 1.75-in thick 2195 Al-Li plate stock and contour formed to an outer skin length of about 130-in and an arc of 45° (fig. 2).

Initial LH_2 Barrel Panel Design

The orthogrid configuration of a typical barrel panel is illustrated in figure 3. Two pocket configurations were primarily used on the LH_2 tank; type 1, with a circumferential stiffener pitch of 10.832-in and a skin thickness of 0.094-in, was used for lighter compressively loaded areas; while type 2, with a circumferential stiffener pitch of 5.416-in and a skin thickness of 0.087-in, was used for regions under higher compressive loads. These are illustrated in figure 4. Type 1 and type 2 pockets were combined in some panels and separated in others depending on the circumferential location and loading. At each circumferential end of the panel was a weld land of 0.32-in maximum thickness, which reduced down to the panel's minimum skin membrane thickness in several steps as one moved along the panel circumference. The weld land region transitioned into the orthogrid region, via several steps in thickness. In addition to the circumferential weld lands, the orthogrid region was similarly bounded by 0.32-in thick axial weld lands.

An 0.08-in deep and approximately 3-in long groove was cut in the axial direction along each axial weld land (the land whose thickness normal is in the circumferential direction of the tank) in each 45° panel to relieve hoop bending stresses in the weld land. This was known as the Dutton groove and is shown in figure 5. The length of this groove along the hoop direction was approximately 3-in initially, but was later amended in a design change to reduce stress concentration without increasing weight. Note that, in all of the initial designs, the weld lands are not symmetric about their centerlines.

The region around each orthogrid stiffener initially consisted of a 0.31-in radius fillet transitioning directly to the uniform skin thickness called for at the stiffener's particular location. Most stiffeners had identical skin thicknesses on either side, but some stiffeners nearer to the weld lands had differing thicknesses on either side. This was true for both circumferential and axial stiffeners.

Modified LH_2 Barrel Panel Design

After the initial panel analysis was completed, NASA and Martin Marietta analysts devised some changes to the initial configurations. The purpose for this was twofold:

(1) To reduce stress and strain concentration at the fillet regions near the weld land stiffener

(2) To reduce bending at the weld land by making the weld land symmetric about its centerline.

To accomplish this without increasing weight, the Dutton groove on the outboard (outer skin) side of the panel was extended about 0.33 in (thus removing material), and the interior skin thickness immediately adjacent to the adjacent stiffener (on the side opposite from the Dutton groove) was increased about 0.025 in for a length of approximately 0.8 in. In addition to these, the weld land itself was made completely symmetric about its centerline. All other geometry details remained essentially the same (fig. 6).

ANALYSIS

All models created during these analyses were made using the PATRAN preprocessing program coupled with solution phase and postprocessing using the ANSYS general-purpose finite element code. The models utilized the four-node ANSYS two-dimensional axisymmetric PLANE42 element with large deflection, stress stiffening, and nonlinear material properties (plasticity). All models were analyzed at the proof test loading of 37.8 lb/in^2 internal gauge pressure.

The analyses were performed using the following models:

(1) An approximately 9° slice of an initial 0.087-in skin thickness SLWT ET LH_2 tank barrel panel, modeling a type 2 pocket configuration (fig. 7)

(2) An approximately 9° slice of an initial 0.087-in skin thickness SLWT ET LH_2 tank barrel panel modified by Martin Marietta to reduce strain at critical areas around the stiffener adjacent to the weld land, modeling a type 2 pocket configuration (fig. 8)

(3) An approximately 15° slice of a 0.094-in skin thickness SLWT ET LH_2 tank barrel panel, modeling a type 1 pocket configuration (fig. 9)

(4) An approximately 15° slice of a 0.094-in skin thickness SLWT ET LH_2 tank barrel panel modified by Martin Marietta to reduce strain at critical areas around the stiffener adjacent to the weld land, modeling a type 1 pocket configuration (fig. 10).

The material properties used in the models are shown in figure 11, which displays the 2195 stress-strain curve versus that for 2219.

RESULTS

Color plots of hoop stresses at the weld land along with hoop stresses, von Mises equivalent stresses, and hoop strains at the stiffener region adjacent to the weld land are shown in figures 12 through 27. A summary of the results is shown in table 1.

Table 1. Summary of results of SLWT ET panels with Dutton grooves.

Panel ID	Internal Pressure (lb/in^2)	Maximum Von Mises Stress at Weld Land Stiffener (ksi)	Maximum Hoop Strain at Weld Land Stiffener (in/in)	Maximum Hoop Stress at Weld Land (ksi)
0.087-in thick skin, initial	37.8	76	1.83%	21.84
0.094-in thick skin, initial	37.8	74.77	1.90%	22.51
0.087-in thick skin, modified	37.8	74.68	1.11%	20.06
0.094-in thick skin, modified	37.8	74.04	1.13%	19.93

DISCUSSION

As expected, all models exhibited high-stress areas at the fillet areas. These included the fillet between the weld land stiffener and the skin membrane as well as the transition between the outer skin at the stiffener and the Dutton groove. A summary of the initial configurations versus the final configurations is shown in table 1. The modifications reduced the highest strain levels (and the highest stress levels) by approximately 40 percent, from 1.9 to 1.13 percent. Since the 2195 material available at the time only had a guaranteed minimum ultimate strain capability of 4 percent, this was a significant reduction in the strain levels encountered at proof pressure loading. Also diminished was the possibility of cracks that could cause problems in flight from forming or growing at the high stress/strain areas.

In addition to stress concentrations, another area of concern was the stress level in the weld land itself. Significant bending occurred in the initial barrel panel designs due to the skin resultant forces and weld land resultant forces being offset from each other. This was alleviated by making the weld land symmetric about its axis and reduced the maximum stress at the weld land by about 8 percent for the 0.087-in skin panel and by about 11.5 percent in the 0.094-in skin panel.

CONCLUSIONS

This effort showed that, in this case, it was possible to deal with stress concentrations in regions with reduced material properties through nonlinear plastic finite element analysis. In the same effort, it was also possible to correct a design problem that created excessive stresses in the weld land under proof pressure. All this was accomplished without increasing the weight of the structure. Initial Martin Marietta tests using geometries identical to those modeled showed close correlation between the analysis and empirical test data. The test effort was still being conducted at the time of this writing and thus could not be described in detail.

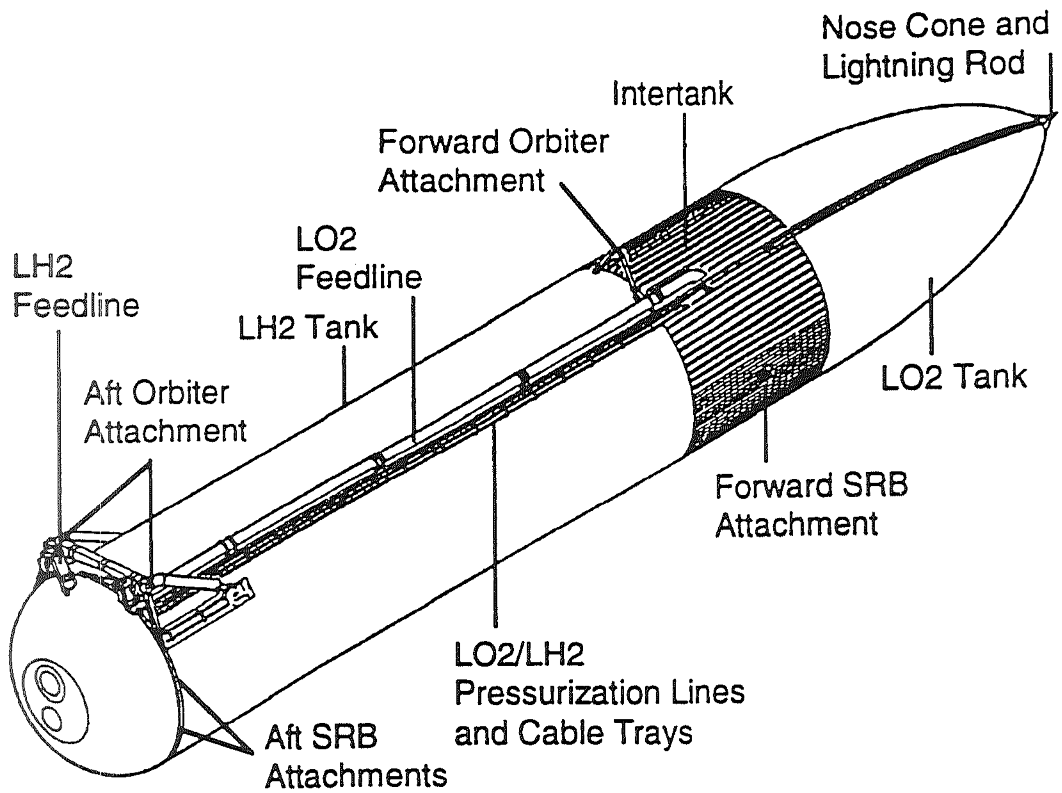

Figure 1. Configuration of SLWT ET.

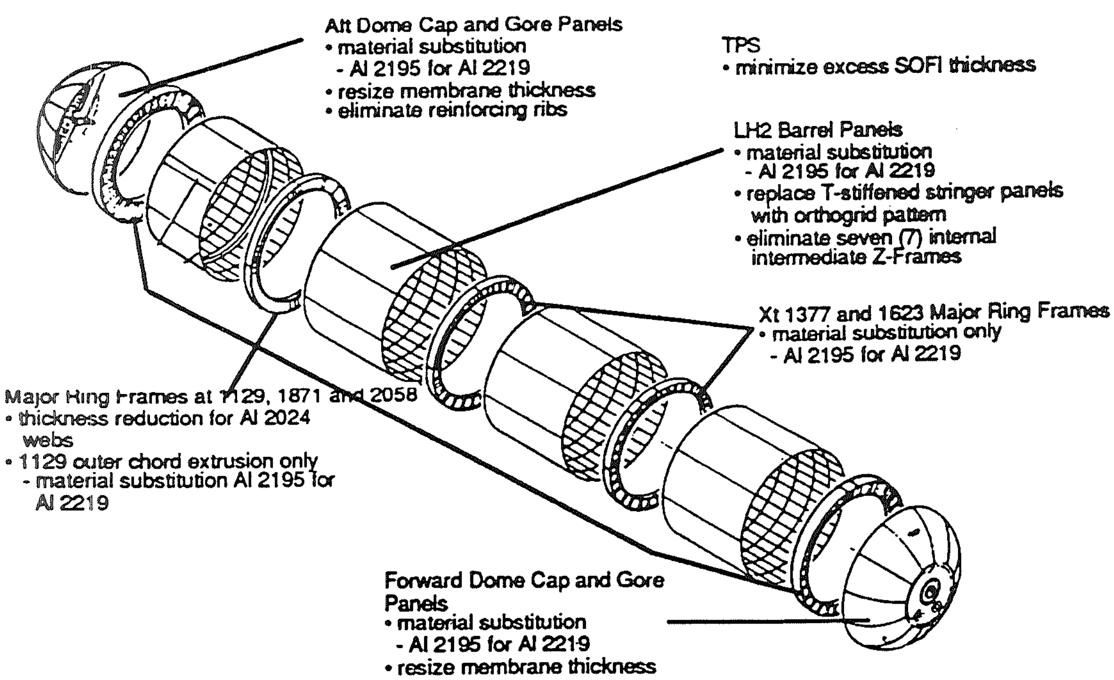

Figure 2. Configuration of SLWT ET LH_2 tank with differences from previous ET.

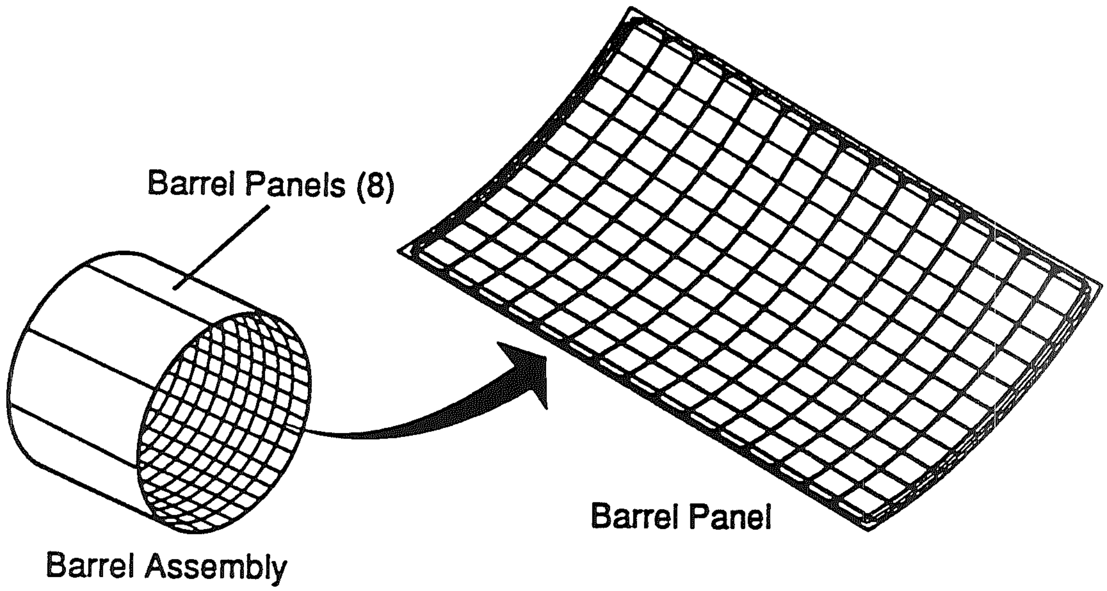

Figure 3. Configuration of LH_2 tank barrel panel.

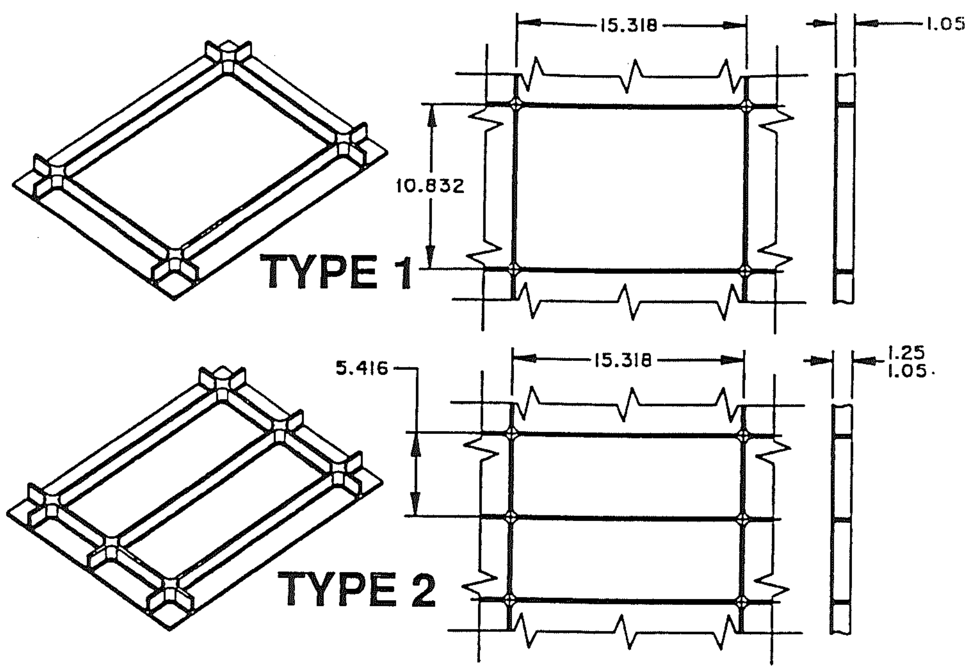

Figure 4. LH_2 barrel panel orthogrid pockets.

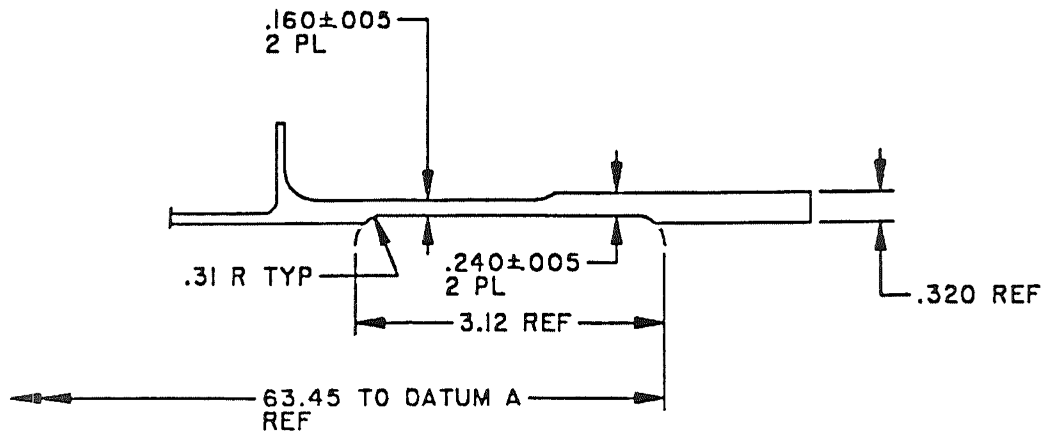

Figure 5. LH_2 barrel panel initial weld land region configuration (axial direction perpendicular to plane of paper).

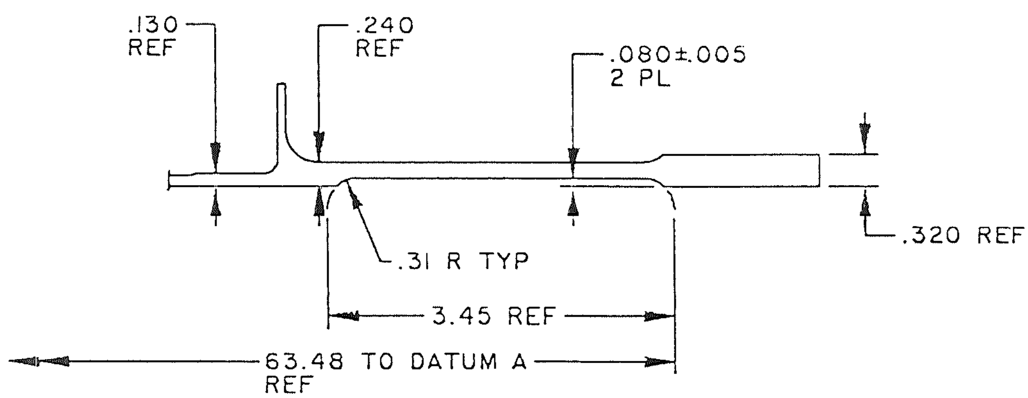

Figure 6. LH_2 barrel modified weld land region configuration (axial direction perpendicular to plane of paper).

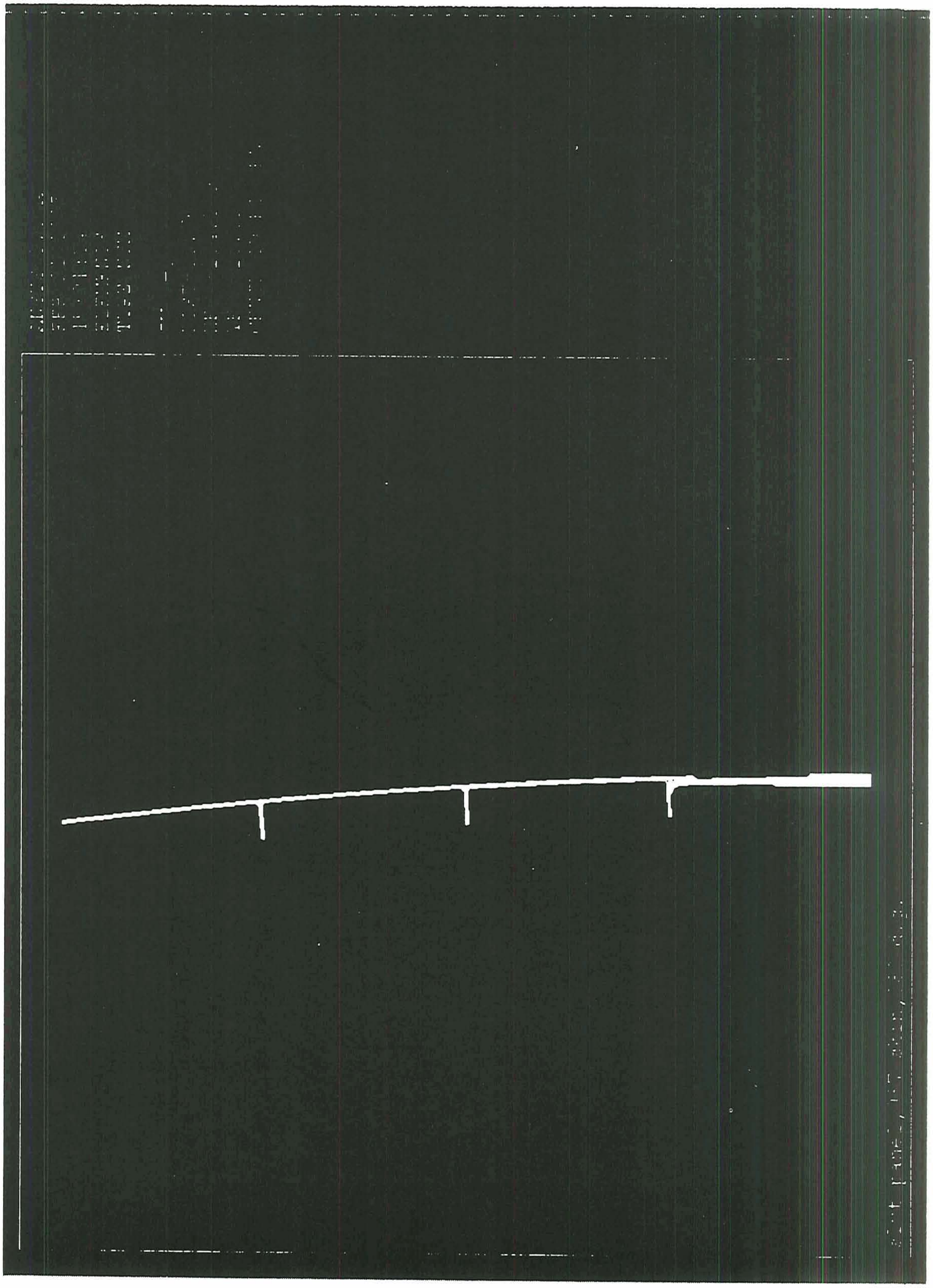

Figure 7. Model of initial SLWT panel with 0.087-in skin, type 2 pocket.

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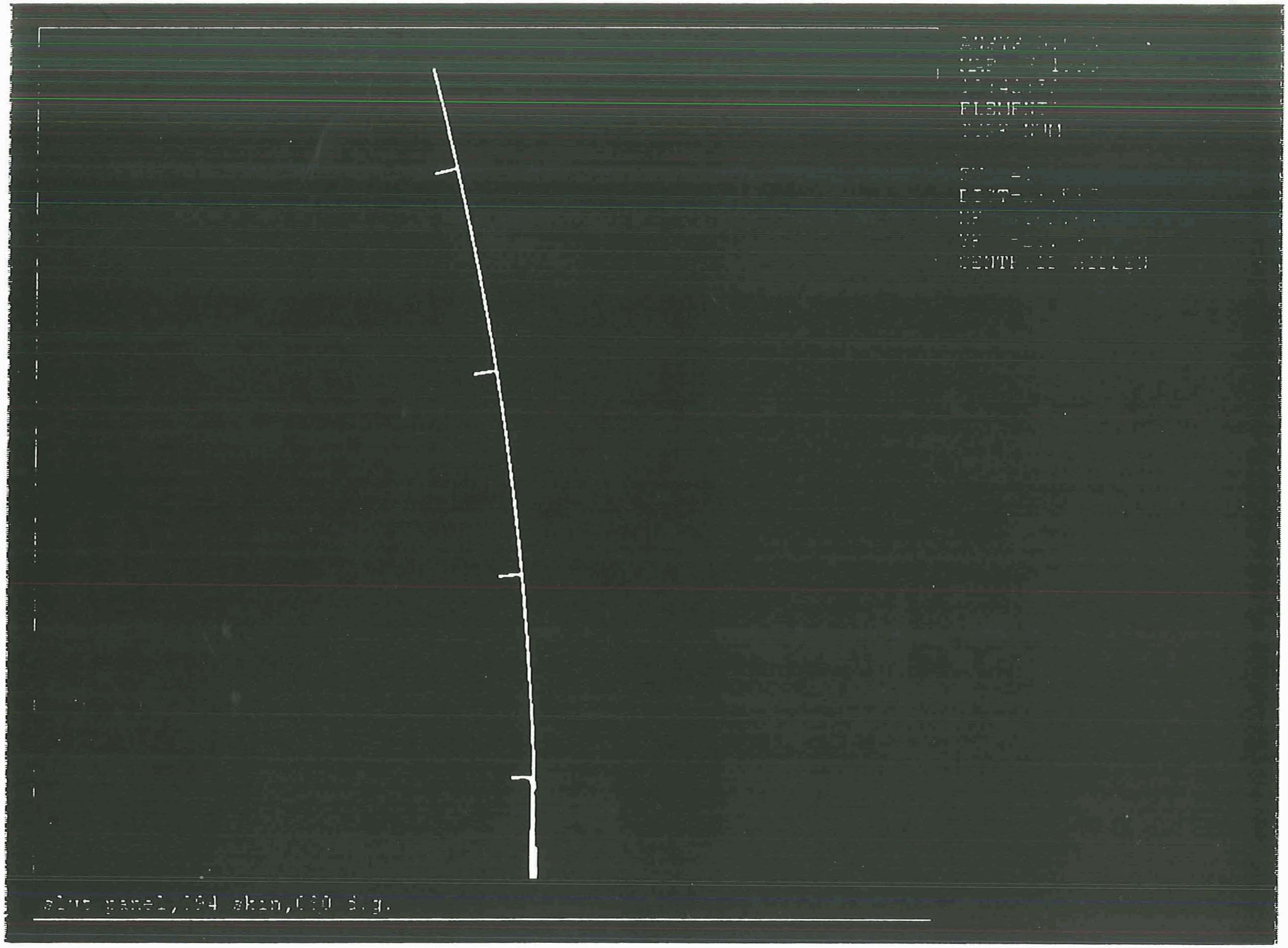

Figure 8. Model of initial SLWT panel with 0.094-in skin, type 1 pocket.

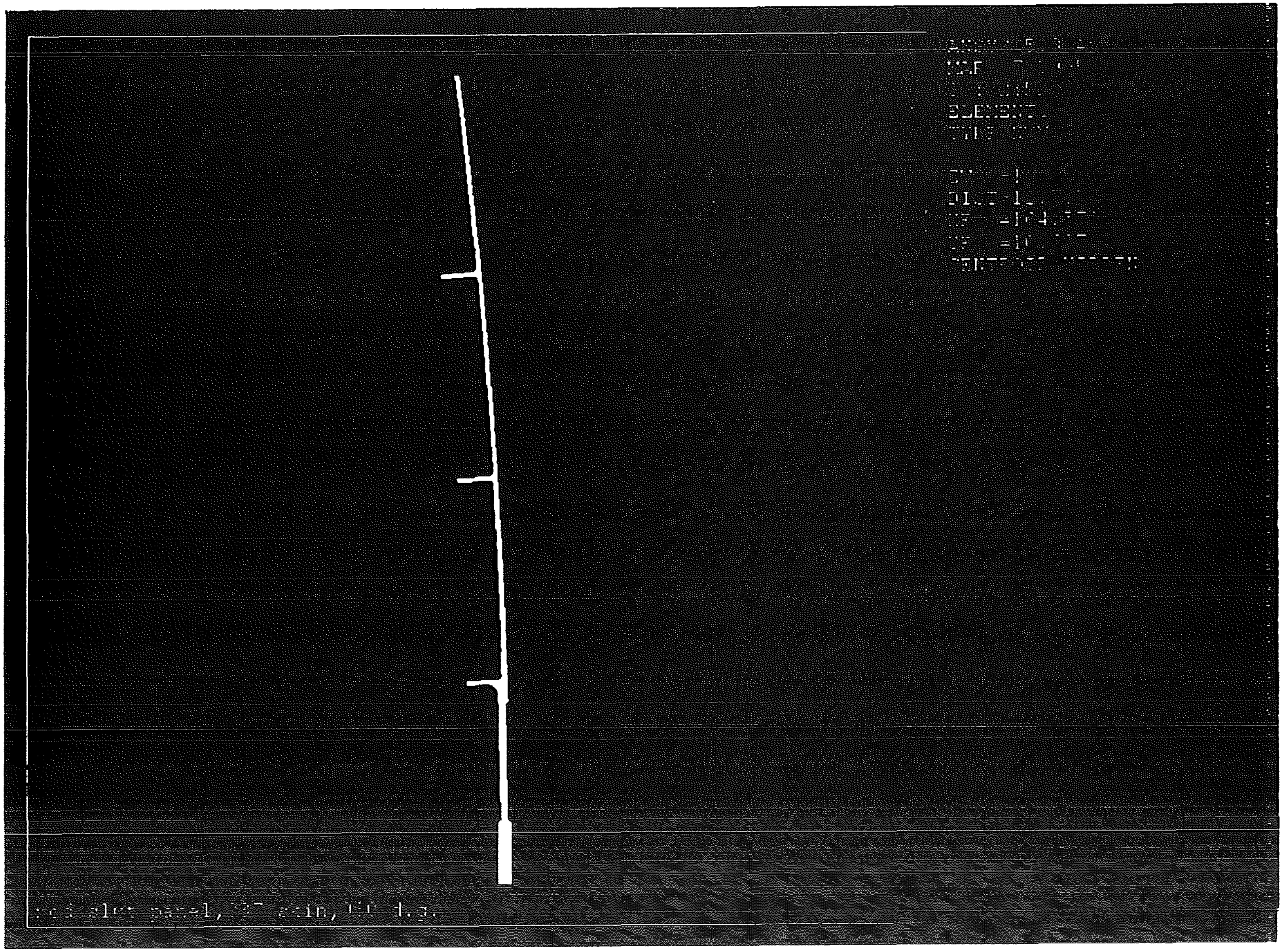

Figure 9. Model of modified SLWT panel with 0.087-in skin, type 2 pocket.

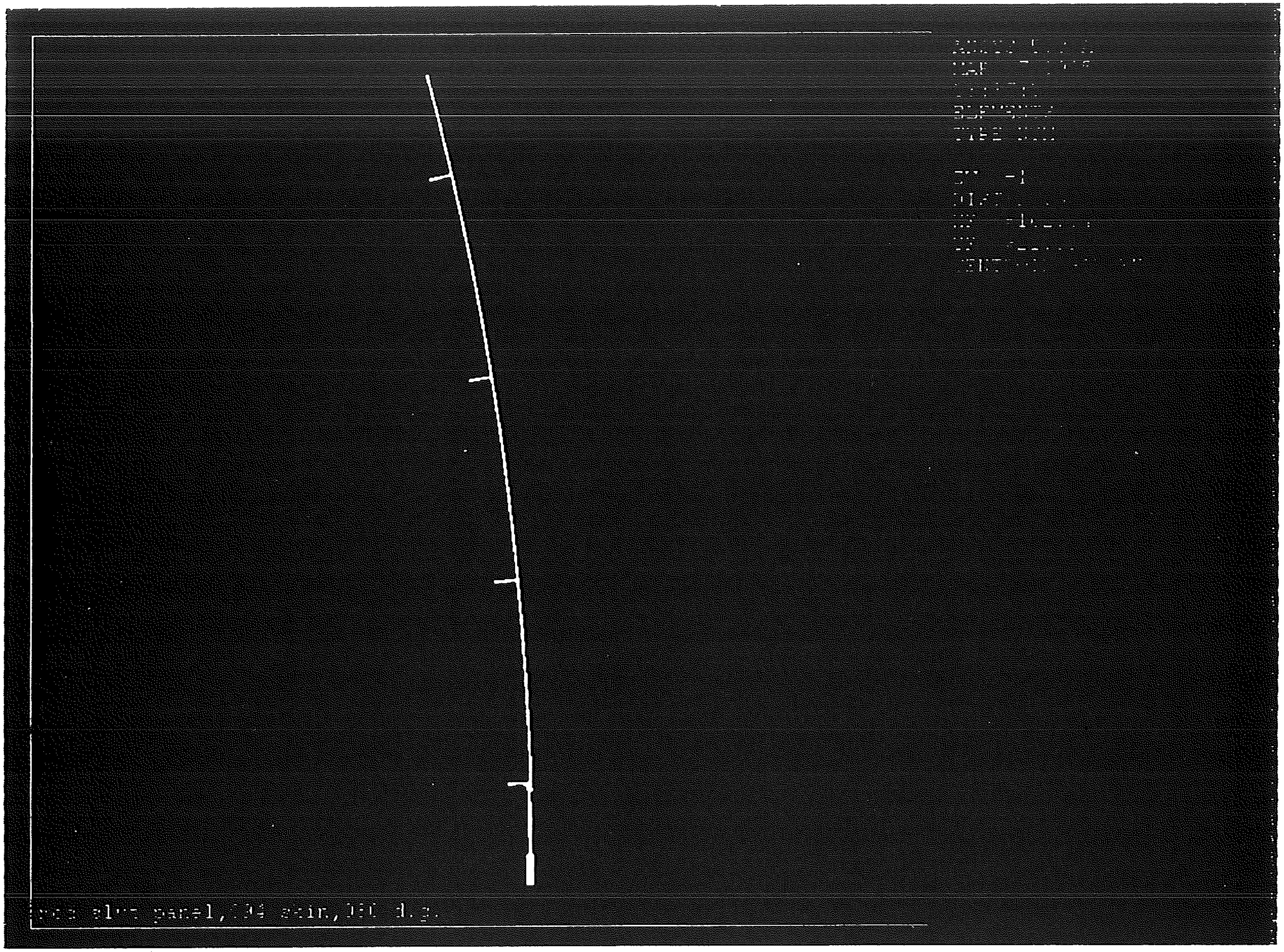

Figure 10. Model of modified SLWT panel with 0.094-in skin, type 1 pocket.

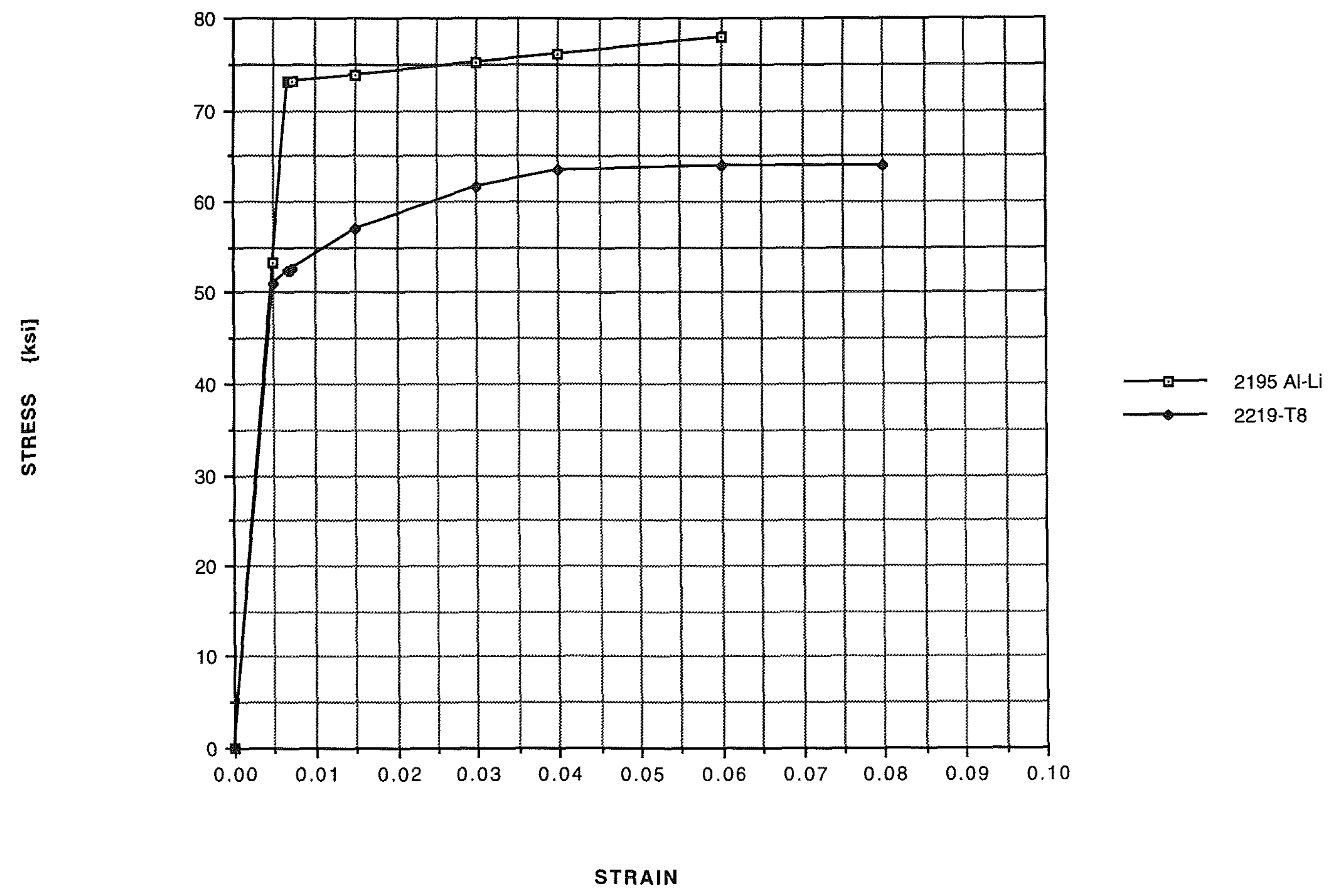

Figure 11. Stress-strain curves for 2195 Al-Li and 2219 Al.

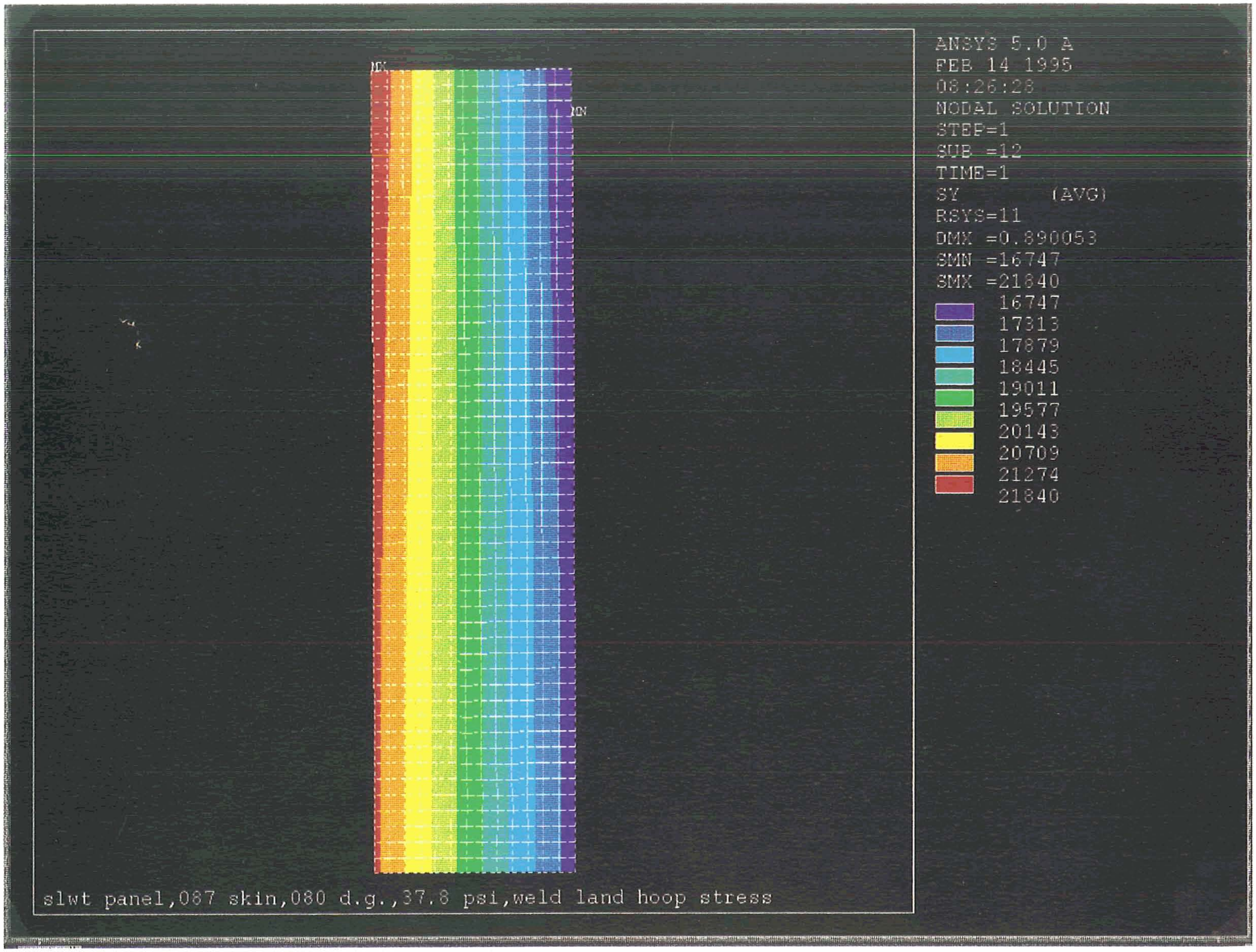

Figure 12. Hoop stress at weld land for initial SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

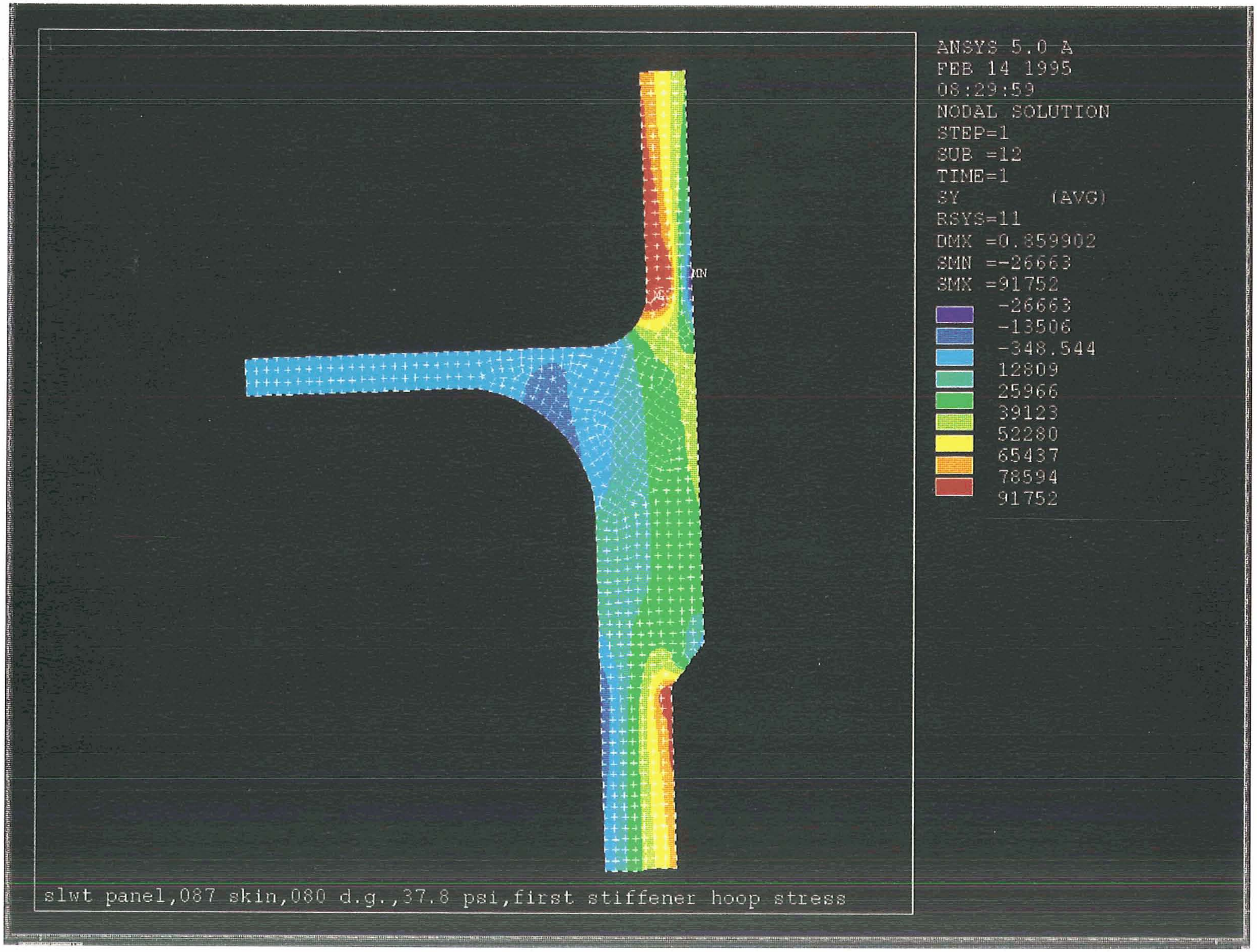

Figure 13. Hoop stress at weld land adjacent stiffener for initial SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

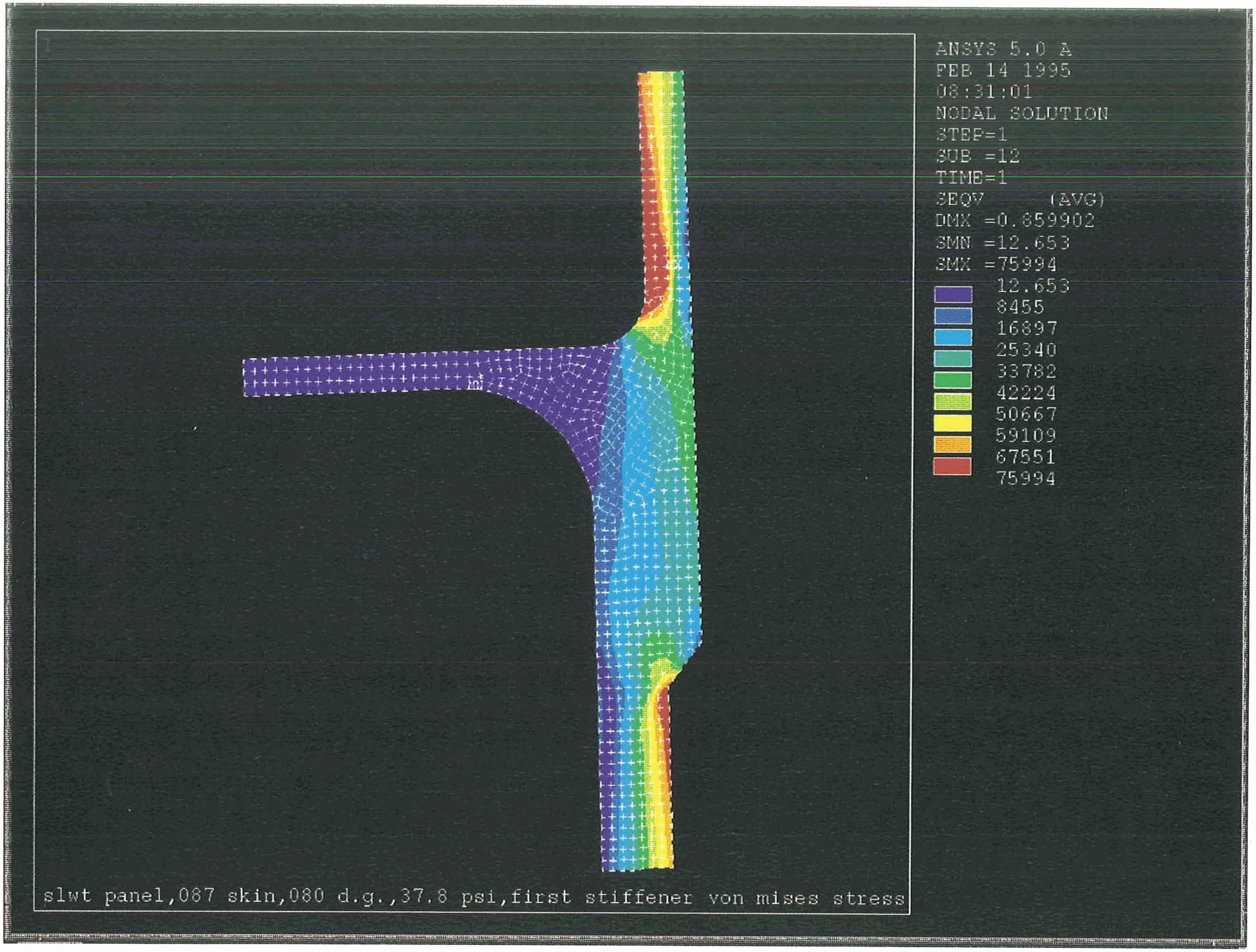

Figure 14. Von Mises stress at weld land adjacent stiffener for initial SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

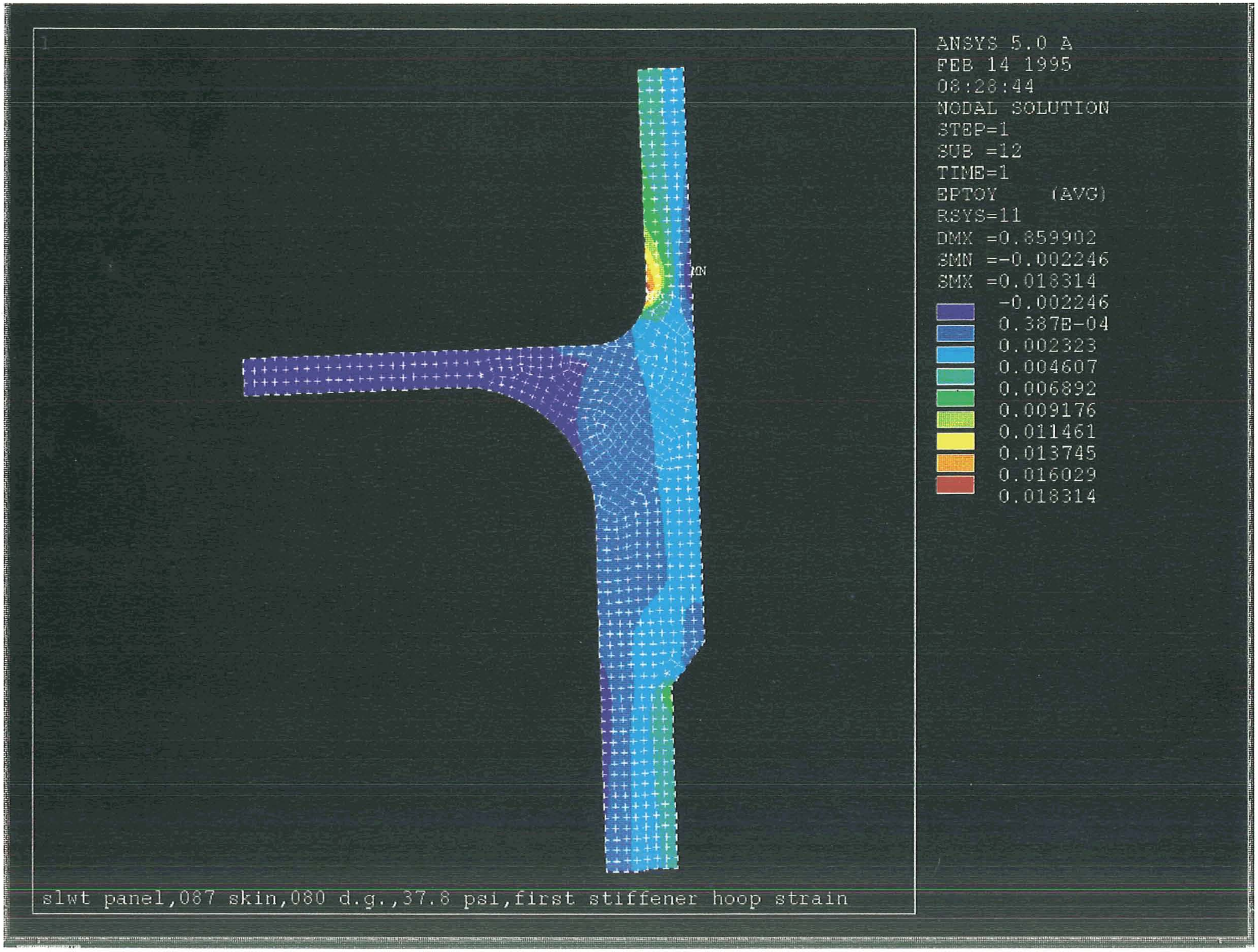

Figure 15. Hoop strain at weld land adjacent stiffener for initial SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

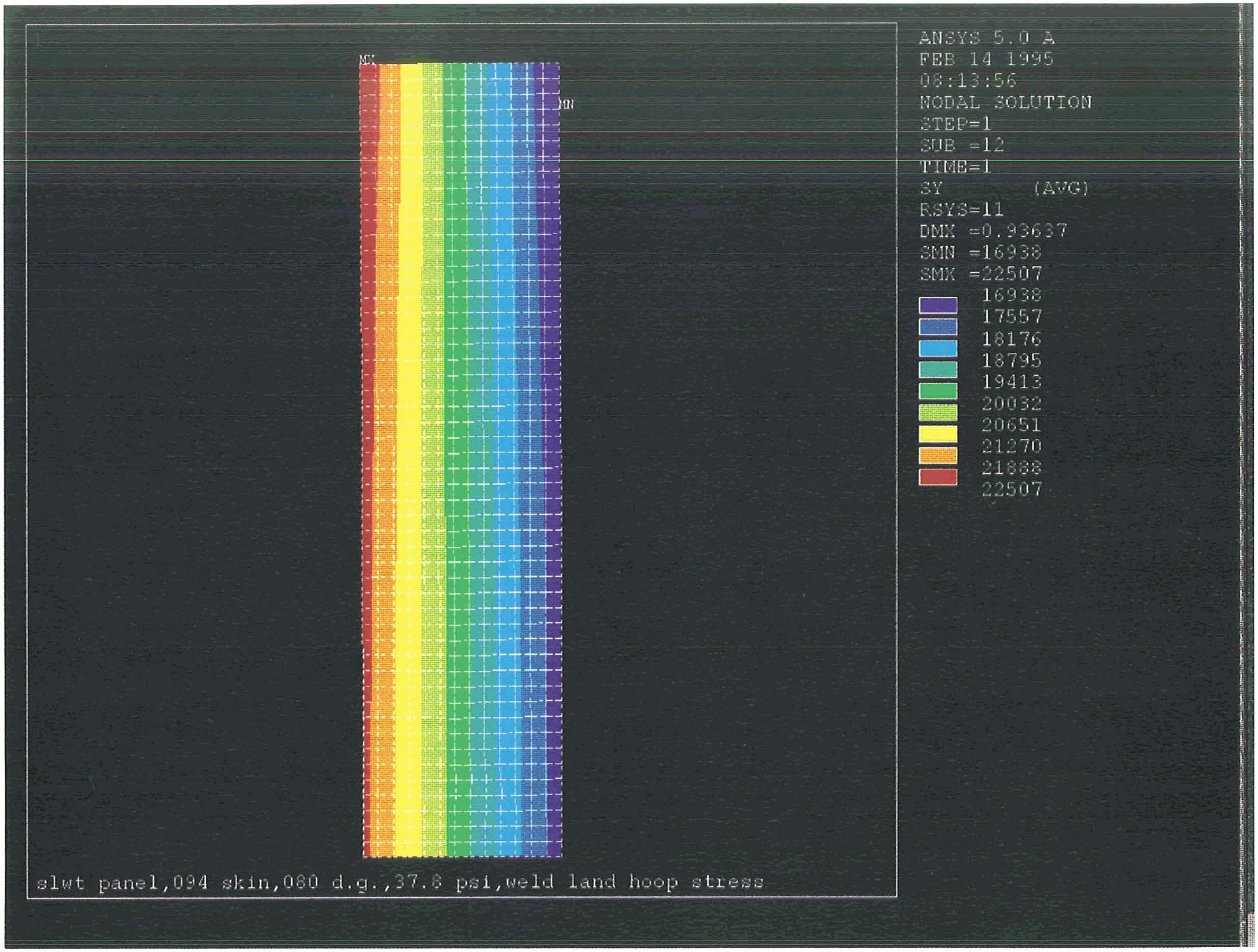

Figure 16. Hoop stress at weld land for initial SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

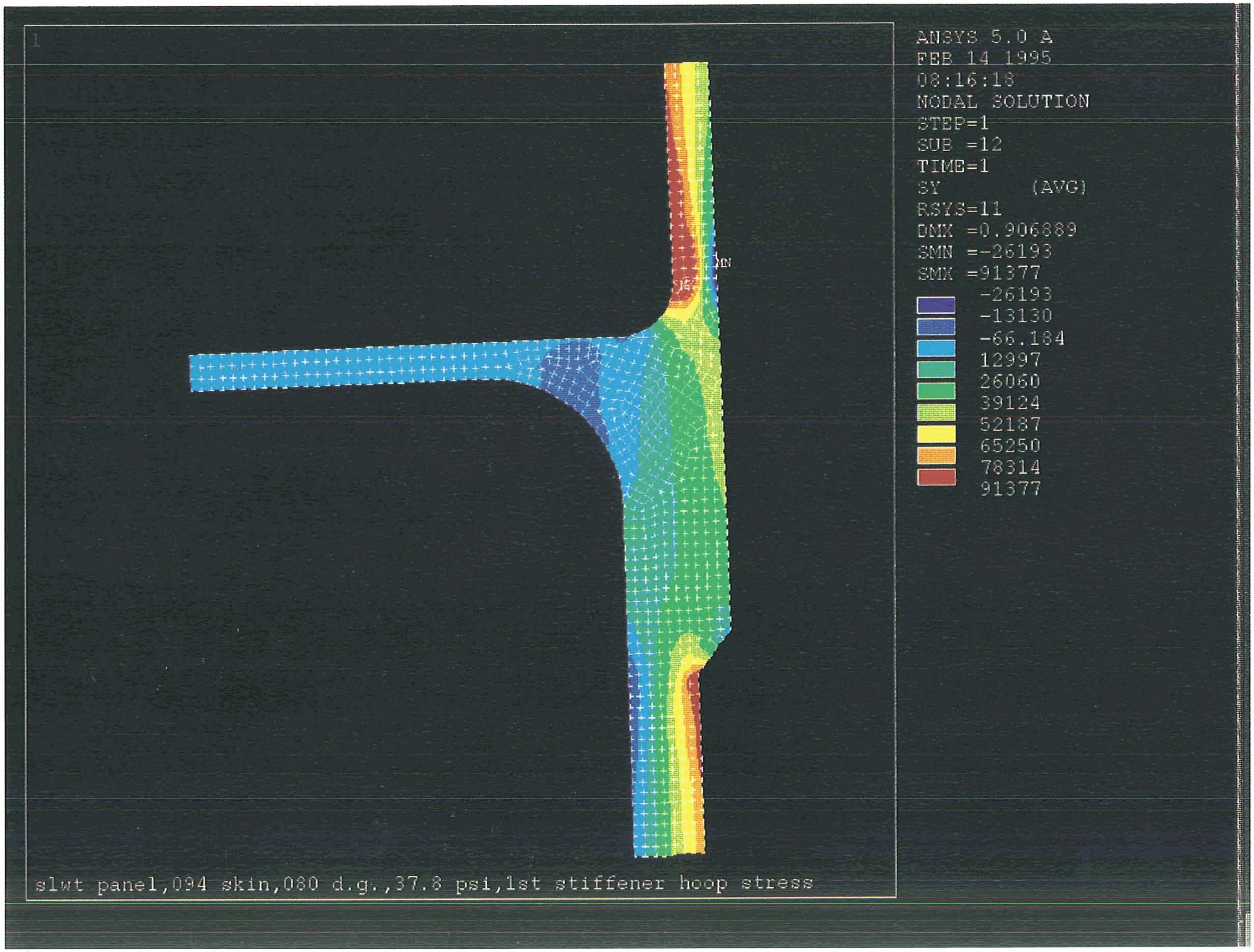

Figure 17. Hoop stress at weld land adjacent stiffener for initial SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

Figure 18. Von Mises stress at weld land adjacent stiffener for initial SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

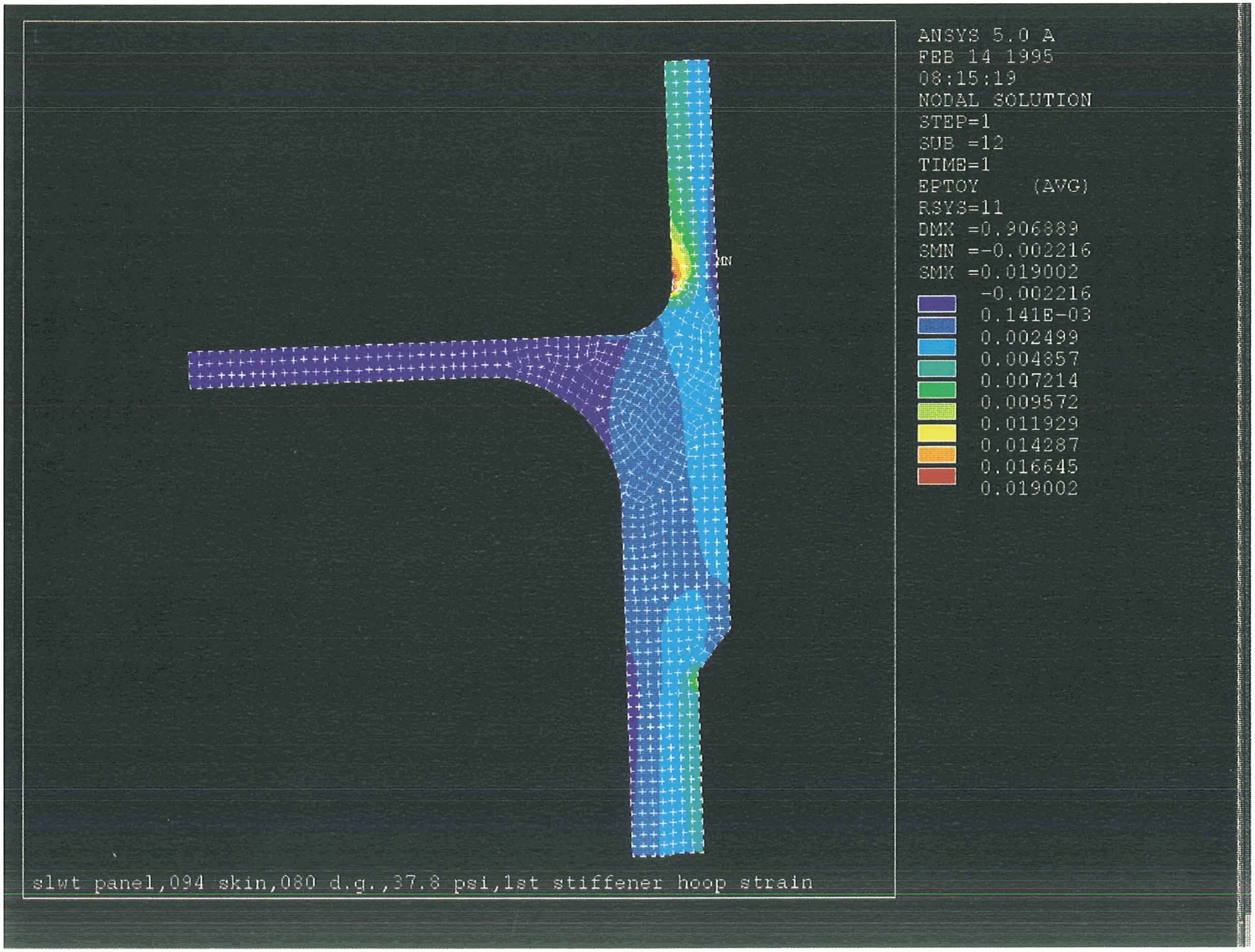

Figure 19. Hoop strain at weld land adjacent stiffener for initial SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

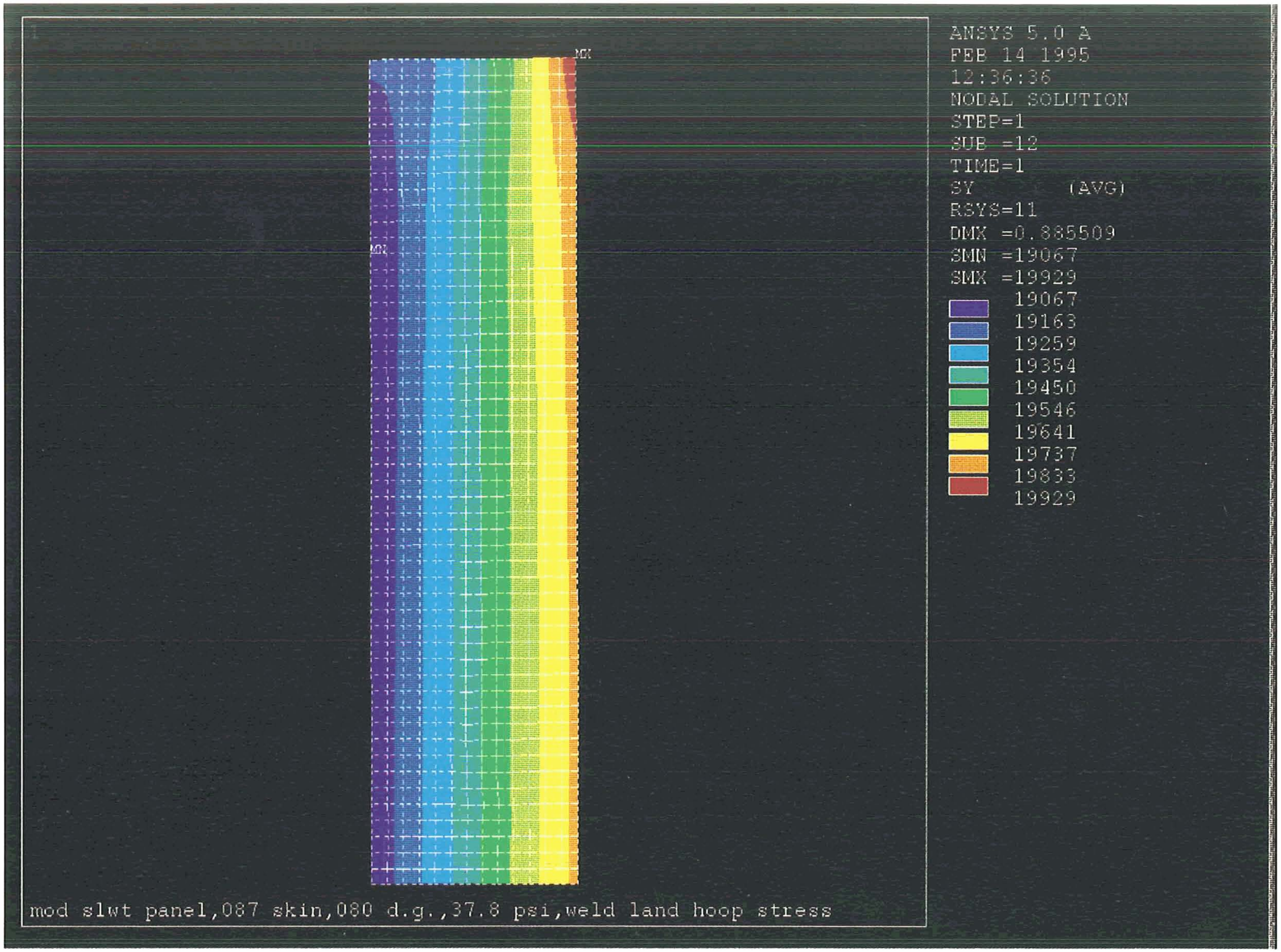

Figure 20. Hoop stress at weld land for modified SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

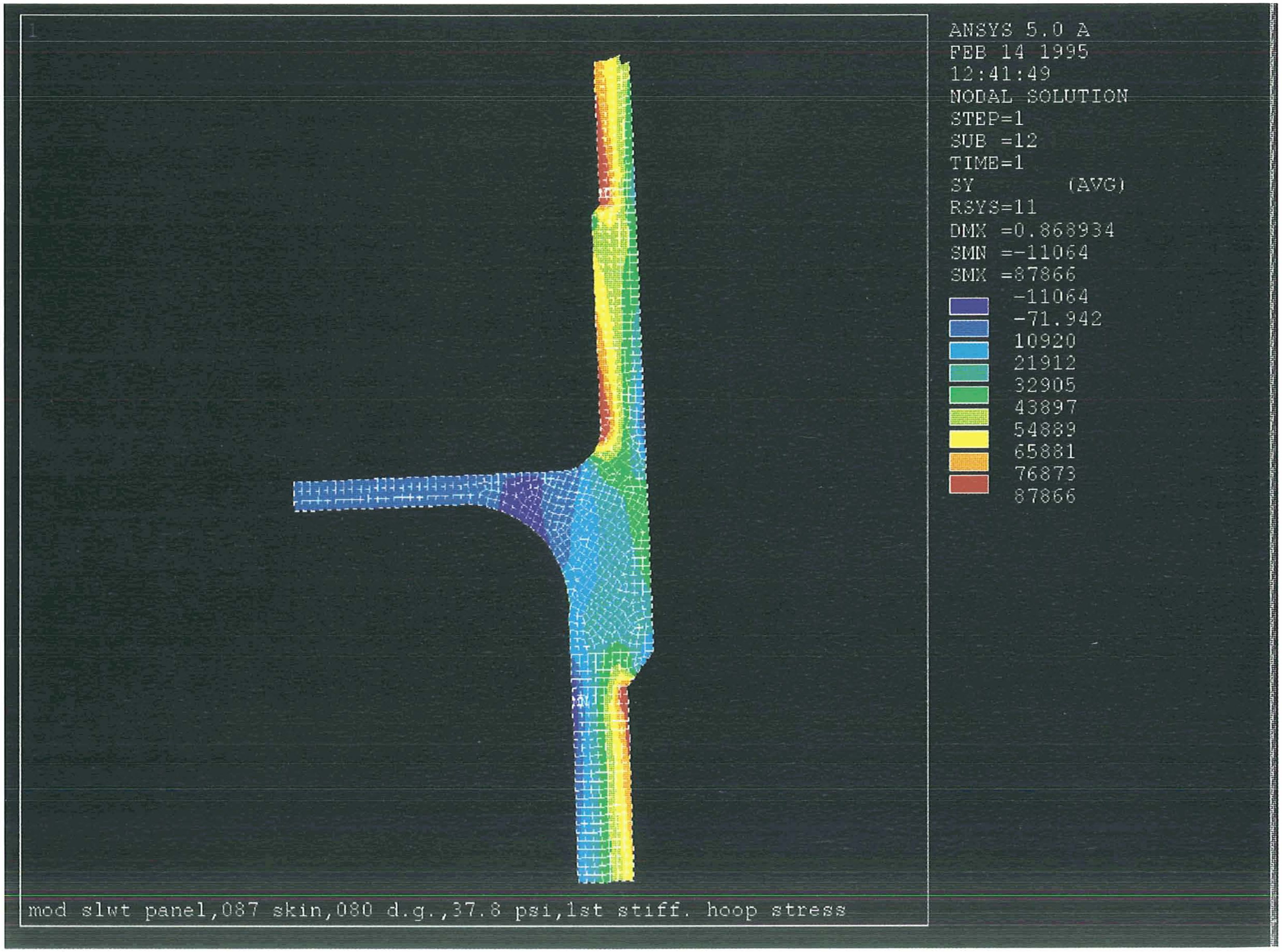

Figure 21. Hoop stress at weld land adjacent stiffener for modified SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

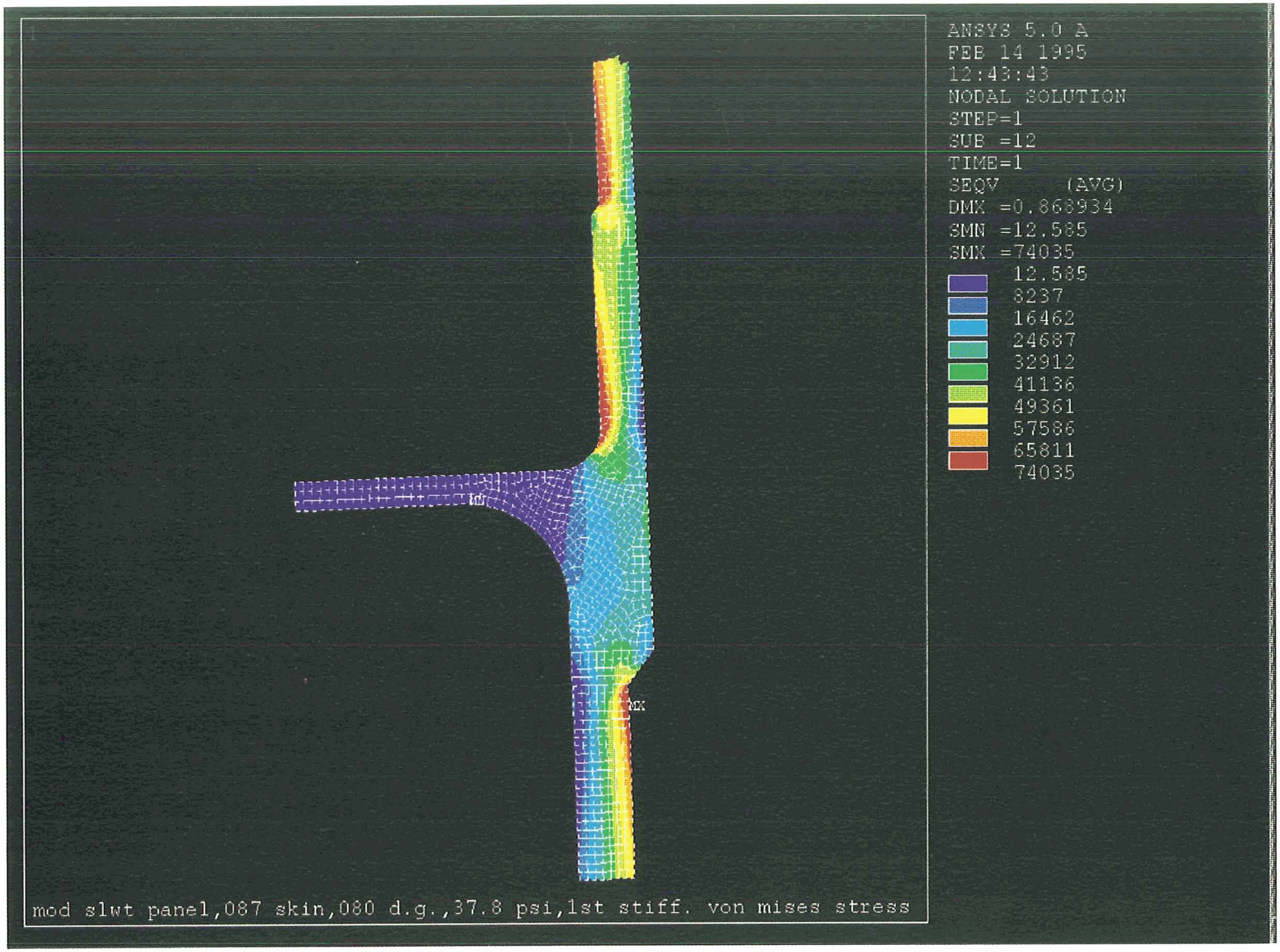

Figure 22. Von Mises stress at weld land adjacent stiffener for modified SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

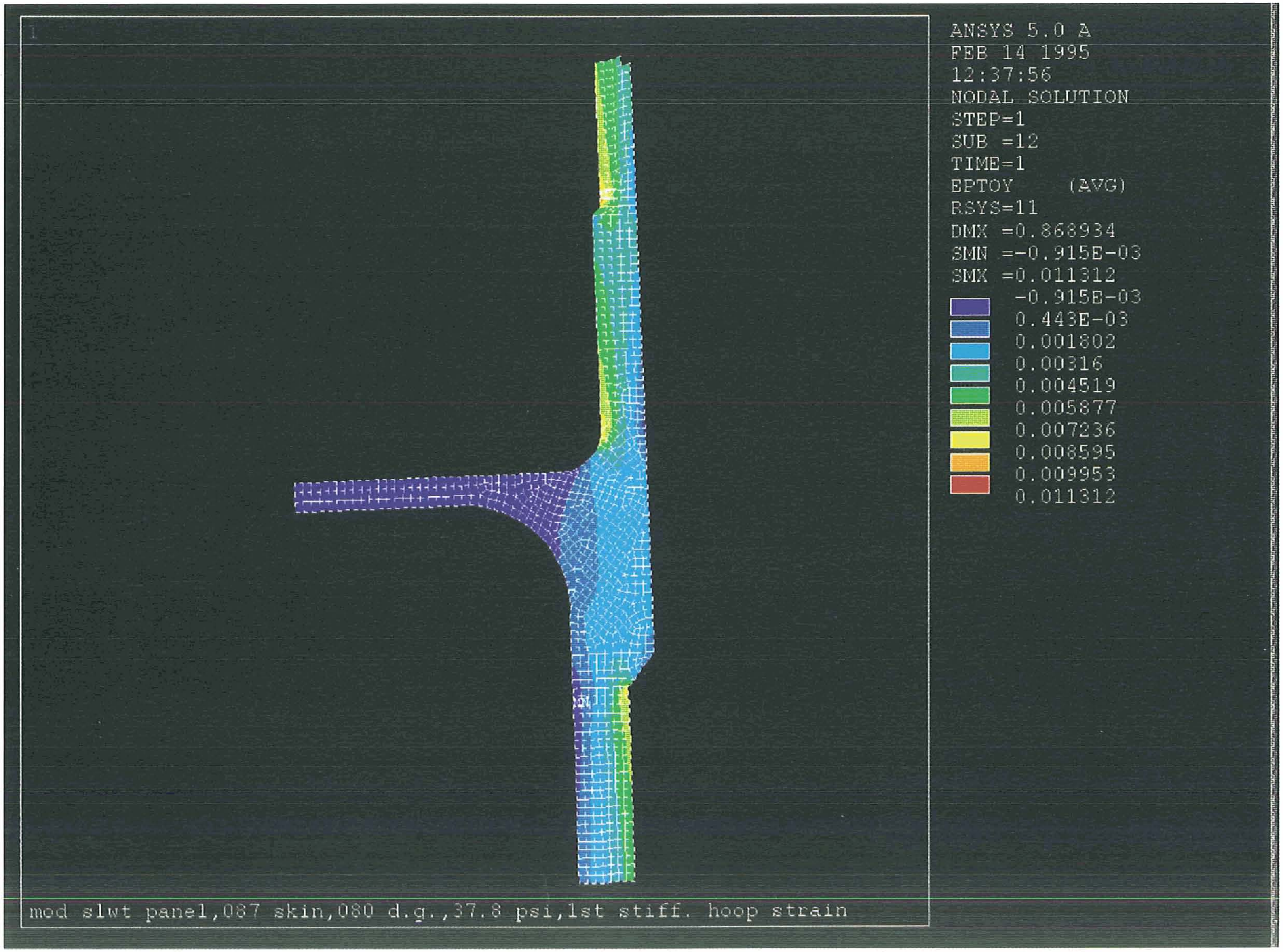

Figure 23. Hoop strain at weld land adjacent stiffener for modified SLWT panel with 0.087-in skin with 37.8 lb/in^2 internal pressure.

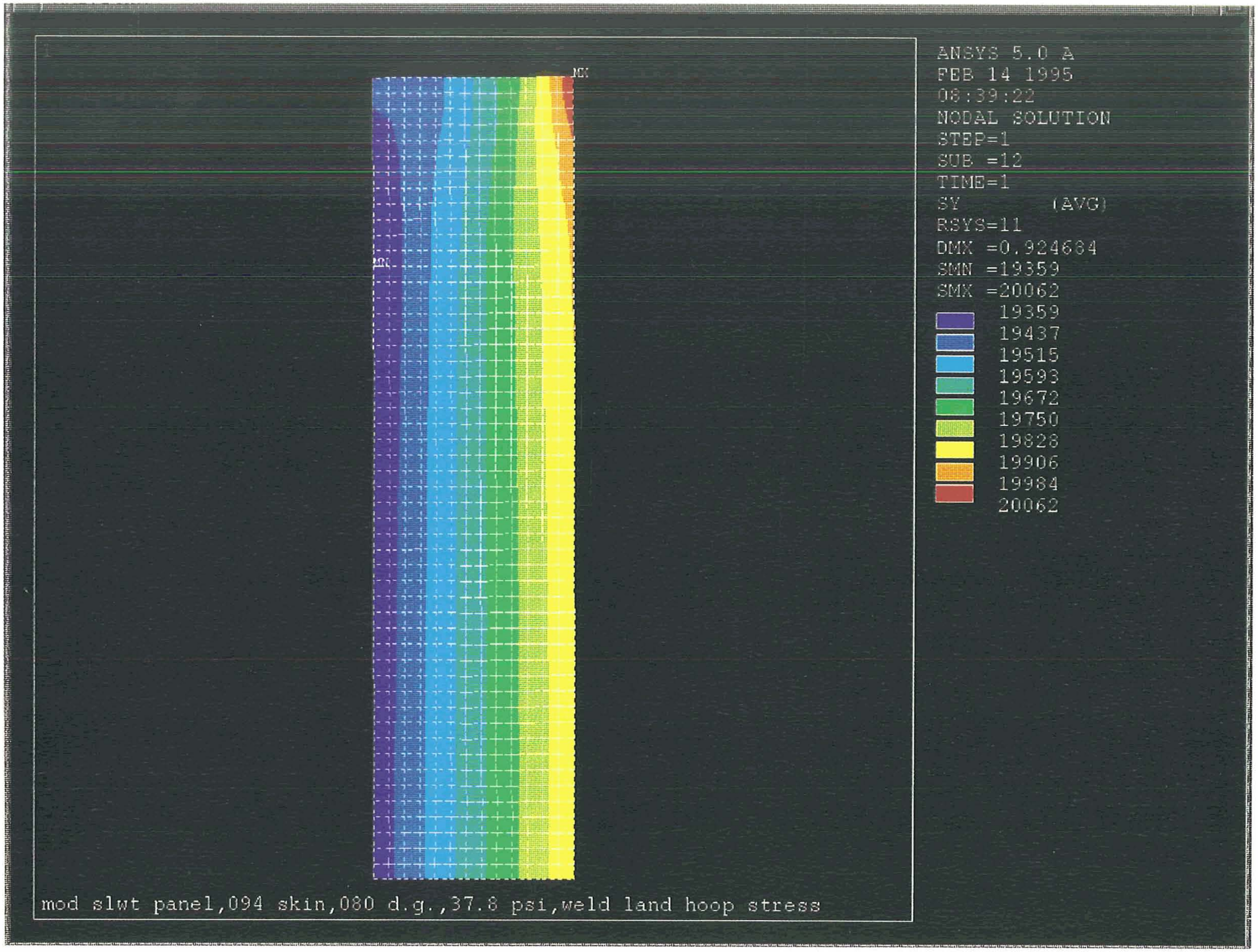

Figure 24. Hoop stress at weld land for modified SLWT panel with 0.094-in skin with 37.8 lb/in[2] internal pressure.

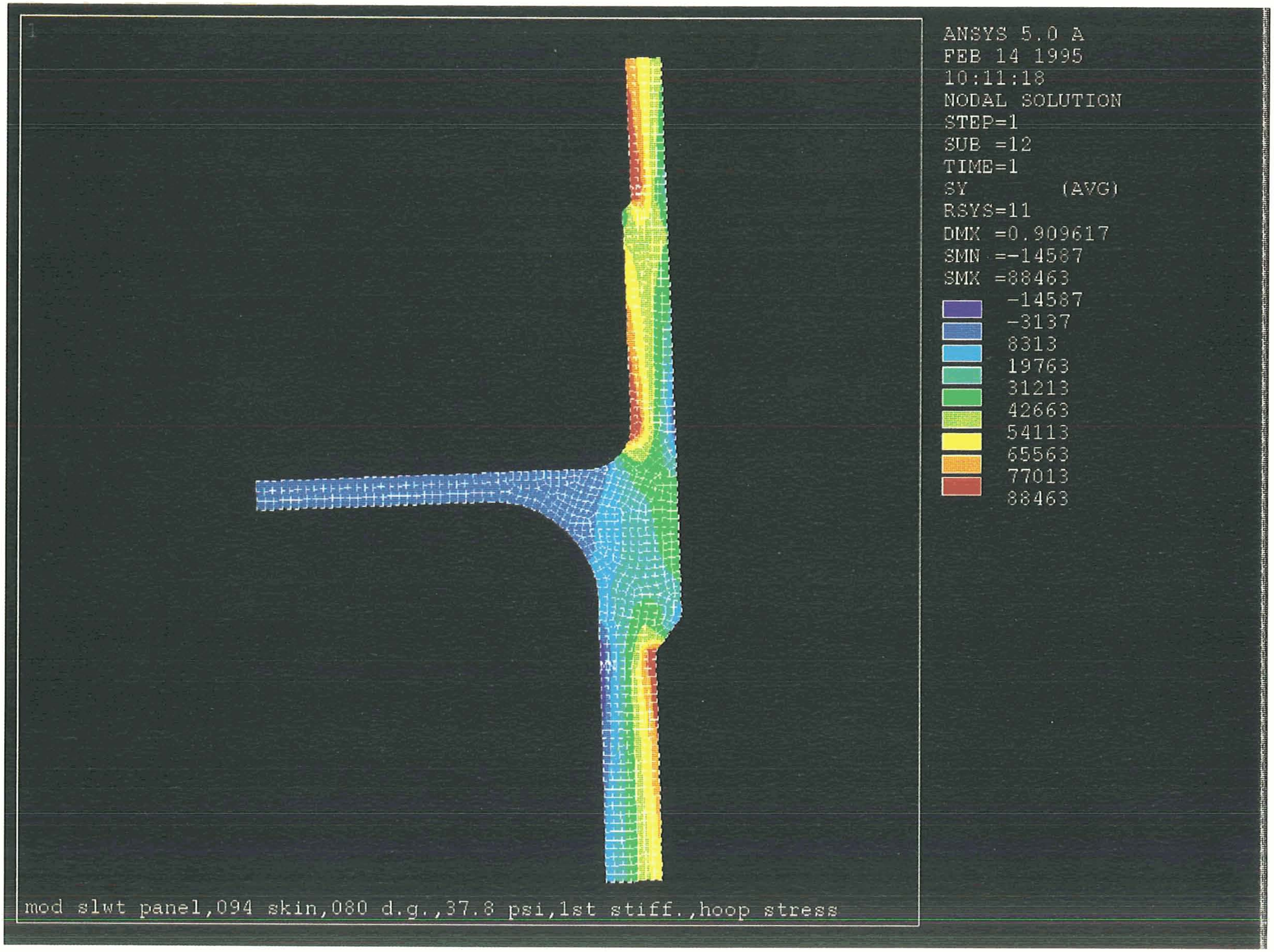

Figure 25. Hoop stress at weld land adjacent stiffener for modified SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

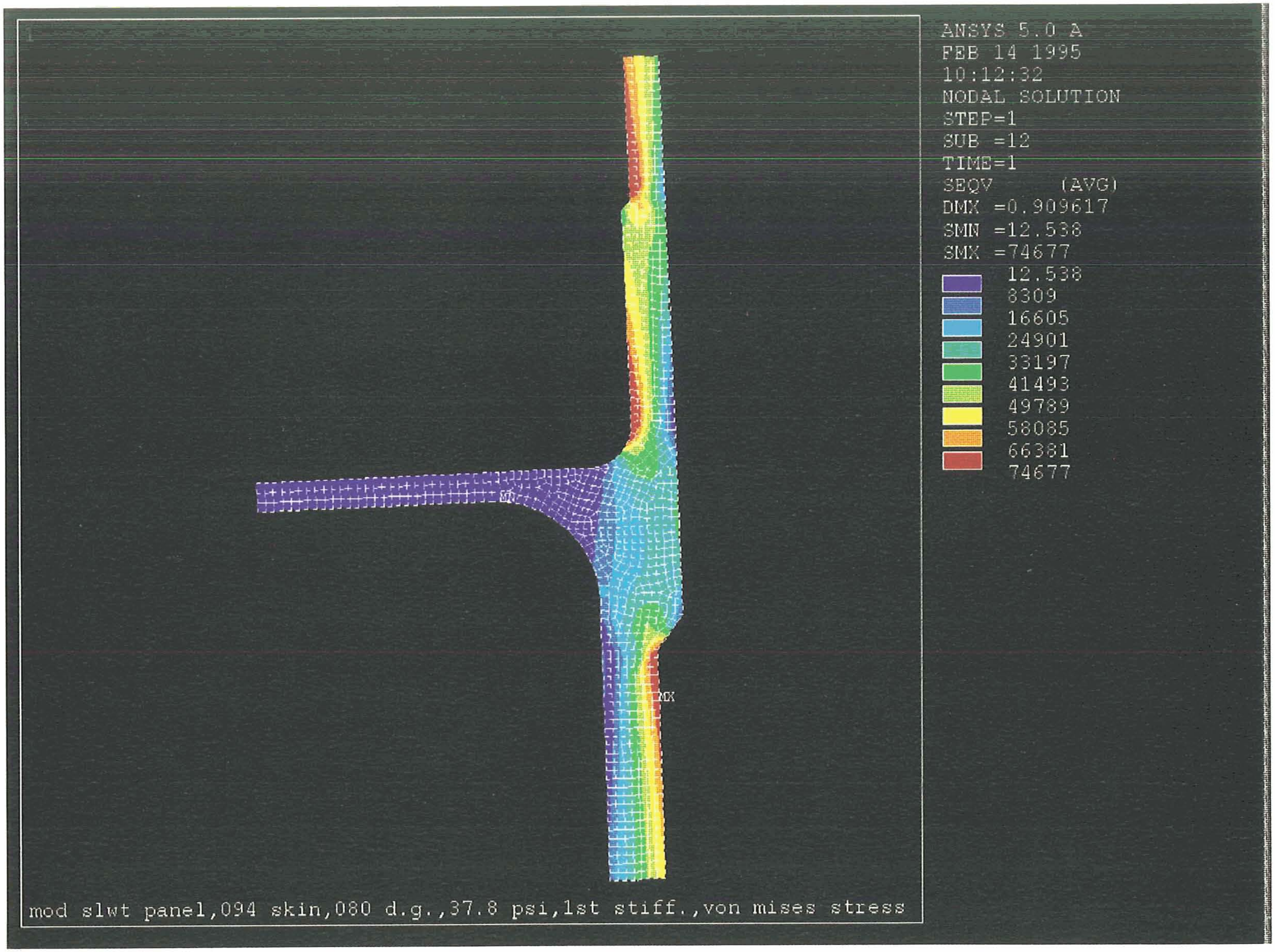

Figure 26. Von Mises stress at weld land adjacent stiffener for modified SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

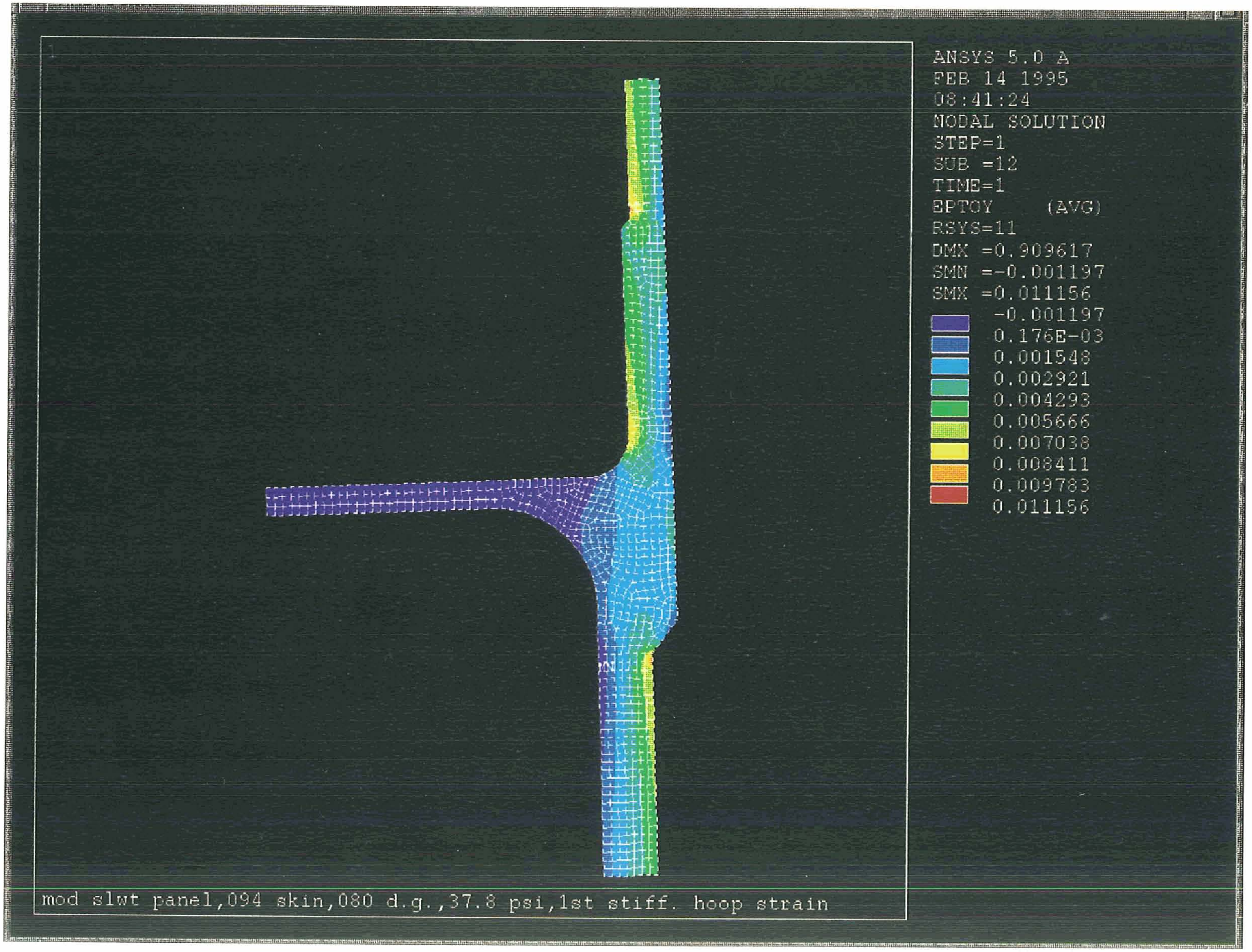

Figure 27. Hoop strain at weld land adjacent stiffener for modified SLWT panel with 0.094-in skin with 37.8 lb/in^2 internal pressure.

APPROVAL

ANALYSIS OF STRESS CONCENTRATION IN THE DUTTON GROOVE REGIONS OF THE SUPER LIGHTWEIGHT EXTERNAL TANK

By R. Ahmed

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

J.C. BLAIR
Director, Structures and Dynamics Laboratory

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13. ABSTRACT *(Maximum 200 words)*
Because the 2195 aluminum-lithium material of the super lightweight external tank (SLWT ET) has a lower toughness than the 2219 aluminum used in previous ET's, careful attention must be paid to stress concentrations. This report details the analysis performed on some of the stress concentrations in the orthogrid panels of the liquid hydrogen tank.

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