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**STRUCTURAL ANALYSIS OF THE
MAGNET SYSTEM FOR MIRROR FUSION
TEST FACILITY (MFTF)**

ADDENDUM I

MASTER

GENERAL DYNAMICS
Convair Division

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ADDENDUM I

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SUMMARY

The stress analysis refinement of the MFTF magnet system using GDSAP (General Dynamics Structural Analysis Program) and NASTRAN finite element computer models has been completed. The objective of this analysis was to calculate a more refined case and jacket stress distribution. The GDSAP model was refined in the minor radius area to yield a more detailed prediction of the stress distributions in critical areas identified by the previous analysis (Reference 1). Modifications in the case plate thickness (from 3.0 inches to 3.2 inches) and in the conductor pack load distribution and stiffness were included. The GDSAP model was converted to an identical NASTRAN model to determine the influence on stress results using higher order elements.

Results showed reduced stresses from the previous analysis in the critical regions of the minor radius. For the normal electromagnetic load, the critical load case, peak principal stresses of 81.5 ksi and 83.3 ksi were predicted by the NASTRAN and GDSAP analyses, respectively. This compares to the 88 ksi peak stresses determined by our previous analysis. The peak stress was found to always occur at 45° from the axis of symmetry in the inner crossover plate of the minor radius. When thermal induced loads were compatibly superimposed on the electromagnetic loads, predicted peak stresses were reduced to 79.8 ksi and 81.2 ksi for the NASTRAN and GDSAP analyses respectively.

In general these results are good. The 1.5 factor of safety on yield strength for the 304 LN case material is satisfied for the entire magnet when NASTRAN is used as the analysis tool for the combination of magnetic and thermal loadings. GDSAP shows the most critical area to be locally stressed only 1.5% greater than the 80 ksi allowable stress for the worst compatible load case (i.e., electromagnetic combined with residual thermal).

Overall, this refinement analysis has verified the structural integrity of the MFTF magnet system.

INTRODUCTION

This report details the refinement of the MFTF magnet system finite element model and summarizes the resulting stress analysis. Attention was focused on the effect of using a finer mesh of elements in the minor radius of the magnet system for obtaining a more accurate prediction of the stresses in this area. The previous finite element analysis (Reference 1) showed critical stresses occurring in the minor radius.

Finite element analyses using NASTRAN and GDSAP programs were conducted. Major refinements included the following:

- o Elements in a 50 degree span in the minor radius were located at 10 degree increments versus the 25 degree increments used in the previous model.
- o A 3.20 inch case plate thickness was used, reflecting the actual thickness of the case now being constructed versus the 3.00 inch case thickness used in previous analysis.
- o The electromagnetic load distribution has been refined and modeled correctly.
- o NASTRAN utilizes higher order elements than GDSAP and accounts for transverse shear flexibility.
- o The offset of the neutral surfaces at the transition from 3.20 inch to 5.00 inch thick plates for the inner and intermediate cross-over plates is now modeled.
- o There is a reduced number of triangular and no highly distorted quadrilateral elements. This tends to improve the accuracy of the finite-element analysis.

A discussion of the model is given in Section 2. Detailed documentation of the refined finite element model is provided in Appendix A. Sections of this model have been plotted using NASTRAN graphics program. The same model geometry was used for both NASTRAN and GDSAP.

Comparisons of stress and bending moment distributions as predicted by this model and the previous model are made in Section 3. The loading conditions analyzed included

the normal electromagnetic load case, a 500 psi internal case quench pressure, the 4.5K operating temperature residual stress condition, and a combination of the electromagnetic and thermal loads.

Complete output data listings from the NASTRAN and GDSAP computer runs are found in Appendices B and C, respectively.

NASTRAN AND GDSAP FINITE ELEMENT MODELS

2.1 Model Definition

The basic modeling techniques used in the previous analysis (Reference 1) were also used for this refinement analysis. The magnet system was modeled using a quarter-symmetric 6600 degree of freedom model (Figures 2.1-2.3) with symmetric loading. Model refinements were made only in the minor radius sections of both coils. The case and jacket structure was modeled by isoparametric quadrilateral elements; CQUAD1 for GDSAP and CQUAD4 for NASTRAN. The same model geometry and loading distribution were used for both GDSAP and NASTRAN.

2.2 Model Refinements

Elements are now located at approximately 10 degree intervals throughout the whole minor radius. Previously elements had been located at 25 degree intervals in the 50 degree span bordering on the transition from major to minor radius, and elements at 10 degree increments through the remaining 40 degree span. A group of narrow elements now span the transition from major to minor radius (Figure 2.3a). These rows of narrow elements in the inner and intermediate crossover plates are inclined to the plane of the bordering crossover elements. This models the offset of the mid-surfaces at the transition from 3.20 inch thick to 5.00 inch thick crossover plates. This element geometry is also discussed in Section 3, and is illustrated in Figure 3.7.

The conductor pack is modeled by six continuous rod elements representing the lumped axial stiffness of the conductor coils. These rods were connected to the case and jacket structure in the transverse directions by additional rod elements. The effective cross sectional areas of these transverse rod elements were modified from the previous analysis to account for the finer mesh of the new model. Experimentally determined elastic moduli (Reference 5) were incorporated to best approximate the conductor pack stiffness in these directions. The magnetic loads as supplied by LLL (Reference 4) were also redistributed to the nodes in accordance with refined mesh. Careful attention was paid to insure the lumped

forces on the rod element nodes were properly oriented within the pack.

The case plate thickness for this model was revised from 3.00 inches to 3.20 inches. This revision reflects the actual case plate now being used in the construction of the actual magnet case.

Figure 2.1 MFTF - Refined Model for GDSAP and NASTRAN Analyses

Figure 2.2 - NIPTF - Refined Model

a) Inner case plate inner and intermediate crossover plates

b) Outer case plate, outer crossover plate, coil extension shell, and stiffeners

c) Coil extension structure (with ribs and intermeid)

d) Lower Intercoil Structure (rotated for better view)

Figure 2.3 - Breakdown of Finite Element Model Components

REFINED STRESS ANALYSIS OF NASTRAN AND GDSAP MODELS

3.1 Background

The NASTRAN and GDSAP analyses results for the refined model are summarized in Figures 3.1-3.12. The same geometry and loading distributions were used for both models. All data reported here has been taken from coil number two (Figure 2.2). In the graphs shown the lines titled "Baseline GDSAP Analysis" refer to data reported previously (Reference 1) from the original model. Lines titled, "Refined NASTRAN", and "Refined GDSAP", refer to new data from the refined model. The sign convention for bending moments used by NASTRAN, defining positive bending moments as causing compression in fibers of the positive z surface, is used for all graphs.

3.2 Stress Analysis

The maximum principal stresses predicted in the critical regions of the minor radius showed reductions of 3% to 8% for NASTRAN and 0% to 7% for GDSAP from those predicted by the previous model. The largest stresses occurred with electromagnetic loading applied by itself.

For this loading situation the NASTRAN analysis found the peak principal stress of 81.5 ksi occurring at 45° from the axis of symmetry in the inner crossover plate of the minor radius (Figure 3.1). This was the only location showing a stress larger than the 80 ksi allowable stress level for the NASTRAN analysis. The GDSAP analysis found stresses above 80 ksi over allowable stress level for the NASTRAN analysis. The GDSAP analysis found stresses above 80 ksi over a 25 degree span with a peak stress of 83.4 ksi (Figure 3.1). These stresses represent reductions of 7% by NASTRAN and 5% by GDSAP from the previously predicted peak principal stress of 88 ksi.

These reductions can be attributed to several factors. The increase in the case plate thickness from 3.00 inches to 3.20 inches results in an increase of 6.7% in membrane stiffness and an increase of 21% in bending stiffness. A simple reduction of stresses by these factors (maximum bending stresses would be reduced

by 12%) could not be assumed however, because the increase in the stiffness of the entire case causes a larger force to be reacted in the minor radius. Reduced stresses by an average of about 3% is observed in the NASTRAN analysis from GDSAP analysis (Figure 3.1-3.4). NASTRAN uses higher order elements and includes for transverse shear flexibility which together account for the differences. Finally, the finer mesh, while mainly intended for a more detailed look at the stress behavior in the minor radius, represents the curvature more closely and hence reduces the modeling discontinuities in this area.

GDSAP stresses also exceeded the 80 ksi level slightly for the intermediate crossover plate over a 10 degree span at the axis of symmetry with a peak stress of 81.7 ksi (Figure 3.2). NASTRAN predicted all stresses below 80 ksi in this area.

When the residual thermal loads due to the cooldown from room temperature to 4.5K operating temperature are superimposed on the electromagnetic loads, a slight reduction of stresses is obtained (Figure 3.3 and 3.4). It is important to note for this load combination that NASTRAN showed all stresses in the magnet to be below the 80 ksi design allowable stress level. GDSAP predicted a peak principal stress of 81.2 ksi, with a span of 10 degrees in the inner crossover plate at stresses over 80 ksi (Figure 3.3). The intermediate crossover plate, for this load combination, showed a peak principle stress of 80.6 ksi at the axis of symmetry (Figure 3.4).

Comparisons between the previous and current models of selected longitudinal and transverse membrane stresses are shown in Figures 3.5 and 3.6. The GDSAP and NASTRAN analyses both predicted essentially the same stresses in all sections as the previous analysis except the chamfer area of the minor radius (Figure 3.6). The differences here are attributed to modeling changes. In the previous analysis, the chamfer was modeled with triangular plate elements (see Appendix A, Reference 1). In the refined model this area was modeled with quadrilateral plate elements. Actual stresses in this area most likely fall between these predictions.

Figure 3.3 Magnet Case Principal Stresses - Magnetic and Thermal Loads

Figure 3.4 Magnet Case Principal Stresses - Magnetic and Thermal

Figure 3.5 Magnetic Case Longitudinal Stresses - Magnetic Load Only

Figure 3.6 Magnetic Case Transverse Stresses - Magnetic Load Only

3.2 Bending Moment Distributions

The transverse bending moment distributions did show some deviations from the previous analysis (Figures 3.8-3.12). Large discontinuities in the transverse bending moment due to the mis-alignment of the neutral axis are found at the transition from the 3.20 inch to the 5.00 inch thick crossover plates. A transverse bending moment is here defined as one causing transverse bending stresses; hence, a transverse bending moment acts about a longitudinal axis (this was the convention used in the previous report). Discontinuities would obviously be expected in the longitudinal bending moment distribution due to the discontinuity of the neutral surface and do show up in the analyses (Figure 3.12). But, the large discontinuities in the transverse bending moments are somewhat surprising. They do exist, however, although not to the extent shown here.

The transverse bending moments arise from the constraining of the longitudinal bending deformations by the relatively stiff case side plates as illustrated by Figure 3.7. The membrane stresses in this area are large tensions at the inner radius and lower tension at the outer radius. Therefore, larger discontinuities would be expected nearer the inner radius than the outer radius as seen in Figures 3.8-3.11.

Another cause of this large increase is that the transverse moment vectors for these transition elements are inclined at significant angles ($\sim 30^\circ$) to the moment vectors of neighboring elements. Hence only that component in the plane of the remaining crossover plate elements might be considered correct. Therefore, while these discontinuities do exist, they are not as large as predicted here. Models with a higher density of elements in the transition area are necessary to obtain better results.

The appreciable differences in the bending moments predicted by GDSAP and NASTRAN at the discontinuity can be attributed to the "crude" approximation of just one row of elements modeling the transition. Differences in the program's

element formation methods have a large effect here. Their predictions of bending moments would be expected to converge with the increase in the number of elements in this area.

No drastic effect on the local stress levels is seen at the plate thickness transition (Figure 3.1-3.6) since secondary bending effects are, in general, smaller than overall or primary bending effects which cause the membrane stresses.

Residual thermal stresses and quench condition internal pressure stresses are very low in comparison to electromagnetic induced stresses, and cause no structural problems.

Figure 3.7 - Transition from 3.2" to 5.0" Thick Plate for the Inner Crossover Plate

Figure 3.8 Transverse Bending Moment Distribution-Magnetic Load Only

Figure 3.9 Transverse Bending Moment Distribution - Magnetic Load Only

Figure 3.10 Transverse Bending Moment Distribution - Magnetic Load Only

Figure 3.11 - Transverse Bending Moment Distribution

Figure 3-12 - Longitudinal Bending Moment Distribution - Magnetic Load Only

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