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Finite Element Analysis of the NC-9 Dipole
Note #5

The Effects of a Horizontal Force Applied Near the Midplane of the NC-9 Dipole

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Introduction

This note reports the results of a finite element calculation of the effects on the NC-9 dipole of a horizontal force applied near the midplane of the prestressed collar/coil assembly.

This calculation is of interest for two reasons: (1) this loading occurs when the dipole is compressed at the horizontal midplane prior to insertion in the yoke, and (2) the calculated deflections and changes in coil stress can be compared with experimentally measured values and thus can be used towards the verification of the finite element model. The model used was created by B. Wands and M. Chapman and is described in detail in "Finite Element Analysis of NC-9 Dipole, Note #1, Model Description", SSC-N-530.

Because the material and mechanical properties of the coil are not very well understood or quantified, it is necessary to make some simplifying assumptions regarding the coil's behavior. To understand the consequences of these assumptions, three different coil models are used, and the results from each are compared. The three models are listed below:

I) E_{coil}=1.5x10^6 psi, conductors free to slide relative to each other and the wedges.

II) E_{coil}=1.5x10^6 psi, conductors not free to slide relative to each other or to the wedges (i.e., coil modeled as a monolith).

III) E_{coil}=0.75x10^6 psi, conductors not free to slide relative to each other or to the wedges (i.e., coil modeled as a monolith).

In all cases, the coils are free to slide with respect to each other and to the collars, and the coils are considered to have linear, elastic, isotropic, and plane strain behavior. The collars are aluminum (E=10x10^6 psi), and the wedges are copper (E=15x10^6 psi). The entire model is linear with the exception of bilinear, compression only, "gap" elements that are used at various interfaces.

Description of Loading

The loading of the models is as follows:

1) Prestressed assembly: the coil midplanes are uniformly displaced to achieve an average preload of 8500 psi on the inner coil and 6600 psi on the outer coil.

2) A horizontal load of 1000 pounds ($F_{midplane}$) is then applied to the collar midplane (Fig. 1).

3) The horizontal load at the midplane is removed and replaced with a 1000 pound load at a point above the keyway (F_{keyway}) (Fig. 1).

   Note: Due to symmetry considerations about the horizontal midplane, the load actually applied in the numerical calculation is 1000 lbs/2 or 500 pounds.

Because the model is elastic (conservative), the final state of the model depends only on the final loads and not on the load path or sequence. Loads were applied at two different locations in order to gain a better understanding of the loading of real dipoles. This will be discussed in more detail later.

Results

The horizontal and vertical deflections due to the applied horizontal force for the three different models and two different load locations are shown in Tables 1-2.

The change in coil azimuthal stress at the coil poles and midplanes for the three models loaded at the keyway are shown in Table 3. For ease of comparison, these stresses have been normalized with respect to the horizontal deflections, resulting in units of psi/mil. Furthermore, the stress changes are resolved into a constant membrane component, which represents the average change across the face, and a linear bending component, which represents the linear bending equivalent of a complicated stress distribution. The sum and difference of these two components result in the stress at the inner and outer edges of the coils, respectively. Because the mesh density of the coils is somewhat too coarse to calculate stress concentrations accurately, these linearized stress quantities are thought to be more representative than individual nodal stresses. The nodal stress deviation from the linearized quantities can be seen graphically for Model II in Figures 2-5 for the inner and outer coils at the poles and midplanes. Stress contours of the change in azimuthal stress for Model II are shown in Figure 6; these contour patterns are typical for all the models. Note that all the azimuthal stresses in the coils are compressive, both before and after the application of the horizontal force. A negative change in stress therefore indicates an increase in compressive stress, while a positive change indicates a decrease in compressive stress.

Discussion

The models predict an inward horizontal deflection of the collars between 3.5–4.3 mil/kip for the horizontal load applied at the midplane ($F_{midplane}$) and between 2.2–2.7 mil/kip for the load applied above the key (F_{keyway}).

In examining these results, it becomes readily apparent that the horizontal stiffness of the assembly is highly dependent on the exact point of loading. Changing the point of loading from F_{keyway} to $F_{midplane}$ produces a change in horizontal deflections of about 60%. It is therefore necessary to know the correct point of loading to accurately calculate the horizontal stiffness of the dipole. The actual measured deflection (per J. Zbasnik) is 2.4–2.5 mil/kip, which suggests that the model loaded by F_{keyway} best represents the actual loading experienced by the dipole.

Further evidence that F_{keyway} best represents the actual loading is revealed by examining how the load is transferred to the dipole during the measurements and during compression prior to insertion of the coil into the yoke. The horizontal load is applied to the collar with a hydraulic press, which contacts the yoke insert that, in turn, contacts the collars (see Figure 7). The yoke insert is designed to mate exactly with the undeformed collar, and one might expect the horizontal load to be distributed along the collars between the midplane and a point above the keyway. However, two factors indicate that this assumption is incorrect: (1) the model predicts that the collar deflections after assembly are such that the yoke insert comes into contact with the collars only at point A, above the keyway, and does not come into contact with the collars at all at the midplane; and (2) shims are placed between the yoke insert and the collars, as shown, thus further preventing the yoke insert from touching the collars at the midplane.

Based on these observations, it seems justifiable and necessary to use the loading above the keyway (F_{keyway}) for the model; and, indeed, the horizontal deflections predicted by the model under this loading (2.2–2.7 mil/kip) agree well with measured deflections (2.4–2.5 mil/kip).

Comparing the deflections of Models I, II, and III shows that the horizontal stiffness of the collars is much greater than that of the coils. It is possible to calculate the ratio of the horizontal stiffness of the collar to that of the coil by comparing the stiffness of Model II to that of Model III, as the coil stiffness in Model II is twice that of Model III. This calculation yields:

Model I:	$k_{collar}/k_{coil} = 13:1$
Model II:	$k_{collar}/k_{coil} = 3:1$
Model III:	$k_{collar}/k_{coil} = 6:1$

Letting the conductors slide relative to each other, as in Model I, produces a coil that is one-quarter as stiff in the horizontal direction as when the conductors are "fixed" together, as in Model II.

Examining the azimuthal stress changes in Table 3, one notices that while the average stress change across the poles and midplanes is relatively small, the is a very large gradient in this change. The contour plot of the coil stress changes for Model II (Figure 6) reveals patterns similar to that of a thick-walled cylinder being loaded with a radially directed force (Figure 8).

The stress distribution and linearized equivalent membrane and bending plots in Figures 2-5 depict the stress changes at the poles and midplanes for Model II (conductors fixed, $E_{coil}=1.5x10^6$ psi), which shows the largest coil stress changes. One should note that these results are given in psi per mil of horizontal deflection (psi/mil) and that the interference fit between the magnet and the yoke at room temperature (which largely shows up as a compression of the magnet) is typically 7–10 mils. Multiplying the stress changes for Model II by a factor of 10 yields an *average* change at the inner coil pole of only –750 psi; however, the stress at the inner radius increases by 5400 psi, and the stress at the outer radius decreases by 3900 psi. These are very large stress changes relative to the desired preload for the inner coil of 8000 psi. Similarly, for the outer coil, the average change at the outer pole is only 150 psi, whereas the stress at the inner radius increases by 3470 psi, and the stress at the outer radius decreases by 3780 psi. Again, these are very large stress changes relative to the desired preload for the outer coil of 6000 psi. It should be noted that the stress changes for Model II are higher than those for Models I and III, so in this respect Model II represents the "worst case scenario." Also, these stress changes are at room temperature; as the cold mass is cooled to 4 K, the differential thermal contraction of the iron yoke and the magnet will tend to eliminate the interference between the yoke and the collars, and the stress changes due to the interference will diminish. Still, if the goal during collaring is to achieve the highest safely allowable prestress, this calculation shows that allowances should be made for an additional 5500 psi of coil stress during insertion into the yoke. Likewise, the deflections of the collars during insertion of the tapered keys should be considered vis-a-vis these same stress changes.

The measured values of the coil stress change at the poles were –150 psi/mil for the inner coil and 11 psi/mil for the outer coil (per J. Zbasnik). When these numbers are compared with the calculated results of –41 to –75 psi/mil for the inner coil and 8 to 20 psi/mil for the outer coil, it is clear that the calculated stresses do not correlate with the measured values nearly as well as the calculated deflections did. However, there is some question about the accuracy of the measured stress changes. This uncertainty is due to the fact that the measurements were taken with the old-style LBL strain gauge packs, which were known to be deficient in measuring coil stresses with large gradients across the pole face, as in this instance. If anything, the measurements indicate that the stress changes are even worse than predicted.

A word about the coil models: for the purpose of this analysis, the coils were considered to be linear, elastic, and isotropic. The actual behavior of the coils is thought to be non-linear, inelastic, and anisotropic. Also, the stress/strain behavior of coil is thought to vary through the radius. There are measurement efforts under way to attempt to quantify some of these properties, but even if they were all known to sufficient precision, the analytical tools available have limited ability to fully model them. Therefore, it is the analyst's task to make the necessary assumptions and simplifications based on the available data and analytical tools, and to evaluate the results in light of these assumptions.

Let us examine the probable effects of some of the assumptions made in this analysis:

1) *Linear azimuthal stress/strain behavior of the coil.* Although the stress/strain behavior of the coil is certainly non-linear, measurements indicate that at stress greater than 3000 psi or so, the coil response is more or less linear, with measured values of the modulus between 0.75×10^6–1.5×10^6 psi depending on the measurement. The calculated stresses discussed here are relative stresses: the change in stress from one high stress state to another. It is therefore likely that throughout the process of insertion into the yoke, the actual coil stress state remains primarily in the linear region. The areas of the coil that might go into the low modulus stress state are at the inner radius of the midplane and the outer radius of the pole, where the stress drops off the most. For a given imposed displacement, the effect of lowering the modulus in the areas that fall below a certain stress would be to reduce the stress loss at these areas. Therefore, the linear model of the coil is a conservative assumption in that it predicts greater stress losses than perhaps actually occur.

2) *Elastic coil behavior.* It is thought that the coil behavior is inelastic, with the modulus during unloading being greater than that during loading. The coil area that would be affected would again be the inner radius at the midplane and the outer radius at the pole. For a given imposed displacement, the effect of increasing the modulus in the areas of the coil that tend to unload would be to increase the stress loss at these areas. Therefore, the elastic model of the coil is not a conservative assumption, and with respect to this issue the model probably predicts stress losses smaller than the coil actually experiences.

3) *Isotropic coil behavior and plane strain assumption.* Measurements of the Poisson's ratio, shear modulus, and coil properties in the radial and axial directions have been scant, so it is difficult to assess the effects of the assumptions that the coil behaves isotropically and that it is in plane strain. One might conjecture that the radial properties of the coil are not so important in this mechanism. One also might conjecture that any tendency towards shearing would occur along radial lines and that letting these lines slide freely, as in Model I, would represent a limiting case for this. The plane strain assumption yields higher stress changes than a plane stress assumption for a given displacement, so in this sense it is a conservative assumption. The differences in the stresses between the plane strain/plane stress assumption will be a function of the θ-axial direction Poisson's ratio and the material properties in the axial direction as well as in the θ direction.

4) $E_\theta\theta \neq E_\theta(r)$. It is thought that the azimuthal modulus of elasticity of the coil is somewhat higher at the inner coil radius than at the outer radius. For a given imposed horizontal displacement, one can imagine that the lowering the modulus of the outer coil radius and simultaneously increasing the modulus of the inner radius to maintain the same average modulus would lessen the stress change along the outer radius and increase the stress

change along the inner radius. Therefore, the stress change at the inner radius of the coils is probably greater than predicted, and the stress change at the outer radius of the coils is probably less than predicted.

As mentioned in the Introduction, the models are linear, except for the bilinear gap elements. To determine the effects of the non-linearities for this type of loading, Model I and Model II were loaded at the keyway with F_{keyway} = 1000, 2000, 3000, and 4000 pounds. The horizontal deflection and the change in the inner coil pole stresses are shown in Figures 9-12 versus load. It is clear from these plots that the non-linear effects of the gap elements are negligible.

Conclusions

Analysis of the effects of a horizontal force applied at the midplane of the NC-9 magnet shows that the stress state of the coil is appreciably changed upon insertion into the yoke blocks. The areas of the coil that are most affected are at the poles and midplanes. The horizontal stiffness of the magnet predicted by the model correlates well with the measured value once the particular loading point is assumed, and the horizontal stiffness of the assembly is shown to be rather insensitive to the particular model of the coil. The average change in azimuthal coil stress predicted by the model does not correlate very well with the measured values; however, the style of coil pressure gauge used in the measurement is thought to inaccurately average large stress gradients. It is planned to repeat the measurements using short magnet F-2, which is fitted with three different styles of coil pressure gauges.

Table 1: Collar Deflections Resulting from Force Applied at Midplane ($F_{midplane}$)
(all deflections in mils on the diameter)

Model:	I E_{coil}=1.5x10^6 conductors free to slide	II E_{coil}=1.5x10^6 conductors fixed	III E_{coil}=0.75x10^6 conductors fixed
Horizontal Deflection	–4.3	–3.5	–3.9
Vertical Deflection	2.2	1.8	2.2

Note: Horizontal deflection measured at point of loading.

Table 2: Collar Deflections Resulting from Force Applied at Keyway (F_{keyway})
(all deflections in mils on the diameter)

Model:	I E_{coil}=1.5x10^6 conductors free to slide	II E_{coil}=1.5x10^6 conductors fixed	III E_{coil}=0.75x10^6 conductors fixed
Horizontal Deflection	–2.7	–2.2	–2.5
Vertical Deflection	1.6	1.4	1.8

Note: Horizontal deflection measured at point of loading.

Table 3: Average Change in Azimuthal Coil Stress Normalized with Respect to Horizontal Deflection (psi/mil)

Model:	I E_{coil}=1.5x10^6 conductors free to slide	II E_{coil}=1.5x10^6 conductors fixed	III E_{coil}=0.75x10^6 conductors fixed
Inner coil (pole)			
Membrane	–41	–75	–44
Bending	–152	–465	–283
Inner radius	–192	–540	–327
Outer radius	111	390	240
Inner coil (midplane)			
Membrane	–13	–7	–2
Bending	75	444	253
Inner radius	62	437	251
Outer radius	–88	–451	–255
Outer coil (pole)			
Membrane	20	15	8
Bending	–78	–363	–233
Inner radius	–58	–347	–225
Outer radius	99	378	241
Outer coil (midplane)			
Membrane	27	37	20
Bending	55	239	118
Inner radius	82	276	138
Outer radius	–29	–202	–98

Note: Positive stress indicates a decrease in compressive stress.

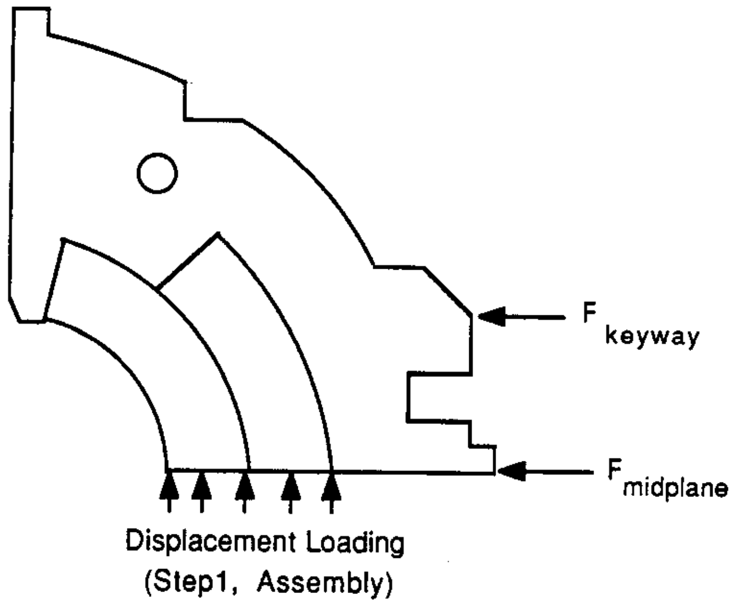


Figure 1: Coil/Collar Quadrant Showing F_{keyway} & $F_{midplane}$

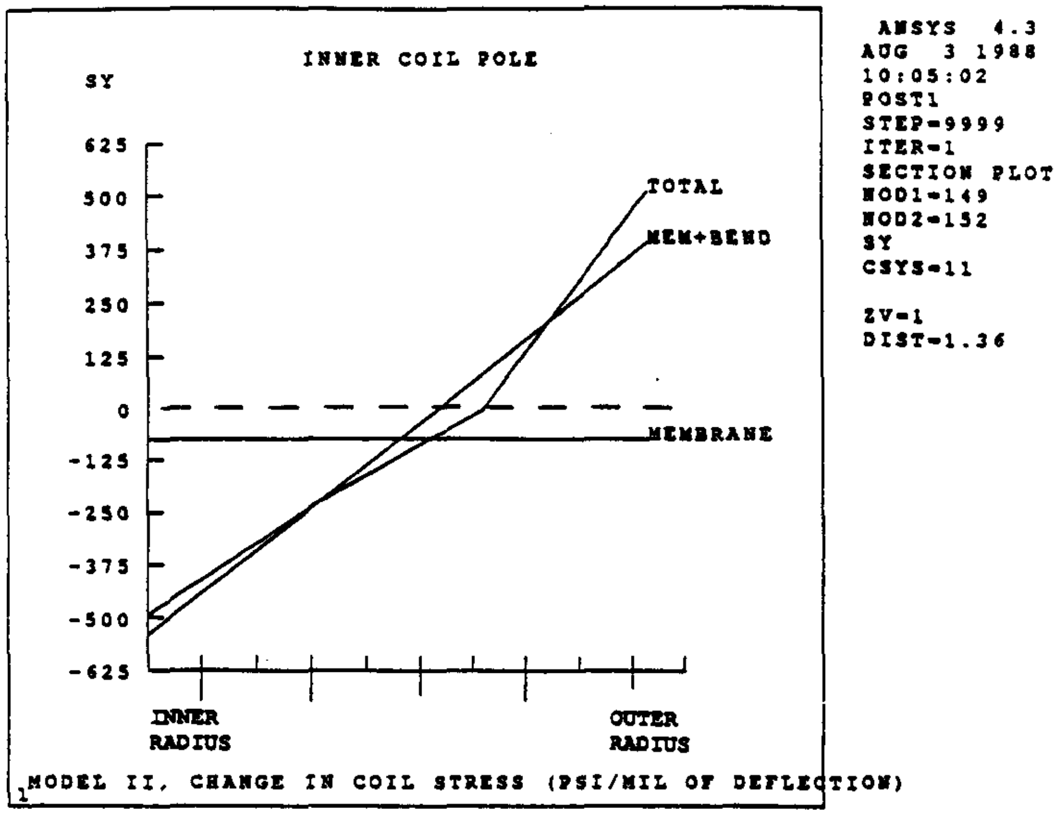


Figure 2

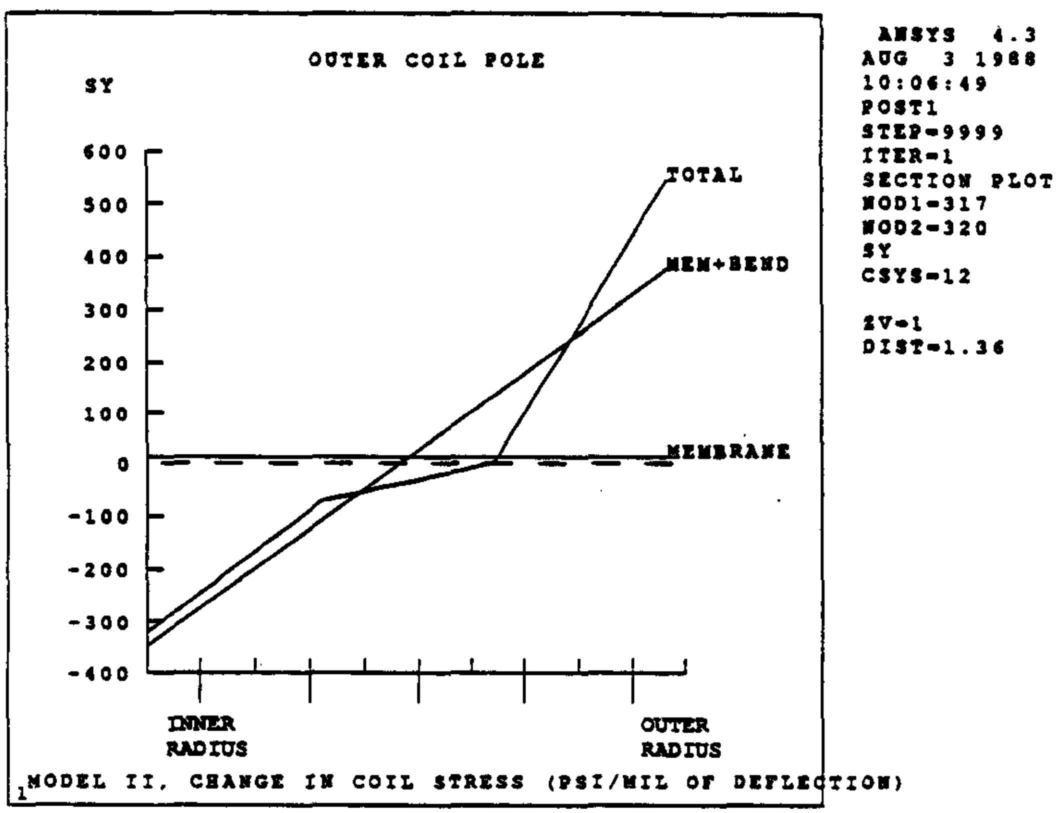


Figure 3

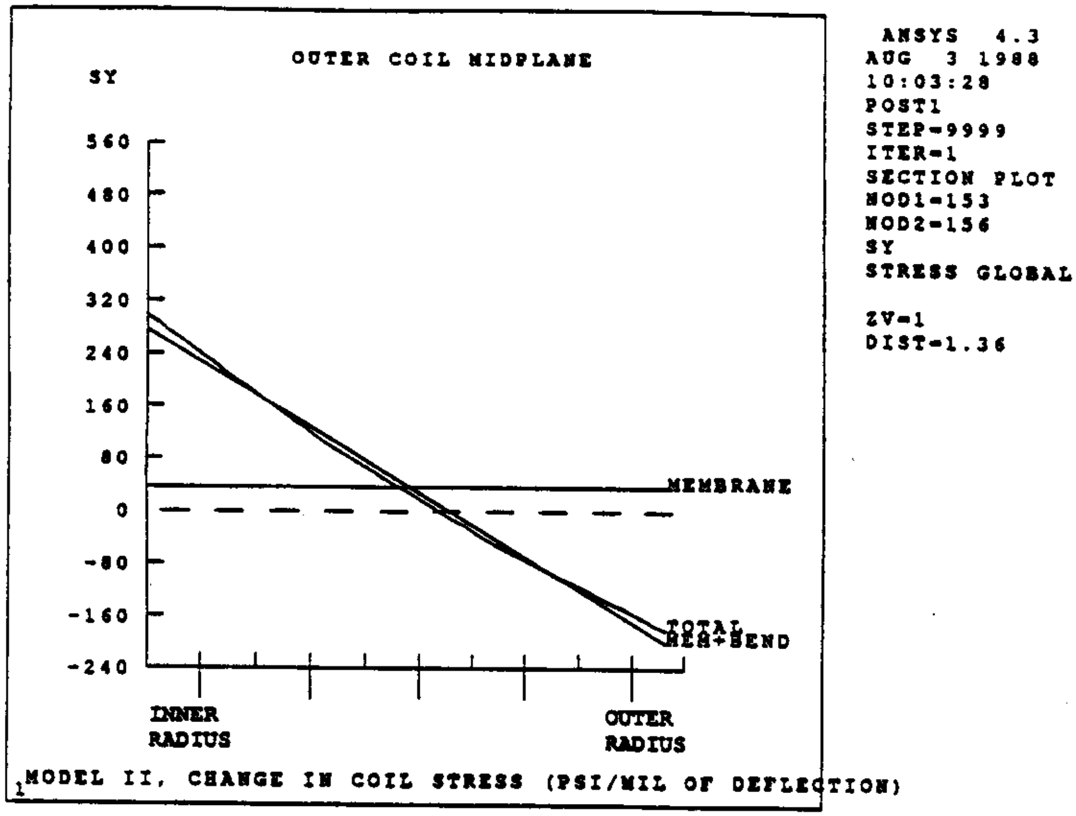


Figure 4

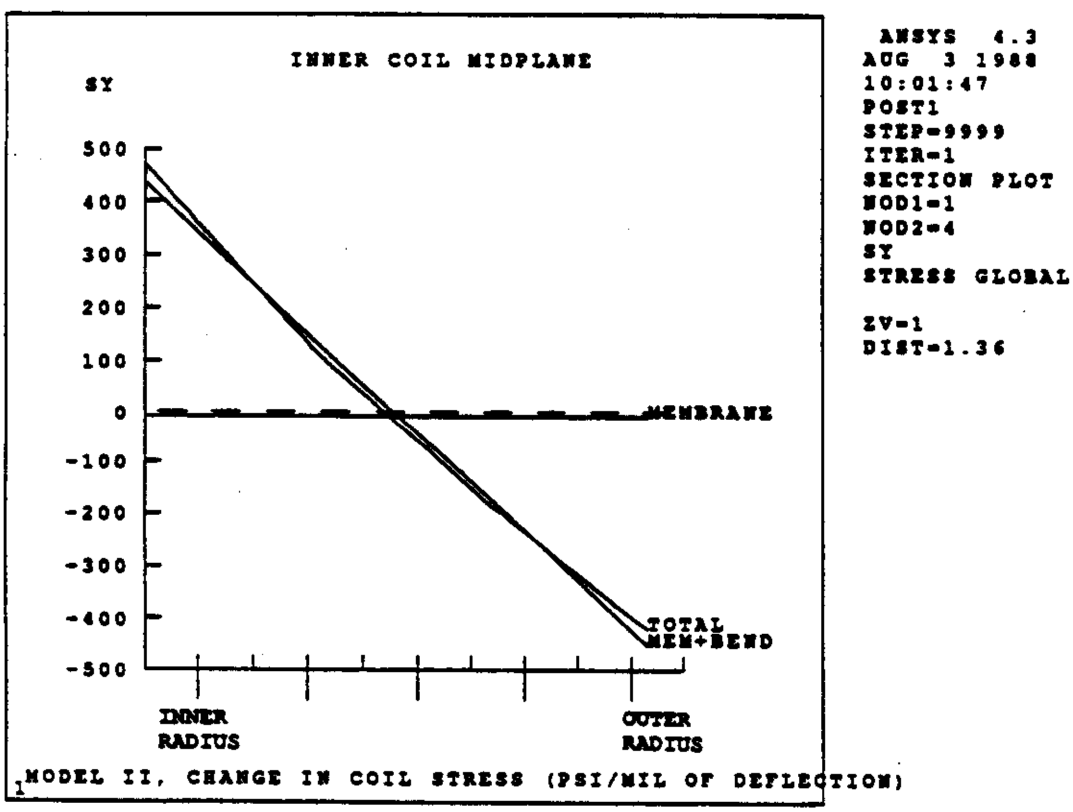
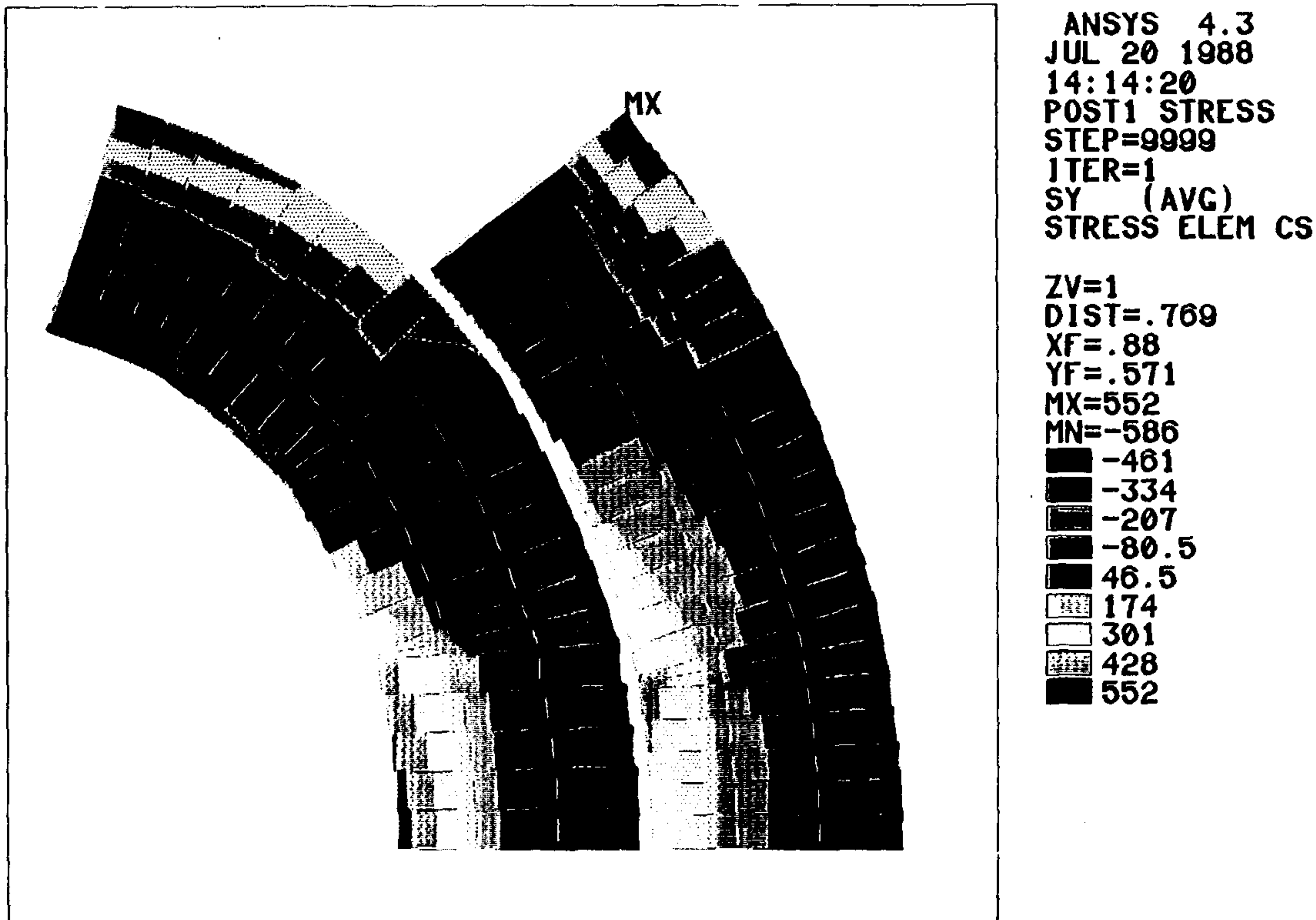


Figure 5



1 MODEL II. CHANGE IN COIL STRESS (PSI/MIL OF DEFLECTION)

FIGURE 6

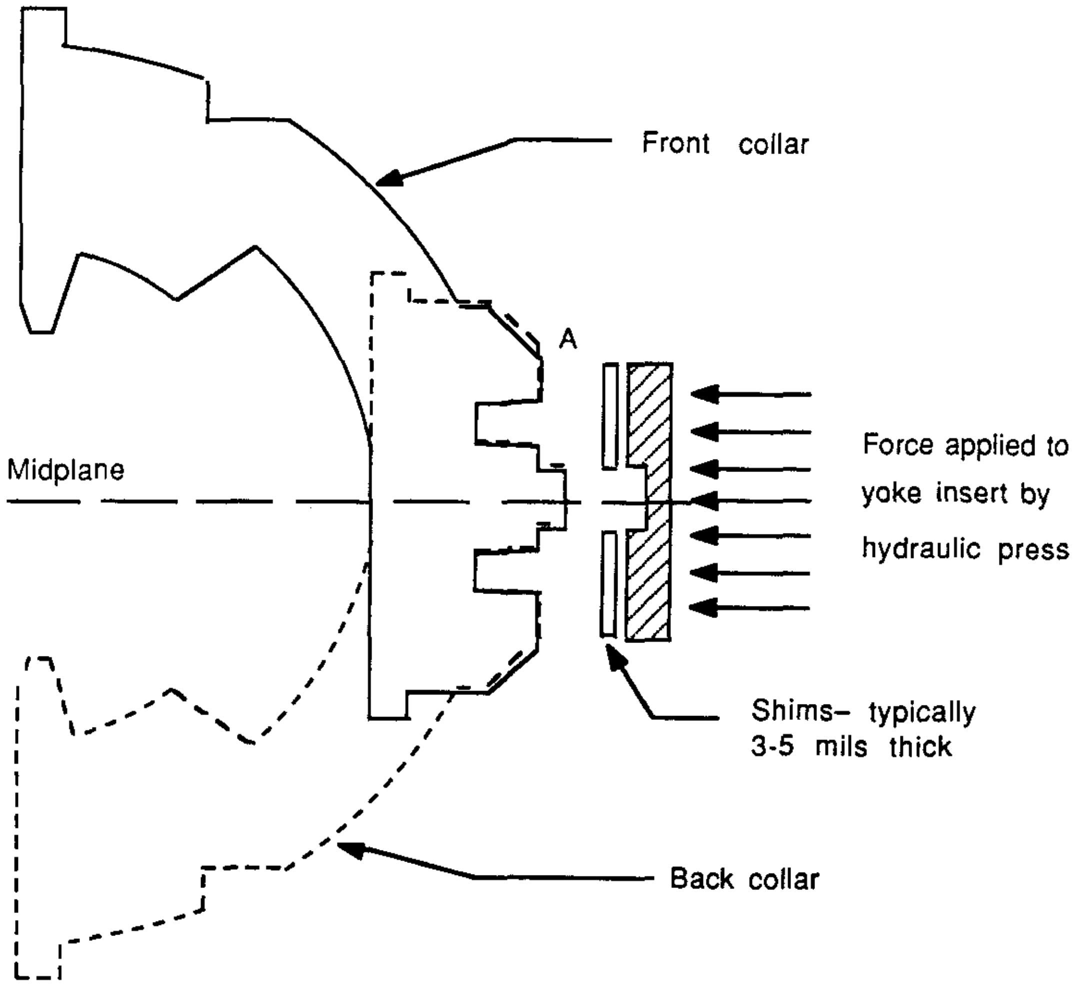
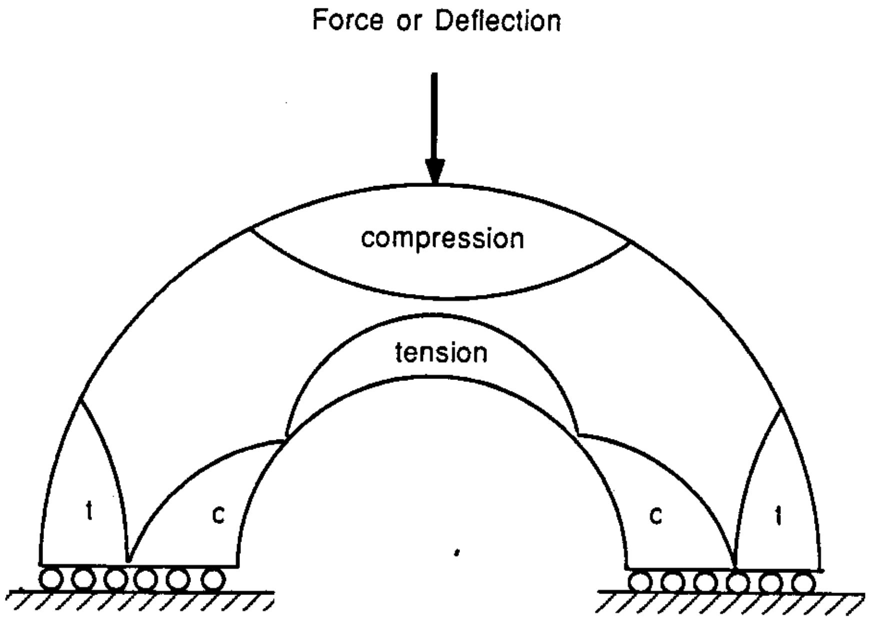


Figure 7: Loading Mechanism During Measurements



Changes in stress in a cylinder due to an applied force or deflection

Figure 8

Figure 9: Diametral Horizontal Deflection vs Load
Model II

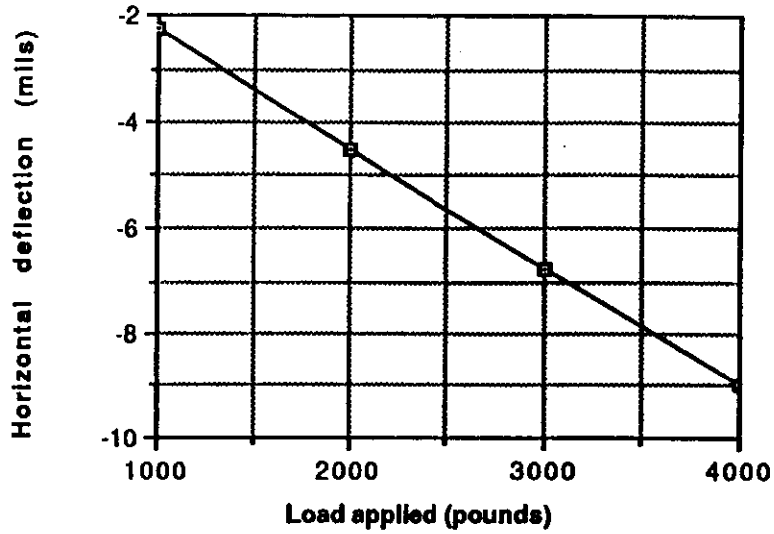


Figure 10: Change in Average Stress vs Load
Model II (stresses measured at inner-coil pole)

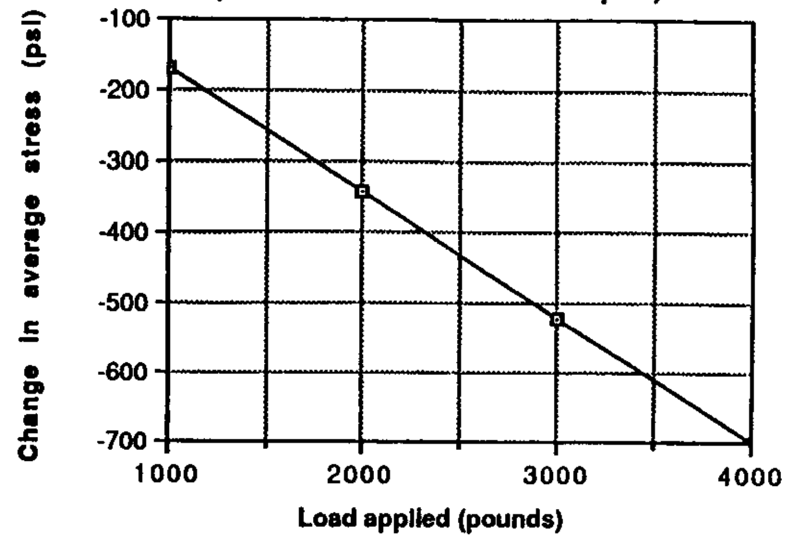


Figure 11: Diametral Horizontal Deflection vs Load
Model I

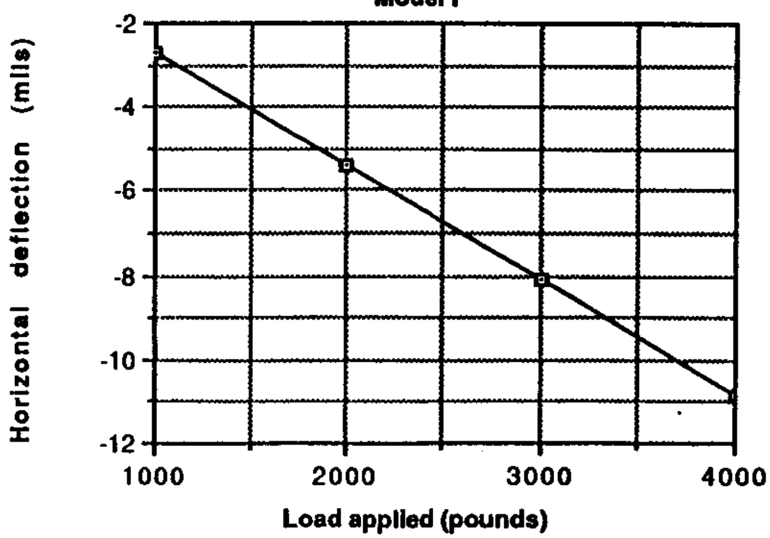


Figure 12: Change in Average Stress vs Load
Model I (stresses measured at inner-coil pole)