A Finite Element Analysis of an SSC Yoke Used for Mechanical Support of the Collared Coil

by

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Abstract

An analysis of the SSC yoke was performed using the finite element method. The model was based on the NC-9 cross-section. Both horizontally split and vertically split yokes were investigated. A variety of load cases were examined. The effects of varying skin prestress due to weld shrinkage and cooldown was investigated. Loading was applied to simulate the effects of magnet excitation. Both the horizontally split and vertically split yokes were given tapers of varying degree (including no taper) on the split midplane as a means of optimizing the load-deflection characteristics of the yoke. The analysis showed that a properly designed taper on the split midplane could improve mechanical performance slightly. However, if improperly chosen, a taper could worsen performance significantly. The study revealed that the most promising configuration was a vertically split yoke with a taper so designed to prevent the midplane from opening upon loading. The stiffness of such a yoke approached the limiting case of a "No Split" yoke. In addition, the investigation showed that one of the most practical ways to increase the overall yoke stiffness was to increase the outer skin prestress by controlling weld shrinkage.

2.0 Description of Model

A 2-D plane stress ANSYS finite element model of the yoke was developed for the calculations performed in this study. The node and element mesh is shown in Figure 2. The symmetry of the yoke permits the use of one quadrant to describe the entire model. The interface between the yoke and outer skin is specified using radial gap elements. The gap elements permit separation and frictionless sliding between the two parts, but allow compression if closed.

To model the horizontally split yokes, the vertical midplane of the yoke was considered a plane of symmetry, and the horizontal midplane was constrained with gap elements which allow separation of the two yoke halves along this midplane. Tapers were developed by varying the size of the gap along the midplane. The vertically split yoke was modeled similarly, except the boundary conditions were switched. The vertical midplane is now constrained with gap elements, while the horizontal midplane is treated as a plane of symmetry.

In a number of cases, the split midplane was given a taper. The motivation behind this is two-fold. First, due to simple geometric uncertainties and manufacturing and assembly processes, it is possible that the two yoke halves will not seat perfectly flush. A taper of one mil is permitted by the current specifications. Tapers can also exist as the result of the ovality of the collared coil combined with the effect of the skin prestress. Since even the slightest deflections are thought to have adverse effects on the performance of the magnets, the effect of a mismatch needed to be addressed. The second motivating factor for the introduction of a taper was that, by dictating what sort of taper exists, it may be possible to fine tune the deflections of the yoke such that the magnet achieves optimal performance. Tapers ranging from 5 mil to -5 mil were investigated for the horizontally split yoke as well as the vertically split yoke.

The convention used in this study was such that a one mil taper is equivalent to a change in elevation along the contacting midplane surface of a total of one mil. Thus, the point of widest separation between the two yoke halves will be 2 mils. In this analysis, a positive taper is one in which the outer radii of the yoke halves contact, while the maximum gap opening is at the inner radii. A negative taper will have the opposite characteristic; the inner radii will contact, while there is a gap at the outer radii. This convention was used for both the horizontally split yoke and the vertically split yoke. Figure 3 illustrates the definitions used in this study.

Material properties used are based on typical values for stainless steel and iron. For both materials, a Young's Modulus of 30 x 10^6 psi and a Poisson's ratio of 0.3 were used.

4. Results

This section discusses the major results obtained from the analysis.

4.1 Deflections

4.1.1 Horizontally Split Yoke

Deflections were determined as a means of evaluating the stiffness of the yoke. For each load case a comparison of the horizontal deflection (U_X) of the point marked "A" in Figure 4 was made. Deflections in this region are an approximate measure of the change in radius in the area adjacent to the collar and are a good indication of how the collared coil will move. This quantity is referred to as "radial deflection" for the remainder of this report. These deflections were shown to be a function of all variables involved in the analysis: initial prestress, applied horizontal loading, and degree of taper on the horizontal midplane. For a no-taper model (the two yoke halves are initially flush), applied force versus radial deflection is plotted for a number of skin prestress values in Figure 5. It is evident that the response of the assembly is non-linear for skin prestresses other than zero. The non-linearity stems from the bi-linear gap elements at the horizontal midplane. The gap has a zero stiffness until closed, at which point the load-deflection behavior is as if the structure were solid. Therefore, the non-linearity of Figure 5 would indicate that the gaps are opening up as loading is increased, and stiffness then decreases. The higher the skin prestress, the harder it is to open up the midplane. Therefore, the 40 ksi prestress case maintains a high stiffness longer than the 20 ksi case. (For the purposes of this report, stiffness is defined as the derivative of the load-deflection curve at a single point.)

For the case in which there is no initial skin prestress, the midplane gaps are all opened immediately upon loading (with the exception of the innermost contact point). As loading increases, the deflections increase, but the status of the gaps remains the same. Therefore, the 0 ksi prestress case results in a linear stiffness, and it yields a lower limit for the stiffness of the horizontally split yoke. Note that the slope of the curves for both the 20 ksi and 40 ksi prestress approaches the slope of the 0 ksi case as load is increased. An upper limit on the stiffness of the yoke is represented by the "No Split" case in Fig. 5. In this case, no gaps are allowed to open, and the structure maintains a high stiffness.

In addition, changing the degree of the taper on the horizontal midplane has a pronounced effect on the load-deflection characteristics of the yoke. In Figure 6 are plotted several curves for various tapers for the case of a constant skin prestress of 20 ksi. The most pronounced effect of the taper is a change in the initial deflection due to the skin prestress. This is the zero applied load deflection. At first, this might be considered to be advantageous, since it would help assure contact between the yoke and collared coil. However, the low stiffness of the structure is undesirable.

On the other hand, a negative taper improves load-deflection response greatly. There is only a small outward initial deflection, and the stiffness approaches that of the "No Split" case. Given these encouraging results, a series of negative taper models were developed and run with a 40 ksi prestress, a value that appears to be more likely than 20 ksi. Figure 10 presents the data from those runs. As can be seen, the data crowds around the "No Split" case, which is the upper bound for stiffness. Only the -1 mil taper model showed signs of significant gap openings. All other curves show a relative stiffness approximately 90% of the "No Split" case. Initial deflections are either negligible or inward, in which case performance may *exceed* the "No Split" case. Of all the configurations investigated, the vertically split yoke with a negative taper appears to provide the best load-deflection response.

4.2 Stresses

The stresses developed in the yoke were of secondary importance, since they were believed to be far below the yield strength of the material. However, it was necessary to determine the stresses, primarily due to the brittle nature of iron at low temperatures. Stresses were a function of the same factors as were displacements. Changing skin prestress, midplane taper, or applied loading all had an effect on the developed stress. In general, the stresses developed for all cases were far below the static strength of the low carbon steel used in the construction of the yoke. The only real concerns are the high tensile stresses in the area of the alignment slot located on the inner radius of the vertical midplane for the horizontally split yoke and in the area of the horizontal midplane outer radius for the vertically split yoke. These areas are illustrated in Figure 11. The nature of the tensile stresses and their relation to the possibility of brittle failure was investigated in a separate study[3].

4.2.1 Horizontally Split Yoke

For a no-taper, horizontally split yoke with a 20 ksi skin prestress and an applied horizontal load of 4000 lb, the maximum tensile stress was 26.9 ksi. The inner corner of the alignment slot was modelled with a sharp corner, rather than the 0.03" corner fillet specified in the design, and the region was not finely meshed so as to pick up the stress concentration accurately. Therefore,

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[3] - J. M. Cortella. *Investigation of Brittle Behavior of SSC Yoke*. MD-TA-105. November, 1988.

4.3 Additional Investigations

An additional model was developed in an attempt to combine the advantages of a negative taper with those of a positive taper. It was hypothesized that a concave interface as shown in Figure 13 would prevent the initial outward deflection characteristic of a positive taper, but at the same time, maintain a high stiffness upon loading. As is shown in Figure 14, this hypothesis appears to be correct. The data is for an interface with a maximum half-gap of 3 mil at the midpoint of the interface. The initial deflection is minimal, and the configuration maintains a stiffness similar to the "No Split" case until after 3000 lb. The stiffness drops off rapidly for higher loads, since once the outer contact point opens, the entire interface is open (with the exception of the inner contact point). It may be possible to adjust the concave interface in such a way to actually get a small inward deflection and maintain high stiffness. However, the gain in stiffness is not likely to yield more than a half mil over the no-taper model for a typical load case. No similar study was performed for the vertically split yoke since it is believed that such an interface will not improve upon the results obtained with the negative taper.

In addition to the determination of deflections and stresses of the various yoke configurations under normal loading, the bending stiffness of a single half of the horizontally split, no-taper yoke was determined. If the collared coil has any ovality, the yoke will come in contact with the upper alignment tab of the collar and then bend downward as the skin prestress compresses the yoke. Using a 20 ksi prestress, the maximum downward deflection was calculated and determined to be 5 mil. With a skin thickness of $\frac{3}{16}$ in, this translates into a bending stiffness of 0.75×10^6 lb/in per unit length of dipole.

For the horizontally split yoke, the lower limit on stiffness is the bending stiffness of the yoke. For the vertically split yoke, the lower limit is the membrane stiffness of the outer shell, a prohibitively low stiffness.

Stresses did not appear to be a major concern. A couple of regions developed high tensile stresses (up to 30 ksi) in areas of stress concentrations. A previous study demonstrated that tensile stresses of this degree are a problem only in the presence of substantially sized cracks (100 mils or greater). Nevertheless, to prevent such high tensile stresses, it is recommended that the skin maintain a prestress of 40 ksi or higher. Magnitudes of tensile stresses were higher in the horizontally split configuration, due to the presence of a high stress concentration. Compressive stresses were far below the yield strength of the material.

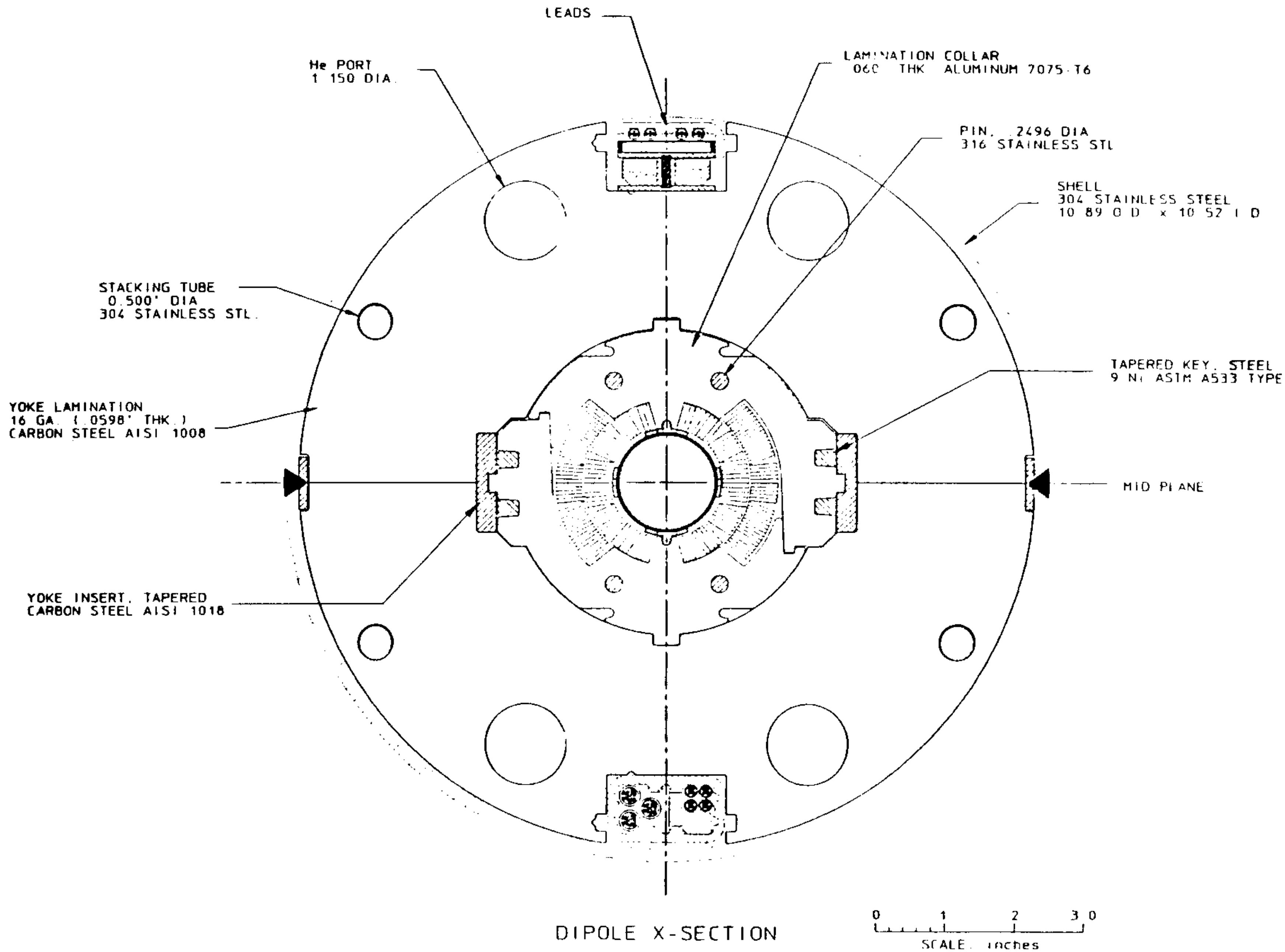

Figure 1 - SSC cold mass based on LBL NC-9 cross-section showing collared coil and yoke.

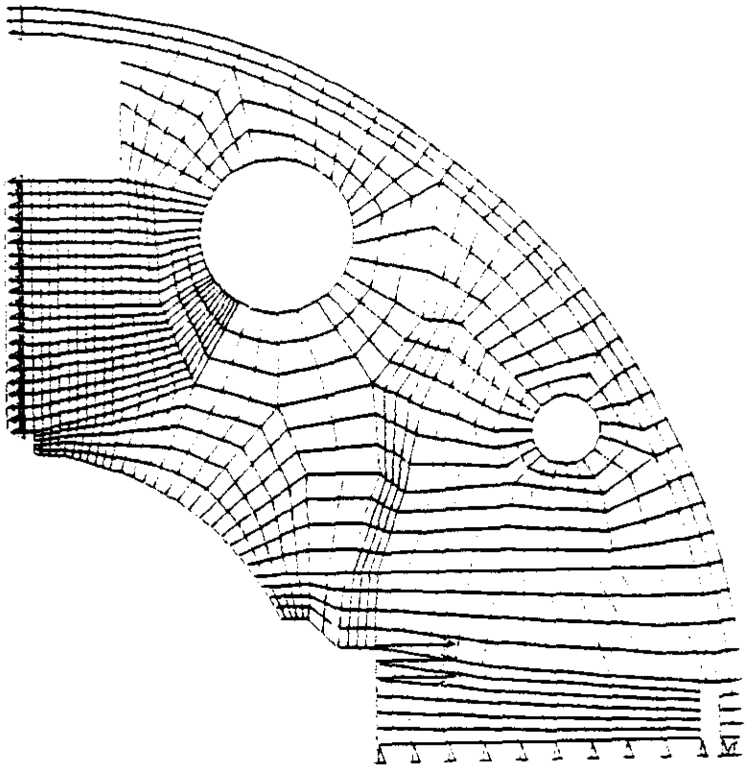

Figure 2 - Node and element mesh used in the analysis. Boundary conditions are changed to reflect the configuration.

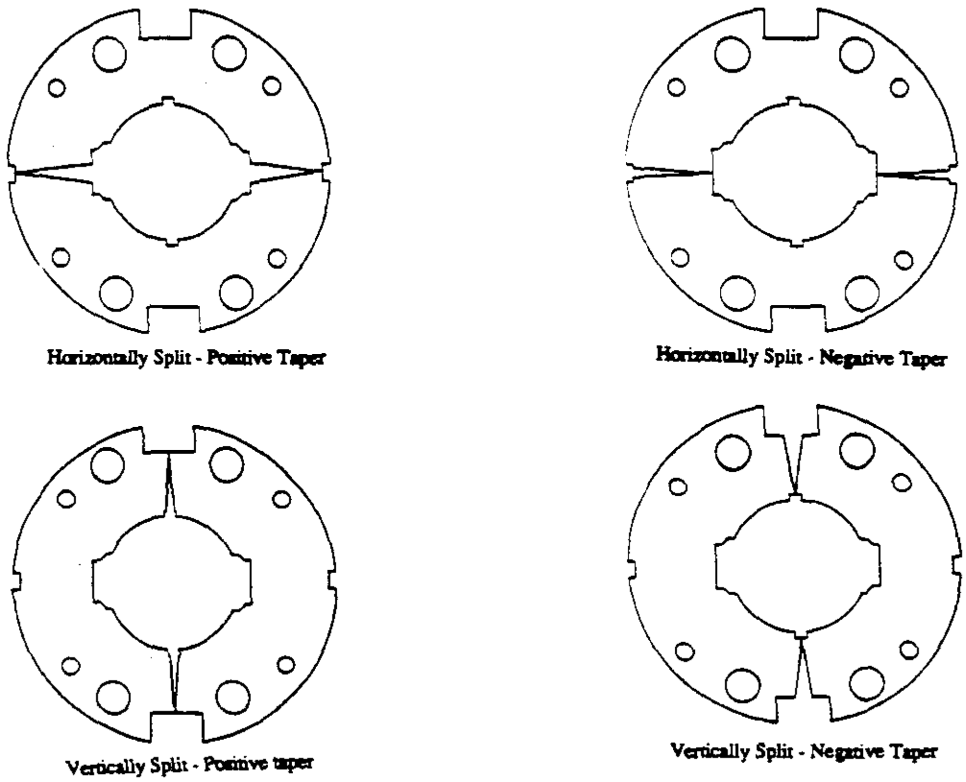

Figure 3 - Definitions of tapered yokes used in this study.

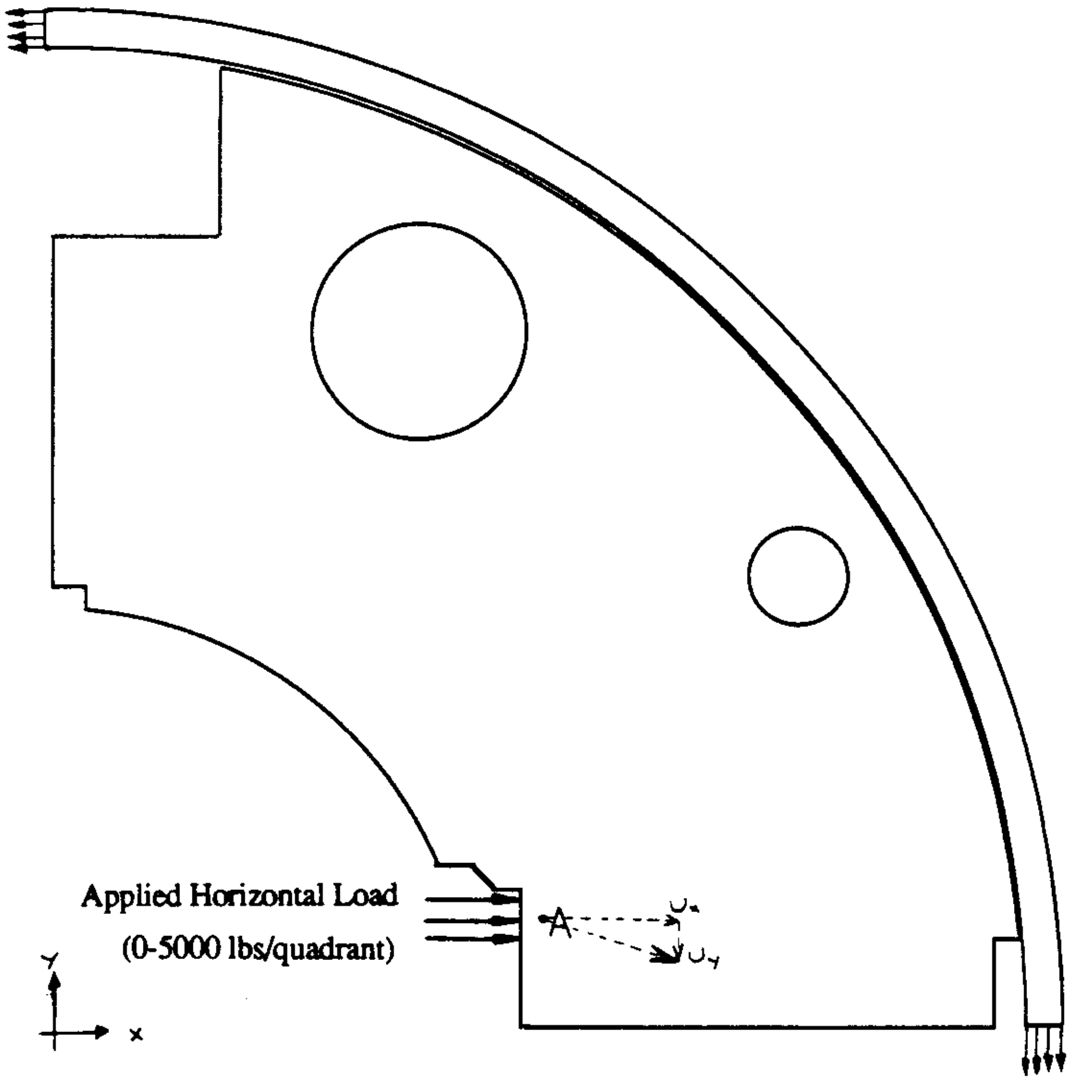

Figure 4 - Forces acting on yoke. Displacements were measured from point A. Only the deflection U_x was compared for the various load cases.

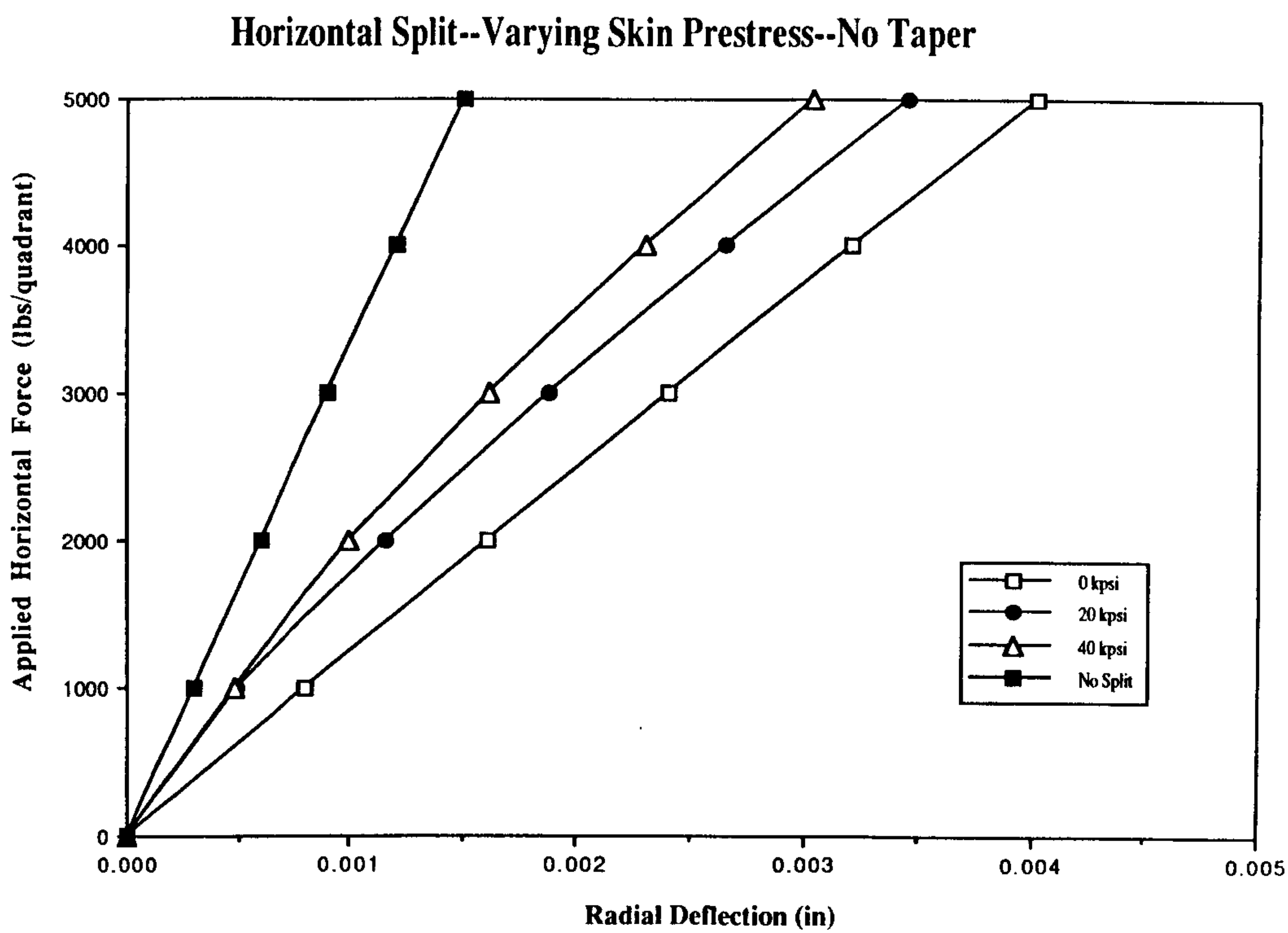

Figure 5 - The effect of varying the outer skin prestress on a horizontally split yoke with no taper on the midplane. The maximum stiffness obtainable is represented by the "No Split" case.

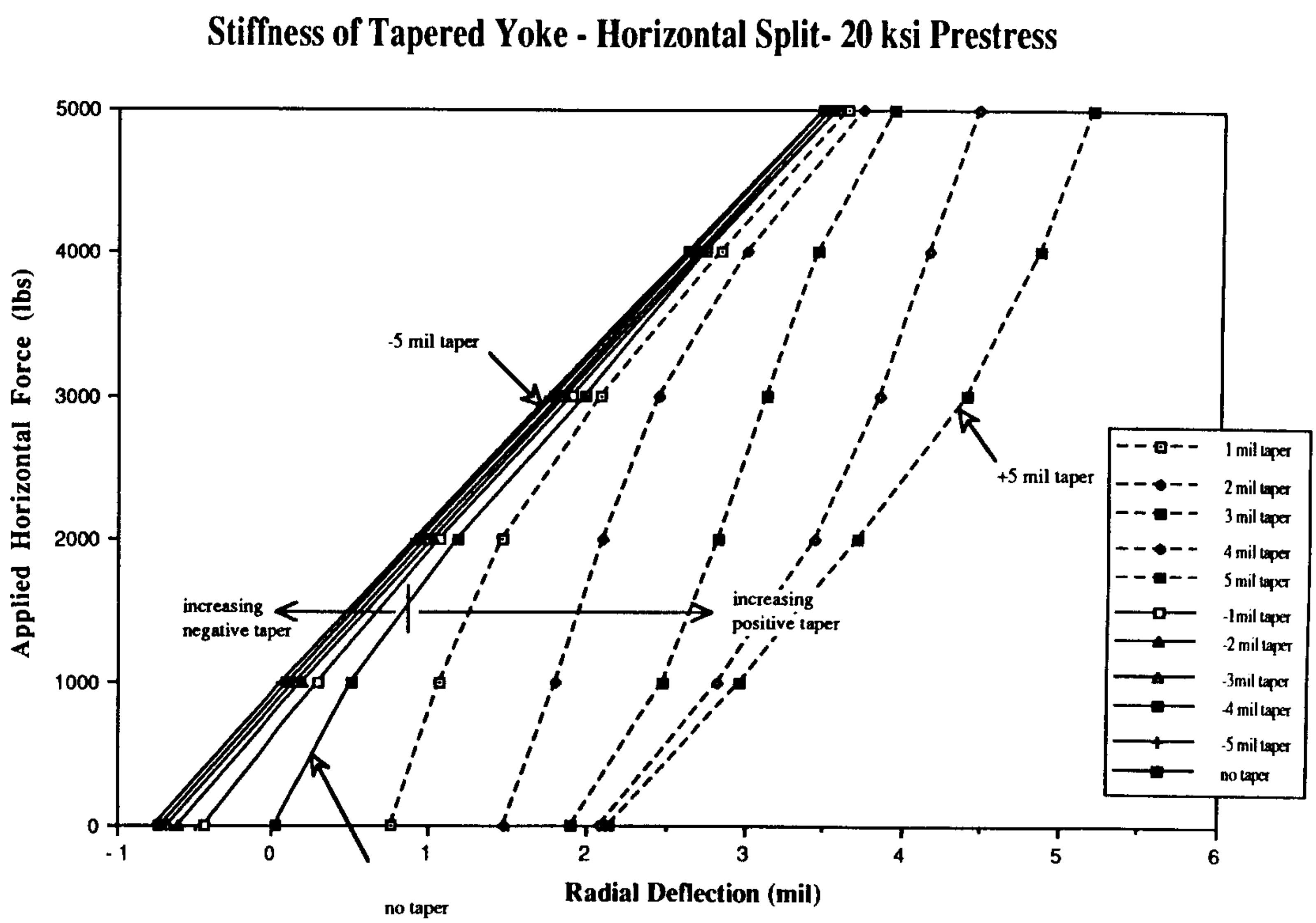

Figure 6 - The effect of placing a taper on the midplane of a horizontally split midplane. Results from using various tapers are plotted.

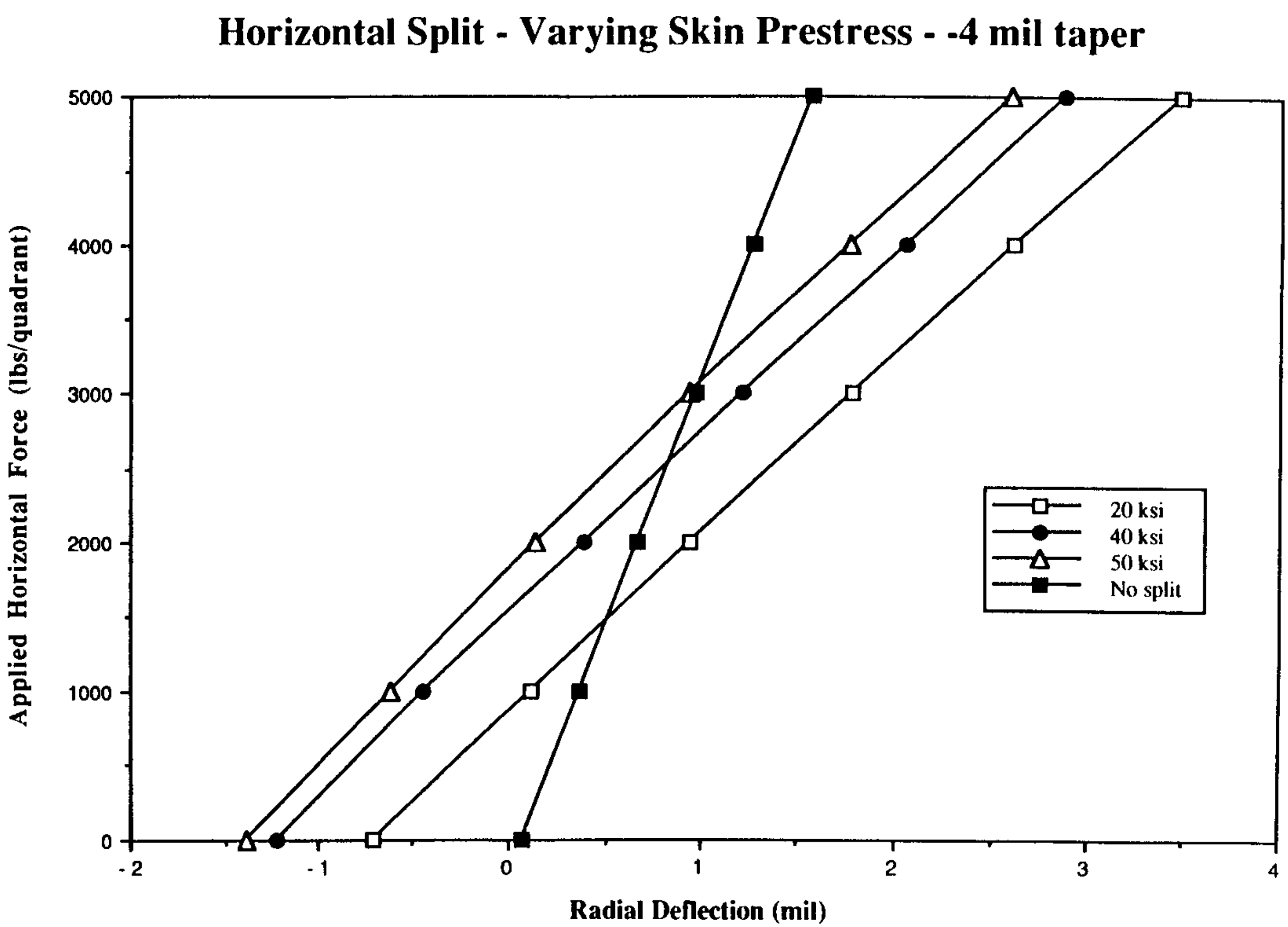

Figure 7 - The effect of varying skin prestress for a negative taper on a horizontally split yoke. Comparison with the "No Split" case shows the low stiffness of an "already-opened" yoke.

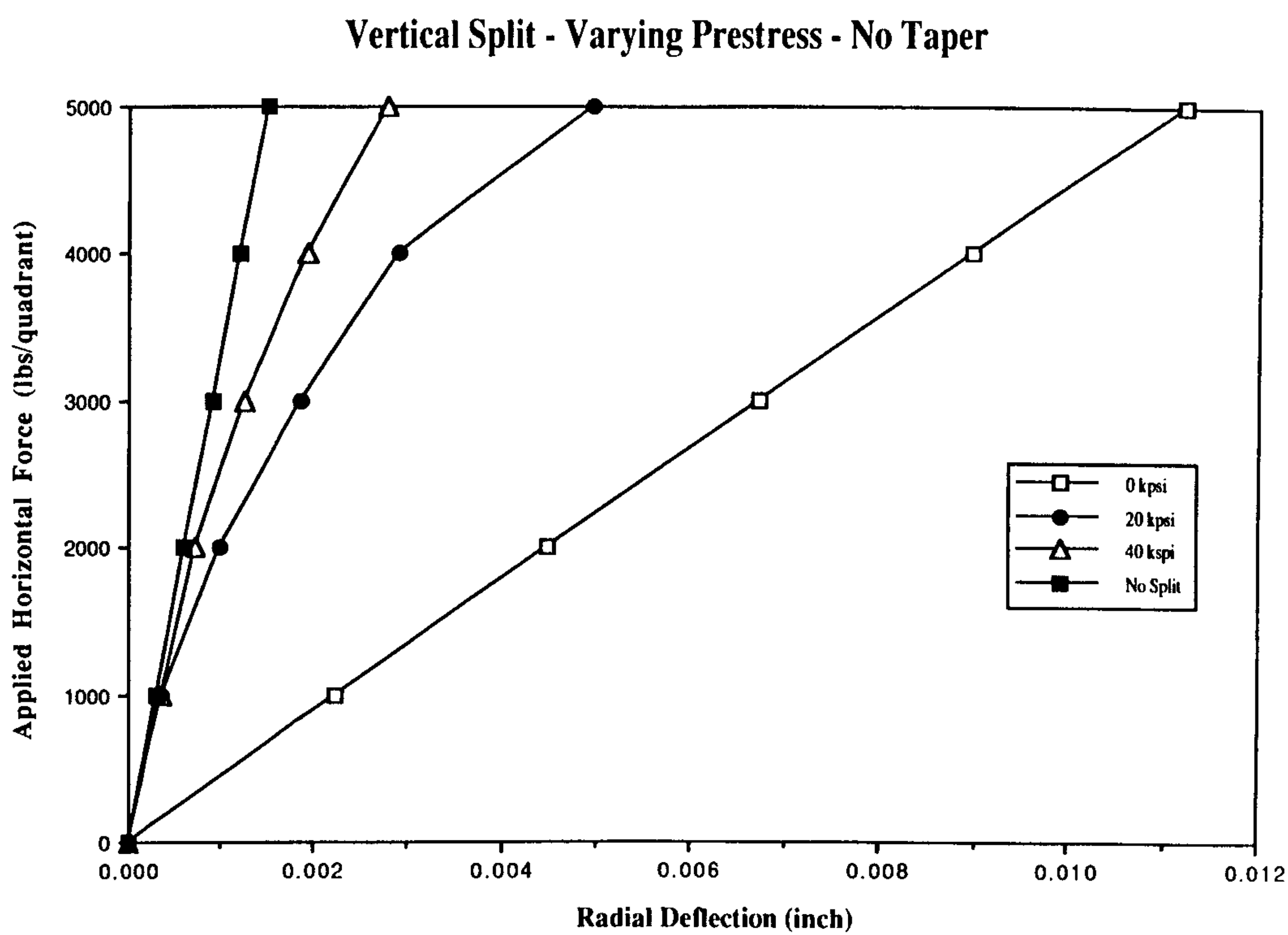

Figure 8 - The effect of varying the outer skin prestress on a vertically split yoke. The 0 kpsi case represents a low-end limit.

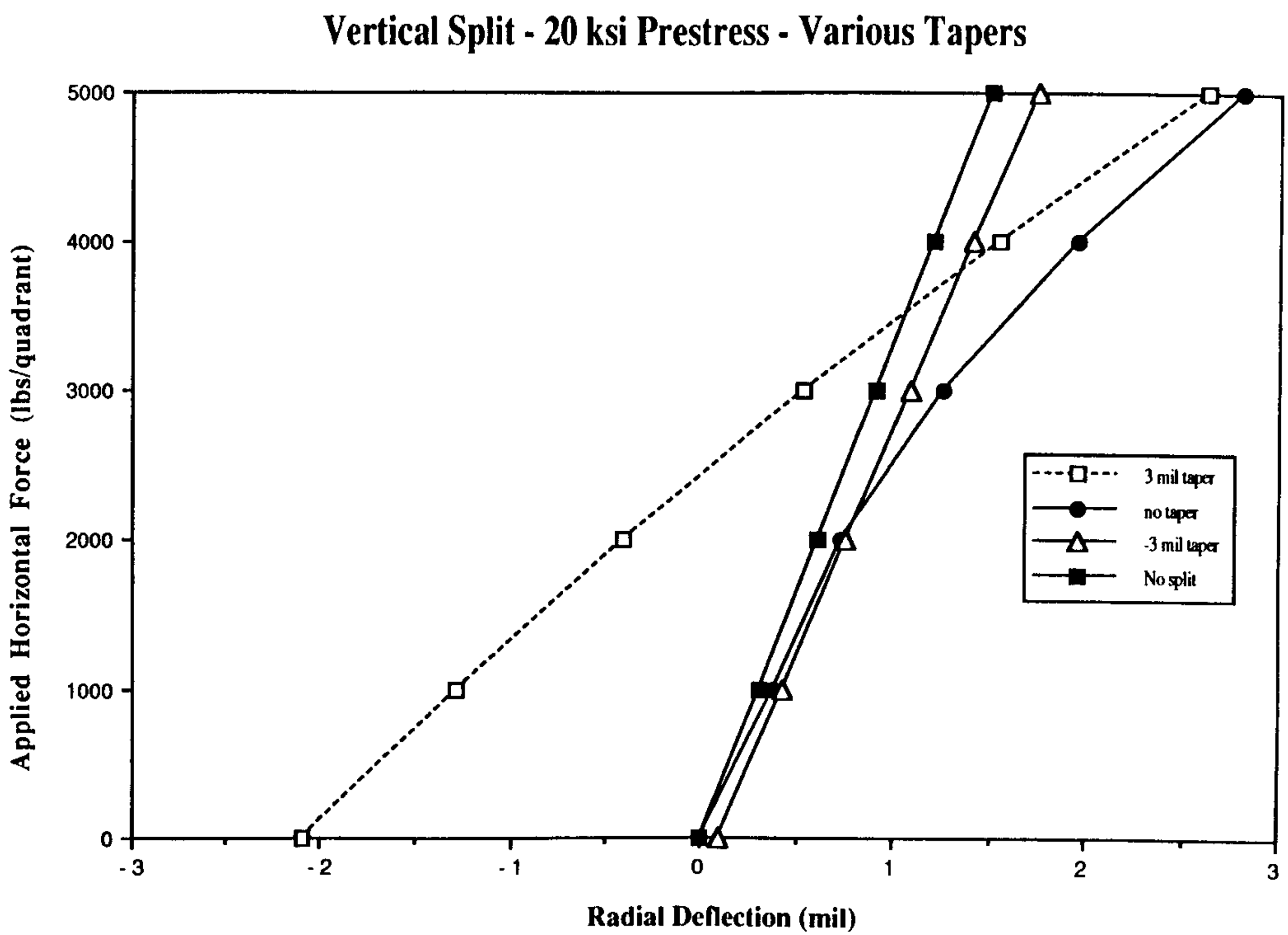

Figure 9 - The effect of varying the taper on a vertically split yoke. Note the very low stiffness of the positive taper case.

Vertical Split - 40 ksi Prestress - Various Tapers

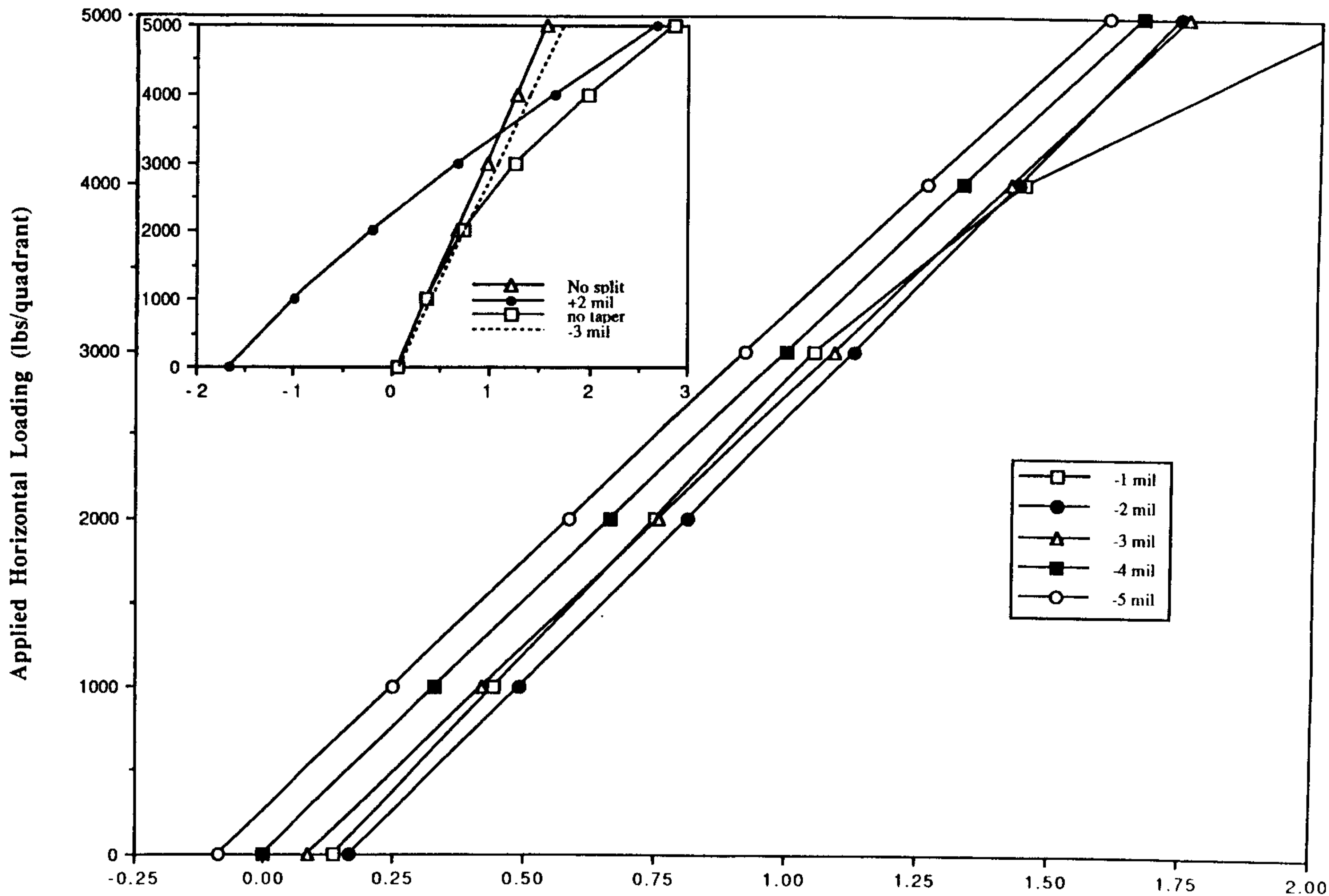

Figure 10 - A comparison of load-deflection response for a vertically split yoke with negative tapers. The curves group around the "No split" curve

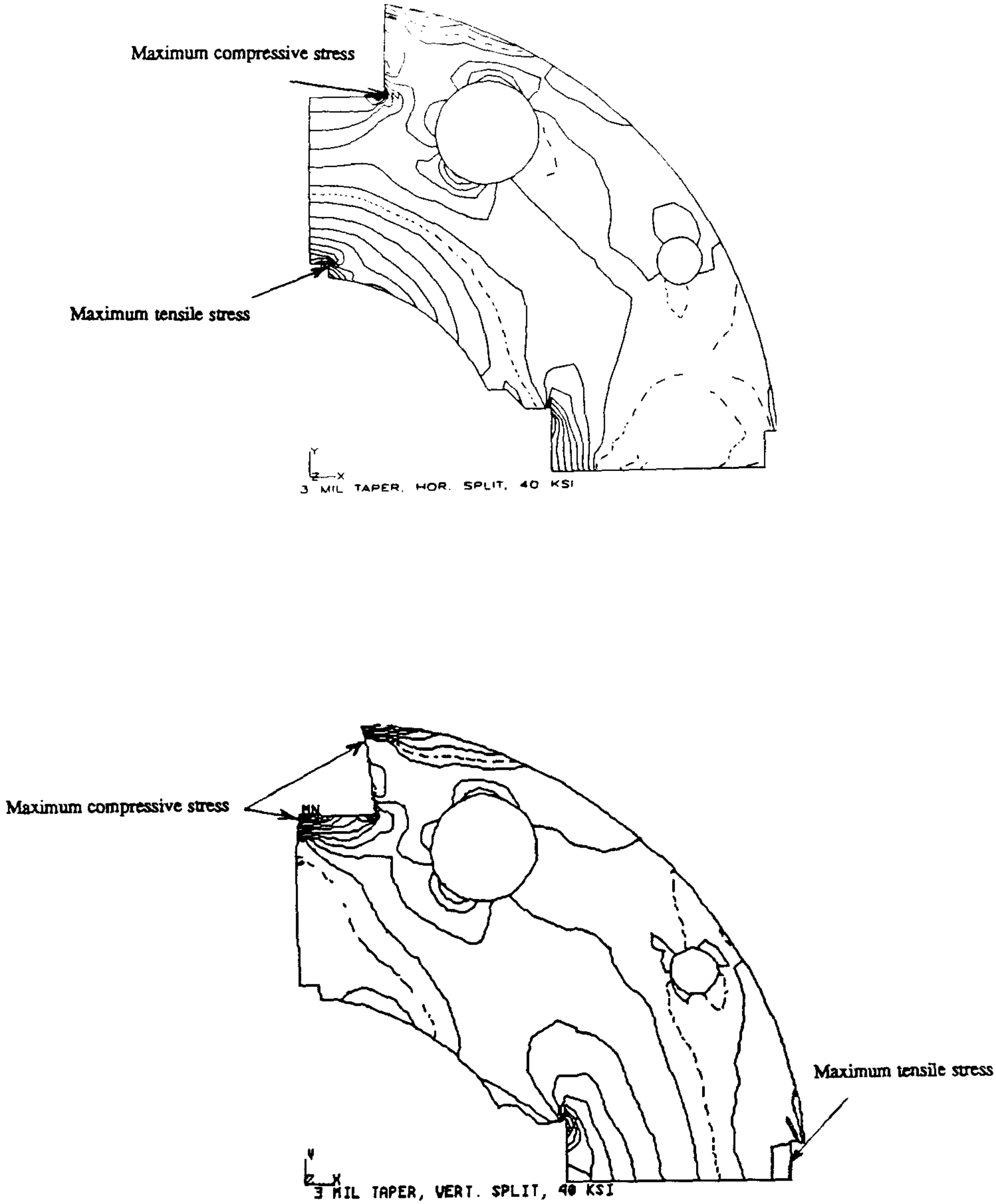

Figure 11 - Typical plots of azimuthal stress for each of the two major configurations, showing areas of maximum stress.

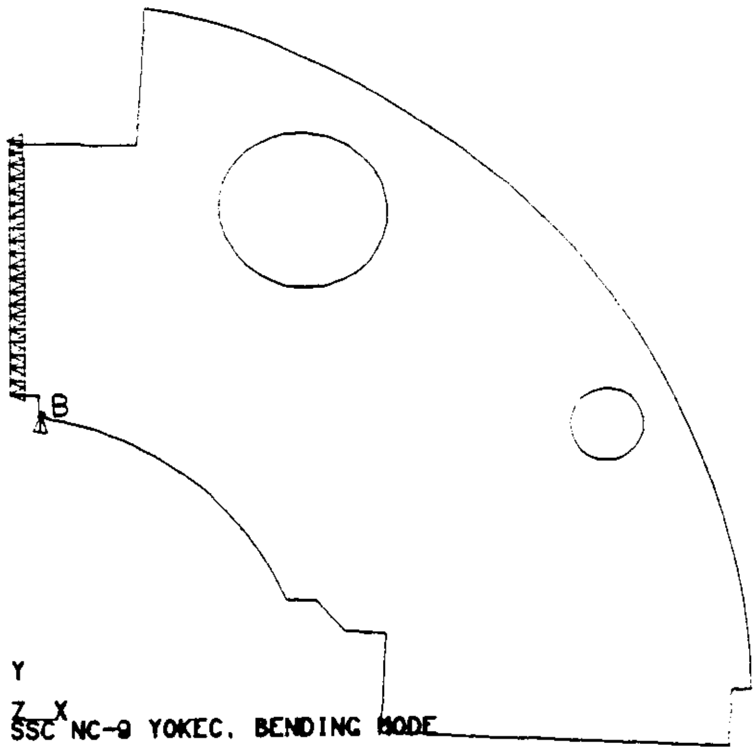

Figure 12 - Bending of yoke subject to outer skin prestress with vertical constraint at point B. There is no constraint on displacement of the horizontal midplane.

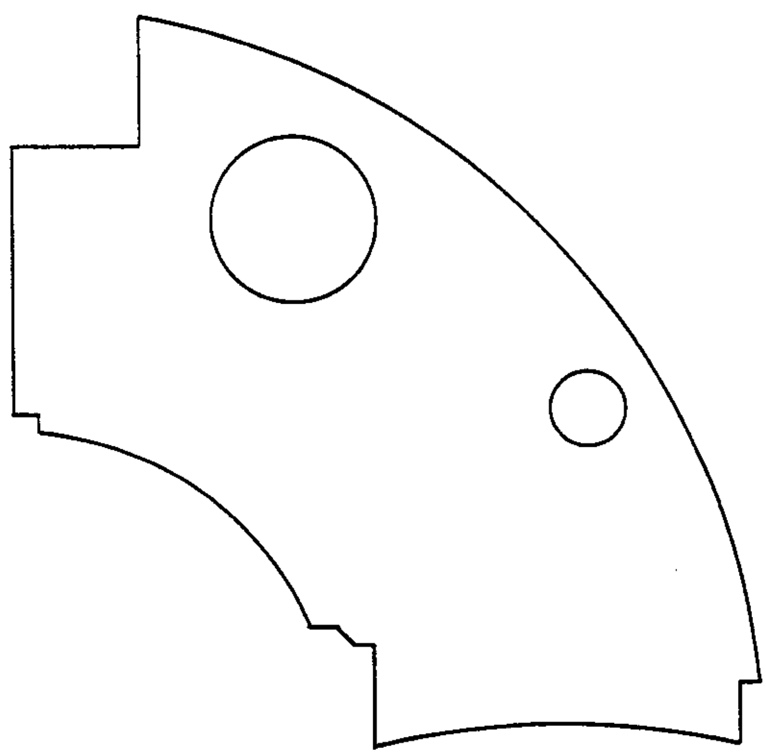

Figure 13 - Configuration of yoke with concave interface.

Horizontally Split Yoke - 40 ksi Prestress - Concave Taper Comparison

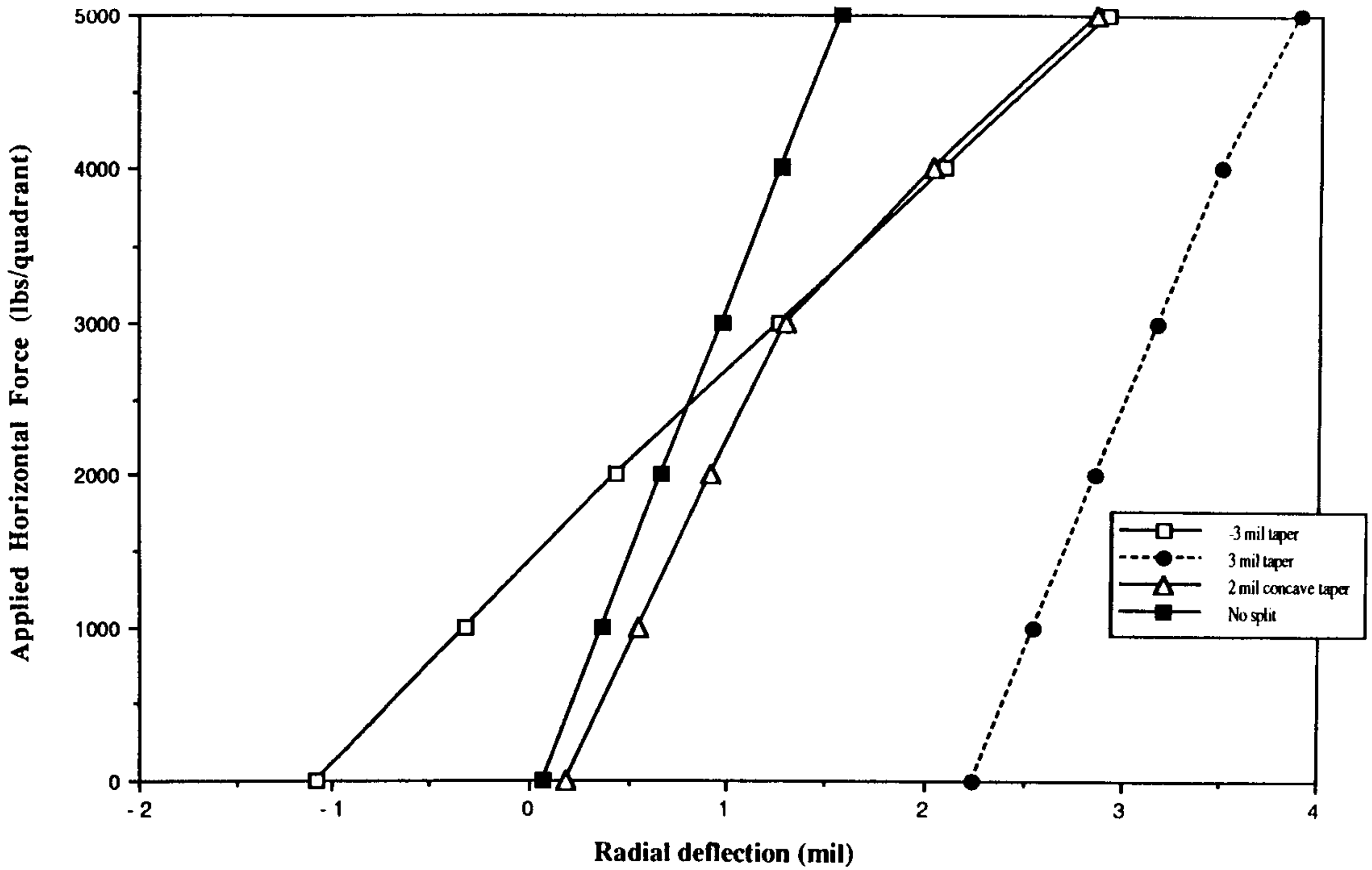

Figure 14 - Comparison of concave interface with various other configurations.