Fermilab

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Plastic Finite Element Analysis of D0 Toroid Iron Welds

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Introduction

The assembly of the D0 toroid iron involves the use of large groove welds to connect massive blocks of steel. These welds are very heavily constrained, and large thermal strains develop which have produced large cracks in the base metal near the weld. The effort to solve these problems has involved investigations of weld geometry, weld preparation, and the metallurgy of both the base metal and the welding rod. The purpose of this analysis was to compare the effects of two welding rods with markedly different yield strengths and post-yieding behaviour on the plastic strains developed in the base metal near the weld.

Approach

The calculation of accurate thermal stresses in welds would require a thorough analysis of the geometry and thermal history of the weld, i.e., the deposition of material and heat by the welding process, and the dissipation of that heat by conduction through the base metal and convection to the surrounding air. The time available for this investigation did not allow such an analysis; Therefore several simplifying assumptions were made in the modeling process. The justification for these assumptions is that the real issue is not the absolute values of stress in the weld, but rather the relative difference between the stresses produced by two welding rods of different yield strength. This difference should be well approximated by the model.

The following simplifying assumptions were made:

1. The actual weld is deposited in several small discrete "stringers". The weld as modeled in this work is assumed to have been deposited as a single stringer.

2. The shape of the actual weld is crudely triangular, without well-defined radii at the transitions near corners. The model of the weld is triangular in shape, with 1/16" radii. This allows a uniform radial meshing around the fillets.

3. The actual weld produces a heat-affected zone where the chemistry and mechanical properties of the base metal are affected by the welding process. This effect is crudely considered in the model by assuming that the weld metal extends 1/8" into the base metal of the weld groove. (see Fig. 1.). The boundary between the base and weld metals is discrete, with no smearing of properties through any transition region.

4. The temperature history of the actual weld would probably show thermal gradients within the weld prior to cooling, as well as significant heating of the base metal. The temperature gradients used in this analysis were generated from the simple assumption of an initial weld stringer temperature of 1350 F, and a surrounding base metal temperature of 70 F.

5. The base metal will develop thermal stresses due to the heating during welding. These stresses will serve to reduce the effects of weld metal shrinkage. In this analysis it was assumed that no such stresses were developed. The base metal is assumed to be unstressed at the beginning of weld cooldown, and does not shrink or expand as the weld cools. This produces a "worst case" thermal stress situation.

6. The Young's modulus, thermal contraction coefficient,and thermal conductivity of the weld and base metals are all functions of temperature. Although the inclusion of these effects is straightforward in the ANSYS program, the data was not readily available. For this reason and because of the approximations already made in calculating the temperature gradient, these material properties were assumed to be temperature-independent throughout the analysis.

Plasticity effects in the weld were modeled by the ANSYS program using a non-linear, non-conservative technique. The option chosen for this analysis was classical bilinear strain-hardening, which is the most simple of the ANSYS plasticity options. The stress-strain curve is input as a piecewise linear curve of two parts. The initial behaviour, up to the yield stress of the material, is assumed to be linear with a slope equal to the Young's modulus of the material. The post-yielding behaviour is also assumed to be linear, but with a slope corresponding to the tangent Young's modulus of the material in the range of interest.

The stress-strain curve for the base metal was available from test performed on the actual material. This curve has a shape characteristic of low-carbon steels, with a well-defined yield point, and a virtually flat, or perfectly plastic, post-yielding curve. The tangent modulus for this material was taken as 0.05 psi, which is the minimum recommended for ANSYS input.

The stress-strain behaviour for the weld metals was not directly available from tests. For these metals it was assumed that the shape of the post-yielding curve would be well approximated by that of metals of the similar composition. Unlike the base metal, both welding metals show significant strain hardening which varies with strain. Therefore, only an approximate tangent Young's modulus could be found.

The welding rods considered in this analysis were (1) E7018, a metal corresponding approximately in chemistry to a 1506 carbon-manganese steel, and (2), Ni55, a nickle alloy rod with a nominal composition of 54.5%, 0.38% Mn, balance Fe. Table I summarizes the properties used in the analysis.

The weld geometry modeled is shown in Fig. 1. A half-filled weld was modeled, because it was at this point in the welding that most cracking was observed. The two separate blocks of base metal are in compressive contact along their boundary. This is modeled by coupling the vertical motion of the nodes along the boundary between the blocks, but allowing the blocks to move independently horizontally. In this way, no shear force can be developed between the blocks.

The temperature gradients were generated by ANSYS in a separate transient thermal analysis. This was done primarily to produce somewhat realistic gradients, and to take advantage of the ANSYS feature that inputs thermal results directly into structural analyses. The gradients used represented an initial weld temperature of 1350 F, and a final weld temperature (and surrounding base metal temperature) of about 100 F.

Results

The amount of base metal which yielded for each of the two weld rods is shown in Fig. 2. Yield was defined by the maximum shear stress criterion. It can be seen that the volume of base metal yielded by the Ni55 rod is approximately half that yielded by the E7018 rod. The extension of yielding into the root area of the weld is consistent with the shrinkage of the weld metal, since this shrinkage will produce a compressive stress parallel to the weld groove face, and a tensile stress perpendicular to the face, resulting in a combined stress state which will produce yielding sooner than either of the two stresses individually.

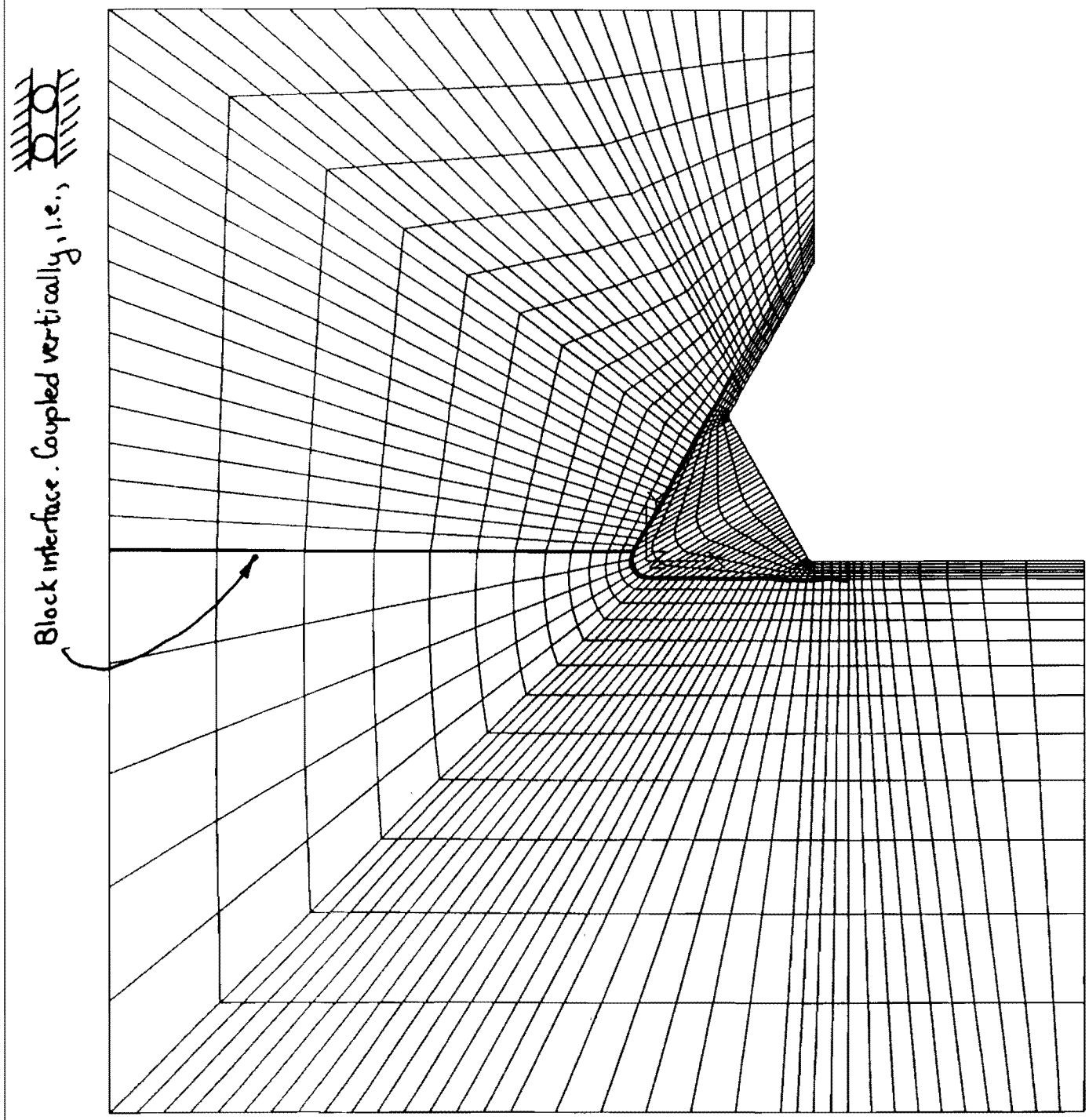
Conclusions

The cracking in the vacinity of the actual weld is a fracture phenomenon, and could be occuring at stresses less than the yield stress of the base metal. This is because fracture is a flaw-sensitive failure, and crack growth is a function of crack geometry as well as stress. This analysis does not deal with fracture mechanics; It simply assumes that reducing the amount of yielding in the base metal will reduce the tendency to fracture.

The numerous simplifications in this model make it impossible to draw a conclusion beyond the indication that the Ni55 rod will yield about half as much base metal as the E7018 rod. In the face of the eight-fold increase in cost of the Ni55 rod over the E7018 rod, this improvement seems modest, and needs to weighed against other possible improvements in weld size and preparation.

Table I. Material Properties

Material	Reference Material	Young's Modulus (psi)	Tangent Modulus (psi)	Thermal Contraction Coefficient in/in-F
Base Metal	Measured	$30(10^6)$	0.05	0.0
E7018 weld	manganese steel	$30(10^6)$	$1.5(10^5)$	$6(10^{-6})$
Ni55 weld	Nickel steel	$21.4(10^6)$	$6.7(10^5)$	$5.5(10^{-6})$



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NOV 20 1987
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POST1 ELEMENTS

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Fig 1. Finite Element Model of DØ Toroid Iron Weld

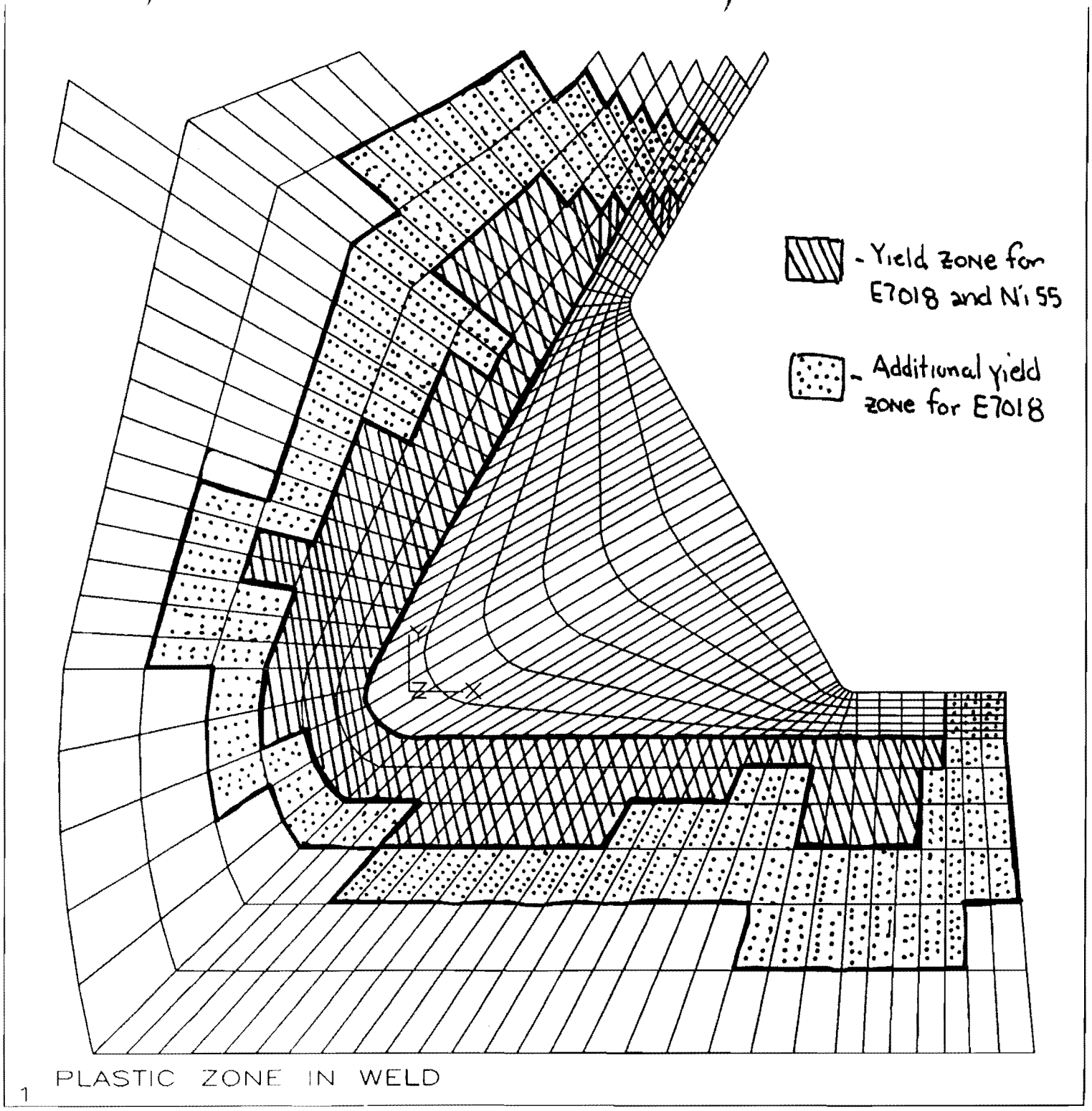

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Fig 2. Extent of Base Metal Yielding