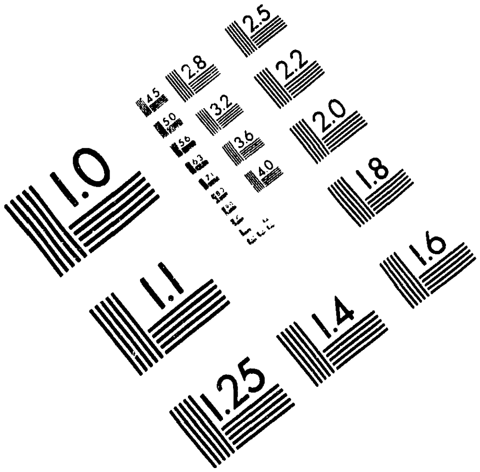

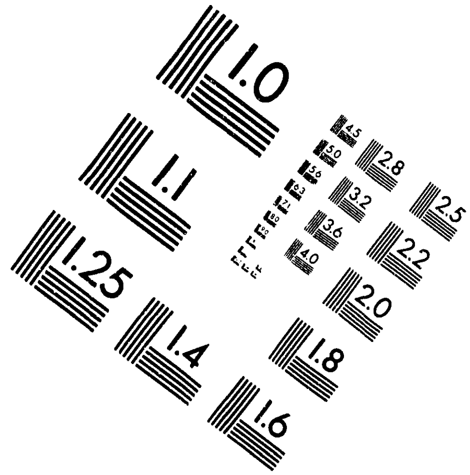

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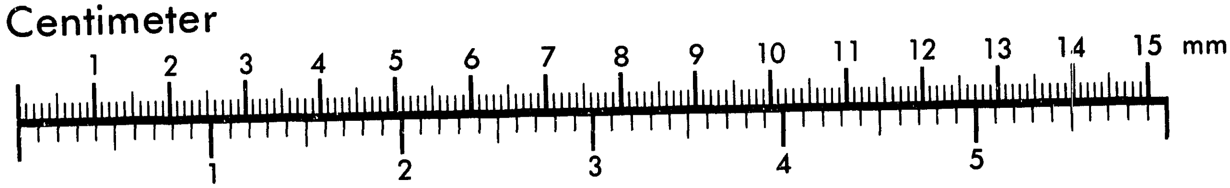

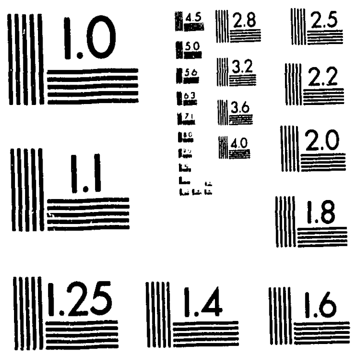

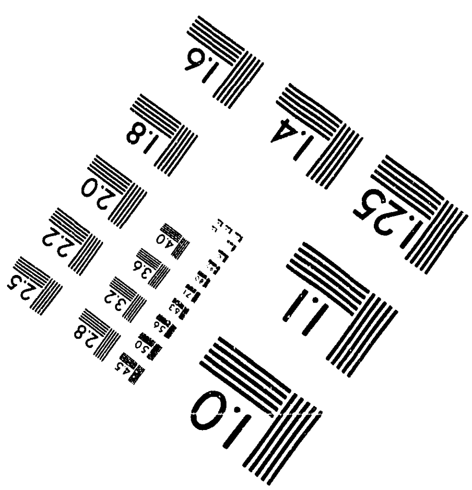

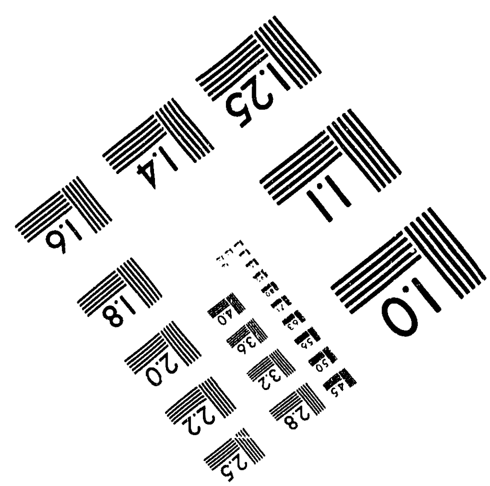

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ITER-Hard Toroidal Field Coil Structural Analysis

Dr. Sarah J. Wineman

October 15, 1992

Lawrence Livermore National Laboratory

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ITER-HARD Toroidal Field Coil Structural Analysis

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June 23, 1992

1 Overview

The High Aspect Ratio Design (HARD) for the International Thermonuclear Experimental Reactor (ITER) has Toroidal Field (TF) coils that are farther out from the center of the toroidal ring and more elongated than the previous design (CDA, [1]). These coils should see higher forces than in CDA and were designed accordingly. The objective of this work, conducted at LLNL and the MIT Plasma Fusion Center, was to determine whether stress levels in the ITER-HARD design are acceptable. A global finite element model, representing one of the coils, was modelled at MIT [2] to obtain stresses and displacements both during operation of the TF coils alone, and during the End of Burn phase with TF and PF (Poloidal Field) coils operating. At LLNL, a detail model of the TF coil straight leg near the equator was used to obtain stresses and displacements during TF operation only. Further detailed analysis of the winding pack of this model was done to estimate stress concentrations in the conduit and insulation.

2 Global model of TF coil

The MIT Plasma Fusion Center modelled one of the reactor's sixteen TF coils (Fig. 1) under magnet loadings [2]. The bottom half of the coil case was left off due to symmetry, but the bottom half of the winding pack was needed for magnetic force calculations. The coil winding pack was modelled as an orthotropic material with averaged properties based on the properties of the components: superconducting strands, conduit, and insulation. The Young's moduli and Poisson's ratios were estimated from rule-of-mixtures arguments [3]; the ANSYS finite element program [4] used these to estimate shear moduli for the winding pack. The material properties used by LLNL and MIT are listed in Table 1. For the MIT analysis, the winding pack was assumed free to slide inside the case.

Table 2 summarizes the results of this analysis and the LLNL analysis described below. Stresses are given in terms of Tresca stress intensity, defined as the difference in maximum and minimum principal stress. Apart from stress concentrations where the TF intercoil structure joins the outer legs, the region of maximum stress is the nose of the case near the equator (horizontal symmetry plane). The Tresca stress intensity here of 620 MPa is comparable to the CDA stress of 609 MPa. The End of Burn operation phase, when the PF and TF coils are both energized, adds out-of-plane loadings to the TF coils. However, this does not have a great effect on the stresses in the straight leg near the equator. MIT's analysis showed [3] only a small (about 10%) excursion in stress between TF only and End of Burn operation for the nose of the straight leg near the equator, even though the stress magnitude there is high. Therefore, a static stress allowable should be sufficient for this region, rather than a fatigue allowable.

The MIT report [2] also gives estimates of stress in individual components of the winding pack from the averaged properties and volume fractions of each component. They estimate a Tresca stress intensity of 510 MPa in the conduit, and 110 MPa and 20 MPa compressive and interlaminar shear stress in the insulation. These are misleadingly low, as shown in Table 2. Detailed models of the winding pack are necessary to capture stress concentrations.

3 Detail model of TF coil

In order to capture the details of stresses both in the case and inside the winding pack, an intermediate 3D detail model of part of one TF coil was done at LLNL, followed by a still more detailed model inside the winding pack. The detail model was of a 1.6 m high part of the inner leg, starting at the equator (Fig. 2). The model used orthotropic elastic properties for the winding pack (Table 1) and isotropic elastic properties for the Incoloy case. The orthotropic properties of the winding pack were determined by three-dimensional finite element analysis of a quarter-section of a conductor. The winding pack was tied to the case so that there could be no relative motion. All stress analysis was performed using the program NIKE3D with pre- and post-processors INGRID and TAURUS [5, 6, 7].

The TF coils are wedged together at their inner straight legs, which have a keystone-shaped cross section. When these D-shaped coils are energized, magnetic forces act to make them more circular, so that the winding pack in the straight leg is stretched vertically and also pushes towards the center of the toroid. There develops, then, a vertical tensile stress in the straight leg, and, because of the wedging together of the coils, a hoop compression around the toroid. There is also some radial stress caused by the winding pack's pressing towards the center, but the hoop compression is the largest stress, followed by the vertical tension. To model this wedging, the side walls of the case were kept from spreading using symmetry planes. The coil model was, however, allowed to move in the radial (y) direction. The coil was restrained from vertical (z) motion at the horizontal symmetry plane, with an applied force on the 1.6 m high face to give the vertical tension combined with displacement constraints so that the face remained planar. Magnet forces pushing the inner leg inward were modelled as nodal forces on the winding pack. Magnet loads had been determined by Bob Wong of LLNL using the program EFFI [8]. It is interesting to note that since the magnet forces are not evenly distributed over the coil, detailed knowledge of them is necessary for correct stress results.

Fig. 3 shows the displaced mesh for TF operation, with the coil displaced inward. Figs. 4, 5, and 6 show the x-, y-, and z-stresses in the coil cross section. Fig. 7 is a plot of the Tresca stress intensity ($\sigma_{max} - \sigma_{min}$). The highest Tresca stress intensity is 606 MPa, in the nose of the case, below the allowable of 800 MPa and comparable to the CDA and MIT stresses.

In order to determine stresses inside the winding pack, a detailed section of the pack was modelled. Fig. 8 shows the finite element mesh of a quarter of a conductor, including the superconducting strands, Incoloy conduit, glass-epoxy insulation and epoxy fill in the corner. Table 1 shows the properties used for these materials. This detailed model represented a conductor at the center of the pack, near the inner edge, where stresses are high but shear stress is very low, and deformation should be fairly uniform between conductors. Therefore, the outer surfaces of this mesh were constrained to remain plane, with pressure boundary conditions taken from the previous detail model. The resulting stresses were high in both the conduit and insulation (Fig. 9). The maximum Tresca stress intensity in the conduit was 1260 MPa, well above the allowable of 800 MPa. Stress components in the insulation were examined to determine the worst-stress location. This was found to be near the corner of the conduit, with 230 MPa normal compressive stress and 140 MPa interlaminar shear, above the interlaminar shear allowable of 33 MPa. These high stresses would not be apparent from estimating stresses from an averaged-properties model.

4 Implications for design

The stresses in the ITER-HARD coil case are comparable to those in the previous, CDA, design, and below the allowable stress. Since there is only about a 10% difference in straight-leg stress when out-of-plane loading is combined with in-plane loading, static stress allowables can be used rather than fatigue allowables to size the TF coil straight leg.

Detailed analysis of the winding pack gives stresses in the conduit and insulation significantly above the allowable stresses. Since previous structural analyses were not detailed enough to include stress concentration effects, the peak stress estimates for previous ITER TF coil designs may also be too low. A new design of the winding pack giving lower stresses is needed.

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Table 1

Material Properties Used in LLNL and MIT Models

LLNL Properties of Coil Components

Superconducting strands

E_x = 0.6 GPa	G_{xy} = 1 Pa	υ_{xy} = 0.01
E_y = 0.6 GPa	G_{xz} = 1 Pa	υ_{xz} = 0.01
E_z = 30 GPa	G_{yz} = 1 Pa	υ_{yz} = 0.01

Insulation

$E_{in\text{-}plane}$ = 30 GPa	G = 8.6 GPa	υ = 0.3
$E_{through\text{-}thickness}$ = 15 GPa		

Epoxy fill

E = 8.0 GPa		υ = 0.3

Incoloy conduit

E = 184.2 GPa		υ = 0.2987

LLNL Calculated Average Winding Pack Properties

E_x = 36.0 GPa	G_{xy} = 3.3 GPa	υ_{xy} = 0.177
E_y = 38.0 GPa	G_{xz} = 9.7 GPa	υ_{xz} = 0.132
E_z = 84.5 GPa	G_{yz} = 10.1 GPa	υ_{yz} = 0.140

MIT Estimated Average Winding Pack Properties

E_x = 42.7 GPa	G_{xy} = 15.5 GPa	υ_{xy} = 0.33
E_y = 40.2 GPa	G_{xz} = 20.1 GPa	υ_{xz} = 0.33
E_z = 63.2 GPa	G_{yz} = 21.3 GPa	υ_{yz} = 0.2

Table 2

Comparison of ITER-CDA and ITER-HARD TF Coil Structural Analysis Results

Maximum stress (MPa) / Analysis Group	ITER-CDA	MIT ITER-HARD Global Model	LLNL ITER-HARD Detailed Model	Static Allowable Stress
Case Tresca Stress	655	620	N/A	800
Case Straight-Leg Tresca Stress at Equator	609	620	606	800
Winding Pack Tresca Stress Smeared Orthotropic Mat'l	181	150	392 localized in corners	N/A
Conductor Conduit Tresca Stress		510 estimated	1260 calculated	800
Insulation Compression Stress	228	110 estimated	230 calculated	450
Insulation Interlaminar Shear Stress	30	20 estimated	140 calculated	33

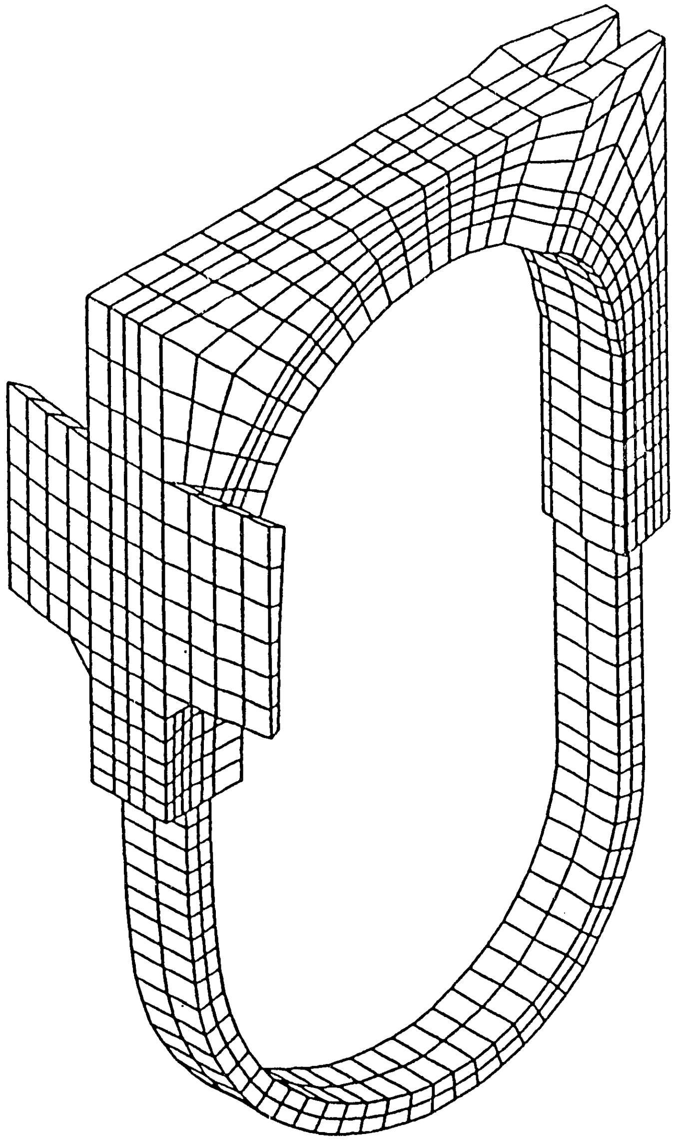

Fig. 1. MIT Plasma Fusion Center global model of the TF coil (from Myatt and Bobrov 1992 [2]).

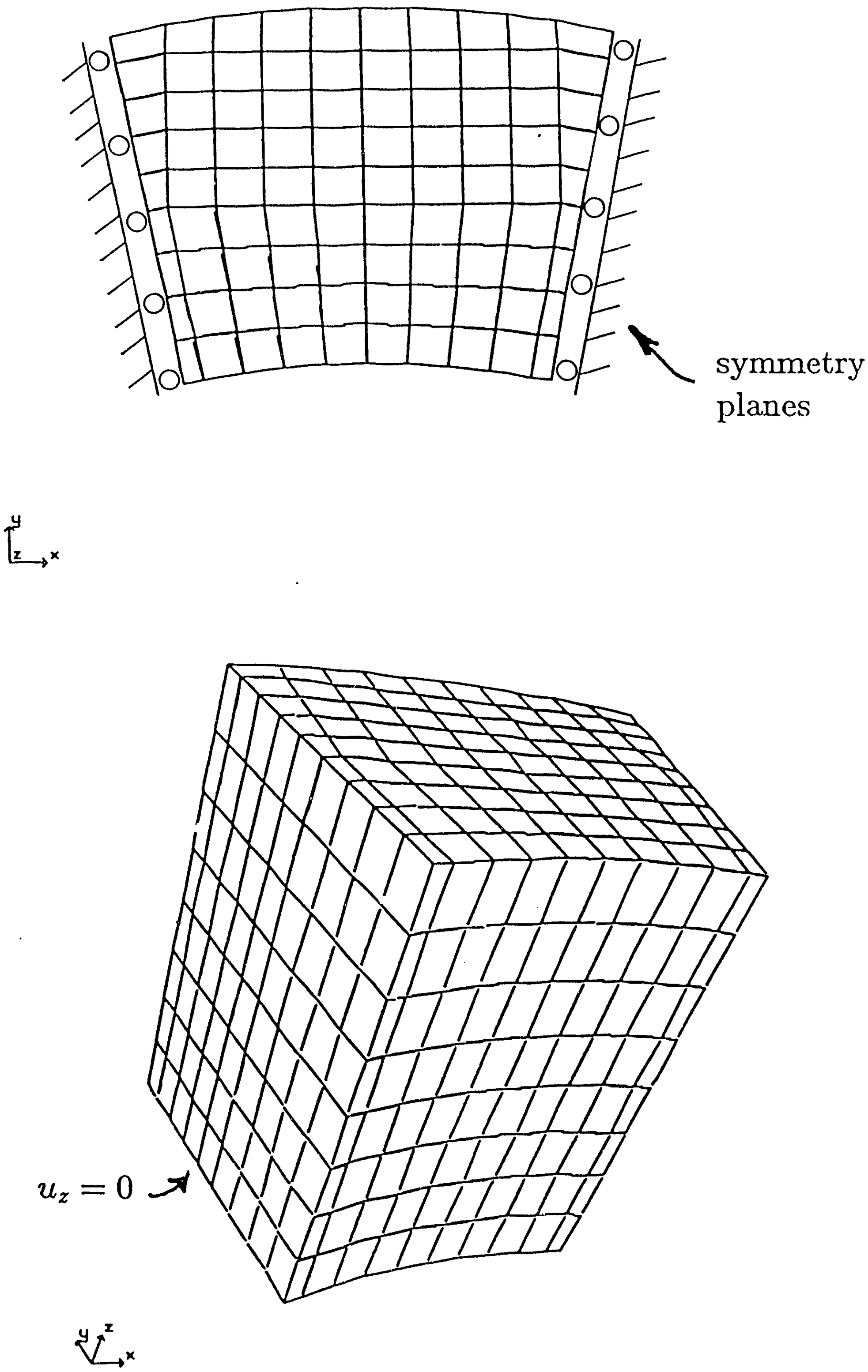

Fig. 2. LLNL intermediate detail model of the TF coil, representing the straight leg near the equator.

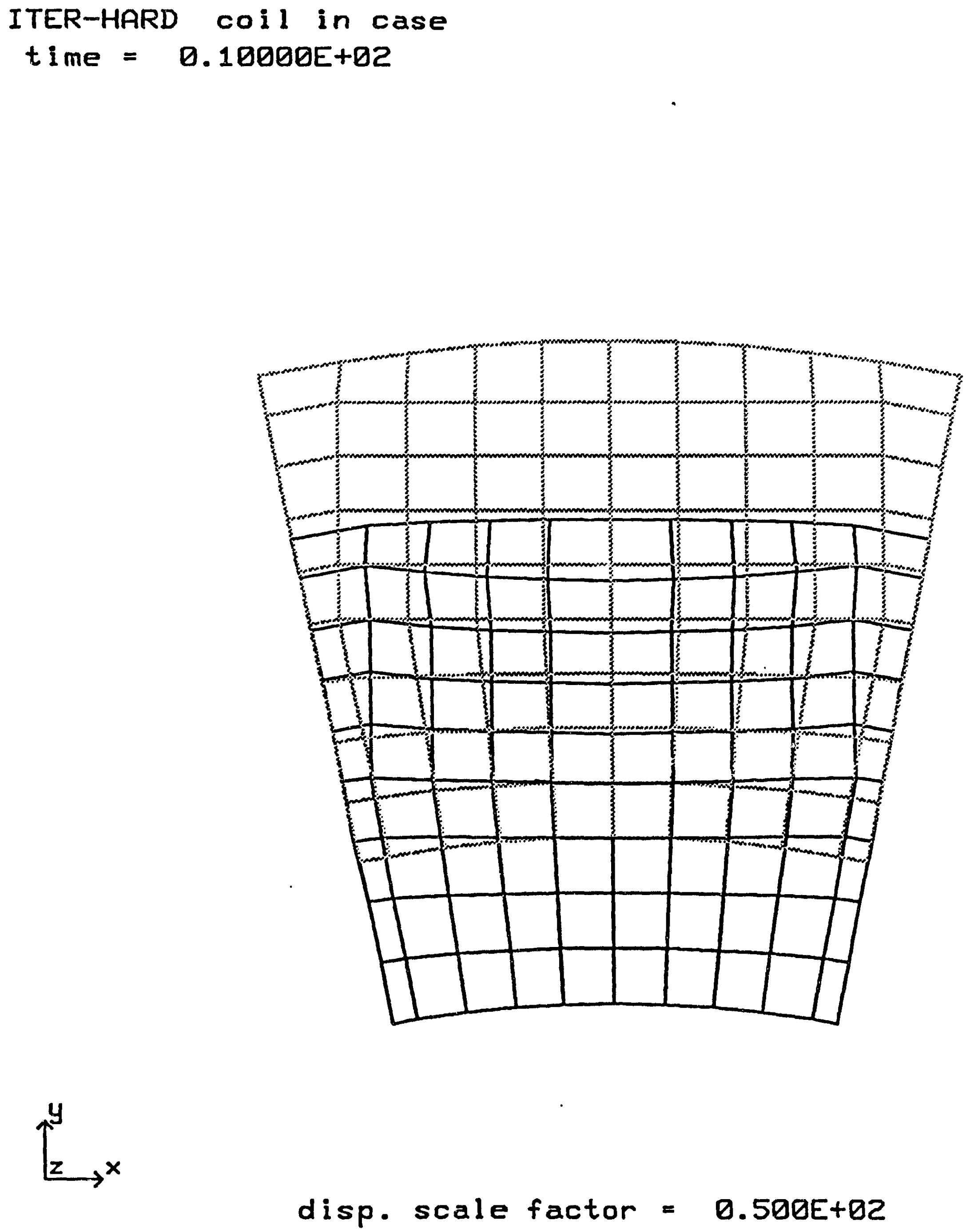

Fig. 3. Displaced mesh for TF coil operation. Magnet loadings push the straight leg towards the center of the toroidal ring.

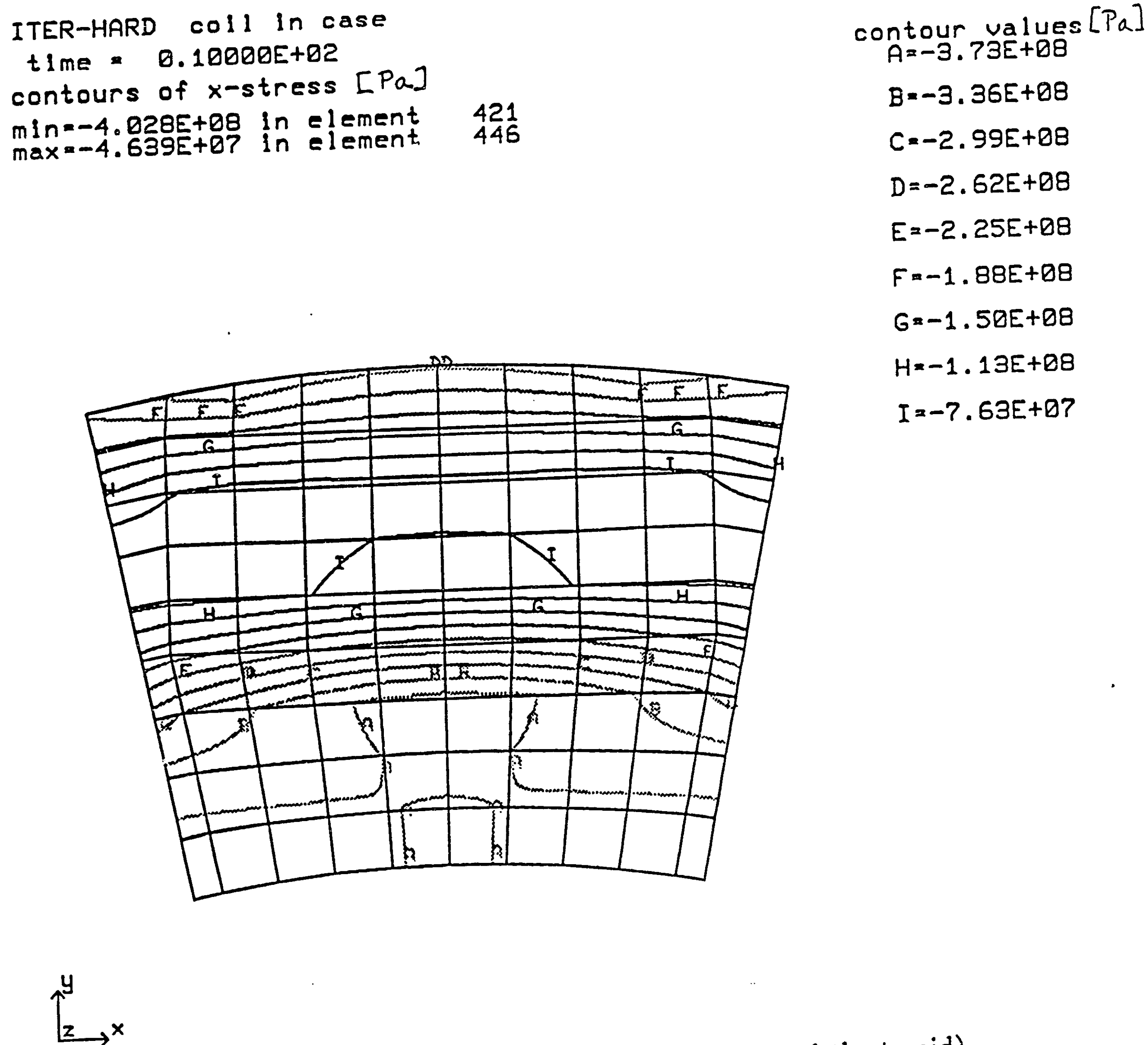

Fig. 4. X-direction stress for TF coil operation (x is directed around the toroid).

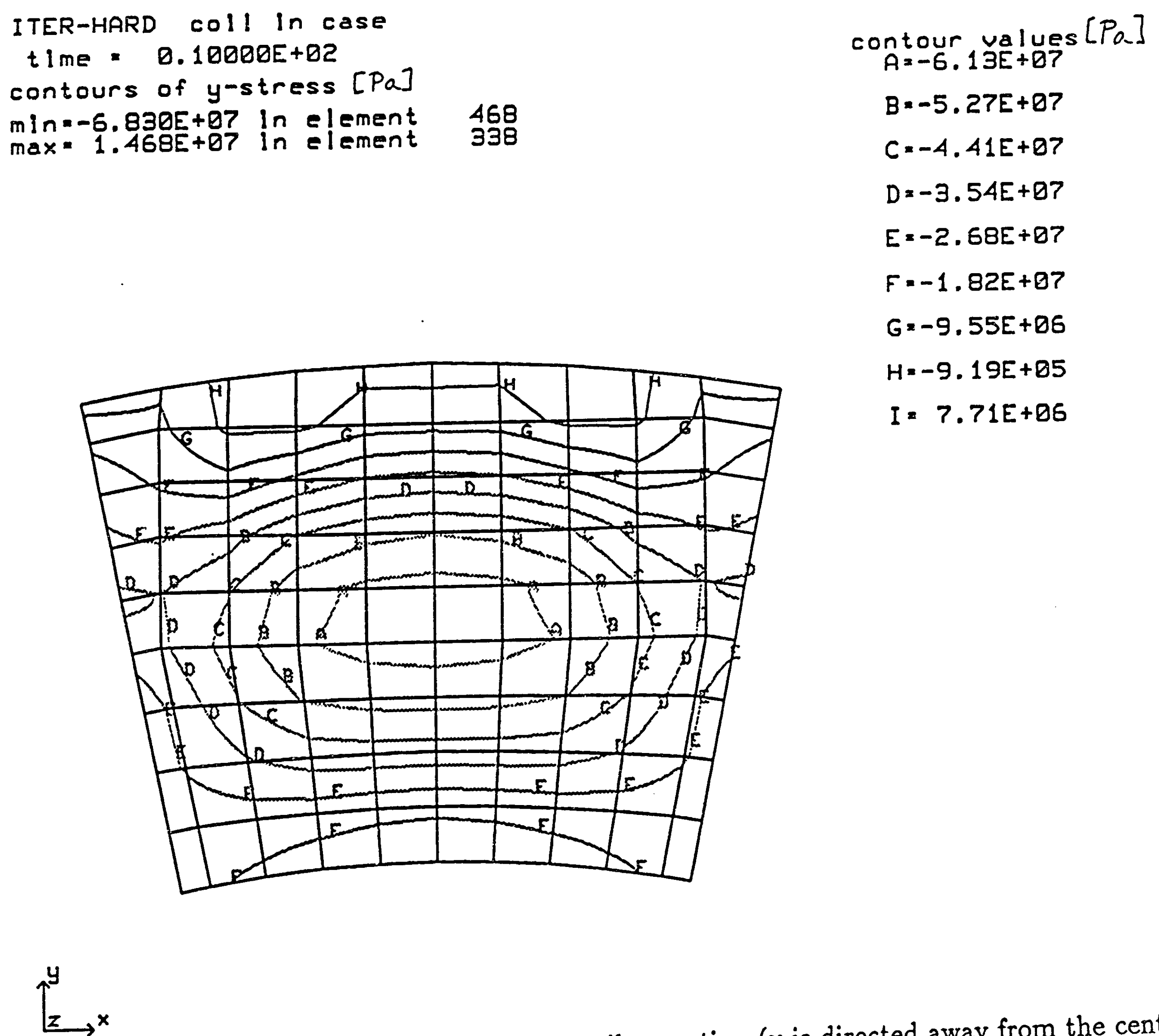

Fig. 5. Y-direction stress for TF coil operation (y is directed away from the center of the toroid).

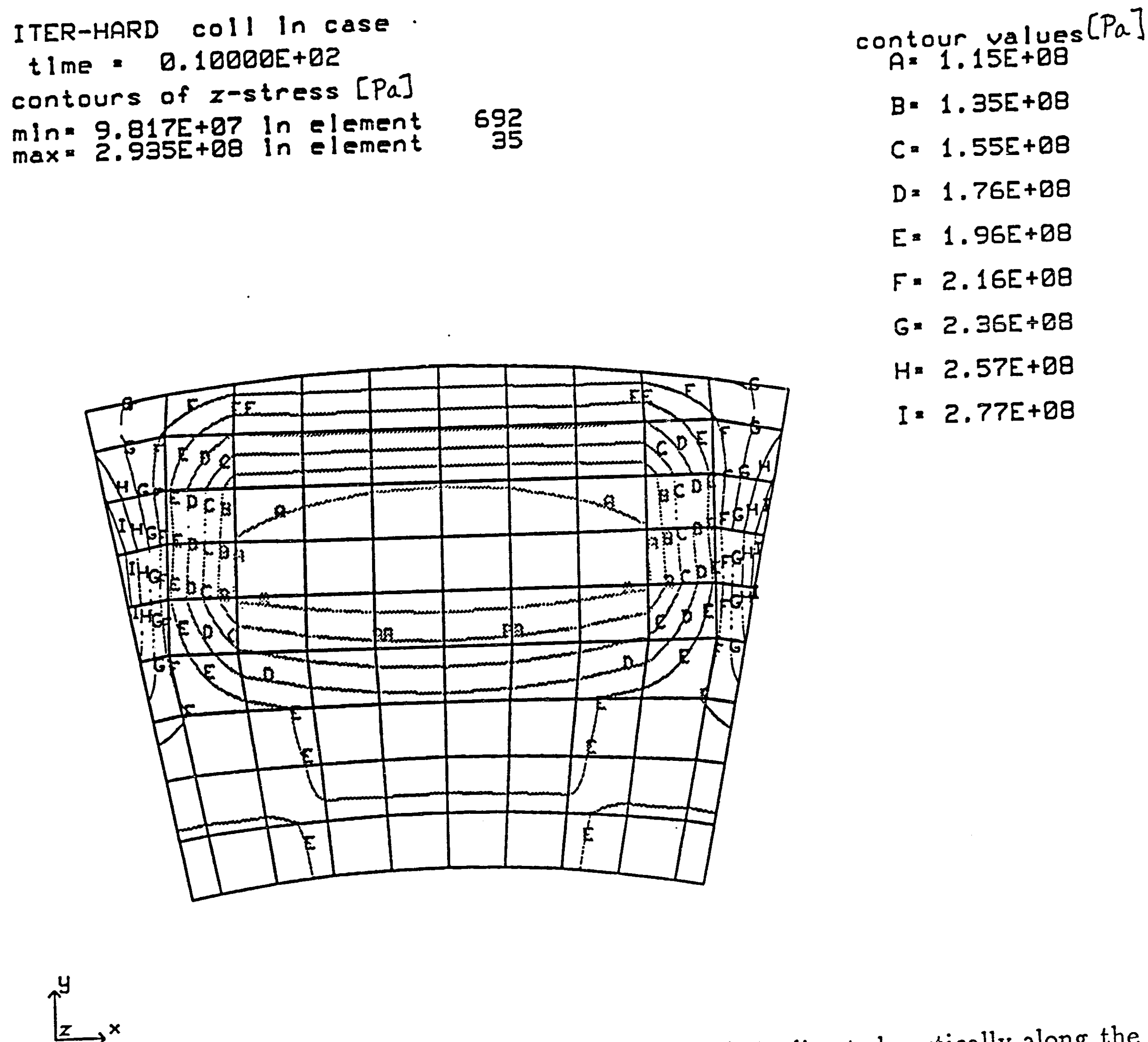

Fig. 6. Z-direction stress for TF coil operation (z is directed vertically along the straight leg).

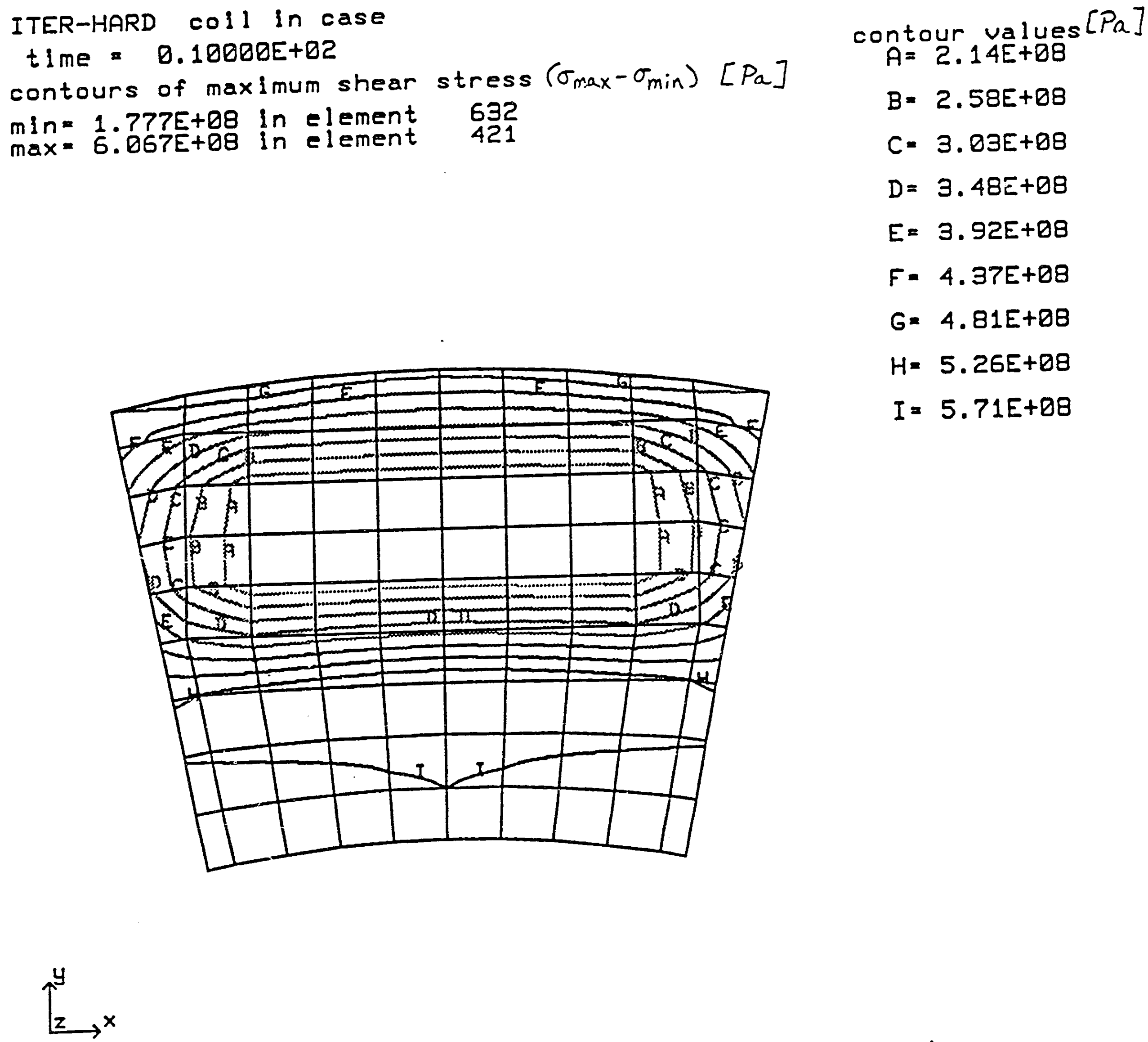

Fig. 7. Tresca stress intensity ($\sigma_{max} - \sigma_{min}$) for TF coil operation.

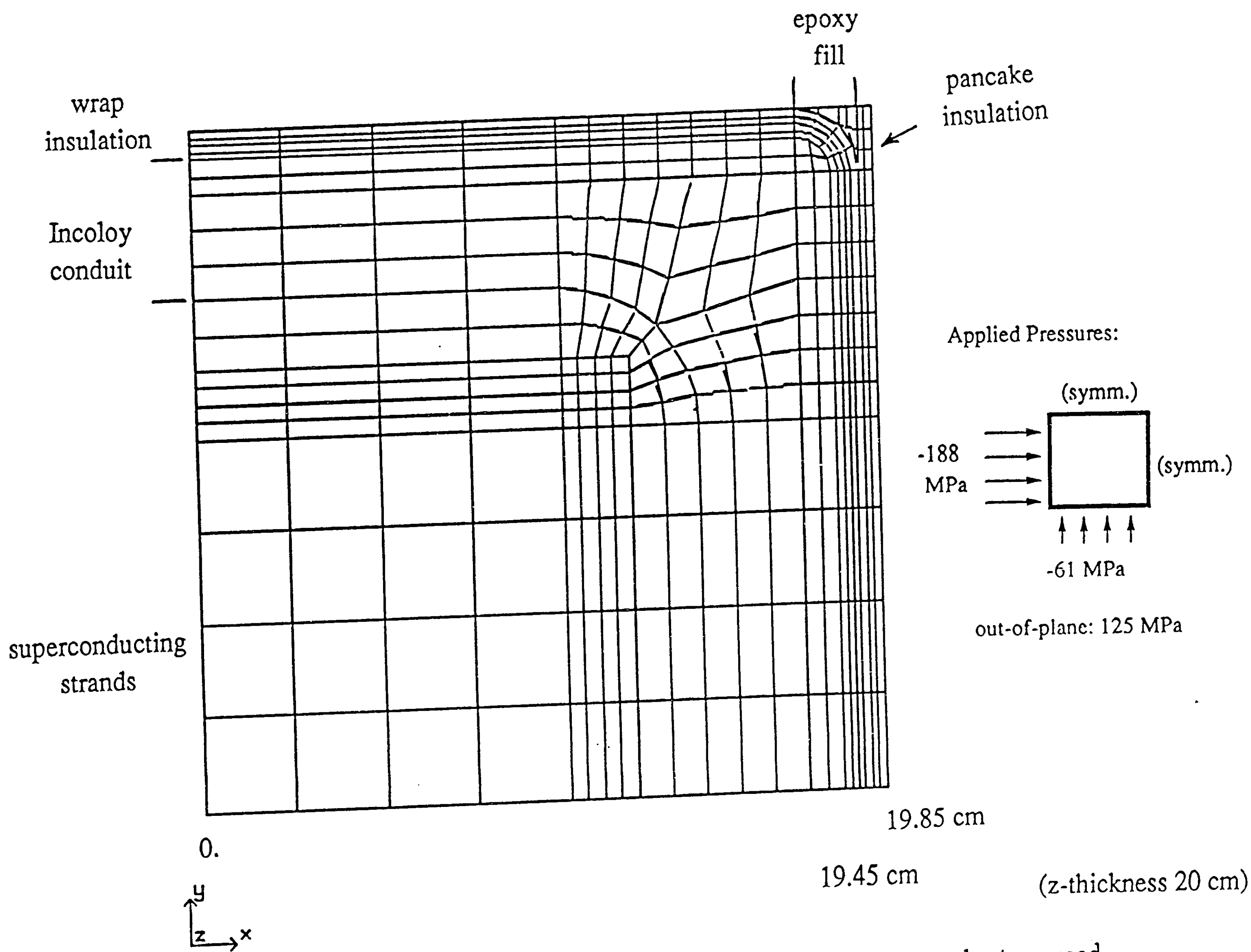

Fig. 8. Three-dimensional finite element mesh of one-quarter of a conductor, used for calculating averaged winding pack properties and for detail modelling of the winding pack.

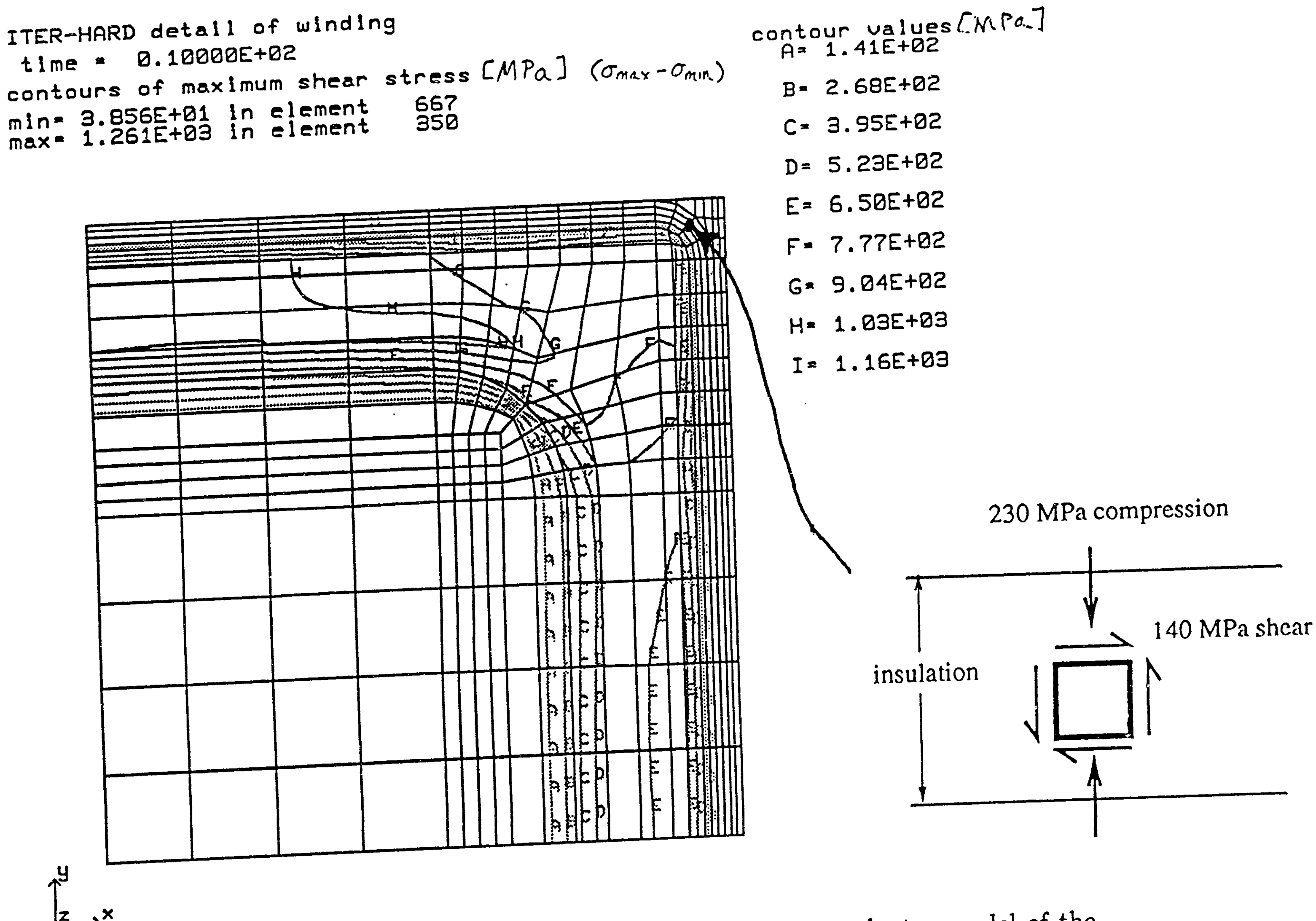

Fig. 9. Tresca stress intensity ($\sigma_{max} - \sigma_{min}$) in a quarter-conductor model of the worst-stress location in the winding pack. Also shown is the worst interlaminar shear and compressive stress state in the insulation.

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