Non-Linear Analysis of the TFTR Toroidal Field Coil

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ABSTRACT

As the Tokamak Fusion Test Reactor (TFTR) reaches new milestones, the ability to assess the performance and safety margins of its components, particularly the toroidal field (TF) coils, becomes increasingly important. Analytical models are required to study actual and potential machine scenarios, then predict limiting operational conditions and the components that set those limits. The application of the finite element method is ideally suited to analyze the TF-coil system. A finite element model with non-linear capabilities has been developed that permits the realistic examination of all aspects of structural behavior. The model is detailed enough to depict such structural features as the individual copper turns of the coil and the bolts assembling the coil case. When the model is subjected to a variety of loading conditions, each analysis generates a comprehensive set of results including stresses, forces, displacements, etc. In turn, the evaluation of this data establishes criteria by which TFTR can operate and suggests areas whose improvement benefits the life of the device. Structural behavior that has been extensively examined with this model has included deformations verified by actual tests, the degree of interlaminar coil bonding, gap studies, and variations in support conditions for load path optimization. Based on the results of the finite element analyses, the performance envelope of TFTR can be extended with greater confidence. The finite element model is also available as a diagnostic tool to determine where structural upgrades should be considered as well as evaluate design modifications prior to implementation. This paper will summarize the development of the TF-coil model and review some of its applications to date.

INTRODUCTION

From the beginning of the TFTR program, the structural analysis of the toroidal field (TF) coil and its supporting structure has been considered essential in determining the coil's behavior and operating limits by providing information about the system that is probably unavailable through other diagnostic means. It was envisioned that such an analysis would be comprehensive and detailed enough to provide an accurate structural representation in highly localized areas of the coil system yet be flexible enough to permit a variety of parametric studies and modifications needed to investigate potential coil scenarios.

Based on the development work done on TF-coil analytical methods (Zatz, 1982 and Zatz, Shibui, 1983), the ability to perform accurate parametric studies on many important and complex conditions can be achieved via the finite element method. A model was developed that, among other things, has the ability to study variations in coil shear stiffness, examine localized effects of coil delamination, predict coil case bolt loads, determine stress concentrations at cut-outs in the coil case, and demonstrate the non-linear effects of variable contact between the potted coil and the case. This diversity of capabilities is accomplished by coupling turn-by-turn detailing with maximized model flexibility. Included in the model are accurate representations of every turn of copper and epoxy in the coil as well as the ground wrap, the coil case, the gap between the coil and case, yokes, shear compression panels, inner support structure, and pedestal. Each component can be geometrically altered or enhanced independently as required. The finite element model was developed using MSC/NASTRAN version 65B.

DEVELOPMENT OF THE TF-COIL MODEL

For the purposes of finite element modelling, the coil itself was assumed to be composed of constant radius copper turns, i.e. each copper turn is assumed to be a concentric circle rather than spirally wound. This approximation has a negligible effect on the structural response of the coil subjected to electromagnetic and thermal loads. Other aspects of the coil geometry included in the model are the two 22-turn pancakes with interlaminar epoxy and the reduced cross-section wedge shape in the nose region.

Copper turns are modelled with plate elements which handle the membrane, bending and transverse shear capabilities of the actual turns. A given coil cross-section cuts through 44 plates, one for each turn (Figure 1). The interlaminar epoxy is assumed to have no bending stiffness but its compressive and shear stiffnesses are provided by rod and shear elements, respectively. Each element was calculated to incorporate an appropriate portion of area and volume in an actual coil. Elements are divided into six-degree poloidal increments around the perimeter of the coil (60 elements for the 360-degrees of a copper turn).

At a time when there was some concern about the possibility of coil delamination and uncertainty about the epoxy shear modulus, a 180-degree, half-coil model, which took advantage of symmetry (Figure 2), was developed to correlate and predict results of a jacking/bending test performed on an actual uncased TFTR TF-coil. Knowledge of the coil shear stiffness leads to the definition of load distribution between the coil, case, and support structure and is therefore critical for establishing the operating limits of the machine based on the design allowables of the components. A mechanical jacking/bending test performed on an uncased TF-coil is ideal for providing a wealth of information in this area because of the relative simplicity of the test.

A series of load and support conditions were tested and analyzed. Various potential delamination scenarios were studied. Most importantly, a normalized curve was generated via the analysis which relates the coil equivalent epoxy shear stiffness, a measure of the epoxy shear modulus in a bonded coil minus any delamination effects, to deformation in the tested TF-coil. The conclusion drawn from comparing the test and analysis data is that the sample coil has minimal, if any, delamination and that the epoxy shear modulus is in the anticipated range of 400,000 - 450,000 PSI. Since no two coils are manufactured identically, the performance of each coil will be different, but the differences between coils are expected to be minimal. The results of this test can therefore be interpreted to represent each of the twenty encased TF-coils in TFTR. Justification for increased confidence in the TF-coil modelling method as well as actual coil performance was demonstrated by this coil test.

The most important consideration in the modelling of the TFTR TF-coil case was the ability to represent the relative rigidity of the inner and outer rings to the flexibility of the sidewalls in an accurate manner. This was achieved by using eight-to-twenty node solid elements. Two, twenty-node solids model each ring and fourteen elements (2-twenty node, 2-twelve node, 10-eight node) model each sidewall. This modelling pattern (Fig. 1), is selected for optimizing element aspect ratio while providing enough detailing to permit higher order deformations of the sidewall. As with the coil, the case elements are incremented in six-degree intervals poloidally. It is important to note that the intricacies of the coil case geometry (e.g. variable ring thicknesses and sidewall reliefs), are all accounted for in detail by the finite element model per the final design modified by the as-built conditions (Figure 3).

The modelling of the coil-to-case interface is achieved with linear and non-linear spring elements which represent the coil overwrap, filler, potting compound and gap. These elements account for all load transferred between the coil and case. It is assumed that load can be transferred by compression only and that no shear load is transferred between the coil and case. In order to avoid potentially enormous computer costs, several linear analyses were performed initially which indicated the general structure behavior enabling the number of non-linear elements to be minimized in the final, follow-up runs.

The center column as well as inner and outer rings of the TFTR inner support structure (ISS) are modelled coarsely with plate elements. The analytical stiffness of the ISS remains accurate but the original intent of the project was to detail the coil and case. The option exists to replace this model of the ISS with one of greater detail, if required. Figure 3 shows the nose region of the case in relation to the ISS. The ISS elements occupy an 18-degree toroidal sector of TFTR corresponding to the space in the model occupied by a single TF-coil and its supporting structure. Boundary conditions are created to constrain the ISS to simulate the symmetric behavior that would be found if it was toroidally homogeneous. In actuality, the ISS is composed of four interlocking 90-degree toroidal segments that is less stiff than the assumed continuous analytical model. However, the difference in stiffness is not considered significant.

A detailed modelling of the TFTR yokes and shear compression panels (SCP) was developed to make it compatible with the case sidewall and to provide as many discrete bolt locations as possible. Solid elements model the one inner and two side yoke plates while the SCP boxes are modelled with plate elements whose boundaries spread 18-degrees, like the ISS, providing for 1/20 toroidal symmetry. Figures 4 and 5 show the TF-coil case, ISS, yokes and SCP of the 18-degree finite element model. The coil itself is not included in the figures to preserve graphic clarity. Figure 6 shows the actual TF-coil, with yokes attached, ajoined to the ISS during the construction phase of TFTR.

The coil is composed of wound turns of OFHC copper with epoxy laminas in between. The epoxy, as well as the overwrap, filler and potting compound, are assumed to be composed of the same material with identical properties in the model. The coil case, yokes and shear compression panels are made of Nitronic 33 alloy. The ISS is composed of titanium alloy Ti-6Al-4V. Material properties for these materials are readily found in the literature.

APPLIED LOADS

During TFTR operation, there are three components of load; toroidal field (TF) electromagnetic (EM) loads, poloidal field (EF) EM loads and thermal loads. It is the interaction of the electromagnetic fields created by the poloidal field coils with the TF coils that produces the EF forces. Full field TF loads represent a 5.2 Tesla, 73.3 kA condition while full field EF loads used in these analyses correspond to a 0.42 Tesla, 36.0 kA condition imposed on the 73.3 kA TF operating level. TF loads are usually referred to as in-plane loads while EF loads are often referred to as out-of-plane loads. It is of great importance and interest to analyze the TF and EF load components separately to determine the contributing effects and behavior of each on the performance of the structure. Naturally, any limiting stress condition would have to be based on the superposition of all loads. Thermal loads are generally combined with TF loads because that EM condition accounts for almost all of the thermal effects.

The TF EM-loads are comprised of two components, in-plane coil forces and offsetting out-of-plane components which represent the compression of the copper/epoxy pancakes towards the coil's toroidal midplane. Radial in-plane load components are symmetric about the coil's horizontal midplane. EF loads are comprised of only out-of-plane components which reduce to zero at the coil's horizontal midplane and are asymmetric about it. With the pedestal, located near the base of the coil, the net effect is for the rotational moment due to the loads imposed on the top half of the coil to dominate over the lower half because of the larger moment arm to the pedestal, and will result in the EF loads tipping the entire coil in that direction. With 88 copper nodes every six-degrees poloidally, ample definition is provided to enable virtually exact EM loads to be applied to the model. An evaluation of the EM loads shows that the TF forces are broken down into a gross 10.5 million pounds of inward radial centering force for each coil coupled with a gross outward radial force of 4.5 million pounds leaving a net inward centering force of approximately 6.0 million pounds per TF-coil. While the net vertical load on each TF-coil due to the TF EM forces is zero because of symmetry, the half-coil tension force generated at the mid-plane is 6.2 million pounds. Sixty-one percent of this force is in the inner leg of the coil. The net force in a coil based on the EF loads is zero due to symmetry but the gross half-coil out-of-plane force is approximately 1.0 million pounds per coil and the overturning moment for an entire coil about the horizontal mid-plane is 104.3 million inch-pounds.

Thermal loads are prescribed in the finite element model by assigning specific temperatures to each node. Resulting thermal gradients induce thermal stresses which can then be combined with other mechanical loads. The key to thermal stresses is that they will depend entirely on the instant of time studied by the static analysis. With EM loads, it is easy to select peak forces directly from peak currents but temperatures are more subtle because of the redistribution effects with time due to conductivity and convection. For the baseline analysis condition, TF heating is established from a full field TF of 73.3 kA at 12 seconds into a first pulse. The timing was selected to be more closely coincident with peak EM fields at the end of 'flat top' rather than peak temperatures because this should represent the severest realistic combined loading condition. Several different thermal profiles were examined that confirm this.

APPLICATIONS

Two different finite element models were utilized in the study of the TF coil system. One is a 180-degree half-coil model that is symmetric about the horizontal midplane. It is generally applicable for in-plane load conditions and generic behavioral studies. The other model represents the full coil and contains over 25,000 elements and 50,000 degrees of freedom. Substructuring is used in the definition of this larger more comprehensive model.

Worthy of note is the interpretation of the coil-to-case springs. It must be recognized that if load cases are to be superimposed to yield a final resultant, each set of contributing loads will want to indicate a unique arrangement of 'closed' (compression) and 'opened' (tension) elements. If these results, each with a different spring arrangement, were combined it would violate superposition. It is also invalid to study the individual load effects by this procedure because the load path is not based on the effects of all loads. Therefore, each load case should have an identical set of 'opened' and 'closed' springs so that the results will be valid when combined. An example is that if the in-plane/thermal loads place a spring in extreme compression ('closed') and the out-of-plane indicates slight tension, then the spring should be left 'closed' for both runs since it will still be in compression when the loads are combined. Pre- and post-processing programs were developed to make the appropriate spring arrangement and stiffness selections automatically.

It has been demonstrated that the model can aid in the visualization of the real structure, particularly in places that are ordinarily inaccessible, e.g. a projection of the coil and case nose region as shown in Figure 1. Deformations can be magnified many times over to permit the study of displaced components as they pertain to tolerances, load paths and stresses. Several options for studying stress data are available including contour plots, color coded plots and numerical graphs. Each has advantages for revealing a variety of structural nuances. Of the numerous parametric studies performed with the model, one of the most interesting dealt with the fact of loosening case bolts that tie the sidewalls to the inner and outer rings of the case. Many variables were considered in this study including the location of loose bolts and their shear stiffness in a loosened condition.

Other applications of the models include variable contact between the coil case and ISS, determination of the effects of the coil system on other tokamak subsystems, and the development of an influence matrix for the coil based on unit loaded coil segments for use in evaluating a variety of different EM conditions quickly. Also, the global effects of this large model have been used as input in the study of localized areas of the coil system with more detailed models. Coil leads and case cutouts have been studied in this manner.

CONCLUSIONS

The development and application of analytical models using the finite element method to study the structural behavior of the TFTR toroidal field coil and its associated supporting structure was presented. Further detailing of the model itself and the presentation of specific results is beyond the scope of this paper. This paper has defined and explained the methodology and models that have been developed, tested, benchmarked and verified, and discussed their flexibility and applications to date.

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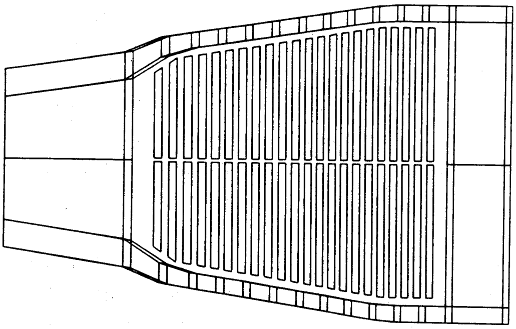

Fig. 1 - TF-Coil and Case Elements at Mid-Plane Nose (6-degree projection)

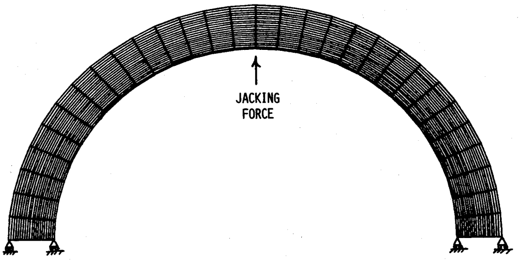

Fig. 2 - Elevation Schematic of TF-Coil Jacking Load Test (idealized)

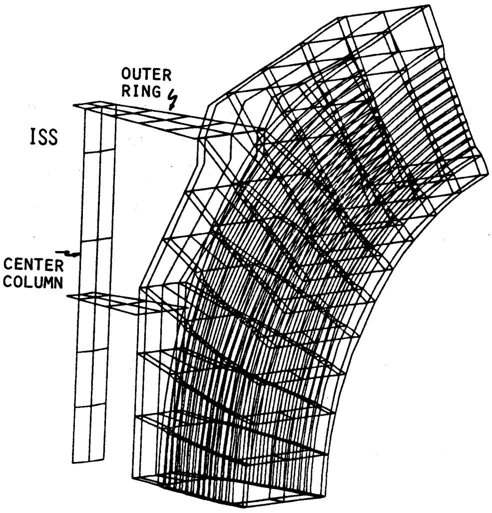

Fig. 3 - Isometric view of ISS & Nose Region of TF-Coil Case (60 degree model segment)

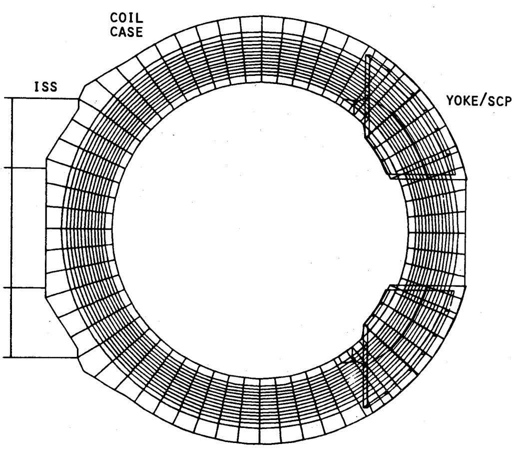

Fig. 4 - Elevation of the TF-Coil Finite Element Model

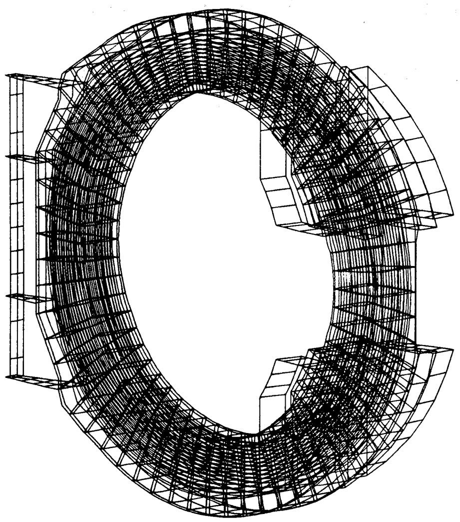

Fig. 5 - Isometric of the TF-Coil FE Model

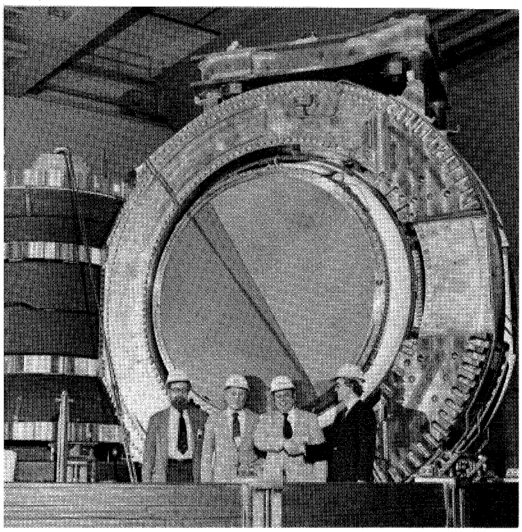

Fig. 6 - TFTR TF-Coil During Installation