Photoelastic Analyses of Stresses in Toroidal Magnetic Field Coils

H. Pih

MASTER

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.50; Microfiche \$3.00

4.00

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Contract No. W-7405-eng-26

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H. Pih
Professor of Engineering Science
University of Tennessee
Consultant, Magnetics & Superconductivity Section
Fusion Energy Division

Date Published: February 1977

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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ABSTRACT

Several two-dimensional photoelastic stress analyses were made on models of circular and oval toroidal magnetic field coils for fusion reactors. The circumferential variation of each coil's in-plane magnetic force was simulated by applying different pressures to 16 segmented regions of the inner surface of the models. One special loading fixture was used for the model of each shape and size. Birefringence and isoclinic angles were measured in a transmission polariscope at selected points on the loaded model. Boundary stresses in the cases of known boundary conditions were determined directly from the isochromatics. Separate principal stresses were calculated using the combination of photoelastic information and isopachic data obtained by the electrical analogy method from the solution of Laplace's equation. Comparisons were made between experimental results and those computed using the finite element method. The stress distribution between theoretical and experimental agrees very well, although the finite element method yielded slightly higher stresses than the photoelastic method; further work is needed to resolve this difference. In this investigation several variations of coil geometry and methods of support were evaluated. Based on experimental results, optimum structural designs of toroidal field coils were recommended.

INTRODUCTION

In the design of toroidal field magnets for tokamak fusion reactors, stresses induced by the toroidal magnetic field are very important. Besides affecting structural considerations, stress could also affect the performance of the superconductor used in the construction of the coils. Stresses in the coil depend not only on the magnetic field but also on the shape of the coil and the manner of support provided to resist the total magnetic body force in the coil. Because large superconducting coils cost millions of dollars to manufacture, every effort

should be made to ensure a complete and correct analysis in the designing stage. This report presents the results of a series of photoelastic stress analyses of two potential coil shapes and the different means of supporting these coils against the large, unbalanced horizontal force in the coil.

The photoelastic method was used to analyze plane models of the coil due to in-plane forces induced by the toroidal magnetic field. Analysis of the same model was also made using a digital computer and the finite element method and results from the photoelastic experiment and finite element method were compared.

The coil shapes considered were circular and oval (a compromise between the circular and the so-called D-shape^{1,2}). Two methods of supporting (bucking) against the unbalanced horizontal magnetic force were used in the experiments: one was to support at two points, simulating two bucking rings; the other was to give continuous support through an arc of 140° in the vertical plane, thereby simulating continuous contact to a center column.

EQUIPMENT

Major equipment used consisted of the loading system and the polariscope, with its associated instruments.

THE LOADING SYSTEM

The Lorentz body force distribution in the coil is given by

$$\Delta \vec{F} = \vec{I} \times \vec{B} \Delta L, \quad (1)$$

where $\Delta \vec{F}$ is the force vector on the length, ΔL , of the conductor, $\vec{I}$ is the electric current vector, and $\vec{B}$ is the magnetic field vector. The force, $\Delta \vec{F}$, is in the outer normal direction of the arc, ΔL . Since the field, $\vec{B}$, varies with the distance from the center line of the toroid, the Lorentz force changes not only with the circumferential position but also with the position throughout the radial thickness of the coil. It would be very difficult to simulate exactly this

force distribution, so for the loading system used in this investigation we assumed the body force to be concentrated on the inner surface of the coil and simulated only the variation along the circumference. This is a conservative simulation since the force at the inner surface is higher than that at other points throughout the thickness; also, the thickness of the coil in the radial direction is usually much less than its radius.

The loading system used in the experiment consisted of a loading fixture and a pressure control panel. A thin-walled rubber tube was pressurized to produce the desired loads on the model. This tubing is constrained by the model on one portion of a cavity, while the loading fixture forms the remaining portion of the cavity. The circumference of the inner surface of the model was divided into 16 segments of equal arc lengths. Each segment was in contact with a rubber tube which was constrained on three sides in the groove in the fixture. One end of the rubber tube was connected to the pressure control through a copper tube and the other end was plugged with a closed-end copper tube. The copper tubes were clamped by appropriate grooves machined in the loading fixture. Each of the 16 rubber tubes was subjected to a different pressure calculated from the magnetic force distribution along the circumference of the coil. A thin partition was inserted between the adjacent tubing compartments to isolate the regions of different pressure. The pressure in each tube segment was controlled by a regulator and a pressure gage mounted in the control panel and was supplied by a compressed nitrogen bottle through a main pressure line. Each tube was isolated into a closed circuit by a shutoff valve after reaching its predetermined pressure. After the regulators were set, pressure could be applied to the 16 tubes simultaneously by leaving all the shutoff valves open and controlling only the main pressure source valve. The main valve was closed after all tubes reached their predetermined pressures and all shutoff valves were closed; thus the gas loss during each loading and unloading cycle was minimized. To guard against overloading, a safety relief valve was attached to the main pressure line to limit the maximum pressure going into the regulator.

The loading fixture was mounted in a frame structure which was bolted on a milling machine table; this arrangement enabled all points of the model to be brought into the field of the polariscope for photoelastic measurements because it provided for accurate movement of the model. Figure 1 shows the control panel and one of the loading fixtures as located in the polariscope. The detailed construction of one of the loading fixtures is shown in Fig. 2.

In the original design of the loading fixture the distance ($1/4$ in.) between the two side plates was the same as the nominal thickness of the photoelastic model. The rubber tubes used had outside diameters of $1/4$ in. and inside diameters of $1/8$ in. It was suspected that only in the contact region corresponding to the $1/8$ in. ID of the tubes was the applied pressure transmitted to the model. The rest of the contact region, which was occupied by the thickness of the wall of the tubes, might transfer less load than the pressure inside of the tube. In order to correct this situation the grooves in the side plates just below the model were widened by $1/16$ in. on each side; thus the contact area between the rubber tubes and the model attained more uniform pressures and these applied pressures were transmitted to the inner surface of the model.

THE POLARISCOPE SYSTEM

The polariscope used in this investigation was a 9-in. field transmission type with field lenses. The light source and polarizing unit were mounted on one optical bench, and the analyzing unit and the camera or observation screen were mounted on the other optical bench. The loading fixture and the model sat in between the two optical benches on the milling machine base. The polarizer and the analyzer of the polariscope were tied together through a common shaft by friction pulleys and steel cables so that they could rotate together with no slippage; this made the determination of isoclinic angles more convenient. The isoclinics and fringe orders were determined with the aid of a microphotometer. The photoelectric search unit of the photometer was mounted in the back of the small aperture in the

observation screen. Fractional fringe orders were determined by the use of a Babinet-Soleil compensator together with the photometer. In the determination of both the isoclinics and the fringe orders, the photometer was used mainly to detect minimum light intensity. Photographs of the fringe patterns were taken by the polariscope camera, using a special film holder and Polaroid Land films.

EXPERIMENTAL PROCEDURES

PHOTOELASTIC MODELS

Two coil shapes were investigated in this research program. The first two models for the circular shape had a major radius of 3.3 m, a minor radius of 1.5 m, and a radial thickness of 0.5 m. (This was the early FBX conceptual design of ORMAK.) A linear scale factor of 1 to 4.516 was used for these circular models. The second pair of circular coil models had a major radius of 3.3 m, a minor radius of 1.5 m, and a radial thickness of 0.45 m. They had a linear scale factor of 1 to 6. The oval models had a major radius of 3.3 m, a minor radius of 1.5 m, a radial thickness of 0.45 m, and a 1 to 7 scale factor.

Two models of each shape and size were used: one for two-point support, and the other for continuous support. The two supporting points for the circular and oval models were located at $\pm 55^\circ$ from the horizontal axis toward the center line of the toroid. The continuous support for the models of both shapes occupied arc lengths corresponding to $\pm 70^\circ$ angles from the horizontal axis toward the center line of the toroid. These selections were based on proposed conceptual designs.

The photoelastic material selected for the models was the polycarbonate plastic PSM-1 supplied by Photolastic Inc. This material has excellent transparency, very high stress-optic sensitivity, very little creep, and practically no time-edge effect. It is ductile and relatively easy to machine. The nominal fringe value is 40 psi/fringe/in. for 5461 Å green light, although the fringe value for each individual sheet was calibrated with beam specimens in pure bending and was found to vary

slightly from this value. The modulus of elasticity and Poisson's ratio for PSM-1 are 3.4×10^5 psi and 0.38 respectively.

In order to control the residual stresses in the model due to machining, a high speed router fitted with carbide bits was used to machine the models. A steel template was prepared for each shape and size of the model and the photoelastic material was rough cut with a band saw to the shape of the model and was bound to one surface of the template with a double-faced adhesive tape. The model was then finished in several steps in the router with a set of guiding pins of gradually reduced diameters. (This technique for preparing two-dimensional photoelastic models was described in open literature of photoelasticity.³)

The load distribution applied to each model was calculated from the resultant Lorentz force acting on each of the 16 arc segments, based on a center magnetic field of 4.5 T and the assumption that the magnetic field is inversely proportional to the distance from the center line of the toroid. For the circular models the pressure distribution varied from 140 psi at the segment nearest to the center line of the toroid to 53 psi at the farthest segment. This load distribution is given in Table 1. The pressure distribution applied to the oval model varied from 100 psi to 37 psi; details are given in Table 2.

PHOTOELASTIC MEASUREMENT

After the model was assembled in the loading fixture, loads were applied by pressure in the rubber tubes. The image of the point of interest was adjusted to the aperture in the observation screen by the horizontal and vertical travels of the milling machine table. For the determination of the isoclinic angle at the point of interest, the quarter wave plates were removed from the light field, thereby producing a plane polariscope. The crossed polarizer and analyzer were rotated simultaneously until the photometer read a minimum, indicating that the dark isoclinic line was passing through the point. For determining the fringe order at the point under consideration, the quarter wave plates were returned to their proper positions. The Babinet-Soleil compensator was inserted between the model and the

Table 1. Distribution of the pressures applied in the rubber tubes in the circular loading fixture

Segment no. *	Pressure (psi)
1	140
2, 16	132
3, 15	113
4, 14	92
5, 13	76
6, 12	65
7, 11	58
8, 10	54
9	53

* No. 1 is nearest to the center line of the toroid and No. 9 is furthest.

Table 2. Distribution of the pressures applied in the rubber tubes in the oval loading fixture

Segment no.	Pressure (psi)
1	100
2, 16	96
3, 15	83
4, 14	70
5, 13	56
6, 12	46
7, 11	41
8, 10	38
9	37

analyzer unit with the axis of the compensator set to the maximum principal direction guided by the isoclinic angle obtained in the preceding step. The compensator knob was rotated until a minimum light intensity was indicated by the photometer. With this method of compensation the fringe order could be determined within 0.01 fringe. Fringe orders at boundary points were obtained by extrapolation from three points along a chosen line at small distances apart (as small as 0.05 in.).

Because the field of the polariscope was much smaller than the model, photographs of the photoelastic fringe patterns were taken for a region at a time. The photographs of local regions were then fitted together to make the composite fringe patterns of the model. Taking advantage of symmetry about the horizontal axis, only half of the model was shown in most of the fringe photographs. Upper and lower portions of the model were checked to ensure that symmetry was achieved.

DETERMINATION OF STRESSES FROM THE MODEL

Tangential stresses at an unloaded boundary or at the inner boundary of the model which experiences known normal pressures were determined directly from the fringe orders. This was done through the stress-optic relation given in Eq. (2), which uses calibrated fringe values of the material.

$$\sigma_1 - \sigma_2 = \frac{Nf}{h}, \quad (2)$$

where σ_1 and σ_2 are the principal stresses, N is the fringe order, f is the material fringe value, and h is the model thickness normal to the light beam. It is clear that if one of the principal stresses is known, the other can be obtained directly from Eq. (2).

Separate principal stress components at an interior point of the model cannot be obtained directly from Eq. (2). However, it should be recognized that $\left(\frac{\sigma_1 - \sigma_2}{2}\right)$ represents the maximum shear stress in the plane of the model, which is useful information in design with ductile materials. Isochromatic fringes indicate the maximum shear stress distribution directly. The complete state of stresses at an interior point of the model can be determined by two different methods,

the first of which is the shear difference method⁴ involving the numerical integration of the differential equation of stress equilibrium. The method is rather laborious and the error is cumulative through the path of integration. Since the isoclinics are not determined as accurately as the fringe order, considerable discrepancy was found in the sample calculations. It was decided that the less ponderous method of electrostatic analogy^{5,6,7} should be used in the analysis.

The electrostatic analogy is based on the fact that both the electric potential in a conducting sheet and the sum of principal stresses in a plane model satisfy the Laplace differential equation. When the boundary condition of electric potential in the conducting sheet model is proportional to the sum of principal stresses at the boundary of a photoelastic model, the measured voltage at an interior point in the electric analogy model can be used to determine the sum of the principal stresses in the photoelastic model at a similar point. This information, together with the photoelastic fringe order which provides the difference of principal stresses, can be used to obtain the separate principal stresses at the point under consideration. With the isoclinic angles or principal directions known, the complete state of stress is determined. Figure 3 shows the apparatus arrangement of the electrostatic analogy. The model was made from the Teledeltos paper⁵ which consists of a uniform layer of graphite particles over a thin paper carrier. Seventy-four points of boundary potential values at the inner and outer boundaries were supplied from a dc power supply through 74 potentiometers which served as voltage dividers. The voltages at points of interest were measured with a precision digital voltmeter with its probe mounted on a rack and pinion slide fixture for accurate positioning.

In order to obtain the stress in the prototype from the stress found in the model, a model law with the following form was used:

$$\sigma_p = \left(\frac{F_p}{F_m} \right) \left(\frac{L_m}{L_p} \right) \left(\frac{h_m}{h_p} \right) \sigma_m, \quad (3)$$

where σ_p and σ_m are the prototype stress and model stress respectively,

and where L_p and L_m , h_p and h_m , and F_p and F_m are the lengths, thicknesses, and loads in the prototype and model respectively. The stress conversion factors calculated from the model law given in Eq. (3), which were used to convert the stresses in the model to those in the corresponding prototype for the six models investigated, are given in Table 3.

EXPERIMENTAL RESULTS

The isochromatic fringe patterns obtained from the models in the polariscope represent the maximum shear stress $\left(\frac{\sigma_1 - \sigma_2}{2}\right)$ distribution in the plane of the models. Figures 4 and 5 show the typical dark and bright background photoelastic fringe patterns from the circular model with two-point support. Zero-order fringes are marked in all dark background fringe patterns for references. At the outer boundary, except the supporting regions, the fringe order is directly proportional to the tangential stress because the normal stress is zero. At the inner boundary the tangential stresses can be determined from the measured fringe orders because the normal stress is the known applied pressure at the point. From the fringe patterns (see Figs. 4 and 5) it was observed that the high maximum shear and tangential stresses occurred at the outer and inner boundaries; attention was therefore directed toward the boundary stresses. It was also observed that there was considerable bending in the coil due to in-plane loading.

Figure 6 (photoelastic measurements from circular model 1 with two-point support; 1 to 4.516 scale, modeling a coil with 0.5 m radial thickness) shows the distribution of the prototype boundary stresses versus the angular position, θ , measured from the horizontal axis toward the center line of the toroid. The peak tangential stress occurred at the outer boundary at 0° and had a value of 35,100 psi. Maximum shear stresses on the outer boundary were simply half the values of the tangential stresses because the normal stresses (σ_2) were zero except in the support region. The maximum tensile stress at the inner boundary occurred at the angular position of 65° with a value of 30,600 psi. At other angular positions, except near 0° and 65° , the stresses on both boundaries were considerably lower.

Table 3. Conversion factors from model stresses to prototype stresses calculated from Eq. (3)

Photoelastic model	Support	Linear scale	Prototype radial thickness (m)	σ_P/σ_M
Circular model 1	Two-point	1:4.516	0.5	58.894
Circular model 2	Two-point	1:6	0.45	59.132
Circular model 3	Continuous	1:4.516	0.5	60.131
Circular model 4	Continuous	1:6	0.45	59.132
Oval model 1	Two-point	1:7	0.45	83.165
Oval model 2	Continuous	1:7	0.45	82.496

The prototype boundary stress distributions from circular model 2 with two supports (1 to 6 scale, modeling a coil with 0.45 m radial thickness) are given in Fig. 7. Again, the peak tangential stress appeared at 0° angular position on the outer boundary with a value of 34,300 psi. The peak tangential stress on the inner boundary occurred at the angular position of 65° and had a value of 41,600 psi. It should be noted that while the distributions of boundary stresses obtained from the two models were similar, the peak tangential and maximum shear stress values from circular model 2 were higher than those obtained from model 1 because the radial thickness of model 2 was smaller than that of model 1. Hence, the in-plane bending of the wall should be more severe in model 2 than in model 1. This was supported by the fact that the compressive tangential stress on the outer boundary opposite to the peak tensile tangential stress was also higher in model 2.

The photoelastic fringe patterns with dark and bright backgrounds from the oval model with two supports (referred to as oval model 1) are given in Figs. 8 and 9. It can be seen by comparing Figs. 4 and 5 with Figs. 8 and 9 that with this kind of support the oval coil was subjected to higher bending effects at 0° and near 65° θ values than the circular coil. The prototype boundary stresses obtained from this model are shown in Fig. 10; the highest tangential stress on the outer boundary again appeared at 0° angular position and had a value of 90,300 psi, while the maximum tangential stress on the inner boundary occurred at 65° of θ and had a value of 100,000 psi. Again the maximum in-plane shear stresses were half the value of corresponding tangential stresses on the outer boundary.

Figures 11 and 12 present the typical dark and bright background photoelastic fringe patterns from the model of a circular coil with $\pm 70^\circ$ continuous support. Figure 13 shows the prototype stress versus angular position on the inner boundary for circular coil model 3, which was the 1 to 4.516 scale model representing a coil with a radial thickness

of 0.5 m. As can be seen from the photoelastic fringe patterns in Figs. 11 and 12, complex and irregular boundary stresses existed in the contact region between the outer surface of the model and the support. The fringe order on the rest of the outer boundary of the model was observed to be lower than that found on the inner boundary. Therefore, only the tangential and maximum shear stresses on the inner boundary are given in Fig. 13. The prototype inner boundary stress distribution calculated from the photoelastic measurements of circular coil model 4 (1 to 6 scale model of the same coil as circular model 3 except with a radial thickness of 0.45 m) with $\pm 70^\circ$ continuous support is shown in Fig. 14. While the distribution of stresses in these two models did not appear drastically different, the peak stress level in circular model 4 was slightly higher than that in circular model 3. The high tangential stresses on the inner boundary from circular model 3 appeared at 0° and 135° θ values and had magnitudes of 33,500 and 34,400 psi respectively. The high tangential stresses on the inner boundary from circular model 4 were 38,600 psi at 10° θ value and 17,200 psi at 170° .

In the case of the oval model with $\pm 70^\circ$ continuous support, referred to as oval model 2, the alignment between the model and the support was very critical. Figures 15 and 16 show the dark and bright background photoelastic fringe pattern of the oval model with good alignment with the support. In this case the fringe pattern was symmetrical with respect to the horizontal axis. By comparing Figs. 15 and 16 with Figs. 8 and 9, it is noted that both the highest fringe order and its location in this case changed drastically from that of the oval coil model with two supports. The highest fringe order appeared at the inner boundary at an angle position of about 35° for the continuous support experiment. Some bending still appeared in the coil wall due to the loading. The distributions of tangential and maximum shear stresses versus angular position, θ , at the inner boundary of oval model 2 with good alignment are given in Fig. 17. Since the normal contact stress in the supported region was not known and the photoelastic fringes were irregular in this region, the tangential stress at the

outer boundary was not obtained. From the fringe patterns in Figs. 15 and 16 it can be seen that significant tangential stresses existed at 85° angular position on the outer boundary but their magnitude was still lower than the peak values at the inner boundary. The highest tangential stress at the inner boundary appeared at $35^\circ \theta$ with a value of 38,100 psi. It should be noted that at $170^\circ \theta$ a high tangential tensile stress of 32,200 psi was obtained.

When oval model 2 was rotated very slightly (about 0.10°) from the continuous support, the photoelastic fringe pattern became unsymmetrical with respect to the horizontal line. On one side of this line the fringe order increased compared with the well-aligned case. The peak tangential stress at the inner boundary of the misaligned model was over 30% higher than that at the inner boundary of the aligned model. The effect of misalignment in the oval coil with continuous support is believed to have practical significance in coil design and should be considered by the designer if this configuration and supporting method are chosen.

COMPARISON OF PHOTOELASTIC AND COMPUTER RESULTS

One of the objectives of this investigation was to verify the stresses in the coils calculated by the finite element method using the existing computer codes FEATS⁸ and SAP.⁹ The photoelastic fringe patterns from the circular model with two-point support shown in Figs. 4 and 5 were compared with the computer-predicted isochromatic patterns given in Fig. 18. Comparison was also made between Figs. 8 and 9, the photoelastic fringe patterns for the oval model with two-point support, and Fig. 19, the computer-predicted fringe patterns. In both cases the distribution of the fringe patterns between photoelastic and computer-predicted results was found to be nearly identical.

The difference of principal stresses along a 3° radial line obtained from photoelastic measurement was compared with the finite element results for circular model 1 in Fig. 20. In most of the high stress region the computed results were higher than those obtained from photoelasticity. (The largest difference was about 21%.) The differences in principal stresses along a 1.5° radial line in oval model 1 from photoelasticity

and from the finite element method were compared in Fig. 21. (In this case the largest difference was nearly 30%.) The results from the finite element method were consistently higher than those from the photoelastic measurement.

The discrepancy between the finite element and photoelastic results was larger than expected. In order to investigate the cause of this discrepancy, two further experiments were carried out. First, two strain-gage-type load cells were placed at the two supports of circular model 2 and oval model 1 to measure the total bucking force of the two supports when the models were loaded. The resultant horizontal force for circular coil 2 was 319.8 lb, which agrees fairly well with the calculated value of 308.9 lb. In the case of oval model 1, the horizontal bucking force was 266.6 lb as compared to the calculated value of 258.0 lb. This experiment indicated that the predetermined loads were transmitted to the models. In the second experiment four delta rosettes of foil strain gages of 0.031-in. gage length were mounted on the 1.5° radial line at locations corresponding to fringe orders 1, 3, 4, and 5, as determined from the photoelastic fringe patterns. Using proper temperature compensation of the gage bridge and reduced input voltage (0.47V) to the bridge minimized the temperature effect on the strain gages. The stress values obtained from strain measurements were 19 to 22% lower than those determined from photoelasticity. This difference was somewhat higher than usual strain gage measurements, and part of the difference could be attributed to the inaccuracy of locating the gages and the finite gage length. Because the strain gages in the rosettes were not stacked, none of the three gages was located directly over the point of interest. Lower principal strains were anticipated. Another effort was made to use two gages of 0.031-in. gage length. One gage was installed over the point of interest in the maximum principal stress direction as determined from the isoclinics of the model; the other was oriented orthogonally to the first at a location as close to the point of interest as practical. This time the stresses obtained were 15 to 17% lower than the photoelastic results, and the agreement with the photoelastic results was acceptable considering the fact that

the second gage was not located over the point. Because the model material is a good insulator, the gages were not stacked in order to avoid a severe heating problem.

The discrepancy between the photoelastic and finite element results may be explained by the following observation. It is recognized in the theory of elasticity for plane multiply connected regions that if on any of the boundaries the load is not in self-equilibrium or reducible to a couple, then the analytical solution for the stresses depends upon the Poisson's ratio of the material.^{10,11} Further investigation with simpler cases is needed to resolve this question.

DISCUSSION

Examination of the fringe patterns for the circular coil model with two-point support shown in Figs. 4 and 5 indicates that near angular positions of 0° and 65° the coil is subjected to significant bending superimposed on the tension effect. This fact is clearly seen from the boundary stress distributions (shown in Figs. 6 and 7) obtained from circular models 1 and 2. At 0° the outer boundary is under high tensile stress in both models, whereas the inner boundary is subjected to a low compressive stress in model 1 and a low tensile stress in model 2. Near 65° angular position the inner boundary experiences high tensile stress and the outer boundary is under high compressive stress. Outside of 100° angular position the stress becomes rather low and is nearly a constant tension, which indicates that in the design of circular coils with two-point support the reinforcement may be drastically reduced in the portion of the coil occupying angles between $\pm 100^\circ$ and $\pm 180^\circ$ without weakening its overall strength. This would reduce the cost of construction of such coils. Examination of the fringe patterns of Figs. 6 and 7 shows where reinforcements are needed in such coil design.

Comparing the stress distribution in Fig. 6 from circular model 1 with that in Fig. 7 from circular model 2, it is seen that for the same inside diameter and under the same loading conditions, the coil with the 0.5-m radial thickness has a peak tensile stress of 30,600 psi as compared

with 40,800 psi for the coil with the 0.45-m radial thickness. This shows the significance of the coil radial thickness. Figures 6 and 7 may be of help in the selection of coil radial thickness for stress and cost consideration in designing such coils.

The fringe patterns in Figs. 8 and 9 and boundary stress distribution in Fig. 10 for oval coils with two-point support are compared with those in Figs. 4, 5, and 7 for circular coils of the same radial thickness with two-point support. It is seen that the oval coil has a peak tensile stress almost 2.5 times that of the circular coil and therefore it is quite obvious that oval coils with two-point support should not be used.

Comparison is made of the fringe patterns in Figs. 11 and 12 and boundary stress distribution in Figs. 13 and 14 (from circular models 3 and 4 with continuous support) with that in Figs. 4, 5, 6, and 7 (from circular models 1 and 2 with two-point support). It can be seen that in the case of a circular coil with continuous support, one of the regions under significant bending appears at the vicinity of 0° angular position with the inside boundary under high tensile tangential stress. The other high bending location depends on the radial thickness of the coil, and is located between the 135° and 170° angular positions with the inside boundary still under fairly high tensile tangential stress. In the case of a circular coil with two-point support the high tension appears at the regions near 0° and 65° angular position; at 0° the tensile tangential stress appears at the outer boundary and at 65° it appears at the inner boundary. However, the peak tensile stresses in both kinds of supports are close to each other. In the case of continuous support, the region between 100° and 180° angular positions is also under relatively high tensile tangential stress. The advantage of reduced reinforcement in this region in the case of two-point support does not apply to continuously supported circular coils. One possible advantage of the continuous support over the two-point support is its large contact area and therefore lower contact stresses at the support.

The fringe patterns in Figs. 15 and 16 and boundary stress distribution in Fig. 17 (from oval model 2 with continuous support) are compared

with those in Fig. 8, 9, and 10 (from oval model 1 with two-point support). The high bending appears near 30° , 90° , and 170° angular positions, with high tensile tangential stresses appearing at the inner boundary in the case of continuous support. In the case of two-point support the high bending occurs at 0° and 65° angular position with high compressive tangential stress at 0° on the outer boundary and high tensile tangential stress at 65° on the inner boundary. The peak stress level for the case with continuous support is much lower than that with two-point support.

Comparing the boundary stress distribution in Fig. 14 for a circular coil with continuous support with that in Fig. 17 for an oval coil with continuous support, it is seen that there is some similarity in these two curves. Except for their angular positions, the peak tensile tangential stresses from these two models with the same radial thickness appear to be almost the same. In the rest of the coil the circular one has lower tangential stress than the oval coil. It should also be noted that the circular coil is more economical to manufacture than the oval coil. This investigation indicates that for continuous support the circular coil is better than the oval coil. Furthermore, the alignment of the oval coil with its continuous support is very critical.

In the analyses the coil was treated as an isotropic and homogeneous structure. The real coil is an anisotropic composite structure. The results obtained in this research represent only the overall stress distribution and serve as a guide in the design of coil geometry and supporting method. The composite nature of the coil construction will modify the stresses locally. Further experimental investigations are needed for the analysis of real coils considered as composite structures.

CONCLUSIONS

It was found that the peak stress in the circular coil with two-point support did not differ much from that with continuous support. In the case of the circular coil with two-point support, the stress in the region outside of 100° angular position approached a low-level constant tension. The reinforcement in this region could be reduced. In the case of the circular coil with $\pm 70^\circ$ continuous support, the

tangential stress in the region outside of 100° angular position was not low compared with the peak tangential stress.

In the case of circular coils with the same minor radius, those with either two-point or continuous support but with a larger radial thickness experienced a lower peak tangential stress than the ones with a smaller radial thickness. This is believed to be a result of the bending effect of the distributed magnetic forces.

The experiments revealed that the oval coil with two-point support experienced a peak tangential stress nearly 2.5 times that of a circular coil with the same radial thickness and supporting method under comparable loading conditions. Much higher bending appeared in the oval coil than in the circular coil with this supporting condition. From the structural mechanics point of view, the circular coil with either two-point support or $\pm 70^{\circ}$ continuous support and the oval coil with $\pm 70^{\circ}$ continuous support are almost equally acceptable designs.

It was also found that with $\pm 70^{\circ}$ continuous support, the peak tangential stresses in both the circular and oval coils with the same radial thickness and subjected to the corresponding load distributions did not appear to be too different. The circular coil had much lower tangential stresses than the oval coil at angular positions larger than 120° .

Furthermore, it was shown (based on the fact that low-level stresses approaching a constant tension existed at the regions outside of $\pm 100^{\circ}$ in the circular coil with two-point support) that the amount of reinforcement could be drastically reduced in this region for this coil.

And finally, the alignment of the oval coil with its continuous support was proven to be very critical. A minute rotation of the coil with respect to the support caused unsymmetrical and higher tangential stresses.

RECOMMENDATIONS

Based on these conclusions, it is possible to make some recommendations:

1. A circular coil with continuous support should be used if the contact stress is excessive for two-point support at the supported regions.
2. If plasma physics considerations require expansion of the coil dimension in the direction parallel to the toroidal axis, then an oval coil with continuous support should be considered.
3. As large a radial thickness as acceptable should be used in the coil designs.

REFERENCES

1. J. File, R. G. Mills, and G. V. Sheffield, "Large Superconducting Magnet Designs for Fusion Reactors," IEEE Trans. Nucl. Sci., NS-18, pp. 277-282 (1971).
2. V. D. Shafranov, "Optimum Shape of a Toroidal Solenoid," Sov. Phys. Tech. Phy. 17(9), pp. 1433-1437 (March 1973).
3. For example: "Instructions for Making Two-Dimensional Photoelastic Models with the Photoelastic High-Speed Router Model HSR-1," Photolastic Inc. Bulletin I-203 (September 1974).
4. M. M. Frocht, Photoelasticity, Vol. 1, Chapter 8, John Wiley and Sons, New York, 1971 Chapter 8.
5. W. F. Stokey and W. F. Hughes, "Tests of the Conducting Paper Analogy for Determining Isopachic Lines," Proc. SESA, Vol. XII(2), pp. 77-82 (1955).
6. P. S. Theocaris, "On an Electrical Analogy Method for the Separation of Principal Stresses along Stress Trajectories," Proc. SESA, Vol XIV(2), pp. 11-20 (1957).
7. N. S. Waner and W. W. Soroka, "Stress Concentrations for Structural Angles in Torsion by the Conducting Sheet Analogy," Proc. SESA, Vol. XI(1), pp. 19-26 (1953).
8. J. A. Swanson, FEATS: A Computer Program for the Finite Element Thermal Stress Analysis of Plane or Axisymmetric Solids, Westinghouse Electric Corporation, Astronuclear Laboratory Report No. WANL-TME-1888 (1969).
9. E. L. Wilson, "Finite Element Analysis of Mine Structures," Final Report to U.S. Department of Interior, Bureau of Mines on Contract No. H0110231, Department of Civil Engineering, Berkeley, California (1972).
10. N. I. Muskhelishvili, Chapter 5 in Some Basic Problems of the Mathematical Theory of Elasticity, P. Noordhoff Ltd., Groningen, Holland, 1953.
11. E. G. Coker and L. N. G. Filon, Chapter 4 in A Treatise on Photoelasticity, Cambridge University Press, 1957.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of S. E. Bolt, Robert Smith, Jr., and C. M. Fitzpatrick in the experimental work of this investigation. The computer results for comparison were supplied by W. H. Gray. The interest, suggestions, and helpful discussion of R. W. Derby and W.C.T. Stoddart are appreciated.

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Fig. 2. Detail construction of the oval shaped loading fixture.

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