FINITE ELEMENT ANALYSIS OF STRUCTURAL RESPONSE OF SUPERCONDUCTING MAGNET FOR A FUSION REACTOR

M. REICH, J. POWELL and P. BEZLER
Brookhaven National Laboratory, Upton, New York, U.S.A.

T.Y. CHANG and S. PRACHUKTAM
Department of Civil Engineering, The University of Akron, Akron, Ohio 44325, U.S.A.

SUMMARY

Superconducting magnets have been considered for use in producing the confining field for future fusion reactor design. The performance of these magnets will affect plasma containment time, particle leakage from the plasma as well as power density of the system. Thus, each superconducting fusion magnet is an extremely critical structural component of the fusion power plant.

In the proposed Tokamak fusion reactor, the superconducting unit consists of an assembly of D-shaped magnets standing vertically and arranged in a toroidal configuration. Each magnet is a composite structure comprised of Nb-22% Ti and Nb-48% Ti, and stabilizing metals such as copper and aluminum or stainless steel held together by reinforced epoxies which also serve as insulators and spacers. The magnets are quite large, typically 15-20 meters in diameter with rectangular cross sections around 0.93 × 2 m.

Under static loading condition, the magnet is subjected to dead weight and large magnetic field forces, which may induce high stresses in the structure. Furthermore, additional stresses due to earthquake must also be considered for the design of the component.

It is important to recognize that the structural performance of the field magnets will significantly affect the overall safety of the fusion reactor, since their primary function is to contain the superconducting current. Excessive structural distortion may lead to localized magnetic transitions from the superconducting state to the normal state, which could cause melting or failure of the structure. Consequently, this can result not only in the loss of hundreds of millions of dollars of investment, but also the destruction and dispersion of highly radioactive fusion blanket surrounding the magnet. Therefore, a detailed and more concise design and analysis of the field magnets is definitely required.

Both static and dynamic analyses of a typical field magnet have been performed by use of the finite element method. The magnet was assumed to be linearly elastic with equivalent homogeneous material properties. Various finite element models have been considered in order to better represent the structure for a particular loading case. For earthquake analysis, the magnet was assumed to be subjected to 50% of the El Centro 1940 earthquake and the dynamic response was obtained by the displacement spectrum analysis procedure. In the paper, numerical results are presented and the structure behavior of the magnet under static and dynamic loading conditions is discussed.

1. INTRODUCTION

Several fusion reactor concepts, including the Tokamak type [1], Stellarator [2], Theta Pinch [3], Mirror [4], etc., have been proposed for future electric power generations. The magnetic design aspects of the various concepts are quite different and it is beyond the scope of this paper to even attempt to consider all the structural problems associated with each of the above designs. Accordingly, we restrict the attention of this paper to the Tokamak concept which, at the present time, appears to be the leading candidate for an eventual practical power reactor.

In the proposed Tokamak reactor [5], superconducting magnets have been considered for use in producing the confining field. In the reactor, the plasma chamber has a torus configuration. Outside the chamber is a blanket region, composed of either lithium or lithium salt, which serves as a moderator as well as a tritium breeder [6]. Surrounding the plasma blanket are a series of magnet field coils (or magnets) standing vertically in a toroidal pattern. Various geometric shapes for the magnets have been suggested but only two were seriously considered: a circular magnet with external reinforcement rings to resist bending and a "D" shaped magnet which provides a constant tension winding region without rings. Considered in this paper is the latter case, the "D" shaped magnets.

2. GENERAL DESCRIPTION

While several different magnet designs have been proposed for the Tokamak reactor system, the following basic characteristics for the magnets should nevertheless prevail:

i) A magnetic field of several tens of kilogauss is generated by a set of discrete superconducting coils arranged in a torus. The toroidal plasma is contained inside of these field coils.

ii) Another set of coils, known as divertor coils create a poloidal magnetic field, (i.e. orthogonal to the toroidal field), which defines the outer plasma surface and prevents it from contacting the first material wall of the blanket region.

iii) A set of ohmic heating coils provide a magnet flux through the center of the toroidal plasma. This flux is periodically varied to produce a toroidal ring current in the plasma. The poloidal field from the plasma ring current serves the function of stabilizing and confining the plasma blanket.

iv) A set of vertical field coils provide a vertical field through the plasma. This field keeps the plasma in equilibrium and prevents its expansion or contraction.

Depicted in Fig. 1 is a typical profile of the "D" shaped toroidal field magnet. Because of symmetry, only one-half of the magnet is shown. In the proposed design, the magnet consists of a stack of identical thin discs separated by plastic discs, which also serve as insulators and spacers (called micarta spacers). Each disc is comprised of Nb-22% Ti and Nb-48% Ti as the superconducting materials, copper (or aluminum) as the stabilizing metal and stainless steel as the structure material. A typical cross section of the disc is shown in Fig. 2.

During the operating conditions, the field magnets are subjected to large radial forces due to the interactions between the field magnets and current carrying conductors embedded in the coils. These forces are generally nonuniform along the circumferential direction of each magnet and produce high stresses in the structure. An abnormal situation, defined as a quench state of the conductor may arise in the magnet, in which the superconductor goes through a phase change and recovers its electrical resistance. When such state occurs, the conductor may rapidly heat up inducing large local temperature gradients which can result in severe thermal stresses. Consequently, this may lead to localized failure or even melting of the coil assembly as a result of uncontrolled temperature rise.

In addition, when the reactor is to be built in a seismic zone, earthquakes present special problems in that excessive displacements of the structure may cause quenching of the field coil, possibly leading to the failure of the system.

Presented in this paper are the finite element analyses of the superconducting magnet subjected to field forces, thermal gradients under quench conditions, and earthquake loads.

3. STRUCTURAL ANALYSIS

The structural reponse of the field magnet was investigated for three different loading cases: (1) magnetic field forces, (ii) thermal stresses under quench state, and (iii) earthquake load. All the analyses were carried out by using the finite element method and the results are summarized as follows.

3.1 Magnetic Field Forces

During the operating condition of the reactor, each magnet is subjected to large field forces along its radial directions. These forces are primarily due to the field-current interaction and are given by

$$p = \frac{B\ I\ R_o}{R} \qquad (1)$$

where

p = Magnet force/arc length/thickness, N/M^2

B = Magnet field at the center of the plasma region, Testa.

I = Current in the coil, A.

R_o = Distance between the center of torus and center of plasma region, M

R = Horizontal distance between any point of the magnet and the center of torus, M.

The distribution of these forces at the inner surface of the magnet along its circumferential direction is plotted in Fig. 3. Essentially, the force increases monotonically from the outer turn to the inner turn. Because of the symmetry in loading, a plane stress model was considered and the finite element grid system used is shown in Fig. 4. In the present analysis, the material behavior is assumed to be isotropic and homogenous. For temperature at 4^oK, the material constants are

Young's modulus	$E = 24.6 \times 10^3$ Ksi
Poisson's ratio	$\nu = 0.3$
Plastic modulus	$E_p = 178$ KSI
Yield Stress	$\sigma_y = 90$ KSI

An elastic-plastic stress analysis was carried out by an incremental loading procedure. The structure first became plastic at 50% of the total load near the fixed end of the inner turn. As the load increased further, larger yielding zone was found in the structure and the propagation of the yielding zone in the magnet as a function of the radial force is shown in Fig. 5. The most severely stressed regions are those near the supports where the magnet is restrained from movements. Plotted in Figs. 6 and 7 are the stress contours for the effective stress at 50% and 100% of the total load, respectively. It is seen that the stress patterns in the structure have changed significantly due to the occurrence of plastic deformations. From the design point of view, it may be desirable to impose partial restraints, rather than rigid supports, at the inner and outer turns of the magnet in order to reduce the bending effect due to the nonuniform radial forces.

3.2 Thermal Stresses Due to Conductor Quenches

Quenches in the superconducting magnet, for conductor temperatures above $100^{O}K$, are expected to produce high thermal stresses and hence will cause yielding in the structure. Excessive plastic deformations resulting from quenches may induce cracking of the epoxy insulation, large distortion of the coolant channels and failure of the micarta spacers. Consequently, such damages may cause short circuits and arcing in the conductor, which in turn may endanger the function of the entire reactor system.

Considered in this paper are the thermal stress analyses for two hypothetical quench states in which the conductors are assumed to have a temperature rise of $100^{O}K$ and $300^{O}K$ respectively, while the steel part of the disc remains at $4^{O}K$. Steady state temperature distribution corresponding to a temperature change of either $100^{O}K$ or $300^{O}K$ in the conductor was determined and this was then used as the input for subsequent stress analysis. Since for the quench state, stress distribution in a cross section of the magnet due to the interaction of conducting material and structural steel was of primary interest, an axisymmetric finite element model was used to obtain an approximate analysis. Elastic stresses were determined from the finite element analysis and the stress contours for the circumferential component are shown in Figs. 8 and 9 for temperature cases $100^{O}K$ and $300^{O}K$, respectively. Presented in these figures are the inner and outer parts of the 93 cm radial coil width where the stress conditions appear to be most critical.

The results indicate that a $100^{O}K$ temperature rise in the conductor approaches a potentially dangerous condition in the magnet. Due to the high-thermal stresses, the steel reinforcement is close to its yielding and fatigue failure of the magnet may become a major concern. It was found that the in-plane stresses in the micarta spacer (not shown in the figures) are in the order of 5000 psi which is near its fracture strength. Fracture of the micarta spacers may potentially block the coolant channels which will subsequently raise the temperature in the conductor, leading to a more critical operating condition.

It is seen from Fig.9 that a $300^{O}K$ temperature rise in the conductor will cause stresses far beyond the yield limit of the magnet material. The steel reinforcement will yield excessively. The peak stresses in the micarta spacers are in the order of 30,000 psi, which by far exceeded the strength limit of the material. Thus, the spacer will crack over a large area and many coolant channels could be effectively blocked.

3.3 Earthquake Response Analysis

For the earthquake response analysis of the toroidal magnet, several assumptions relative to the characteristics of the structure and typical earthquake were made. The toroidal magnet was assumed to be linearly elastic with homogeneous material properties and its elastic constants are as defined in section 3.1. The unit weight of the structure is 370 lb/ft^3. Response spectra method was used with 50% of the El Centro 1940 earthquake as the input response spectrum [7]. The vertical displacement was assumed to be 2/3 of the horizontal components. The two ends of the finite element model were restrained from lateral movements as well as rotations.

For comparison of results, two finite element models were used: one consists of three-dimensional beam elements capable of deforming in the space and the other one is a three-dimensional solid structure consisting of 39 brick elements (8 nodes per element). Table 1 shows the comparsion of the natural frequencies for the beam and brick models and good agreement was obtained for the first five frequencies. Examination of the modal participation factors revealed that the dynamic response of the structure was predominated by the first two vibrational modes. Higher modes had little significance on the structural response.

The normal stresses were calculated for both the brick and beam elements at location A as designated in Fig. 10 and the stress distributions (vs. angular positions) are plotted in Fig. 11 for comparison. It is seen that the difference between the two analyis models is insignificant.

The computer program for the 3-D brick element gives stresses at the center sections of the element, at which the stress may not assume its maximum value. In fact, the maximum stress occurs near one of the corners of the element due to the combined bending actions. The beam model does give such maximum value as shown in Fig. 12. From the figure, high bending stresses occurred near the fixed ends. Nevertheless, the stress condition in the magnet caused by earthquake alone is rather low and thus does not seem to cause any concern for the proposed design at present.

4. CONCLUSION

Presented in this paper are merely some of the structural problems associated with the design of superconducting magnets of the proposed Tokamak fusion reactor. This, by no means, has covered all the design problems that have been considered. Continuing effort is being carried out to examine other design and safety considerations for the magnet and other structural components in the proposed fusion reactor system.

REFERENCES

[1] Wisconsin TOKOMAC Reactor Design, Nuclear Engineering Dept., University of Wisconsin, UWFDM-68 1974.

[2] GIBSON, A., HANCOX, R., BICKERTON, R.J., "On the Economic Feasibility of Stellarator and Tokomak Fusion Reactors", Proceedings, Fourth IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin (June, 1971).

[3] "An Engineering Design Study of A Reference Theta Pinch Reactor (RTPR)" ANL-8019/LA5339, 1974, Krakowski, R., Editor.

[4] MOIR, R., and TAYLOR, C.E., "Magnets For Open-ended Fusion Reactors", p. 853 in Technology of Centrolled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors, CONF-721111, Technical Information Center US AEC (1974).

[5] "A Fusion Power Plant", R.G. Mills, Editor. Princeton University Plasma Physics Lab MATT 1050 (Aug. 1974).

[6] DE MICHELE, D.W. AND DARBY, J.B., JR., "An Analysis of the Material Constraints on Superconducting Magnets for Controlled Thermonuclear Reactors," Proc. of the Texas Symposium on the Technology of Controlled Thermonuclear Fusion Experiments and Engineering Aspects of Fusion Reactors, Austin, Texas, Nov. 20-23, 1973.

[7] NEWMARK, N.M. and HALL, W.J., "Seismic Design Criteria for Nuclear Reactor Facilities", Pressure Vessel and Piping: Design and Analysis, vol. 2, The American Society of Mechanical Engineers, 1973, pp.1414-1427.

TABLE 1 COMPARISON OF NATURAL FREQUENCIES

Mode	3-D Brick	3-D Beam
1	71.8	70.0
2	88.7	88.4
3	189.9	191.4
4	193.2	196.1
5	353.9	352.6
6	361.3	404.9

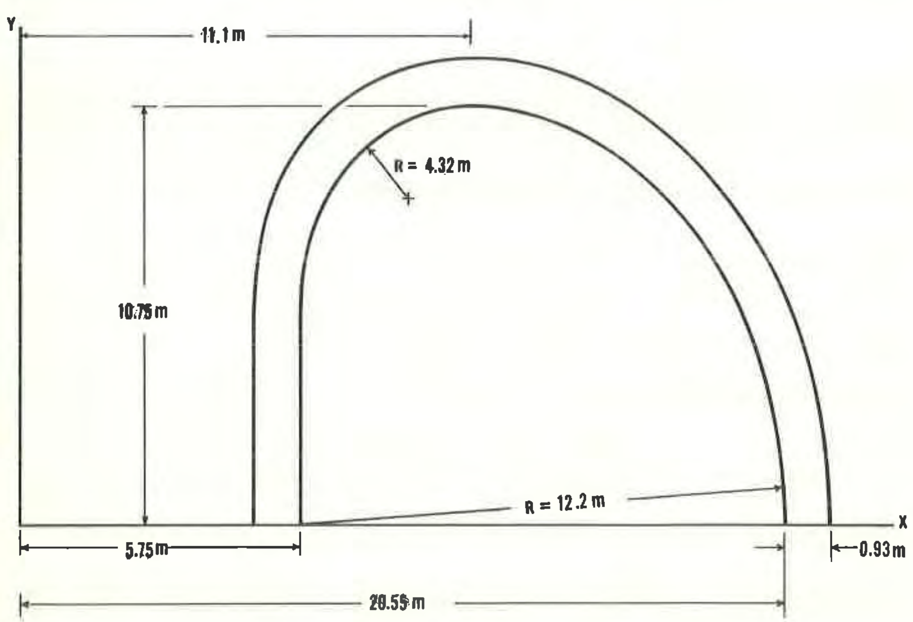

Figure 1 "D" Shaped Toroidal Field Magnet (After Reference [1]).

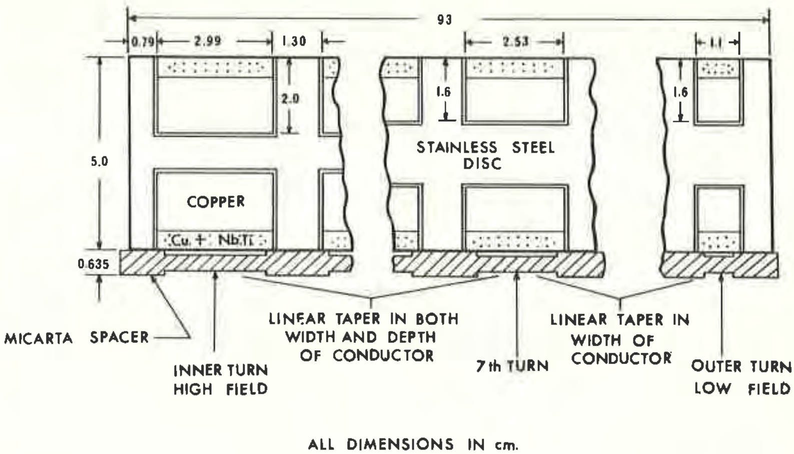

Figure 2 Cross Section of Conductor and Structural Disc for the "D" Shaped Toroidal Field Magnet (After Reference [1]).

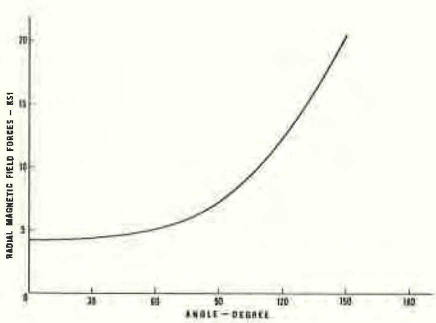

Figure 3 Radial Magnet Forces on the "D" Shaped Magnet.

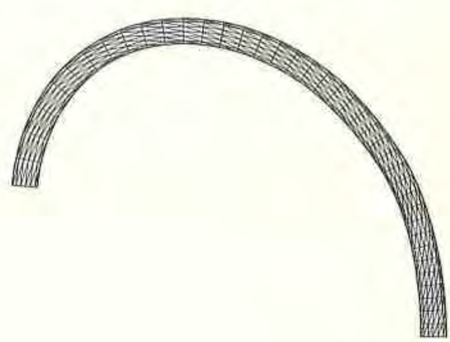

Figure 4 Finite Element Grid for "D" Shaped Magnet.

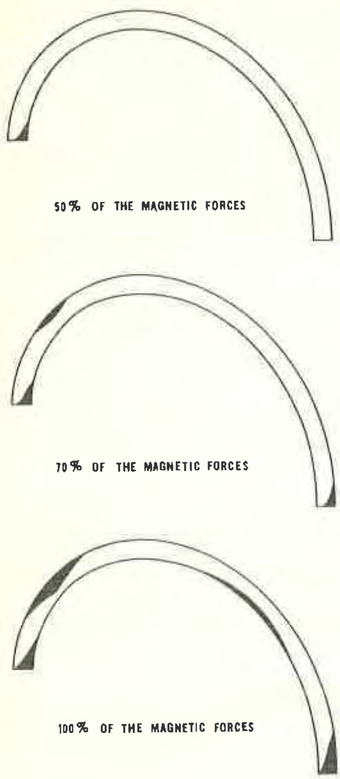

Figure 5 Propagation of the Plastic Zone in the "D" Shaped Magnet.

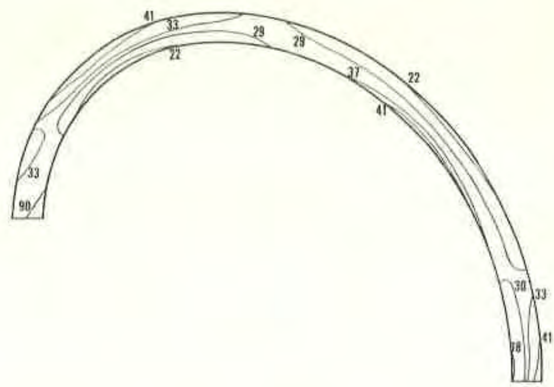

Figure 6 Contours of the Effective Stress at 50% of the Magnet Field Forces.

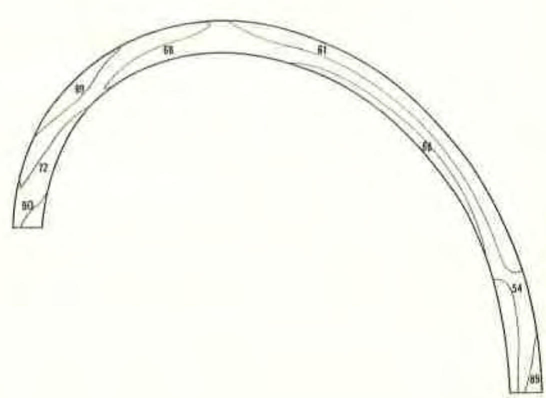

Figure 7 Contours of the Effective Stress at 100% of the Magnet Field Forces.

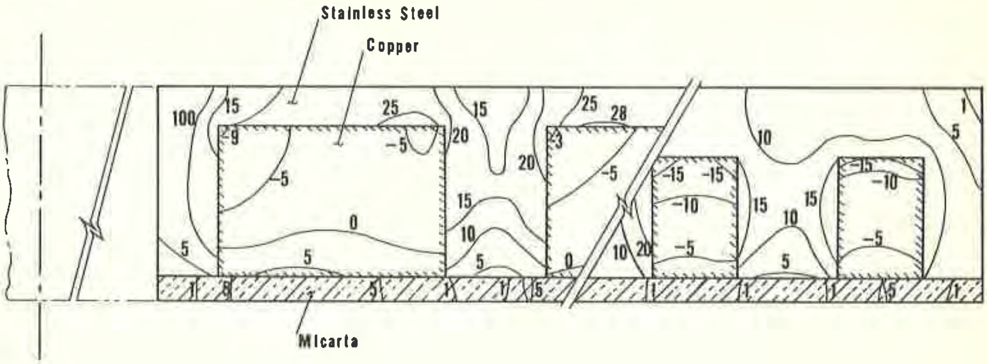

Figure 8 Contours of Circumferential Stress at 100°K Temperature Rise.

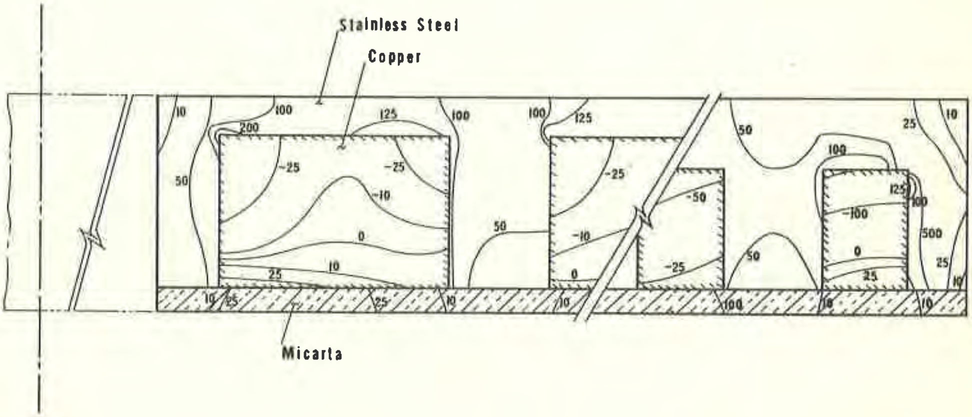

Figure 9 Contours of Circumferential Stress at 300°K Temperature Rise.

M ?/9

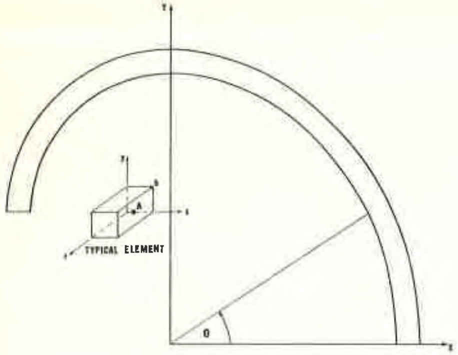

Figure 10 Analytical Model of "D" Shaped Toroidal Magnet.

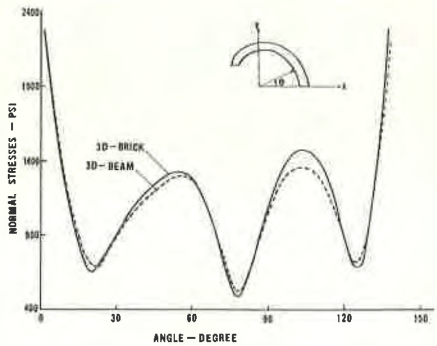

Figure 11 Stress Distribution vs Angular Positions of Normal Stresses at Center of the Interior Face (Location A).

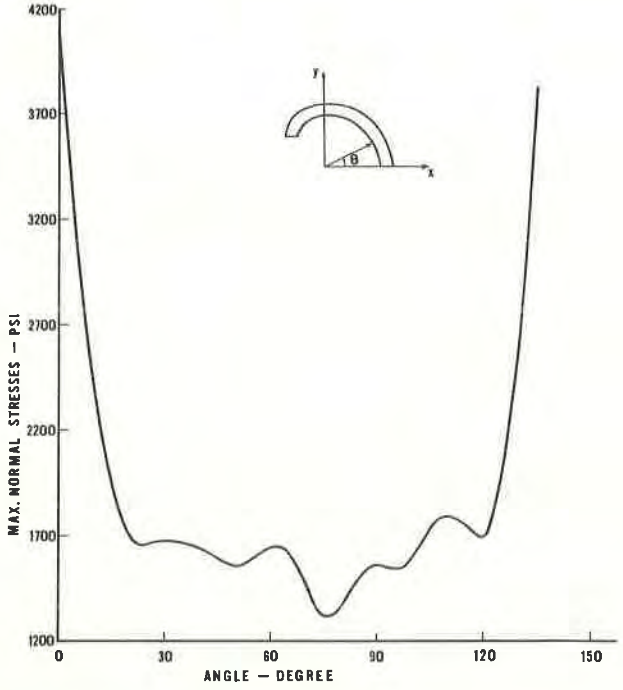

Figure 12 Stress Distribution vs Angular Positions of Normal Stresses at Corner of the Face (Location B).