

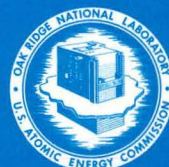
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Inelastic Analysis of Two Plates Under Deformation Dependent Loads

S. K. Iskander

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Reactor Division

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DEFORMATION DEPENDENT LOADS

S. K. Iskander* C. W. Collins†

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FEBRUARY 1976

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ABSTRACT

Cover plates are used in current designs for high temperature gas-cooled reactors to compress the mineral fiber insulation against the inside of the liner of the prestressed concrete pressure vessel. In the upper plenum, these plates are hexagonal and specified as carbon steel; in the lower cross ducts, the plates are square and made of Hastelloy X. The General Atomic Company has specified both damage and safety limit criteria for these plates. These plates have been analyzed at these limits using the inelastic finite element computer program EPACA. The results indicate that the total strains for the square plate were within the specified values; however, the maximum deformations at the free corners indicate separation from the insulation and failure to achieve one of the design requirements. Since no material data were available for carbon steel at the limiting temperatures, it was assumed that the hexagonal plates were constructed of 2 $\frac{1}{4}$ % Cr-1% Mo material. Although this material was found to produce satisfactory performance, extrapolation of available information would lead to the conclusion that the performance of carbon steel plates would not be satisfactory at the specified conditions.

Key words: carbon steel, cover plates, deformation, gas coolant, Hastelloy X, mechanical properties, reactors, stress analysis, thermal insulation.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has requested the Oak Ridge National Laboratory (ORNL), as part of the studies performed for the Gas-Cooled Reactors Branch (GCRB) of the Division of Reactor Licensing (DRL), to assist in the evaluation of the first licensing topical report¹ for high-temperature gas-cooled reactors (HTGR). As part of this effort, two typical metal cover plates for the insulated liner of the prestressed concrete reactor vessel (PCRV) were analyzed at specified limiting conditions.

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Current designs for the HTGR at normal operating conditions use high pressure helium with a core inlet temperature of about 600°F which is heated to an outlet temperature of about 1400°F; higher temperatures are reached at upset and faulted conditions. To protect the liner of the PCRV from these temperatures, fibrous insulation is installed between the liner and a metal cover plate which confines the insulation and provides a smooth, clean inner surface that is exposed to the flowing helium. Different amounts of insulation, metal types and shapes, are used throughout the pressure vessel.

Two types of cover plates were selected for analysis as being typical for the entire reactor. The first plate is a 1/4-in. Hastelloy X square plate, shown in Fig. 1, used in the outlet plenum. The second plate is a 1/4-in. carbon steel hexagonal plate, shown in Fig. 2, used in the inlet plenum. Both plates are supported at the center and at the edges as shown in Figs. 1 and 2. A typical support is shown in Fig. 3. Pressure applied to the plates compresses the 4 in. of Kaowool to 3 in., and the plates are then attached to the supports resulting in an initial maximum preload to the plates of 3 psi. The General Atomic Company tested Kaowool to determine the effects of temperature, time, irradiation, and different amounts of precompression.² From these data, it was determined that the initial plate preload would decrease from 3 psi to 0.75 psi due to loss of resiliency at elevated temperature for a relatively short period of time.

The topical report¹ (GA-LTR-1) gives the design bases for the core cooling systems as determined by subjecting the core and PCRV internals to a set of hypothetical thermal transients to establish the conditions at which component damage could occur. For purposes of evaluating transient severity, two threshold limits for temperatures of important primary system components are defined:

Damage Limit — Defined as that component temperature at which damage may be incurred to the extent that normal plant operation may not be resumed without repairs. "Damage" is defined as the condition when total creep deformation strain exceeds the design limit by 1%. For the square plate, the damage limit was reported as 1800°F for 10 hr; for the hexagonal plate as 1000°F for 10 hr.

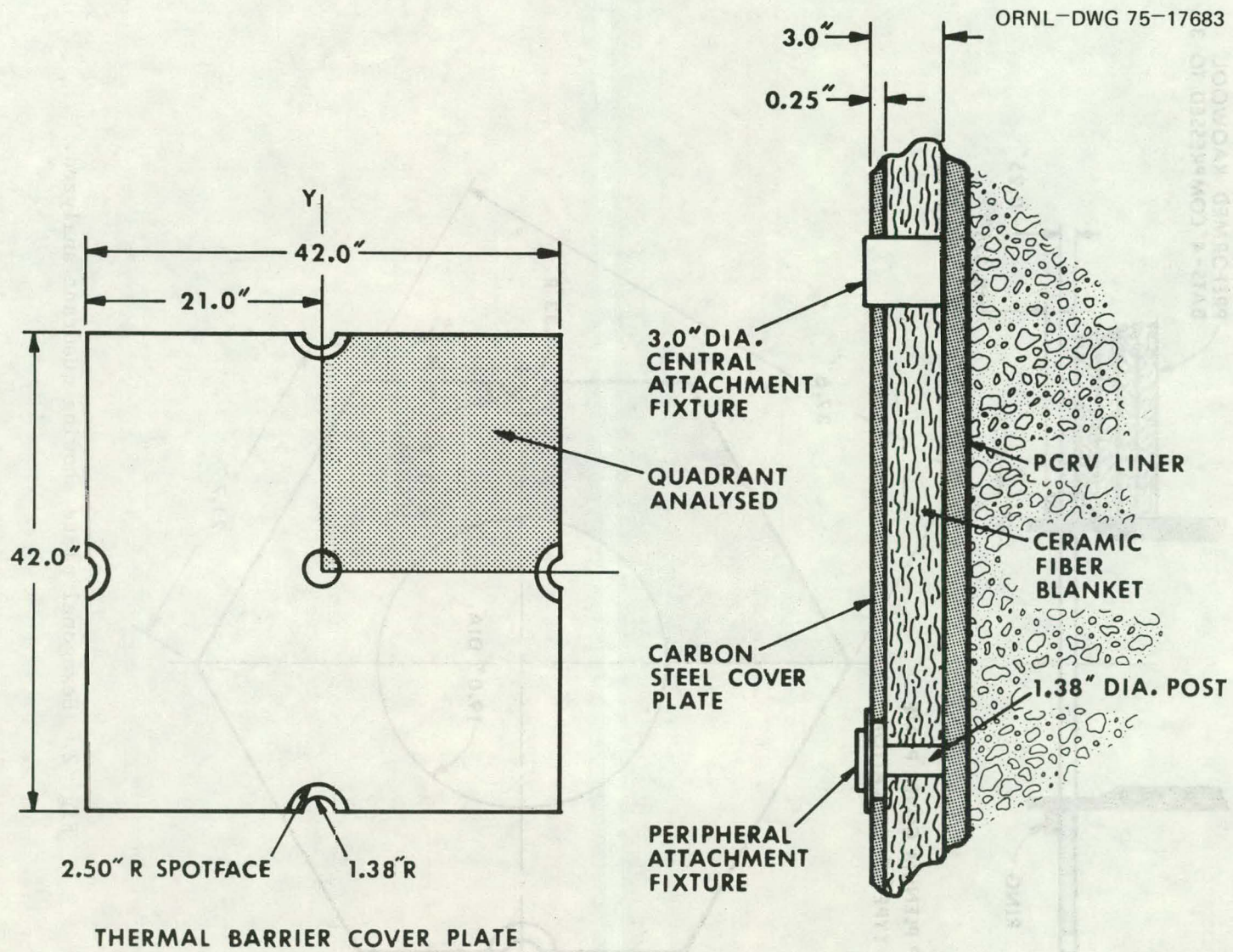


Fig. 1. Square plate showing quadrant analyzed.

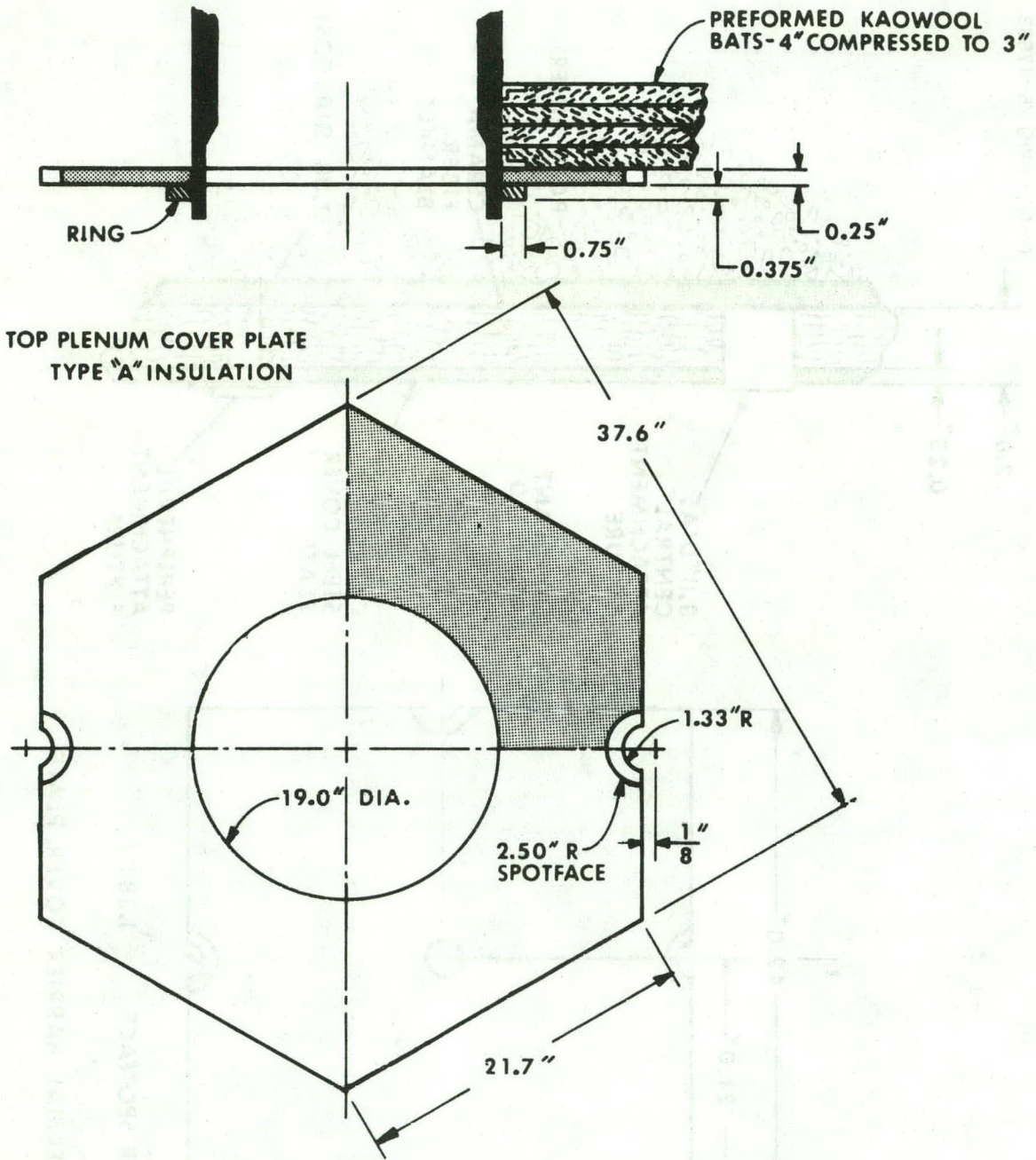


Fig. 2. Hexagonal plate showing quadrant analyzed.

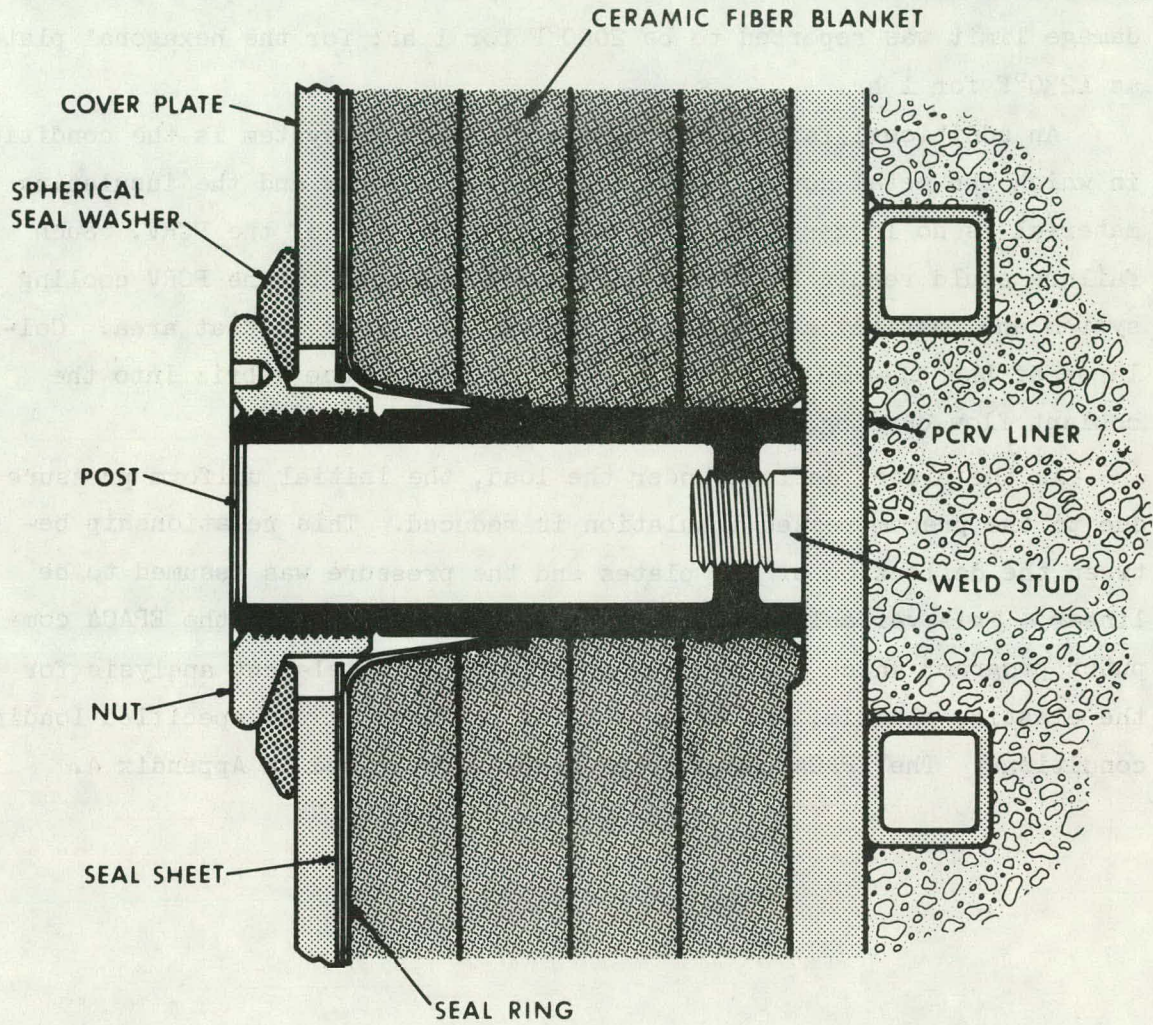


Fig. 3. Typical support for the plates analyzed.

Critical Safety Limit — Defined as that component temperature at which damage may be incurred to the extent that it would interfere with effective core cooling. Exceeding the "Critical Safety Limit" results in "failure", which is defined as the condition where total creep deformation strain exceeds the design limit by 3%. For the square plate, the damage limit was reported to be 2000°F for 1 hr; for the hexagonal plate as 1230°F for 1 hr.

An additional failure of the thermal barrier system is the condition in which the metal cover plates deflect excessively and the insulating material is no longer compressed against the liner of the PCRV. Such failure could result in local excessive heat input to the PCRV cooling system and possibly a buckling failure of the liner in that area. Collapse of the thermal barrier itself could introduce debris into the coolant flow causing blockage of some flow passages.

As the plates deflect under the load, the initial uniform pressure due to the precompressed insulation is reduced. This relationship between the deflection of the plates and the pressure was assumed to be linear. This variable loading was taken into account in the EPACA computer program³ which was used to provide a finite element analysis for the elastic, plastic, and creep strains produced by the specified loading conditions. The EPACA computer program is described in Appendix A.

METHOD OF ANALYSIS

The finite element method necessitates the modeling of the component to be analyzed as an assemblage of elements. In this case, the members to be analyzed were a square plate, Fig. 1, and a hexagonal plate, Fig. 2. Their symmetrical shapes and loads required only one quadrant to be modeled and analyzed, thereby simplifying the calculations. The outlines of the quadrants are hatched in Figs. 1 and 2. In both cases, the semi-circular recesses were ignored and a straight edged outline was assumed. Although these recesses could lead to stress peaks in the elastic region, these peaks will level off in the plastic region. Also, the washers supporting these plates (see Fig. 3) tend to mitigate any eventual adverse effects of the recesses.

The finite element model of the square plate is shown in Fig. 4. The quadrant of the plate was uniformly subdivided into 49 elements connected by 64 nodal points. The boundary conditions on two adjacent edges simulated the presence of the remaining parts by restricting the rotations about the x and y axes. Furthermore, the plate was simply supported on the three corners of these same edges, leaving one corner free (Fig. 4).

The internal operation of the code requires the specification of a number of Gaussian integration points in the plane of the plate and parallel to each side of the element. Two such points along each axis were specified. Furthermore, six layers of these points were specified through the thickness for a total of 24 integrating points in each element (see Fig. 5), which is sufficient for accuracy within $\pm 10\%$. The strains and stresses at these points have a certain amount of freedom to take on the necessary values (see Appendix A).

The hexagonal plate was represented for the finite element analysis as shown in Fig. 6. In this case, there were 65 nodal points connecting 48 elements. The edges along the x and y axes were restricted from rotations, as in the case of the square plate, to simulate the remainder of the plate. Furthermore, the plate was simply supported at the points indicated on Fig. 6.

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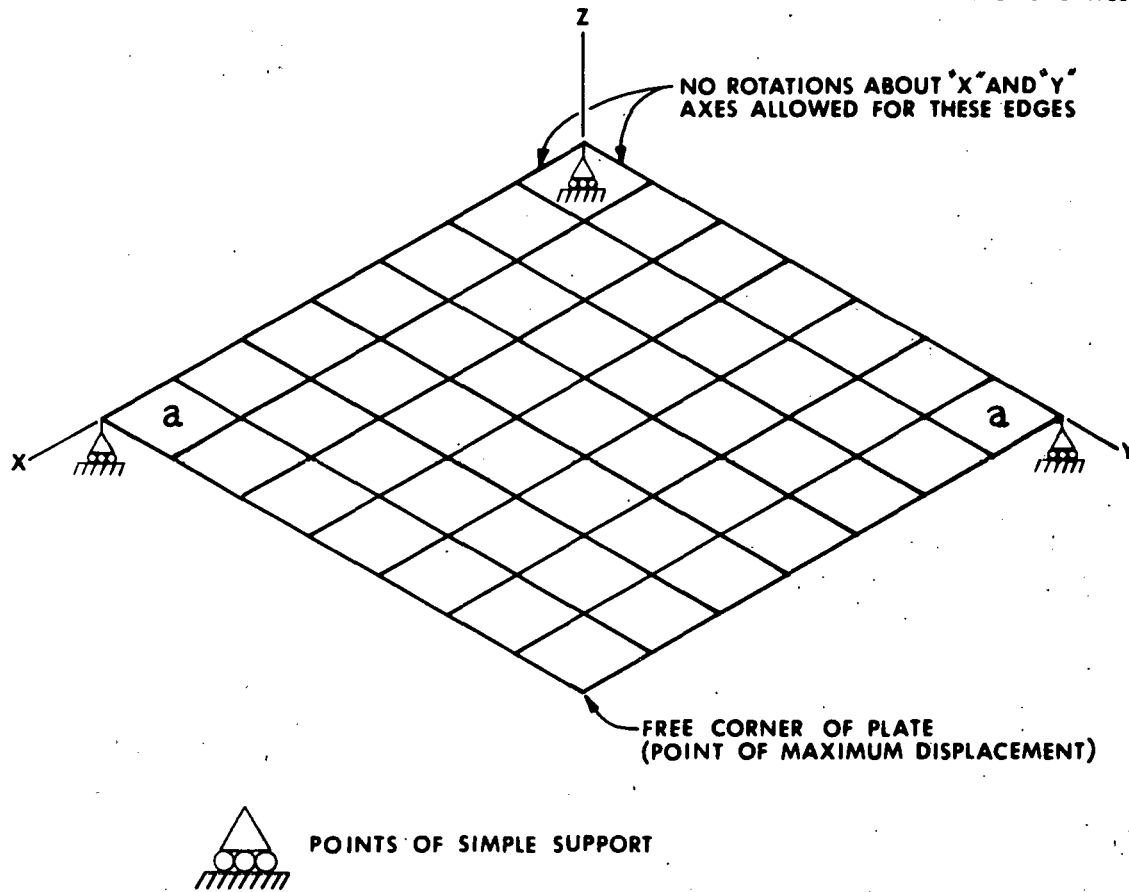
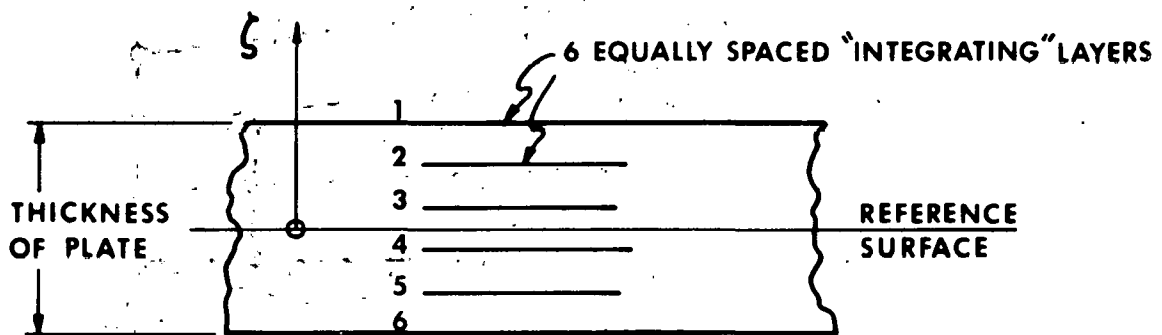
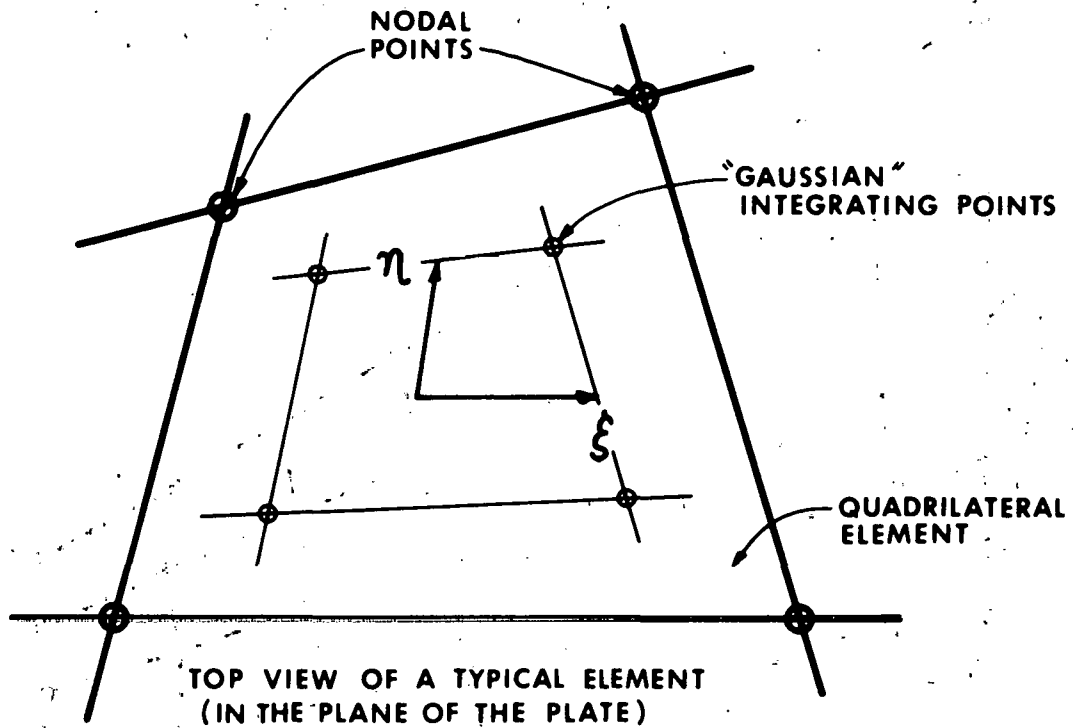


Fig. 4. Finite element representation of one quadrant of the square plate showing boundary conditions.

η - ξ - ζ - LOCAL AXES IN EACH ELEMENT



SECTION THROUGH THE THICKNESS OF AN ELEMENT

Fig. 5. Concept of integrating points and layers in each element.

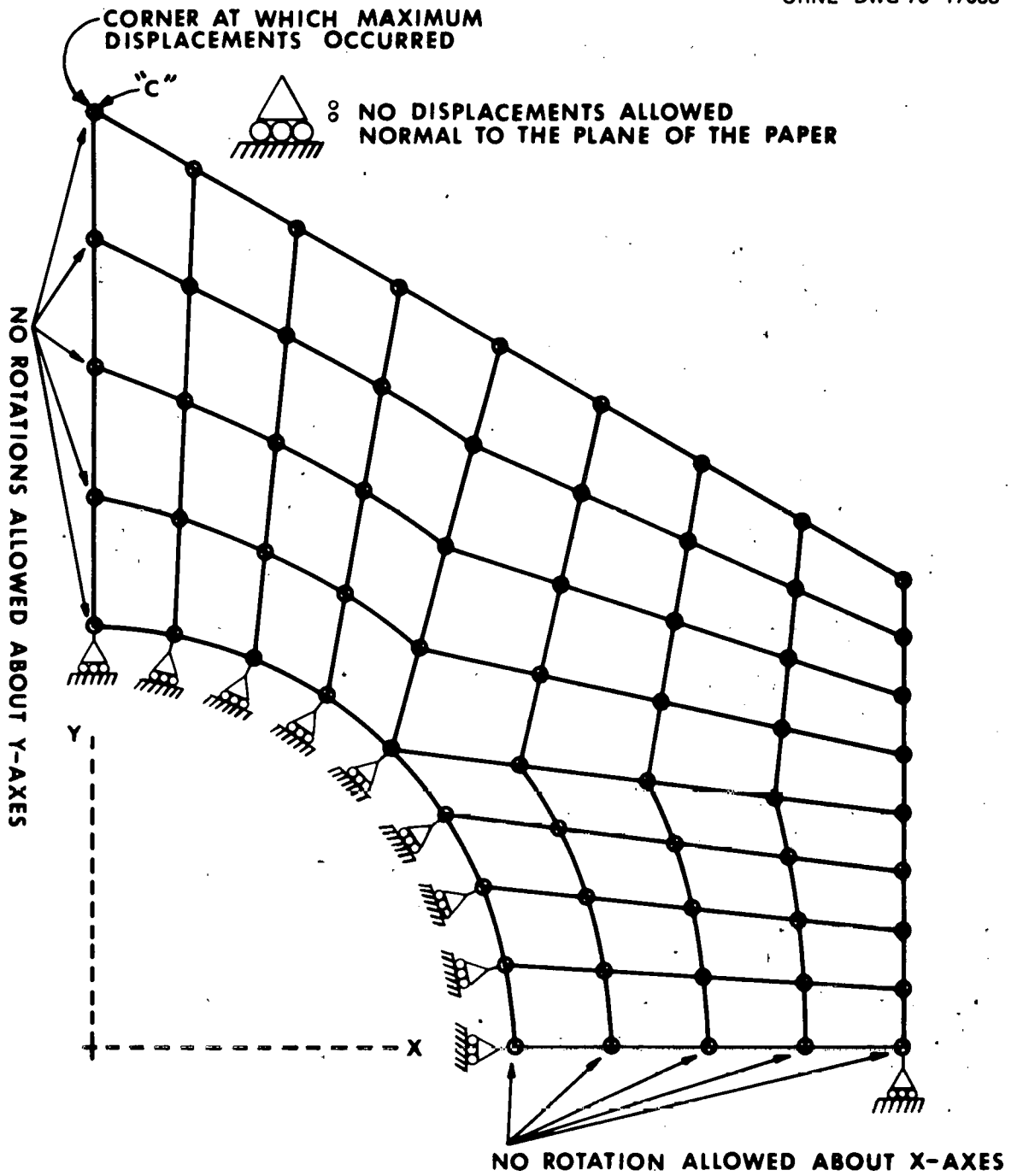


Fig. 6. Finite element representation of one quadrant of the hexagonal plate showing boundary conditions.

A preliminary analysis showed that the hexagonal plate remained substantially in the elastic region, thus only three integration layers were required through the thickness, although four points were specified in the plane of the plate as in the case of the square plate.

As explained in the appendix, the total load is applied in small increments. The size of these increments started with 0.005 of the full load and remained at this level for several steps. These were then gradually increased to 0.05 toward the end of the analysis. There were about 25 steps in each of the analyses at 1800°F and 2000°F.

At the end of each increment, the total load for the subsequent steps is reduced at each nodal point by a factor of $(1-\delta)$, where δ is the displacement normal to the surface of the plate at the node under consideration. If the displacement exceeded 1 in., no load was applied at that particular node. The 1-in. displacement in the above discussion represented the precompression of the Kaowool insulation.

The load on each plate consists mainly of 0.75 psi uniform pressure due to the precompressed insulation. To this was added a relatively small amount to account for the dead weight of the 0.25-in. plate.

MATERIAL PROPERTIES

The material properties⁴ used in the analysis of the square plate were for solution treated Hastelloy X and are shown in Figs. 7 and 8. Figure 7 shows the isochronous stress-strain curves at 1800°F in 10 hr, while Fig. 8 shows the curves at 2000°F for 1 hr. The curve labeled as the minimum was used. The initial yield and Youngs Modulus (or the modulus of elasticity) were estimated from these curves. Note the particularly low values of yield, 1 and 0.5 ksi for 1800°F and 2000°F, respectively, as these are of critical importance in the calculations.

For the hexagonal plate, the material properties were those for 2½% Cr-1% Mo at 1000°F for 10 hr and 1200°F for 1 hr. They can be closely approximated by the so-called bilinear representation and are shown in Fig. 9, taken from ASME code case 1592 (Ref. 5). Note the relatively high yield strengths as compared to the Hastelloy X material. The plastic region of the representation was not utilized in the analysis since the plates remained elastic.

The General Atomic Company had specified the use of carbon steel for the hexagonal plate. However, no data for isochronous stress-strain curves for 1000°F and 1200°F were available, so the superior high temperature material, 2½% Cr-1% Mo, was substituted because it appeared satisfactory for the service, and the needed isochronous stress-strain curves were available from ASME code case 1592.

For both plates, the isotropic hardening rule was used in analysis. Since no load reversals occurred, this is of little consequence; however, operation of the code requires the specification of either isotropic or kinematic hardening.

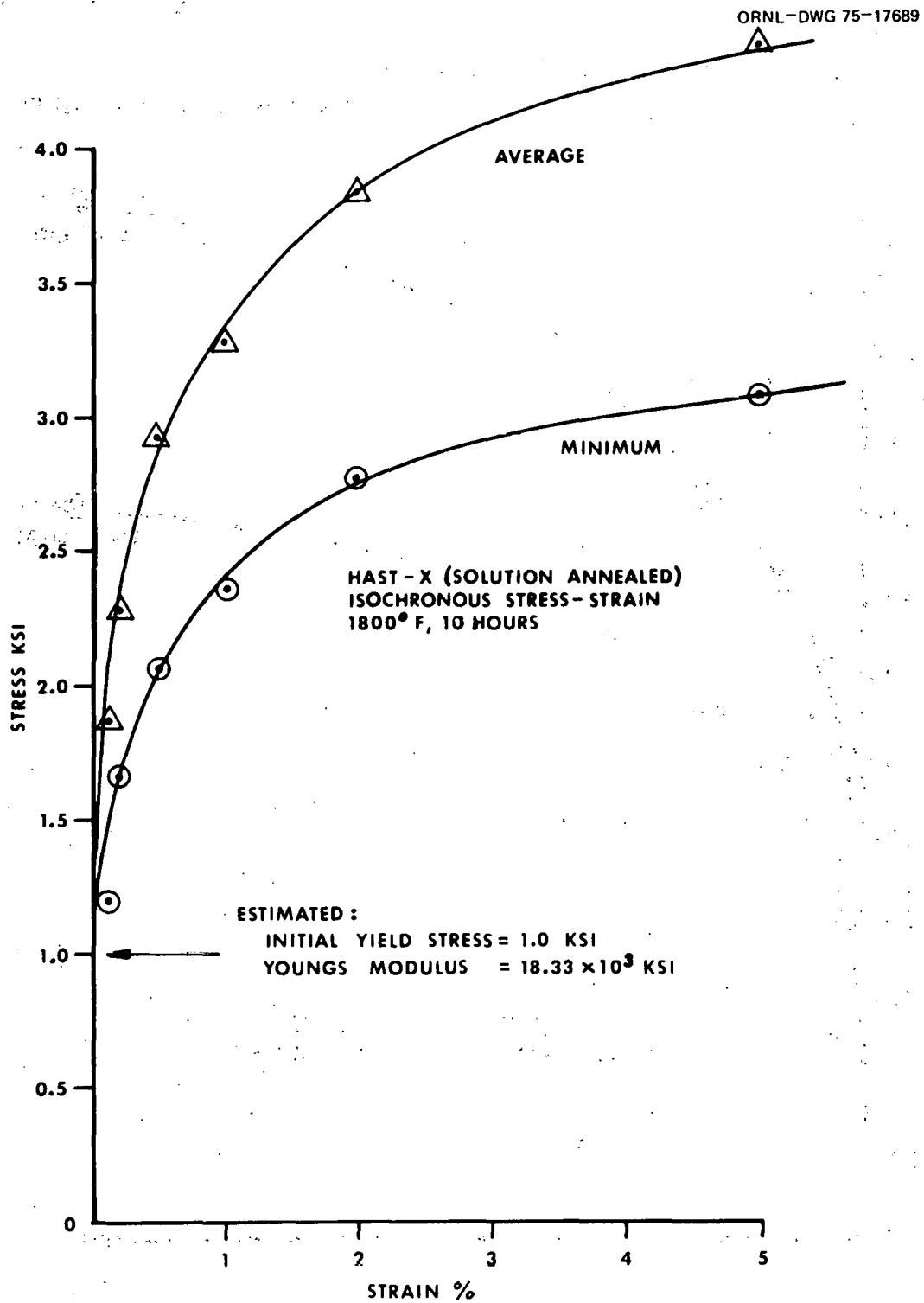


Fig. 7. Isochronous stress-strain curves for HASTELLOY X at 1800°F - 10 hours used in the finite element analysis.

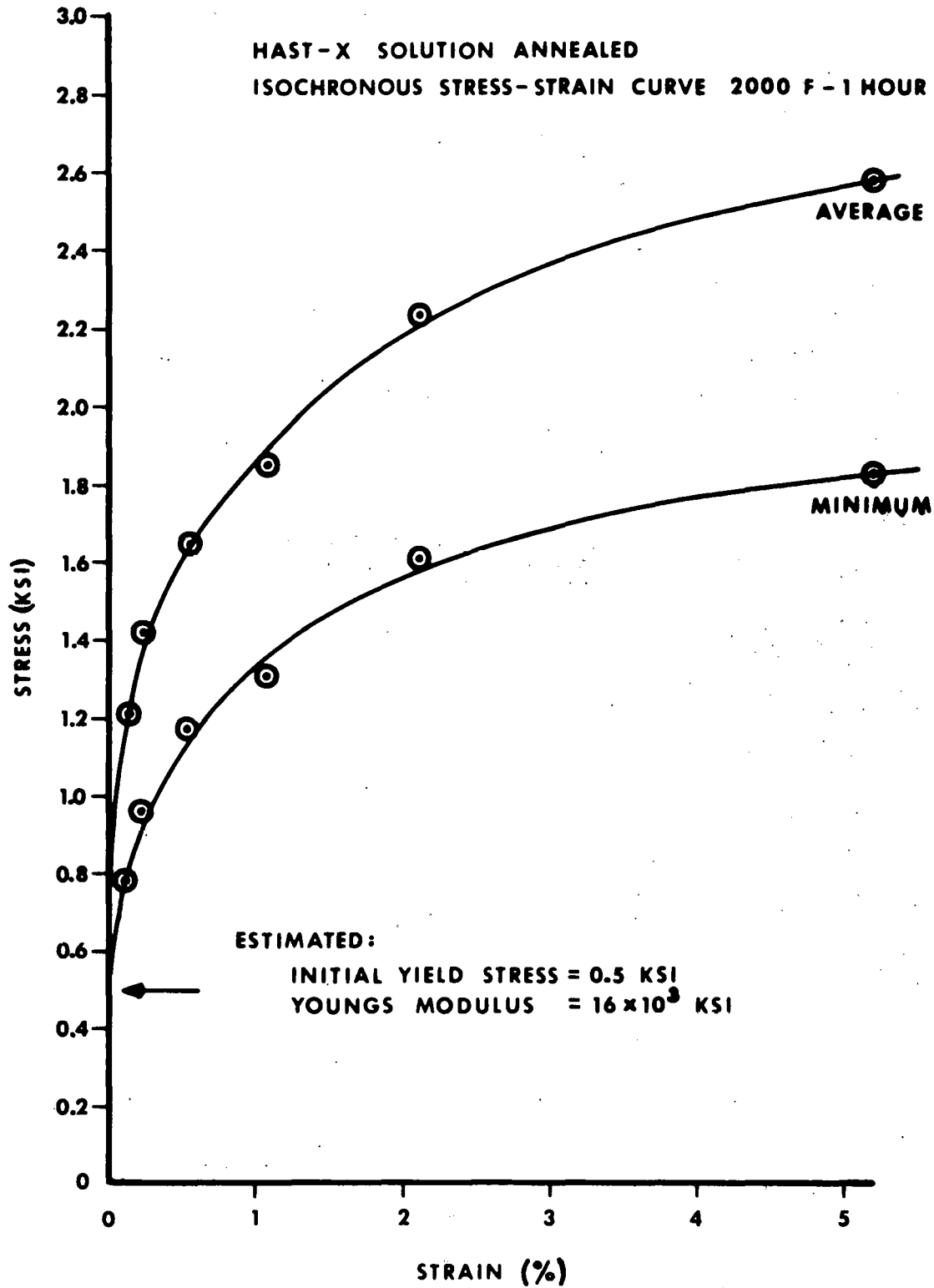


Fig. 8. Isochronous stress-strain curves for HASTELLOY X used in the finite element analysis (2000°F - 1 hour).

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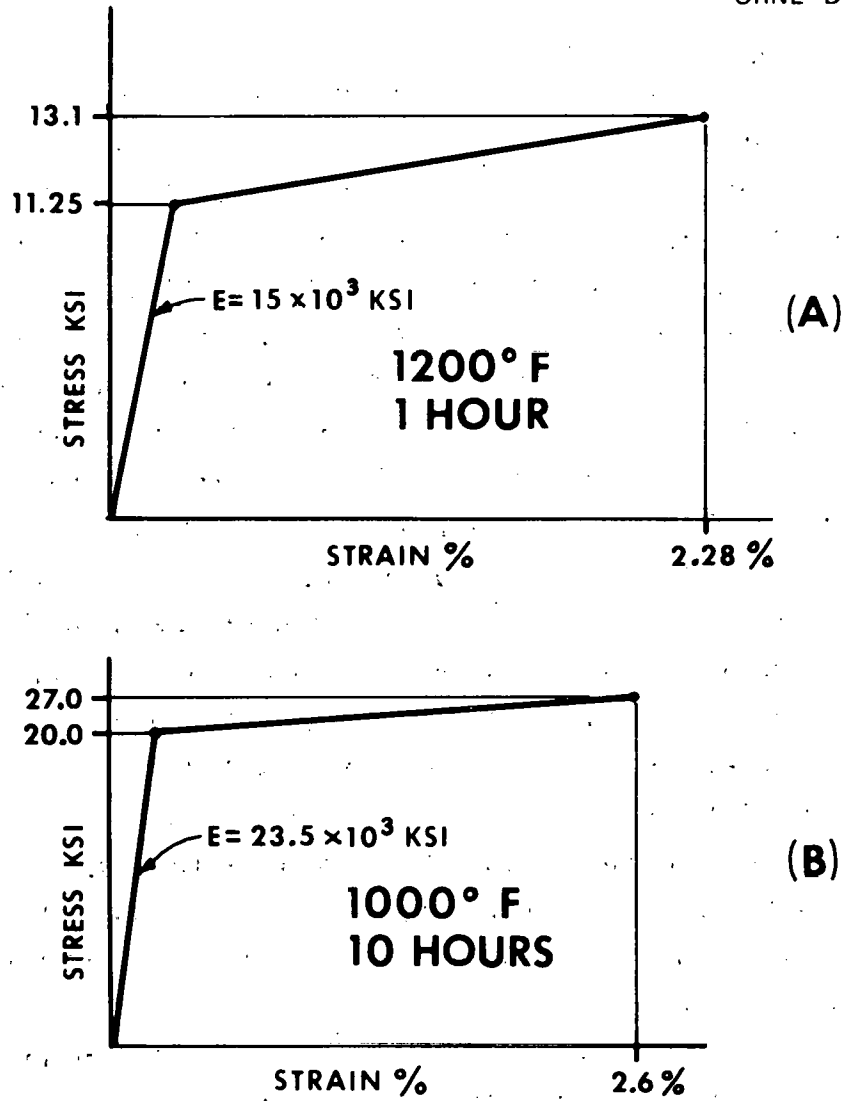


Fig. 9. Average stress-strain curves for 2 $\frac{1}{4}$ % Cr-1% Mo used in the finite element analysis of the hexagonal plate. Source ASME code case 1592. (A) For 1200°F and 1 hour; (B) 1000°F and 10 hours.

RESULTS OF THE ANALYSIS

The results of the analysis for the square plate show that the maximum total (elastic, plastic, and creep) strains are 0.35% and 0.54% at 1800°F and 2000°F, respectively. These strains occurred close to the mid-side supports, which would correspond to the elements designated "a" in the finite element representation, Fig. 4. Moreover, the plates have also undergone extensive inelastic yielding so that they have become permanently warped even under the small loads to which they were subjected. This is due to the very small elastic strength remaining in the plates at these high temperatures. Another manifestation of this is the fact that the free corners of the plate will displace more than 1 in., thus indicating they lift off the insulation, thereby failing to meet one of the design criteria. This occurred for both temperatures, the displacement of the free corner being 1.2 in. and 1.63 in. at 1800°F and 2000°F, respectively. It should be mentioned that these large displacements are beyond the range of "small" displacements for which the usual linear theory of strains apply. However, previous experience with incremental inelastic analysis of structures for which experimental data exist indicates that such analyses reproduce the essential features of the structural response. Exact figures on the accuracy are impossible to obtain. They are, however, adequate to indicate a possible problem.

The deformed shape of the quadrant analyzed is shown in Fig. 10. The remaining portions of the square plate deflect in a symmetric manner about the x and y axes.

Results for the hexagonal plate did not reveal any such problem. In fact, they indicate that the plate remained substantially elastic and no inelastic strains occurred for the 2 $\frac{1}{4}$ % Cr-1% Mo material substituted for the analysis. The maximum equivalent stresses were of the order of 10 ksi, sufficiently below the yield stress of 11.25 ksi, at the higher temperature level of 1200°F for 1 hr considered.

The maximum deflection of the hexagonal plate was 0.43 in. which occurred at corner C (Fig. 6) and was for the 1200°F temperature.

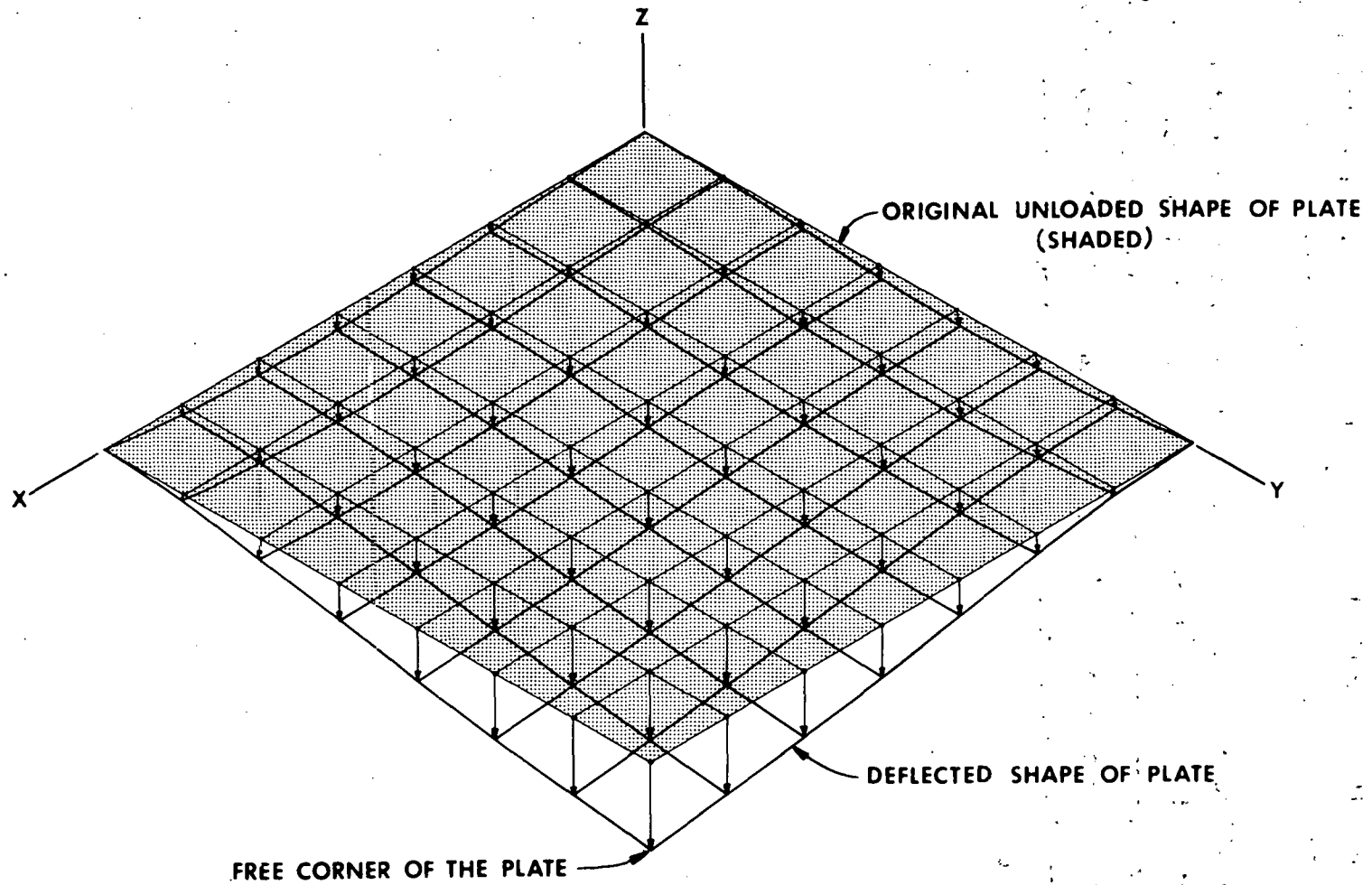


Fig. 10. Deflected shape of square plate.

Although the 2½% Cr-1% Mo hexagonal plate was found satisfactory, it must be concluded that the integrity of the carbon steel plates at the specified conditions would be very doubtful since available data show the strength of carbon steel to decrease rapidly at temperatures above 800°F.⁶

Many of the plate liners for the prestressed concrete reactor are curved rather than flat and are of sizes other than those analyzed in this study. Since the plates are typical, the results indicate most of the plates would satisfy the "Damage Limit" and "Critical Safety Limit" if 2½% Cr-1% Mo material were used instead of carbon steel for the hexagonal plates.

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APPENDIX A

BRIEF DESCRIPTION OF THE EPACA CODE

The EPACA code (Elastic-Plastic and Creep Analysis) was originally developed by the Franklin Research Institute for the High Temperature Structural Design Methods program (HTSDM). It has been implemented by the Computer Sciences Division. Part of the implementation consisted of analyzing structures for which experimental results are available and thus verify that the code is operating satisfactorily. This has in fact already been done, and a sample problem shown in the quarterly progress report, ORNL-4977, has been included as an indicator that the code is operating satisfactorily. This shows that the results of computer analysis of plates and beams under loads leading to inelastic strains agree reasonably well with experimental results.

The code is capable of analyzing any structure that can be modeled as an assemblage of flat or curved elements using the finite element method. A system of linear equations relating the unknown generalized displacements to the generalized known forces is formed and solved to yield the displacements from which the strains and stresses can be calculated. The generalized unknown displacements are the three displacements u , v , and w , and the two rotations θ_x and θ_y at each node. The rotations and displacements are coupled so that an approximation of shell behavior is possible. Thus, stretching of the mid-plane (membrane behavior) and rotations of the normal to this plane (plate behavior) are represented leading to five degrees of freedom at each node. The discrete Kirchoff-hypothesis is invoked at the nodes to relate the transverse displacements w to the rotations θ_x and θ_y about axes in the plane of the shell. This permits a close approximation to shell behavior. The transverse shear can also be represented by suitable choice of element type, thus "thick" shells can be analyzed.

Within the plane of the shell or plate, the stresses and strains have a degree of freedom to take arbitrary values at the so-called Gaussian integration points. The number of these points can range

anywhere between four (two parallel to each of the elements) to sixty-four (8×8). Furthermore, three to six layers of these integration points could be specified depending upon the degree of "yielding" in these layers. In this analysis, because of the extensive yielding, six layers were specified. There were, therefore, 2^4 points at which the stresses and strains were calculated; correspondingly, each element had that many "internal degrees of freedom", roughly speaking. Hence, the number of elements or nodal points required for an analysis does not need to be as great as with other codes which employ constant strain elements.

The loads are applied in increments since the theory is formulated in an incremental form. The choice of the size of these increments is still very much a matter of trial and error plus some experience based upon similar analysis. At the end of each step, a test is made at every integration point to determine whether it is on the yield surface (if yielding has occurred at that point). If it deviates from the yield surface by more than a specified tolerance (0.1%), then controls are set for iterative steps whose purpose it is to bring these points back to the yield surface.

Furthermore, at the end of every incremental or iterative step, the unbalanced loads due to the deviations from equilibrium between the calculated loads, and the actual external loads are corrected in the subsequent steps.

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