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# EVALUATION OF STRUCTURAL ANALYSIS METHODS FOR LIFE PREDICTION

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## INTRODUCTION

Hot section components of gas turbine engines are subject to severe thermomechanical loads during each mission cycle. Inelastic deformation can be induced in localized regions leading to eventual fatigue cracking. Assessment of durability requires reasonably accurate calculation of the structural response at the critical location for crack initiation.

Nonlinear finite-element computer codes, such as MARC (ref. 1), have become available for calculating inelastic structural response under cyclic loading. The plasticity computations in these codes have been based on classical incremental theory using a hardening model to define the cyclic yield surface, a yield criterion, and a flow rule. Generally the von Mises yield criterion and the normality flow rule are used. Creep analyses are based on a separate creep constitutive model that is not directly coupled to the plasticity model. However, analytical studies of hot section components such as turbine blades (ref. 2) and combustor liners (ref. 3) have demonstrated that existing nonlinear finite-element computer codes based on classical methods do not always predict the cyclic response of the structure accurately because of the lack of interaction between the plasticity and creep deformation response.

Under the HOST Program, the NASA Lewis Research Center has been sponsoring the development of unified constitutive material models and their implementation in nonlinear finite-element computer codes for the structural analysis of hot section components (refs. 4 to 7). The unified constitutive theories are designed to encompass all time-dependent and time-independent aspects of inelasticity including plasticity, creep, stress relaxation, and creep recovery. These theories avoid the noninteractive summation of inelastic strain into plastic and creep components and most of them avoid specifying yield surfaces to partition stress space into elastic and elastic-plastic regions. In discarding these overly simplified assumptions of classical theory, unified models can more realistically represent the behavior of materials under cyclic loading conditions and high temperature environments.

A major problem with nonlinear, finite-element computer codes is that they are generally too costly to use in the early design stages for hot section components of aircraft gas turbine engines. A program has been underway at NASA Lewis to develop a simplified and more economical procedure for performing nonlinear structural analysis using only an elastic finite-element solution or local strain measurements as input (refs. 8 and 9). Development of the simplified method was based on the assumption that the inelastic regions in the structure are local and that the total strain history can be defined by elastic analyses. Corrections have been incorporated in the method to account for

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strain redistribution under applied mechanical loading. This procedure was implemented in a computer program and has been exercised on a wide variety of problems including multiaxial loading, nonisothermal conditions, various materials and constitutive models, and dwell times at various points in the cycles. Comparisons of the results of the simplified analyses with nonlinear finite-element solutions for these problems have shown reasonably good agreement.

More than 30 methods for predicting low-cycle fatigue life have been identified in a recent review article by Halford (ref. 10). These methods differ somewhat in the structural analysis parameters used for life prediction. Basic structural response information required by various life prediction methods includes the total and inelastic strain ranges, inelastic strain rate, proportion of time-dependent and time-independent inelastic deformation, peak tensile and mean stresses, stress range, and cycle frequency.

The purpose of this study was to evaluate several nonlinear structural analysis methods (of different levels of sophistication) with regard to their effect on the life prediction of a hot section component. The methods selected for evaluation were nonlinear finite-element analyses based on both classical and unified theories, as well as the simplified nonlinear procedure.

The component under consideration was the airfoil of an air-cooled turbine blade being studied for use in the first-stage, high pressure turbine of a commercial aircraft engine. A mission cycle typical of a transatlantic flight was assumed for the analyses. Initially, this airfoil and mission were used for a demonstration problem involving a Walker unified model by Pratt & Whitney (P&W) (ref. 7) under contract to NASA as part of the HOST Program.

MARC nonlinear finite-element analyses were conducted for this airfoil problem at NASA Lewis to calculate the stress-strain hysteresis loop at the critical location for life prediction purposes. The classical type of analysis used conventional creep-plasticity models, whereas the unified analyses were based on two quite different constitutive theories, those of Bodner and Walker (ref. 6). The simplified procedure was also applied to this problem using elastic finite-element solutions for three peak temperature points of the cycle. Comparisons were made of calculated fatigue lives based on these structural analysis results by using the total strain version of the strain range partitioning (TS-SRP) life prediction method (ref. 11).

## PROBLEM DESCRIPTION

The turbine blade under study is a Pratt & Whitney (P&W) generic design for use in the high-pressure-stage turbine of a commercial aircraft engine. The airfoil span measures about 6 cm; the chord width, 2.5 cm; and the tip-to-hub radius ratio is 1:15. Material properties and model constants for a cast nickel-base superalloy, B1900+Hf (ref. 6), were used for the analyses.

The three-dimensional finite-element model created by P&W for the MARC analyses of the turbine blade airfoil is shown in figure 1. A total of 173 solid elements with 418 nodes and 1086 unsuppressed degrees of freedom was used to model the airfoil shell. This model included twenty-four 20-node elements around the expected high strain region of the leading edge and 149 8-node elements for the remainder of the airfoil. Displacements were tied at the interfaces of the two types of elements to prevent separation around midside nodes. Boundary conditions were applied to constrain all nodes at the base of the model to lie on the base plane of the airfoil. Additional boundary conditions were applied to prevent rigid body motion.

Figure 2 illustrates the flight mission originally selected by P&W and subsequently used for these analyses. This type of cycle is representative of a transatlantic flight for an advanced commercial aircraft engine. High, transient, thermal stresses and inelastic strains are induced during the engine takeoff, climb, and descent parts of the cycle. Creep occurs during the maximum takeoff, climb, and cruise steady-state hold times. On shutdown at the end of each cycle, a uniform airfoil temperature of 429 °C and a rotational speed of 200 rpm were assumed.

## ANALYTICAL PROCEDURE

### Finite-Element Analyses

Metal temperatures were calculated from MARC transient and steady-state three-dimensional heat transfer analyses. The input for these heat transfer analyses are proprietary P&W information. The calculated metal-temperature, cycle-time profiles for the midspan leading edge, trailing edge, and cold spot locations are shown in figure 3. Figure 4 shows the temperature distribution at the maximum takeoff condition when the highest temperatures occurred.

The MARC code was also used to perform elastic and nonlinear structural analyses for the airfoil. The mission cycle was subdivided into 81 load-time increments. Structural analyses were carried out for two complete flight cycles. Plasticity calculations were performed for the transient parts of the cycle and creep calculations during the steady-state maximum takeoff, maximum climb, and cruise hold times. The classical creep-plasticity analyses used temperature-dependent cyclic stress-strain and creep properties for B1900+Hf alloy. Plasticity calculations were based on a kinematic hardening rule and the von Mises yield criterion; creep was determined from a power law model in conjunction with a time hardening rule.

MARC finite-element analyses were also performed with the unified models of Bodner and Walker. The Walker model is of the common back-stress, drag-stress form; where the back stress is a tensor internal variable defining the directional hardening (Bauschinger effect), and the drag stress is a scalar internal variable defining the isotropic hardening. Of the many unified models which have been proposed in the literature, the Walker model has undergone the most development for finite-element analysis. All 14 material constants of this model are temperature-dependent..

The major exception to the back-stress, drag-stress form is the Bodner model. This model has one internal variable which is partitioned into directional and isotropic hardening components. Since it lacks a back stress, it assumes that the inelastic strain rate vector is coincident with the direction of the deviatoric stress. Another difference between the Bodner model and the more common back-stress, drag-stress model is that the former uses the plastic work rate as the measure of hardening whereas the latter uses the magnitude of the inelastic strain rate. There are essentially nine material constants to be determined for this model, only three of which have been found to be temperature-dependent for most materials studied.

Under a NASA sponsored effort with Southwest Research Institute and Pratt & Whitney Aircraft, the unified constitutive theories of Bodner and Walker were evaluated and further developed to model the high-temperature cyclic behavior of B1900+Hf alloy. A detailed discussion of these unified constitutive models, as well as the material constants for both models, are presented in the contractor annual status reports (refs. 6 and 7). The models were implemented into the MARC code through a user subroutine, HYPELA. The model constitutive equations were integrated using an explicit Euler technique and a self-adaptive solution scheme.

## Simplified Analysis

The basic assumption of the simplified procedure is that the inelastic region is localized and, therefore, the material cyclic response can be approximated using as input the total strain history obtained from elastic analyses. One version of the procedure uses Neuber corrections to account for strain redistribution due to mechanical loading; however, this version was not utilized for this study because of the dominance of the thermal loading during the peak strain parts of the cycle. Classical incremental plasticity methods are used; the material is characterized by a von Mises yield criterion, to describe yielding under multiaxial stress states, and a bilinear kinematic hardening model, to describe the motion of the yield surface under cycling.

Only elastic solutions for peak strain points in the cycle are normally required to create the strain history input; these are linearly subdivided into a sufficient number of increments to define the stress-strain cycle. The strain states calculated from the elastic finite-element analyses are correlated in the form of von Mises effective strains. To compute cyclic hysteresis loops for life prediction purposes, the input effective strains must be given signs, usually on the basis of the signs of the dominant principal stresses and strains. In this case, elastic finite-element analyses were performed for the startup, maximum takeoff, and shutdown conditions in order to create the input strain history at the critical location.

The increments are analyzed sequentially to obtain the cumulative plastic strains and to track the yield surface. Creep computations are performed for increments involving dwell times by using the creep characteristics incorporated in the code. Depending on the nature of the problem, the creep effects are determined on the basis of one of three options: (1) stress relaxation at constant strain, (2) cumulative creep at constant stress, or (3) a combination of stress relaxation and creep.

A FORTRAN IV computer program (ANSYMP) was created to automatically implement the simplified analytical procedure. Previous papers (refs. 8 and 9) on the development of this procedure present a detailed description of the calculational scheme.

## DISCUSSION OF RESULTS

The entire discussion of the structural and life analyses results for the airfoil presented herein are based on the critical location at the leading edge at midspan, which was the hot spot as indicated in figure 4. This location contained the element and Gaussian integration point which exhibited the largest total strain change during a mission cycle.

The calculated stress-strain hysteresis loops at the critical location for the first two mission cycles are shown in figures 5 to 7 for MARC finite-element analyses (using the classical creep-plasticity, Bodner, and Walker models, respectively), and in figure 8 for the simplified analysis. Figures 5 to 7 are plotted in terms of von Misses effective stress and strain with a sign criterion based on the sign of the dominant normal stress. Comparison of figures 5 to 7 shows that the maximum compressive strain, which occurs at the hot end of the cycle, was about the same for the classical and unified model finite-element analyses on the first cycle. This result is to be expected since the problem was largely thermally driven, and it indicates that the thermal strain calculations were consistent among these three analyses from startup at room temperature to maximum takeoff. However, the stress-strain loops on subsequent cycling were substantially different among the models, especially in regard to the peak strains during the cold part of the cycle in descending to shutdown. These differences result in a smaller cyclic strain range for the unified analyses than for the classical creep-plasticity analysis. The calculated stress-strain loops shown in figure 6 for the Bodner model are questionable because of computational instabilities that were encountered in the analysis on the cooldown part of the cycle. These instabilities are apparently due to a discontinuity in the isotropic hardening term of the model's internal variable when the stress sign changes during a steady-state hold time; it is believed that this problem can be circumvented by refinements to the numerical procedure for integrating the constitutive equations. The maximum compressive strain for the simplified analysis (shown in fig. 8) was somewhat smaller than for the finite-element analyses because the maximum compressive strain did not quite occur at maximum takeoff. Therefore, the selection of the maximum takeoff condition as one of the mission points for a finite-element analysis resulted in a slight truncation in the calculated peak strain and strain range. In all the analytical cases, except with the Bodner model, the stress-strain response had essentially stabilized by the end of the second cycle.

The results from these structural analyses (elastic-plastic-creep, Bodner unified, Walker unified, and simplified) are summarized in table I in terms of the total strain range and mean stress for the second cycle. CPU (central processor unit) times for two complete analytical cycles are indicated in the first column. The CPU time for the simplified analysis, including 81 sec to perform the elastic finite-element analyses for the startup, maximum takeoff, and shutdown conditions, and 1 sec for the actual simplified procedure, was 50 times faster than for the MARC classical finite-element analysis. The MARC analysis using the Walker model was somewhat more economical in CPU time than with the creep-plasticity models. Because of the computational problems that were encountered with the Bodner model, it used somewhat more CPU time than the classical models.

Also presented in table 1 are predicted cyclic lives to crack initiation using the TS-SRP method. These predictions were based on unpublished NASA data for out-of-phase bithermal behavior of B1900+Hf alloy at maximum and minimum temperatures of 871 and 483 °C, respectively. Comparisons of the calculated strain ranges and lives (shown in table I) for the different structural analysis methods demonstrate the sensitivity of life prediction to the constitutive models and analytical methodologies employed. In the present case, the lowest cyclic life prediction was obtained using the classical nonlinear finite-element analysis, and the largest using the Walker unified model. The simplified procedure probably would have given the most conservative life prediction if the maximum compressive strain used for the input total strain history had been more accurately defined.

## SUMMARY OF RESULTS

This paper evaluates the utility of advanced constitutive models and structural analysis methods in predicting the cyclic life of an air-cooled turbine blade for a gas turbine aircraft engine. Structural analysis methods of various levels of sophistication were exercised to obtain the cyclic stress-strain response at the critical airfoil location. Calculated strain ranges and mean stresses from the stress-strain cycles were used to predict crack initiation lives by using the TS-SRP life prediction method. The major results of this study were as follows:

1. The predicted strain range and life varied with the constitutive model used. Differences in the calculated strain ranges between the unified and classical models were mainly due to differences in the peak strains computed at the cold end of the cycle. However, the maximum compressive strain on the first cycle was not significantly affected by the constitutive model, thereby indicating that the thermal expansion calculations were consistent.

2. The stress-strain responses calculated by using the Bodner and Walker unified models were very similar. Computational instabilities encountered with the Bodner model during the steady-state hold times probably can be circumvented by refinements in the numerical integration procedure.

3. Because of the differences in the calculated strain ranges, the lowest predicted cyclic life resulted from using the classical nonlinear finite-element analysis and the highest one from using the Walker unified model. The simplified procedure probably would have given the most conservative life prediction if the input total strain peak at the hot end of the cycle had been more accurately defined.

4. The simplified procedure, including the computing times for the initial elastic finite-element analyses, was about 50 times faster than the cyclic finite-element analyses, and about 4000 times faster for just the cyclic inelastic computations. The CPU time for the MARC finite-element analyses was somewhat less for the Walker unified model than the classical creep-plasticity models. Because of its computational problems, the Bodner model analysis used the most CPU time.

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TABLE I. TURBINE BLADE STRUCTURAL ANALYSIS RESULTS

| Analytical Method (CPU time, sec ) | Strain Range, Microstrain | Mean Stress MPa | Predicted Cyclic Life |
|---|---|---|---|
| Elastic-Plastic Creep (4038) | 2886 | 2 | 42,400 |
| Unified (Bodner) (4938) | 2440 | 50 | 89,500 |
| Unified (Walker) (3660) | 2360 | 90 | 103,800 |
| Simplified (81+1) | 2771 | -5 | 50,700 |

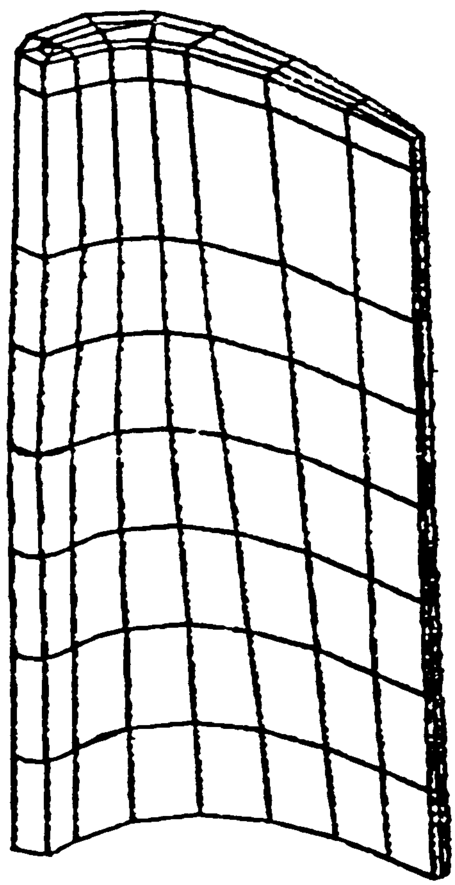

FIGURE 1. - AIRFOIL FINITE-ELEMENT MODEL

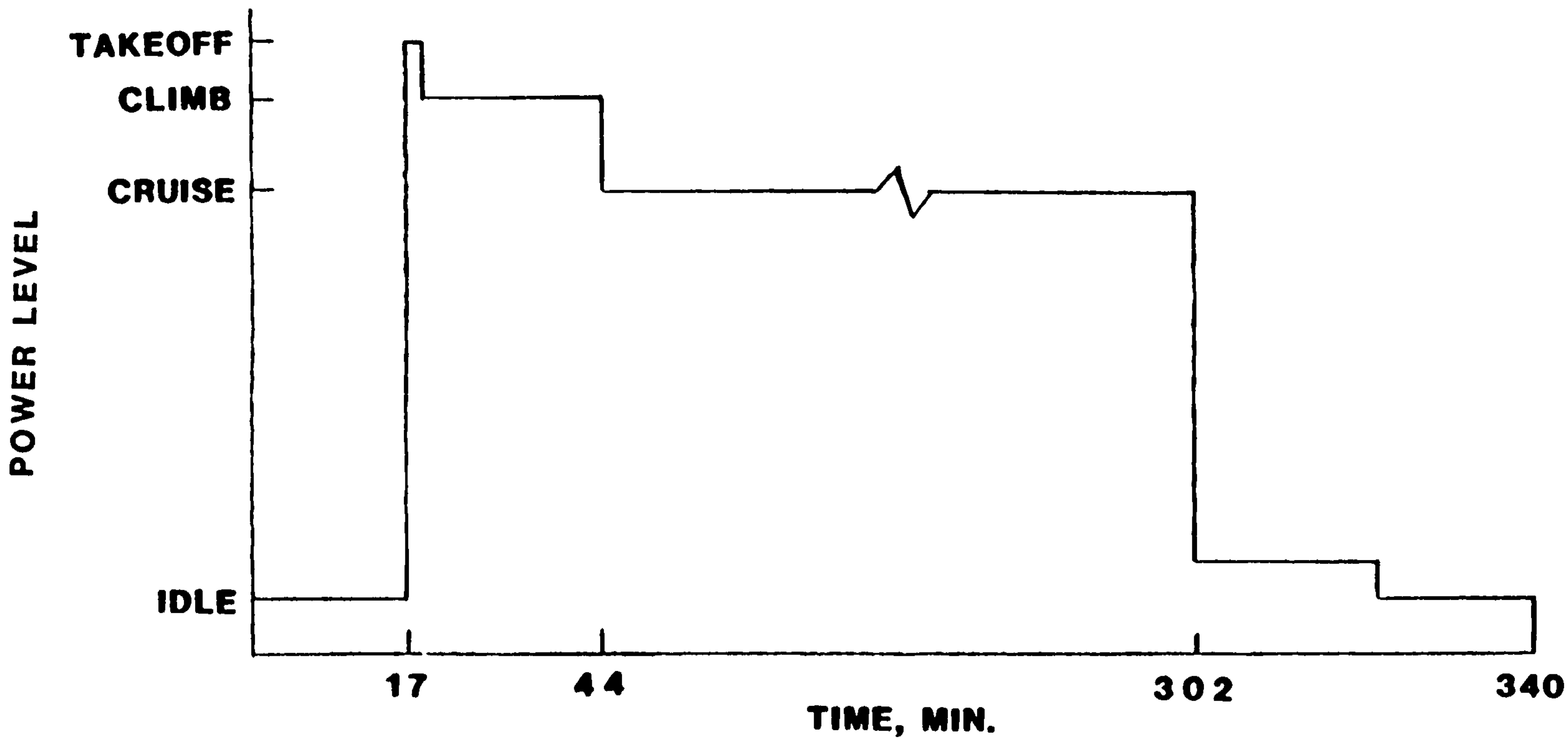


FIGURE 2. - MISSION CYCLE USED FOR ANALYSIS

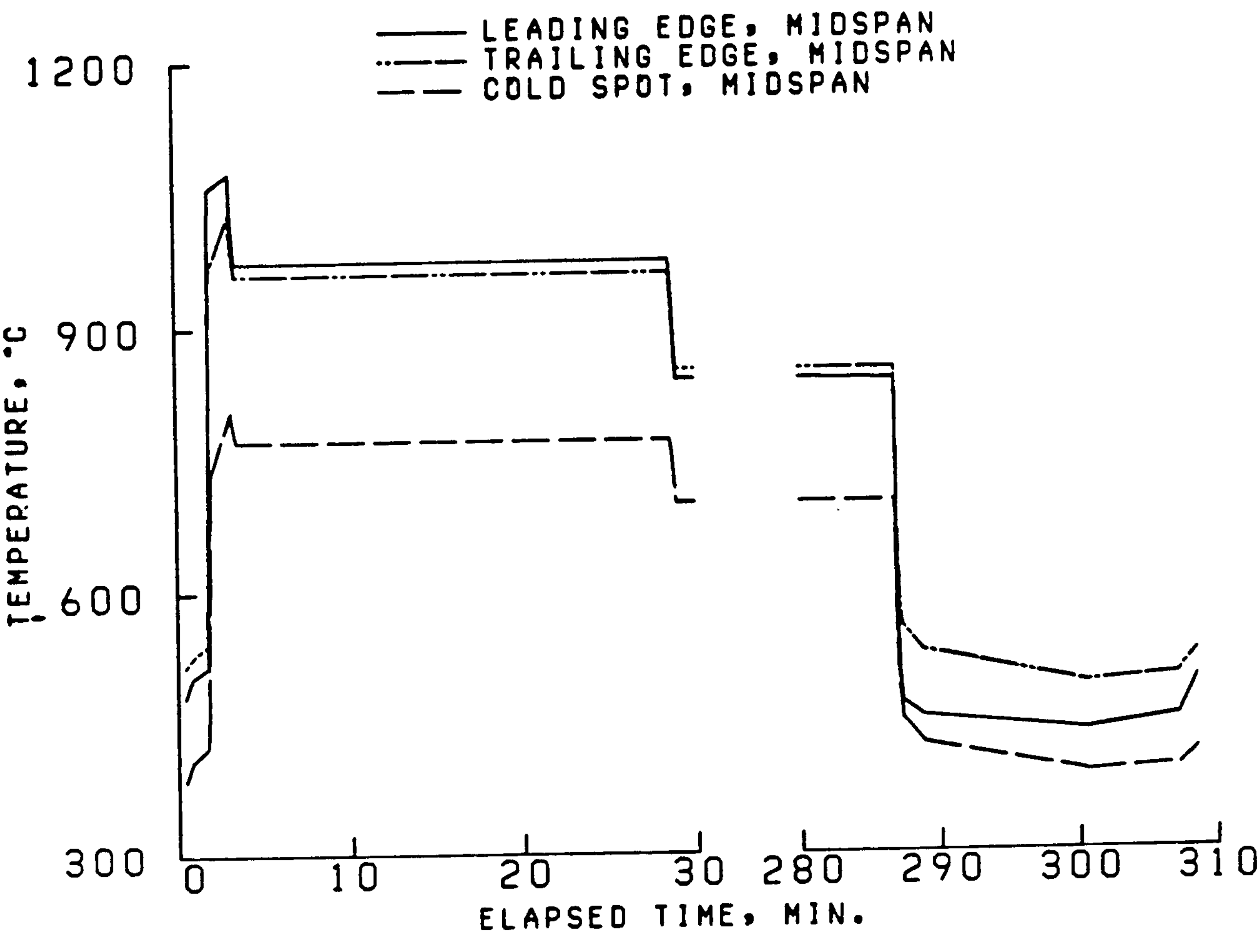


FIGURE 3. AIRFOIL TEMPERATURE CYCLE

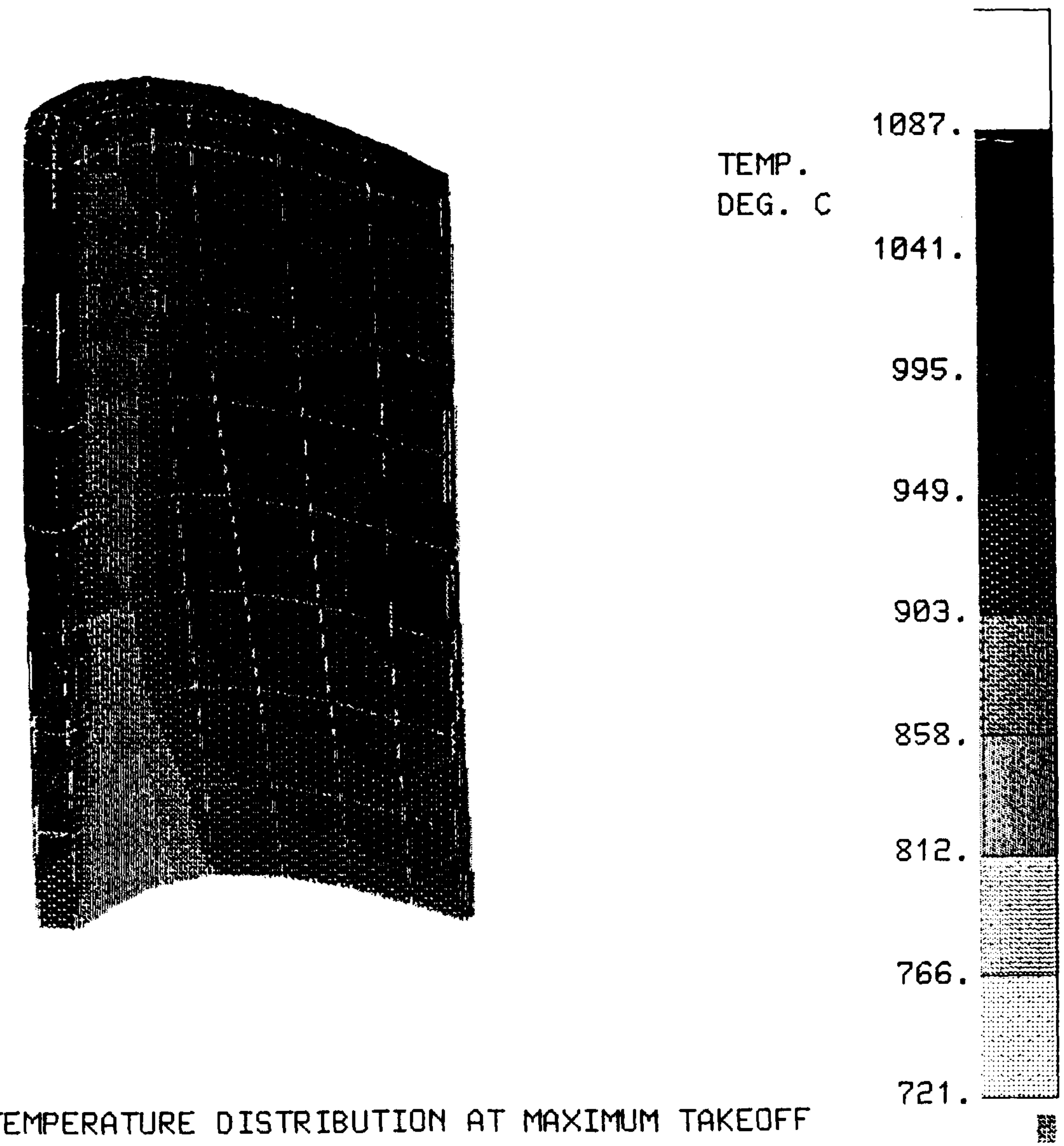


FIGURE 4. - AIRFOIL TEMPERATURE DISTRIBUTION AT MAXIMUM TAKEOFF

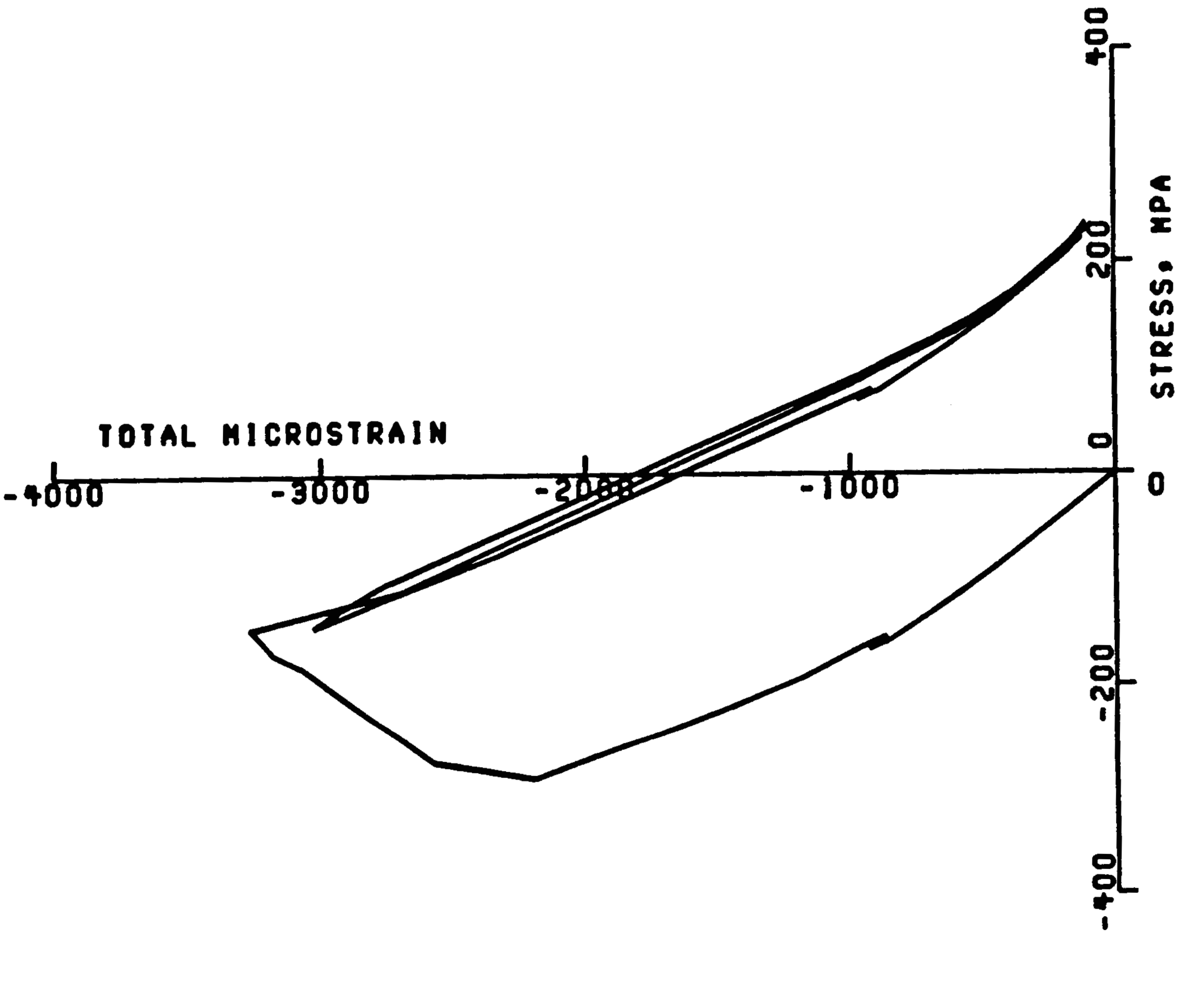


FIGURE 5. - MARC FINITE-ELEMENT ANALYSIS STRESS-STRAIN CYCLE USING CLASSICAL CREEP-PLASTICITY MODELS

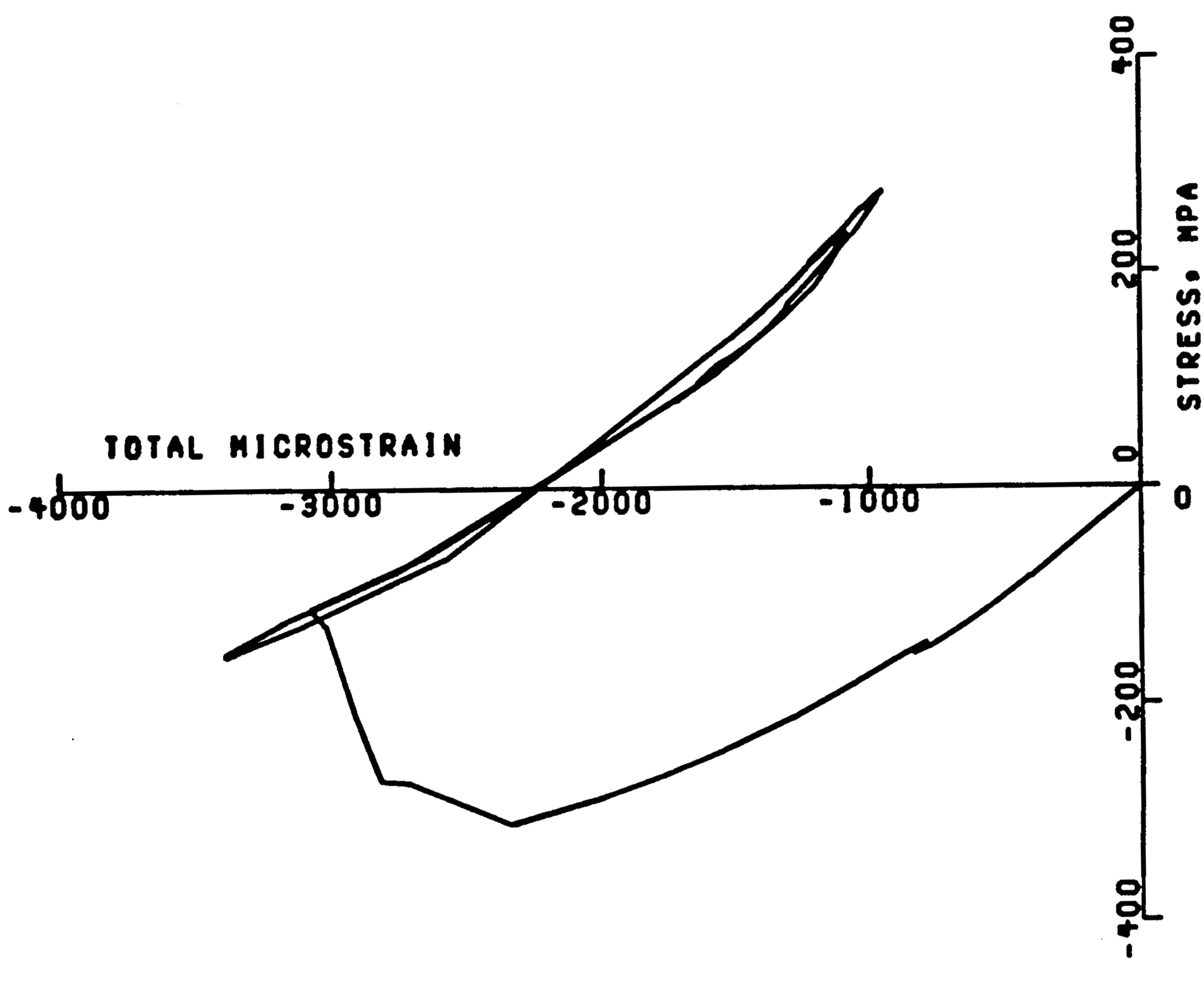


FIGURE 6. - MARC FINITE-ELEMENT ANALYSIS STRESS-STRAIN CYCLE USING BODNER UNIFIED MODEL

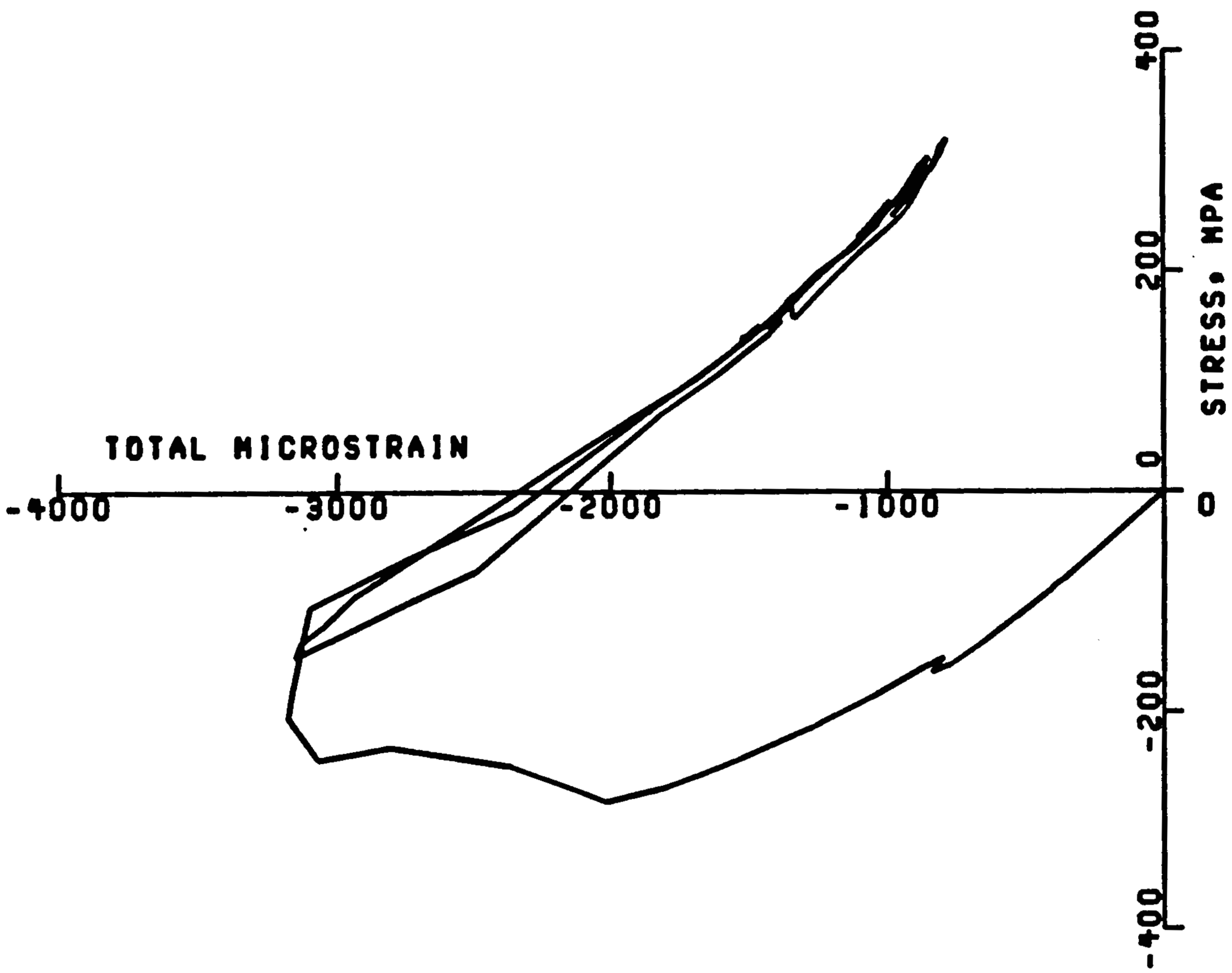


FIGURE 7. - MARC FINITE-ELEMENT ANALYSIS STRESS-STRAIN CYCLE USING WALKER UNIFIED MODEL

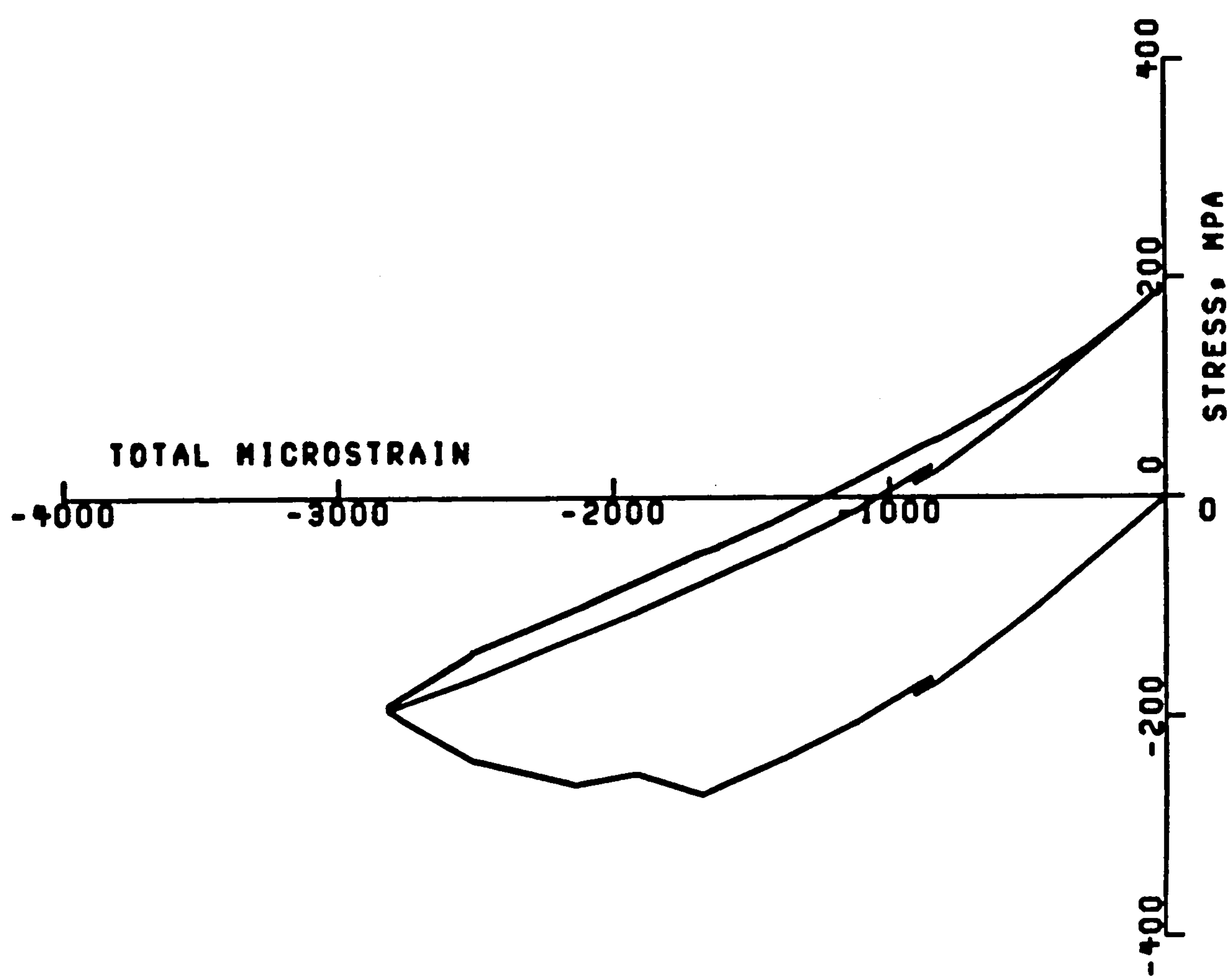


FIGURE 8. - SIMPLIFIED ANALYSIS STRESS-STRAIN CYCLE