N88-22384

LIFE ASSESSMENT OF COMBUSTOR LINER USING UNIFIED

CONSTITUTIVE MODELS

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ABSTRACT

Hot section components of gas-turbine engines are subject to severe thermo-mechanical 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.

In recent years nonlinear finite-element computer codes have become available for calculating inelastic structural response under cyclic loading. Most of these, in keeping with an accepted practice in the elevated-temperature design community, partition nonlinear elevated-temperature material behavior into rate-dependent creep and rate-independent plasticity components. However, ana-lytical studies of hot-section components such as turbine blades (McKnight, 1981) and combustor liners (Moreno, 1981) have demonstrated that the classical creep and plasticity methods do not always predict the cyclic response of the structure accurately because of the lack of the interaction between plasticity and creep behavior. Experimental results have shown that the interaction of elevated temperature is very significant and cannot be ignored (Corum, 1977; Kujawski et al., 1979; Pugh and Robinson, 1978; and Senseny et al., 1978).

Under the Hot Section Technology Project (HOST), NASA Lewis Research Center sponsored the development of unified constitutive material models and their implementation in nonlinear finite-element computer codes for the structural analyses of hot-section components (Ramaswamy et al., 1984 and 1985; and Lindholm et al., 1984 and 1985). These unified constitutive models account for the interaction between the time-dependent and time-independent material behavior. In eliminating the overly simplified assumptions of the classical material model, unified models can more realistically represent the behavior of materials under cyclic loading high-temperature environments. The purpose of this study was to evaluate these unified models with regard to their effect on the life prediction of a hot-section component. The component under consid-eration was a Pratt & Whitney gas-turbine-engine combustor liner. A typical
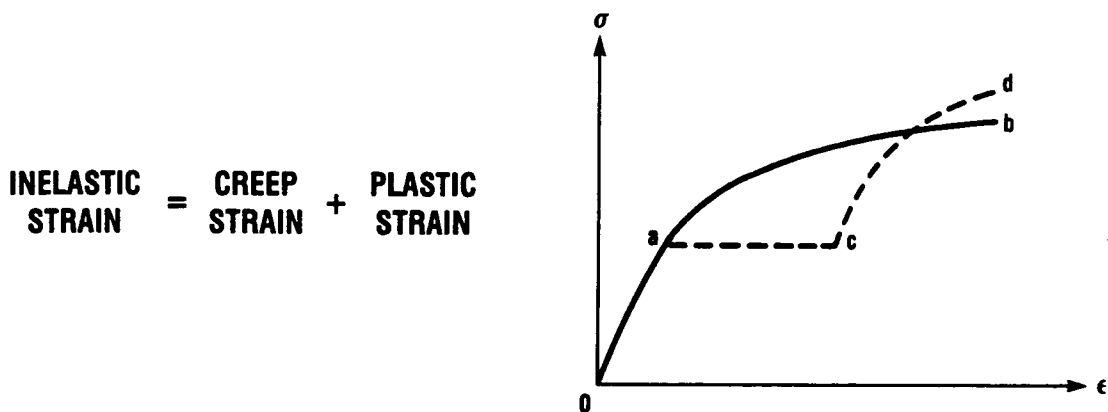

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engine mission cycle was used for the thermal and structural analyses. The analyses were performed at Lewis Research Center on a CRAY-XMP computer using the MARC finite-element code. Unified constitutive models of Bodner and Walker were used for the analyses. The results were compared with laboratory test results, in terms of crack initiation lives.

OVERVIEW

## HARDENING EFFECT OF CREEP ON PLASTICITY

Life assessment of engine hot-section components requires a thorough knowledge
of the thermal environment, accurate material characterization, calibrated
failure data, and reasonably accurate calculation of the structural response
at the critical location for crack initiation. In recent years, nonlinear
finite-element computer codes have become available for calculating inelastic
structural response under cyclic loading. Most of these computer codes are
based on the classical inelastic methods. They partition nonlinear, elevated-
temperature material behavior into rate-dependent creep and rate-independent
plasticity components. In other words, inelastic strains are decoupled and
formulated independently for the creep and plasticity portions, as illustrated
in the left figure. However, analytical studies of hot-section components such
as turbine blades (McKnight, 1981) and combustor liners (Moreno, 1981) have
demonstrated that the classical creep and plasticity methods do not always pre-
dict the cyclic response of the structure accurately because of the lack of the
interaction between the plasticity and creep behavior. Experimental results
have shown that the interaction at high temperature is significant and cannot
be ignored (Corum, 1977; Kujawski et al., 1979; Pugh and Robinson, 1978; and
Senseny et al., 1978). The interaction is illustrated in the figure, wherein
two loading paths are indicated by o-a-b and o-a-c-d. In the second loading
path the applied stress is held constant between a and c, which results in
creep deformation. As a consequence of the accumulated creep strain, c-d may
appear to be stiffer than a-b for a creep hardening alloy. Creep softening
alloys would exhibit a less stiff response.

$$\begin{matrix} \textbf{INELASTIC} \\ \textbf{STRAIN} \end{matrix} = \begin{matrix} \textbf{CREEP} \\ \textbf{STRAIN} \end{matrix} + \begin{matrix} \textbf{PLASTIC} \\ \textbf{STRAIN} \end{matrix}$$

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ANNULAR COMBUSTOR LINER

Under the Hot-Section Technology Project (HOST), NASA Lewis sponsored the development of unified constitutive material models and their implementation in nonlinear, finite-element computer codes for the structural analyses of hot-section components. These unified constitutive models account for the interaction between the time-dependent and time-independent material behavior. In eliminating the simplified assumptions of the classical material model, unified models should more realistically represent the behavior of materials under cyclic loading and high-temperature environments. In an application of the unified material constitutive models, life assessment of a Pratt & Whitney gas turbine engine annular combustor liner (as shown below) was conducted. Unified constitutive models of Walker and Bodner were used. The results were compared with laboratory test results, in terms of crack initiation lives.
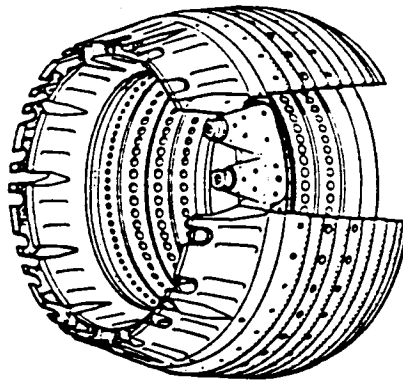
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## CLASSICAL MATERIAL CONSTITUTIVE MODEL – DECOUPLED STRAINS

Conventionally, the most widely used constitutive description of metals at
high-temperature employs the time-independent classical theory of plasticity
to characterize short-term deformation, while relying upon time-dependent clas-
sical theory of creep to characterize long-term deformation. The total strain,
or strain increment, then, consists of four additive contributions – elastic,
plastic, creep, and thermal components. In other words, constitutive equations
are decoupled and formulated independently for the elastic-plastic, creep, and
thermal portions. Although the classical theories of plasticity have been used
quite extensively to characterize the behavior of metallic structures at room
temperature, it does not necessarily justify their applicability to other load-
ing conditions such as high-temperature environment. Analytical studies of
engine hot section components such as turbine blades and combustor liners have
demonstrated that the classical theories do not always predict the cyclic
response of the structure accurately. For high-temperature applications the
most severe shortcoming of classical theories is that the interaction between
creep and plasticity is not adequately taken into account. Experimental
results have shown that the interaction at elevated temperature is significant
and cannot be ignored.

INELASTIC STRAIN = CREEP STRAIN + PLASTIC STRAIN

CLASSICAL UNCOUPLED

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CREEP-PLASTICITY INTERACTION

Two types of creep-plasticity interactions are generally observed. First, accumulated creep strain has a hardening effect on subsequent plastic response. This phenomenon is shown in the left figure, wherein two loading paths are indicated by o-a-b and o-a-c-d. In the second loading path the applied stress is held constant between a and c, which results in creep deformation. As a consequence of the accumulated creep strain, c-d appears to be stiffer than a-b. Second, recent history of plastic strain has significant influence on subsequent time-dependent behaviors. In the right figure, a-b and c-d represent creep strains corresponding to creep tests performed at loading and unloading branches, respectively, but at the same stress level. While the former undergoes a significant amount of creep deformation, the latter shows virtually no creep. The same kind of phenomenon is also observed when relaxation tests are conducted as designed by e-f and g-h in the right figure.

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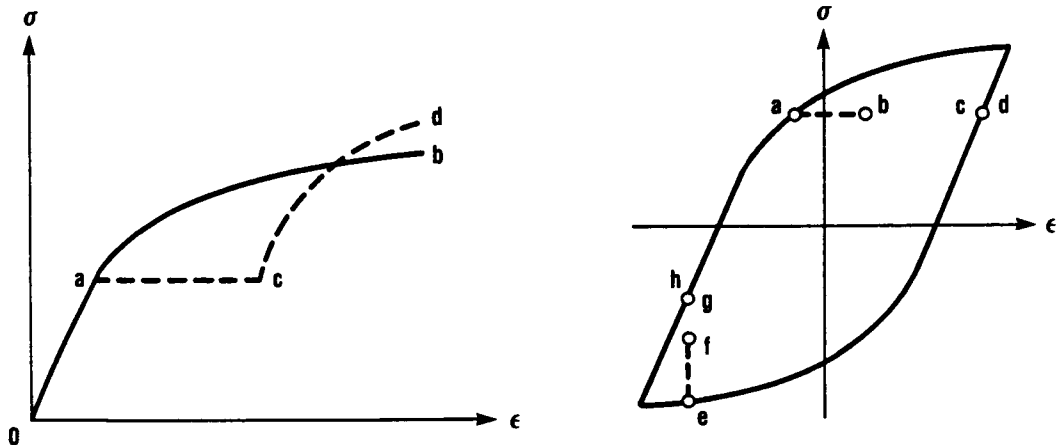
UNIFIED MATERIAL CONSTITUTIVE MODELS

In light of the previous discussion, it is apparent that effort must be made
to improve the prediction of inelastic behavior of metals at high temperatures.
The new theories toward characterization of material behavior at high tempera-
tures are known as unified theories in the sense that plastic and creep strains
are represented and treated by a single kinetic equation and a discrete set of
internal variables. They are also known as viscoplastic theories because they
are capable of modeling both rate-dependent and rate-independent behaviors.

$$\dot{\sigma} = E(\dot{\epsilon} - \dot{\epsilon}^I - \dot{\epsilon}^{TH}) \qquad \dot{\alpha} = h_{\alpha}\dot{\epsilon}^I - r_{\alpha}$$

$$\dot{\epsilon}^I = f\left[\frac{\sigma - \alpha}{K}\right] \qquad \dot{K} = h_k |\dot{\epsilon}^I| - r_k$$

WHERE

h_{α}, h_k **STRAIN HARDENING FUNCTIONS**

r_{α}, r_k **RECOVERY FUNCTIONS**

α, K **STATE VARIABLES**

ϵ^I **INELASTIC STRAIN**

ϵ^{TH} **THERMAL STRAIN**

σ **STRESS**

COMBUSTOR LINER AND ITS FINITE ELEMENT MODEL

In an application of the unified material constitutive models, life assessment of a Pratt & Whitney gas-turbine-engine annular combustor liner was conducted. The liner is air-cooled and is made of Hastelloy-X alloy. The finite-element model has 546 elements and 1274 nodes. Eight-node solid elements were used. Because of symmetry only a section of the liner was modeled.

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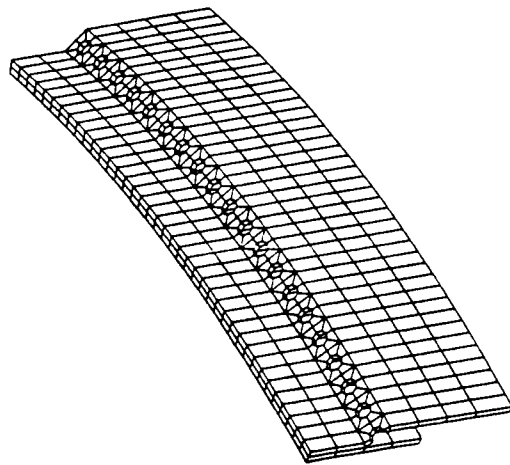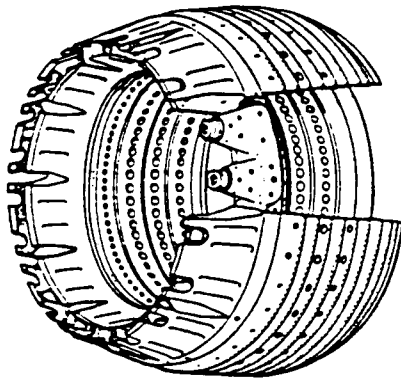
THERMAL ANALYSIS OF ANNULAR COMBUSTOR LINER

Thermal analysis was first conducted to determine the temperature distribution of the combustor liner. These temperatures were later used for the structural analysis of the liner. A typical engine mission cycle was used for the analysis. Temperature histories at the combustor liner critical locations were also determined.

AT MAXIMUM POWER

COOL SIDE　　　　**HOT SIDE**

TEMPER-
ATURE,
°F

1650

1200

750
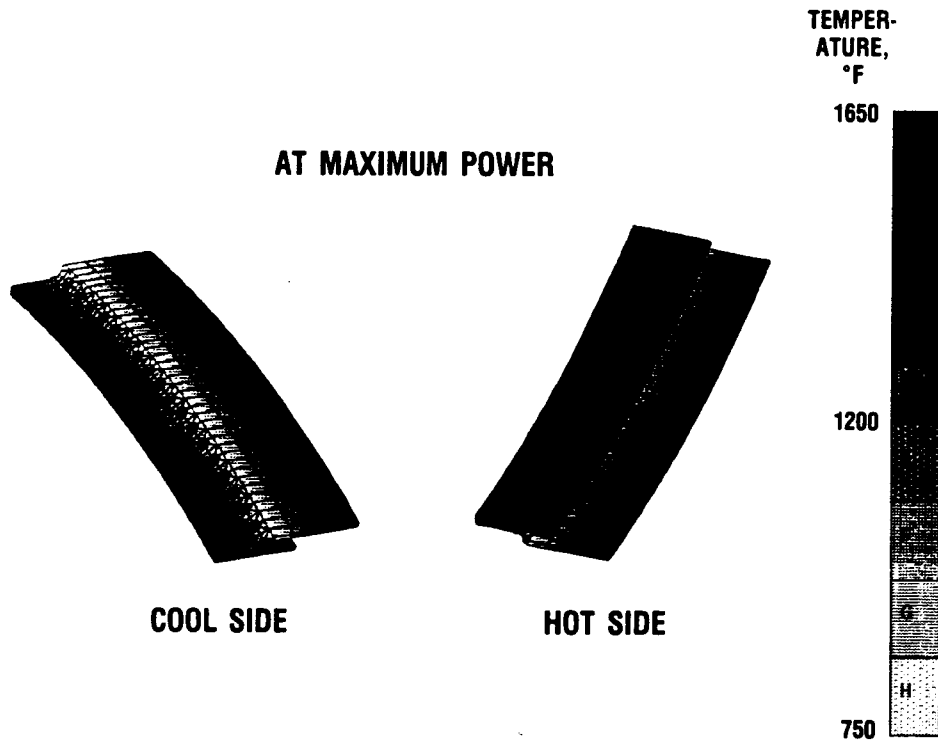
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COMPARISON WITH TEST RESULTS

Subsequent nonlinear structural analysis of the combustor liner was performed. The analysis was conducted with the unified constitutive models of Walker and Bodner (Lindholm et al., 1984 and 1985). Both models were implemented into the MARC finite-element code. Stress and strain ranges at the liner critical locations were determined.

The total strain and inelastic strain ranges were used for the life assessment of the combustor liner, based on the experimental results by Jablonski (1978). In conjunction with the analyses, laboratory tests were performed on the combustor liner. Comparisons were made of crack inititation lives. Good agreement between predicted and measured life was obtained.

ANALYTICAL METHOD	MECHANICAL STRAIN RANGE, %		PREDICTED LIFE, CYCLES
	TOTAL	INELASTIC	
UNIFIED (WALKER)	0.587	0.315	1000 TO 1500
UNIFIED (BODNER)	.580	.270	1000 TO 1500

OBSERVED LIFE = 1603 CYCLES

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