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Localized Thermal Buckling Due to Hot Streaks in a Combustor Liner

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Localized thermal buckling due to hot streaks at the louver lip is a common failure mode of louver-type combustors in some gas turbine engines. Investigations of the localized buckling of louvers under engine service condition using nonlinear finite element methods are described. Simulated buckling modes from buckling eigenvalue analysis were used to define the initial shape for analysis of cyclic inelastic stress and strain responses. Inelastic strain components were obtained to provide input for thermo–mechanical fatigue lifetime prediction of the liners using the strain-range partitioning method.

Nomenclature

A = creep coefficient
E = Young's modulus
N = number of applied cycles
n = power law creep exponent
T = temperature
t = current time
α = coefficient of thermal expansion
Δ = range
ε = strain
ν = Poisson's ratio
σ = effective stress
σ_{ys} = yield stress

Subscripts

c = creep
in = inelastic
p = plastic

Introduction

DURING engine operation, a louver-type combustor liner experiences high lengthwise temperature gradients, with maximum temperatures at the louver lip where cooling is least effective and lower temperatures in better cooled regions near the louver knuckle. Also dome geometry imperfections and nonuniform fuel injector/swirl cup spray patterns may result in hot streaks, with nonuniform temperature distribution around the liner circumference, especially in the louver lip region. Thus, liner louvers are subject not only to high axial temperature gradients but also to high localized circumferential temperature gradients.

At overhaul inspection of an engine, combustor liners typically reveal damage with axial cracks, localized buckling and burning near the louver lip as shown in Fig. 1 (Ref. 1). The louver lip that is relatively distant from the cooling holes tends to expand, whereas the welded knuckle region of the louver constrains this expansion. The temperature gradient along the liner, thus, induces compressive stress fields in the region of the louver lip, and these stresses may be of a magnitude capable of causing structural instability and buckling. Local overheating will result in preferential buckling in the region of the hot streaks.[2] Buckling may in turn disrupt flow of the cooling air and result in local burning and cracking.

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Earlier research into thermal buckling concentrated on thin plates and shallow cylindrical shells under temperatures varying through the thickness.[3] In recent years, problems of high-speed flight[4–6] have led to considerable interest in the thermal buckling of a plate subject to in-plane temperature gradients. Nevertheless, all of the studies so far have been limited to the analysis of global buckling behaviors of the plates at a relatively low temperature. The main motivations for this study are the analysis of cyclic plastic and creep behaviors and, consequently, the prediction of lifetimes of locally buckled combustor liners under engine service conditions.

This paper describes numerical analysis of the elastic and viscoplastic buckling behaviors of combustor liners subjected to hot streaks and high lengthwise temperature gradients found in the engine service, using nonlinear finite element methods. Temperature profiles are obtained from laboratory tests on a rig combustor. Thermal buckling modes of the louver under this loading are predicted. A predicted eigenmode, similar to damage modes observed in service, is used to define an initial shape for investigating the effect of localized buckling on the cyclic inelastic stress and strain response. Inelastic strain components are calculated and used as input to predict thermo–mechanical fatigue life of the combustor liner by the strain-range partitioning method.[7] The different sizes of initial buckling and the different degrees of local overheating are specified, and their effects on both cyclic inelastic stress/strain response and thermo–mechanical fatigue lifetimes are studied.

Finite Element Modeling of Combustor Liner

A typical local overheating area near the louver lip is highlighted in Fig. 2. The model analyzed consisted of a section of the second louver between the two dashed lines that sufficiently represents the problem.

The commercial finite element (FE) package LUSAS was used for analysis because of its capability for solving nonlinear material and geometric problems. The FE model of the critical louver was generated, as shown in Fig. 3, using the actual geometry of the liner being studied. Because the louver is cyclically symmetrical, only a 30-deg louver segment was meshed, using 288 semiloof curved thin shell elements. To model the seam weld connection, 26 compatible joint elements were used.

The effect of the complete cylindrical liner segments was simulated by applying appropriate cyclo-symmetric boundary conditions. The surfaces in the ±15-deg meridional planes were constrained not to move in the circumferential direction, and edges lying in the meridional planes were constrained against rotation. Surfaces at the front of the louver were constrained in the axial direction to simulate the liner support. Other boundary conditions were free.

LUSAS material models are capable of modeling bilinear isotropic plasticity combined with power law creep. The material of the combustor liner is a fine-grained nickel base superalloy

Hastelloy X that has moderately good strength characteristics up to about 900°C (Ref. 8). Temperature-dependent Young's modulus and plastic and creep properties are given in Tables 1 and 2. The elasto–plastic von Mises yield surface model was used for multiaxial behavior. The creep model is expressed by

$$\varepsilon_c = A\sigma^n t^m \tag{1}$$

where ε_c is creep strain and σ is the effective stress. Both m and n are power law creep exponents; A, m, and n are strongly temperature dependent. In this study, the Norton law ($m = 1$) was selected because it provides the best correlation with the material experimental data for steady-state creep as indicated in Table 2.

Table 1 Material properties of fine-grained Hastelloy X

Temperature, °C	$E \times 10^5$, MPa	ν	$\alpha \times 10^{-5}$/°C	σ_{ys}, MPa
21	2.05	0.320	1.42	380
505	1.70	0.326	1.49	316
649	1.61	0.334	1.54	304
760	1.52	0.339	1.58	263
871	1.37	0.345	1.62	101
980	1.24	0.351	1.66	49

Table 2 Creep properties of fine-grained Hastelloy X

Temperature, °C	A	n
705	$1.8455E-17$	4.41
760	$3.5861E-17$	4.75
816	$6.3954E-17$	5.09
871	$1.0757E-16$	5.42
927	$1.3576E-12$	3.78
980	$1.1540E-09$	2.53

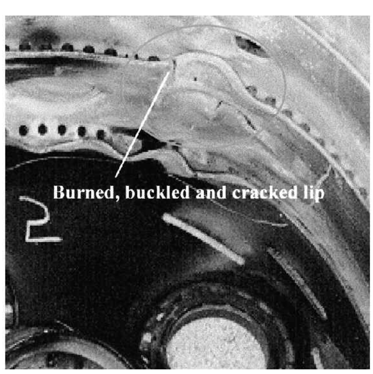

Fig. 1 Combustor louver damage.

Determination of Thermal Loading

Two flight conditions were simulated in the combustor test rig. Temperature distributions on the inner walls of the louver were measured by thermocouples and are given in Table 3. During the experiments, hot spots and hot streaks were also observed at several locations in the liner, using thermal indicating paint. By the use of the limited thermocouple data, a finite element thermal analysis was carried out to obtain the temperature distribution over the louver. Similar meshes were used for thermal and structural analyses to facilitate transfer of temperature data to the structural model.

Table 3 Liner temperature distributions from rig combustor test

	Temperature, °C	
Location	Case A	Case B
Midlouver	683	730
Seam weld	761	813
Knuckle	550	588
Midlip	670	716
From lip 1.0 mm	825	882
Midlouver	634	677

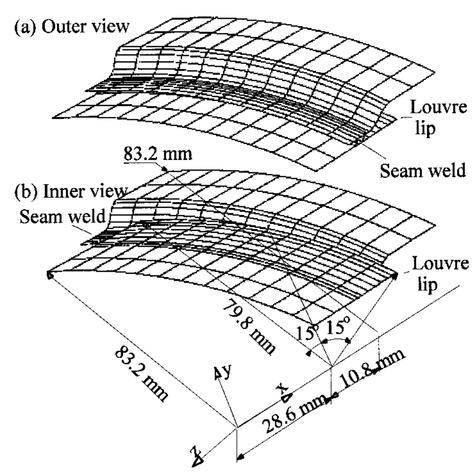

Fig. 3 FE model for the louver.

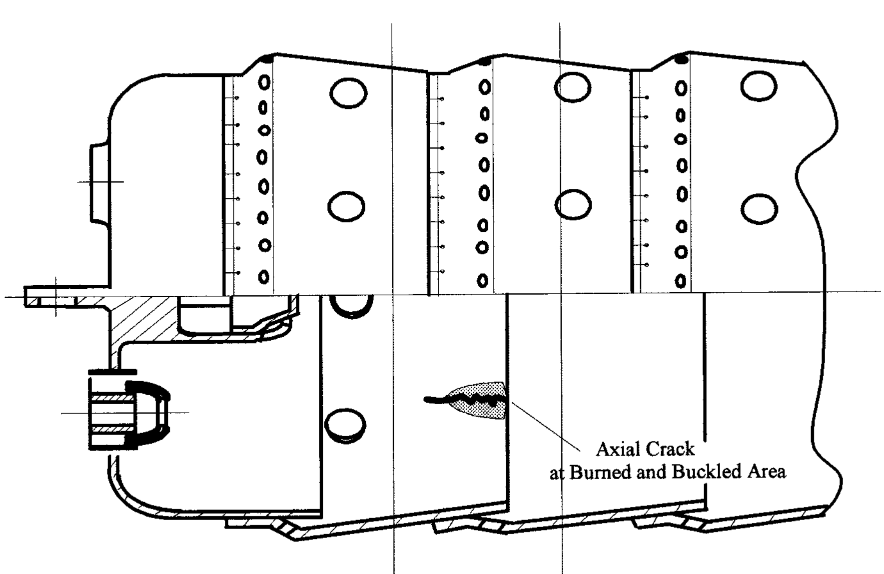

Fig. 2 Critical louver segment in the liner.

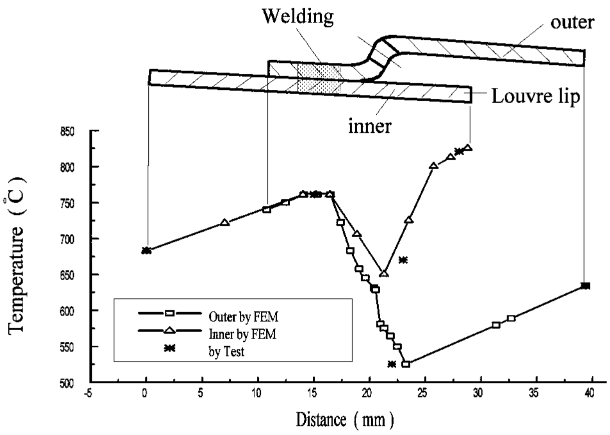

Fig. 4 Temperature distribution.

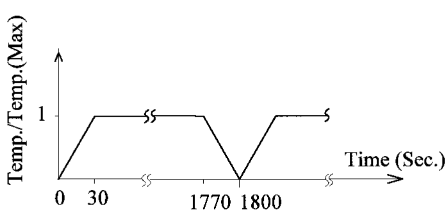

Fig. 5 Cyclic thermal loading applied to the louver.

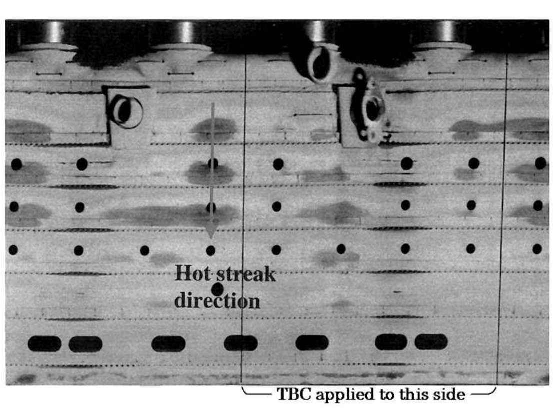

Fig. 6 Hot streaks observed in the rig test.

Figure 4 shows the temperature distribution of the liner for a typical full-power operating condition. During the rig combustor testing, the maximum temperature difference between the outer and inner wall of the louver is less than 2%. The temperature distribution for the FE results is, thus, assumed to be constant in the thickness direction. Temperature values peak near the louver lip, where cooling is least effective, and vary elsewhere on the liner. In Fig. 4, the line with open square symbols represents the temperature distribution in the outer louver, whereas the line with open triangle symbols is for the temperature distribution in the inner louver. Temperatures indicated by star symbols are obtained from the rig combustor liner test.

In the rig combustor test the liner heats at about 80 ± 2°C/s and cools at about 30 ± 2°C/s, but response of the engine is generally slower. For this study, a heating and cooling rate of approximately 30°C/s was chosen from the conservative point view of thermo–mechanical fatigue life prediction. Thermal loading cycles shown in Fig. 5 were applied to the FE model for the steady-state condition. From the engine usage survey, it was determined that one complete thermal cycle of half an hour should be used to simulate the expected engine combustor operation cycles.

From the rig combustor liner test, by using thermal indicating paint, it was determined that gas turbine combustors often exhibit indications of hot streaks on the liner wall, as shown in Fig. 6. The image of temperature contours was captured from the outside of the combustor can. The dark areas represent the hot spots that clearly indicate the direction of hot streaks. The extent of local overheating is also indicated by the damage of in-service liners, such as that shown in Fig. 1. Within a 10-deg segment in the lip region, local overheating of 20% compared with the rest area at the louver lip was assumed. In other words, the peak temperature in that 10-deg segment is 1041°C rather than 882°C in the rest area at the louver lip for the engine condition (case A). Metallographic examination of in-service liners confirms that peak temperatures of this order are experienced.

Localized Thermal Buckling and Its Effect

A typical localized thermal buckling mode shape was calculated, as shown in Fig. 7, and is chosen to resemble that of the real combustor liner in Fig. 1. By using this buckled shape as an initial imperfection of the cylindrical shell, cyclic inelastic stress–strain responses of the buckled louver were calculated. Because the observed liner cracks propagate axially from the lip edge toward the weld, the crack propagation should be dominantly driven by hoop stress. Predicted hoop stress/strain components at nodes A and B (see Fig. 7) define the response of the lip. Node A is located at the center of the buckled louver lip, whereas node B is at the side where the crack initiated as shown in Fig. 1.

Because the material exhibits shakedown during first load cycles, it was found that the hysteresis loops normally need about four loading cycles to stabilize. The stress/strain responses with and without local buckling are obtained for cycles 5 and 6 at nodes A and B as shown in Fig. 8. The results indicate that the cyclic responses at both nodes are identical before thermal buckling. From Fig. 8, at node B, the cyclic response before localized buckling reveals compressive mean strain that changes to tensile mean strain after localized buckling. Material at node B suffers large inelastic deformation, which is consistent with crack initiation observed in the damage liners. However, after buckling, the structural stiffness near node A is lower because the structure is acting in bending rather than in direct compression. Therefore, buckling may limit compressive stress/strain development at the center of local overheating zone due

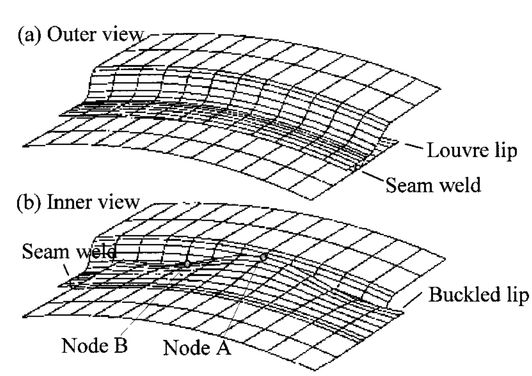

Fig. 7 Localized thermal buckling mode of the louver.

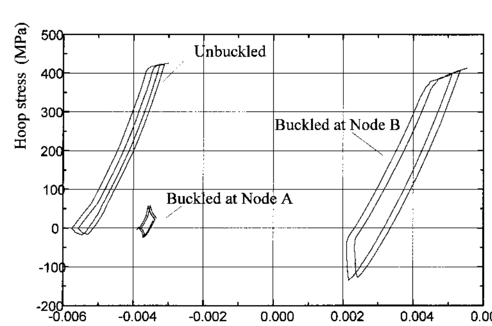

Fig. 8 Cyclic response before and after buckling.

Table 4 Effect of initial buckle size on inelastic strain range

	Initial buckle size, %		
Initial size	42	63	83
$\Delta\varepsilon_{in}$	0.294	0.347	0.350
$\Delta\varepsilon_{pp}$	0.195	0.223	0.221
$\Delta\varepsilon_{pc}$	0.099	0.124	0.129

Table 5 Effect of local overheating (initial buckle 83% of liner thickness)

Local overheating	10% (971°C), %	20% (1041°C), %
$\Delta\varepsilon_{in}$	0.189	0.350
$\Delta\varepsilon_{pp}$	0.098	0.221
$\Delta\varepsilon_{pc}$	0.091	0.129

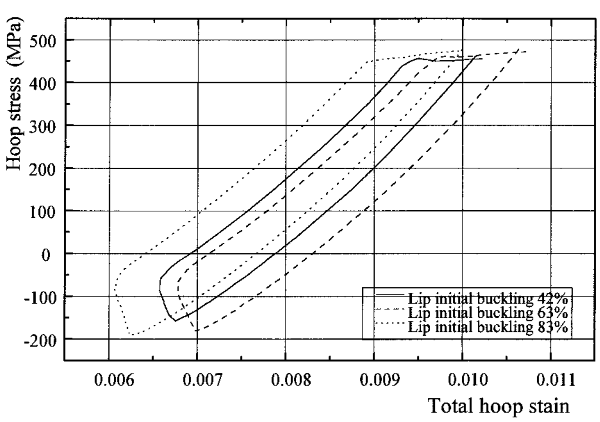

Fig. 9 Effect of initial buckling on cyclic response at node B.

to the softer material properties and lower flexural stiffness. Nevertheless, at the border of the local overheating zone, such as at node B, inelastic strain may increase.

Initial Buckle Size Effect on Inelastic Stress/Strain

The effect of initial buckle size on the cyclic inelastic stress/strain response is shown in Fig. 9. The cyclic thermal loading is the same as given earlier, with local overheating of 20% (1041°C in the center of local overheating zone at the louver lip). Initial buckle sizes of 42, 63, and 83% of the liner thickness (defined as the maximum initial deformation at node A) are calculated. With increasing initial buckling, inelastic strain at node B increases, as seen in the top three rows of Table 4, where $\Delta\varepsilon_{in}$ is the total inelastic strain range.

Effect of Hot Streak on Inelastic Strain Range

The influence of hot streak intensity on inelastic strain range was studied for local overheating of 10 and 20% (971 and 1041°C in the center of the local overheating zone at the louver lip). The results, shown in Table 5, indicate that inelastic strain components for these values increase substantially with the overheating.

Life Estimation of Louver Liner

In the strain-range partitioning method,[7] inelastic strain consists of time-independent plasticity plus time-dependent creep. Under cyclic reversed loading, there are four possible combinations of inelastic behavior. These comprise tensile plasticity reversed by compressive plasticity (PP), tensile creep reversed by compressive creep (CC), tensile creep reversed by compressive plasticity (CP), and tensile plasticity reversed by compressive creep (PC). For cyclic thermal loading on the liner, all of the time-dependent response occur at

Table 6 Effect of initial buckle size on lifetimes

Initial size	42%	63%	83%
N_{PP}	3920	3243	3286
N_{PC}	7987	5136	4753
N_{total}	4727	3734	3707

Table 7 Effect of local overheating (initial buckle 83% of liner thickness) on lifetimes

Local overheating	10% (971°C)	20% (1041°C)
N_{PP}	10,866	3,286
N_{PC}	9,422	4,753
N_{total}	10,119	3,707

the higher temperature when the louver lip is in compression. Thus, the cyclic responses at the lip were only PP and PC,[8] and Tables 4 and 5 list only the strain ranges in PP and PC, that is, $\Delta\varepsilon_{PP}$ and $\Delta\varepsilon_{PC}$.

The strain-range partitioning relationships for PP and PC required to calculate life for the Hastelloy X material were obtained from Ref. 8. The total predicted life N_{total} is given by the following equations:

$$\frac{1}{N_{total}} = \frac{1}{\Delta\varepsilon_{in}}\left(\frac{\Delta\varepsilon_{PP}}{N_{PP}} + \frac{\Delta\varepsilon_{PC}}{N_{PC}}\right) \tag{2}$$

$$N_{PP} = (\Delta\varepsilon_{PP}/0.544)^{-(1/0.68)} \tag{3}$$

$$N_{PC} = \left(\frac{\Delta\varepsilon_{PC}}{0.0968}\right)^{-(1/0.51)} \tag{4}$$

By the use of Eqs. (2–4) and the data from Table 4, the effect on estimated life of initial buckle size is obtained and shown in Table 6. Inelastic strain increases with buckle amplitude. Doubling the buckle size increases the amplitude of inelastic strain by 19% and reduces the life by 22% roughly the same proportion.

Similarly, the effect of the intensity of local overheating on the predicted lifetimes are also obtained and are shown in Table 7, which indicates that overheating leads to a more drastic reduction in life. Furthermore, it reveals that a 7% increase, in lip temperature causes about a two times increase in inelastic strain, resulting in a three times reduction in total life. This is because the increased temperature not only increases the amplitude of inelastic strain, but also causes a substantial reduction in material strength.

Conclusions

The elastic and viscoplastic localized buckling behaviors of combustor liners subjected to hot streaks and high lengthwise temperature gradients found in the engine service have been investigated using nonlinear FE methods. Temperature profiles that represent engine service conditions were obtained from laboratory tests on a rig combustor. The effects of both initial buckle size and intensity of local overheating on inelastic stress/strain responses of the louver liner have been determined. Finally, thermo–mechanical fatigue lifetimes of the louver liner under service conditions, subjected to and not subjected to hot streaks, have been predicted using the strain-range partitioning method. From the study, the following recommendations may be made.

1) The thermal loading, combining axial temperature peaks at the louver lip with circumferential hot streaks, leads to compressive buckling in the hot region. The buckle may restrict cooling airflow, leading to further local overheating and burning.

2) Cyclic thermal loading leads to significant cyclic inelastic strain. Inelastic strain increased with buckle amplitude and proportionally reduced the predicted life at the louver lip.

3) Local overheating caused substantial life reduction. At the level estimated to occur in hot streaks, it significantly increased the

cyclic strain amplitude, reduced the material strength, and severely reduced life.

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