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Life Assessment of Structural Components Using Inelastic Finite Element Analyses

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INTRODUCTION

The need for enhanced and improved performance of structural components subject to severe cyclic thermal/mechanical loadings, such as in the aerospace industry, requires development of appropriate solution technologies involving time-dependent inelastic analyses. Such analyses are mandatory to predict local stress-strain response and to assess more accurately the cyclic life time of structural components. The NASA-Lewis Research Center is cognizant of this need. As a result of concerted efforts at Lewis during the last few years, several such finite element solution technologies (in conjunction with the finite element program MARC (Ref. 1)) have been developed and successfully applied to numerous uniaxial and multiaxial problems. These solution technologies, although developed for use with MARC program, are general in nature and can easily be extended for adaptation with other finite element programs such as ABAQUS, ANSYS, etc.

This paper presents the description and results obtained from two such inelastic finite element solution technologies. The first employs a classical (non-unified) creep-plasticity model. An application of this technology is presented for a hypersonic inlet cowl-lip problem. The second of these technologies uses a unified creep-plasticity model put forth by Freed (Ref. 2). The structural component for which this finite element solution technology is illustrated, is a cylindrical rocket engine thrust chamber. The paper also demonstrates the advantages of employing a viscoplastic model for nonlinear time-dependent structural analyses.

The life analyses for cowl-lip and cylindrical thrust chambers are presented. These analyses are conducted by using the stress-strain response of these components obtained from the corresponding finite element analyses.

It is believed that the results from the present work will encourage other researchers to perform such finite element analyses to assess more accurately the deformation behavior and cyclic life time of structural components.

COWL LIP
(Classical Creep-Plasticity Analysis)

A three-dimensional finite element model of the cowl lip, Fig. 1, was constructed by Melis and Gladden (Ref. 3). The model consists of 3294 eight-noded, solid, isoparametric elements and 4760 nodes. A considerably large number of elements was required to handle the steep temperature gradient produced by the severe thermal loading imposed on the component. The steady-state temperature distributions in the cowl lip were obtained from Ref. 3. A linear interpolation technique was then employed to calculate the temperatures during the transient state. The simplified thermal loading cycle used to perform the time-dependent non-unified creep-plasticity analysis is shown in Fig. 2.

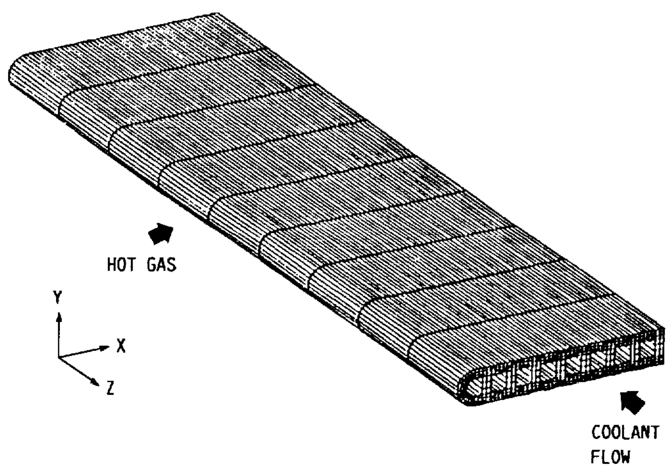

Figure 1 - Cowl lip finite element model

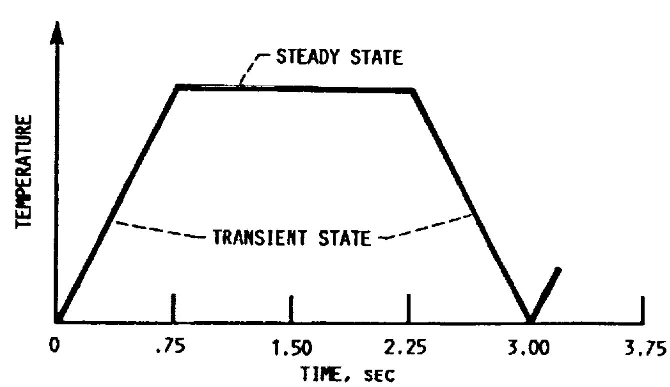

Figure 2 - Simulated thermal response used in structural analyses

STRUCTURAL ANALYSES

Linear elastic, nonlinear elastic-plastic and elastic-plastic-creep analyses were performed using the finite element program MARC. The values of material constants and the description of creep law used in the analysis are given in Arya, et al (Ref. 4). Figure 3 depicts the elastically calculated stress along a cross section of the cowl lip at thermal steady state. The magnitude of the largest stress predicted from this analysis is much higher than the yield strength for copper (the material of cowl lip). This shows that an elastic analysis for this severely thermally driven problem is inadequate. The stress values from an elastic-plastic analysis are exhibited in Fig. 4. The figure shows the reduction of maximum compressive stress (from about 554.3 MPa) to a more reasonable value (of about 196.5 MPa). The effect of time on stress distribution is obtained by conducting an elastic-plastic-creep analysis and it is shown in Fig. 5. The maximum compressive stress still occurs at the leading edge but with a further reduced magnitude of about 131.0 MPa.

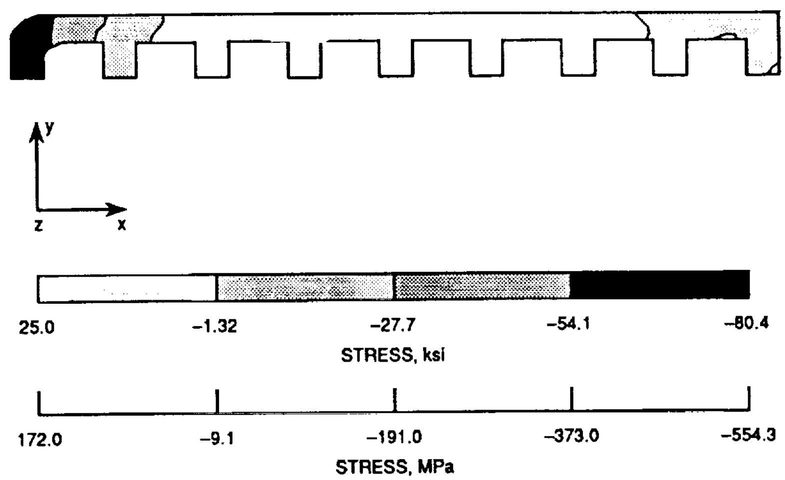

Figure 3 - Elastic analysis

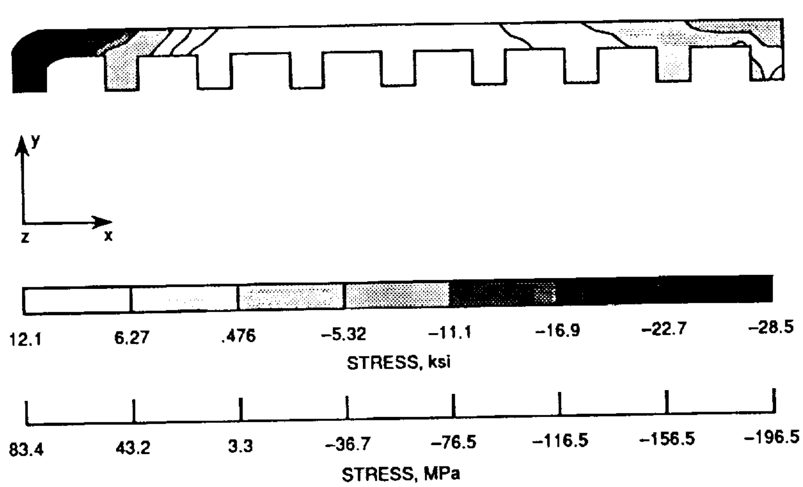

Figure 4 - Elastic-plastic analysis

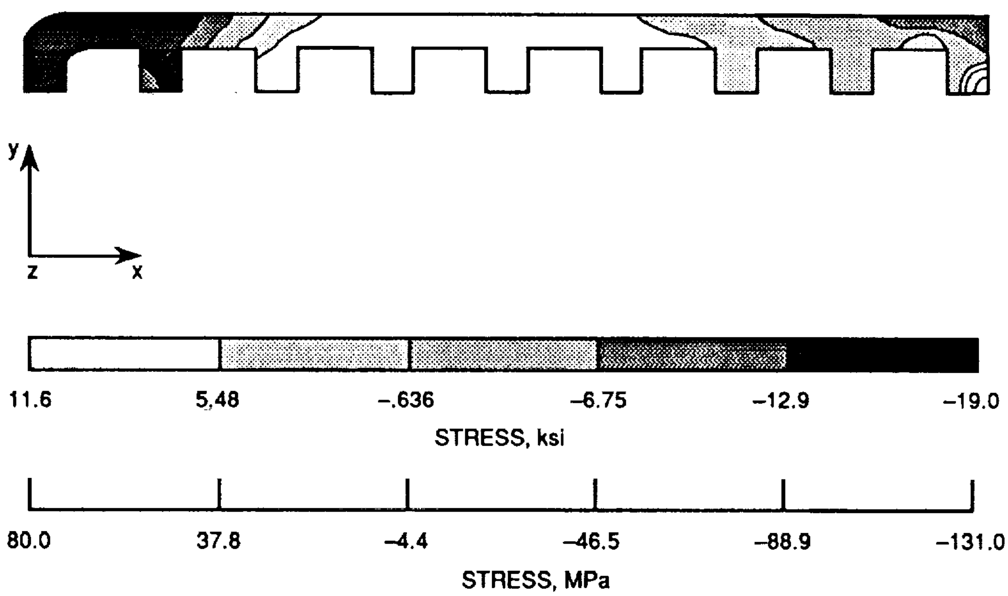

Figure 5 - Elastic-plastic-creep analysis

LIFE ANALYSIS OF COWL LIP

The stress-strain results from the structural analyses were used in estimating the cyclic crack initiation life of the cowl lip. The thermo-mechanical fatigue (TMF) loops calculated at the 'critical' cowl lip location are shown in Fig. 6. The critical location is defined as the location with largest total strain range. Using this total strain range and the fatigue curve of Fig. 7, the cyclic crack initiation lives from different structural analyses can be estimated. The fatigue curve of Fig. 7 is obtained by Conway, et al (Ref. 5). The details of life analyses and justification for using data of Fig. 7 for current life analyses may be found in Arya, et al (Ref. 4).

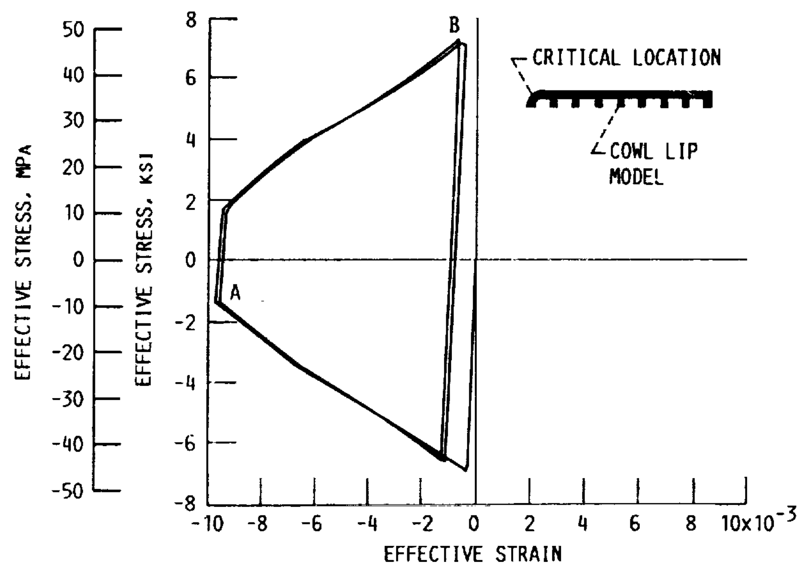

Figure 6 - Hysteresis loops for cowl lip

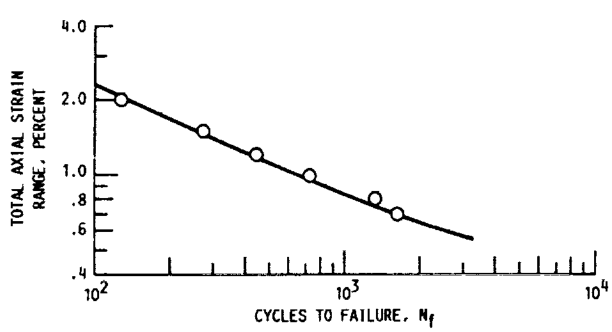

Figure 7 - Fatigue curve (taken from Conway et al [5])

COMPARISON OF HYSTERESIS LOOP CHARACTERISTICS

A comparison of hysteresis loop characteristics (total strain range, stress range, elastic strain range, plastic strain range and the approximate creep strain range) is presented for three different (elastic, elastic-plastic and elastic-plastic-creep) analyses in Table I. Using the total strain ranges shown in this table and fatigue curve of Fig. 7, the elastic, elastic-plastic and elastic-plastic-creep analyses are shown to predict the cyclic crack initiation lives as 2300, 1000 and 800 cycles, respectively. Since the elastic-plastic-creep analysis is judged to give the most realistic structural analysis results, the corresponding life of 800 cycles to failure is also judged to be the most realistic estimate of expected life time of cowl lip.

Table I - Comparison of Hysteresis Loop Characteristics

Analysis	Effective Stress at Maximum Temperature, MPa	Effective Stress Range, MPa	Total Mechanical Strain Range	Elastic Strain Range, $\Delta\varepsilon_{el}$	Plastic Strain Range, $\Delta\varepsilon_{pp}$	Creep Strain Range, $\Delta\varepsilon_{pc}$	Cycles to Failure, N_f
Elastic	-554.4	726.7	0.0062	0.0062	------------	------------	2300
Elastic-plastic	-9.7	60.7*	0.0085	0.0005	0.0080	------------	1000
Elastic-plastic creep	-9.0	60.0*	0.0092	0.0005	(»)0.0080	(»)0.0007	800

**Strain range between points A and B of hysteresis loop of Figure 6.*

CYLINDRICAL THRUST CHAMBER LINER
(Unified Creep-Plasticity or Viscoplastic Analysis)

To demonstrate the development and application of a finite element solution technology pertaining to viscoplastic models, the problem of a cylindrical thrust chamber is presented. Two types of channel geometries, rectangular and circular, were analyzed. The latter configuration is more thermally compliant. The finite element models for these geometries together with the number of elements and nodes are shown in Fig. 8. The thermal and pressure loading cycles are shown in Fig. 9.

Thermal Analyses: Steady-state heat transfer analyses were performed for the two channel geometries using MARC program. The temperature values thus obtained were linearly interpolated to obtain the temperature distributions for the two geometries over the complete loading cycle. The plots of these temperature distributions may be found in Arya, et al (Ref. 6).

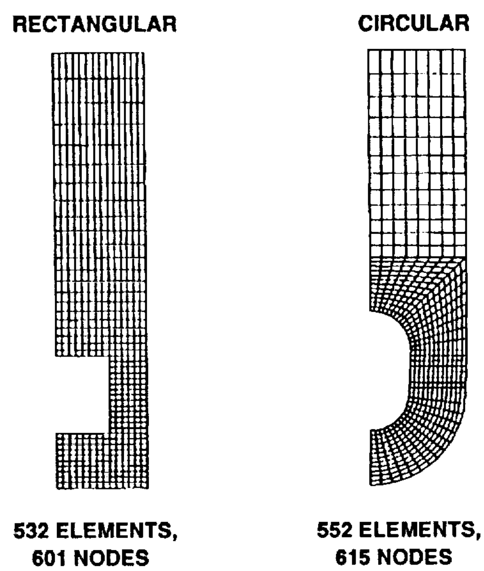

Figure 8 - Finite element models for two channel geometries

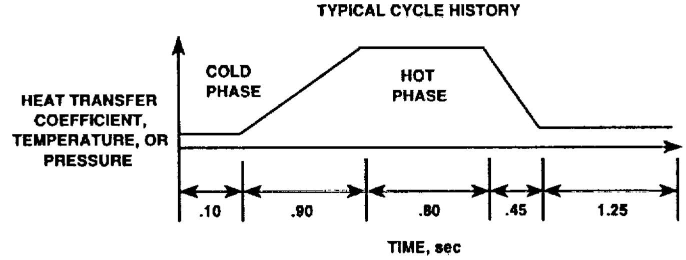

Figure 9 - Cyclic thermal and pressure loadings

A viscoplastic model put forth by Freed (Ref. 2) was employed to conduct the nonlinear structural analyses. The model was implemented in MARC program through user subroutine HYPELA. Complete details of implementation are given in Arya and Kaufman (Ref. 7). The material of the segments is copper. The values of material constants taken from Freed (Ref. 2) were utilized in numerical computations. Figure 10 depicts the deformed geometries of channels after five loading cycles. To facilitate visual interpretation, the deformations are magnified by a factor of 1000. The figure shows significant deformation of rectangular channel. The circular channel shows little apparent deformation.

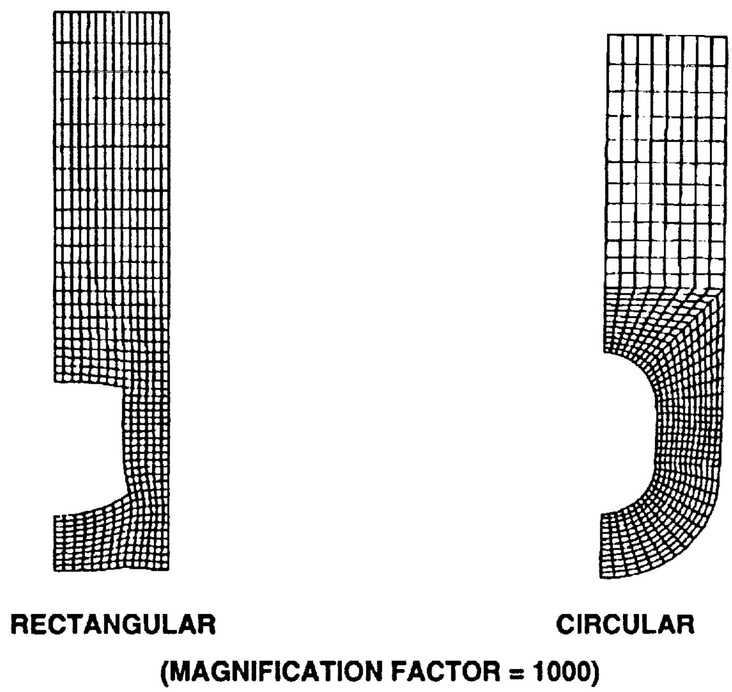

Figure 10 - Deformed shapes of the channels after five loading cycles.

THINNING OF COOLANT CHANNEL WALLS

Figures 11 and 12 show the thinning of coolant channel walls after different loading cycles in x and y directions, respectively. These figures show that the rectangular channel wall thins more rapidly than the circular channel wall in both the x and y directions. The circular channel geometry may thus have a greater cyclic ratcheting lifetime than the rectangular channel geometry.

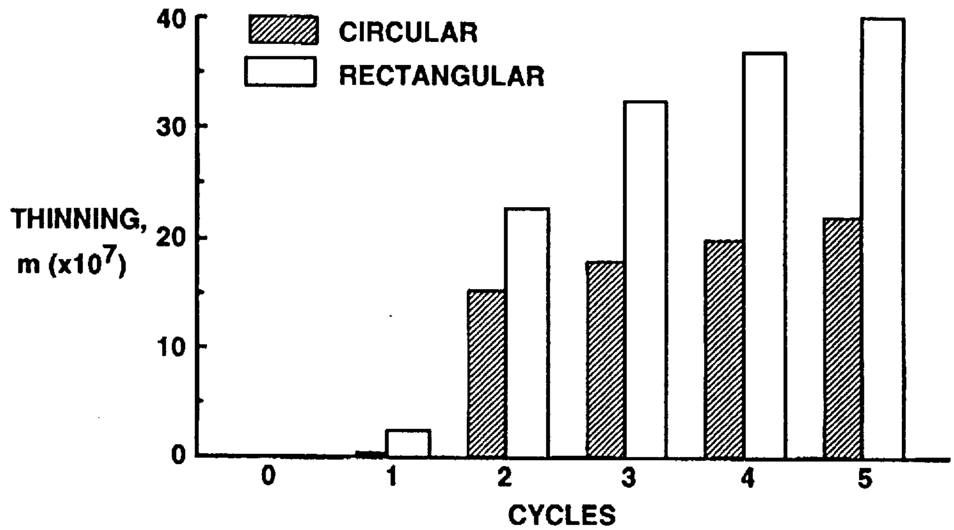

Figure 11 - X-Direction

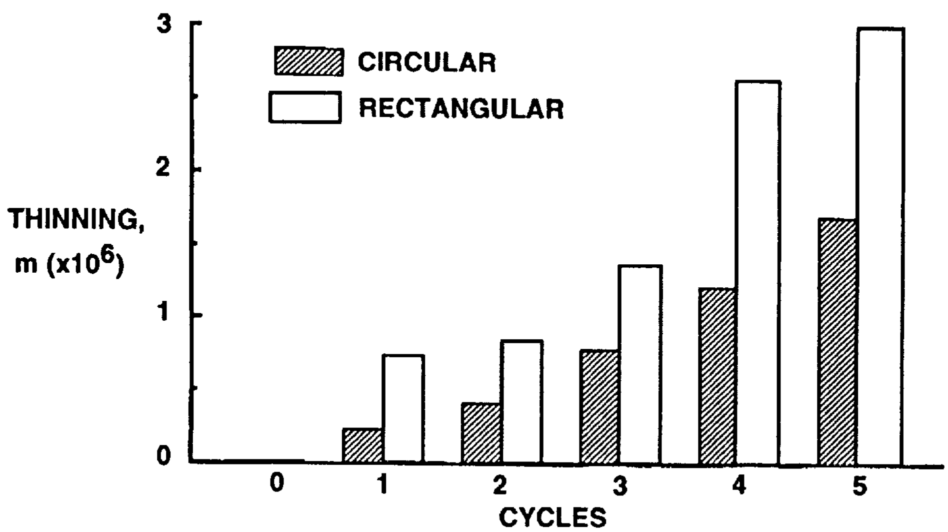

Figure 12 -Y-Direction

LIFE ANALYSES OF THRUST CHAMBERS

As in the case of the cowl lip problem, the 'critical' locations were determined for the rectangular and circular geometries. By calculating the total strain ranges at these critical locations and using the fatigue curve of Fig. 7, the cyclic lives for rectangular and circular geometries can be estimated. The lower total strain range for the circular channel geometry is the evidence of its greater thermal compliance. The results are summarized in Table II. Complete details of life analyses may be found in Arya et al (Ref. 6). It is seen from this table that the circular channels have significantly higher cyclic lives than the rectangular channels for identical loading cycles. Also, keeping in view the uncertainties associated with life prediction and approximations used therein, it is seen from this table that the predicted lives for two channels are in fair agreement with their observed lives.

Table II - Calculated and Observed (Experimental) Lives of Thrust Chambers (Viscoplastic Analysis)

Channel Geometry	Total Strain Range	Cycles to Failure	
		Calculated	Experiment
Rectangular	2.6%	75	200
Circular	1.05%	600	>637

CONCLUSIONS

The finite element solution technologies for time-dependent inelastic analyses are described. These include classical (non-unified) creep-plasticity and unified creep-plasticity (viscoplastic) analyses. The classical creep-plasticity analysis is applied to a hypersonic inlet cowl lip problem and the unified creep-plasticity analysis to a cylindrical rocket engine thrust chamber problem. The stress-strain responses calculated from these analyses are used to assess the cyclic lives of these components. It is concluded from the results presented in this paper that the assessments of cyclic lives based on inelastic finite element analyses are realistic (cowl lip) and in fair agreement with the observed lives (thrust chamber).

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