

# **NASALife –Component Fatigue and Creep Life Prediction Program and Illustrative Examples**

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## **SUMMARY**

NASALife is a life prediction program for propulsion system components made of ceramic matrix composites (CMC) under cyclic thermo-mechanical loading and creep rupture conditions. Although, the primary focus was for CMC components the underlying methodologies are equally applicable to other material systems as well. The program references data for low cycle fatigue (LCF), creep rupture, and static material properties as part of the life prediction process. Multiaxial stresses are accommodated by Von Mises based methods and a Walker model is used to address mean stress effects. Varying loads are reduced by the Rainflow counting method. Lastly, damage due to cyclic loading (Miner's rule) and creep are combined to determine the total damage per mission and the number of missions the component can survive before failure are calculated. Illustration of code usage is provided through example problem of a CMC turbine stator vane made of melt-infiltrated, silicon carbide fiber-reinforced, silicon carbide matrix composite (MI SiC/SiC)

## **INTRODUCTION**

Engine companies are constantly striving to improve the performance and life of their gas turbine engines. As a result, materials within the engines are pushed to new limits making life prediction very important. NASALife [1] was written to provide a convenient package for determining the component life under cyclic thermo-mechanical loading using existing damage accumulation theories and primarily for CMC components life prediction methods.

## **TECHNICAL DESCRIPTION**

The high temperature structural components of gas turbines such as combustor liners and vanes experience thermal cycling, body forces, and extraneous loads from combustion gas flow, mechanical loading, and maneuvering loads. These conditions can cause crack initiation and propagation through a component at highly stressed locations, eventually leading to component failure.

NASALife requires as input a complete mission stress (uniaxial or multiaxial) and temperature profiles during a typical mission. Also required for input are a stress versus life data, a Walker exponent, and the nonlinear stress-strain curve information. The program will then compute the major LCF cycle, identify all subsequent minor cycles, and finally produce a calculated LCF life for the given mission. All calculations in NASALife are performed using elastic stresses. In addition, NASALife can also estimate life relative to creep rupture and life due to the combined effect of LCF and creep.

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The fatigue data input contains a series of values for stress and life at various temperatures. Extrapolation beyond either the maximum temperature or maximum stress of the fatigue data is not permitted. The lowest temperature LCF data is used to determine failure when the mission temperature is below the lowest available data temperature. The LCF life is determined for a given stress amplitude by interpolation of the data file.

Engine components perform under multiaxial stress fields. Multiaxial stresses are converted into an equivalent uniaxial stress in NASALIFE. This conversion included the treatment of both the mean stress,  $\sigma_m$ , and the stress amplitude, also referred to as the alternating stress,  $\sigma_a$ .

Six Von Mises based methods [1], described in the literature for calculating a single effective stress from the multiaxial stresses, are utilized in NASALIFE. The methods include the Manson-McKnight method, Modified Manson-McKnight method, Sines method, Smith-Watson-Topper method, R-Ratio Sines method, and Effective method. In addition, new subroutines can be added to future versions of NASALIFE to accommodate different stress reduction methods.

Most components operate with a varying mean stress occurring during their cyclic mission. The Walker [2] model may be used in NASALIFE to address the influence of mean stresses on fatigue lives.

The application of a varying load over time requires the use of a technique for counting the different cycles. The simplest method of considering the full damage content of a mission is through the use of a rainflow counting technique as presented by Endo [3,4]. The rainflow counting technique is a standardized cycle counting method as per American Society for Testing and Materials (ASTM) [5] E 1049-85. A common rainflow approach is to use the effective stress at the end points of a particular cycle. This will properly calculate the magnitude of the stress amplitude, but does not take into account the influence of the mean stress of the cycle or the variation of temperature during the cycle. As a result, NASALIFE uses a damage rainflow approach.

Damage counting schemes identify the most damaging cycle based on the stress and temperature data. In NASALIFE, a damage counting algorithm is used to identify the most damaging major cycle. The most damaging major cycle is determined by evaluating every combination of mission points,  $N*(N-1)$  permutations for  $N$  mission points, to find the combination which will produce the lowest life. The life for each subcycle is calculated using the one of the multiaxial methods and the mean stress model described above. All subsequent minor cycles are then identified using the more traditional stress rainflow techniques.

This damage rainflow approach can select any point in a mission, not necessarily a maximum or minimum stress. A good example of this would be a relatively slow loading ramp where the temperature goes through a large maximum. If the fatigue life of the material in question decreases with increasing temperature, an intermediate stress point at a high temperature might be in the most damaging cycle.

The fatigue life for a particular stress can be determined from the appropriate LCF curve. The durability life for the mission is obtained by combining the LCF damage

of each of the individual cycles. NASALIFE estimates the LCF damage using Miner's [6] rule:

$$\frac{I}{N} = \sum_i \frac{X_i}{N_i} \quad (1)$$

where  $X_i$  is number of cycles of one magnitude and environmental condition and  $N_i$  is the life with those cycles at the same environmental condition.

NASALIFE will provide a calculated rupture life if rupture data is included in the input file. A very simple integration over the mission is performed. The step size is determined based on the larger of the time increment or the stress increment. Rupture time is calculated for each increment. The rupture data may either be tables of temperature and stress versus life, or Larson-Miller [7] parameters.

The basic Larson-Miller equation is:

$$P = T(C + \log t) \quad (2)$$

where:

T - temperature

C - material constant

t - time

P - Larson-Miller parameter

The Larson-Miller parameter is a function of the log of the stress. For NASALIFE the Larson-Miller parameter is entered as a polynomial function of stress with simple adjustments as presented by Conway [8]. As a result, it is assumed that the Larson-Miller parameter has a normal distribution or, equivalently, the rupture time follows a lognormal distribution as noted by Zuo, et. al [9].

NASALIFE uses the above equation solved for time as shown by the following equation

$$t = 10^{(P/T - C)} \quad (3)$$

It was noted above that the Larson-Miller parameter is entered as a polynomial function. The function is illustrated below

$$P = P_0 + P_1\sigma + P_2\sigma^2 + \dots + P_i\sigma^i \quad (4)$$

where:

$P_i$  - polynomial coefficients

- applied effective stress

In NASALIFE, the total damage caused by a mission is the sum of the damage due to cyclic fatigue and the damage due to creep. Damage is the life used by a mission divided by the total available life. As a result, damage that is greater than or equal to unity constitutes failure. Initially the life is determined for the creep life under a given

loading condition. Damage,  $D_{creep}$ , is taken as the inverse of the life,  $L_{creep}$  as shown by the following equation

$$D_{creep} = \frac{1}{L_{creep}} \quad (5)$$

Also, NASALIFE converts the LCF life,  $L_{LCF}$ , to LCF damage,  $D_{LCF}$ , as illustrated by the equation below

$$D_{LCF} = \frac{1}{L_{LCF}} \quad (6)$$

The total damage,  $D$ , is

$$D = D_{LCF} + D_{creep} \quad (7)$$

NASALIFE can utilize an exponential creep damage rate leading to the following equation

$$D = D_{LCF} + D_{creep}^b \quad (8)$$

where  $b$  is the exponent for the creep damage.

Design engineers must often consider factors other than those discussed in this document in determining the fatigue life of their components. Some of these issues are:

- a) Time dependent deformation
- b) LCF/HCF Interaction
- c) Role of feature testing
- d) Composite material failure mechanisms

These factors may be important, but until methods are established and verified for these they will not be included in NASALIFE. When those methods are developed, they will be included in future releases and the corresponding revised manual.

Another failure issue, particularly, with CMCs is peeling as presented by Ogbuji [10]. Peeling is the oxidative degradation of CMCs in a service environment at intermediate temperatures. As mentioned above as models become available they can be incorporated into NASALIFE.

### **CMC STATOR VANE EXAMPLE**

In order to illustrate how the code can be used a CMC stator vane is chosen. The complete details of this analysis can be found in Reference [11]. A typical vane with the location of highest stress is shown in Fig 1. The mechanical and other high temperature material properties database is limited due to the fact the material system is relatively new. As a result, for this study the range of data was expanded by extrapolation. Higher and lower stresses were linearly extrapolated using the log of life. Due to the limitations of the MI SiC/SiC data as described above, the data should be viewed only for demonstrating the functionality of NASALife and is not be used for design purposes. Figure 2 shows the applied load cycle that was used to obtain the LCF data in lab. The loading was repeated until complete fracture of the specimen. Data from low cycle fatigue tests, creep rupture tests, and static tensile tests are used as the reference for

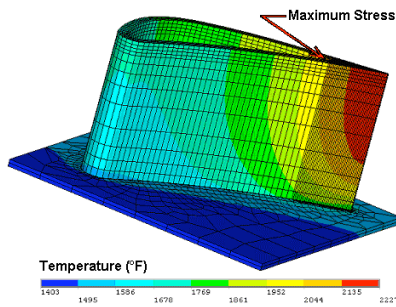


Fig.1. MI SiC/SiC stator vane showing temperature distribution and the location of the max. stress.

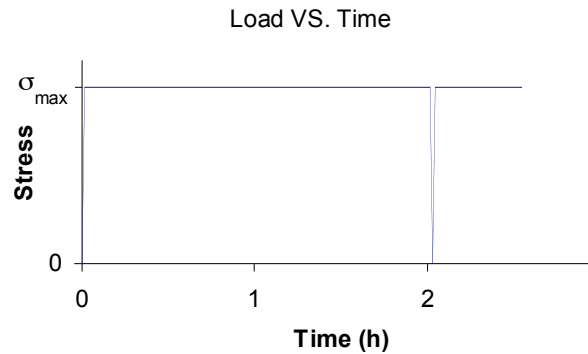


Fig. 2. Load cycle used to generate the cyclic fatigue data

predicting the number missions a component can survive under a given thermo-mechanical loading condition. Several analyses consisting of a number of mission profiles of temperature and mechanical loading were conducted using the program. It was seen that at higher temperatures ( $>2000$  °F), creep becomes a significant part of the failure process when considering the life of a thermo-mechanically loaded component. For example, at 14.1 ksi (97.2 MPa) applied constant stress when the hold duration was varied from 5 seconds to 4 hours, the number of missions relative to creep damage reduced from 22532 to 42.

The life prediction results from NASALife showed trends as one would expect. Varying the hold duration at high temperatures while keeping the stress constant did provide the expected results of increased damage due to creep while the fatigue damage stayed constant. On the other hand, superimposing a low magnitude variable load over the hold stress and altering the frequency of the variable load had minimal effect on creep but increased the damage due to the cyclic loading.

## CONCLUSIONS

With a limited database NASALife is shown to provide reasonable estimates for life of a thermo-mechanically loaded structural component made of a MI SiC/SiC ceramic composite system. The trends predicted by NASALife are as expected for the loading conditions that were used for this study. A full range of material properties data is required to make any kind of plausible life prediction. In particular, the data must cover the operating conditions for which the analysis is to be conducted.

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