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Implementation of creep–fatigue model into finite element code to assess cooled turbine blade

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Turbine blades which are designed with airfoil cooling are subject to thermo-mechanical fatigue as well as creep damage. These problems arise due to thermal cycling and high operating temperatures in service. An implementation of fatigue and creep damage models into a finite element code is presented. The implementation was designed to be practical and streamlined, as the damage models used require a minimum of materials testing; and by integrating all the code into an existing finite element package, there is no need to search through or transfer large amounts of output data in order to assess results.

INTRODUCTION

Advanced gas turbine engines which make use of hot section airfoil cooling present a range of design problems, as the blades operate in a damaging environment of high temperatures, centrifugal and gas pressure forces and thermal cycling. These conditions combine at every point in the blade to create an interaction between creep and thermo-mechanical fatigue damage. Determining the more damaging or life-limiting mode of failure, as well as estimating the expected lifetime of the blade is of primary concern for all stages of the design process. Blades which exhibit geometrically simple cooling passages can be analysed using crude techniques assuming the thermal and stress conditions are known. However, this is usually not the case, and finite element methods must be employed if meaningful results are to be achieved. Also, because of stress redistribution due to the creep process, it is necessary to include a full inelastic creep step in the finite element analysis, as over-conservative creep life predictions usually result when only the initial elastic stresses are considered.

While software codes exist for the treatment of conventional fatigue, few are available for determining creep–fatigue interaction in a geometrically complex cooled blade subject to transient thermal loadings. This paper presents a creep–fatigue damage model implementation into the general purpose non-linear finite element code ABAQUS. The creep model uses a Norton power law, Larson–Miller and Robinson's rule approach, while the fatigue model combines Miner's law and the universal slopes method. In both creep and fatigue cases crack initiation was considered as defining the design life. A linear summation of the creep and fatigue damage parameters provides the analyst with a measure of the total damage at any point over the blade at any time in the load history, and a breakdown into the failure mode components. This is a similar approach to the well-established ASME Code Case N47,[1] and although the models employed are not the latest to be found in the literature, they have the advantage of being easy to implement and require less mechanical testing than more complex models. With this in mind, the analyst is able to use the damage parameters to assess the effectiveness of design changes and examine trends, rather than to attempt to obtain a definitive time-to-failure value. However, as the designer has full control over the code implemented into the user subroutine, more complex damage models can be substituted as more material data become available, or as higher levels of accuracy are required in later design stages.

In order to demonstrate the output of the implementation, a cooled blade has been analysed and the results are presented here.

To obtain accurate thermal load histories, computational fluid dynamics (CFD) analyses were performed to obtain convection boundary conditions over the external and internal surfaces of the blade. The CFD code STAN5 was used for this purpose, and the resulting data was interpolated onto the finite element mesh.

DAMAGE MODEL

As the blades operate at metal temperatures in excess of $0{\cdot}4T_{\text{melt}}$ in Kelvin, creep rupture is clearly a possible failure mode. Also, as the engine cycles through start-up and shut-down with each flight, the transient thermal and body loading stresses cause fatigue damage, which can lead to ultimate failute. The problem becomes one of predicting the relative amounts of creep and fatigue damage at each point in the blade at each moment of the cycle, which in turn depends upon knowing the stress and temperature conditions at each instant and at each spatial point.

The finite element method is well suited to finding the solution here, as these values are calculated at each iteration during the analysis. The stress and temperature values obtained in this way were used to calculate the creep and fatigue damage parameters w_c and w_f as described below.

Fatigue damage parameter, w_f

At start-up, the thermal load was applied to the blade, resulting in a transient thermal stress response. These stresses often reached a maximum value $\sigma_{\max}$ at some point in the transient before attaining a lower steady-state condition.

It was necessary therefore to record this maximum stress value $\sigma_{\max}$ at each point over the blade and use it in the fatigue life calculation. One cycle was assumed to include start-up, operation at a given stress and temperature level, and shut-down.

The number of cycles to failure, N_f, was calculated from the strain range $\Delta\epsilon$ using the method of universal slopes. This method has the advantage of using material data obtainable from simple tensile tests. The equation combines the Coffin–Manson law:[2]

$$\Delta\epsilon_p = \epsilon_f N_f^{-0{\cdot}6} \tag{1}$$

and the Basquin law:[3]

$$\Delta\epsilon_e = 3{\cdot}5\frac{\sigma_{\text{UTS}}}{E}N_f^{-0{\cdot}12} \tag{2}$$

into the form

$$\Delta\epsilon_{\text{tot}} = 3{\cdot}5\frac{\sigma_{\text{UTS}}}{E}N_f^{-0{\cdot}12} + \epsilon_f N_f^{-0.6} \tag{3}$$

where $\Delta\epsilon_e$, $\Delta\epsilon_p$ and $\Delta\epsilon_{\text{tot}}$ are the elastic, plastic and total strain ranges; ϵ_f is the failure strain; σ_{UTS} is the ultimate tensile stress and E is Young's modulus.

The maximum strain range $\Delta\epsilon_{\text{tot}}$ was obtained from the finite element analysis at each integration point in the model, and a Newton–Raphson iterative scheme was used to calculate the value of N_f using a residual of one cycle. A factor of safety of 1·5 on stress was built into eqn (3). Taking a starting condition of

$$N_0 = \left(3{\cdot}5\frac{\sigma_{\text{UTS}}}{E\,\Delta\epsilon_{\text{tot}}}\right)^{8{\cdot}33}$$

typically less than 10 iterations were required for the solution to converge. Once N_f was found, the fatigue damage parameter w_f was calculated:

$$w_f = \frac{n}{N_f} = \frac{t_a}{t_d n_f} \tag{4}$$

where n is the number of cycles completed, t_a is the total analysis time and t_d is the flight duration time (30 min). The value of w_f ranges from 0 (no damage) to 1 (failure).

Creep damage parameter, w_c

After the initial transients at start-up, the blade metal temperatures and stresses approach a steady-state condition. However, as these temperatures are typically greater than 40% of T_{melt} in Kelvin, creep occurs, resulting in stress redistribution. It is therefore important to model the creep process throughout the life of the component.

The creep law used was a power law based upon a minimum creep rate principle:

$$\dot{\epsilon}_s = A\left(\frac{\sigma}{\sigma_0}\right)^m e^{-(Q_c/RT)} \quad (5)$$

where $\dot{\epsilon}_s$, σ, T, Q_c and R are the creep strain rate, von Mises stress, metal temperature, activation energy and molar gas constant, respectively. The quantities σ_0, A and m are material constants.

The Larson–Miller equation[4] was then used to calculate the rupture time:

$$\log_{10}\left(\frac{t_R}{t_0}\right) = 1000\frac{T_0}{T}\left(e - \frac{\log_{10}\left(\frac{\sigma}{\sigma_0}x_{fos}\right)}{f}\right) - 20 \quad (6)$$

where t_R is the time to tupture and t_0, T_0, e and f are material constants. The factor of safety x_{fos} was taken as 1·3 in this case. The creep damage parameter w_c was defined according to Robinson's rule:

$$w_c = \sum_{i=1}^{N} \Delta t_i/t_R \quad \text{where } 0 \le w_c \le 1 \quad (7)$$

At each increment during the FEM creep analysis, t_R was calculated from eqn (6), Δt_i was the time increment just passed, and N was the total number of increments. In this way a running total of creep damage was accumulated, and this information could be accessed for any increment, and at any spatial point in the model.

Total damage parameter, w_{tot}

The interaction between creep and fatigue damage was assumed to vary in a linearly independent manner:[5,6]

$$w_{tot} = w_f + w_c \quad (8)$$

Typically, either w_f or w_c dominates, and plots of the three damage parameters versus time allow the designer to gain a clear first impression of the most damaging mode. These damage parameters were coded into the finite element input deck using the CREEP user subroutine facility in ABAQUS, allowing the designer to obtain contour plots and time history graphs of damage from a normal post-processing session. This process is described in more detail in the following sections.

IMPLEMENTATION INTO FINITE ELEMENT CODE

The implementation requires that the user has some access into the code, usually via a user subroutine. Solution-dependent variables, which may be defined by the user, were then used to measure maximum stresses, predicted times to failure and damage parameters. The coding was written in FORTRAN, and involved the following aspects:

(a) full creep analysis: creep strains were calculated using the power law eqn (5).
(b) predicted creep rupture: solution-dependent variable 2 (SDV2)—eqn (6)
(c) creep damage: SDV3 used for w_c—eqn (7)
(d) maximum stress: SDV4 used for σ_{max}
(e) Newton–Raphson scheme used to calculate N_f—eqn (3)
(f) fatigue damage: SDV5 used for w_f—eqn (4)
(g) total damage: SDV6 used for w_{tot}—eqn (8)

Although the various equations above were chosen for their simplicity and the availability of materials data, any one of them could be replaced with ease, without affecting the use of the others. For example, the creep power law in (a) above could be replaced by a θ-projection[7,8] or Kachanov damage law[9] approaches if such data were available for the material being analysed.

The results were able to be viewed using the standard post-processor, as this allows the use of contour or graph plotting of SDV*n* solution-dependent variables. By selecting the relevant time increment, a view of the spatial variation of the various damage parameters through a contour plot was possible; and by selecting a point in a critical region, history plots provided an estimate of the time to failure and the failure mode.

ASSESSMENT OF COOLED TURBINE BLADE

To demonstrate the output of the implementation, a finite element analysis of a first stage stator blade was performed, incorporating the damage models.

A mesh was produced using 504 20-noded isoparametric brick elements, each with 27

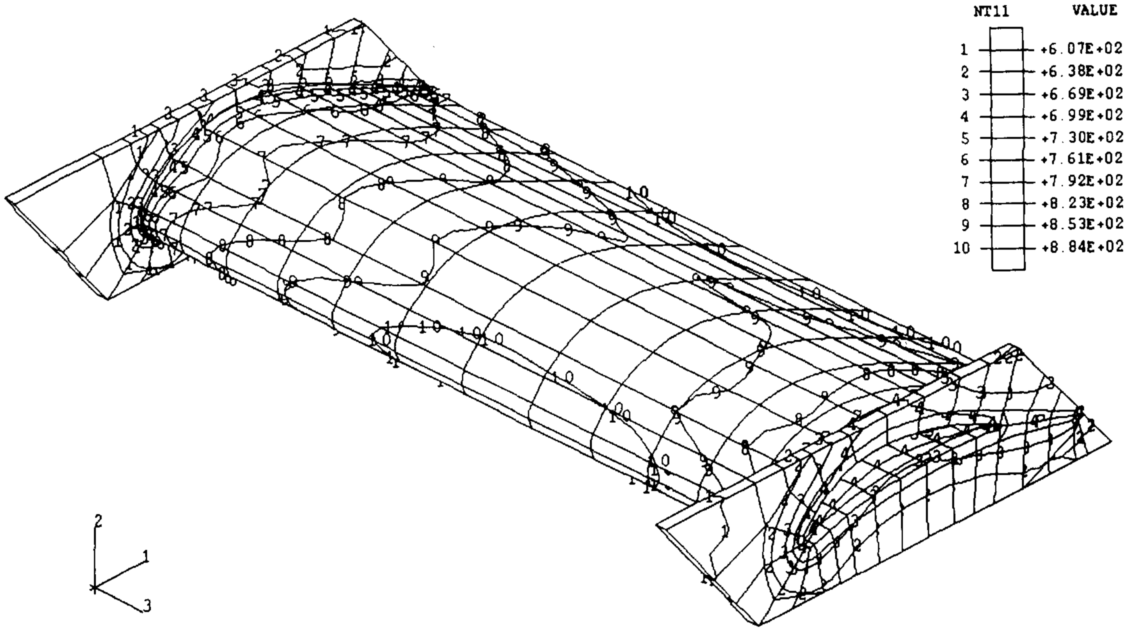

Fig. 1. Blade metal temperature distribution.

integration points, while convection boundary conditions were obtained from CFD analyses. As the CFD and finite element meshes were dissimilar, a two-dimensional interpolation was performed over the exterior and interior surfaces of the model, to apply the correct sink temperature and film coefficient data to each element.

A transient thermal analysis was then performed, and the resulting nodal temperatures were saved to a results file, to be used in the stress analysis. The final distribution of the blade metal temperatures is shown in Fig. 1.

These results were used in a static stress analysis to determine the thermal stresses and, in particular, the maximum stress value σ_{max} at each

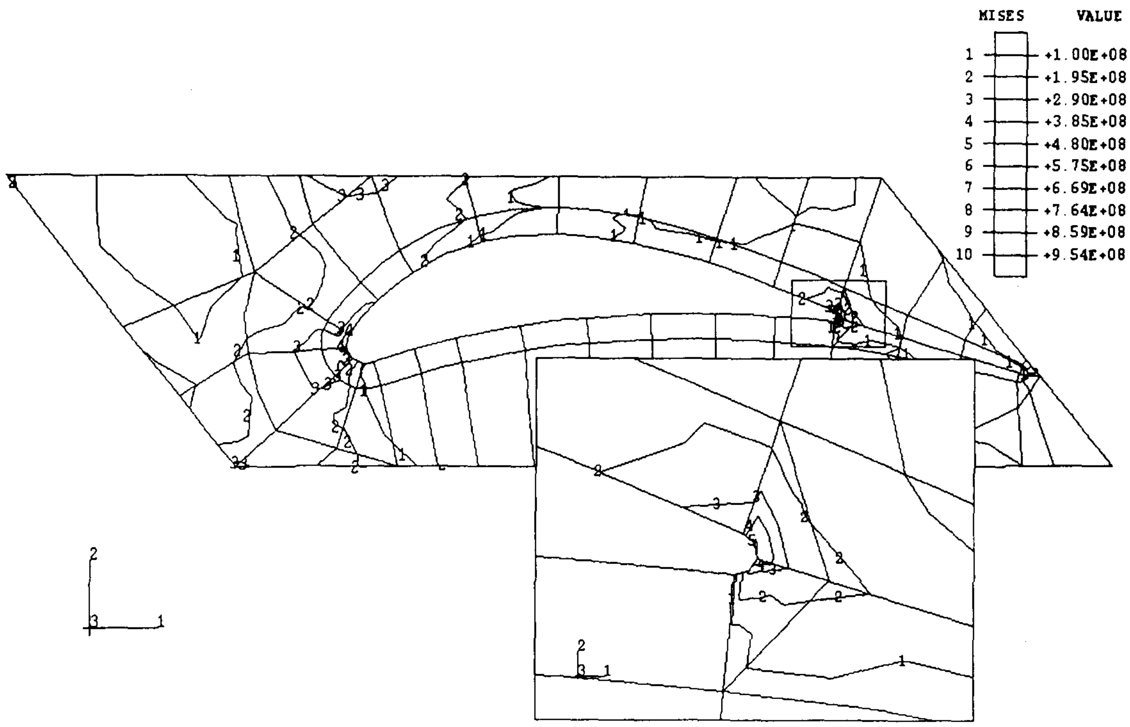

Fig. 2. Von Mises stress distribution.

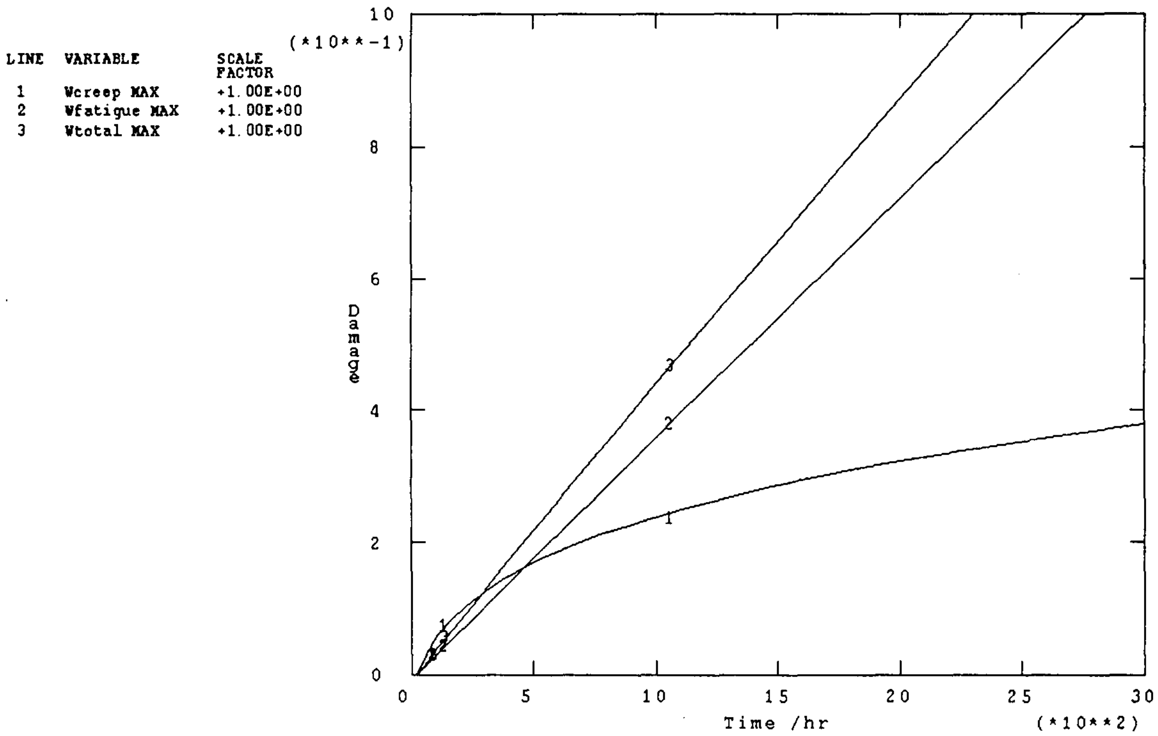

Fig. 3. History plot of the maximum damage parameters.

point in the blade. Figure 2 displays a contour plot of von Mises stress, showing high stress regions at the leading and trailing edges.

Once the σ_{max} stresses were found, a creep step was performed, using eqn (5), which ran until the total damage parameter w_{tot} exceeded a value of unity. At this point a crack was assumed to have formed at the relevant element. The mode of local failure could be ascertained by examining history graphs of the damage parameters at the critical element. Figure 3 shows a history plot of the maximum values of w_c, w_f and w_{tot}. It is clear that fatigue was the more damaging mode, causing local failure after roughly 2700 flying

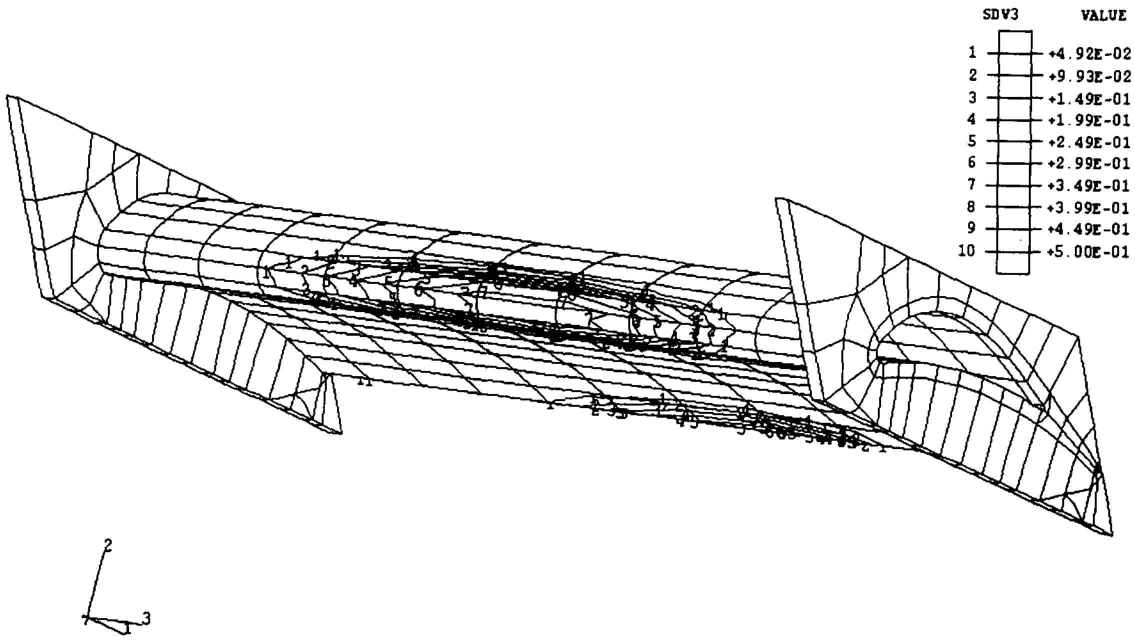

Fig. 4. Contour plot of creep damage parameter w_c.

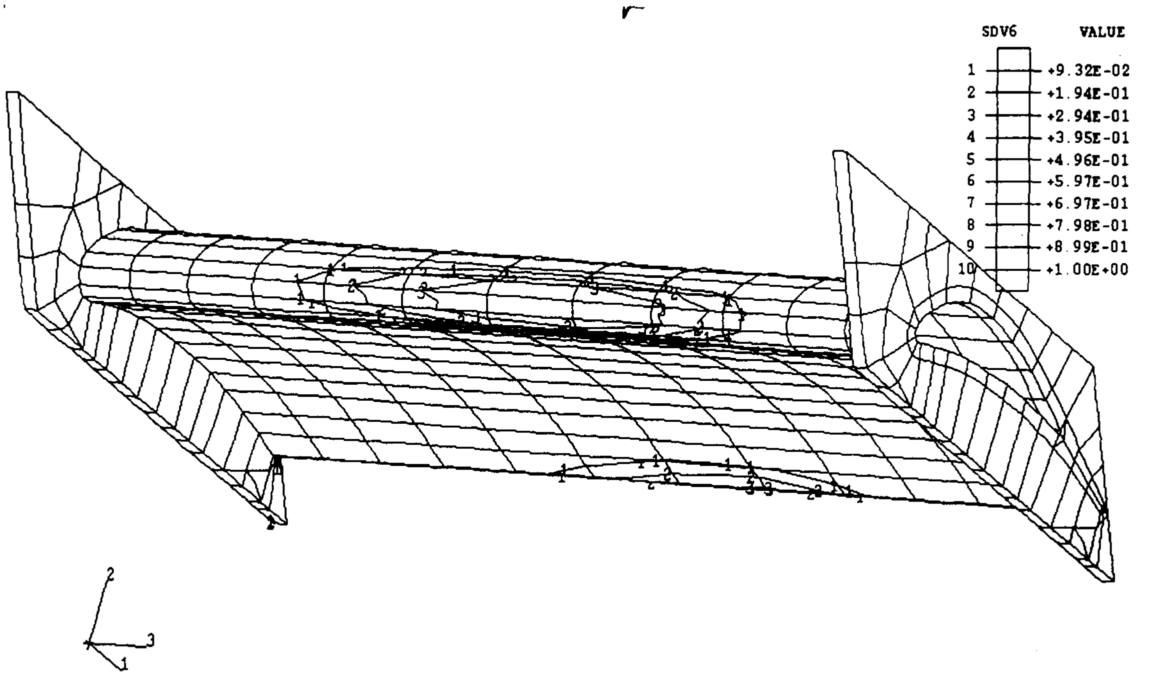

Fig. 5. Contour plot of total damage parameter w_{tot}.

hours. However, some creep damage at the same region contributed to the total damage, shortening the design life to about 2300 h. The creep damage rate was initially higher than the fatigue rate, but as stress relaxation occurred, this dropped off considerably, demonstrating the need for a full inelastic creep analysis. The fatigue damage was not affected by the drop in peak stresses, as the stress range remained the same, due to a reversal of the stress state on shut-down. These maxima did not necessarily occur at the same place in the blade, and this is shown in Fig. 4, where the creep damage w_c (SDV3) was contained mainly near the hottest portions of the blade. The fatigue damage w_f was very localised at the peak stresses near the interfaces between the blade and the end plates, on the leading and trailing edges. This was also the position of maximum total damage w_{tot}, and coincided with observations made on real blades in service. Figure 5 shows a contour plot of w_{tot} (SDV6), and both the creep and fatigue damage areas are visible.

CONCLUSIONS

A fatigue–creep damage model has been implemented into a general-purpose finite element code without resorting to costly and limiting software. The implementation is flexible and provides first estimates of the effects of design or operating point changes on the life of a component. Complex three-dimensional shapes can be assessed, and contour plots and damage history graphs are easily obtained using the standard post-processor, providing the designer with quick initial estimates of failure modes and times to crack initiation, and where they can be expected to occur.

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