



# Investigation of Creep Behavior of a Gas Turbine Bode with a Visco Plastic FEM Model to Estimate the Blade Life

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ARTICLE INFO	ABSTRACT
<p>Article History:            Received 11 May 2024            Received in revised form 13 July 2024            Accepted 14 September 2024            Available online 18 September 2024</p>	<p>Creep deformation is a major failure mechanism in turbine blades operating under high-temperature and high-stress conditions over extended periods. Traditional approaches to estimating the service life of turbine blades such as the Larson-Miller Parameter (LMP) method rely on simplified assumptions and offer only approximate predictions, which may not adequately reflect the complex time-dependent behavior of materials. In this study, a more accurate and physically realistic methodology is proposed using finite element (FE) analysis based on time-dependent plasticity to simulate creep in turbine blades. Three different constitutive models accounting for creep deformation are employed to evaluate their effectiveness in predicting the blade's lifespan. The turbine blade is assumed to be composed of Inconel 738LC, a cast nickel-based superalloy widely used in aerospace and power generation applications due to its high-temperature strength and corrosion resistance. The simulation results are benchmarked against experimental creep data and compared to predictions obtained using the LMP method. The findings demonstrate that the proposed time-dependent plastic models provide a significantly improved prediction of creep life, showing a longer service duration compared to those estimated by conventional elastic stress analysis and the LMP approach. This modeling framework offers a more robust and accurate tool for the design and durability assessment of critical turbine components.</p>
<p>Keywords:            Visco Plastic, FEM, Creep,            Turbine Blade, Blade Life Time</p>	

## 1. INTRODUCTION

In contemporary mechanical engineering, the analysis of creep behavior in structural components is of paramount importance, particularly in applications where components are exposed to high temperatures and mechanical loads. Achieving high thermodynamic efficiency especially in power generation and petrochemical industries requires critical parts to endure prolonged exposure to elevated temperatures and stresses. Under such conditions, many engineering materials exhibit creep deformation, which can significantly affect component lifespan.

Turbine blades, especially those used in gas and steam turbines, are among the most critical components operating under creep-dominated conditions. Gas turbines play a vital role across various industrial sectors [1], and given the

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considerable cost associated with their design, manufacturing, and maintenance, accurately predicting blade failure before catastrophic breakdown is essential. Turbine blades are subjected to complex loading conditions, including high rotational (centrifugal) forces, thermal gradients, low-amplitude vibrations, and thermal fatigue. To mitigate these challenges, blades are typically manufactured using advanced materials, most notably nickel-based superalloys, which offer superior resistance to combined mechanical and thermal stresses [2].

It is also important to recognize that the failure of a single blade can trigger a chain reaction, leading to the failure of other components. Therefore, comprehensive failure analysis must incorporate both mechanical and metallurgical investigations. While some researchers have focused solely on the mechanical behavior of turbine blades using elastic static and dynamic analyses to determine critical stress regions, others have taken a metallurgical approach to assess damage mechanisms and estimate remaining life.

Several factors contribute to the degradation of turbine blades, including:

1. Harsh physical environments (e.g., high temperatures, fuel/air contamination, and particulate erosion);
2. Severe mechanical stresses (e.g., centrifugal and vibratory loads);
3. Significant thermal stresses resulting from steep thermal gradients [3, 4].

Often, the simultaneous presence of these conditions accelerates blade deterioration. Historically, Baily pioneered stress analysis under creep conditions in the 1930s. Further advancements occurred by the late 1950s, as detailed in the foundational work of Finnie and Heller [5].

Given the high cost of turbine blade replacement estimated at over \$10,000 per blade, and more than \$1,000,000 for an entire stage accurate life prediction is economically crucial. This is especially true for first-stage blades, which operate under the most severe thermal and mechanical loads and are thus most prone to premature failure [6].

The use of Larson Miller Parameter is a usual way for estimating lifetime of turbine blades. The Larson Miller Parameter,  $P_{LM}$ , is one of the creep extrapolate parameters of experimental tests in which temperature and time effects are considered. Larson Miller Parameter is an important part in uniaxial stress test. However, it has some restrictions. The Larson Miller Parameter can be stated as

$$P_{LM}(\sigma) = \frac{\Delta H}{2.3R} = T(C + \log t_r) \tag{1}$$

Where  $\Delta H$  is activation energy;  $C$  is Larson Miller constant, where is equal to 20 for more metals.  $R$  is Universal gas content,  $T$  is temperature and  $t_r$  is rupture time.

In Larson Miller method, the effect of changing physical structure during creep time is not considered. Because of micro structure exchange in blade alloy after long time at high temperature, real reached life will be different from estimated life. It is necessary to determine  $C$  for each material and each time period.

It is desirable to design parts for high temperature conditions with acceptable accuracy. The elastic analysis and simple design methods which are based on tables and empirical formulations are not accurate sufficiently for the new requirements arise in the design of high temperature parts. Therefore, in this paper, using ANSYS software, a more accurate approach based on finite element modeling is employed to investigate the creep behavior of turbine blades.

## **2. CREEP MECHANISMS**

Generally, creep is a time-dependent plastic deformation under a fixed stress at temperatures of roughly  $0.3-0.5T_m$ , where  $T_m$  is the melting temperature. Plastic theories can be divided in two groups: time-dependent and time-independent. In time-independent theories the increment of strain tensor is related to stress tensor through a flow rule. While, in time-dependent theories, material flow rule is a function of time and the strain rate tensor is related to stress tensor [1].

The standard creep curve has been shown in Fig.1. According to Fig.1, after the instantaneous elastic strain, there are three creep stages: a decelerating strain rate stage I (primary creep), a steady minimum strain rate stage II (secondary creep) and an accelerating strain rate stage III (tertiary creep) [7].

The main reason of creep fracture is nucleation, growth and coalescence of voids along the grain boundaries. The nucleation and growth of voids reduce the load bearing section and accelerate the creep damage and this, in turn, increases the void growth rate. When the voids grow from an initial size to half the mean cavity spacing, the coalescence of voids occurs, as shown in Fig. 2.

Studies have shown that the nucleation of cavities usually occurs during the creep stage I and II. Their growth and coalescence lead to the creep stage III when creep rupture occurs because of a significant increase of net section stress resulting from the decrease of the load bearing section [7].

In this paper the ANSYS software is used to generate a finite element model of turbine blades based on time-dependent inelastic behaviors. Three different inelastic models considered to analyze a turbine blade and estimate its life.

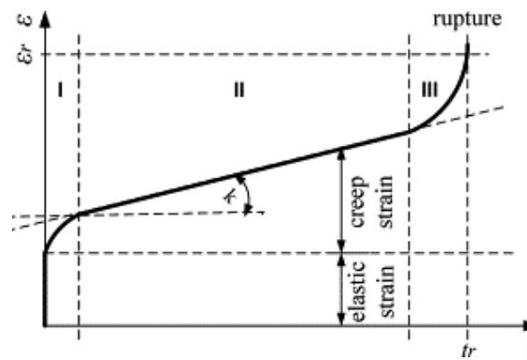


Fig1. Standard creep curve

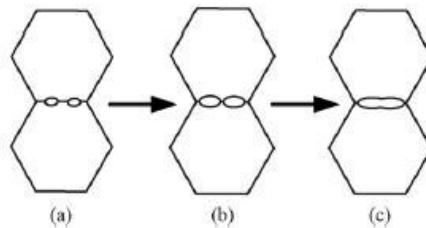


Fig 2. The process of creep cavity growth: (a) nucleation, (b) growth, (c) coalescence

### 3. ANAND'S VISCOPLASTIC MODEL

According to the Anand's viscoplastic model, the plastic strain rate  $d^p$  relates to stress and temperature through the following equations.

$$\begin{aligned}
 d^p &= Ae^{\frac{Q}{R\theta}} \left[ \text{Sinh} \left\{ \xi \frac{\sigma}{S} \right\} \right]^{\frac{1}{m}} \\
 \dot{s} &= \left\{ h_0 (|B|)^a \frac{B}{|B|} \right\} d^p \\
 B &= 1 - \frac{S}{S^*}, S^* = S^{\wedge} \left[ \frac{d^p}{A} e^{\frac{Q}{R\theta}} \right]^n
 \end{aligned}
 \tag{2}$$

The parameters introduced in the above equations are defined in Table 1. In the ANSYS software three elements of Visco106, 107 and 108 have the capability to simulate the material behavior according to the Anand's model [8]. For the material considered in this paper, i.e., Inconel 738LC, the nine constants of the Anand's model were determined experimentally in Razi research center in Tehran. The values of these constants are presented in Table 2.

**Table 1.** parameters of Anand model

$d^p$	effective inelastic deformation rate
$\sigma$	effective Cauchy stress, Mpa
$s$	deformation resistance, Mpa
$s^*$	saturation value of deformation resistance, Mpa
$\dot{s}$	time derivative of deformation resistance
$\theta$	absolute temperature, K
$n$	strain rate sensitivity of saturation (deformation resistance) value, dimensionless
$R$	universal gas content
$a$	strain rate sensitivity of hardening or softening, dimless
$Q$	activation energy, kj/mol
$A$	pre-exponential factor, 1/time
$m$	strain rate sensitivity of stress, dimensionless
$\xi$	multiplier of stress, dimless
$s^\wedge$	coefficient for deformation resistance saturation value, Mpa
$h_0$	hardening/softening constant, Mpa

**Table 2.** 9 coefficients obtained from Razi research center

$S_0 = 66.1\text{mpa}$	Initial value of deformation resistance
$Q/R = 37.56$	activation energy/ universal gas content
$A = 2.284e15\text{hr}^{-1}$	pre-exponential factor
$x_i = 3.25$	multiplier of stress
$m = 0.1956$	strain rate sensitivity of stress
$h_0 = 3093.1\text{mpa}$	hardening/softening constant
$s^\wedge = 125.1\text{mpa}$	coefficient for deformation resistance saturation value.
$n = 0.06869$	strain rate sensitivity of saturation (deformation resistance) value
$a = 1.5$	strain rate sensitivity of hardening or softening

#### 4. PERZINA MODEL

Based on Perzina model the relation between the current state of stress with the time rate of change of plastic strain can be written as

$$\sigma = [1 + (\frac{\dot{\epsilon}^{pl}}{\gamma})^m] \sigma_0 \tag{3}$$

Where  $\sigma_0$  is the yield stress of material;  $\dot{\epsilon}^{pl}$  is plastic strain rate;  $m$  is equivalent strain hardening parameter and  $\gamma$  is viscosity parameter.

In ANSYS program, Perzina model are available for some elements including link 180; shell 181; plane 182,183; Beam 188,189; solid 185, 186, 187.

When  $\gamma$  converge to  $\infty$  or  $m$  converge to zero or  $\epsilon^{pl}$  converge to zero, the problem exchange to time-independent plasticity [8].

For steel and Nickel alloys values of  $\gamma = 1$  and  $m = 0.5$  are replaced for viscosity and strain hardening parameters respectively.

## 5. EXPONENTIAL RELATION FOR SECONDARY CREEP

In this model an exponential relation has been proposed for creep strain of stage II (secondary creep) in terms of stress and temperature [8]:

$$\dot{\epsilon}_c = C_1 e^{\sigma/C_2} e^{-C_3/T}, C_1 > 0 \quad (4)$$

Where  $C_1, C_2$  and  $C_3$  (or  $Q/R$ ) are constants.  $Q$  is activation energy for IN738LC at  $1400^{\circ}C$  which its value is  $620kj/kmol$ ;  $R$  is Boltzman constant and is  $8.314j/kmol^{\circ}K$ ; and the values of  $C_1, C_2, C_3$  are

$$\begin{aligned} C_1 &= 1.0272 \times 10^{18} s^{-1} \\ C_2 &= 4 \times 10^7 Pa \\ C_3 &= 74573.009K \end{aligned} \quad (5)$$

## 6. LOADING AND STRESSES ON GAS TURBINE BLADES

Due to the high rotational speed of turbine rotors, significant **centrifugal forces** are exerted on each blade. While at lower temperatures these forces may not substantially affect blade integrity, under conditions of elevated temperature and high rotational speed two key factors influencing creep blades are prone to time-dependent elongation caused by creep deformation.

In general, turbine blades are subjected to four major sources of stress:

1. Axial centrifugal stresses, which arise from the mass of the blade rotating around the turbine axis;
2. Bending stresses induced by centrifugal forces, especially in blades with non-uniform geometry;
3. Bending stresses due to pressure differentials between the pressure and suction surfaces of the blade, resulting from aerodynamic loading;
4. Thermal stresses, generated by steep temperature gradients along the blade during operation.

These stress components interact and, when combined with high-temperature exposure, significantly accelerate material degradation and creep strain accumulation. In particular, centrifugal forces become critical in blades with long spans or varying cross-sections, such as conical blades.

For turbine blades with a conical cross-sectional profile, the uniform centrifugal stress at the blade root can be calculated using classical mechanics formulas, which account for blade geometry, material density, and angular velocity. Accurate estimation of this stress is essential for assessing creep damage and predicting blade life under operational conditions.

$$\sigma_c = (2\pi\rho N^2 A_n)K, A_n = \pi(r_t^2 - r_h^2) \quad (6)$$

Where  $\rho$  is blade density;  $r_h$  is rotor radius;  $r_t$  is blade tip radius;  $N$  ( $rev/sec$ ) is rotational speed of turbine rotor,  $A_n$  is cross sectional area and  $K$  is conical factor [9].

In addition to centrifugal stresses, a turbine blade is faced to bending stresses due to fluid pressure. According to Fig.3 the bending stress due to pressure may be written as:

$$\sigma_B = \frac{x}{I_{yy}} [M_\theta \cos \phi - M_a \sin \phi] - \frac{y}{I_{yy}} [M_a \cos \phi + M_\theta \sin \phi] \tag{7}$$

## 7. NUMERICAL EXAMPLE

A gas turbine blade with a mass of 3 kg and the geometry illustrated in Figures 4 and 5 was selected for the numerical analysis. The blade is made of Inconel 738LC, a cast nickel-based superalloy, whose mechanical properties are provided in Tables 3 and 4, as well as in Figures 6 and 7. Under peak operating conditions typical of gas turbine engines, the temperature of combustion gases in contact with the blade airfoil can reach up to 1400 °C, particularly on the leading edge [3, 4]. For this study, the temperature-dependent mechanical properties of the material, such as tensile yield strength and Young’s modulus, were considered at 1400 °C [9].

The influence of centrifugal forces was included in the analysis for each specified rotational speed. Additionally, the pressure differential between the pressure and suction surfaces of the blade arising from the pressure drop between the first and second turbine stages was modeled as a distributed load acting on the inner side of the blade.

The finite element (FE) model, shown in Figure 8, consists of 4,228 elements and 6,224 nodes. The model employs 3D 8-node viscoelastic elements capable of handling viscoplastic and creep behavior.

Based on the aforementioned conditions, the following loading and boundary conditions were applied:

- A uniform operational temperature of 1400 °C across the entire blade.
- Radial centrifugal forces, dependent on blade rotational speed.
- A uniform internal pressure of 11 kPa, calculated based on:

$$P = \frac{1400}{36} \times 0.3 = 11kpa$$

where 1400 kPa is the total pressure, the number of first-stage blades is 36, and the pressure drop across the first stage is 30% [10].

- A clamped boundary condition applied at the blade root, preventing displacement.

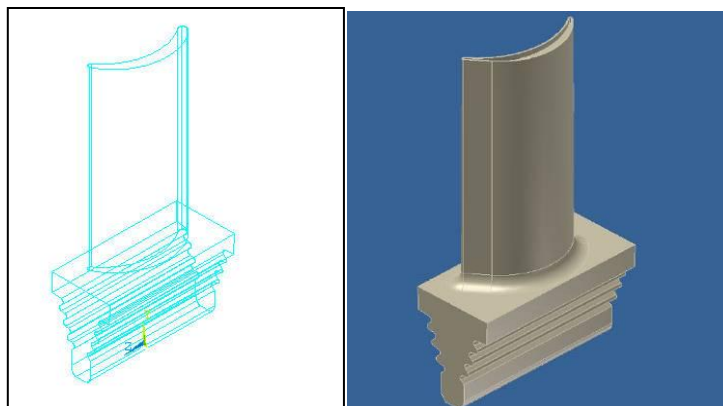
This modeling approach enables a comprehensive evaluation of the blade’s structural response under realistic operational loads, including temperature-induced creep and centrifugal effects.

**Table 3.** material properties of turbine alloys at ambient temperature

Component	Material	Mass density (kg/m <sup>3</sup> )	Tensile yield strength (Pa)	Tensile ultimate strength (Pa)
Bucket	IN-738LC	8110	9.5 × 10 <sup>8</sup>	1.1 × 10 <sup>9</sup>
Disc	A471-CI10	7800	6.2 × 10 <sup>8</sup>	7.25 × 10 <sup>8</sup>

**Table 4.** Mechanical Properties of IN738LC

Temperature (C)	Poisson`s Ratio	Young`s `Modulus
22	0.34	212
100	0.33	208
150	0.33	205
200	0.34	203
250	0.34	201
300	0.35	199
350	0.34	196
400	0.34	194
450	0.32	191
500	0.32	188
550	0.33	185
600	0.34	183
650	0.33	179
700	0.31	178
750	0.31	177
800	0.33	176
850	0.33	176
900	0.33	176
950	0.31	176
1000	0.31	175
1050	0.31	175
1100	0.3	175
1150	0.3	175
1200	0.3	175
1250	0.3	175
1300	0.3	175
1350	0.3	175
1400	0.3	175



**Fig 4.** Blade model in Autodesk Inventor soft ware

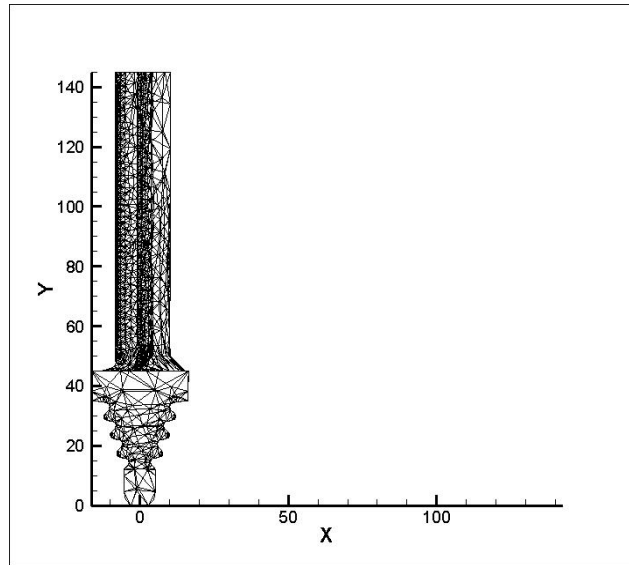


Fig 5. Blade Model Dimension (mm)

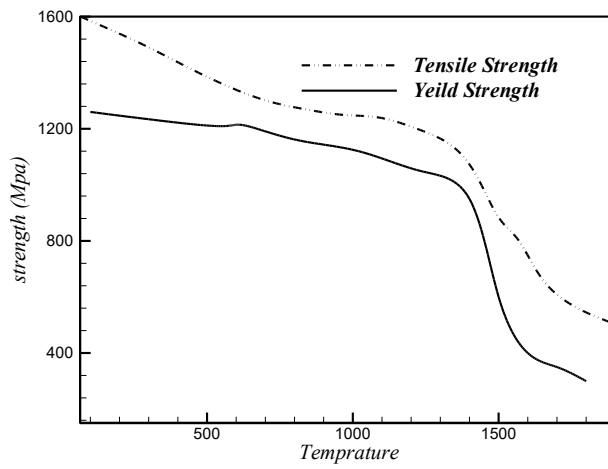


Fig. 6. IN738LC mechanical properties

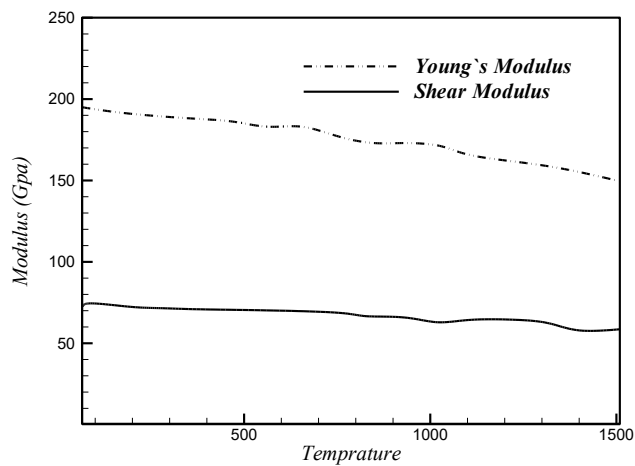


Fig 7. IN738LC Modulus

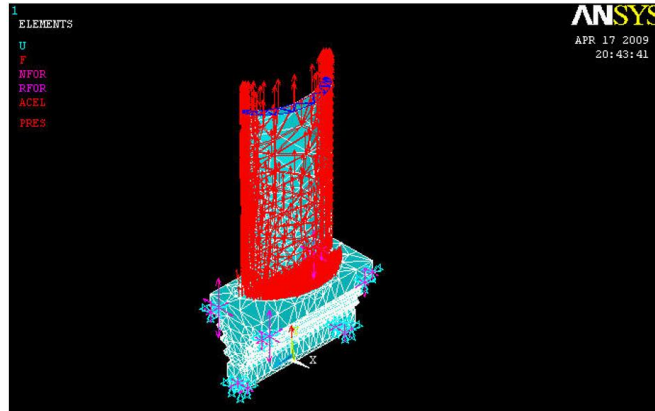


Fig. 8. Meshing model in Ansys and impose boundary conditions

### 7.1. Estimating Blade Life Using the Larson-Miller Parameter

To estimate the operational life of the turbine blade, the critical stress values were first determined through stress analyses at various rotational speeds, under the loading conditions described earlier. These critical stresses were computed based on two different material behavior assumptions: (1) elastic deformation, and (2) creep deformation [11]. Representative stress distributions resulting from these analyses are illustrated in Figures 9 and 10.

For the IN738LC nickel-based superalloy, the constant C in the Larson-Miller Parameter (LMP) relation is taken as 16.59, which is suitable for the range of calculated stress values. The variation of the LMP with respect to stress for IN738LC is presented in Figure 11.

By using the critical stresses obtained from both elastic and creep analyses (as shown in Figures 9 and 10), the corresponding Larson-Miller Parameter values ( $P_{LM}$ ) can be extracted from the LMP-stress curve in Figure 11. These values are then substituted into the Larson-Miller equation:

$$P_{LM} = T(C + \log_{10} t) \quad (8)$$

to estimate the blade lifetime (t) for each rotational speed, where T is the absolute temperature (in Kelvin), and C = 16.59.

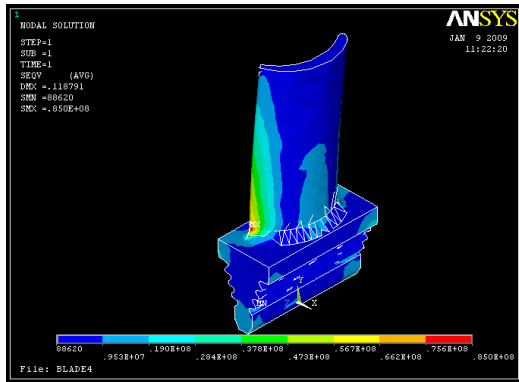
For instance, at a rotational speed of 3000 rpm, the procedure yields the following result: (The specific calculation should follow this sentence if numerical data or results are to be included.)

$$\begin{aligned} rpm = 3000 \rightarrow \sigma_{elastic} = 85\text{mpa} \rightarrow P = 24.2 &= (850 + 273.15) \times (16.59 + \log t_r) * 10^{-3} \Rightarrow \\ t_{r_{elastic}} &= 82,000\text{hr} \\ \rightarrow \sigma_{creep} = 78\text{mpa} \rightarrow P = 24.3 &= (850 + 273.15) \times (16.59 + \log t_r) * 10^{-3} \Rightarrow \\ t_{r_{creep}} &= 100,000\text{hr} \end{aligned} \quad (9)$$

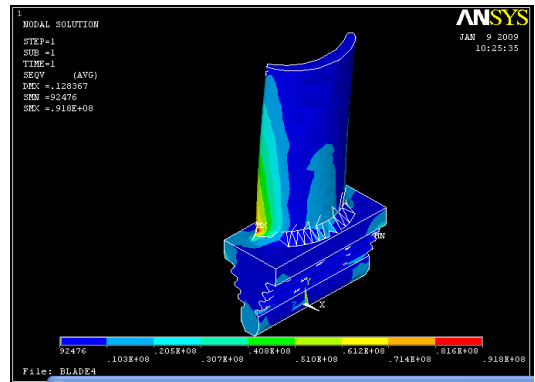
The results for the other blade speeds are presented in Table 5.

Table 5. Results of Larson Miller Life

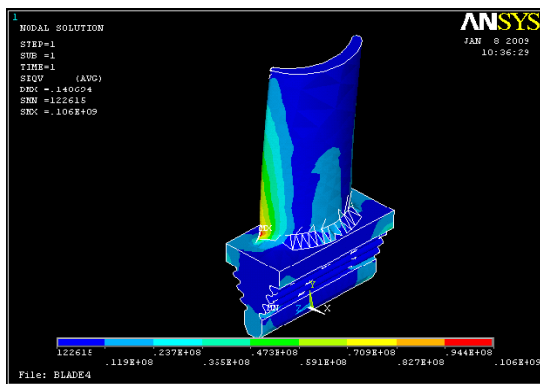
N(rpm)	Elastic stress (mpa)	Creep stress (mpa)	$t_{r_{elastic}}$ (hr)	$t_{r_{creep}}$ (hr)
3000	85	78	82,000	100,000
4000	92	85	73,000	82,000
5000	106	96	49,000	60,000
6000	166	110	22,000	30,000



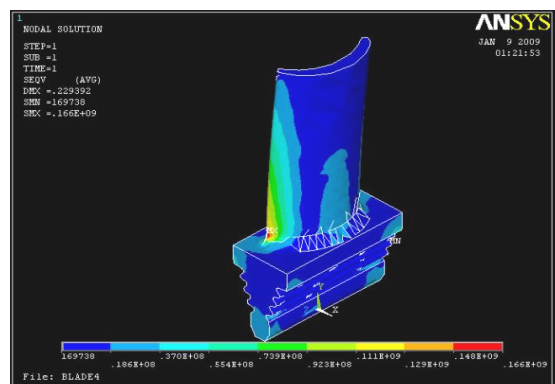
(a)



(b)

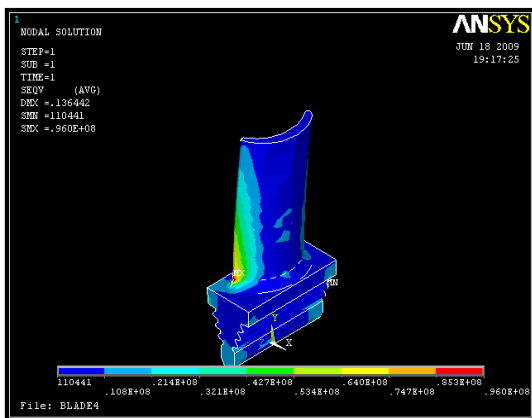


(c)

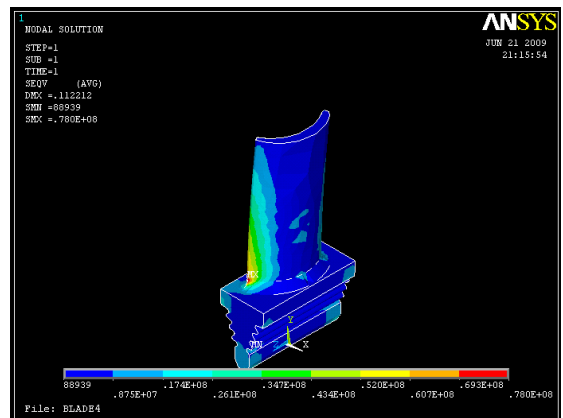


(d)

Fig. 9. Elastic stress at (a) 3000 rpm (b) 4000 rpm (c) 5000 rpm (d) 6000 rpm



(a)



(b)

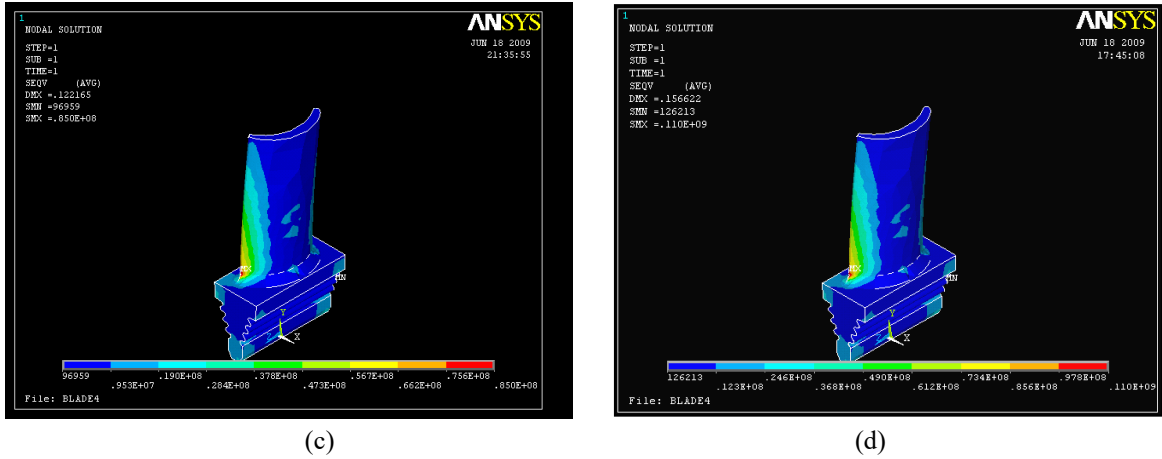


Fig. 10. Creep stress at (a) 3000 rpm (b) 4000 rpm (c) 5000 rpm (d) 6000 rpm

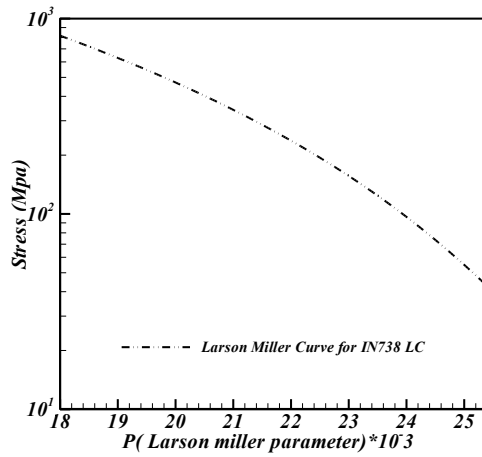


Fig. 11. Larson miller curve for IN738LC supper alloy

## 7.2. Results from the Finite Element Model Based on Time-Dependent Plastic Behavior

Figure 12 illustrates the contour plot of blade elongation obtained using the Anand viscoplastic model at a rotational speed of 5000 rpm. According to the simulation results, the maximum elongation at this speed reaches approximately 0.0062 cm after 66,000 hours of operation. This value corresponds to the maximum allowable elongation specified in the turbine’s application manual, thereby indicating that 66,000 hours can be considered the effective operational life of the blade. This result is also reported in Table 6 [10].

Table 6. blade effective life time

Software Results	Allowable elongation of first stage blade
66000 hr	0.062 mm

Figure 13 presents a comparison of the predicted blade lifetime based on the Anand model with those estimated using the Larson-Miller creep model and the conventional elastic analysis. The comparison reveals that the Anand model provides a more comprehensive and realistic estimate under high-temperature conditions.

Figure 14 demonstrates the predicted elongation of the turbine blade at various rotational speeds after 66,000 hours, using three models: Anand, Perzyna, and an exponential secondary creep model. Furthermore, Figure 15 depicts the standard creep test curve of the blade material, showing strong correlation with the curve derived from the Anand model simulation.

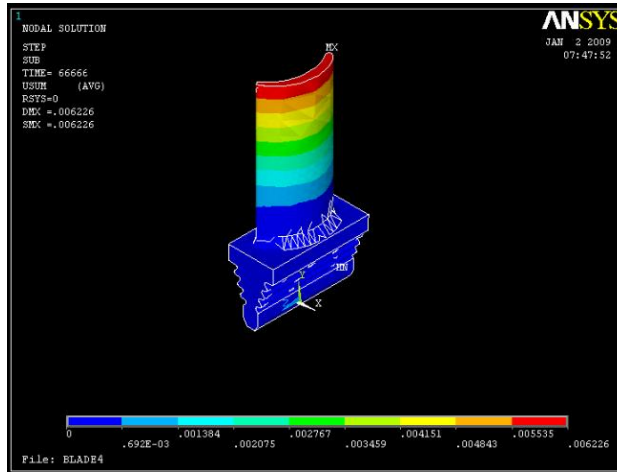


Fig. 12. ANAND elongation at 5000 rpm

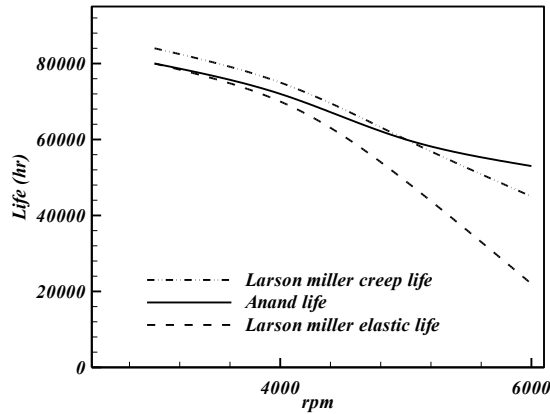


Fig. 13. Comparing Anand results with Larson Miller and elastic life

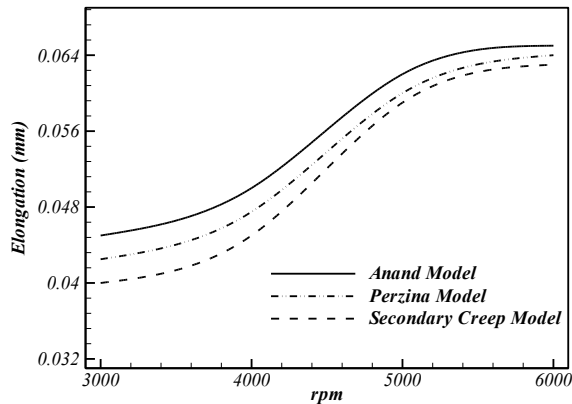


Fig. 14. blade elongation based on Anand , Secondary creep and Perzina

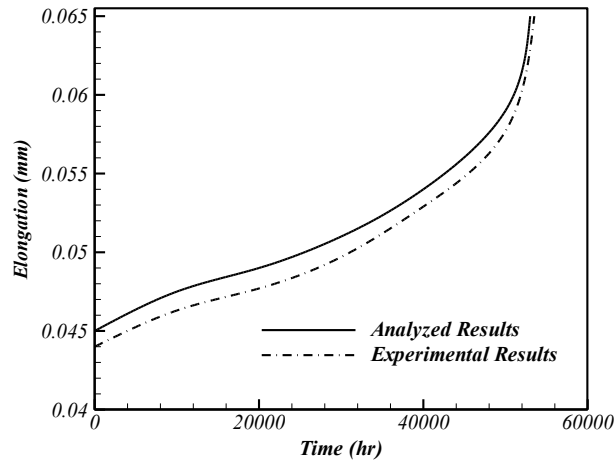


Fig. 15. Comparing Analyzed Creep curve with creep tests by 160 MPa stress

## 8. CONCLUSIONS

Gas turbine blades operate under extreme thermal and mechanical stresses, making them particularly susceptible to creep deformation over prolonged periods. Creep is therefore recognized as a critical failure mechanism in turbine blades, and accurate prediction of creep behavior and lifetime is essential for reliability and cost-effective maintenance planning.

While the Larson-Miller Parameter (LMP) remains a widely used empirical method for estimating creep life, it lacks the precision required for modern engineering analysis. In the present study, finite element (FE) simulations incorporating time-dependent plasticity were conducted to assess the creep behavior of a turbine blade made from Inconel 738LC. Three viscoplastic models were employed: the Anand model, the Perzyna model, and an exponential secondary creep model.

The results indicate that the Anand and Perzyna models provide reliable and accurate predictions of the blade's creep response. The elongation profiles generated by these models showed close agreement with experimental data obtained from standard creep tests. Furthermore, the blade life estimated by the Anand model was longer than that predicted by the Larson-Miller method and aligned more closely with the empirical data provided in the turbine's technical documentation.

Overall, the findings underscore the advantages of using advanced viscoplastic finite element modeling approaches, particularly the Anand model, for accurately predicting the long-term performance and lifespan of gas turbine blades under service conditions.

### Declaration

We acknowledge that we used ChatGPT to enhance the academic writing of our manuscript while ensuring the originality and integrity of our work.

### Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

### Acknowledgments

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## **Declaration of Interest**

The authors declare that they have no competing interests.

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