A review on damage modelling under creep deformation

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## ABSTRACT

This study focuses on the enhancement of the creep crack growth model to improve the accuracy of predicting the lifespan of various components utilized in different industrial sectors. Different creep crack growth models have been developed to enhance the accuracy and reliability of predicting outcomes, while also ensuring experimental validation. Scientists and engineers are actively engaged in the pursuit of developing a novel model that integrates continuum damage-based and finite element method (FEM) analysis-based models. The objective of this review article is to present fundamental concepts pertaining to various stress-based, strain-based, and finite element method (FEM)-based models.

Keywords- stress-based damage model, creep crack growth, finite element analysis, stress-based damage model, strain-based damage model.

## I. INTRODUCTION

 Many components operating at high temperatures in industrial applications, such as the nuclear, thermal power, and aerospace industries, play a crucial role [1]. Predicting the lifespan of these components is essential for their smooth functioning [2] When components operate at elevated temperatures, there's a likelihood of diffusion and cavity formation, which can ultimately result in cracks forming within the component [3]. In the event of a crack being present while the system operates at high temperatures, understanding the phenomenon of creep crack growth becomes imperative.

The creep crack growth test often creates a correlation between the creep strain exhibited by the specimen and the corresponding period, similar to a traditional creep test. Figure 1 depicts the deformation resulting from creep. The process of creep crack growth can be categorized into various distinct stages. The primary stage is characterized by a gradual increase in creep strain attributed to the strain-hardening effect. Following this, the subsequent phase arises, in which a state of equilibrium is achieved between strain hardening and thermal softening, leading to a constant rate of strain. Subsequently, the tertiary stage results, displaying a persistent increase in the amount of strain. Finally, the tertiary stage follows, exhibiting a continuous acceleration in strain rate [4].

To understand the durability of components under creep and creep crack growth conditions, it is important to analyze how they behave during the final (tertiary) stage of creep. Continuum damage mechanics is commonly utilized in order to model the occurrence of material creep damage and provide a comprehensive understanding of the properties exhibited during tertiary creep and help to predict the life of component.

In the creep crack growth Study of an analytical model was proposed for the analysis of stress and strain field in the initiation of sharp crack and growing crack under steady state condition is happen due to accumulation of creep strain in process zone ahead of crack in creeping material [5]. The creep damage model can be classified stress-based creep damage model and strain-based damage model [6]. Some of the creep damage modelling is based on the Finite element analysis like the node release technique [7]. Where the crack growth is simulated with the experimental data by making different steps with help of ABAQUS software.

## **Figure 1: Creep strain versus time**

The objective of this article is to provide a comprehensive overview of damage models used in the creep crack growth simulation. These models are mostly based on finite element analysis and employ stress and strain-based damage modeling techniques. The intention is to enhance the foundation of damage modeling in the context of creep crack growth.

## II. DAMAGE MODEL BASED ON STRESS

Multiaxial creep approach is the foundation of stress-based creep damage models, some of the stress-based model are following type.

**A. Kachanov-Rabotnov Damage Model**

The Kachanov-Rabotnov damage model is a well-known and widely used approach in the field of materials science and fracture mechanics for creep and creep crack growth. Stress based multiaxial approach form of the Kachanov model is given [8,9].

 (1)

where,

The symbol represents the multi-axial creep strain components, Sij represents the components of deviatoric stress and the symbol eq represents the Mises equivalent stress.

 (2)

=damage parameter where 0<<1

 no damage, failure

where,

 = (3)

Here, α represents a material constant that characterizes the influence of the material's response to a multi-axial stress condition. = 0 means equivalent stress dominant and = 1 means maximum principal stress dominant. Precise estimation of value holds significance in utilizing the multi-axial Kachanov-Rabotnov damage model effectively.

 By integration of equation 2 in limit to 1

 (4)

For uniaxial creep from equation 1

 (5)

Uniaxial creep versus time relation

 (6)

A,n, are material constants and these values are different for different materials which is shown in Table 1. The calculation procedure for these constants is explained in subsequent sections.

**Calculation of A and n Value**

Norton’s power law

 =A (7)

where represents the lowest creep strain rate, while 'A' and 'n' are constants specific to the material, describes the creep constitutive relation for secondary stage or power law creep deformation. In the logarithmic form as,

 ) =log (A) +n log ( (8)

the values of the material constants A and n are obtained through the utilization of a log-log plot, which involves plotting the experimental logarithm of minimum creep strain rate against the log of applied stress. The 'n' value is determined from the slope, and the intercept provides the value for 'A'.

**Calculation of and M**

The uniaxial failure time (tf) is determined by the following expression

 tf = (9)

where, m and are material constants determined by plotting of log(tf) against log(

 ) =-log (M) - log ( (10)

The slope of the line of the best fit is - and the intercept is -log (M).

**Calculation of B, and m**

 In equation (6) B and are material constants and are related as,

 M= B (1+ φ) (11)

The material constant φ can be determined through the process of fitting a collection of uniaxial creep curves, which are computed using equation (6), to the experimental creep curves data obtained at various values of φ. It is important to note that all other material constants remain unchanged during this procedure. The φ The value that provides the most optimal match is subsequently selected as the accurate value. B, φ, and γ are material constants that govern the characteristics of tertiary creep behaviour. Equation (4), which is created by integrating equation (2), is useful for calculating the creep failure time. The material constants γ and B(1+ φ) can be determined by analysing the plot on a logarithmic scale showing the relationship between the duration until creep failure and the applied stress. Additionally, the values of B and value of φ that provide the best match for predicting creep failure time with minimal deviation can be determined through a trial-and-error approach [11].

First, until the right value of is found, the material constant m is set to zero. Then, to improve the fitting, the m value is significantly altered while the is kept constant. When the m value is modified within a very short range, it is discovered that the fitting does not improve.

The Kachanov-Rabotnov damage model is a constitutive model used to describe the evolution of damage in materials under mechanical loading. In this model, stress is measured in MPa and time is measured in hours. Different Material constant values of Kachanov and rabotnov model of SS316LN stainless steel , Nickel base alloy,P91 steel etc are given in table no.1.

## Table 1: Different material constant values of the damage model developed by Kachanov and Rabotnov

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Material | Temp (oC) |  A |  B | n | m |  |  |  |
| 316 stainless steel[10,11] | 550 | 1.383× 10-5 | 2.774 ×10-3 | 1.737 | -0.94 | 0.75 | 1.914 | 0.478 |
| Nickel–base alloy[12] | 700 | 2.355 × 10-43   | 1.907×10-41   | 14.205  |  0 | 0.15 | 13 |  13.49 |
| P91 steel[13] | 650 | 1.092×10-20  | 3.53×10-17  | 8.462 | -0.000475  | 0.215 | 7.34 |  6.78 |
| 1/2Cr1/2Mo1/4V steel[14] | 565 | 2.853 × 10-16  | 1.452 × 10-10  | 4.897 | -0.203  | 0.5955  | 5.414  | 3.011 |
| Titanium alloy [15] | 650 | 5.623×10-18  | 1.92×10-16  | 5.911 | 0 | 0 | 4.8 | 5.416 |
| Inco718 Alloy[16] | 620 | 2.306×10-60  | 4.0×10-42 | 18.97  | 0 | 0.3 | 7.0 | 13.105 |

**B. Liu and Murakami creep damage mode**

The localization of damage is significantly influenced by the sensitivity of stress in the Kachanov-Rabotnov creep model, as it is closely linked to the sequential development `of damage. In order to address this particular difficulty and get an accurate depiction of the development of damage caused by creep crack propagation, Liu and Murakami proposed a model. This damage model has been developed to avoid the extremely high damage, and consequently, strain, rates that occur for the Kachanov model as approaches unity (these can cause convergence issues in FE creep calculations) [17].

The multi-axial expression of the creep damage law proposed by Liu and Murakami is stated as follows

 (12)

n (13)

The value of failure stress exhibits a similar mathematical shape as observed in the Kachnov-Rabonov model, which may be determined using Equation (3). The material constants A, M, n, q, and x can be determined using the process of curve fitting applied to the uniaxial creep curves.

The Liu-Murakami creep damage model incorporates several constant values for the material constants, with stress measured in megapascals (MPa) and time measured in hours. The damage parameter follows the following relation as,

 (14)

## Where, was calculated from equation (8). The strain increment then can be calculated as,

 (15)

## **Calculation of q value**

In the Liu/Murakami model, q is a material constant that is used to calculate the damage, for more information, see equation (14). By fitting the suitable experimental curves to the creep strain curves, q may be calculated.   The creep strain curves are computed using equation (15) and fit to the experimental creep curves data. The "best fit" found is represented by the curves. Other material constant kept same during fitting process for q calculation.

Different material constant use in Liu-Murakami for SS316 steel and P91 steel are given in table 2.

Table 2. Different constant values for the Liu-Murakami creep and damage model's material constants.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Material | Temp (oC) | A | n | M |  |  |  |
| 316 stainless steel [18] | 600 | 1.47 × 10-29 | 10.147 | 2.73 × 10-30 | 10.949 | 0.478 | 6.35 |
| P91 steel[19] | 650 | 1.092 × 10-20 | 8.462 | 2.952 ×10-16 | 6.789 | 0.313 | 3.2 |

## Stainless steel grade 316 creep deformation was simulated by the application of Liu-Murakami [18].

## Liu and Murakami [17] performed a comparative analysis between the Kachanov-Rabotnov damage model versus the Liu-Murakami damage model. The research conducted revealed that the Liu-Murakami model exhibits mesh independence in close proximity to the crack tip. The aforementioned statement suggests that the use of this model leads to a substantial advancement in the localization of damage and reduces the dependence on numerical findings pertaining to the arrangement of the mesh. The assertions made in the preceding statement are reinforced by the findings of Hyde et al. [18, 19]. The research findings indicate that the utilization of the Liu and Murakami model of damage permits for analysis to be conducted within more feasible time periods, leading to comparatively reduced computing durations.

## III. STRAIN-BASED DAMAGE MODEL

Strain-based models utilized in the prediction of creep crack propagation or creep damage are based on the concept that the damage parameter tends to converge towards unity when the accumulated local creep strain surpasses a critical value associated with creep ductility. This category encompasses various models, such as the Spindler model and the Nikbin-Smith-Webster (NSW) model [20].

A. **Nikbin-Smith-Webster model of creep damage**

For steady-state conditions, a power law is applicable in creep

 (16)

The average creep rate value is directly calculated from the creep rupture data where all three stages, i.e., primary, secondary, and tertiary, are present.

 (17)

Failure strain

=Time of rupture

In the work of Liu and Murakami [19] is a multi-axial creep ductility that was derived from the mechanism of grain boundary cavitation.

 (18)

where h= , and σm and σeq are hydrostatic stress and equivalent stress, respectively. In the case of uniaxial creep, the h=1/3, putting in equation (18) obtained. This model shows a better correlation of the effect of the triaxiality on rupture life prediction of C-Mn steel [21]

Creep damage initiation occurs when the crack propagates and reaches the process zone, resulting in the presence of a damage gradient within the range of 0 < r <.Here is the creep process zone that is formed at the crack tip. The steady-state creep crack growth due to damage at the crack tip is determined using the following expression (equation19) [22].

 = (19)

In the value of taken as for plain stress conditions and for plain strain conditions, is equal toThe plane stress and plane strain NSW lines should collectively encompass the experimental Creep crack growth data. Equation (18) predicts that the creep crack growth rate in plane strain conditions is approximately 30 times greater than that in plane stress conditions for the equivalent value of C\* (additional effects of stress state on CCG rate are incorporated via the term "In" in Equation (18)).

= (20)

 is a parameter that depends on the creep exponent n. A broader expression can be derived to account for the variation of and with respect to the angle, θ. In such cases, the (NSW) model can be expanded to provide a revised crack growth rate, which we will refer to as the 'NSW-MOD model':

Different Material constant which use for different material for NSW mode is shown in Table .3.

Table .3 Different Material constants in NSW damage model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Material | T (oC) | A | (%) | n |
| 316H stainless steel[24] | 550 | 7.24x10-22 | 21 | 10.62 |
| P91 steel[25] | 600 | 1.22x10-35 | 30 | 14 |
| P92 steel[26] | 650 | 2.64x10-16 | 16 | 5.23 |

B. **Spindler damage model**

The accumulation of damage at the crack tip is directly correlated with the equivalent creep strain rate [23].

 (21)

The variable exhibits temporal variation as a result of the accumulation of creep strain, with an initial condition at t=0 where is equal to zero. Failure is observed at the specific location within the material when the ω =1.

 = (22)

To characterize the initiation of creep crack growth, a pragmatic model has been embraced to depict the influence of stress conditions on ductility, expressed as follows in equation (20)[27]. This is called Spindler damage model [28].

 (23)

In this context, we offer two novel material constants, namely p and q, which are utilized to characterize the reduction in ductility as stress triaxiality increases, as indicated by the equation mentioned above. The initial term in Equation (20) describes the process of cavity nucleation, while the subsequent term depicts the phenomenon of cavity growth by creep deformation. The utilization of Type 316 austenitic stainless steel involves the application of parameters p = 2.38 and q = 1.04, as stated in reference [29].

## IV. FINITE ELEMENT CREEP CRACK GROWTH MODEL

In this work ductility exhaustion methodology to consider the phenomenon of creep-induced damage accumulation. The damage parameter, denoted as, is defined within the range of 0 to 1, indicating that failure happens when approaches 1. The link between the rates of damage build-up denoted as, and the equivalent creep strain rate is established. This is explained in equation no (18).

M. Yatomi, et al. [30] investigated a 2-Dimentional finite element model of a compact tension specimen with dimensions W = 25 mm, B = 12.5 mm, and a/W = 0.45. Two different meshes have been used for the compact tension specimen in order to investigate the impact of mesh size. The study of significant displacements and rotations is conducted with thorough consideration, particularly in relation to factors such as the blunting of the crack point that was once sharp.

Two models have been proposed for crack propagation. The initial model, referred to as the ‘fixed-node model’, assumes that the fracture has undergone propagation after the damage, denoted as and calculated using equations (18), reaches a value of 1 at two integration sites located forward of the crack tip. When damage propagates within the specimen under same boundary conditions, identifies the precise location of the crack tip. 2nd model known as the ‘node-release model’ involves the release of the node located at the crack tip after approaches 1. Consequently, the crack propagation takes place across the mesh along the axis of symmetry.

The study revealed a superior agreement with the experimental data by the node-release model compared to the fixed-node model [30].

Therefore, the utilization of the nodal release technique fails to mitigate the influence of mesh size on crack growth estimations. The observed correlation between a decrease in mesh size and an increase in crack growth rate can be attributed to the heightened levels of stress and strain experienced in the immediate area of the crack tip when a finer mesh is utilized.

## V. SUMMARY

* Stress-based creep damage models involve the utilization of empirically derived models, for instance, the Kachanov-Rabotnov model of damage and the Liu-Murakami model of damage. These models aim to quantify the reduction in strength resulting from various degradation mechanisms by identifying a single empirical math parameter.
* Liu and Murakami compared two damage models: The kachanov-Rabotnov model and Liu-Murakami model. The findings demonstrated that the numerical analysis results obtained from the Liu-Murakami model of damage showed a damage delocalization effect, which does not get affected significantly by element size close proximity to crack tip. Also, it exhibits notable enhancements in terms of the localization of damage and the dependence of numerical consequences on the mesh. The Liu and Murakami damage model conducts analysis through more realistic time steps, resulting in comparatively reduced computation time.
* The study revealed that the node-release model has a superior consistency with the empirical evidence compared to the fixed-node damage model.

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