A MODIFIED WILSHIRE MODEL FOR CREEP DEFORMATION AND DAMAGE PREDICTION

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DEDICATION

Dedicated to God

"Ad maiorem Dei gloriam"

A MODIFIED WILSHIRE MODEL FOR CREEP DEFORMATION AND DAMAGE PREDICTION

by

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ABSTRACT

In this work, a new constitutive model, the WCS model, is derived that combines the Wilshire equations with continuum damage mechanics (CDM) for the long-term prediction of creep deformation, damage, and rupture. Long-term creep data is expensive and time-consuming to obtain because conventional creep testing is real-time. There is a need to extrapolate long-term creep behaviors from short-term data. Models that can accurately predict long-term creep behavior over a wide range of boundary conditions are vital for design engineers. The classic Wilshire equations can accurately extrapolate the long-term stress-rupture, minimum-creep-strain-rate, and time-to-strain of various alloys as their functional form has an explicit description of stress and temperature dependency. Recently, the time-to-creep-strain equation has been exploited to generate full creep deformation curves; however, with the addition of a CDM model, the equations become suitable for finite element analysis (FEA). The Sinh model can predict creep deformation, damage, and has been implemented into FEA software; however it lacks a description of temperature-dependence which limits the range in which predictions can be made. The combination of the Wilshire and the Sinh model enables stress-rupture, minimum-creep-strain-rate, creep deformation, and damage predictions with explicit stress and temperature dependency. In order to accomplish this goal; **(a)** the current Wilshire equations are evaluated for one material in in different forms and **(b)** the new CDM-based WCS model is developed and the realistic performance of the model is assessed. The WCS model predicts creep behaviors such as stress-rupture, minimum-creep-strain-rate, damage evolution, and creep deformation with an explicit stress and temperature gradients. The explicitness of the stress and temperature gradients across makes the model suitable for FEA software. Parametric studies are performed on the WCS model and is observed that the model behaves in a realistic manner.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Drives to increase the efficiency of Advance Ultrasupercritical (A-USC) and Fossil Energy (FE) power plants lead to designs with steam pressures up to 4000 psi and temperatures ranging $0.3T_m < T < 0.6T_m$, where T_m is the melting temperature of the specific material. The complexity in which these power plants operate, especially for the hot gas path in industrial gas turbines (IGTs) illustrated in Figure 1.1, pushes the limits of material science and the properties of materials [1]. Failure that occurs on IGTs turbine blades are caused by many phenomena such as fatigue and creep which are encounter at the extreme conditions that power plants operate [2-3]. Maintenance must be performed regularly to avoid catastrophic failure, as illustrated in the turbine blade of Figure 1.2, caused by creep and combined damage factors [4]. Maintenance costs are of the major concern in IGTs which inspections of hot gas path components occurring every 2 years and major inspections between 4 and 5 years [5]. Unexpected failures can emerge in the time interval in which inspections are made, due to the uncertainty and the continuum damage that creep generates. There is a need to predict these behaviors accurately to have a better maintenance interval and to avoid failures.

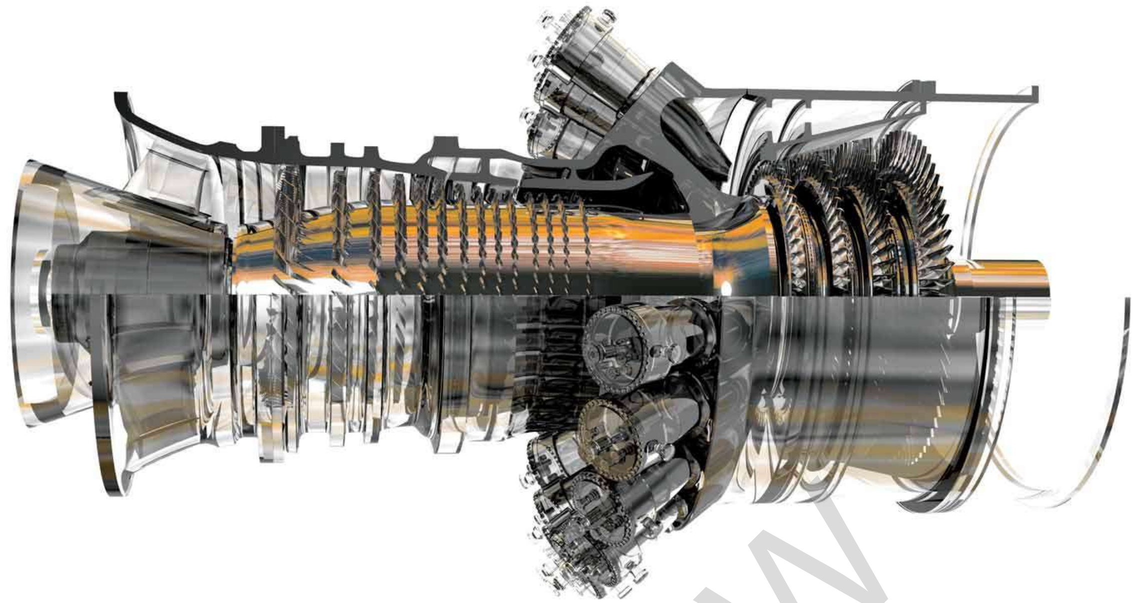

Figure 1.1 – GE H-Class 9HA.01/.02 Gas Turbine (50 Hz) (9HA.01 at 446 MW and the 9HA.02 at 571 MW) [5].

Figure 1.2 – Industrial gas turbine blade creep failure (Berkeley Research Company, Berkeley California) [4].

The current understanding and ability to predict long-term creep behaviors ($\geq 10^5$ hours) such as rupture time, minimum-creep-strain-rate (MCSR) and creep deformation curves, and damage is limited. Long-term creep is difficult to predict due to the lack of data at such extreme durations; where experiments must run continuously for greater than 10 years [6]. Over the years, an immense number of models have been developed as an alternative of conducting those long duration experiments. Numerous constitutive models have been developed to predict the creep deformation of materials; however extrapolations are not as accurate for some models and for others is impossible because of the complex dependence on stress and its parameters [6-8]. There is a need for reliable prediction methods with stress and temperature dependency to better extrapolate creep and damage behavior and to perform finite element simulations as well.

1.2 Research Objectives

The objective of this research study is to develop a continuum damage model (CDM) using the Wilshire equations, the WCS model, that can predict long-term creep deformation, damage, and rupture with explicit stress and temperature dependency. The goals are to **(a)** assess the current Wilshire laws, and **(b)** developed the novel CDM WCS model and validate the realistic performance of the model. To accomplish goal

(a) the Wilshire stress-rupture and minimum-creep-strain-rate (MCSR) equations predictive capabilities are assessed using short-term data ($<10^4$). The equations are calibrated to alloy P91 data in tube, plate and pipe form. Post-audit validation is performed using long-term data ($\geq 10^4$) and the normalized-mean-squared error (NMSE) is reported for each material isotherm and material form. Additionally, using the stress-rupture equation, contour design maps are created as tools for design engineers.

(b) the new WCS model is derived, where the Wilshire stress-rupture and MCSR equations are incorporated into the Sinh CDM model. Creep deformation data is collected for alloy P91 for a single isotherm and multiple stress levels and is fitted to the model. Material constants are obtained for the WCS model using the calibration approach from the Wilshire equations and the Sinh model. Using the material constants, plots for creep deformation and damage demonstrate the accuracy of the novel model. A parametric study is performed to assess the interpolation and extrapolation ability of the novel model.

1.3 Organization

The organization of this study is as follows: Chapter 2 provides background information on creep deformation and damage. Some constitutive models that have predicted different creep behaviors, such as MCSR and creep deformation, are discussed in a non-exhaustive manner. Chapter 3 introduces and describes the material used in each study providing mechanical properties and nominal chemical composition. Data is introduced in Chapter 3 and used in Chapter 4 for the application of the Wilshire equations, stress-rupture and MCSR, using alloy P91 tube, plate, and pipe form. The Wilshire equations are introduced in this chapter as well as the calibration approach. The model is then fitted, and post-audit validation is performed to vet the accuracy of the models. Chapter 5 introduces the novel WCS model for creep deformation and damage predictions. Material constants are obtained, and the model is calibrated to generate predictions. After the model is calibrated to the data, parametric simulations are performed to vet the performance of the model in realistic scenarios. Finally, Chapter 6 offers an overview of the results and conclusions as well as the future work that is related to this area of study.

CHAPTER 2: BACKGROUND

2.1 Introduction

In order to create the novel WCS model, background study is needed to understand creep phenomenon. Creep is a phenomenological event that is divided in regimes. Many models are designed to understand different behaviors such as rupture time, MCSR, and creep deformation. A brief summary of a few traditional models is provided as well as their current limitations. Understanding such limitations provides guidelines on recent modeling needs and how the WCS model addresses such issues. Note both the Wilshire model and CDM Sinh model are not included on this analysis as they are discussed later to give a stronger flow to the narrative.

2.2 Creep Phenomenon

Creep is a rate-dependent non-recoverable plastic deformation of materials as a function of stress and temperature [9]. The resulting conventional creep deformation curve is illustrated in Figure 2.1 [9]. Creep strain is activated thermally, and when stress is applied, typically to a metal or ionic solid, deformation leading to failure arises [10]. Most high temperature failures in materials are attribute to creep, fatigue, and combinations of damage [11]. Temperature ranges for creep deformation are: $T > 0.6T_m$ for high temperature , where T_m is the melting temperature, $0.3T_m < T < 0.6T_m$ for intermediate temperatures and $T < 0.3T_m$ for low temperature [2]. Assuming constant stress, high and intermediate temperatures generate short rupture times and low temperatures might extend to infinite life. There is an interest in such low temperature studies as many models intend to predict decades of life. Mechanical systems such as gas turbines, nuclear reactors, and chemical industries operate at these temperature ranges [11]. Therefore creep is