

Comparative Study of Nonlinear Cumulative Creep Damage Model and Time Fraction Rule to Predict Residual Creep Life of Pressure Vessels

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Keywords— Creep damage, asme sec viii div 1, Creep-fatigue interaction, time fraction rule, pressure vessel

I. INTRODUCTION

Prediction of creep damage and remaining life of an product is a complex task. There are many types of creep material models and they provide significantly different predictions. Furthermore, the necessary material data required for the material models are rarely available. Creep tests are typically performed in uniaxial tension under constant load and temperature. However, such similar conditions are rarely encountered in practical engineering applications where multiaxial stresses and cyclic load and temperature often are present. Creep-fatigue interaction and correlation between uniaxial and multiaxial stress states also add on to the complexity of the damage assessment in creep conditions.

Pavlou have proposed a nonlinear cumulative creep damage model (NCCDM) that considers the sequence effect from the previous load history in the damage assessment. NCCDM has been evaluated for use in design applications and compared to a widely-used linear summation method known as the time fraction rule (TFR); TFR is used in several engineering design codes. Pavlou, Grell et. al, Lin and Teng have shown that NCCDM can predict creep damage more accurately than TFR under stepwise constant uniaxial stress and temperature conditions. However, NCCDM has not been used yet in practical engineering design applications.

In this thesis, NCCDM will be applied to a SA 316L pressure vessel designed in accordance with ASME VIII-2 to demonstrate its use in conjunction with practical engineering problems. The pressure vessel will be subjected to elevated temperatures with applied variable two-step loading. This is used as a representative engineering example for the comparison of the two models, i.e., NCCDM vs. TFR.

II. LITERATURE SURVEY

[1] H. E. Boyer, *Atlas of creep and stress-rupture curves*. Metals Park, Ohio: ASM International, 1988.

Creep is a time dependent inelastic deformation which is induced in materials that are subjected to stress. The slow deformation can result in permanent change in shape and rates are usually less than 1.0% per minute, faster rates are generally associated with mechanical working such as forging and rolling. Although creep can occur at any temperature, the point when the material experiences the full effects of creep are dependent on the melting point TM of the material. For metals this starts at the temperature $T > 0.4TM$. At lower temperatures creep deformation occurs with continuously decreasing strain rate, while at elevated temperatures creep typically proceeds through three different stages which ultimately leads to failure.

[2] F. C. Campbell, *Elements of Metallurgy and Engineering Alloys*. Materials Park: A S M International, 2008.

The main creep mechanisms are those that are controlled by dislocation movement and those that are controlled by diffusion. The governing mechanism is dependent on stress and temperature however, many mechanisms can occur simultaneously. Higher stress and lower temperature generally promote dislocation movements while the diffusion controlled mass transport occur at low stresses and high-temperatures. Diffusion which is the atomic movement in metals is due to thermal vibration of atoms and is more difficult below the temperature of $0.3Tm$ but becomes more significant at higher temperatures above $0.4Tm$ when the atomic vibration increase. In dislocation creep dislocations can move through the crystal lattice both by dislocation glide along slip planes and by climbing onto parallel slip planes by the aid of diffusion

[3].R. K. Penny and D. L. Marriott, *Design for creep*, 2nd ed. ed. London: Chapman & Hall, 1995.

In primary or transient creep, redistribution of stresses occurs which eventually lead to the steady-state creep condition. Both the rate and extent of the redistribution depends on both the initial stress level, metal temperature and creep response of the material.

[4].W. Gan, P. Zhang, R. H. Wagoner, and G. S. Daehn, "Effect of load redistribution in transient plastic flow," *Metallurgical and Materials Transactions A*, journal article vol. 37, no. 7, pp. 2097-2106, 2006.

The term creep transient is the change of isotropic strength in a material because of an increase in dislocation density or by change in directional hardening. Transient conditions are frequently essential under factor stacking when new high stresses are restored toward the start of each cycle.

[5].ASME: Boiler & Pressure Vessel Code, Section III, Division 1, Subsection NH - Class 1 Components in Elevated Temperature Service, 2015.

Another phenomenon that must be considered under cyclic actions is the plastic strain accumulation that may occur, called ratcheting. Below the creep range this progressive incremental plastic deformation occurs when the cyclic stresses reach the yielding point. The total inelastic strain may either be stable as illustrated, where the inelastic strains are constant for each cycle or the plastic strain may vary for each cycle.

[6].J. R. Davis and A. S. M. International Handbook Committee, *ASM specialty handbook: Heat-resistant materials*. Materials Park, Ohio: ASM International, 1997.

[7].J. R. Davis and A. S. M. I. H. Committee, *ASM Metals handbook: 8 Mechanical testing and evaluation*, 10th ed. ed. Materials Park, OH: ASM International, 2000.

Time dependent stress relaxation is a kind of creep damage that occurs under hold periods at constant fixed strain. The relaxation rate is dependent on the creep strength of the material. To maintain the total strain constant, the elastic strain must decrease with a corresponding decrease in stress. A typical example where creep relaxation is an issue is for high-temperature bolting, where the stress progressively relaxes after the initial torque, therefore bolt retightening must be made on for example flanges to avoid leakage. Both relaxation and redistributions of stresses have large significance on the creep damage. Especially under cyclic operations. However, often appropriate relaxation data does not exist and relaxation analyses are made with constant load isothermal data.

[8].G. A. Antaki, *Fitness-for-service and integrity of piping, vessels, and tanks : ASME code simplified* (McGraw-Hill mechanical engineering). New York: McGraw-Hill, 2005.

Elevated temperatures cause changes in mechanical properties. These temperature dependent properties can be divided into time-independent and time-dependent properties. The following properties fall into the category of time independent material properties.

[9] F. C. Campbell, *Elements of Metallurgy and Engineering Alloys*. Materials Park: A S M International, 2008.

Elevated temperature tests for creep resistance and creep rupture are similar, however rupture strength is typically measured with stress-rupture tests, which measures the time to failure for a given stress, while creep resistance is determined with so called creep tests which measure time dependent strain. A major difference between stress-rupture and creep tests is the total strain during the test. For creep tests the total strain does generally not exceed 0.5%, while the strain can reach up to 50 % in a stress-rupture test. In addition, for stress-rupture test, the specimens are typically loaded at higher stresses than in creep tests. The duration for a stress-rupture test is also generally shorter compared to the creep test. Stress-rupture tests are concluded when failure occurs, which is often approximately after 1000 hours, while the duration of creep tests can vary from a few months to several years.

[10] B. Geddes, H. Leon, and X. Huang, *Superalloys: Alloying and Performance*. ASM International, 2010.

Many of the components operating in in the high-temperature range are subjected to biaxial and triaxial stresses. Nevertheless, most creep tests of materials are typically performed by uniaxial creep tensile test. The various multiaxial creep testing techniques are primarily used for modelling and validation purposes since they better represent various stress states. But since experimental testing on multiaxial creep rupture and creep damage development are not as easily executed as uniaxial testing methods, uniaxial creep testing will most likely remain to be the main creep testing method.

[11]F. R. Larson and J. Miller, "A time-temperature relationship for rupture and creep stresses," *Trans. ASME*, vol. 174, p. 765-775, 1952.

Among all parametric methods used to predict allowable time to rupture for metals under constant load conditions, the Larsson-Miller parameter is one of the most widely used extrapolation techniques and due to its simplicity it has got a considerable attention since it was proposed in the early 1950s

[12] D. G. Pavlou, "Creep life prediction under stepwise constant uniaxial stress and temperature conditions," *Engineering Structures*, vol. 23, no. 6, pp. 656-662, 2001.

[13] S. Subramanyan, "A Cumulative Damage Rule Based on the Knee Point of the S-N Curve," *Journal of Engineering Materials and Technology*, vol. 98, no. 4, pp. 316-321, 1976.

Linear summation models described in the previous subchapter does not account for the effect of load or temperature sequence in the load and temperature history. Although other more complex nonlinear damage methods have been suggested that more accurately predicts damage, these have not had the same success as the resilient life fraction rule, partially due to that of they require additional material testing for determination of necessary material constants.

In the journal of engineering structures from 2001 D.G. Pavlou [12] presents a nonlinear cumulative creep damage model that is analogous to a fatigue damage model proposed by Subramanyan [13] in 1976.

[14] C.-K. Lin and H.-Y. Teng, "Creep properties of Sn-3.5Ag-0.5Cu lead-free solder under step-loading," *Journal of Materials Science: Materials in Electronics*, journal article vol. 17, no. 8, pp. 577-586, 2006.

The nonlinear cumulative creep damage model proposed by Pavlou has been the subject in studies made by other researchers. It has either in its original form or slightly modified version given satisfactory predictions of variable step creep test data. Grell and co-workers [14] made experimental variable load creep testing for aluminium casting alloy 354 with tensile and three-point bending specimens. The experimental creep data was compared to predictions made with various creep damage models. In their evaluation, the nonlinear Pavlou damage model [12] gave the most accurate predictions for the tested material when compared with other linear summation models used in their evaluation, including the time fraction rule.

[15] A. P. Boresi and R. J. Schmidt, *Advanced mechanics of materials*, 6th ed. ed. New York: Wiley, 2003, pp. 8-15, 104-141.

Von Mises criterion, also known as the octahedral shear stress criterion or the distortional energy criterion, assumes that failure by yielding occurs when the distortional strain-energy density in the material reaches the same value as for yielding by uniaxial tension or compression.

[16] R. D. Cook, D. S. Malkus, M. E. Plesha, and R. J. Witt, *Concepts and applications of finite element analysis*, 4th ed. ed. New York: Wiley, 2002.

New York: Wiley, 2002.

Finite element analysis (FEA) is a numerical method used to solve field problems for example displacement, stress and temperature distributions. Differential equations or integral expressions are used to describe the field problem and a field or structure is discretized in to smaller parts which are called finite elements. Each finite element is only allowed to have a limited spatial variation which can be modelled by simpler equations. This yields an approximate solution of the field problem since the actual variation is often more complicated.

[17] J. R. Davis and A. S. M. I. H. Committee, *ASM Metals handbook: 8 Mechanical testing and evaluation*, 10th ed. ed. Materials Park, OH: ASM International, 2000.

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As previously mentioned in the introduction, there are several national codes that provide rules and guidelines for design of components at elevated temperatures. In the following sections, the design rules for construction at elevated temperatures according to ASME, Section III, Subsection NH are discussed. Behind the rules in standards, engineering corrections and safety factors are often based on extensive research and detailed analysis. However, the fundamental principles behind the methods are not often apparent to the user.

[18] M. H. Jawad and R. I. Jetter, *Design and analysis of boiler and pressure vessel components in the creep range*. New York: ASME Press, 2009.

According to the definition in ASME VIII-1, pressure vessels are containers used for containment of either internal or external pressure, which may be obtained from an external source or by applying heat from a direct or indirect source. Pressure vessels operating under high-temperature service where the effect of creep is significant can be found in chemical plants, refineries and power generation plants. One of the design issues for such pressure vessels are the variable loading conditions due to start up and shut down in combination with the effect of long time exposure at elevated temperatures. The capability of a pressure vessel shell to perform properly depends on several factors, like the stress level, material properties, operating temperature and temperature range and pressure cycles.

III. CONCLUSION

Different researcher's works about each one have been reviewed. The nonlinear cumulative Pavlou creep damage model has been studied and compared to the linear time fraction rule. The comparison of two models was made by studying the creep life of a pressure vessel subjected to two-step variable loading at different load sequences.

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