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

Mr. Hemant V. Ghule [1], Prof Dr. Mahendra P. Nimkar [2]

[1]*Research Scholar, DBACER, Department of Mechanical Engineering, Nagpur University, Nagpur, India*

[2]*DBACER, Department of Mechanical Engineering, Nagpur University, Nagpur, India*

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Abstract - Predicting creep damage and remaining life of an engineering design 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 SS 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.

Firstly, by considering proposals made by Pavlou, Grell, Lin and Teng, an evaluation of the best use of the NCCDM was made. The model behaviour was also studied by considering fictive load cases. Based on the findings, conditions for further use of the model was established. Secondly, rupture and creep strength data obtained from a material database were used to create fitted curves with the Larson-Miller parameter from which time-to-rupture and time-to-1% strain could be obtained for different stresses. Thirdly, the finite element (FE) method was used to evaluate several types of stress criteria on a generic model of a pressure vessel. Variable-step internal pressure at a constant elevated temperature was applied to the model. A linear-elastic and an elastic-plastic material model was used in the analysis. By considering high-to-low (H-L) and a low-to-high (L-H) loading sequence the remaining life to rupture and to 1% strain was calculated for the pressure vessel with both NCCDM and TFR.

It was found that the NCCDM and the TFR gave very different predictions. For the L-H type of loading sequence the NCCDM predicted more conservative remaining life than TRF. The opposite was seen for the H-L type of loading. Larger variation in stress between the two load steps resulted in an increased difference between the predictions made with the two models. Due to the difficulty of performing a time-dependent creep analysis, the NCCDM model would benefit from being combined with an elastic-analysis procedure to approximate the time-dependent stress distribution, like the procedure in ASME-NH. Because of the simple use of NCCDM, there is potential for it to gain acceptance for engineering applications. However, further analysis and research should be made to fully understand the damage processes considered in the NCCDMs remaining life assessment.

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

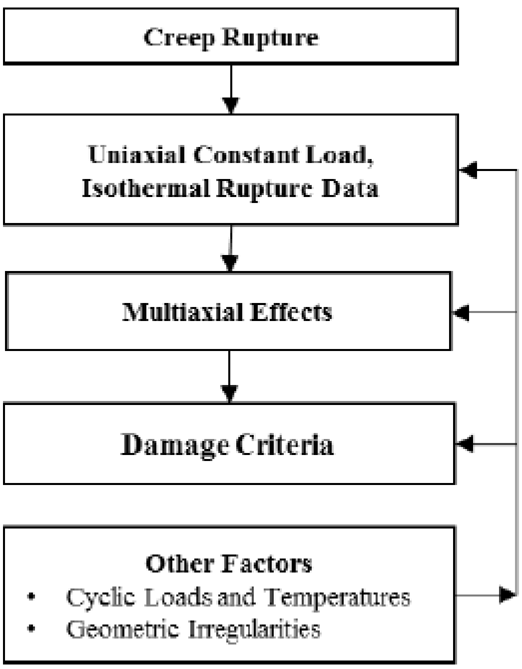
1.INTRODUCTION

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.

Background: - Creep has been studied extensively ever since the creep phenomenon was recognized as a problem in design of high-temperature components . One of the earliest research on creep was carried out by Andrade in 1910, and by the 1920s creep strength in metals was studied systematically with short term creep tests and later in the 1950s with long term creep tests. Although great advances have been made in research of understanding the creep phenomena, creep damage can be difficult to assess due to the complex nature of creep and the many factors affecting the creep damage process. Some of the main difficulties regarding creep rupture prediction is shown in Figure



The time-dependent damage process that constitutes creep is mainly influenced by stress and temperature. Creep and stress-rupture tests are typically performed under isothermal uniaxial constant load conditions to determine the long-term damage effect on the material due to stress and temperature. However, similar conditions are rarely found in practical engineering problems where multiaxial stress states, cyclic or variable load and temperature conditions are often present.

Creep:- 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 experience 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.

Stage	Temperature	Characteristic
Primary	$T>0.4TM$ or $T\leq0.4TM$	$\dot{\varepsilon}$ decreases as t and ε increase
Secondary (steady state)	$T\geq0.4TM$	$\dot{\varepsilon}$ is constant
Tertiary	$T\geq0.4TM$	$\dot{\varepsilon}$ increases as t and ε increase

2. 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, were 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.

3. OBJECTIVE AND SCOPE

The main objective of this thesis is to evaluate the practical use of the nonlinear Pavlou creep damage accumulation model and compare it to the widely-used life fraction rule also known as Robinson's rule which has been incorporated in several national codes. The difference in remaining creep life between the two damage accumulation models is to be compared by studying a representative engineering example subjected to variable loads at elevated temperatures in the creep range.

The component to be studied is a generic model of a pressure vessel subjected to internal pressure at a constant elevated temperature of 700 °C (973 K). Internal pressure will be applied in a low-high sequence and high-low sequence and remaining life using the two creep models is to be evaluated for each sequence.

To reach the objectives of this thesis, the following sub-objectives are to be carried out:

- Study creep mechanisms and current creep damage assessments methods.
- Evaluate methods used in standards for design of components in high-temperature service.
- Evaluate the Pavlou creep damage model by considering suggestions from previous research.
- Study how to account for multiaxial stress states and stress concentrations in creep damage assessment. Evaluate how various stress criterions can impact damage assessment and remaining life.
- Construct a creep-rupture curve from applicable creep data for the material being used and study potential error and uncertainties from the creep data fit
- Carrey out a stress analysis in ANSYS using various material models and calculate remaining life for the pressure vessel with the linear and nonlinear creep damage models and compare the remaining life

4. METHODOLOGY

Creep-fatigue analysis method:- When the inelastic strain- and deformation-limits for functional- and structural integrity requirements are met the creep fatigue analysis can be carried out. The rules for cyclic loads in Subsection NH involve determining points within a cycle time for which the stress levels in a certain point of a component are at a maximum. Stresses are then evaluated against load- and strain-controlled limits for creep and fatigue.

- Inelastic creep-fatigue analysis
- Elastic creep-fatigue analysis

Conceptually, creep-fatigue evaluation with inelastic analysis is relatively straightforward and will not be discussed further. However, the difficulties associated with inelastic analysis as mentioned above still apply.

Pressure vessel design methods

There are three alternative analysis methods

- ***Elastic Stress Analysis Method*** – Stresses are computed using a linear-elastic material model and classified into categories and compared to related limiting values which have beenestablished conservatively.
- ***Limit-Load Method*** – The procedure involves determining the lower bound limit load of a component. An elastic-perfectly plastic material model with small displacement theory shall be used and the concept of load and resistance factor design (LRFD) is used to establish the limit load as a safety measure against plastic collapse.
- ***Elastic-Plastic Stress Analysis Method*** – In this analysis procedure a plastic collapse load is derived from an elastic-plastic analysis by using either a material model that includes hardening and softening or an elastic-perfectly plastic material model. Like the Limit-Load method, design factors are used to establish the maximum allowable load.

5. RESULT

Remaining creep rupture life of pressure vessel

Remaining creep rupture life from linear-elastic analysis for L-H type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep Rupture life, t_{2CRS} Nonlinear Pavlou model [h]	Time fraction rule [h]	Δt_{2CRS} [h]	Δt_{2CRS} %
Von Mises, σ_{VM}	40.7	1216	1865	-649	-53.4
Tresca, σ_{TR}	46.1	619	1097	-477	-77.1
Maximum principal Stress, σ_{MPS}	42.1	1022	1618	-596	-58.3
Mixed criteria, σ_{eq}, α=0.8	40.9	1176	1814	-638	-54.3
Mixed criteria, σ_{eq}, α=0.9	40.8	1196	1839	-644	-53.8
Huddleston, σ_{HUD}	41.9	1043	1644	-601	-57.7

Remaining creep rupture life from linear-elastic analysis for H-L type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep Rupture life, t_{2CRS} Nonlinear Pavlou model [h]	Time fraction rule [h]	Δt_{2CRS} [h]	Δt_{2CRS} %
Von Mises, σ_{VM}	40.7	11514	8883	2630	22.8
Tresca, σ_{TR}	46.1	7585	5625	1960	25.8
Maximum principal Stress, σ_{MPS}	42.1	10283	7854	2429	23.6
Mixed criteria, σ_{eq}, α=0.8	40.9	11257	8668	2589	23.0
Mixed criteria, σ_{eq}, α=0.9	40.8	11385	8775	2610	22.9
Huddleston, σ_{HUD}	41.9	10414	7963	2451	23.5

Remaining creep rupture life from plastic analysis for L-H type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep Rupture life, t_{2CRS} Nonlinear Pavlou model [h]	Time fraction rule [h]	Δt_{2CRS} [h]	Δt_{2CRS}%
Von Mises, σ_{VM}	33.0	1765	2441	-676	-38.3
Tresca, σ_{TR}	37.9	931	1429	-499	-53.6
Maximum principal Stress, σ_{MPS}	35.4	1416	2035	-619	-43.7
Mixed criteria, σ_{eq}, α=0.8	33.2	1712	2377	-665	-38.8
Mixed criteria, σ_{eq}, α=0.9	33.1	1739	2409	-671	-38.6
Huddleston, σ_{HUD}	34.2	1518	2145	-627	-41.3

Remaining creep rupture life from plastic analysis for H-L type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep Rupture life, t_{2CRS} Nonlinear Pavlou model [h]	Time fraction rule [h]	Δt_{2CRS} [h]	Δt_{2CRS}%
Von Mises, σ_{VM}	33.0	11094	8906	2188	19.7
Tresca, σ_{TR}	37.9	7313	5640	1673	22.9
Maximum principal Stress, σ_{MPS}	35.4	9969	7876	2093	21.0
Mixed criteria, σ_{eq}, α=0.8	33.2	10844	8691	2152	19.8
Mixed criteria, σ_{eq}, α=0.9	33.1	10967	8798	2170	19.8
Huddleston, σ_{HUD}	34.2	10036	7984	2052	20.4

Remaining life to 1% strain of pressure vessel

Remaining life until 1% strain from linear-elastic analysis for L-H type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep Rupture life, $t_{2_{Rp1}}$ Nonlinear Pavlou model [h]	Time fraction rule [h]	$\Delta t_{2_{Rp1}}$ [h]	$\Delta t_{2_{Rp1}}$%
Von Mises, σ_{VM}	40.7	305	468	-163	-53.4
Tresca, σ_{TR}	46.1	137	243	-106	-77.1
Maximum principal Stress, σ_{MPS}	42.1	248	393	-145	-58.3
Mixed criteria, σ_{eq}, α=0.8	40.9	293	452	-159	-54.3
Mixed criteria, σ_{eq}, α=0.9	40.8	299	460	-161	-53.8
Huddleston, σ_{HUD}	41.9	254	401	-147	-57.7

Remaining life until 1% strain from linear-elastic analysis for H-L type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep Rupture life, $t_{2_{Rp1}}$ Nonlinear Pavlou model [h]	Time fraction rule [h]	$\Delta t_{2_{Rp1}}$ [h]	$\Delta t_{2_{Rp1}}$%
Von Mises, σ_{VM}	40.7	3892	3003	889	22.8
Tresca, σ_{TR}	46.1	2370	1758	612	25.8
Maximum principal Stress, σ_{MPS}	42.1	3405	2601	804	23.6
Mixed criteria, σ_{eq}, α=0.8	40.9	3790	2918	871	23.0
Mixed criteria, σ_{eq}, α=0.9	40.8	3840	2960	880	22.9
Huddleston, σ_{HUD}	41.9	3456	2643	813	23.5

Remaining life until 1% strain from elastic-plastic analysis for L-H type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep life, $t_{2_{Rp1}}$ Nonlinear Pavlou model [h]	Time fraction rule [h]	$\Delta t_{2_{Rp1}}$ [h]	$\Delta t_{2_{Rp1}}$%
Von Mises, σ_{VM}	33.0	309	464	-154	-49.8
Tresca, σ_{TR}	37.9	220	337	-118	-53.6
Maximum principal Stress, σ_{MPS}	35.4	362	520	-158	-43.7
Mixed criteria, σ_{eq}, α=0.8	33.2	453	629	-176	-38.8
Mixed criteria, σ_{eq}, α=0.9	33.1	461	639	-178	-38.6
Huddleston, σ_{HUD}	34.2	393	555	-162	-41.3

Remaining life until 1% strain from elastic-plastic analysis for H-L type of loading

Stress type	$\Delta\sigma$ [MPa]	Remaining Creep life, $t_{2_{Rp1}}$ Nonlinear Pavlou model [h]	Time fraction rule [h]	$\Delta t_{2_{Rp1}}$ [h]	$\Delta t_{2_{Rp1}}$%
Von Mises, σ_{VM}	33.0	3752	3012	740	19.7
Tresca, σ_{TR}	37.9	2286	1763	523	22.9
MPS	35.4	3302	2609	693	21.0
Mixed criteria, σ_{eq}, α=0.8	33.2	3652	2927	725	19.8
Mixed criteria, σ_{eq}, α=0.9	33.1	3701	2969	732	19.8
Huddleston, σ_{HUD}	34.2	3332	2651	681	20.4

6. CONCLUSION

The following observations listed below are conclusions of the present work.

1) The isodamage lines plotted in Figure 36 using the stepped-load experimental data from other research showed that the isodamage lines all intersected with the rupture curve (D=100%) at the value of the fitting parameter. This indicates that Pavlou's hypothesis of isodamage lines all intersecting at a common point is correct. It also suggests that the fitting parameter should be used instead of the creep endurance limit in the nonlinear creep damage model.
2) Stress cycling cause larger deviation than temperature cycling between the time fraction rule and the Pavlou damage model. The percental difference in remaining life between the two models are only dependent on the stress difference between the loading steps $\sigma 1$ and $\sigma 2$ and/or the temperature difference ΔT
3) Pavlou's creep damage model predicts a longer remaining life for the high-low load sequence and predicts a more conservative remaining life for the low-high load sequence compared to predictions with the fraction rule.

7. RECOMMENDATIONS FOR FURTHER WORK

1) Investigate if there are alternative ways to obtain the fitting parameter.

2) Study the temperature dependence of the fitting parameter.
3) Studying the effect of creep-fatigue interaction.
4) Investigate how to incorporate safety factors in the nonlinear damage assessment.
5) Study possibility for improvement of the cumulative nonlinear creep damage model

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