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ASSESSMENT OF LONG TERM CREEP USING STRAIN RATE MATCHING FROM THE STEPPED ISOSTRESS METHOD

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ABSTRACT

Creep testing is an ongoing need, particularly with the development of new candidate alloy systems for advanced energy systems. The conventional creep test (CT) is regarded as a proven method to gather creep data however, the test is impractical due to being real-time: lasting up to 10^5 hours to characterize the service of long-lived turbomachinery components. Accelerated methods to gather the long-term creep properties of materials are needed to reduce the time to qualification of new materials. The time-temperature-stress-superposition principle (TTSSP) and the derivative time-temperature superposition principle (TTSP), time-stress superposition principle (TSSP), stepped isothermal method (SIM), and stepped isostress method (SSM) are accelerated creep tests (ACT) commonly used to predict the long-term creep behaviors of polymers and composites. The TTSP and TSSP tests require multiple specimen tested at various temperatures/stresses whereas the SIM and SSM tests employ a single specimen where temperature/stress are periodically step increased until rupture. The stepped creep deformation curve can then be time and strain shifted to produce a master creep curve. While these ACTs are useful tools to predict long-term creep, the drawback is the lack of mathematical laws to determine the virtual start time and time shift factors, especially for different materials.

In this paper, a new self-calibration approach is developed and compared to existing SSM data for Kevlar 49. This new approach focuses on matching the creep strain rates between stress steps and fitting the data to a master curve using a modified theta projection model. This is performed using a MATLAB code consisting of five subroutines. The first subroutine takes the stress, time, and creep strain from SSM/SIM tests, and segregates the data intro arrays corresponding to each stress level. The second subroutine finds the constants for the modified theta projection model for each stress level. The third subroutine performs a time shift adjustment using creep strain rate matching. The fourth subroutine calculates the accelerated time of rupture. The last subroutine generates accelerated creep versus time plots. Kevlar 49 SSM data is gathered from literature and run through the MATLAB code. The master curves generated from the MATLAB are compared to the conventional creep curve of Kevlar 49 as well as the master curve gathered from literature in order to validate the feasibility of this new approach. The goal of this project is to vet if the self-calibration approach can produce results similar to the reference calibration approach.

INTRODUCTION

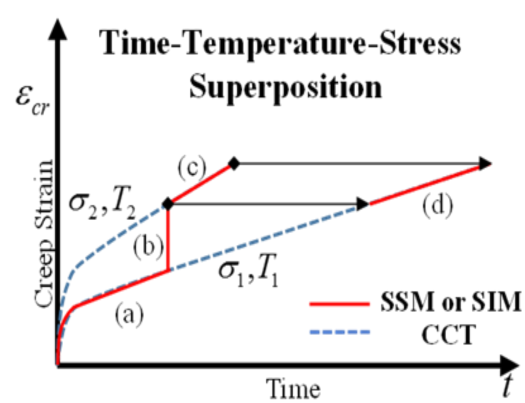

Figure 1– Time-Temperature-Stress Superposition Principle (TTSSP) visualization of (a) reference stress or temperature level (b) stress or temperature step (c) elevated stress or temperature level (d) accelerated creep strain

Conventional Creep testing (CT) of materials are real time test. In power generation, testing may last up a minimum of 10^5 hours or 10 years [1]. With the development of new candidate alloy systems, extensive testing must be performed to characterize the creep properties at significant time and costs expense. There is a need to rapidly characterize the creep properties of a candidate material so that it can be quickly determined if the material exhibits superior creep resistance to traditional alloys.

Two proposed methods to accelerated creep testing are the time-temperature superposition principle (TTSP) and the time-stress superposition principle (TSSP). At higher temperatures and stresses, creep deformation is accelerated allowing for long-term creep properties to be gathered from short term data given adequate mathematical justification [3-[*4*]. During TTSP, multiple specimens are tested under a constant load at different temperatures resulting in separate plots of creep strain versus log (time) at different temperatures, and vice versa for TSSP where specimens are tested isothermally as shown in Figure 1. A reference temperature/stress is then selected, and all individual curves are shifted along the log (time) axis to produce a creep master curve [5,*[10-[14*].

While TTSP and TSSP have been proven to predict creep rupture, there are several downsides to these methods. At each level of temperature/stress, there are multiple specimens used. Creep tests exhibit uncertainty where the creep response varies from specimen to specimen. The resulting accelerated creep curve then represents the aggregate uncertainty of multiple specimen. The certainty of calibration and resulting creep properties are difficult to assess [6-[*8*].

The stepped isostress method (SSM) and stepped isothermal method (SIM) are capable of recording over a short period of time, the long-term multistage creep deformation to rupture of materials. Where the TTSP and TSSP method require multiple specimens, the SIM and SSM tests require only one. Each specimen is subjected to several controlled step increases of temperature/stress [9]. Having one specimen for each stress level vs having multiple specimens preserves the uncertainty of the creep response in each material. Using similar concepts from TTSP/TSSP, the stepped temperature/stress levels are segregated into individual curves and time and strain shifted to produce a creep master curve at the reference stress/temperature [8].

In this study, the research objective is to use a modified theta-projection constitutive model to fit data gathered from an SSM test to a master curve [20]. In order to meet the research objective, the following activities are performed; SSM data from Kevlar 49 data is gathered, the data is inputted into a MATLAB code programmed for self-calibration, and the data shifts from the MATLAB code are exported and compared to the results of the reference calibration approach.

METHODOLOGY

The self-calibration method for SSM is divided into three steps: the creep strain adjustment, the virtual start time adjustment, and the time-shift adjustment.

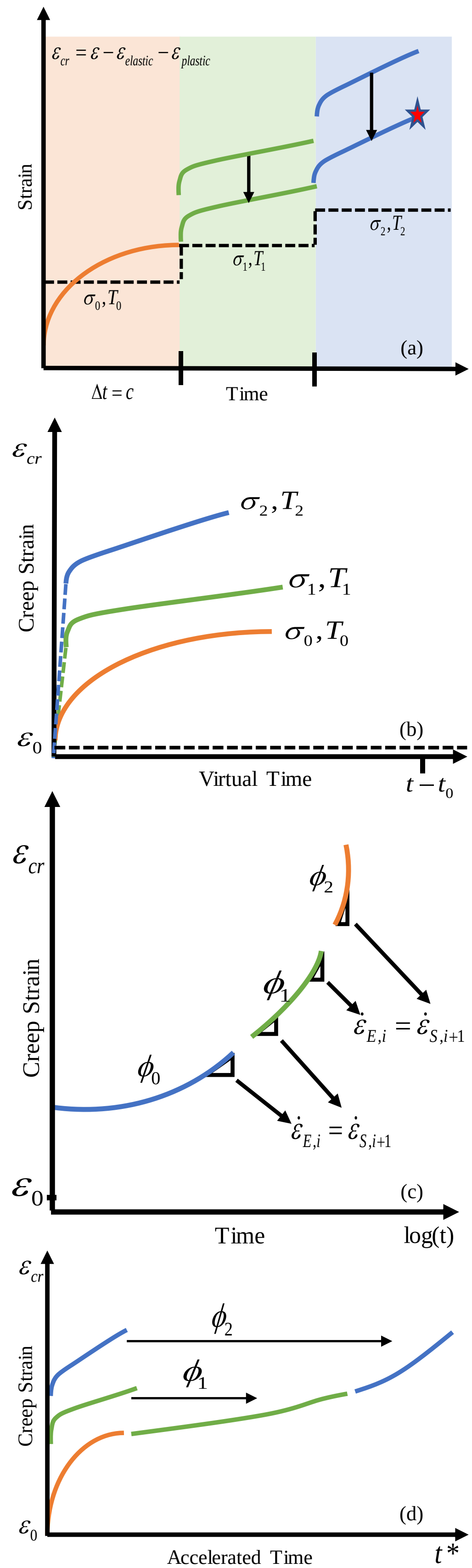

Figure 2-Self Calibration Approach: (a) Creep Strain Adjustment (b) Virtual Start Time Adjustment (c) Time-Shift Adjustment and (d) Accelerated Time

Step 1 – Creep Strain Adjustment

When conducting SSM tests, the total strain from the experiment is given. Before the virtual start time and time-shift adjustments can be determined, the creep strain must be calculated. The creep strain, ε_{cr} is calculated from the measured total strain, ε by rearrangement as follows

$$\varepsilon_{cr} = \varepsilon - \varepsilon_{elastic} - \varepsilon_{plastic} - \varepsilon_{misc} \tag{1}$$

where $\varepsilon_{elastic}$ is elastic strain, $\varepsilon_{plastic}$ is rate-independent plastic strain, and ε_{misc} are miscellaneous strains due to equipment compliance, unrelieved thermal strains, and others. The resulting adjusted creep strain curve is depicted in Figure 2(a). Elastic strain is calculated using Hooke's law, while plastic strain is calculated using the .2% offset line gathered from separate monotonic tests of the material.

Step 2 – Virtual Start Time Adjustment

The virtual start time adjustment, converts the measured continuous creep deformation curve into a series of individual creep deformation curves. This is achieved by calculating a virtual start time, t_0, as if the curve for each stress level was produced from an independent, initially unloaded creep test. The virtual start time, t_0 is obtained by fitting a constitutive law to each stress/temperature level and then shifting the individual temperature/stress levels to zero time as shown in Figure 2(b). The existing approach is to fit a polynomial equivalent to Graham-Walles or a Prony series to the data [3]. In the self-calibration approach, constitutive models are recommended. The following rules for the constitutive models must be enforced:

- be able to model primary, secondary, and tertiary creep. Ideally, the regimes should be separated into independent functions such that the model can be simplified to better fit the given stress level. For instance, if there is no tertiary creep regime at a stress level, the function associated with tertiary creep should be zeroed out to increase the statistical dependencies of the material constants for primary and secondary regimes.
- be able to predict zero strain at a non-zero time. In most models, this can be enabled by replacing t with $(t-t_0)$ everywhere; however, care must be taken to prevent the constitutive model from becoming over-defined. Zeroing out unnecessary creep regimes can help mitigate this issue.

In this study, a modified Theta Projection constitutive model is applied in the following form

$$\varepsilon = \theta_1(1-\exp(-\theta_2(t-t_0))) + \theta_3(\exp(\theta_4(t-t_0))-1) \tag{2}$$

where ε is the creep strain, t is the time, t_0 is the virtual start time, and $\theta_1, \theta_2, \theta_3$, and θ_4 are scaling and rating parameters for the primary and tertiary creep regimes [20].

The model is also able to predict zero strain from a non-zero time while remaining well-defined. Taking the derivative of creep strain [Eq. (2)] with respect to time provides the creep strain rate.

$$\dot{\varepsilon}_{cr} = \theta_1\theta_2\exp(-\theta_2(t-t_0)) + \theta_3\theta_4\exp(\theta_4(t-t_0)) \tag{3}$$

where due to the exponential functions the form remains simple.

Step 3 – Time-Shift Adjustment

The time-shift adjustment converts the individual creep deformation curves into a single accelerated creep deformation curve. This is achieved by calculating time-shift factors, ϕ_i, for each stress level.

In conventional creep tests, the creep strain rate does not exhibit a dramatic change in rate; rather, the rate evolves as a continuous decreasing or increasing function with respect to primary and tertiary creep regimes respectively. If the steps between stress levels remain moderate, the time-shift factors can be obtained from creep strain rate match. In this case, the time between stress levels is 5 hours until rupture. Accelerating SSM data using creep strain rate matching between the stress level is as follows

$$\dot{\varepsilon}_{E,i}* = \dot{\varepsilon}_{S,i+1}* \tag{4}$$

where $\dot{\varepsilon}_{E,i}*$ is the accelerated creep strain rate of the end of the i^{th} stress level, and $\dot{\varepsilon}_{S+i}$ is the accelerated creep strain rate of the beginning of the $i^{th}+1$ stress level. This relationship can be restated in incremental form as follows

$$\frac{\Delta\varepsilon_{E,i}}{\Delta t*_{E,i}} = \frac{\Delta\varepsilon_{S,i+1}}{\Delta t*_{S,i+1}} \tag{5}$$

where acceleration arises due to an acceleration of the time increment $\Delta t*$. The accelerated time is expressed as follows

$$t*_i = \frac{t_i - t_{0,i}}{\phi_i} \tag{6}$$

where t_i is the time for each stress step, t_0 is the virtual start time adjustment calculated in step 2, and ϕ_i is the time shift adjustment for the i^{th} stress level. When introduced into the incremental form as seen in [Eq.(5)], the strain rates become

$$\frac{\Delta\varepsilon_{E,i}\cdot\phi_i}{\Delta t_i} = \frac{\Delta\varepsilon_{S,i+1}\cdot\phi_{i+1}}{\Delta t_{i+1}} \tag{7}$$

where ϕ_{i+1} is the time-shift factor corresponding to the $i+1$ stress level. This can be simplified into

$$\phi_i\cdot\dot{\varepsilon}_{E,i} = \phi_{i+1}\cdot\dot{\varepsilon}_{S,i+1} \tag{8}$$

The time shift factors can then be determined directly as follows

$$\phi_{i+1} = \frac{\phi_i\cdot\dot{\varepsilon}_{E,i}}{\dot{\varepsilon}_{S,i+1}} \tag{9}$$

where the first time-shift factor in all exponents is $\phi_1 = 1$.

Unfortunately, experiment creep strain rate data fluctuates too much to produce reliable ϕ values. Instead, the calibrated modified-theta model rate as seen in [Eq.(2)] is employed. In practice, it is best to numerically solve [Eq.(6)] with [Eq.(2)]

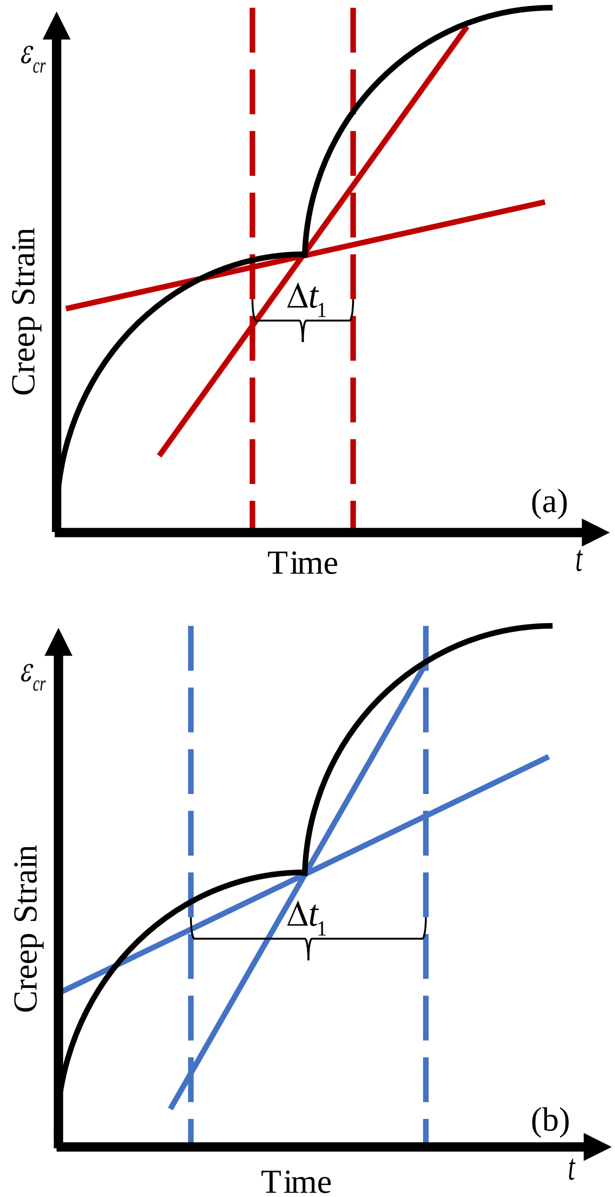

Figure 3-illustration of time-shift sensitivity issues for (a) a narrow and (b) wide time overlap

embedded over an overlapping range of real time. This produces a more realistic and continuous accelerated creep curve.

The calibration of time-shift factors is extremely sensitive to the selected overlapping time interval in materials that exhibit a prominent primary creep regime. This sensitivity is illustrated in Figure 2(c) using a linear function in lieu of [Eq.(2)] for simplicity of interpretation.

When a narrow time interval is employed (Figure 3a), the difference slope between stress levels is maximized resulting in greater acceleration while with a wider time interval (Figure 3b), the slopes not as far apart resulting in less acceleration. This problem would disappear in materials that exhibit little to no primary creep. This problem can exacerbate by accounting for time-independent plasticity when operating above the yield strength of a material. As a consequence of this issue, the time interval must be calibrated specific-to-material.

MATLAB CODE

To generate the accelerated creep curves, a MATLAB code was written as outlined in Figure 4. The code is divided into five subroutines and is currently configured to accelerate one SSM test at a time. The algorithm starts with reading the SSM data (stress, creep strain, and time) into MATLAB. The data is processed to identify the number of stress steps, creep strain at each level of stress, and the real time for each level. For each stress step, the modified Theta constitutive law [Eq.(2)] is calibrated (using nonlinear least squares) to obtain the material constants but more importantly the virtual start time, unique to each stress level. Next, for each stress step, the time shift factor, is obtained (using nonlinear least squares) according to the self-calibration approach described in the previous section. Finally, the accelerated time, is calculated for each stress level and the accelerated creep curve generated. The last subroutine exports all data generated in the acceleration process as well as the squared residual norm, of the nonlinear least squares routines.

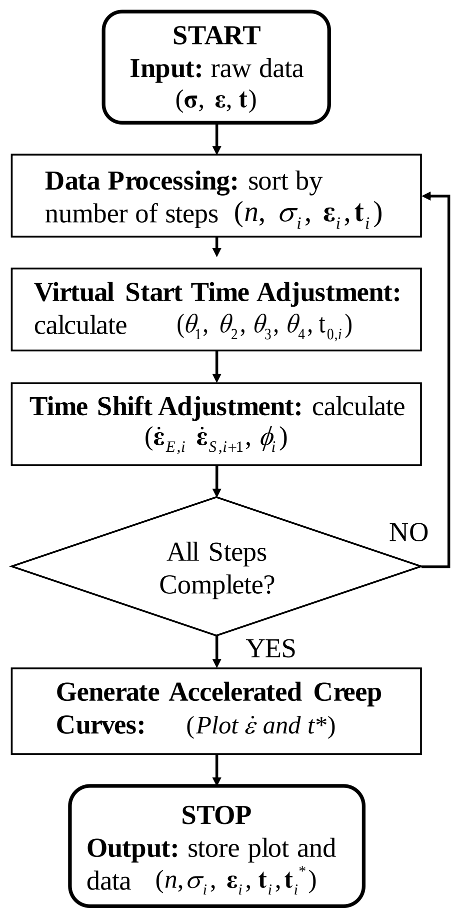

Figure 4-MATLAB Code Map

RESULTS AND DISCUSSION

The reference material used in this study is Kevlar 49 [14]. Existing SSM data for Kevlar 49 was collected from literature and digitized for input into the MATLAB code [12]. Both the reference approach and self-calibration approach require creep strain data as shown in Figure 5(a). Where the reference uses a polynomial to calibrate the creep strain data, the self-calibration uses a constitutive model as seen in Figure 5(b). Data from the reference calibration method for an SSM test is shown in Table 1. The data was gathered at 333.75MPa. The creep strain curve was digitized and inputted through the MATLAB algorithm. The results for each step of the self-calibration method are shown in Table 2. A comparison of creep master curves is shown in Figure 5(c).

Table 1. Data from Reference Calibration for Kevlar 49

Load Sequence (MPa)	Time (hr)	Virtual Start Time, t_0 (hr)	Time Shift log (ϕ_i)
333.75	5	0.00	0
344.88	5	3.52	0.69
356.00	5	8.63	1.53
367.13	3.9	13.84	2.40

Table 2. Data from Self-Calibration for Kevlar 49

Load Sequence (% ABL)	Time (hr)	Virtual Start Time, t_0	Time Shift log (ϕ_i)
333.75	5	0.00	0
344.88	5	3.58	0.76
356.00	5	8.67	1.79
367.13	3.9	13.47	2.40

Reference calibration produces a creep rupture point of 1213 hours, and self-calibration produces a creep rupture point of 1281 hours with a percent difference of 5.45%. The two methods produce smooth master curves, however, the adjustments needed in each method are subjective. In the case of self-calibration, the virtual start time and the accuracy at the beginning and ending of each stress level impacts calibration. For example, a percentage of 2% of data taken for each stress step will overestimate the creep rupture point, but 1% of data for each step will underestimate the creep rupture point. This is due to change in rate being applied. This sensitivity in calibration may also be affected by the data taken as the data was digitized and missing points. Having creep rupture data will help for the material with the creep rupture point.

Using the self-calibration approach to calibrate SSM data is feasible.

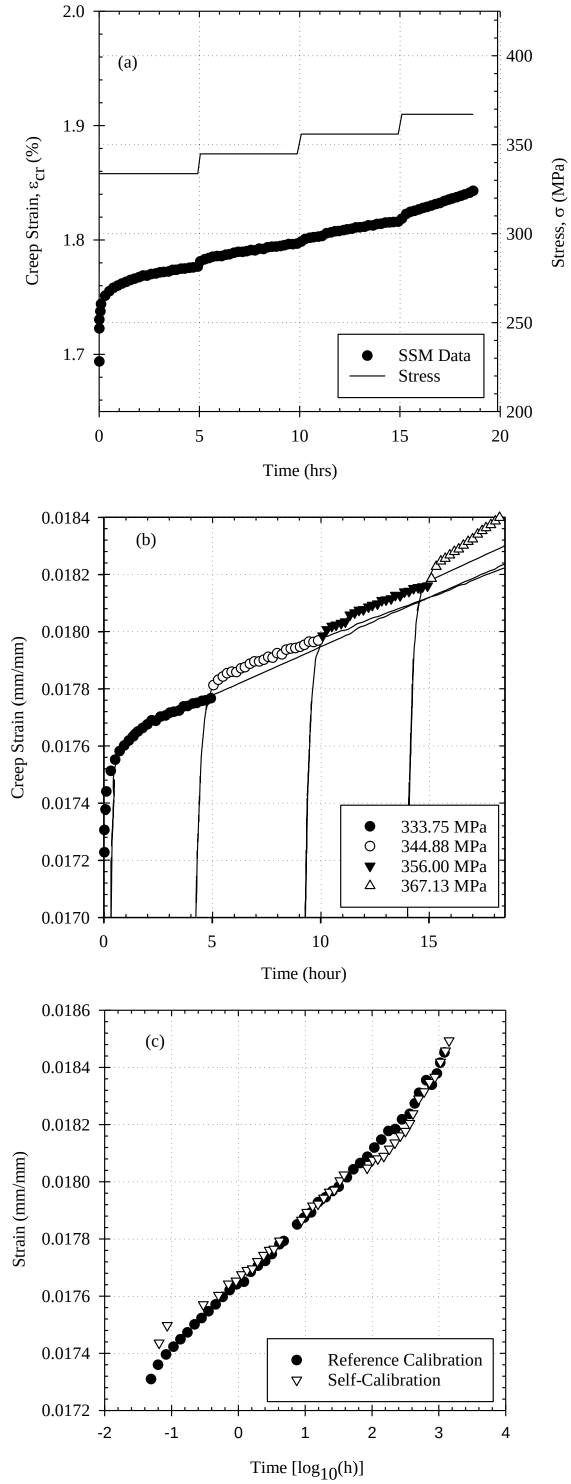

Figure 5- (a) SSM Creep Strain Data for Kevlar 49 (b) Creep Strain Data with the Modified Theta Projection Fit and (c) Reference Calibration vs Self Calibration Master Curve

CONCLUSION

While new materials are developed for power generation, a need to characterize the creep properties of these materials in a short amount of time is necessary. A new self-calibration is vetted as another alternative to the current reference calibration approach seen applied in the TTSP/TSSP and SIM/SSM tests. The self-calibration approach is applied to SSM data of Kevlar 49 with the use of a MATLAB algorithm. Shifts and results from self-calibration and reference calibration are compared. The percentage of time used to match the strain rates at the beginning and end of each stress step is the determinant for predicting creep rupture. When comparing the results of self-calibration to reference calibration the virtual start time data and time shift data for each stress step are relatively similar with a predicted creep rupture difference of 5.45%. Comparing the self-calibration approach to experimental creep data, however, would provide greater accuracy in predicting creep rupture.

FUTURE WORK

While SSM/SIM experiments have been conducted on various yarns and fibers, testing on metallics is limited. Conventional creep testing for metallics have the possibility of running for 10^6 hours which is unrealistic for gathering material creep properties. SSM/SIM testing on Inconel 718 (IN718) will be conducted as CT data to 10^5 hours is readily available [21]. Monotonic Tensile tests at various elevated temperatures will be conducted to gather the stress-strain properties of IN718. Short-term creep rupture data will be gathered in order to use the self-calibration approach on the SSM/SIM data.

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