Material Testing 2.0: Uncertainty Quantification for Accelerated Creep Tests

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Abstract. The rapid development of new structural materials for fusion powerplants has highlighted the need for accelerated creep tests (ACT). Whilst Materials Testing 2.0 (MT2.0) may provide the answer, validating the tests by quantifying the random and systematic uncertainty is essential. Uncertainty quantification (UQ) techniques were applied to a series of conventional creep tests of Al 1050 to identify uncertainty in the Digital Image Correlation (DIC) process for long-term high-temperature testing. The findings were used to propose a clear procedure that can be followed before, during, and after testing to validate the results. The procedure was applied to ACT methods optimised for DIC, with the results compared to the conventional creep test.

Introduction

Creep is the primary failure mode of nuclear fusion in-vessel components such as breeder blankets and diverters. The development, qualification, and selection of creep-resistant materials represent some of the most significant challenges for fusion. Through the UK Atomic Energy Authority's NEURONE project, novel structural materials for fusion applications are rapidly developed and require an accelerated method for characterising creep behaviour. Current design codes necessitate that materials undergo creep testing across a wide range of stress levels, temperatures, and neutron damage states [1]. This results in time-consuming test programs, compounded by limited material availability and the increased cost and complexity associated with testing irradiated materials. Therefore, a new material testing method is needed to generate significantly more creep data across the fusion operational range, utilising limited material and reducing testing time for the efficient down-selection of new materials.

DIC combined with inverse identification methods such as the Virtual Fields Method (VFM) revolutionised the extraction of data from mechanical testing by providing full-field measurements from a single test, earning the title MT2.0 [2]. Developing a new method of creep testing that utilises the full capability of DIC [3] could drastically accelerate testing campaigns, with optimised topology [4] reducing the quantity of material required whilst also providing a rich dataset. However, this method also increases the potential sources of error. The challenges of identifying, quantifying, and reducing uncertainty in the DIC procedure have been well-documented [5] with a variety of simulation, experimental, and post-processing approaches. Yet limited literature exists on UQ applied to creep testing to validate the results.

This work aims to understand and quantify the random and systematic errors inherent to DIC during creep testing. An optimised creep test methodology is then designed to maximise the obtainable information per test while minimising the errors and biases inherent to DIC and applied to an ACT [6].

Experimental procedure

Design and validation. A digital twin synthetic image deformation UQ approach of an ISO 6892 Al1050 sample was created to quantify the impact of grey level noise, sample size, speckle (size, distribution, uniformity), and sampling rate. A convergence study [7] was used to highlight the systematic error in low-pass filtering by comparing subset, step, and linear vs quadratic shape functions. 30-hour static tests were performed at room temperature to characterise the inherent systematic error in the DIC arrangement and at high temperature to demonstrate and quantify the effect of self-radiation, change in chambers glass refractive index, heat haze, lighting and bandpass filters. An optimal stereo-DIC setup for creep testing was presented and additional procedures such as image averaging for noise reduction were also introduced.

Traditional tests. ISO 6892 tensile samples were cut from a 6mm plate of Al 1050 procured from West Yorkshire Steels, tested as manufactured. Creep tests were performed following ISO 204, using both extensometer and DIC to extract strain data to find the time to 1% strain, minimum creep rate, stress exponent *n*, activation energy, calculation of the Monkman-Grant relation, and assessment of creep life using the Larson-Miller Parameter. Post-test characterisation by SEM was performed on identical unstressed samples under the same thermal conditions to provide a baseline for the thermal effects. A static sample was integrated within the test rig to identify heat haze, noise, and rigid body motion during the creep test. A simulation of the test was created in ABAQUS using the experimental data.

Accelerated creep tests. The Stepped Iso-Stress Method (SSM) and Stepped Iso-thermal Method (SIM) were applied to the ISO 6892 tensile samples to assess the accuracy in comparison to conventional creep tests.

Optimisation for MT2.0. Ground truth data from conventional creep testing allowed for the exploration of non-traditional testing methods, geometries, and boundary conditions. Sample geometries with heterogeneous stress distributions were tested and strain data was extracted. Stepped samples were used to produce multiple regions of stress within a sample. It was proposed that the VFM could be applied for several applications, including finding constitutive parameters to solve the creep model. In further work, SIM could be applied to the stepped sample to provide the full range of data from a single test.

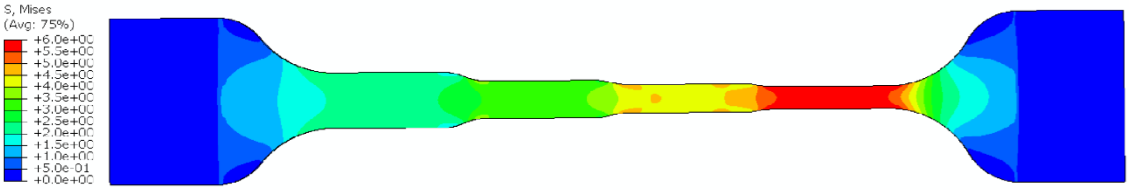

Figure 1: Example of stress distribution in a stepped sample.

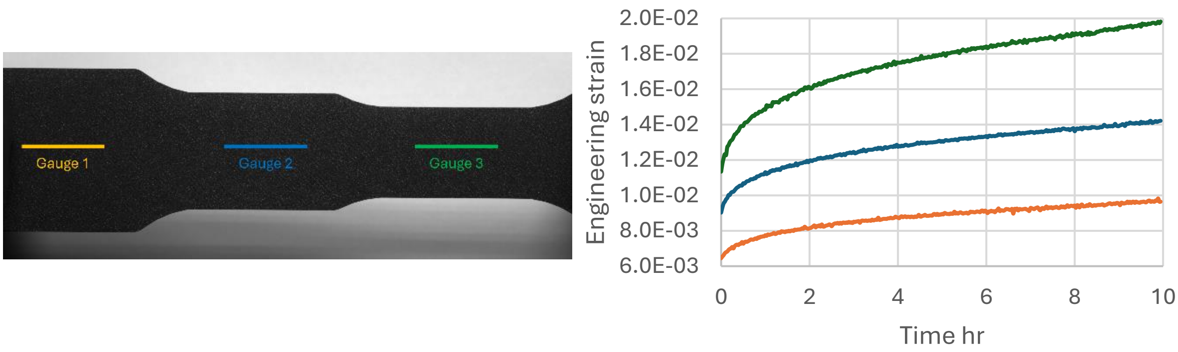

Figure 2: Example of a 3D printed stepped sample under a 10hr constant load to find the engineering strain of each section using 2D-DIC.

Conclusion

There is clear room for improvement in creep testing by generating optimised creep test methodologies that make full use of MT2.0. Understanding the uncertainties in this process is key to the adoption of new testing methods by industry. Validating accelerated creep tests proposed in the literature and using complex geometry samples provide a richer dataset that will ultimately reduce time, expense, and material requirements.

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