Predicting Fatigue in Reactor Components using Artificial Intelligence/Machine Learning and Computational Mechanics

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The effects of environment on fatigue resistance of materials used in operating pressurized water reactor (PWR) and boiling water reactor (BWR) plants require an assessment of environmentally assisted fatigue under extended service conditions. Fatigue modeling of a reactor component is a complex problem due to time-dependent cyclic hardening/softening, the load-sequence effect, and the effects associated with a corrosive environment. Because of this complexity, fatigue is traditionally modeled using experimental data. However, the test-based empirical approach often requires hundreds of fatigue tests to model the intermixing failure modes even for a single material system. To address these limitations, we are developing a hybrid modeling framework for predicting the time-series structural states of nuclear reactor components. This is based on combining artificial intelligence (AI)/machine learning (ML) techniques with computational mechanics. In 2020, we developed an AI/ML guided fatigue testing methodology to improve the U.S. environmental fatigue testing capabilities [1]. Conventional low-cycle fatigue evaluation of nuclear reactor components requires constant-amplitude-strain-controlled fatigue test data (e.g., strain versus life [ε-N] curves). However, controlling strain in a PWR water test can be a great challenge, since an extensometer cannot be placed in a narrow autoclave due to the lack of space inside an autoclave. The difficulty in using an extensometer in a PWR loop led us to use an outside-autoclave displacement sensor, which measures the displacement of a pull-rod-specimen assembly. However, in our earlier study based on in-air fatigue test data, we found that a pull-rod-control-based fatigue test can lead to substantial cyclic hardening/softening resulting in different cyclic strain amplitudes and their rates compared to the target conditions. In 2020, we applied a k-Mean clustering technique to improve the pull-rod-control-based fatigue test method, achieving reasonable gauge-area strain amplitudes and rates. Figure 1(a) shows the grouping of fatigue test data into different clusters based on different sets of test inputs that were selected to maintain a steady-strain amplitude and rate in a pull-rod-displacement-control test. Figure 1(b) compares the strain rate observed under a usual strain control test and under usual (non-AI) pull-rod displacement control and AI-guided pull-rod displacement control fatigue tests. The result shows the AI-guided test improves the strain rate as compared to the usual pull-rod displacement control test.

In addition, we also developed AI/ML-based data-driven models for predicting time-series strain from other sensor

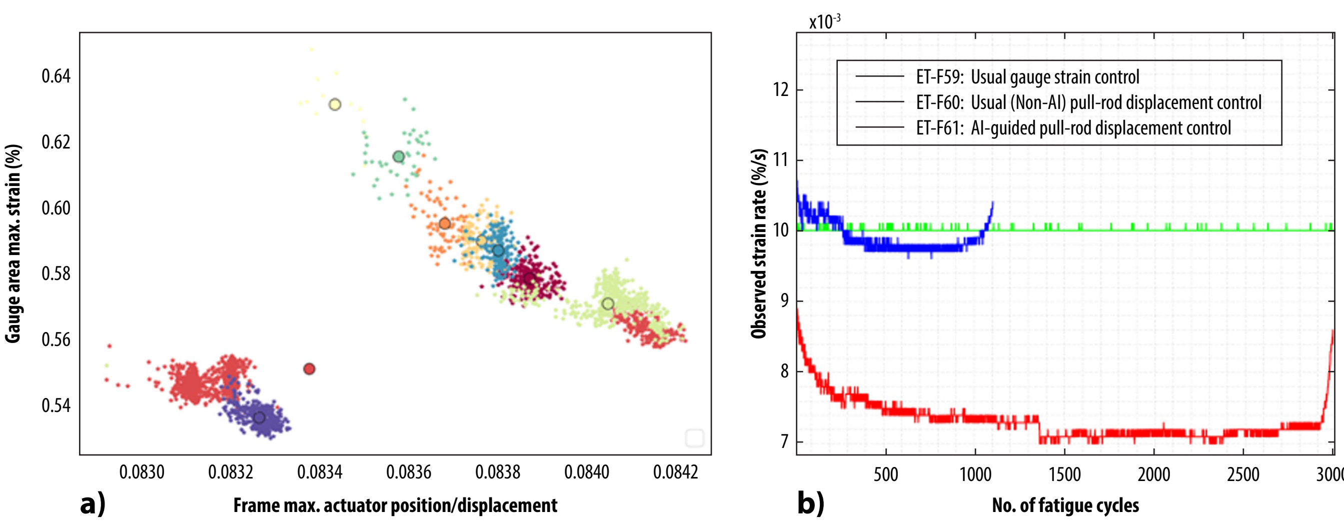

Figure 1. (a) Clustered fatigue test data. (b) Observed strain rates in non-AI and AI-guided fatigue tests and their comparisons with respect to the usual strain control test-based strain rates.

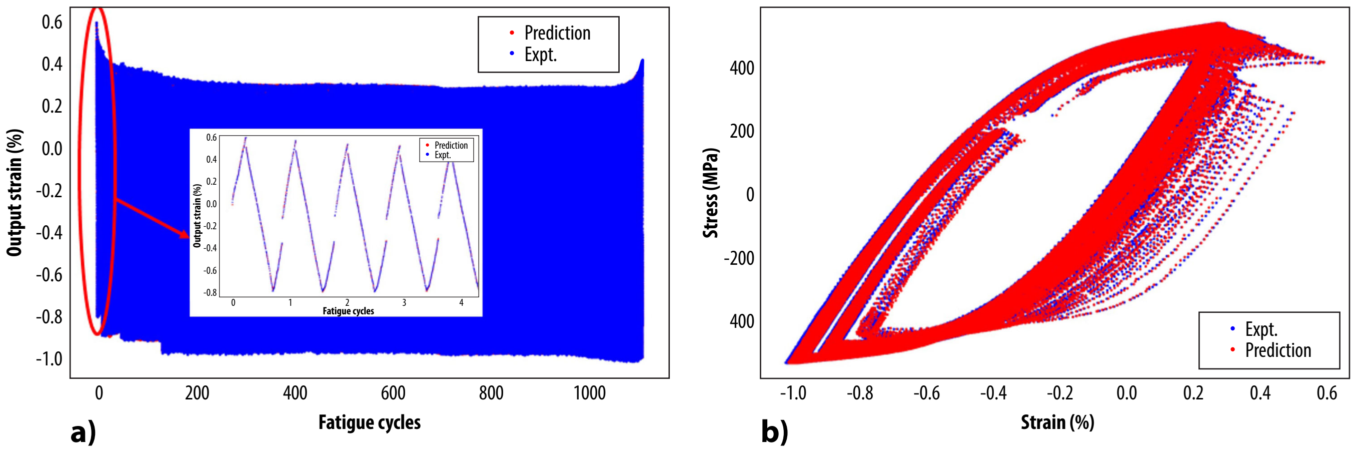

Figure 2. (a) Experiment versus AI/ML model predicted cyclic strains in a dissimilar-metal-weld (508LAS-316SS) subjected to hundreds of fatigue loading cycles. (b) Corresponding hysteresis curves.

measurements, such as load cell, frame pull-rod displacement, and actuator displacement sensors [1]. The framework was trained and validated against in-air fatigue test data for which the strain was measurable. The validated model was used to predict strains in a reactor-coolant fatigue test loop in which direct strain was not measurable. Although the original aim of this research was to improve the U.S. environmental testing and measurement capabilities for conducting fatigue tests in a high-temperature-pressure reactor-coolant flow environment, a similar approach can be used for predicting strain in an actual reactor component in which strain cannot be directly measured due to accessibility constraints. Figure 2 shows examples of model validation results.

To address the issue of data insufficiency, which is more pervasive for weld metals, the hybrid AI/ML and computational mechanics based predictive modeling was applied to model fatigue in dissimilar-metal-weld (DMW) 82/182 [1]. Figure 3 shows some sample results of the predicted versus experimentally observed cyclic stress for the entire fatigue life of a DMW specimen. For the shown test case, the cyclic stress-strain curves were first estimated using AI/ML-based TensorFlow library. Then, the resulting cyclic stress-strain properties were used for predicting the time-/cycle-dependent stresses using a cyclic-plasticity based on the mechanistic or physics model. Predicting stress and strain in reactor components using AI/ML and computational mechanics is on a path to provide more accurate results that will improve light water reactor (LWR) sustainability.

Reference

1. Mohanty, S., and Listwan, J., 2020, "A Hybrid AI/ML and Computational Mechanics Based Approach for Time-Series State and Fatigue Life Estimation of Nuclear Reactor Components," Report No. ANL/LWRS-20/01, Argonne National Laboratory, September 2020.

Figure 3(a) Predicted versus experimentally observed cyclic stress for the entire fatigue life of 82/182 DMW specimen subjected to variable amplitude loading. (b) Magnified view of (a) at half-life.