Finite Element Based Full-Life Cyclic Stress Analysis of 316 Grade Nuclear Reactor Stainless Steel Under Constant, Variable, and Random Fatigue Loading

Although S–N curve-based approaches are widely followed for fatigue evaluation of nuclear reactor components and other safety critical structural systems, there is a chance of large uncertainty in estimated fatigue lives. This uncertainty may be reduced by using a more mechanistic approach such as physics based three-dimensional (3D) finite element (FE) methods. In a recent paper (Barua et al., 2018, ASME J. Pressure Vessel Technol., 140(1), p. 011403), a fully mechanistic fatigue modeling approach which is based on time-dependent stress–strain evolution of material over the entire fatigue life was presented. Based on this approach, in this work, FE-based cyclic stress analysis was performed on 316 nuclear grade reactor stainless steel (SS) fatigue specimens, subjected to constant, variable, and random amplitude loading, for their entire fatigue lives. The simulated results are found to be in a good agreement with experimental observation. An elastic-plastic analysis of a pressurized water reactor (PWR) surge line (SL) pipe under idealistic fatigue loading condition was performed and compared with experimental results.

[DOI: 10.1115/1.4040790]

1 Introduction

The current design codes and standards [1–5] for assessing fatigue life of nuclear reactor components are usually based on stress/strain versus life (S–N) curves. In stress versus life approach stress within the elastic limit are applied and stress amplitude versus life is determined. In strain versus life approach (e.g., Coffin–Manson rule) significant plastic strain is applied and the number of cycles to failure is determined as a function of plastic strain. In recent years, several improvements to fatigue design (S–N) curves have been recommended by various researchers. Some of the improvements are considering the effects of environments [6,7], surface finish [8], mean stress [9], and hold time [10]. To assess fatigue damage under variable/random amplitude loading using the fatigue design (S–N) curves, currently, the linear damage accumulation rule [11] along with rainflow cycle counting method [12] is used. Although the S–N curve-based fatigue evaluation approaches allow engineers to quickly assess the components’ design lives, these curves are empirical curves and are estimated based on final life of a fatigue-test specimen without considering cumulative and time-dependent damage evolution in a material. Basically, they are not based on firm mechanistic understanding of how the stress–strain behavior of material evolves over time and its impact on overall fatigue lives. Moreover, as the S–N curves are generated from uniaxial fatigue test data and may not truly represent the multiaxial stress–strain state at the component level. Furthermore, the linear damage accumulation rule does not take into account the nonlinear and time-dependent material hardening/softening of material. Additionally, as many different codes and standards [13] use different approaches (e.g., based on stress or strain range methods), it is sometimes difficult to decide which method to use. By adopting more mechanistic-based approaches for fatigue evaluation, the issues associated with present fatigue life evaluation methods can be greatly reduced. Moreover, with the current availability of advanced computation tools, such as the finite element (FE) method, along with high-performance computing, it may be possible to model a component or an overall system more mechanistically.

Nuclear reactor components experience arbitrary cyclic loading during day-to-day operations due to the changes in mechanical and thermal loadings as the system goes from one load set (e.g., plant startup, shut down, or change in heat output or pressure) to another load set. In some situations, cyclic loading may induce large-amplitude stress reversals, which may exceed the elastic limit. Under these conditions, the behavior of materials such as 316 stainless steel (SS) may become inelastic and may exhibit related phenomena such as the Bauschinger effect, cyclic hardening/softening, and mean stress relaxation [14]. Thus, the development of advanced models that can address the aforementioned phenomena and the successful incorporation of those models into a generalized finite element code are necessary to ensure more accurate evaluation of the mechanistic-based structural integrity of reactor and other safety-critical components. In previous work [15–19], an evolutionary cyclic plasticity model was presented for key reactor materials, such as 316 SS base, 508 low alloy steel base, and 316 SS-316 SS weld. It is assumed that the material yield surface and the corresponding hardening and softening behavior evolve over time. Thus, a single set of material parameters is not enough to predict material behavior for the entire fatigue life time. We demonstrated that material parameters (estimated from uniaxial fatigue experiment) such as elastic modulus, yield stress, and kinematic hardening parameters do not stay constant but evolve over the lifetime of the specimen. Thus, material parameters should be functions of time or other physical states of

Contributed by the Pressure Vessel and Piping Division of ASME for publication in the Journal of Pressure Vessel Technology. Manuscript received March 22, 2018; final manuscript received June 23, 2018; published online August 2, 2018. Associate Editor: Steve J. Hensel.

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the material which can be defined as field variable. The use of field variable dependent material properties is important for accurate estimation of the stress–strain state of a component that has a complex geometry or is subjected to complex fatigue loading (e.g., random amplitude loading). In addition, the nuclear reactor components are subjected to thermal cyclic loading which requires use of temperature dependent material properties. Use of field variable-dependent material modeling will allow to take into account the temperature-dependent material behavior during FE simulation of large nuclear components. Based on the evolutionary cyclic plasticity model, a fully mechanistic fatigue modeling approach for 316 stainless steel was presented in a recent paper [20]. Material parameters as functions of time or accumulated plastic strain energy (APSE) were considered. In this work, the evolutionary cyclic plasticity model is incorporated into a commercial FE code. Various fatigue experiment scenarios are three-dimensional (3D) modeled using the developed FE modeling framework and verified with experimental data. Results from elastic-plastic analysis of a pressurized water reactor (PWR) surge line (SL) pipe using the FE modeling framework are also presented.

2 Finite Element Implementation of Evolutionary Cyclic Plasticity Model

The proposed evolutionary cyclic plasticity model is developed based on Chaboche [21–23] or Armstrong–Frederick [24] type analytical expressions for nonlinear kinematic hardening and can be expressed as

$$d\sigma = \frac{2}{3} C_1, d\varepsilon^{pl} - \gamma_1, x dP$$

(1)

where $C_1$, is a proportional constant that gives a linear relation between the increment in the back stress, $d\sigma$, and the increment in the plastic strain, $d\varepsilon^{pl}$, while $\gamma_1$, describes the rate at which the back stress decreases with the increase in accumulated effective plastic strain, $dP$. At any instant, the von Mises yield function $f_Y$ corresponding to the evolutionary cyclic plasticity model, can be expressed as

$$f_Y(\sigma, \varepsilon) = \frac{1}{2} \left( S - \sigma \right)^T : \left( S - \sigma \right) - \sigma_y^{\nu} = 0$$

(2)

where $\sigma$ is the stress tensor at that instant, $\varepsilon$ is the corresponding back stress tensor, $S$ is the deviatoric stress tensor, and $\sigma_y^{\nu}$ is the yield stress. Note that the subscript $\nu$ is used to demonstrate that the material parameters are not constant as they are in the case of conventional cyclic plasticity model, rather they are variable and can be function of time or fatigue cycle/block or any other physical state (e.g., APSE). The complete details of the model development and time-dependent material parameter estimation technique are discussed elsewhere [15,20].

The cyclic plasticity model was incorporated into the developed FE code for Chaboche-type models in the ABAQUS/Standard environment [25]. A user subroutine was developed to enable the use of time- or APSE-dependent material properties in the implementation of the evolutionary cyclic plasticity model into ABAQUS. The time- or APSE-dependent material properties such as elastic modulus, yield stress, and kinematic hardening for 316 SS can be found elsewhere [20].

3 Experimental

Uniaxial fatigue tests under constant, variable, and random amplitude loading were conducted on 316 SS base metal using small hourglass specimens. All the tests were performed in air at 300 °C using a hydraulic-controlled mechanical testing system test frame. The details of the specimen geometry and test setup can be found in a previous Argonne report [15]. A 0.5% strain amplitude was applied during constant amplitude test. During the variable amplitude test, a repetitive block consists of 12 cycles with different strain amplitudes was applied (Fig. 1(a)), while a repetitive block of random strain inputs was applied to the specimen during the random-amplitude fatigue test (Fig. 1(b)). The strain inputs during random amplitude test were selected based on a MATLAB-based random number generator. During all the strain-controlled fatigue experiments, 316 SS material exhibited significant stress hardening followed by stress softening.

4 Finite Element Modeling of Fatigue Experiments

One of the major tasks in mechanics-based fatigue modeling is to develop an FE modeling framework based on the evolutionary cyclic plasticity model. The FE modeling framework can then be used for extrapolating uniaxial fatigue test-based material behavior to a multiaxial domain for stress analysis and fatigue evaluation of realistic reactor components, which are ideally subjected to multiaxial loading. Compared to the conventional FE model, the evolutionary cyclic plasticity FE model would be able to predict the cyclic hardening and softening behavior of a component. It is assumed that, similar to the conventional tensile-test-based FE model, which is extensively used by industry for stress analysis of metallic components subjected to monotonic loading transients, the proposed evolutionary cyclic plasticity-based FE model framework would be able to simulate a component subjected to
cyclic loading. Also, similar to the tensile-test-based FE model, it is assumed that the translation from a uniaxial to multiaxial fatigue-test-based model is isotropic and based on the assumption that the metallic components are homogeneous, with material behavior being similar in all directions. However, before the new FE model can be used for component-level stress analysis, the FE framework must be validated with experimental test cases. A single 3D eight-node brick element representing the gauge section (0.5 in) was used for FE simulation of the fatigue experiments. A single element was used to reduce the computational time for simulating thousands of fatigue cycles. In the proposed FE model, the cross section of the 3D brick element (hexahedral eight-node linear brick element: C3D8) was considered equal to the nominal cross section of the specimen. The geometry information of the actual specimen and FE modeled equivalent specimen is shown in Fig. 2. Simulations representing strain-controlled fatigue tests with constant, variable, and random amplitude loadings were performed by applying corresponding deformation in the z-direction, as shown by the arrows in Fig. 2.

4.1 Time-Based Modeling. Two 3D-FE simulations representing the constant- and variable-amplitude experiments using time-dependent material properties were presented. The 3D-FE simulated axial stress along with the experimentally observed stress for the entire life of constant- and variable-amplitude fatigue specimens are shown in Figs. 3(a) and 4(a), respectively. Magnified versions of Figs. 3(a) and 4(a), demonstrating initial stress hardening and then softening followed by stabilized cycles, are shown in Figs. 3(b) and 4(b), respectively. Figures 3(b) and 4(b) demonstrate that model predicts not only the stress hardening but also the stress softening with significant accuracy. The model also predicts the stabilized cycles, as seen in Figs. 3(b) and 4(b), which represent a quasi-stable state during fatigue. Most importantly, as shown in Figs. 3(c) and 4(c), it accurately predicts the fast stress drop toward the end of the fatigue life of the specimen, which represents unstable or rapid crack propagation.

4.2 Accumulated Plastic Strain Energy-Based Modeling. A time-based approach was used for constant- or variable-amplitude loading test cases, but could not be used to model fatigue behavior under random loading. This is due to the complexity in tracking the time associated with load reversals. To solve this issue, a more versatile approach based on APSE is used. In this work, APSE-based 3D-FE modeling was performed for all the fatigue test cases such as constant-, variable-, and random-amplitude tests. Note that, for the APSE-based modeling, the material parameters estimated from the variable-amplitude test were used. The predicted axial stress profiles from the APSE-based 3D-FE simulation of constant- and variable-amplitude fatigue tests were compared with the experimentally observed stress profiles in Fig. 5. As seen from the figures, the simulated stress profile exhibits all the characteristic behavior (initial hardening followed by softening and stabilized cycles and rapid crack propagation toward the end of fatigue life) of 316 SS under constant- and variable-amplitude fatigue loads. However, the APSE-based prediction is not as close to the experimental data as the time-based prediction. For example, the predicted fatigue life...
from simulation was found to be 6151 cycles, while the experimentally observed fatigue life was 6914 cycles under constant amplitude loading. However, considering the robustness it provides in predicting material behavior under any arbitrary loading, including random-amplitude, the APSE-based prediction is considered to be a reasonable prediction.

Figure 6(a) shows the 3D-FE simulated axial stress profiles along with the experimentally observed stress history of random-amplitude test. The figure shows that the model can accurately predict all the characteristic behavior (initial hardening followed by softening and stabilized cycles and rapid crack propagation toward the end of fatigue life) of 316 SS under random-amplitude loading. A magnified version of Fig. 6(a) is shown in Fig. 6(b). The experimental and predicted stresses shown in this figure correspond to the strain input shown in Fig. 1(b) (magnified inset). The corresponding stress–strain hysteresis plot is shown in Fig. 6(c). Figure 6(c) depicts the intricacy in the stress–strain variation during random loading. Despite this variation, the FE model prediction of stress response is reasonably good.

4.3 Summary of Finite Element Modeling Results in Context of Predicting Maximum Hardening Stress and Fatigue Life of Specimens. Results from the 3D-FE modeling are summarized here to provide an overall picture of the predicted results and to compare them with the experimental results. Table 1 compares the experimentally observed maximum hardening stress and fatigue life during all the fatigue tests with those predicted through time-based and APSE-based 3D-FE modeling. As seen from the table, the maximum hardening stress predicted through 3D-FE simulation is more than 90% accurate for all the fatigue test cases. To determine the fatigue life of the specimens, a failure criterion is required. As all the tests were performed uniaxially and under strain control, a drop in uniaxial stress amplitude in the
The direction of applied strain was used for determining a failure criterion for the fatigue tests. Conventionally, a 25% load-drop from the maximum load is used as a failure criterion of fatigue specimens. The experimental and predicted lives for all fatigue tests and the 3D-FE modeling cases are given in Table 1. As seen from the table, the accuracy in predicted life from time-based 3D-FE simulation is almost 100% for both constant- and variable-amplitude fatigue tests. Because the time-based approach cannot be used for predicting material behavior under random-amplitude loading, the APSE-based approach was used. The predicted lives from APSE-based modeling are found to be 89%, 93%, and 95% accurate for constant, variable, and random amplitude tests, respectively.

### Table 1 Experimentally observed and predicted (3D-FE modeling) maximum hardening stress and fatigue life

<table>
<thead>
<tr>
<th>Amplitude type</th>
<th>Maximum hardening stress (MPa)</th>
<th>Fatigue life unit</th>
<th>Fatigue life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment</td>
<td>Time-based</td>
<td>APSE-based</td>
</tr>
<tr>
<td>Constant</td>
<td>245.5</td>
<td>251.2</td>
<td>240.8</td>
</tr>
<tr>
<td>Variable</td>
<td>234.9</td>
<td>241.6</td>
<td>241.5</td>
</tr>
<tr>
<td>Random</td>
<td>223.5</td>
<td>N/A</td>
<td>240.7</td>
</tr>
</tbody>
</table>

*Time-based modeling is not possible for random amplitude loading.

5 Finite Element Modeling of a Pressurized Water Reactor Surge Line Pipe

The mechanics-based fatigue-modeling work is aimed at developing an FE modeling framework to estimate the life of nuclear reactor critical safety components. The overall picture of this modeling framework is shown in Fig. 7. As shown in the flowchart, mechanics-based fatigue modeling starts with uniaxial fatigue experiments followed by material model development along with material model parameter estimations. The details of this work and related results are discussed in Refs. [15,20]. The next step is validation of the evolution cyclic plasticity model through analytical and 3D-FE modeling of the specimen. Results from the analytical modeling of 316 SS specimens under uniaxial fatigue loading are presented in Ref. [20]. The 3D-FE modeling results of the fatigue specimens are discussed in Sec. 4. In the final step, as seen in Fig. 7, the developed FE model framework and material model validation of these results are presented.
parameters are utilized to extrapolate uniaxial fatigue test-based material behavior to a multiaxial domain for structural (ST) analysis of nuclear reactor components subjected to multiaxial fatigue loading. This section presents some preliminary results from the final step of proposed fully mechanistic fatigue evaluation framework.

An elastic-plastic analysis of a PWR SL pipe was performed. The FE mesh of the PWR SL along with the boundary conditions and the direction of applied displacement is shown in Fig. 8(a). Cyclic displacements equivalent to ±0.5% constant strain amplitude in z-direction were applied to nodes near one of the ends, as shown in Fig. 8(b). Application of 0.5% strain amplitude is considered reasonable. The profile of the applied cyclic displacement is shown in Fig. 8(c).

The motivation of selecting an equivalent constant strain amplitude is based on a computational fluid dynamics-heat transfer analysis and subsequent ST analysis results of SL pipe under outsurge condition. The related analysis results are discussed in Ref. [26]. However, unlike the actual case as in Ref. [26], where the strain loading is multiaxial due to multiaxial actual thermal-mechanical loading, in this work, the strain was applied only along the vertical direction. There are two reasons for applying strain loading along only one direction: First, applying multiaxial strain loading at different nodes (according to actual loading conditions) in FE model is nearly impossible. Second, to compare the life of the SL pipe with the experimentally observed life of the uniaxial specimen (constant-amplitude fatigue test), a similar loading condition for the component was maintained. Through this idealistic loading case, this study tries to determine whether the FE framework based on the evolutionary cyclic plasticity model can be utilized for component-level elastic-plastic analysis and studies how the stress profiles in components differ from those in uniaxial fatigue specimens.

The APSE-based modeling approach was used for structural simulation of the PWR SL pipe. Figure 9 shows the contour plot of the von Mises stress at a typical instant. As shown in the figure, maximum stress concentration occurs in the elements that are directly subjected to the applied deformation. One of these elements, as shown in the magnified inset in Fig. 9, is selected as the element of interest for analyzing results from simulation. All the simulated stress-strain results presented are at the centroid of this element. Figure 10(a) shows the simulated strain in the direction (z-axis) of applied displacement as a function of fatigue cycles. As shown in the figure, the strain amplitude is 0.5%. Note that the simulation was performed only for 100 fatigue cycles. The
simulated stresses in the principal coordinate system are shown in Figs. 10(b), 10(c), and 10(d) for maximum, mid, and minimum principal stress, respectively. The figures also compare the simulated principal stresses with the values calculated from the uniaxial fatigue experiment. Because of the multi-axiality, simulated principal stress amplitudes are very different from experimental amplitudes. However, the evolutionary cyclic plasticity model uses von Mises stress for checking the yield criteria during elastic-plastic analysis, von Mises stress should be used for comparing simulation results with experimental observations. The comparison between von Mises stress amplitudes of experimental observation and those of simulation is shown in Fig. 11. The plots indicate material hardening followed by softening in the simulated stress profile. This behavior is typical of 316 SS as observed during uniaxial fatigue tests. The value of maximum hardening von Mises stress from simulation is found to be 245.7 MPa, which is very close to the experimentally observed value (244.2 MPa).

Note that, due to long simulation time (for example 29 h for 20 fatigue cycles using 1 cpu and 1 gpu) the PWR SL component was simulated for only 100 fatigue cycles. However, fully mechanistic determination of the fatigue life of PWR SL pipe requires elastic-plastic analysis of the component for thousands of fatigue cycles. Future work includes high performance computing implementation of the FE modeling framework so that large components/systems can be simulated for thousands of fatigue cycles for fully mechanistic fatigue evaluation.

6 Conclusion

An FE modeling framework is developed for 316 grade nuclear reactor stainless steel SS to extrapolate material behavior under uniaxial fatigue test to multiaxial domain for structural analysis.
of nuclear reactor components subjected to multiaxial fatigue loading. Two modeling frameworks are discussed: a time-based approach to model constant- and variable-amplitude fatigue tests and a more generalized and robust approach based on APSE to predict material behavior under any arbitrary loading inputs, including random-amplitude cyclic loading. Several fatigue experiment scenarios such as constant, variable, and random amplitude loading are 3D-FE modeled. The simulated stress is found to capture all the important stages of material behavior (initial hardening, softening, stabilized cycles, and finally rapid crack propagation followed by failure) during the entire fatigue life of the specimens with good accuracy. The predicted fatigue life is found to be more than 90% accurate for all the test cases. An elastic-plastic analysis of a PWR SL pipe under idealistic loading condition is performed to demonstrate mechanics based fatigue life estimation without using conventional $\Delta \sigma - N$ curve based approach. Simulated (up to 100 cycles) von Mises stress amplitudes are found to be in reasonable agreement with experimental results.

Acknowledgment

This research was supported through the U.S. Department of Energy’s Light Water Reactor Sustainability program under the work package of environmental fatigue study, program manager Dr. Keith Leonard.

Funding Data

- U.S. Department of Energy’s Light Water Reactor Sustainability program.

References