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Effect of Cyclic Loading Mode on the Failure of Structural Materials under Extremely Low Cycle Fatigue Regime

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1. Introduction

Understanding the failure characteristics of materials in the extremely low-cycle fatigue (ELCF) regime is important for reliably evaluating the structural integrity of system, structure, and components (SSCs) in nuclear power plants (NPPs) under the beyond design-based earthquake (BDBE) condition [1,2]. Thus, a number of experimental studies have been conducted to evaluate the failure characteristics of structural materials in the ELCF regime [3-5]. However, most of studies have been conducted under displacement-controlled cyclic loadings, although seismic load has both displacement- and load-controlled cyclic loading characteristics. Thus, it is necessary to clarify the effect of cyclic loading mode on the failure characteristics of materials. In this study, failure tests were performed under both displacement- and load-controlled cyclic loads with large amplitudes that could cause ELCF damage. From the results, the failure characteristics, such as failure cycles and failure mode, were evaluated for each loading mode, and the effect of loading mode on the failure characteristics of materials in the ELCF regime was investigated.

2. Experiments

SA508 Gr.1a low-alloy steel (LAS) and SA312 TP316 stainless steel (SS) piping materials, which are commonly used as structural materials in NPPs, were used for the experiment. In the tests, round-bar type notched specimens with notch radii (R_n) of 1.5mm and 6.0mm were used. Fig. 1 illustrates the dimensions of the specimens used for the experiments.

All tests were conducted at RT under a quasi-static rate. The displacement- and load-control mode cyclic loads were regarded in the tests. In the displacement-controlled test, fully reversed cyclic displacements with constant amplitudes (δ_a), ranging from 0.4 % to 2.4 %., were applied. Here, δ_a is the displacement amplitude normalized with respect to the gauge length. In the load-controlled test, also, fully reversed cyclic loads with constant amplitudes (P_a), ranging from 75.0%P_{mono} to 99.7%P_{mono}, were applied. Here, P_{mono} is the collapse load for each type of the specimen obtained from the monotonic test.

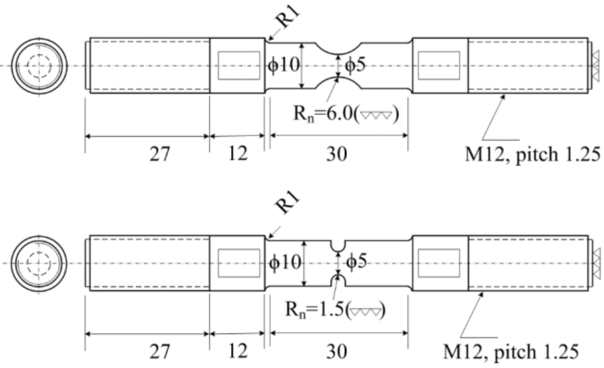

Fig. 1. Specimens used for experiment

In all tests, a servo-hydraulic universal testing machine with a 100kN load-cell was used, and an extensometer with a gauge length of 12.5 mm was used to measure the displacement. Since it is difficult to directly determine the strain from the measured displacement for notched specimen, the plastic strain amplitude corresponding to each displacement amplitude was calculated by finite element analysis.

3. Results and Discussion

Tests under displacement- and load-controlled cyclic loads were carried out. Fig. 1 shows samples of normalized load vs. displacement curves tested for both cyclic loading modes.

Displacement-controlled cyclic test showed that the failure cycles of both materials increased linearly with decreasing plastic strain amplitude in the log-log coordinates. Regardless of the material type, the slopes of failure cycles vs. plastic strain amplitude data for both notch radii were nearly identical, and were similar to those of the same grade material under the conventional LCF regime. This implies that the failure characteristics under large amplitude displacement-controlled cyclic load are less dependent on the stress and strain concentration and are the same as those observed in the LCF regime. This is well supported by the examination of the fracture surface. In all specimens, multiple cracks initiated on the surface and propagated inward. That is, all specimens showed the same failure mode, i.e., fatigue failure, regardless of the material type, notch radius, and displacement amplitude.

In the results of the load-controlled cyclic test, unlike in the displacement-controlled cyclic load, the failure cycles varied bi-linearly with the normalized load amplitude in the log-log graph. That is, at the large amplitudes ($P_a/P_{mono} \approx 1.0$), the failure cycles ranged from 1 to 10 cycles for SA508 Gr.1a LAS and ranged from 1 to 40 cycles for SA312 TP316 SS. At the small amplitudes of $P_a/P_{mono} < 0.95$, the failure cycles decreased linearly with decreasing the load amplitude. Large scattering of failure cycles at large amplitudes is associated with the cyclic hardening of the material. Also, as a result of examining the fracture surface, it was found that the failure mode of the specimen under load-controlled cyclic load was different from that under displacement-controlled cyclic load. That is, the fracture surface tested at large amplitudes showed a cup-cone mode, which is a ductile fracture typically observed under monotonic loads. However, in the specimens tested at small amplitudes, the fracture surface exhibited multiple-cracks initiated on the surface, which is a typical failure mode of LCF. Thus, it is seen that the failure mode under load-controlled cyclic load is ductile fracture and fatigue failure, depending on the amplitude of the cyclic load. Also, the magnitude of the load amplitude at which the failure mode is distinguished depends on the type of materials.

4. Conclusions

In this study, failure tests were performed on the notched specimens under displacement- and load-controlled cyclic loads, and the failure cycles of the specimen were obtained for each test condition. In addition, the fracture surface was examined to determine the failure mode of the specimen. From the results, the effect of the cyclic loading mode on the failure characteristics was investigated.

Acknowledgements

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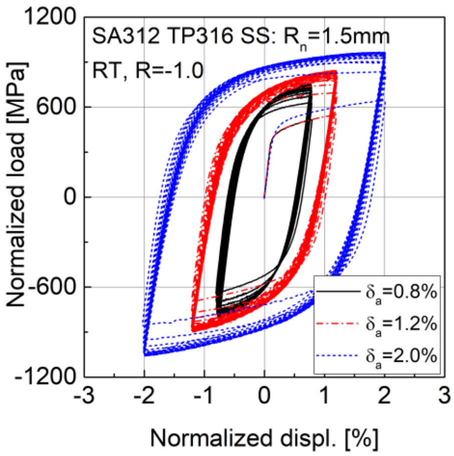
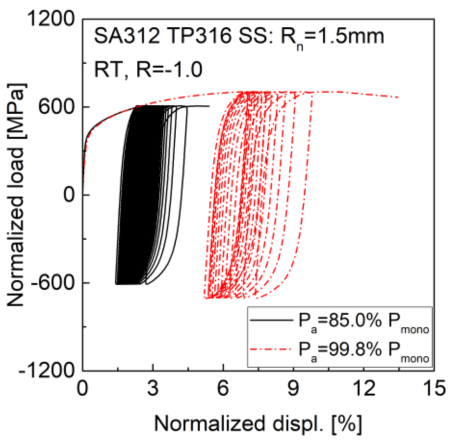


(a) Displacement-control mode



(b) Load-control mode

Fig. 2 Samples of load-displacement curves under large amplitude cyclic loads