Effect of Load Ratio on the Deformation and Failure Behaviors of Nuclear Structural Materials under Large Amplitude Load-controlled Cyclic Loads

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1. Introduction

System, structure, and components (SSCs) of nuclear power plants (NPPs) are designed to have sufficient safety margins under design basis earthquake (DBE) events. However, under beyond design basis earthquake (BDBE) events, as a large amplitude cyclic load is applied, the possibility of failure due to cyclic plastic deformation is raised in the area where stress and strain are concentrated. Therefore, in order to evaluate the structural integrity for SSCs of NPPs under BDBE, it is important to clearly understand the deformation and failure behaviors in vulnerable area where stress and strain are concentrated under large amplitude cyclic loads. Typically, the effect of stress and strain concentrations on the deformation and failure behaviors of materials are well known under low amplitude cyclic loads [1-3]. However, the deformation and failure behaviors under large amplitude cyclic loads are not yet clearly understood.

Thus, this study conducted cyclic failure tests using notched-bar type specimen with two different notch radii. A large amplitude, load-controlled cyclic load with various maximum loads and load ratios was applied to the test. All tests were conducted at room temperature (RT) under a quasi-static rate. As a result, the load-displacement behavior, failure cycle, and failure mode were analyzed, and the effect of the maximum load and load ratio on the deformation and failure behaviors was investigated.

2. Experimnets

2.1 Materials and Specimen

SA508 Gr.1a LAS and SA312 TP316 SS piping materials, which are commonly used as structural materials in NPPs, were used for the experiment. In general, for fatigue tests, round-bar type specimens designed according to ASTM E606-92 with a length (l) of 2 to 4 times their diameter (φ) are used [4]. In this experiment, however, hourglass-shaped round-bar type specimens with notch radii (R_n) of 1.5mm and 6.0mm were used to investigate the effect of cyclic loading on deformation and failure behaviors under different stress states. Fig. 1 illustrates the dimensions of the notched bar specimens used for experiments.

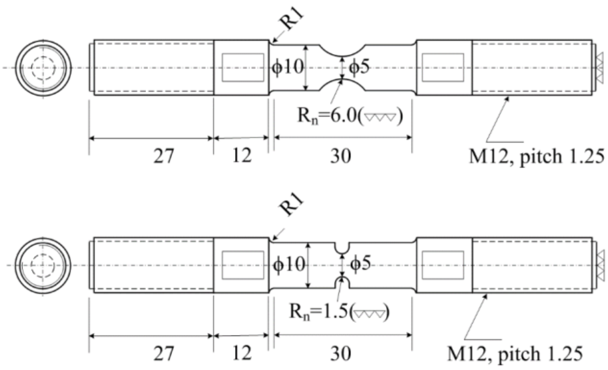


Fig. 1. Specimens used for experiment

2.2 Test Condition and Procedures

All tests were conducted at RT, and the load-controlled cyclic loads with various maximum loads and load ratios were applied. For each type of specimen, four maximum loads (P_{max}) corresponding to 75% to 99.8% of monotonic collapse load ($P_{max,mono}$) and load ratios of 0.0, -0.5, -1.0, and -1.1 were regarded for the test. 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 strain.

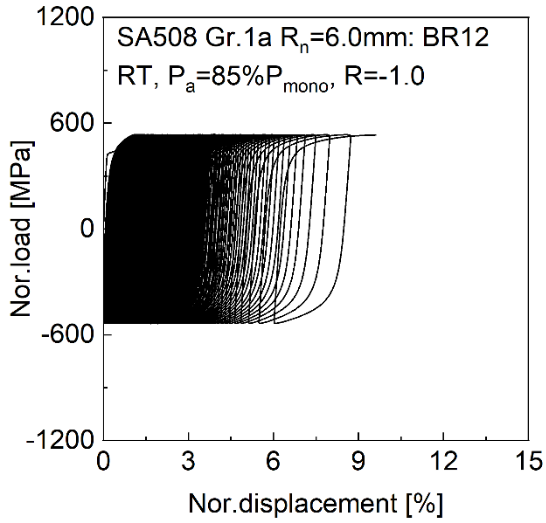
3. Results and Conclusions

Fig. 2 shows samples of the load-displacement curves form cyclic test. In order to exclude the influence of the specimen dimension, the load and displacement in Fig. 2 were normalized to the cross-sectional area of the notch and the gauge length of extensometer, respectively. As shown in Fig. 2, the hysteresis loop shifted and the area of hysteresis loop gradually increased as the number of cycles increased at a constant amplitude. The shift of the hysteresis loop and the change in area depended on the applied load ratio.

In the case of SA508 Gr.1a LAS, the failure cycles increased as the compressive load decreased, *i.e.*, the load ratio increased, for all maximum loads regarded in the test. The same trend was observed regardless of the notch radius. For the SA312 TP316 SS, the trend was slightly different from that for SA508 Gr.1a LAS. When the cyclic loads with a maximum load less than 85% $P_{max,mono}$ were applied, the failure cycles increased as the compressive load decreased. However, the failure cycles increased with increasing the compressive load, when applying the cyclic loads with a maximum load of

99.8% $P_{max,mono}$. The increase in the failure cycles of the specimen with decreasing the compressive load is explained by the decrease in the amplitude of the cyclic load. On the other hand, in the case of SA312 TP316 SS subjected to a cyclic load with a very large maximum load, the increase in the failure cycles with increase in compressive load is associated with a large cyclic hardening effect. That is, as the compressive load increased, the cyclic hardening increased and the load-carrying capacity of the specimen was improved.

Fracture surface examination showed that most of SA508 Gr.1a LAS and SA312 TP316 SS failed by ductile fracture and some specimens failed by fatigue crack growth. For the SA508 Gr.1a LAS, fatigue failure was more likely to occur as the maximum load and load ratio of cyclic loading were smaller. The larger the notch radius, the smaller the maximum load at which fatigue failure occurred. This failure mode was also observed in the SA312 TP316 SS specimen. Only, when comparing with SA508 Gr.1a LAS specimen, the load ratio at which fatigue failure occurred at the same maximum load was slightly large.



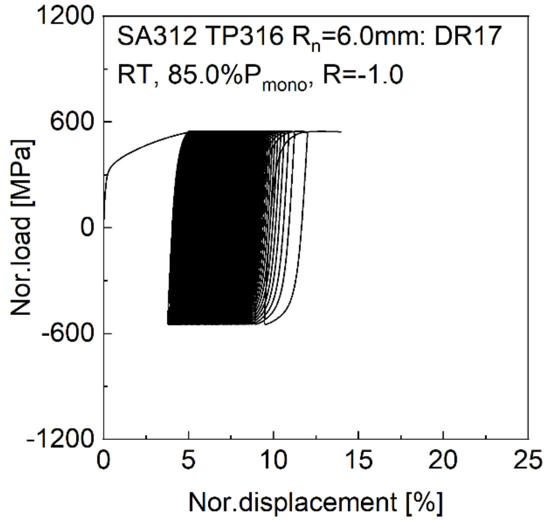


Fig. 2. Normalized load-displacement curves of the SA508 Gr.1a LAS and SA312 TP316 SS

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