Failure Behaviors of Pipes with Circumferential Surface Crack under Large Amplitude Cyclic Loads

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1. Introduction

The structural integrity of system, structure, and components (SSCs) of nuclear power plants (NPPs) under seismic events is an important issue in the design of NPPs [1]. As several NPPs have experienced large earthquakes exceeding design basis, the safety-related SSCs are also required to be ensure the structural integrity under beyond design basis earthquake as well as design basis earthquake [2]. Thus, the rational structural integrity assessment procedures have been developed and applied to seismic margin analysis of SSCs under excessive seismic loads. However, these procedures do not take into account the effect of cracks on the integrity of SSCs, although cracks have been detected in some SSCs of long-term operated NPPs. In this regard, several experiment and numerical studies have been performed to develop an appropriate assessment procedure for cracked pipe under excessive seismic loads [3]. However, most of these studies have focused on pipes containing through-wall crack (TWC).

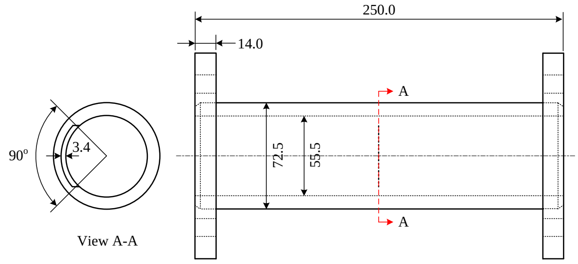
Therefore, this study conducted cyclic fracture tests using small-scale pipe specimen with circumferential surface crack (SC). The tests were conducted under displacement-controlled and load-controlled cyclic loads without internal pressure at RT. From the results, the effect of cyclic loads on the load carrying capacity, deformation, and number of cycles to failure of pipes with SC was evaluated.

2. Experiment

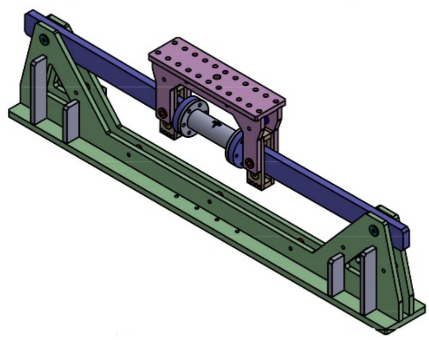
Small-scale pipe specimens with circumferential SC machined by EDM at inside wall were used for the tests (Fig. 1(a)). The specimen has an outer diameter of 72.5 mm, a thickness of 8.5 mm, and a length of 250 mm. The surface crack has a uniform depth (*a*) of 40% of thickness (*t*) and a circumferential angle (2θ) of 90º. The specimen was made of SA508 Gr.1a low-alloy steel (LAS) and SA312 TP316 stainless steel (SS) pipes. Table 1 summaries the mechanical properties of both pipes.

Small-scale pipe specimens were tested under quasi-static 4-point bending load. To apply bending load, both ends of the specimen was connected with loading bars. Fig. 1(b) shows the schematic view of test set-up. Displacement-controlled cyclic loads and load-controlled cyclic loads were applied in the tests. In addition, monotonic test was also conducted to obtain the reference data for each pipe materials.

In the displacement-controlled cyclic tests, two types of cyclic loads were applied. One was to apply a constant displacement increment for each cycle. This is to investigate the cyclic loading effect on the load-carrying capacity and deformation ability of pipe with SC. The



(a) Small-scale pipe specimen



(b) Schematic view of test set-up

Fig. 1 Specimen and test set-up for the experiment

Table 1 Mechanical properties of the SA508 Gr.1a low-alloy steel (LAS) and SA312 TP316 stainless steel (SS) pipes used for the experiment

Materials	Yield stress, YS [MPa]	Tensile stress, TS [MPa]	Uniform elongation, UE [%]	Total elongation, TE [%]
SA508 Gr.1a LAS	338.3	516.4	17.1	32.3
SA312 TP316 SS	265.9	615.8	49.9	68.3

other was to apply incremental multiple loading blocks. Each loading block consisted of 20 cycles with a constant displacement amplitude, and block loading was applied until the crack penetrated while increasing the amplitude of loading block. The displacement amplitudes of loading blocks were determined to induce maximum stress levels from 1.67 to 5 times stress limit of safe-shutdown earthquake (SSE). This test is to investigate ultimate strength of cracked pipes under large amplitude displacement-controlled cyclic loads. In the load-controlled tests, the cyclic loads with constant amplitude and load ratio were applied. The load amplitudes and load ratio applied to the test were $P_a = 75\%P_L, 85\%P_L$ and $R = -1.0$. Where P_L is the limit load of pipe specimen with SC. The cyclic load was applied until the surface crack penetrated. This is to investigate the number of cycles to failure under large amplitude load-controlled cyclic loads.

3. Results and Conclusions

The displacement incremental cyclic tests showed that, regardless of pipe material, the maximum load and displacement to maximum load were decreased when applying cyclic load compared to monotonic load (Fig. 2(a)). In particular, the decrease in the displacement to maximum load was significant. This indicates that the displacement-controlled cyclic load slightly reduces the load-carrying capacity, but significantly decreases the deformation ability of pipes with SC. These are consistent with observations from the tests on CT specimen and pipe specimen with TWC [4,5]. The ultimate strength tests conducted under incremental multiple block loads showed that the surface crack penetrated when applying cyclic loading block with displacement amplitude corresponding to 3×SSE and 5×SSE (Fig. 2(b)). This implies the pipe has sufficient margin for failure under large amplitude displacement-controlled cyclic loads, even though the pipe contains a sizable surface crack. Load-controlled cyclic tests showed that the number of cycles to penetration was larger than 20 cycles under cyclic load with $P_a = 85\%P_L$ for both pipe materials. Considering the assumption of 20 cycles of cyclic load in the fatigue design of NPPs against seismic loads, the present result indicates that the pipe is safe enough under load-controlled cyclic load with an amplitude of $P_a = 85\%P_L$, even though it has a surface crack with depth of 40% of the thickness and circumferential angle of 90°.

Acknowledgment

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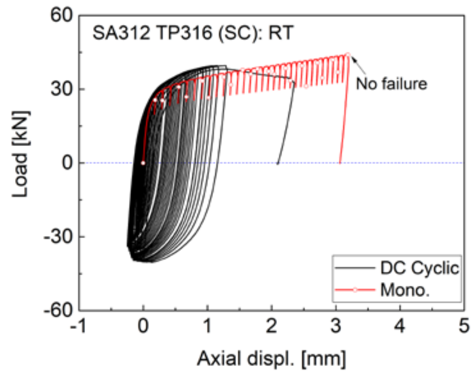
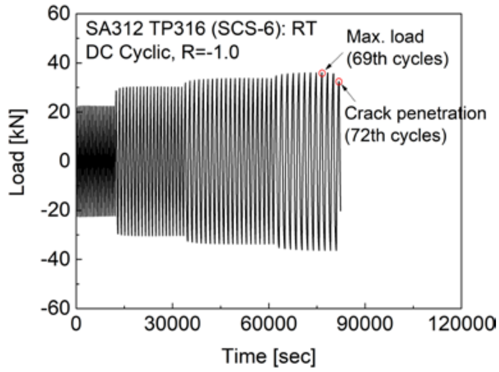
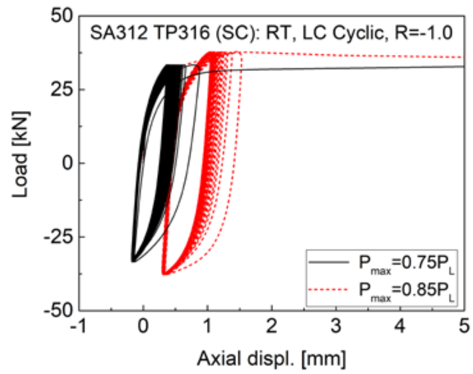


(a) Constant displacement increment



(b) Displacement-controlled multiple block load



(c) Load-controlled loading

Fig. 2 Load-displacement curves of pipe with surface crack for different loading types

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