Ultimate Strength Test using Simulated Specimen under Excessive Seismic Loads

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1. Introduction

Interest in the structural integrity of systems, structures, and components (SSCs) of nuclear power plants (NPPs) during a seismic event increased greatly after the nuclear accident in the Fukushima Daiichi NPPs [1]. Since several NPPs experienced a beyond design basis earthquake (BDBE) [1,2], in particular, structural integrity under excessive seismic conditions has come under greater scrutiny; recently, integrity assessments for SSCs under excessive seismic conditions are required for newly designed NPPs. Thus, the reliability of integrity assessments under excessive seismic conditions has become an important issue, and several studies have conducted to improve and develop integrity assessment procedure for SSCs under excessive seismic conditions [3-5]. For such studies, the verification of analytical model and acceptance failure criteria using experimental data are essential to ensure the reliability of assessment procedure. In general, the experiment data for verification are obtained from the large-scale system tests that can take into account realistic seismic loading characteristics and geometry effects. However, these are too expensive and difficult to handle.

Therefore, this study designed specimen and loading, which can simulate strain accumulation and crack initiation in SSCs of NPPs under excessive seismic loading condition, and conducted failure test at RT and 316°C using these specimen and loading. From the results, the deformation behavior and failure condition under excessive seismic loading condition are investigated.

2. Experiments

2.1 Materials and Specimen Design

Two types of structural material were used in the experiment. One is SA312 TP316 stainless steel (SS), which is piping material used in the SC line of the NPPs, and the other is SA508 Gr.3 Cl.1 low alloy steel (LAS), which is used as nozzle of reactor pressure vessel of NPPs.

Based on finite element analysis, we designed the specimen that can adequately represent the deformation and failure behaviors under excessive seismic loading conditions. In the design, the cyclic load level and strain distribution under displacement-controlled cyclic loading were considered to be design parameter. The measurability of crack initiation and strains were also regarded. Fig. 1 shows the specimen designed in this study. As shown in Fig. 1, the basic dimensions are the same as those of 1T-CT specimens in accordance with ASTM E1820-15[6], except that it has a round notch with a radius of 6.0mm.

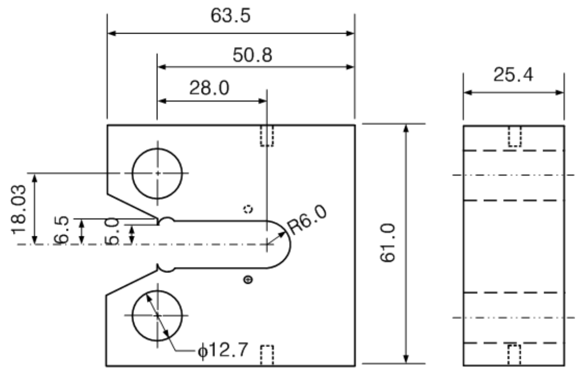

Fig. 1 Simulated specimen used for experiment

2.2 Test Conditions and Procedures

In the experiment, displacement-controlled cyclic load was applied. One set of cyclic load was consisted of 20 cycles with constant amplitude of load-line displacement (*LLD*). In the tests, six levels of *LLD* amplitude for SA312 TP316 SS and five levels of *LLD* amplitude for SA508 Gr.3 Cl.1 LAS were considered as listed in Table 1. These amplitudes of *LLD* were selected to induce a maximum stress levels from 1 to 7 times stress limit of safe-shutdown earthquake (SSE).

Table 1 Load-line displacement amplitudes applied to experiment

Stress limit	SA312 TP316 SS		SA508 Gr.3 Cl.1	
	RT	316°C	RT	316°C
SSE($6S_m$)	0.46774	0.44508	0.59779	0.66005
1.67×SSE	0.77827	0.74042	0.99545	1.09942
3×SSE	1.39468	1.32670	1.78484	1.97161
4×SSE	-	-	2.39116	2.62739
5×SSE	2.32162	2.20832	2.97189	3.28318
6×SSE	2.80644	2.67048	-	-
7×SSE	3.27418	3.08994	-	-

Here the stress limit of SSE is assumed as 6 times design stress intensity ($6S_m$).

The tests were conducted at RT and 316°C using servo-hydraulic UTM with high temperature chamber. *LLD* was measured using high temperature COD gage and used as input to control the amplitude of cyclic load. In all tests, *LLD* speed was 2mm/min.

As illustrated in Fig. 2, a set of cyclic load with 20 cycles was applied to the specimen, while increasing *LLD* amplitude of cyclic load listed in Table 1, until the specimen was failed. Here the occurrence of failure was defined as detection of crack from the specimen. When cracks were not detected up to 5×SSE for SA508 Gr.3 Cl.1 LAS and up to 7×SSE for SA312 TP316 SS, the amplitudes of 5×SSE and 7×SSE were repeated until the failure occurred.

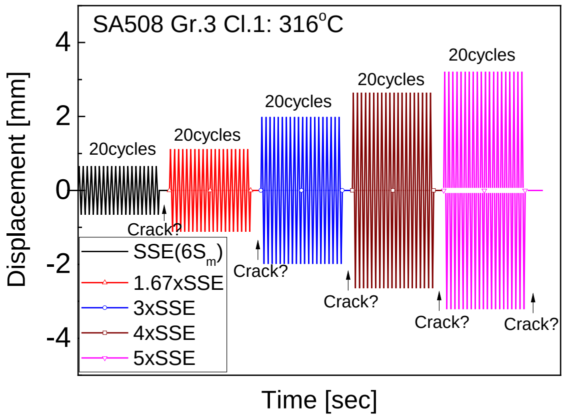

Fig. 2 A sample of applied cyclic load with constant *LLD* amplitude

3. Results and Conclusions

The results showed, regardless of test material and temperature, the cracks initiated at the center of round notch, at which the maximum strain appeared from the finite element analysis. For SA316 TP316 SS, the cracks were detected at cyclic load of 7×SSE for RT and at cyclic load of 6×SSE for 316°C. The cracks for SA508 Gr.3 Cl.1 LAS were detected at 4×SSE for both RT and 316°C. The strains measured at both sides and back side of specimen showed that the strain amplitude proportionally increased with increasing applied *LLD* amplitude of cyclic load. The mean strains increased with increasing number of cycles at a given *LLD* amplitude; i.e., the strains were accumulated during the cyclic load and the failure was the results of fatigue ratcheting.

From these results, it is concluded that for both materials the failure of specimen occurs under seismic load levels several times higher than the design basis earthquake. Also, SA316 TP316 SS has higher safety margin under excessive seismic loading condition than SA508 Gr.3 Cl.1 LAS regardless of test temperature. Finally, it is confirmed that the specimen used in this study can adequately simulate the deformation and failure behaviors of SSCs under excessive seismic loading condition.

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