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Fatigue assessment for seismic loads considering material degradation due to stress corrosion cracking

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HIGHLIGHTS

- Fast growth rate (0.32 mm/cycle) was gotten in tests using plate specimens.
- Fatigue damage assessment could be replaced with crack growth prediction.
- Effect of stress corrosion cracking was considered in fatigue damage assessment.

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ABSTRACT

This study was aimed at showing a fatigue damage assessment procedure for seismic loads considering material degradation, specifically stress corrosion cracking (SCC), caused during long term operation of nuclear power plants. To superpose the damage due to cyclic loading and SCC, crack growth analysis was applied to the fatigue damage assessment, although this assessment is conventionally performed using the usage factor. To show applicability of the crack growth prediction to seismic loads, fully-reversed stress- or strain-controlled crack growth tests were conducted using plate specimens made of Type 316 stainless steel. A relatively large load amplitude was applied to simulate a fast growth rate, which was 0.32 mm/cycle for the maximum rate case. It was shown that obtained crack growth rates correlated well with the strain intensity factor range. Furthermore, the effect of crack closure was corrected by using the effective strain intensity factor range. Fatigue life estimated by the crack growth prediction with an initial depth of 50 μm correlated well with the fatigue life obtained by low-cycle and extremely low-cycle fatigue tests, for which the maximum strain range was 12%. Finally, a fatigue damage assessment procedure considering the effect of SCC was presented, in which the initial crack depth was determined by SCC initiation and growth predictions.

1. Introduction

In Japan, structural integrity of nuclear power plant (NPP) components for seismic loads is assessed according to the Japan Electric Association Code (JEAC) 4601-2008 (JEA, 2008) (hereafter called JEAC4601). The critical failure mode considered in the JEAC4601 is fatigue caused by cyclic loading. In fatigue damage assessment done according to the JEAC4601, various cyclic loads experienced during plant operation are taken into account in addition to cyclic seismic loads; e.g. cyclic thermal loads caused by changes in operation mode such as plant startup and shutdown contribute to the fatigue damage accumulation. Therefore, the risk of fatigue failure increases as plant operation time becomes longer. For aging NPPs, not only the fatigue damage accumulated during plant operation but also various material degradations may affect the assessment for seismic loads. Wall-thinning and stress corrosion cracking (SCC) are the main degradation phenomena which can accelerate the fatigue damage accumulation.

Takahashi et al. (2009) investigated influence of the wall-thinning on fatigue strength of carbon steel pipes and elbows. In fatigue damage assessment, the degree of the fatigue damage is represented by the usage factor (UF). Urabe et al. (2013) found that an increase in UF due to seismic loads was not enhanced so much by wall-thinning because the critical positions for fatigue damage were not identical to those for wall-thinning. On the other hand, influence of SCC on the fatigue damage assessment has not been fully understood yet. It is not easy to superpose the damages due to fatigue and SCC because the degree of SCC damage is represented by crack size (Takeuchi et al., 2002), whereas the UF is quoted in fatigue damage assessment (Nakamura et al., 2007). In the fitness-for-service (FFS) assessments according to the

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American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI (ASME, 2015) and the Japan Society of Mechanical Engineers (JSME) FFS Code (JSME, 2012), both SCC and fatigue damages are assessed by crack growth prediction using the stress intensity factor (SIF). By using the crack size as a measure of the damages, it is possible to superpose the damages caused by fatigue and SCC. In the same manner, the effect of SCC on the fatigue damage due to seismic loads can be considered by incorporating crack growth prediction. It is reasonable to apply the crack growth prediction for fatigue damage assessment because the fatigue damage is intrinsically equivalent to the crack growth (Murakami and Miller, 2005).

For seismic loads, when so-called beyond design conditions are considered, the SIF is not always applicable to the crack growth prediction because the magnitude of loads may exceed the elastic condition, for which application of the SIF is valid. The J-integral is generally used to predict the fatigue crack growth for large loads (Dowling and Begley, 1976; Tanaka, 1989; McEvily, 1998). However, only limited J-integral solutions have been published (EPRI, 1989; Kim et al., 2004; Kamaya, 2009) and material deformation characteristic (i.e., stress-strain curve) is required to derive the J-integral. Furthermore, treatment of the crack closure effect on crack growth prediction is not simple for the J-integral (Dowling and Begley, 1976; Roy et al., 2009; Yamaguchi et al., 2011). Therefore, the J-integral has not been used for crack growth prediction in the FFS assessment codes. The strain intensity factor also has been used to predict the fatigue crack growth for large loads exceeding the elastic condition (Haigh and Skelton, 1978; Kitagawa et al., 1979; Tanaka et al., 1982). The strain intensity factor is obtained by replacing the stress component with the strain in the equation for obtaining SIF. Since strain is obtained to calculate UF in the fatigue damage assessment, the strain intensity factor can be obtained without difficulties. It is reasonable to apply the strain intensity factor for the crack growth prediction because the driving force of the fatigue damage is not stress but strain (Jaske and O'Donnell, 1977). The UF is calculated based on the strain, although fictitiously elastic stress is used in the assessment. It has been shown that crack growth rates of stainless steel exhibited a good correlation with the strain intensity factor for both small- and large-scale yielding conditions and low- and high-cycle fatigue regimes (Kamaya, 2015a)

In order to apply the strain intensity factor to predict the crack growth by seismic loads, it is necessary to validate the strain intensity factor for predicting the fatigue damage corresponding to the extremely low-cycle fatigue regime, in which fatigue life is less than a hundred cycles. The strain range applied for the fatigue damage assessment using the strain intensity factor was about 2% in the maximum case (Kamaya and Kawakubo, 2012a). The strain range of more than 10% was considered in the fatigue tests for the extremely low-cycle fatigue regime (Kamaya, 2010). Therefore, applicability of the strain intensity factor to predict the crack growth for such a large load should be addressed.

The objective of this study is to show the fatigue damage assessment procedure in which the effect of SCC can be considered. To achieve this objective, the crack growth prediction was applied to assess the fatigue damage both for the low-cycle and extremely low-cycle regimes. The material considered was Type 316 stainless steel, which is generally used in primary loop of NPPs and susceptible to SCC. First, crack growth tests were conducted using plate specimens, which enabled the strain range during the tests to be identified using a strain gage. Target maximum crack growth rate was more than 0.2 mm/cycle, which is the threshold value for ductile crack initiation in fracture toughness tests (ASTM, 2011). Second, the obtained growth rates were correlated to the strain intensity factor range derived using the measured strain range. Then, to validate the use of strain intensity factor for the crack growth prediction, the growth prediction results were compared with the fatigue lives obtained by the low-cycle and extremely low-cycle fatigue tests conducted in a previous study using the same stainless steel material (Kamaya, 2010). Finally, the fatigue damage assessment procedure using the strain intensity factor was presented.

2. Crack growth test procedure

2.1. Plate specimen

The test material was a solution heat-treated Type 316 austenitic stainless steel, for which the alloying constituents and mechanical properties are shown in Tables 1 and 2, respectively. The material was provided as a bar of 38 mm diameter. Then, a specimen having the configuration shown in Fig. 1 was machined along the longitudinal direction. The specimen had a 36 mm long parallel portion in order to achieve uniform deformation and nominal strain was measured using a strain gage attached at this parallel portion. An initial notch was machined at the longitudinal center to localize the crack initiation site and to allow attachment of a clip gage. The crack length a was measured from the edge of the notched side as shown in Fig. 1. The initial length, which was equivalent to the notch length, was $a = 1$ mm. The width of the specimen was 15 mm and the thickness was 6 mm at the parallel portion. The thickness was increased to 10 mm at the grip portions to prevent buckling.

2.2. Crack growth test

The specimens were subjected to stress- or strain-controlled crack growth tests in a room temperature laboratory environment. A fully-reversed constant cyclic load was applied throughout the tests. Target stress amplitude values were $\sigma_a = 100$ MPa, 200 MPa and 350 MPa for the stress-controlled tests and the strain ranges of $\Delta\varepsilon = 0.5\%$, 1.0% and 1.2% were applied for the strain-controlled tests. In order to obtain large crack growth per cycle, the maximum loading amplitude was set to be as large as possible. It should be noted that the tests for stress amplitude of 400 MPa and strain range of 1.4% were also conducted, although the specimens were buckled during the tests. The test speed was 0.2–5 Hz for stress-controlled tests and 0.1–0.4 Hz for strain-controlled tests.

The crack length was monitored by the compliance method using a correlation between the applied load and crack mouth

Table 2
Mechanical properties of test material.

0.2% offset yield strength	Tensile strength	Elongation	Reduction of area
294 MPa	602 MPa	0.60	0.76

Table 1
Chemical content of test material (wt%).

Fe	C	Si	Mn	P	S	Ni	Cr	Mo
Bal.	0.05	0.25	1.31	0.032	0.030	10.17	16.81	2.00