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Development of disc bending fatigue test technique for equi-biaxial loading

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ABSTRACT

The disc bending fatigue test technique was developed to investigate the fatigue life under an equi-biaxial loading condition. In this test, a uniform thickness disc specimen was subjected to a bending load by applying air pressure on the specimen surface. Eleven specimens made of Type 316 stainless steel were tested in a room temperature ambient environment. The crack initiation and growth behaviors during the test were observed through a transparent window. The fatigue life was defined when the peak pressure measured near the specimen surface was reduced to 95% of the supplied air pressure. The fatigue life obtained by the disc bending fatigue test was shorter than that obtained by the uniaxial and plate bending fatigue tests for the same principal strain range. It was confirmed that the equi-biaxial loading condition reduced the fatigue life. The finite element analysis together with test results revealed that the crack was initiated at the edge of the specimen when the specimen thickness was less than 1.0 mm. The specimen thickness should be 1.2 mm in order to maximize the strain range at the specimen center. It was concluded that the disc bending fatigue test can derive the fatigue life under an equi-biaxial loading condition, for which strain range is measured at the specimen center.

1. Introduction

Fatigue damage considered in design of nuclear power plant components is mainly brought about by the water temperature fluctuation due to changes in plant operating conditions, such as plant start-up and shutdown. The allowable number of cycles for plant design has been determined from the fatigue life obtained by pull–push uniaxial fatigue tests [1]. However, the stress fluctuation caused by the temperature fluctuation is equi-biaxial rather than uniaxial. The local water temperature fluctuation caused by mixing water of different temperatures (thermal striping) also causes the equi-biaxial stress fluctuation [2–4]. Thermal expansion causes the equi-biaxial stress state on a component surface.

In order to determine the allowable number of cycles for such thermal stress fluctuation, fatigue tests for determining the allowable number of cycles for component design should be conducted simulating the equi-biaxial loading condition. Fatigue life of stainless steels under an equi-biaxial loading condition (hereafter, called biaxial fatigue life) has been investigated using cruciform specimens [5,6]. The biaxial fatigue life was shown to be shorter than the fatigue life obtained under the uniaxial loading condition for the same principal strain range [6]. Therefore, it is important to take into consideration the equi-biaxial loading effect on the component design. However, testing using the cruciform specimen is difficult to apply for general use, because it requires a special testing apparatus with four loading actuators. Additionally careful specimen design is required in order to initiate a crack at the center of the cruciform specimen, where the equi-biaxial loading is applied. Although the cruciform specimen shape has been used for obtaining biaxial fatigue life for various materials [7–11], the numbers of the data were not enough for quantitative evaluation of the component design.

In order to obtain the biaxial fatigue life more easily, the current author and co-worker developed the pressurized disc fatigue (PDF) testing technique [12,13]. In the PDF test, a disc-type specimen is bulged by applying air pressure to the specimen surface, and the center of the specimen is subjected to an equi-biaxial loading. Cyclic equi-biaxial loading can be applied by alternating the pressurized side of the specimen surface periodically. The facility for the PDF test is relatively simple and no special control is required to achieve the equi-biaxial loading condition. The PDF test technique has been successfully applied to obtain the fatigue lives for carbon steel [12] and stainless steel [13]. There is a limitation in the application of the PDF test technique, which requires that the thickness of the specimen is not uniform. In order to initiate a

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fatigue crack at a specimen center, where the equi-biaxial loading is applied, the thickness of the specimen has to be thinner near the center. It is not easy to machine such a specimen in small size. Actually, the specimen diameter used in the PDF test has been more than 250 mm [12,13].

In this study, the disc bending fatigue test technique was developed for a uniform thickness specimen to carry out the fatigue test under an equi-biaxial loading condition. The basic idea of the disc bending fatigue test was presented by Ives et al. [14] and Shewchuk et al. [15] about 50 years ago. In this test technique, a disc specimen is subjected to bending load by applying air pressure on the specimen surface as done in the PDF test technique. By altering the constraining condition at the edge of the specimen, a crack can be initiated at the specimen center even when a uniform thickness specimen is used. Since it is easy to produce the uniform thickness disc and to polish the specimen surface, it is possible to reduce the specimen size. First, in this work, the testing apparatus was developed for the disc bending fatigue test. Then, the test was conducted using Type 316 stainless steel. Crack initiation and growth behaviors were observed during the fatigue test runs and the definition of the fatigue life was discussed. Finally, the deformation and strain distribution were investigated for various specimen thicknesses and applied pressures by performing finite element analysis simulating the disc bending fatigue test.

2. Disc bending fatigue testing technique

As mentioned in the Introduction, a uniform thickness disc specimen is subjected to a pressure for the disc bending fatigue test as schematically shown in Fig. 1 [16,17]. The pressure bulges the specimen and makes an equi-biaxial stress on the surface at the specimen center. By applying the pressure alternately to both sides of the specimen surface, it is possible to perform the biaxial fatigue test with a negative stress ratio. In the PDF technique, which has been developed in previous studies [12,13], the edge of the disc specimen is constrained as schematically shown in Fig. 2a. The fixed edge does not allow the strain to become a maximum at the specimen center when a uniform thickness specimen is used. Therefore, the specimen thickness has to be thinner at the center in order to initiate a crack at the specimen center. On the other hand, a fee edge boundary condition is applied in the disc bending fatigue test as shown in Fig. 2b. This boundary condition induces the maximum strain at the specimen center even when a uniform thickness specimen is used.

Fig. 3 depicts a schematic drawing of the disc bending fatigue testing system developed for this study. The disc specimen was fixed by top and bottom cover cases via rubber rings. Pressurized air was injected into a gap between the cover case and specimen inside the rubber rings. When the air pressure was applied on the top side, the bottom side pressure was released, becoming atmospheric pressure. By using an on/off switching valve, the disc specimen surface were alternately subjected to pressurization and

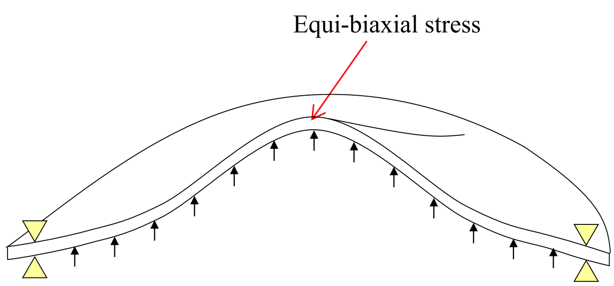

Fig. 1. Schematic drawing for the deformation of the disc specimen during the bulge test.

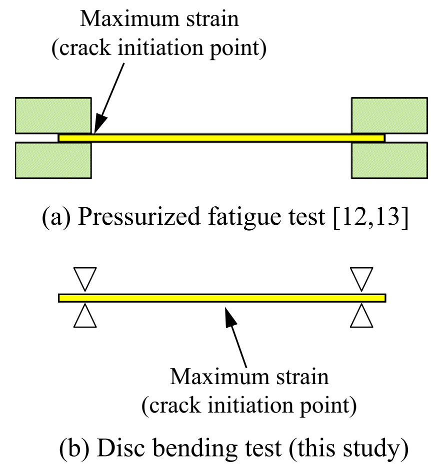

Fig. 2. Schematic drawings representing the maximum strain portion when a uniform thickness disc specimen is used.

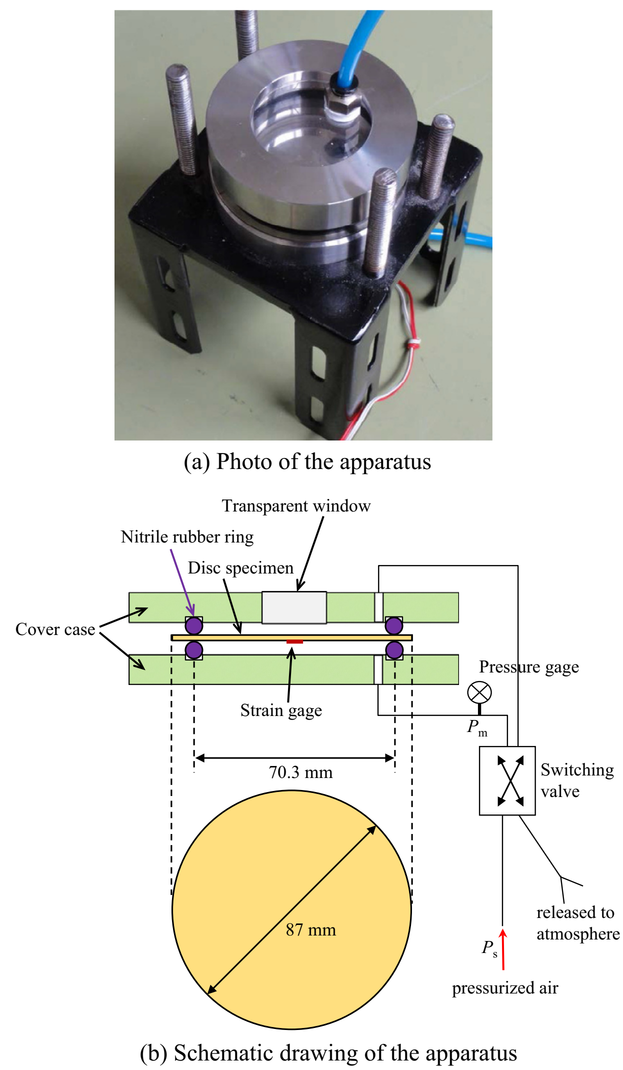

Fig. 3. Disc bending fatigue testing system.

release. By keeping the supplied air pressure constant, the peak load applied to the specimen could be kept at a constant value. The strain at the specimen center was monitored by a strain gage. The top surface of the specimen was observed during the test