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Evaluation of equi-biaxial fatigue of stainless steel by the pressurized disc fatigue test

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ABSTRACT

The pressurized disc fatigue (PDF) test technique was employed to obtain fatigue lives of Type 316 stainless steel under equi-biaxial stress conditions. In the PDF test, a disc-type specimen was subjected to the cyclic bulge test. The biaxial fatigue lives were successfully obtained by the PDF tests, and they were longer than those obtained by the uni-axial and plate bending fatigue tests under the same equivalent strain range. Observations of crack initiation and growth behavior during the PDF test revealed that the relatively large size of the disc-type specimens had only a minor influence on the fatigue lives. Finite element analysis results showed the PDF test was valid for evaluating the fatigue lives under equi-biaxial conditions. It was concluded that the influence of equi-biaxial condition was not necessary to be considered in the design fatigue curve.

1. Introduction

Fluctuations of fluid temperature due to changes in plant operating conditions, such as plant start-up and shutdown, are the primary cause of fatigue damage considered in the design of nuclear power plant components. Even under stable plant operating conditions, however, fatigue damage can be brought about by a local temperature fluctuation. For example, fatigue cracks were found at a mixing tee where fluids of different temperatures flow in [1]. Mixing of different temperature fluids brings about the local temperature fluctuation (thermal striping) [2,3]. Thermal stratification may also induce fatigue damage [4,5]. At a small pipe branching off from the main pipe, a thermal stratification layer can be formed. The main flow initiates a cavity flow in the branch pipe which causes the stratification layer to move. In a nuclear power plant in Japan, initiation of fatigue cracks was found and they penetrated the wall thickness at a branched elbow [6].

In order to prevent fatigue damage from occurring at the mixing tees and branched elbows, the Japan Society of Mechanical Engineers issued a design guideline [7]. In the JSME guideline, the magnitude of the accumulated fatigue damage is assessed using the design fatigue curve, which prescribes the relationship between the stress amplitude and allowable number of cycles. Although the thermal stress caused by the local temperature fluctuation is nearly equi-biaxial [3,8], the design fatigue curve has been determined based on test results obtained by uni-axial tension–compression fatigue tests.

Fatigue lives under an equi-biaxial stress condition (hereafter, called biaxial fatigue life) have been investigated using cruciform specimens for stainless steels, that are widely used for nuclear power plant components. Ogata and Nitta [9] showed that the biaxial fatigue lives were longer than fatigue lives obtained by uni-axial fatigue tests for the same Von Mises equivalent strain range. On the other hand, Sakane et al. [10] showed that the fatigue lives were reduced by the equi-biaxial stress condition under the same principal strain range. No experimental data could be found for the fatigue limit of the biaxial fatigue life of stainless steels. For a reasonable assessment of the fatigue damage caused by the local temperature fluctuation, it is necessary to consider the effect of biaxial loading in the design fatigue curve.

This study was aimed at obtaining biaxial fatigue lives and the fatigue limit of Type 316 stainless steel in order to investigate the effect of biaxial loading on the design fatigue curve. Although cruciform specimens have been used for obtaining biaxial fatigue lives for various materials [11–15], complex test equipment is necessary to perform the tests. Furthermore, careful specimen design is required to get fatigue crack initiation at the center of the cruciform specimens. Cylindrical hollow specimens also have been used for the equi-biaxial fatigue tests [16,17]. The equi-biaxial load can be applied as the combination of axial tensile load and internal pressure. However, it is difficult to apply a compressive load and to control the stress/strain to be equi-biaxial. The equi-biaxial fatigue tests also can be conducted by using sheet specimens [18], although it is difficult to apply a large stress/strain.

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In the current study, the pressurized disc fatigue (PDF) test technique was applied to obtain biaxial fatigue lives of Type 316 stainless steel. The PDF test is the authors' original technique for which a prototype testing system was developed in a previous study [19] to obtain the fatigue lives of carbon steel. Some improvements were made in order to accelerate the test speed and reduce the specimen size. To validate the PDF test technique, the influences of the specimen geometry and inhomogeneous strain distribution were investigated. Then, the effect of biaxial loading on the design fatigue curve was discussed.

2. PDF testing technique

In the PDF test, a disc-type specimen is subjected to a cyclic bulge test [20,21]. Fig. 1 depicts the deformation of the disc-type specimen during the bulge test. Due to the pressure applied to the specimen surface, the specimen bulges and the equi-biaxial stress is loaded to the center of the specimen. By applying the pressure alternately to both sides of the specimen surface, it is possible to perform biaxial fatigue test with a negative R ratio.

Fig. 2 shows a schematic drawing and photo of the PDF test system used for this study. The disc-type specimen was put between two cover cases. Pressurized air was injected into a gap between the case and the specimen. The gap on the other side of the specimen had an outlet that allowed release to atmospheric pressure. By using an on/off switching valve, the gaps were alternately subjected to pressurization and release. By keeping the supplying air pressure constant, the maximum load applied to the specimen could be controlled without difficulty. On the other hand, the wave form of the change in pressure could not be controlled.

Fig. 3 shows the geometry of the specimen used for the tests. It had a radius of 129 mm and the thickness was 2.0 or 2.2 mm near the center, while it was 4.6 or 5.1 mm at the edge. The thickness was less near the center in order to initiate a fatigue crack from the center. Biaxial strain gages were attached at the center of the specimen. The temperature of the specimen was monitored by a thermocouple attached to it.

The specimen and cases attached to the specimen were completely modified from those used in the original setup [19]. The volume of the gaps and the specimen size were reduced significantly. These modifications enabled the test speed to be raised to 0.4 Hz, although it was 0.1 Hz originally. The specimen surface could be observed during the tests through the transparent windows.

3. Test procedure

3.1. Test material

The material used in the tests was solution heat-treated Type 316 austenitic stainless steel, which was provided in plates of 20 mm thickness. Its chemical composition is shown in Table 1. Tensile tests were performed using round bar specimens of 8 mm diameter. Four tests were carried out using the specimens taken along the longitudinal or transverse directions, which are respectively denoted as L and T in the figure. The test speed was 10 MPa/s until 2% in total strain, and then, it was changed to 30% in strain per minute. Obtained nominal stress–strain curves are shown in Fig. 4 and tensile properties are summarized in Table 2. The tensile properties were almost isotropic in the longitudinal and transverse directions.

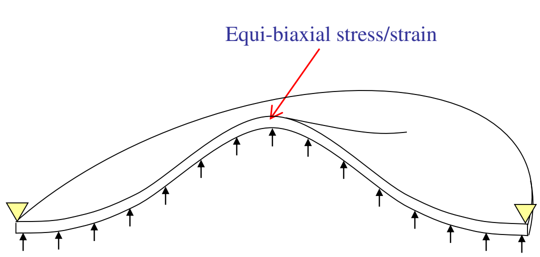
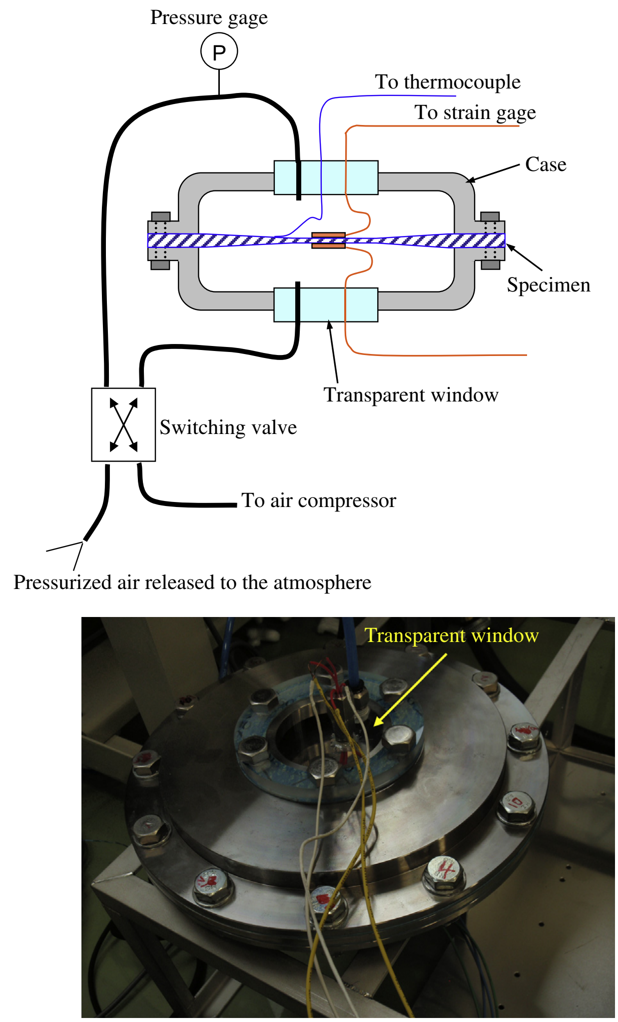


Fig. 1. Schematic drawing for the deformation of the disc-type specimen during the bulge test.



Loading part.

Fig. 2. PDF testing system.

3.2. Uni-axial fatigue tests

In order to obtain the basic fatigue properties, pull–push fully reversed axial stress or strain controlled fatigue tests (hereafter, uni-axial fatigue tests) were conducted in a room temperature laboratory environment using a servo-electric test machine. Fig. 5 shows the geometry of the cylindrical specimens used for the tests. The specimens were taken along the longitudinal (for stress and strain controlled tests) or transverse (for stress controlled tests) directions and their surface were polished using up to 3 μm diamond paste. For the stress controlled tests, the test speed was 0.2 Hz at the beginning of the tests and the maximum speed was 3 Hz. By controlling the test speed, the temperature rise in the specimen was suppressed. For the strain controlled test, the test seed was kept at 0.2 Hz throughout the tests. An extensometer