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Thermal fatigue damage assessment at mixing tees (elastic-plastic deformation effect on stress and strain fluctuations)

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HIGHLIGHTS

- Stress and strain were analyzed for a mixing tee pipe using measured temperatures.
- Strain ranges obtained by elastic-plastic and elastic analyses were identical.
- Elastic-plastic analysis was not necessary to derive strain range.

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ABSTRACT

This study was aimed at showing a procedure for calculating ranges of stress and strain fluctuations from a given wall temperature transient to assess the fatigue life at tee junctions where fluids of different temperatures flow in. The elastic and elastic-plastic structural analyses were performed for a mixing tee pipe made of stainless steel. The pipe wall temperature transient obtained by a mock-up test was used for the analyses. Bi-linear stress-strain curves were assumed for the elastic-plastic analysis. Results obtained by the elastic and elastic-plastic analyses were compared to investigate the influence of the plastic deformation on stress and strain fluctuations. It was shown that the stress and strain fluctuations were relatively large near the boundary of the hot spot, where relatively large compressive stress was caused by hot water that came from the branch pipe. The strain range obtained by the elastic-plastic analysis was almost the same as that obtained by the elastic analysis even if plastic strain was significant. It was concluded that, since the fatigue life was correlated not with the stress range but with the strain range, the fatigue life could be predicted using the strain range obtained by the elastic analysis without considering the plastic deformation. It was also pointed out that consideration of the effects of the mean stress and mean strain was not necessary in the fatigue damage assessment.

1. Introduction

Fatigue cracks have been found downstream from tee junctions where fluids of different temperatures flow in (Chapuliot et al., 2005; McDevitt et al., 2015). The hot and cold water mixing flow causes the fluid temperature fluctuation, which is referred to as thermal striping, and induces cyclic stress and strain at the pipe wall. In order to assess the possibility of crack initiation for a given pipe and flow conditions, the mixing flow, thermal convection from the fluid to pipe wall, thermal conduction in the pipe wall, stress and strain fluctuation and material strength for cracking have to be identified. Extensive studies have investigated the spatial and temporal temperature fluctuations at the mixing tee using mock-ups (Braillard et al., 2006; Fontes et al., 2009; Kamide et al., 2009) and computational fluid dynamics techniques (Coste et al., 2008; Gillis et al., 2013; Howard and Pasutto, 2009; Nakamura et al., 2009; Tanaka et al., 2008). The fluid temperature fluctuation near the pipe wall was measured for various pipe and flow conditions and summarized as the assessment rule issued by the Japan Society of Mechanical Engineers (2004). On the other hand, the magnitude of the stress and strain fluctuation at the pipe wall is not yet understood well, although several attempts have been made to clarify it (Stephan and Curtit, 2005; Gardin et al., 2010; Kamaya and Nakamura, 2011; Utanohara et al., 2016). Since it is not easy to measure the thermal stress and strain, the stress and strain are estimated from the structural analysis using the wall temperature identified by the fluid dynamic calculation or mock-up tests. However, there are mainly two problems to identify the stress and stress fluctuations. The first problem is estimation of heat convection from the fluid to pipe wall.

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Identifying the heat transfer coefficient is not an easy task for unstable mixing flow. Also, much effort is required to analyze the heat convection between the fluid and pipe wall (Utanohara et al., 2016). To solve this problem, in the authors' previous study (Miyoshi et al., 2016a), the pipe wall temperatures were measured using 148 thermocouples in a mock-up test. The heat convection analysis can be skipped by measuring the pipe wall temperature directly. The used of multiple thermocouples allows the location of the maximum temperature fluctuation to be identified.

The second problem is identification of elastic-plastic deformation of the pipe. It has been shown that the stress amplitude was large enough to induce cyclic plastic strain for initiating fatigue cracks in stainless steel (Kamaya and Kawakubo, 2012). In other words, fatigue cracks are not initiated without the cyclic plastic strain. Therefore, the stress and strain fluctuations should be calculated considering the plastic strain. A simple way to consider the effect of the plastic strain is to apply the elastic follow-up models (Kasahara et al., 1995; Lang et al., 2011). The constants for the elastic follow-up models are determined assuming certain loading, boundary and material conditions. The existing elastic follow-up models, however, may not be applicable to the cyclic load at mixing tees.

This study was aimed at showing a procedure for identifying ranges of stress and strain fluctuations to assess the fatigue damage for a given pipe wall temperature. The material assumed in this study was stainless steel, which is a major material used for nuclear power plant piping systems. First, the stress and strain fluctuations at a mixing tee were calculated by a linear-elastic finite element analysis. The pipe wall temperature transient obtained in the authors' previous study (Miyoshi et al., 2016a) was used for the analysis in order to avoid the heat convection problem. Characteristics of the stress transient and its distribution were discussed. Second, in order to resolve the problem of identification of the pipe elastic-plastic deformation, the elastic-plastic finite element analysis was performed using the same pipe wall temperature transient. The results obtained by the elastic and elastic-plastic analyses were compared. Finally, the procedure for deriving the strain range for fatigue damage assessment from the elastic calculation was presented. Treatment of the mean stress and mean strain for predicting fatigue life was also discussed.

2. Analysis procedure

2.1. Pipe wall temperature transient

A pipe wall temperature transient at a mixing tee has been obtained using the mock-up test loop shown in Fig. 1 (Miyoshi et al., 2014a). The test loop simulated the mixing of heated water and room temperature water at the test section, for which a detailed figure is shown in Fig. 2. The inner diameter and thickness of the main pipe were respectively 150 mm and 7.6 mm whereas they were 50 mm and 5.3 mm for the branch pipe. Both pipes were made of stainless steel. A total of 148 thermocouples were installed in the main pipe wall at the positions shown in Fig. 2 (Miyoshi et al., 2014b). The range of the measurement area was about 275 mm in the axial direction and 60° in the hoop direction. Only a half side from the axial symmetry line was measured (see A-A′ cross section in Fig. 2). The pipes were covered with heat insulator.

In the test, the hot water of 60 °C was supplied from the branch pipe (vertical pipe in Fig. 2) to the main horizontal pipe, in which the cold water of 25 °C flowed. It should be noted that the objective of the mock-up test was not to initiate fatigue cracking but to measure the pipe wall temperature transient and investigate the spatial distribution of the temperature. The wall temperatures were measured at the positions 0.45 mm from the inner pipe surface. Then, the temperature distribution in the thickness direction was obtained by a heat conduction analysis using the measured temperatures. The test duration was 160 s and the results from 60 to 160 s were used in this study because it took about 60 s for the inner temperature fluctuation to penetrate the wall thickness (Miyoshi et al., 2016a). The details of the test conditions, temperature measurements and temperature analysis are described elsewhere (Miyoshi et al., 2016a). Also, detailed measured temperature data are available from Miyoshi et al. (2016b).

2.2. Structural analyses

The temperature transient obtained by the mock-up test and the heat conduction analysis were used for structural analyses to calculate the stress and strain. The general purpose finite element analysis code Abaqus version 6.14 together with the finite element model shown in Fig. 3 were employed for the analyses. The model consisted of 81,856 8-node brick elements. The number of

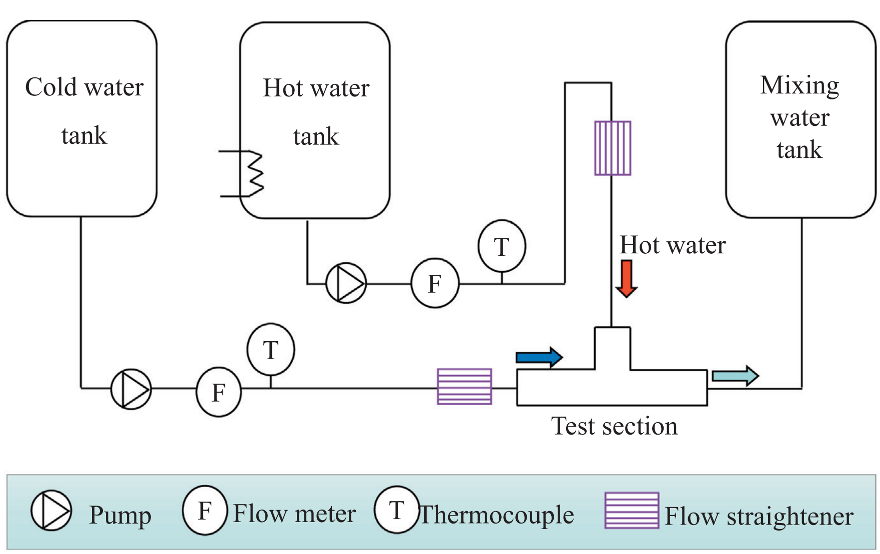

Fig. 1. Test loop simulating mixing flow at tee junction. The loop consisted of three water tanks, two pumps and test section (mixing tee); a detailed configuration of the test section is shown in Fig. 2.