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Evaluation of fatigue damage induced by thermal striping in a T-junction using the three-dimensional coupling method and frequency response method

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1. Introduction

Thermal fatigue cracking induced by thermal stratification, cycling and striping have been observed in several PWR plants. Especially, thermal striping, the highly fluctuating thermal layer, became one of the significant problems, since it can cause unpredicted high cycle thermal fatigue (HCTF) at piping systems.

This problem are usually found in T-junctions of energy cooling systems, where cold and hot flows with high level of turbulence mix together. Thermal striping can cause the networks of fatigue crack at the vicinity of weld parts and these cracks can propagate to significant depth in a relatively short time [1]. Therefore, thermal striping and fatigue crack initiations should be predicted in advance to prevent the severe failure of piping systems.

The final goal of this research is to develop a rational thermal and mechanical model considering thermo-hydraulic characteristics of thermal striping and an evaluation procedure to predict the initiation of thermal fatigue crack. As a first step, we evaluated the fatigue damage in a T-junction using two widely used methods. Then, we analyzed the results of each method and conducted comparisons and verifications.

2. Methods and Results

In this section, two methods used to evaluate the fatigue damage induced by thermal striping are briefly described. In addition, the results such as thermal stresses and fatigue damage factor from each method are depicted.

2.1 Three-dimensional coupling method

The coupled hydro-thermo-mechanical analysis has been revealed that have an advantage of describing detailed information on the fluctuating temperature and stress in the pipe [2-3]. Therefore, we carried out a coupling analysis on a T-junction considering operating conditions described in Table 1 and using the grid model illustrated in Fig. 1. Namely, three-dimensional temperature fields of coolants and pipe obtained by computational fluid dynamics (CFD) are used to compute the resulting mechanical stresses.

2.2 Frequency response method

We considered a frequency response method, a one-dimensional simplified method, which was presented by Kasahara research group [4]. This method assumes a simple thermal and mechanical model which consider the structural response depend on the frequency of fluid temperature fluctuations. Too low and high frequency of fluctuation does not lead to large thermal stress because of attenuation by thermal homogenization in pipe and delay of structural response, respectively. It means that there is intermediate frequency cause the maximum thermal stress. The procedures of this method described in Fig. 2 and more detail features are explained in other reference [5].

Table I: Thermo-hydraulic conditions in the T-junction

Parameters	Main	Branch
Inner dia. [mm]	247.65	247.65
Temp. [^oC]	177	60
Flow rate [m^3/hr]	290	580
Material	ASME SA312 Gr. TP304	

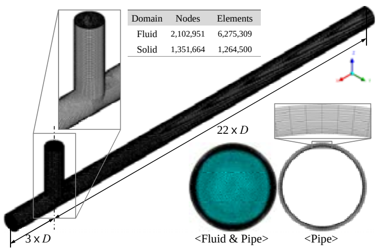

Fig. 1. The grid model for the coupling analysis

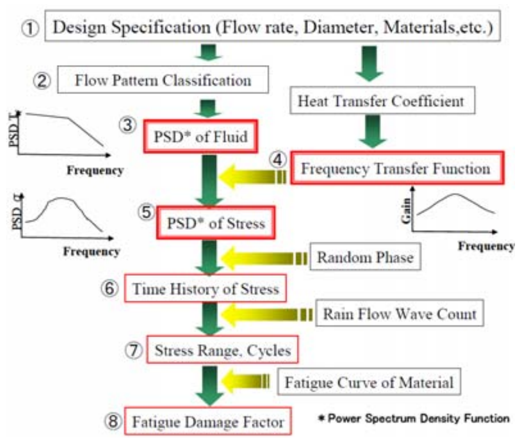

Fig. 2. Thermal fatigue evaluation procedure of the frequency response method [4]

2.3 Comparison of two methods

Fig. 3 shows the instantaneous distribution of stress intensity from the coupling analysis. Although the maximum mean stress occurs near the junction, maximum alternating stress intensity occurs at E points where maximum temperature fluctuations develop. Fig. 4 shows the temperature history at this point and we calculated thermal stresses and fatigue damage factors using this data based on the frequency response method.

Fatigue damage factors was calculated using following equation and considering the counted cycle numbers, the allowable cycle numbers evaluated from stress range and fatigue curves of material based on rain-flow counting method.

$$D_f = \sum_i \frac{N_i}{N_f(\Delta\sigma_i)_i} \quad (1)$$

To validate two methods, estimated fatigue damage factors were compared each other and depicted in Fig. 5. The damage factor ‘A’ was calculated from the PSD of predicted fluid temperature without consideration of structural response characteristics. The damage factor ‘B’ was calculated from the PSD of stress based on PSD of predicted fluid temperature. Damage factor ‘C’ was calculated from the results of coupling analysis. Among them, ‘C’ is conservative compared with ‘A’ and ‘B’ because of the constraint effects and spatial distribution of stresses.

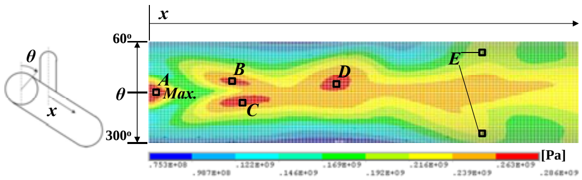

Fig. 3. Instantaneous distribution of stress intensity from the coupling analysis (pipe inner surface)

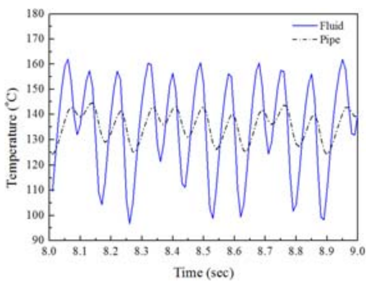

Fig. 4. The temperature history of fluid and pipe at x=1m, θ=45^o where maximum temperature fluctuating location

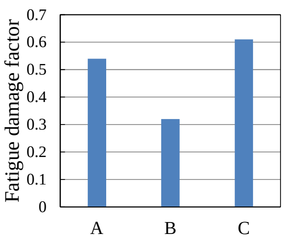

Fig. 5. Comparison of estimated fatigue damage factors

3. Conclusions

The three-dimensional coupling method and frequency response method are both useful for evaluating fatigue damage induced by thermal striping. Especially, the frequency response method is easy to use and shows reasonable results. However, this method does not consider the effect of the membrane constraints and verified PSD charts and frequency transfer functions are needed for generalization. From this research, we revealed that the effect of membrane constraints on fatigue damage is small. Therefore, we are going to develop the thermal and mechanical model and evaluation procedure for thermal striping based on this method.

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