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RESEARCH PAPER

Creep-fatigue life prediction of a welded pipe structure under complex bending-torsion loading

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Abstract
An idealized explicit finite element method is efficient to analyze mechanical behaviors of large-scale welded structures. A numerical model combining Norton's law, ductile exhaustion law, and Manson-Coffin's law was developed for the prediction of creep-fatigue life of a welded pipe system under complex bending-torsion loading. Its validity was verified by comparing predicted creep-fatigue life with the experimental one.

Keywords Creep-fatigue · Finite element method · Welded pipe structure · Tension–torsion loading

1 Introduction

With the spread of clean energy, thermal power plants will be used as a load-following power plant; temperature and strain variations will occur during load fluctuations, including start and stop, and large-diameter pipes may suffer the risk of damage from creep-fatigue. To evaluate the creep-fatigue induced risk, Javanroodi et al. [1] analyzed creep-fatigue crack propagation behavior from a fracture mechanics perspective. Li et al. [2] investigated cyclic damage behavior at high temperatures. Tang et al. [3] proposed a new damage model for G115 steel. Nandha Kumar et al. [4] evaluated microstructural changes and creep rupture properties in dissimilar welded joints. Song et al. [5] studied the effects of loading modes on creep-fatigue behavior and developed a dislocation-based viscoplastic model. However, all these studies are based on a simple uniaxial loading condition. Practically, the external load may include thermal load, internal pressure, bending, torsion, and their combinations. Especially, predicting the creep-fatigue life of the large-scale welded pipe structure subjected to the complex bending-torsional loading is strongly expected by thermal power plants.

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2 Finite element models for creep-fatigue analysis

Figure 1a, b, and c show a practical pipe structure in a thermal power plant, analysis flow, and a welded pipe joint, respectively. Solid elements were employed for both the pipe structure and welded pipe joint. The total length of the pipe structure is about 200 m. The outer and inner diameters are 609.6 mm and 529.6 mm, respectively. The thickness of the pipe is 40 mm. The constraint and support positions are marked in Fig. 1a. Figure 1b shows the analysis flow using an idealized explicit finite element method accelerated by GPU parallel processing [6]. To improve computing efficiency, three levels of mesh were employed and results

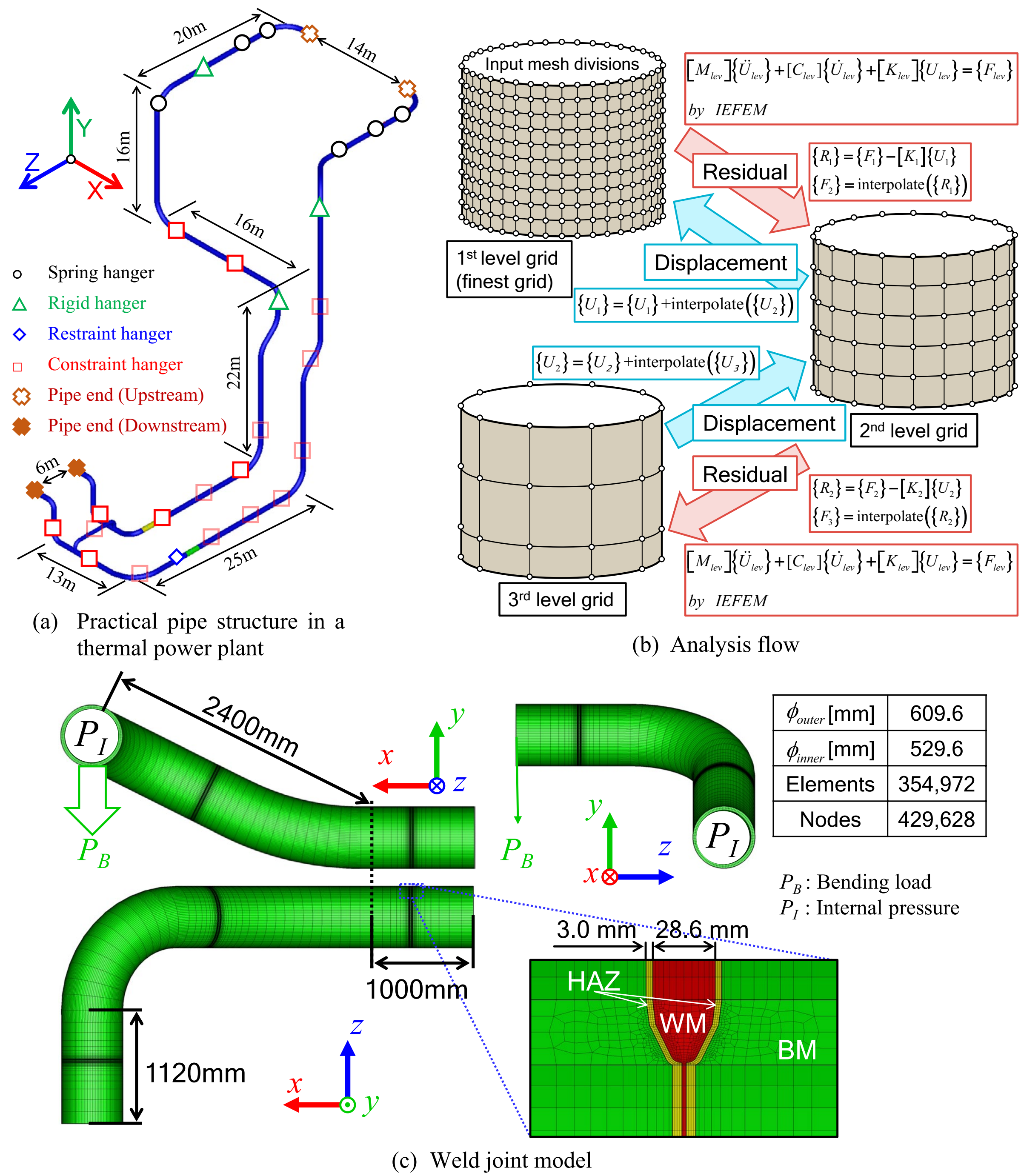

Fig. 1 **a** Practical pipe structure in a thermal power plant, **b** analysis flow, and **c** welded joint model

were mapped among them [7]. Figure 1c shows the detailed mesh in the locally small-scale welded pipe joint.

The width of welded metal (WM) and heat-affected zone (HAZ) are 28.8 mm and 3.0 mm, respectively. The minimum element size in WM and HAZ is 1.0 mm. The largest element size in base metal (BM) away from WM and HAZ is about 100 mm. The total elements and nodes are 354,972 and 429,628, respectively.

Figure 2 shows the experiment setup of creep-fatigue test under bending-torsion loading [7, 8]. The length of the welded pipe is 870 mm, and its thickness is 5 mm. The center zone with a length of 300 mm was heated to 650 ℃. The loading force is applied at two positions where their distance is 400 mm. Clamping jigs are mounted to the two edges of the pipe. The left corner of the bottom jig and the right corner of the upper jig are constrained to allow the twisting deformation.

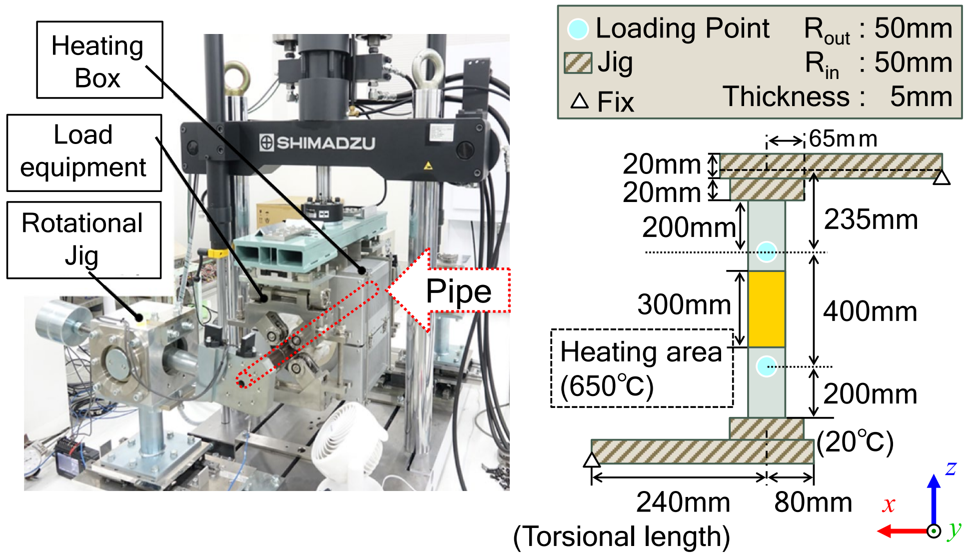

Fig. 2 Experimental setup for creep-fatigue test under bending-torsion loading

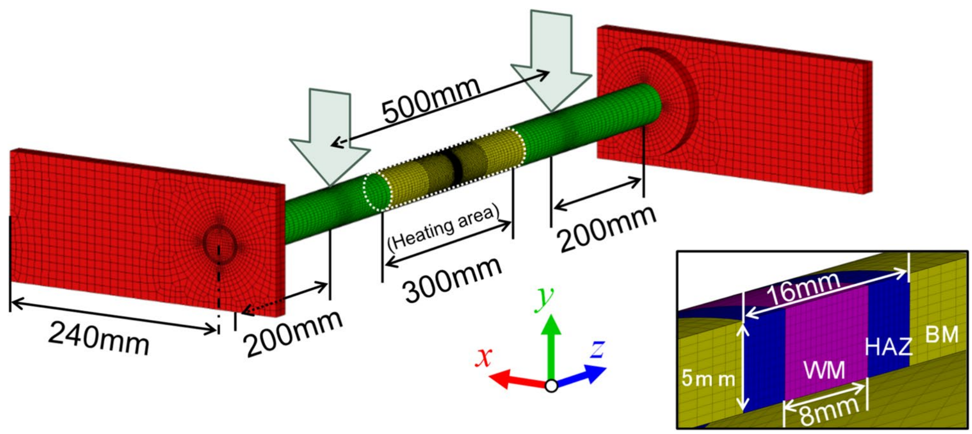

Fig. 3 Finite element model of a welded pipe joint for creep-fatigue analysis

To analyze the creep-fatigue damage, the finite element model for simulation was developed as shown in Fig. 3 [7, 9]. The pipe thickness and length of the finite element analysis model are 5 mm and 900 mm, respectively. The distance of 4-point bending loading positions is 500 mm larger than the experimental case, which does not influence the bending moment on the welded zone. The mesh in the welded metal, with a width of 16 mm, and HAZ, with a width of 4 mm, is zoomed for easy viewing of the element size.

The temperature dependence of material mechanical properties in the weld pipe (2.25Cr-1Mo) used in welding residual stress analysis is shown in Fig. 4 [7]. The yield stress of base metal and HAZ at room temperature is 550 MPa. The yield stress of welded metal is 870 MPa at room temperature and higher than that of BM and HAZ, which is 550 MPa. The yield stress of BM, HAZ, and WM at temperatures higher than 700 ℃ decreases to 10% of its value at room temperature. The Young's modulus at room temperature is 206 GPa and decreases gradually with the

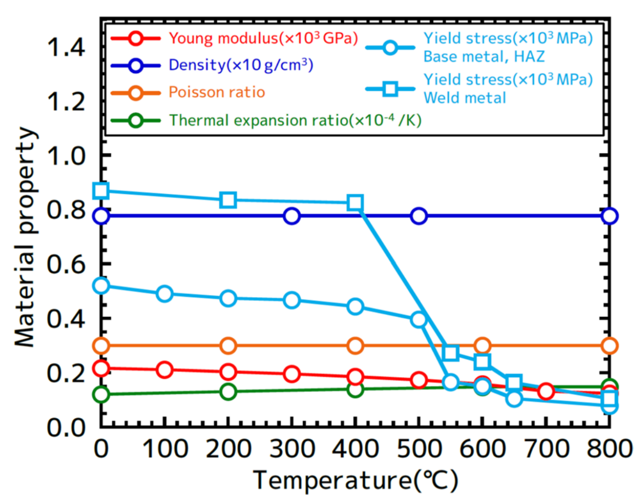

Fig. 4 Temperature dependent mechanical properties of welded pipe (2.25Cr-1Mo)

increase in temperature The thermal expansion coefficient at room temperature is about 1.8E – 05 and increases slowly with the increase in temperature. The density and Poisson's ratio are assumed to be constant and independent of temperature.

The creep strain increment is defined by Eq. (1) following Norton's Law. The related parameters for BM, WM, and HAZ at the working temperature 650 °C are shown in Table 1. The magnitude of parameter A is 1.31×10^{-16} $MPa^{-4.39}$ s^{-1}, 1.02×10^{-14} $MPa^{-4.41}$ s^{-1}, and 3.37×10^{-17} $MPa^{-4.39}$ s^{-1} for BM, HAZ, and WM, respectively. The creep strain rate in HAZ is about 1000 times higher than that in BM and WM. The high creep rate in HAZ is related to grain coarsening and altered carbide precipitation in welding thermal cycles.

$$\Delta_{\varepsilon}^{-C} = A_{\sigma}^{-n}\Delta t \tag{1}$$

Figure 5 shows the cyclic loading curve in which dynamic loading, static holding, and unloading processes are included.

Based on the equation proposed by Rice and Tracy, the creep damage value D_c due to one cycle and damage limit strain ε_f are, respectively, defined by Eqs. (2) and (3) [7, 8]. The parameter h is stress triaxiality, and the material constant Z is 5.0 for pipe steel 2.25Cr-1Mo.

The fatigue failure cycle is expressed by D_f based on Manson-Coffi's law (Eq. 4) at an applied stress range σ_a. Since the bending-tortional stress state is complicated, von Mises equivalent stress is here employed. The material constant a and b for 2.25Cr-1Mo pipe steel are a = 0.3506, b = 12,508.2. Strictly, these parameters in BM may differ from the weld metal (WM) and heat-affected zone (HAZ) due to welding thermal cycles and microstructural changes. Currently, there is insufficient fatigue test data specific to the HAZ and WM. Therefore, the same parameters a and b are here used as representative values. Then, the creep-fatigue life N can be predicted using Eq. (5).

$$D_c = \Delta\overline{\varepsilon}^c/\varepsilon_f \tag{2}$$

$$\varepsilon_f = Zexp\left[\frac{(1-h)}{2}\right] \tag{3}$$

$$D_f = \left(\frac{b}{\sigma_a}\right)^{\frac{1}{a}} \tag{4}$$

$$N = \frac{1}{D_f + D_c} \tag{5}$$

The stress and deformation due to bending-torsion loading in the experimental welded pipe model are analyzed using the developed FE model shown in Fig. 3, and the results are shown in Fig. 6 [7, 8].

The creep strain and equivalent stress in WM, HAZ, and BM predicted by the developed FE model are shown in Fig. 7 [7, 9]. The creep strain is largest in HAZ, indicating that special attention needs to be paid. Through large numbers of FE analyses, the creep-fatigue life and its distribution from 10^3 to 10^8 cycles under various bending-torsion loading conditions are predicted and presented in Fig. 8[7, 10]. The broken lines in Fig. 8 show the same creep-fatigue life. Compared with the pure bending and pure torsion, the creep-fatigue life under the mixed bending-torsion loading becomes shorter.

The comparison between predicted and experimentally measured creep-fatigue life is shown in Fig. 9 [7, 10]. It can be seen that the good prediction accuracy was obtained.

Table 1 Parameters of Norton's law for creep strain rate at 650 °C

Base metal		HAZ		Weld metal	
A	*n*	*A*	*n*	*A*	*n*
1.31×10^{-16}	4.39	1.02×10^{-14}	4.41	3.37×10^{-17}	4.39

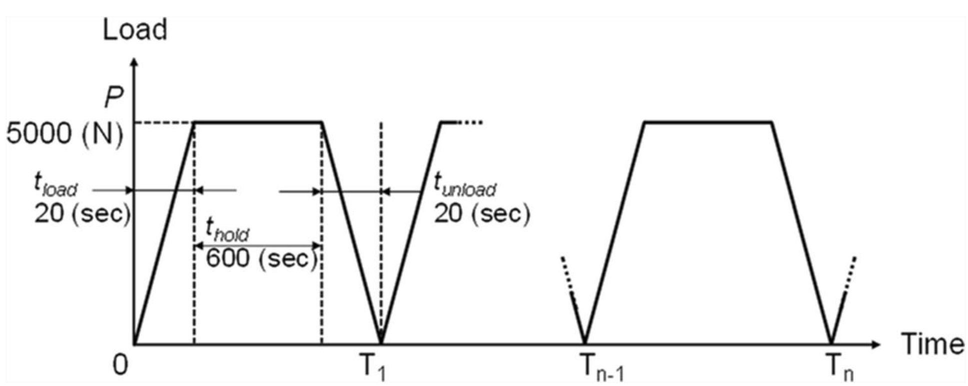

Fig. 5 Cyclic loading curve with load holding

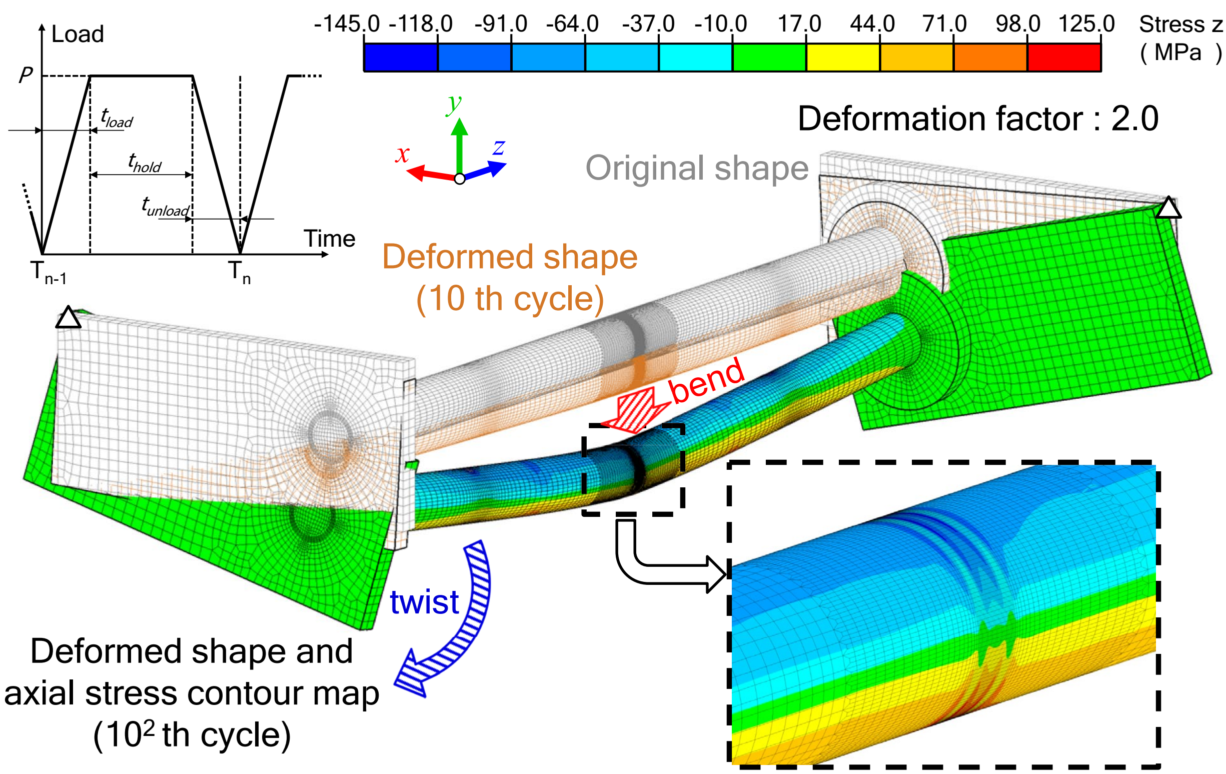

Fig. 6 Analyzed stress and deformation due to bending-torsion loading

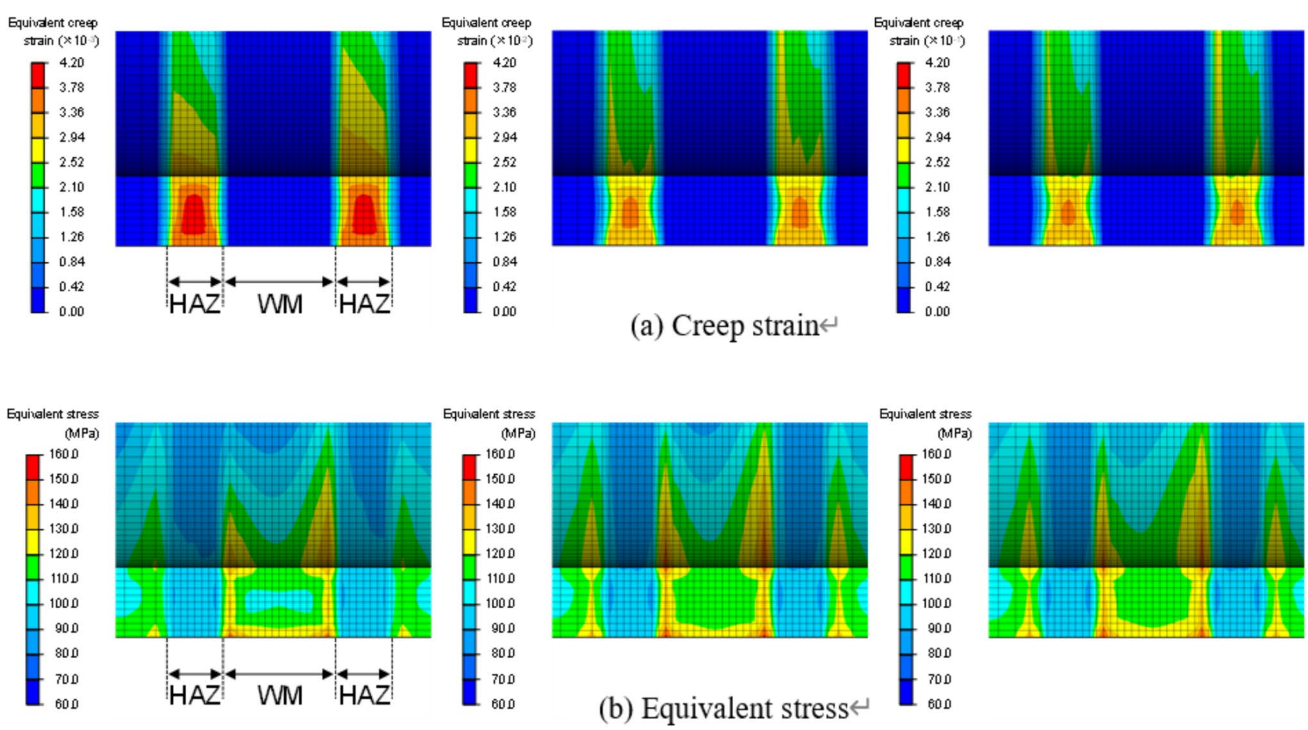

Fig. 7 Cyclic loading induced **a** creep strain and **b** equivalent stress in WM, HAZ, and BM

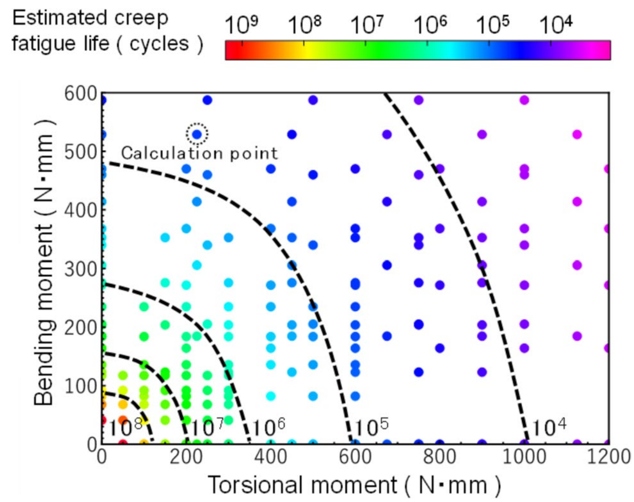

Fig. 8 The predicted creep-fatigue life distribution under various bending-torsion loading conditions

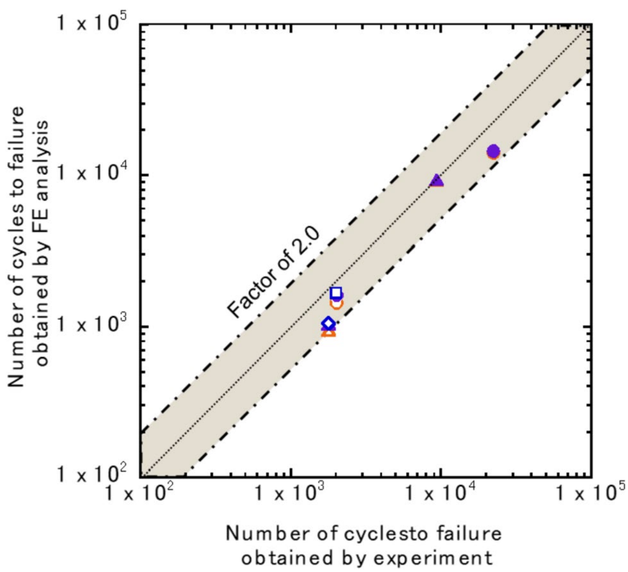

Fig. 9 Predicted creep-fatigue failure cycles and comparison with experimental results

3 Conclusions

(1) With the aid of finite element analysis on a large-scale welded pipe structure under bending-torsion loading, the creep-fatigue damage index was proposed.
(2) The predicted creep-fatigue life under bending-torsion, and its good accuracy, was validated by experiment.
(3) The welding-induced HAZ has a shorter creep-fatigue life than that of weld metal and base metal of 2.25Cr-1Mo steel welded pipe.
(4) Creep-fatigue life map under the combined bending-torsion loading was obtained. The creep-fatigue under bending-torsion loading induced shorter creep-fatigue life than pure bending and pure torsion.
(5) Predicted strains on the practical welded pipe structure were consistent with measured ones by strain gauges.

Although the creep-fatigue life was well predicted, it is still necessary to improve its accuracy. For example, mechanical properties and microstructures in HAZ need to be investigated by experiments. Additionally, the influence of residual stress on creep-fatigue life can be important. In the future, multi-scale analysis for the creep-fatigue life with consideration of residual stress and microstructure can be one of the significant approaches.

Author contribution Masakazu Shibahara: conceptualization, methodology, supervision, funding. Kazuki Ikushima: programming, analysis. Yuji Kitani: formal analysis, writing. Masayuki Arai: experiment, funding. Hidetaka Nishida: experiment, funding. Ninshu Ma: writing, editing, supervision, funding.

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Data availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

This article is based on author's original data, which is not covered by any copyright other than that of the author.

Declarations

Competing interests The authors declare no competing interests.

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