Comparison of Creep and Stress Relaxation Behavior for Induction Bent P91 Piping between Structural Tests and Finite Element Analysis

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1. Introduction

Mod.9Cr-1Mo (P91) steel is widely recognized as a superior structural material for high-temperature applications in Gen-IV reactors, such as the Sodium-cooled Fast Reactor (SFR), and is listed in the ASME Boiler and Pressure Vessel Code, Section III, Division 5. To enhance the feasibility and safety of such high-temperature piping systems, the application of the induction bending process is being considered to significantly reduce weld points. The induction bending process involves locally heating the pipe using a high-frequency induction coil, followed by bending with a bending arm and subsequent cooling, as illustrated in Fig. 1 [1]. However, there are currently limited applications of induction bending technology in SFR piping systems globally. This is largely because the effects of inevitable thickness variations (thinning at the Extrados position and thickening at the Intrados position) and microstructural changes induced by the bending process on high-temperature structural integrity have not been fully characterized. To address this, the authors have been conducting preliminary verification studies to introduce induction bending technology to SFR piping [1-5]. In this study, material constants for a creep analysis model were determined by curve-fitting the results of specimen creep tests performed at various stress levels under 550°C conditions [2]. Subsequently, these constants were applied to a precise Finite Element Analysis (FEA). The validity of the design analysis model and the feasibility of the technology were verified by comparing the FEA results with those of structural tests conducted on bent pipes under the same 550°C high-temperature conditions [3].

Figure 1. Induction heating bending process

2. Analysis Model and Identification of Material Constants

Developing a reliable inelastic analysis model is essential for efficiently analyzing the behavior of reactor structures under various loading conditions without performing experiments for every case [4]. In this study, a combined elasto-plastic and creep model was applied to simulate the behavior of P91 bent piping.

2.1 Chaboche Combined Hardening Plasticity Model

To describe the non-linear material response during the initial loading stage, the Chaboche combined hardening model was adopted. A preceding study [1] has already demonstrated that this model effectively simulated elasto-plastic behavior of the bent pipe, including the Bauschinger effect under initial and cyclic loading. The yield function (1), isotropic hardening equation (2) and kinematic hardening equation (3) are defined as follows:

$$f = |\sigma - X| - R - \kappa \tag{1}$$

$$\dot{X} = \frac{2}{3} C\, d\varepsilon^{p} - \gamma X \dot{p} \tag{2}$$

$$\dot{R} = b(Q - R)\dot{p} \tag{3}$$

Hear σ, X and R represent the equivalent stress, back stress and drag stress, respectively, while κ denotes the initial yield stress. The parameters C and γ govern kinematic hardening, and Q and b define isotropic hardening. $\dot{p}$ indicates the accumulated plastic strain rate. The elasto-plastic material parameters used in this analysis were derived from tensile test and Low-Cycle Fatigue (LCF) test data for specimens extracted from an induction bent pipe at 550°C [1] (see Table 1, upper section).

2.2 Combined Time Hardening (CTH) Creep Model

To simulate time-dependent creep behavior, the Combined Time Hardening (CTH) model, an extension of the Norton law, was applied [4].

$$\dot{\varepsilon}_{cr}(t) = C_1 \sigma^{C_2} t^{C_3} e^{-\frac{C_4}{T}} + C_5 \sigma^{C_6} e^{-\frac{C_7}{T}} \tag{4}$$

The constants in equation (4) were determined by curve-fitting creep test results obtained from round bar specimens extracted from induction bent pipes at 550°C [2] (see Table 1, lower section). As shown in Fig. 2, the derived model accurately predicted the creep deformation behavior of the specimens across various stress levels [4]. However, the model tended to predict strain values conservatively, with an average error of approximately -16% at the end of the secondary creep stage compared to the test data.

Table 1. Material constants of elasto-plastic-creep analysis model

Chaboche combined hardening							
	Young's Modulus [GPa]	Poisson's Ratio	κ [MPa]	C [MPa]	γ	Q [MPa]	b
Material Properties & parameters	174	0.3	269	32,960	160	-95	1.277
Combined time hardening creep							
Reference unit : mm, s, K, tonne	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Creep constants	3.25E-15	4.1298	-0.52237	0	2.99E-106	39.237	0

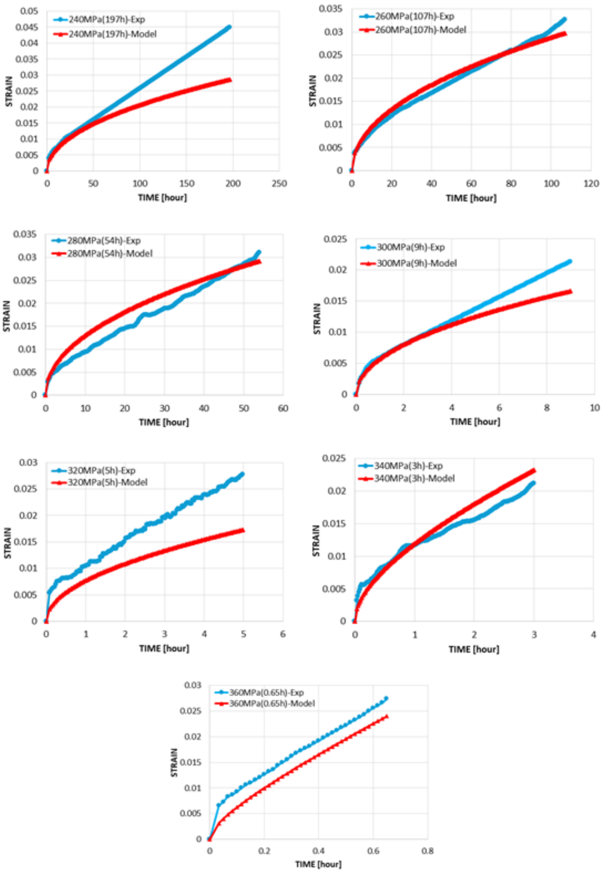

Fig. 2. Comparison of strain-time curves between combined elasto-plastic-creep analysis models and specimen test data.

2.3 FE Modeling and Boundary Conditions

The finite element analysis was performed using the commercial software ANSYS 2020R2 [6]. To efficiently analyze the creep behavior of the bent pipe structure, a 1/2 3D model with XY plane symmetry was constructed as shown in Fig. 3[4]. The geometry of the FE model was constructed by mapping actual thickness distribution (Intrados, Extrados, and Neutral positions of the elbow), measured via an ultrasonic thickness gauge. This ensured that the geometric characteristics of the actual manufactured pipe were accurately simulated.

Boundary conditions were applied to replicate the actual test setup. The flange side at the bottom of the pipe was fixed. A reference node was created at the center of the load pin-hole, and it was coupled with the nodes on the inner surface of the hole to apply load or displacement in the in-plane closing direction(Y-direction).

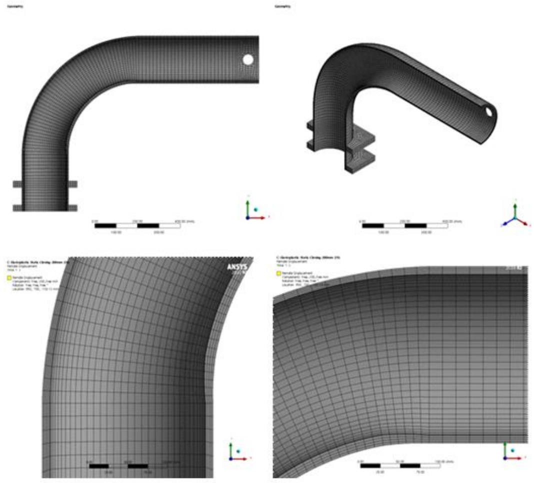

Fig. 3. Finite element model of bent pipe structure

3. Structural Creep Test and FE Analysis Results

Using the constructed analysis model, two preceding structural tests [3] were simulated, and the results were quantitatively compared.

3.1 Comparison of Constant Load Test (CREEP1)

The CREEP1 test was conducted to evaluate the creep behavior under a primary load by applying a constant load of 72 kN at 550°C [3].

The analysis was performed up to 295 minutes for the load condition, consistent with the test duration. As shown in Fig. 4, the analysis results exhibited a primary creep stage with decreasing creep rate during the initial hour, followed by a secondary creep stage with a constant displacement rate. This behavior showed excellent agreement with the displacement-time curve observed in the test.

Notably, the analyzed displacement at the end of the test (295 min) was 65.3 mm, showing a difference of within 7% compared to the test result of 60.8 mm [4]. This demonstrates that the proposed CTH creep model satisfactorily simulates the high-temperature creep deformation behavior of induction bent piping structures.

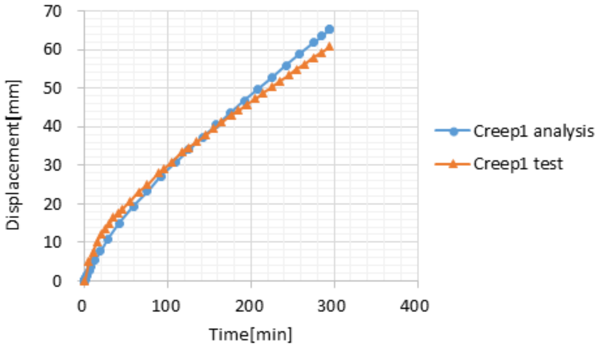

Fig. 4. Comparison of load-displacement curve between FE analysis and structural test (CREEP1)

3.2 Comparison of Stress Relaxation Test (CREEP2)

The CREEP2 test was performed to examine the stress relaxation behavior under a secondary load (e.g., thermal stress) [3]. In both the test and the analysis, displacement-controlled loading was applied until the reaction force reached the target initial load of 72 kN, and the corresponding displacement was maintained for approx. 720 h at the 550°C.

From the analysis results, it was confirmed that the maximum stress at the neutral position of the elbow, relaxed significantly from 379 MPa to 79 MPa. Comparing the load history in Fig. 5(a), both the test and analysis showed a consistent trend where the load dropped sharply from 72 kN to 63 kN within the first 300 seconds.

As shown in Fig. 5(b), Over the entire test period, the test load relaxed to 41.2 kN (approx. 42.8% reduction), whereas the analysis result showed a larger reduction to 17.8 kN (approx. 75.3% reduction) [5]. This quantitative difference suggests that the analysis model evaluates stress relaxation and the resulting creep strain more conservatively than the test results. From a design perspective, this is considered valid as it ensures a safety margin without underestimating structural deformation.

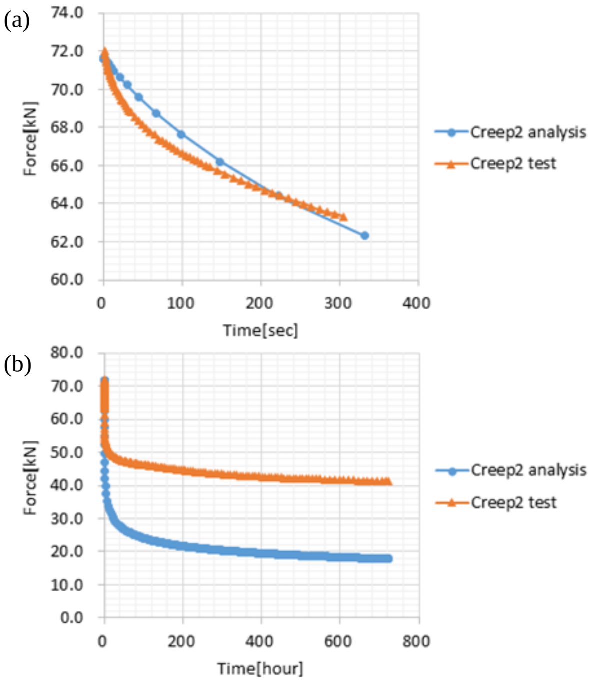

Fig. 5. Comparison of load relaxation behavior between FE analysis and structural test (CREEP2): (a) initial relaxation up to 300 s, and (b) long-term relaxation up to approx. 720 h.

3.3 Failure Location Prediction

To verify the local damage prediction capability of the analysis model, the location of maximum stress/strain in the FE analysis was compared with the damage location observed in the actual test.

The analysis indicated that the maximum equivalent creep strain occurred at the inner surface of the neutral position of the elbow, where the stress induced by the bending moment is maximized (Fig. 6). This prediction is consistent with the location of maximum microstructural damage observed in the actual test specimen, as reported elsewhere [5]. This confirms that the analysis model can accurately identify potential failure locations in induction bent piping systems.

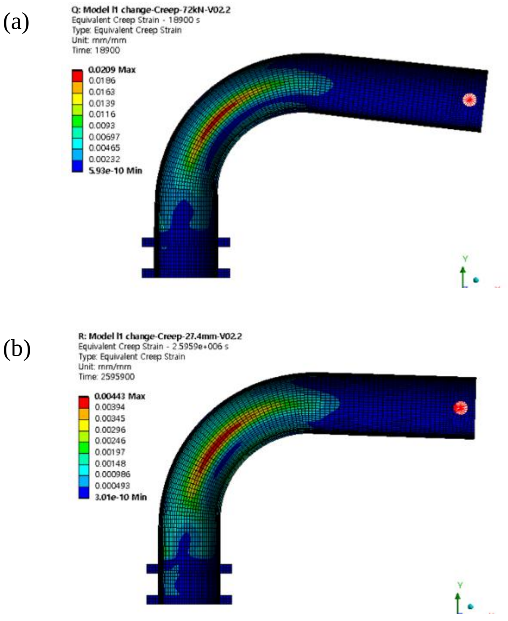

Fig. 6. Distribution of equivalent creep strain in the bent pipe FE model (FEA results): (a) CREEP1, and (b) CREEP2

4. Conclusion

This study performed a comparative verification between structural tests and FE analyses for applying induction bending technology to SFR piping.

(1) The material constants for Chaboche and creep models, derived from specimen tests, predicted the creep deformation and stress relaxation behavior of the piping structure well.
(2) The FE model, incorporating actual geometry via ultrasonic thickness measurement, appropriately simulated the boundary conditions of the test rig, and the predicted failure location matched the damage analysis results.
(3) The results confirm that P91 piping applied with the induction bending process secures sufficient structural integrity under 550°C high-temperature conditions.
(4) In particular, the reliable inelastic analysis model verified in this study is expected to contribute to the efficient analysis of reactor structural behavior under various loading conditions without the need for repetitive expensive testing.

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