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Ratchetting response of pipes and elbows under cyclic displacement controlled loads

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ABSTRACT

This paper proposes the critical rotation of straight pipes and short elbows against the ratchetting due to bending by cyclic displacement-controlled loads at room and elevated temperatures. The straight pipes with several r/t, L/r are subjected to cantilever bending and the short elbows with several r/t are subjected to in-plane bending. The critical rotations which correspond to the start point of ratchetting are determined from the experimental and numerical results.

1. INTRODUCTION

In the structural design of piping components of nuclear and fossil power plants used at high temperature, classified stresses and corresponding allowable stresses are considered in order to prevent the failure modes, such as burst or buckling by primary stress due to internal pressure and mechanical loads, ratchetting by secondary stresses due to thermal stresses combined with primary stresses, and creep-fatigue by peak stresses. The additional restriction for piping components is the so-called Se criteria in which the thermal expansion stress Se of elbows and straight pipes is limited to shakedown condition, $Se < 2\sigma_y$ (or 3Sm).

A project for developing new design criteria which aim at the rationalization of piping design by eliminating the Se criteria is ongoing in Japan.

In order to develop the new design criteria which replace the conventional design criteria $Se < 2\sigma_y$, the following two items should be clarified.

(1) Prediction method of rotation of pipes and elbows in piping system due to the elastic-follow -up in plastic and creep regime.
(2) Critical rotation of pipes and short elbows against plastic local buckling, ratchetting and creep-fatigue.

Piping system should be designed in order to satisfy the condition that the predicted rotations of pipes and elbows are less than the critical rotations.

In the related papers [1][2] which will be presented at SMiRT-14, the prediction method of rotation of pipes and elbows in piping system is proposed together with the prediction method of local strain of pipes and elbows for predicting creep/fatigue damage under prescribed rotation. The critical rotation of straight pipes against the plastic local buckling was presented by the authors in the previous paper [3]. The experimental study on the plastic collapse of short elbows is reported at SMiRT-14 [4].

As for the ratchetting of straight pipes and elbows, several experimental works have been performed [5][6][7], in relation to the behavior under seismic loading. But the critical rotation against the ratchetting of pipes and short elbows under cyclic displacement-controlled bendings has not been clarified.

This paper proposes the critical rotation of straight pipes and short elbows against the ratchetting due to bending by cyclic displacement-controlled loads at room and elevated temperatures.

2. EXPERIMENT OF STRAIGHT PIPES

2.1 Test Method

Figure 1 shows testing apparatus. A straight pipe was fixed on one side and the other side was cyclically pulled by the testing machine in the displacement-controlled manner. Seven specimens tested were the ark welded thin wall stainless steel pipes which were made of type 304 stainless steel and solution heat treatment was performed after fabrication. Test conditions are summarized in Table 1. The specimens of Cases 1 and 2 have the reference configuration. The influence of configuration of specimen, L/r and r/t were studied in Cases 3 and 5 at room temperature. The influence of internal pressure of 9.8MPa was examined in Case 4. The behaviors at 600℃ without and with hold time were studied in Cases 6 and 7.

The strains at around the root of specimen were measured by setting the strain gauges at inner and outer surfaces of compression side of the test specimen. In the test at high temperature, strain gauges for high temperature such as strain pecker and capsule gauge were used.

The cyclically-loaded displacement was stepwisely increased as shown in Table 1, and the minimum number of cycles of each step was taken as ten. The main purpose of these tests is to obtain the ratchetting behavior which has the acceration mode of plastic local buckling as indicated in the related paper [3]. The following two kinds of displacement is the key values in the experiment.

$$\delta_1 = \beta\ PL^3 / (3E\pi R^3 t) + L \cdot \theta_{cr} \qquad (1)$$

$$\delta_2 = \delta_1 / 1.67 \qquad (2)$$

$$\theta_{cr} = 0.003 + 0.15\ (t/R) \qquad (3)\ ,$$

where δ_1, δ_2 and β are the critical deformation with regard to the initiation of plastic local buckling which is obtained from the eq.(3) defining the critical rotation angle θ_{cr}, the displacement for design considering the safety factor 1.67, and a correction factor of the load considering the actual load-displacement relation in elastic range, respectively.

2.2 Test Results

Strain growth in cycling of constant displacement was seen and the failure pattern was similar to the plastic local buckling, so-called elephant foot failure mode. Figure 2 expresses examples of growth of hoop strain at the bulging part of outer surface during the cycling of displacement δ_2 corresponding to the allowable displacement for plastic local buckling for design.

The progress of strain was evaluated by the following value.

$$B = (\varepsilon_{(N)} - \varepsilon_{(1)}) / (\log_{10} N) \qquad (4)$$

The number of N was taken as ten, and so the value of B expresses the progress of strain in ten cycles. The values of B were determined for each stepwise level of loading, and the results were arranged against S_{max}/σ_y, δ/δ_{cr} and θ/θ_{cr}, which are expressed as follow.

$$S_{max}/\sigma_y = (M/Z) / \sigma_y \qquad (5)$$

$$\delta/\delta_{cr} = \delta/\delta_1 \qquad (6)$$

$$\theta/\theta_{cr} = (\delta - \delta_{e(1.27\sigma_y)}) / (\delta_1 - \delta_{e(1.27\sigma_y)}) \qquad (7),$$

where S_{max}, σ_y, M, Z and $\delta_{e(1.27\sigma_y)}$ are bending stress, bending moment, section modulus and displacement corresponding to $1.27\sigma_y$, respectively.

The results showed that the dependence of B on the L/r remained in the arrangement against S_{max}/σ_y, but this dependence became small in the arrangement against δ/δ_{cr} and θ/θ_{cr}.

The results which are arranged against θ/θ_{cr} are shown in Fig.3. The values of B becomes large at around $\theta/\theta_{cr} = 0.3$.

3. EXPERIMENT OF SHORT ELBOWS

3.1 Test Method

Testing apparatus is schematically shown in Fig.4. Test specimens were 6B (6-inch) 90 degree short-radius elbows with straight pipes about 3 times the diameter long attached on both ends. The material of the specimens was type 304 and 316FR stainless steels. The material plates were first cold-bent into the shape and welded axially at the intrados and then solution treated.

The seven specimens were prepared as shown in Table 2 together with the test conditions. All tests were performed under the cycling of fully-reversed displacement. Cases from Case 1 thru Case 6 have the same configuration which cover the plastic ratchetting at room and high temperatures and displacement hold effect at high temperature. In the Case 7, the difference of r/t was examined.

The cyclically loaded displacement was stepwisely increased just as the case of straight pipes. Strain measurement is as follows. The strain distribution of the center section of bent angle was measured in the elastic range previously by setting the strain gauges. At the critical part corresponding to 95° from the extrados, the strain gauge at room temperature and the strain pecker at high temperature were set there for getting the growth of ratchetting strain.

3.2 Test Results

The examples of strain growth at the stress levels of 1.5(3Sm), 2.5(3Sm), 3.4(3Sm) for two cases are shown in Fig.5. Ratchetting pattern was the same as reported in the previous works [8][9], that is to say, partial bulging at around 90° from the extrados. Growth of strain was gradual and from this change the same procedure as straight pipes was taken for evaluating the growth rate of ratchetting strain. The same parameter B was determined from the test results, and the obtained results are shown in Fig.6. The start point of ratchetting strain was at around 1.4(3Sm) that is similar to previous works for long and short elbows [8][9].

4. ANALYSIS

The inelastic analyses were performed to discuss the initiation of ratchetting of straight pipes and short elbows together with the experimental results. The ABAQUS Code and three dimensional shell elements were used for analyses. Examples of FEM modeling of straight pipe and short elbow are shown in Fig.7 and Fig.8.

As for constitutive equation, the elastic-perfectly-plastic model was used. In some cases treating the displacement hold effect, the conventional strain hardening creep rule was used, and reset of the strain hardening variable was considered after the inverse plastic strain.

The same procedure was adopted for obtaining the growth rate B of ratchetting strain.

5. EVALUATION OF RATCHETTING

Numerically obtained growth rate B of ratchetting strain of straight pipes is shown together with the experimental results in Fig.9.

As for the start point of ratchetting strain, the FEM results using the elastic-perfectly-plastic material properties were employed because strain accumulation trends were expressed more apparently than those measured in the tests.

Regarding the evaluation of ratchetting strains, both the numerical and experiment results were employed.

The final results of evaluation of ratchetting of straight pipes are summarized as follows.

Start point of ratchetting ;

$$\theta/\theta_{cr} = 0.3 \qquad (8)$$

Ratchetting strain growth (membrane) ;

$$B=(2000\times(\theta/\theta_{cr})-600)\times 10^{-6} \text{ mm/mm/10 cycles} \qquad (9)$$

Ratchetting strain growth at outer surface (membrane+bending) ;

$$B=(2500\times(\theta/\theta_{cr})-750)\times 10^{-6} \text{ mm/mm/10 cycles} \qquad (10)$$

The same procedure was taken for the case of short elbows. The growth rate B of ratchetting strain from experimental and numerical results are shown in Fig.10.

The equations for evaluating ratchetting strain of short elbows are as follows.

Start point of ratchetting ;

$$\theta/\theta_0=0.45 \qquad (11)$$

Ratchetting strain growth (membrane) ;

$$B=(700\times(\theta/\theta_0)-315)\times 10^{-6} \text{ mm/mm/10 cycles} \qquad (12)$$

Ratchetting strain growth at outer surface (membrane+bending) ;

$$B=(10000\times(\theta/\theta_0)-4500)\times 10^{-6} \text{ mm/mm/10 cycles} \qquad (13)$$

Here the reference rotation θ_0 is expressed as follow.

$$\theta_0=1.08\lambda^{(2/3)}\times(\sigma_y\pi RK)/(rE) \qquad (14)$$

, where the σ_y, E, K, R, r, λ are yield stress, Young's modulus, flexibility factor, bent radius of elbow, mean radius, and pipe factor expressed as $\lambda=Rt/r^2$.

The reference rotation θ_0 means the twice of the elastic rotation angle corresponding to the collapse moment of 90 degree elbow subjected to inplane bending.

6. CONCLUSION

This paper proposes the critical rotation of straight pipes and short elbows against the ratchetting due to bending by cyclic displacement-controlled loads at room and elevated temperatures. The straight pipes with several r/t, L/r are subjected to cantilever bending and the short elbows with several r/t are subjected to in-plane bending. The critical rotations which correspond to the start point of ratchetting are determined from the experimental and numerical results.

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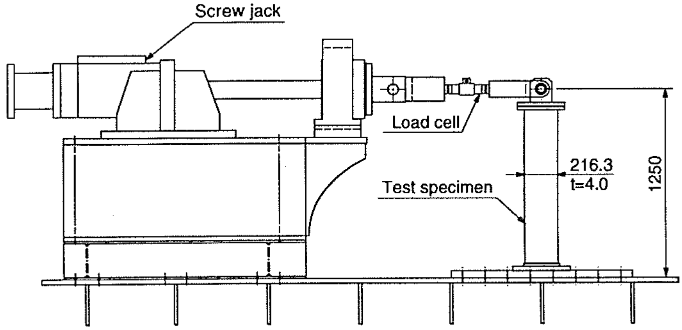


Fig.1 Testing apparatus of straight pipes

Table 1 Test condition of straight pipes

Case	D (=2r) (mm)	t (mm)	L (mm)	Temp. (℃)	Hold time (hr/cycle)	σ_y (MPa)	δ_1 (δ_{cr}) (mm)	δ_2 (δ_{cr}/1.67) (mm)	S_{max}/σ_y	Notes
1	216.3	4	1000	RT	0	287	19.02	11.39	2.64	$\delta_2\times10 \rightarrow \delta_1\times10$
2	216.3	4	1000	RT	0	287	18.56	11.11	2.65	$\delta_y\times10 \rightarrow \delta_2\times100$
3	216.3	4	500	RT	0	248	8.80	5.27	3.44	$\delta_y/1.4\times10 \rightarrow \delta_2\times100$
4	216.3	4	1000	RT	0	248	17.40	10.42	2.91	$\delta_y/1.4\times10 \rightarrow \delta_2\times100$
5	457.2	4	2000	RT	0	263	25.99	15.56	2.35	$\delta_y/1.4\times10 \rightarrow \delta_2\times100$
6	216.3	4	1000	600	0	143	15.70	9.40	3.39	$\delta_y\times10 \rightarrow \delta_2\times10$
7	216.3	4	1000	600	5.0	143	16.0	9.58	3.31	$\delta_y\times10 \rightarrow \delta_2\times10$

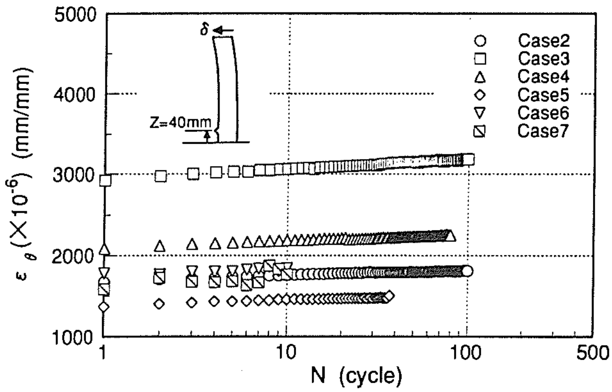


Fig.2 Growth of hoop strain at outer surface of straight pipes

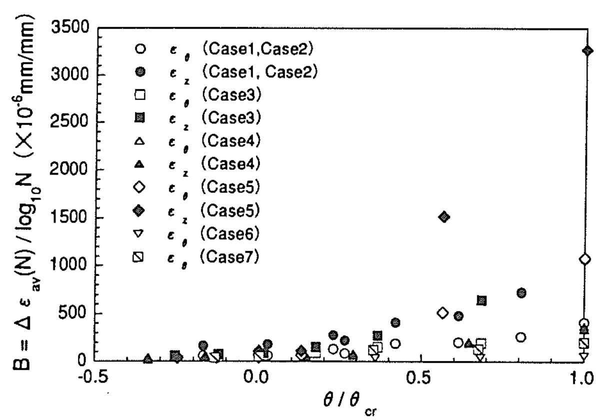


Fig.3 The parameter B expressing the progress of strain in 10 cycles for straight pipes

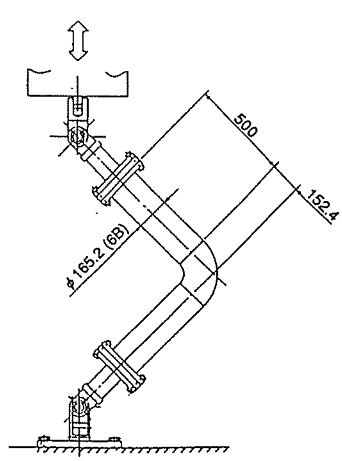
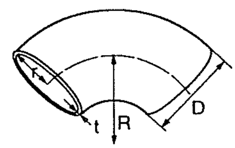


Fig.4 Testing apparatus for short elbow

Table 2 Test condition of short elbows

Case	D(=2r) (mm)	t (mm)	R (mm)	Material	Temp. (℃)	Hold time (hr/cycle)	σ_y (MPa)	Stress level	Cycles
1	165.2	3.4	152.4	SUS304	RT	–	282	3.4 (3Sm)	100
2	165.2	3.4	152.4	SUS304	RT	–	282	2.5 (3Sm)	100
3	165.2	3.4	152.4	316FR	650	–	165	1.5 (3Sm) 2.5 (3Sm) 3.4 (3Sm)	10 10 100
4	165.2	3.4	152.4	316FR	650	–	145	2.8 (3Sm)	100
5	165.2	3.4	152.4	316FR	650	0.5	145	2.8 (3Sm)	50
6	165.2	3.4	152.4	SUS304	650	5.0	116	2.2(3Sm)	50
7	165.2	7.1	152.4	SUS304	RT	–	245	1.5 (3Sm) 2.5 (3Sm) 3.4 (3Sm)	10 10 100

$Sm=0.9\sigma_y$



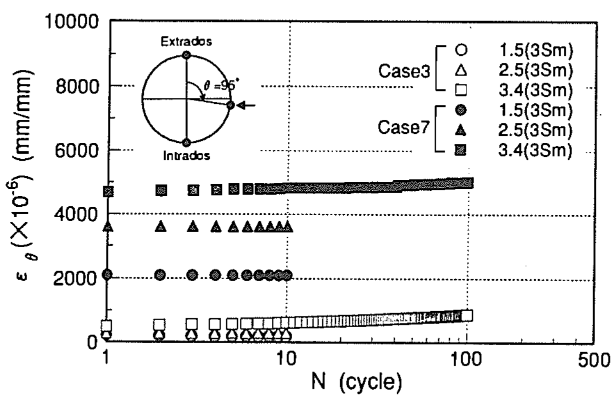


Fig.5 Growth of hoop strain at outer surface of short elbows

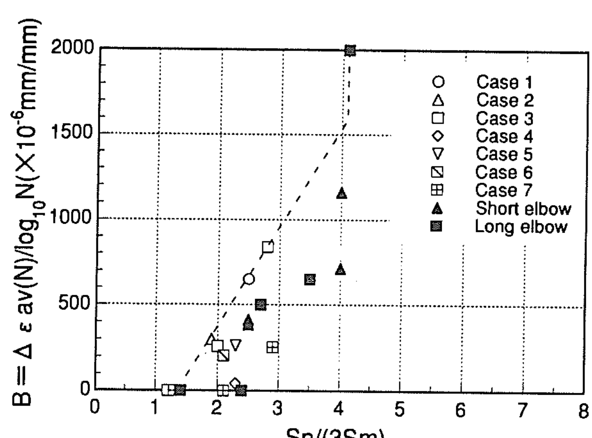


Fig.6 The parameter B expressing the progress of strain in 10 cycles for short elbows

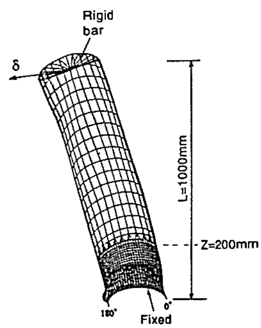


Fig.7 FEM model for straight pipe

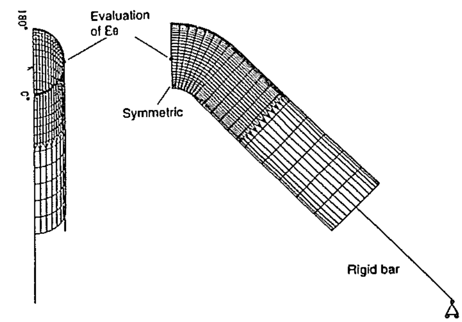


Fig.8 FEM model for short elbow

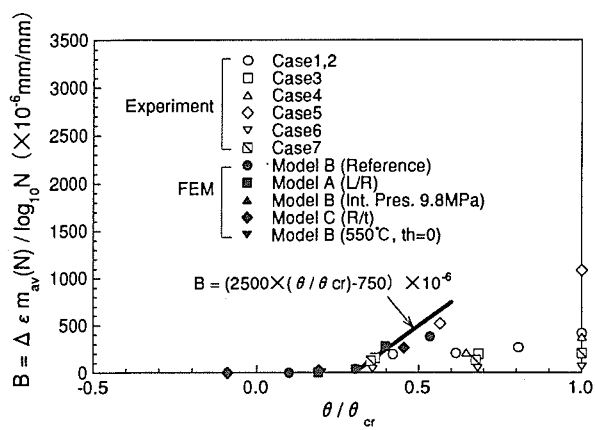


Fig.9 Evaluation of strain growth B of straight pipes (membrane+bending)

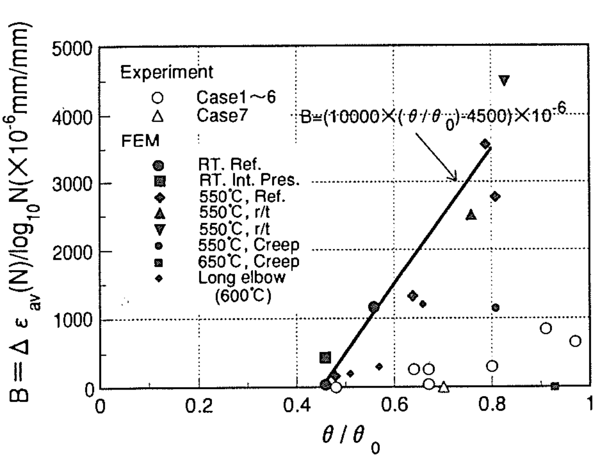


Fig.10 Evaluation of strain growth B of short elbows (membrane+bending)