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A Study on the Strength of Locally Thinned Wall Pipes Subjected to Cyclic Loading

Akihito Otani[1], Hiroe Kobayashi[1], Nobuyuki Ogawa[2], Izumi Nakamura[2] and Masaki Shiratori[3]

1) Ishikawajima-Harima Heavy Industries Co., Ltd., Japan
2) National Research Institute for Earth Science and Disaster Prevention, Japan
3) Yokohama National University, Japan

ABSTRACT

Carbon steel is used extensively in piping systems of power generating plants. When high temperature pressurized water and steam flow through the piping at high speed, erosion/corrosion could occur and cause wall thinning in the piping. To evaluate seismic performance of locally thinned piping is one of the important issues. It is a matter of argument if the failure mode during large seismic event is one of or combination of collapse, buckling and fatigue with ratcheting. Collapse caused by excessive progressive deformation during cyclic loading is a point of controversy as a failure mode to be considered in seismic design for piping system.

In order to clarify the failure mode and the limit load, displacement-controlled bending test on straight pipe and dynamic excitation test on 2-D piping model were performed. The straight pipe and 2-D piping model were locally thinned. The straight pipe test was performed as a component test to investigate the relation between displacement and reaction force and the progressive strain behavior. The failure mode of the displacement-controlled test was found to be low cycle fatigue with ratcheting. 2-D piping model was excited by narrow band random wave of which stress level calculated linearly was equivalent to about 5Sm. The failure mode of the dynamic test was not collapse but fatigue.

INTRODUCTION

A research program to clarify the seismic capability of aged piping system has being conducted by National Research Institute for Earth Science and Disaster Prevention (NIED) and Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) from 1996 to 2000. The program was named "Evaluation of Seismic Performance of Aged Piping System". This program is discussed and evaluated by the Aged Piping committee(AP committee). The committee members join from Yokohama National University (YNU), Japan Atomic Energy Research Institute (JAERI), Central Research Institute of Electric Power Industry (CRIEPI), Tokyo Electric Power Co., Inc. (TEPCO), Kansai Electric Power Co., Inc. (KEPCO), et. al. This paper reports the results of four- point bending test and 2-D piping model excitation test which are performed on above program. A locally thinned pipe part was installed in the model.

Carbon steel pipe is used in power plants broadly. There is some case that erosion/corrosion occurred in the piping by high-temperature, high pressure, high speed water or vapor flow. It is important to clarify the dynamic response characteristic and seismic integrity of the locally thinned piping which is one of the aged piping.

It is considered that the failure mode of piping system undergoing excessive seismic load is one of or combination of collapse, buckling and fatigue with ratcheting. In this paper, the collapse means the excessive progressive deformation at undergoing cyclic load. It is regarded as an important issue for seismic design of piping system.

In this study, four-point bending tests and excitation tests for 2-D piping model were performed to clarify the failure mode and seismic capability when the locally thinned piping undergoes excessive seismic load. These vibration tests were carried out using Large-scale Shaking Table of NIED. The specification of Large-scale Earthquake Simulator is shown as follows.

- Size of vibration table : 15 x 14.5m
- Max. loading weight : 500tons
- Amplitude : -22 to +22 cm (horizontal direction)

Four-point bending test was a displacement-controlled test to obtain the relation between the reaction force and displacement and the strain progress behavior of the thinned pipe. Excitation test with the 2-D piping model was the test to understand the dynamic response characteristic, the failure mode and the seismic capability of thinned wall piping. For comparison, the test of piping model without thinning was also performed. The effect of gravity contributing to collapse is small in the 2-D piping model, but the shape of this model is the configuration which there can be in the actual piping system.

FOUR-POINT BENDING TEST

Test Model

The test model had thinned wall part in full circumference by machining so that wall thickness became 1/2 for 100A sch80 pipe as shown in figure 1. The specifications of the test models are shown below.

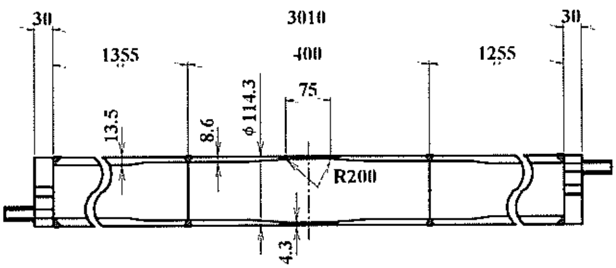


Fig. 1 Four-Point Bending Test Model

- Pipe outer diameter : 100A(114.3mm)
- Thickness of the general part : sch80 (8.6mm)
- Thickness of the reinforced part : sch160(13.5mm)
- Wall thinning type : Fully circumferential thinning
- Thickness at wall thinning part : 4.3mm(t/2)
- Material: Carbon Steel

Test Equipment

The test equipment is shown in figure 2. The test model are set on the shaking table with two fixed supports and two sliding supports, and this equipment has the mechanism which test model is bent by the relative displacement between the shaking table and the foundation. A hand-pump and an accumulator are installed. The internal pressure of the test model is applied by the hand-pump, and it is maintained by accumulator.

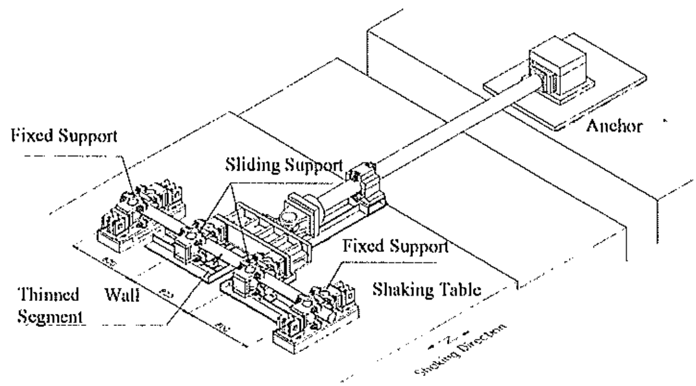
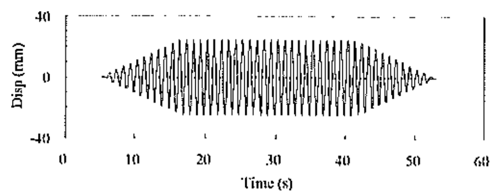


Fig. 2 Four-Point Bending Test Equipment

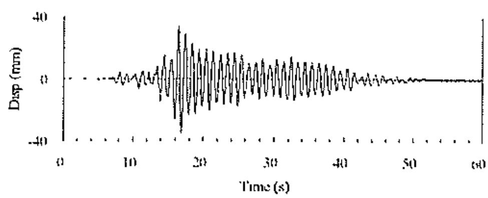
Input Condition

Bending load was applied to the test model repeatedly by the displacement-controlled motion of the shaking table. A sine wave and the random wave which had the spectrum peak 1 Hz were used as input wave, and those waves are shown in figure 3. The amplitude increasing was arranged in the front period of the sine wave and the amplitude decreasing was also arranged in the end period of the wave as shown in this figure. The maximum amplitudes of the sine wave and random wave were 25 mm and 35 mm, respectively.

The internal pressure 11 MPa was applied to the test model.



(a) Sine Wave



(b) Random Wave

Fig. 3 Input Wave for Four-Point Bending Test

Measurement

Displacement of shaking table, reaction force, internal-pressure, acceleration and strain on the outside surface of the test model were measured. The reaction force was measured by a load cell installed at an end of the rod connected to an anchor. The internal pressure of the test model was measured by strain-gauge-type pressure sensors installed at the both ends of the test model. Strain gauges which could measure large strain in two direction were used.

All data of the measurements were recorded with sampling frequency 500 Hz after processing with the analog low pass filter 100 Hz. The digital low pass filter of 30 Hz was used in the post processing.

Test Result

The result of the four-point bending test is summarized in table 1. The failure of test models shown with this table was fatigue failure enhanced by ratchet. The example of the failure is shown in photo 1. The swell by ratcheting appeared in the thinned wall part of the test model as shown in this photograph, and a crack penetrated at the central part.

This crack is considered as fatigue crack. It is expected that the applying sine-wave is easier to cause damage than by the random wave of which the maximum amplitude is same as the sine wave.

The force-displacement curves provided by the test of EC04 is shown in figure 4. This figure shows elasto-plastic behavior. The strain time history is shown in figure 5. As shown in this figure, both of the hoop strain and the axial strain progressed in the tensile direction only on the first shaking, mostly. It is considered that little progression of the strains after the first shaking was due to the hardening by the plastic deformation.

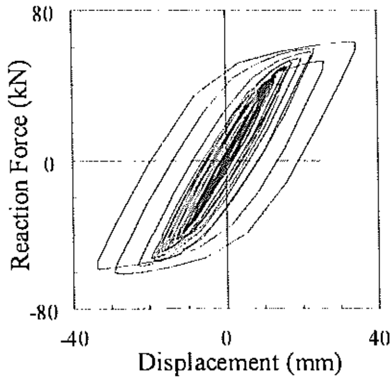


Fig. 4 Force-Displacement hysteresis (EC04 1st shaking)

Tab. 1 THE VIBRATION CHARACTERISTICS OF THE TEST MODEL

Model No.	Material	Sm (N/mm2)	Thickness of Thinned Wall part (mm)	Input Condition: Pressure (MPa)	Input Condition: Input Wave	Test Result: Max. Amp. & Num. of Shakings	Test Result: Failure Appearance
EC01	Carbon Steel	157	4.3 (1/2t)	10.4	Random	15 mm x 15 times 25 mm x 15 times 30 mm x 5 times 35 mm x 5 times 45 mm x 5 times	Crack Penetration
EC02	Carbon Steel	157	4.3 (1/2t)	10.4	Sine	25 mm x 3 times	Crack Penetration
EC04	Carbon Steel	170	4.3 (1/2t)	11.0	Random	35 mm x 5 times	Crack Penetration

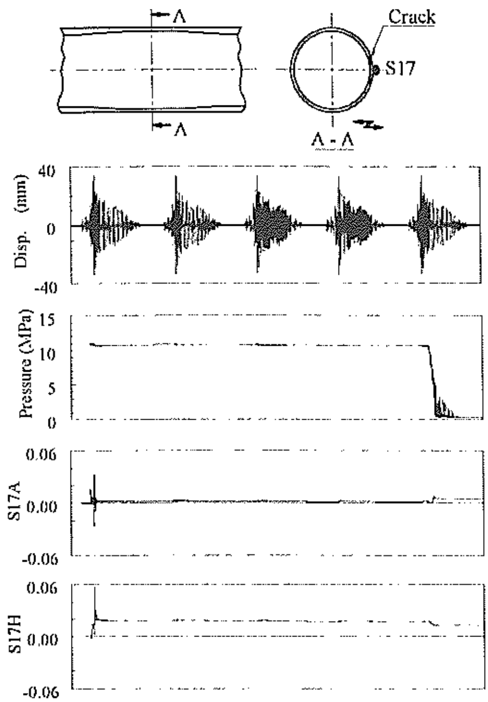
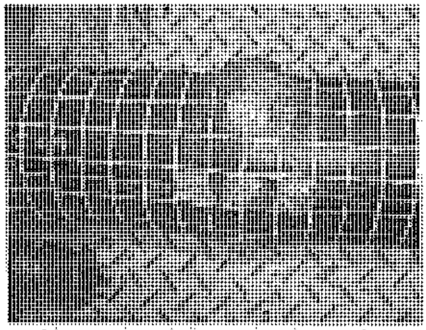
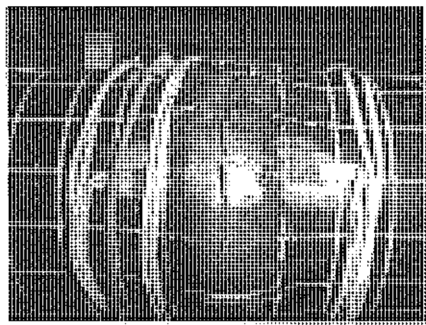


Fig. 5 Strain Time History (EC04)



The section deformation by ratchet



The Crack Penetration on the Bulging part

Photo. 1 Example of the Failure (Model No. EC04)

2-D PIPING MODEL EXCITATION TEST

2-D Piping Model

As the first step of the dynamic test for piping system, the excitation test of a 2-D piping model was performed. The configuration of the test model is shown in figure 6. Three kinds of test model made of carbon steel were used as shown in table 2. The model B01 had the fully circumferential wall thinning at the straight pipe near an anchor and C01 had a sch40 elbow which was thinner than another elbow.

The vibration mode of the 2-D piping model obtained by modal analysis is shown in figure 7.

Input condition

Excitation tests by the narrow band random wave were performed for the 2-D piping models. The time history of the input wave and the response spectra are shown in figure 8.

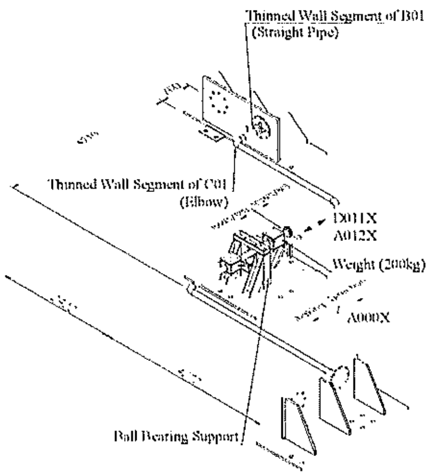
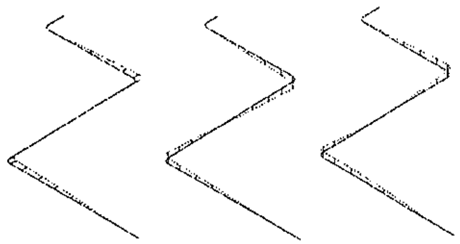
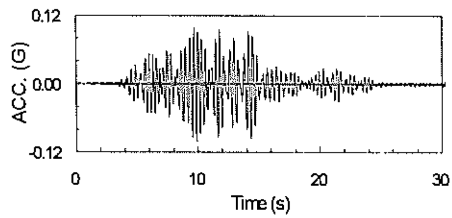


Fig. 6 2-D Piping Model

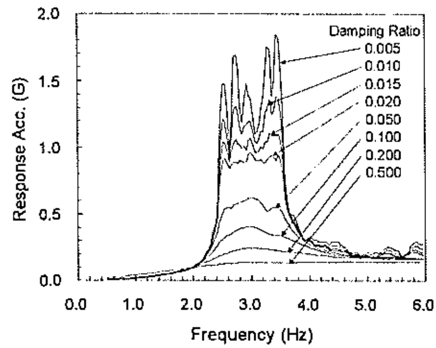


The 1st Mode 3.2Hz　The 2nd Mode 5.7Hz　The 3rd Mode 14.3Hz

Fig. 7 The vibration mode of 2-D piping Model



ACC. Time History



Response Spectra

Fig. 8 Narrow Band Random Wave (Input Level 0.1G)

This input wave is random wave having the frequency band from 2.5 to 3.5 Hz, and only the first mode of the 2-D piping model can be excited by the input wave. The excitation test was performed with several acceleration level from the elastic level to about 1.5 G. In the test by the maximum level, the stress level of the model A01 was about 5 Sm at the elbow near an anchor. Sm was calculated from the actual yield stress and ultimate stress. The stress index B2=2.15 of 100A*sch80 long elbow was used into the above calculation.

In this test, the internal-pressure about 11 MPa was applied to a half part of the model having thinned wall part. The part of remaining half was maintained with atmospheric pressure.

Measurement

The acceleration of shaking table was measured and the accelerations at several points of the piping model were measured in the shaking and vertical direction. The response displacement at the center of the model was also measured. Hoop and axial strains on the outside surface of the elbows and thinned wall part in the straight pipe were measured. Moreover, the axial strains of the straight pipes near two anchors and close to both ends of elbow were measured.

Test Result

The test results of the 2-D piping model excitation are shown in table 2. All test model did not fail with five times of excitation of the stress level of 3 Sm. The response reduction by energy dissipation due to the elasto-plastic behavior was observed. The relationship between the response displacement of the model and the input acceleration are shown in figure 9. And the transfer function of the response acceleration at the center of model to the input level is shown in figure 10. Obviously, the response of the model decreases with plastic deformation as shown in figure 9 and 10. The gain decreased with input level increasing as shown in figure 10. More than 3 Sm stress level was able to be realized by setting the input level larger than the response decreasing by the plastic deformation.

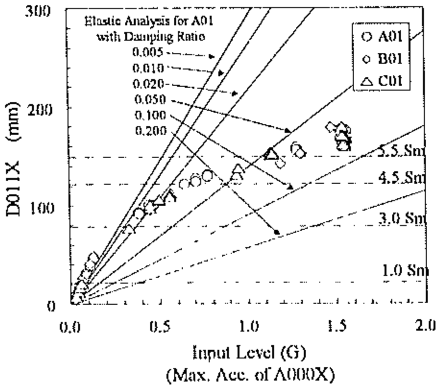


Fig. 9 The Response Displacement of 2-D piping Model

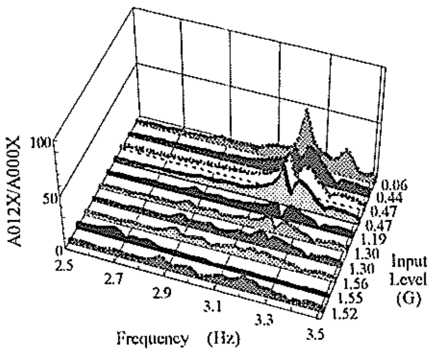
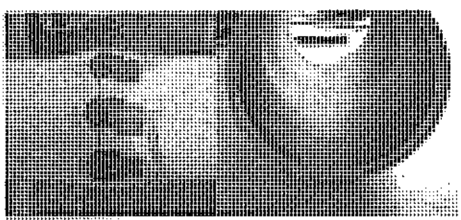


Fig. 10 The Transfer Function of B01

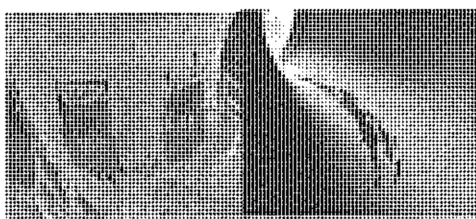
The failure of all test models was the penetration of axial direction crack on the side inner face of elbow as shown in table 2. The results of the flaw inspection of the inner surface and thinned wall part at B01 are shown in photograph 2. There were elbows on which the crack did not penetrate, but the many small cracks as shown in this photograph were observed at the side inner surface of every elbow. It is expected that the crack appeared with low cycle fatigue.

Although a remarkable sectional deformation by ratcheting was observed in the thinned wall part on the straight pipe of the test model B01, the fatigue crack did not appear on the inner surface yet. The failure was not reached at the thinned wall part on the straight pipe. It is considered that the section modulus became large with the bulge and that the sectional deformation acted as effect to reinforce for this part.

On the excitation of the maximum input level for B01, the break of pipe at near an anchor. Several times of shaking were performed for the broken model. However, the several shakings with the unexpected break were not on the condition that the stress on the elbow could became larger than the stress of thinned wall part on the straight pipe. Therefore, it is considered that the result of the stronger damage on elbow is not overturned.



The Bulge at Thinned Wall Part
but no Crack at Thinned Wall Part



Crack on Inner Side Face of Elbow

Photo. 2 The Failure of 2-D Piping Model B01

Tab. 2 The Results of 2-D Piping Model Excitation Tests

Model No.	Material	Sm (N/mm^2)	Thickness of Thinned Wall part (mm)	Test Results	
				Max. Input Acc.(Stress level) & Num. of Shakings	Failure Appearance
A01	Carbon Steel	155	No thinning	Elastic x 8 times 370- 430 gal (3 Sm)x 5 times 620- 750 gal (4.5Sm)x 5 times 1280 gal (5.5Sm)x 5 times	• No penetration of crack. • Crack was observed on the inner surface of elbow.
B01	Carbon Steel	155	4.3 (1/2) on straight pipe part	Elastic x 6 times 430- 460 gal (3 Sm)x 5 times 1160-1280 gal (4.5Sm)x 5 times 1490-1530 gal (5.5Sm)x 28 times	• Crack Penetrated at the elbow of model center. • The thinned part bulged but no crack on inner surface. • Crack was observed on the inner surface of every elbow.
C01	Carbon Steel	155	6.0 (sch40) on the anchor side elbow	Elastic x 5 times 320- 550 gal (3 Sm)x 10 times 920-1120 gal (4.5Sm)x 8 times 1500-1530 gal (5.5Sm)x 27 times	• Crack Penetrates at the thinned wall elbow. • Crack was observed on the inner surface of every elbow.

CONCLUSION

In this study, four-point bending test of locally thinned wall straight pipe and excitation tests of 2-D piping model with thinned wall part were performed. The four-point bending test was performed to obtain the relation between the displacement and the reaction force and the strain progress behavior of the thinned wall pipe. The 2-D piping model excitation test was performed to obtain the dynamic response characteristic, the failure mode and the strength of the piping system which had thinned wall part.

The strain progress enhanced by ratchet at thinned wall part was observed in the result of the four-point bending test, and the penetration of the fatigue crack in the hoop direction occurred. The 2-D piping model excitations were performed by using the high input level corresponding to the linearly calculated stress level more than 5 Sm. The fatigue failure at elbow occurred for every model. The location where fatigue crack appeared was the side inner surface of elbow, and the direction of crack was the axial.

ACKNOWLEDGMENT

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