FAILURE BEHAVIOR OF PIPING SYSTEMS WITH LOCAL DEGRADATION UNDER EXCESSIVE SEISMIC LOAD

Izumi Nakamura
National Research Institute for Earth Science and Disaster Prevention, Japan
Akihito Otani
Ishikawajima-Harima Heavy Industries Co., Ltd, Japan
Masaki Shiratori
Yokohama National University, Japan

Abstract

An experimental and analytical research program on degraded piping systems has been conducted to clarify the effect of degradation on the dynamic behavior and the failure mode of the piping system. The degradation conditions considered in the program were both cracks and wall thinning. From the results of cyclic bending tests on the pipe elements and the shake table tests on the simply-designed piping system models with degradation, it is shown that the failure mode of the degraded piping system is mainly due to the accumulation of damage. The effect of degradation on the dynamic characteristic of the piping system should be considered in the case of wall thinning, but the estimation of the dynamic response of the piping system and the integrity of the degraded part can be conducted independently in the case of crack.

Introduction

Pressurized piping systems used in nuclear power plants are supposed to be degraded by aging effects, and defects such as local wall thinning or stress corrosion cracks (SCC) may occur to such piping systems. In order to maintain the plants in safe conditions under destructive earthquakes, it is important to estimate the effects of degradation on the dynamic behavior and the ultimate strength of the piping systems. Though there are a lot of excitation tests for piping system models without defects which focused on the elastic-plastic behavior of the system [1-3], or loading tests for pipe elements with degradation under static load [4-8], there are very few studies on degraded piping systems under seismic events, and the failure behavior of such piping systems is still not clear.

National Research Institute for Earth Science and Disaster Prevention (NIED) has conducted a lot of excitation tests on piping system models from 1982 using the one-directional shake table in NIED. On 1986, the excitation tests for piping system models with electric discharge machining (EDM) notches were conducted for the first time and the effect of the notch on the piping system models' vibration characteristic was investigated [9]. In order to clarify the dynamic behavior and the failure modes of piping models with degradation, both wall thinning and cracks, a series of experiments and finite element analyses has been conducted on pipes and piping systems with degradation under seismic loads from 1996 – 2005 (scheduled) by NIED, Yokohama National University (YNU), and Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI). In the experiments, pipe element tests and piping system tests were conducted. Pipe element tests consisted of displacement-controlled cyclic bending tests on pipe elements with degradation. The purpose of the tests is to clarify the failure modes of degraded pipes under the high level cyclic bending load. Piping system tests consisted of shake table tests using simplified piping system models with degradation. The purpose of the tests is to clarify the effects of degradations on the dynamic characteristics and the failure behavior of piping systems under high-level excitation. FEM analyses were carried out to reproduce the experimental results, and the applicability of an analytical method to predict the failure of degraded pipes under seismic loads was also investigated. The test and FEM analyses results have already been reported [10- 17]. In this paper, the summary of the experiments and the feature of the failure mode of pipes with degradation will be described.

Outline of the research program

Pipe element tests for straight pipes

Straight pipes and bend pipes (elbows) were used for the pipe element tests. Straight pipe element tests were the cyclic four-point bending tests on the pipes with degradation. The degradation conditions considered in the tests were either of local wall thinning (modeled by mechanical machining), electric discharge machining (EDM) notch, or SCC. The outer diameter and the wall thickness of the pipe were 114.3mm and 8.6mm, respectively. Material of the pipe was Carbon Steel STS410 for the specimens with wall thinning, and Stainless Steel SUS304 for the specimens with EDM notch or SCC. The configurations of the defects are shown in Fig. 1 - Fig. 3. The specimens were subjected to 2 types of displacement wave, which were the constant amplitude sinusoidal wave and the random amplitude wave. The patterns of the input displacements are shown in Fig.4. The frequency of the sinusoidal wave was 1Hz. The number of steady amplitude cycles in the sinusoidal wave was 26. The random amplitude wave was obtained from a seismic response wave of a piping system, and was modified so as to the dominant frequency of the response became to 1Hz. The random amplitude wave includes 46 cycles. The reason to use the sinusoidal wave is to obtain the number of cycles to cause failure to the degraded pipes, and the reason to use the random amplitude wave is to investigate the effect of the applied wave form. All specimens except for one were pressurized to 11MPa for thinned wall specimens and 8MPa for cracked specimens with room temperature water. One specimen with wall thinning was tested without internal pressure in order to compare the failure pattern with the pressurized specimen.

The test conditions and the results of the straight pipe element tests are shown in Table 1. The failure mode of the pipes with wall thinning was mainly the fatigue failure accompanied with ratchet deformation (*1), and that of the pipes with cracks (EDM notch or SCC) was crack penetration caused by the fatigue crack propagation from the initial EDM notch or SCC. Figure 5 shows the typical failure mode of the specimen with wall thinning.

(*1) It is well known that increase of pipe diameter occurs to pressurized pipes subjected to cyclic loading [18], and this phenomenon is usually called as “mechanical ratchet”, or more simply, “ratchet”. In this paper, “ratchet deformation” means the deformation caused by a ratchet phenomenon.

Pipe element tests for elbows

For the bend pipe element tests, the degradation condition was wall thinning. The outer diameter and the wall thickness of the pipe were 216.3mm and 12.6mm, respectively. Material of the pipe was Carbon Steel STS410. The configurations of the wall thinning are shown in Figs. 6 and 7. The bending tests were displacement-controlled, and the input displacement wave of the bend pipe test was only the constant amplitude sinusoidal wave, shown in Fig.8. The frequency of the input wave was 0.2Hz, and the number of steady amplitude cycles in the sinusoidal wave was 20. All specimens were pressurized to 10MPa with room temperature water.

The test conditions and results of the bend pipe element tests are shown in Table 2. The failure mode of the bend pipes with wall thinning was mainly the fatigue failure accompanied with ratchet deformation. The fatigue cracks were observed at the flank of the elbow in the longitudinal direction. For the thinned wall bend pipes subjected to out-of-plane bending, a remarkable ratchet deformation was observed and the failure mode was fatigue and buckling [12].

From the pipe element tests, the failure mode features which depended on the degradation conditions or loading conditions were elucidated. The stiffness of the pipe was affected by wall thinning, but not by the existence of cracks. The failure modes for thinned wall pipes were affected by the occurrence of the ratchet phenomena. The configuration of wall thinning and the type of applied bending load affects the degree of occurrence of the ratchet phenomena.

Piping system tests

Shake table tests with 2-D or 3-D piping models were conducted in order to clarify the effect of degradation on the dynamic behavior and the failure modes of piping systems. The configurations of the piping models used for the tests are shown in Fig.9. The degradation condition induced in the models was wall thinning at elbows or at a straight pipe, or EDM notch. The outer diameter and the wall thickness of the pipe were 114.3mm and 8.6mm, respectively. The wall thinning at the straight pipe was made by mechanical machining, but the wall thinning at the elbows was achieved by using thinner elbows. Material of the pipe was mainly Carbon Steel STPT370, but Carbon Steel FSGP was used for the thinner elbows. Stainless Steel SUS304 was used at the EDM notch induced part. Figure 10 shows the vibration modes and natural frequencies of the piping model without defects obtained by modal analyses. The one directional shake table of NIED was used for the piping model excitation tests. The shaking direction is shown in Fig.9. Narrow band random waves shown in Fig.11 and Fig.12 were used for the shake table tests. The wave excites the first mode of the piping models. The reason to use the narrow band random wave is to have the test models resonate and to produce a large plastic deformation to the test models even though the dominant frequency of the model changed due to the elastic-plastic deformation or the existence of degradation. The tests were performed from the elastic level to the maximum acceleration level which the shake table was able to produce. In all cases, the piping models were pressurized with room temperature water. The tests at the maximum input level were repeated until the model failed and a leak of pressurized water occurred.

The test conditions and the results of the piping system tests are summarized in Table 3 and Table 4. The failure mode of the models with wall thinning or without defects is the fatigue failure accompanied with ratchet deformation at the flank of the weak elbow. Figure 13 shows the typical failure mode of these models. The failure mode of the models with EDM notch was the crack penetration for 3D_D02, and no failure for 3D_D01. Tables 3 and 4 also show that the dominant frequency of the test model was reduced by the existence of wall thinning, but not by the existence of a crack. Residual deformation was observed in some models, but unstable failure, such as excessive progressive deformation, did not occur except for 3D_D02, which was the model with a full circumferential 50% EDM notch.

From the excitation tests at the elastic level of 3D_A01 (the model without wall thinning), the stress intensity at Elbow1 reached to $3S_m$.(*2) at 320Gal input acceleration. But the model did not show any sign of failure at 400Gal excitation test, so the input acceleration was risen up to 1850Gal, the maximum acceleration that can excite by the shake table. The stress level at Elbow1 caused by the excitation test at 1850Gal input reached to 16.5Sm, 5.5times larger than the allowable stress level determined by the current code. But as shown in Table 4, the test model required several times excitation at that level until failure. One to three times excitation tests at 1850Gal were required to cause failure even to the models with 50% full circumferential wall thinning.

(*2) 3S_m is the allowable stress determined by the current Japanese seismic design code

Failure mode of piping system and influence of degradation on the seismic safety

From the results of the pipe element tests and the piping system tests, the failure mode of the piping system with degradation is expected to be the fatigue failure with ratchet deformation in the case of wall thinning, and the fatigue crack propagation from the initial crack in the case of crack. That is, the failure of the piping system is caused by the accumulation of damage. As a result, the important factors to evaluate the seismic safety of the degraded piping system are considered to be the maximum applied moment caused by the seismic response of the piping system and the histogram of the applied moment. Note that the effect of velocity or displacement of the input motion was not considered at determining the input motion of the excitation test. The effect of multi-axial excitation was also not considered in the tests. To confirm the failure mode of the piping system with degradation, the effects of these factors might be investigated.

In order to evaluate the seismic safety of the degraded piping system, the effect of degradation on the strength and the dynamic behavior of the piping system should be considered. Experimental results showed that the piping systems with cracks can be treated as piping systems without cracks for seismic response analysis, and the integrity of the degraded part can be evaluated from the piping response. The estimation of the response of the piping system and the integrity at the cracked part can be done independently. On the other hand, the effect of degradation should be considered to estimate the response of the piping systems with wall thinning, because the existence of wall thinning may affect the stiffness, the vibration characteristics, and the failure modes of the piping systems. From the feature of the failure mode, the effects of wall thinning on the estimation of the seismic safety of the piping system are shown in Fig. 14. As shown in Fig.14, it is necessary to consider the effect of wall thinning both on the globally seismic response of the piping model and the locally stress at the thinned wall part in order to assure the seismic safety of the degraded piping system.

At present, the effects of wall thinning on the seismic safety shown in Fig.14 are considered qualitatively. For example, test results show that the dominant frequency of the piping system is affected by the wall thinning, but the influence of wall thinning on the system’s dominant frequency varies depending on the configuration of the piping system, its vibration mode, wall thinning condition, etc. Thus more investigation and tests should be done to estimate such effects quantitatively and to determine the acceptable wall thinning configuration under seismic load. The FEM analytical model established in this research program [14 - 17] may useful to investigate such effects.

Summary

The experimental and analytical research program has been conducted to clarify the effect of degradation on the dynamic behavior and the failure mode of the piping system. The test results show that the failure mode of such piping system under excessive seismic load is mainly the fatigue failure, and the first excursion failure was not observed in the test, though the piping system had 50% wall thinning and excited much higher input acceleration than the allowed level by the current code. Considering the effect of degradation on the strength and the dynamic behavior of the piping system, the estimation of the response of the piping system and the integrity at the cracked part can be done independently for the piping system with crack, but the effect of the degradation should be considered to estimate the response of the piping systems with wall thinning.

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Table 1 Test conditions and results of the straight pipe element tests

Name	Material	Condition of defect			Internal pressure (P) [MPa]	Input condition		No. of loading	Max. reaction force [kN]	Test results
		Type	Full angle [deg]	Depth*		Pattern of input disp. wave	Max. amp. of input [mm]			
SC01	SUS304	SCC	Natural crack	Natural crack	8	Sinusoidal	50	5 (108 cycles)	96	Crack penetration at SCC
SC03								5 (128 cycles)	95	Crack penetration at SCC
SC07								5 (127 cycles)	92	Crack penetration at SCC
SC08								5 (117 cycles)	93	Crack penetration at SCC
EM01	SUS304	EDM	360	0.5 t	8	Random	15	35	71	Full circumferential break
							30	2		
EM02						Sinusoidal	25	1 (16 cycles)	67	Full circumferential break
EM03						Random	25	10	69	Full circumferential break
EM04						Sinusoidal	21	1 (18 cycles)	66	Full circumferential break
EM05			90	0.5 t		Random	35	4	79	Crack penetration at EDM notch
EM06			25.73 *1	0.49 t *1		Sinusoidal	50	2 (32 cycles)	94	Crack penetration at EDM notch
EM07			14.87 *2	0.49 t *2		Sinusoidal	50	3 (55 cycles)	108	Crack penetration at EDM notch
EM08			16.64 *3	0.34 t *3		Sinusoidal	50	4 (108 cycles)	90	Crack penetration at EDM notch
EM09			90	0.5 t		Sinusoidal	35	1 (19 cycles)	77	Crack penetration at EDM notch
EC01	STS410	Wall thinning	360	0.5 t	11	Random	15	15	78	Low-cycle fatigue failure with swelling by ratchet
							25	15		
							30	5		
							35	5		
							45	3		
EC02						Sinusoidal	25	3 (73 cycles)	67	Low-cycle fatigue failure with swelling by ratchet
EC04						Random	35	5	64	Low-cycle fatigue failure with swelling by ratchet
EC05						Sinusoidal	35	1 (11 cycles)	86	Low-cycle fatigue failure with swelling by ratchet
EC06					0	Sinusoidal	35	1 (9 cycles)	69	Buckling and low-cycle fatigue at thinned wall part
EC07				0.75 t	11	Sinusoidal	25	1 (9 cycles)	38	Mixture of low-cycle fatigue with ratchet and burst
EC08				0.25 t		Sinusoidal	35	7 (164 cycles)	80	Low-cycle fatigue failure with swelling by ratchet
EC09				0.6 t		Sinusoidal	25	1 (22 cycles)	51	Low-cycle fatigue failure with swelling by ratchet
EA01	STS410	No defect	0	0	11	Monotonic	Up to 140	–	186	No failure (No crack was found after the test)
EA02						Sin 5 cycles	2.5 - 95	1 for each input	135	Crack penetration at weld line

* 't' denotes the normal pipe thickness

*1 Same size as SCC in SC01 *2 Same size as SCC in SC03 *3 Same size as SCC in SC07

Table 2 Test condition and the results of the bend pipe element tests

Name	Condition of wall thinning	Bending direction*	Support condition	Internal Pressure (P) [MPa]	Input disp. [mm]	No. of input cycles	Max. reaction moment [kN-m]	Test results
ELB01	No defect	I	Pin - Pin	10	70	179	146	Fatigue failure at flank of the elbow
ELB02	50% full circumferential			10 ～ 7		319	85	Fatigue and buckling failure accompanied with ratchet deformation
ELB03	50% partial			10		231	102	Fatigue failure at flank of the elbow (thinned wall side) * A number of small cracks observed at the inner surface of nominal thickness side.
ELB04	70% partial					177	91	Fatigue failure at ratchet deformation
ELB05	50% full circumferential					264	78	Fatigue and buckling failure accompanied with ratchet deformation
ELBI_01	No defect	I	Pin – Fixed support	10	185	110	134	Fatigue failure at flank of the elbow
ELBO_01	No defect	O			195	300	137	No failure
ELBO_02	50% full circumferential					40	105	Fatigue and buckling failure accompanied with ratchet deformation
ELBM_01	50% full circumferential	I + O			185	34	90	Fatigue and buckling failure accompanied with ratchet deformation

* I : In-plane, O : Out-of-plane

Table 3 Test conditions and results of 2-D piping system test

Name	Condition of defect		Internal pressure (P) [MPa]	Natural frequency (f) and damping ratio (h) at 1st mode	Contents of the excitation test by narrow band random wave		Test results
	Type	Depth*			Max. input acc. [Gal]	Number of times	
2D_A01	No defect	0	11	f = 3.35 [Hz] h = 0.0044	30 – 120 (Elastic level)	10	* No failure occurred after 5 times excitation test with input level 1300Gal. * Small cracks were observed on the inner surface of elbows.
					400	5	
					700	5	
					1300	5	
2D_B01	Wall thinning at straight pipe	0.5 t	11	f = 3.28 [Hz] h = 0.0042	30 – 120 (Elastic level)	7	* A fatigue crack penetrated at Elbow2. * Thinned wall part swelled because of ratchet but no crack on inner surface. * Small cracks were observed on the inner surface of elbows.
					400	5	
					1200	5	
					1600	29	
2D_C01	Wall thinning at Elbow1	0.3 t	11	f = 3.22 [Hz] h = 0.0045	30 – 120 (Elastic level)	5	* A fatigue crack penetrated at Elbow1 (the thinned wall elbow) * Small cracks were observed on the inner surface of elbows.
					400	10	
					1200	5	
					1600	27	

* ‘t’ denotes the thickness at normal part of the pipe

Table 4 Test conditions and results of 3-D piping system test

Name	Condition of defect		Internal pressure (P) [MPa]	Natural frequency (f) and damping ratio (h) at 1st mode	Contents of the excitation test by narrow band random wave		Test results
	Type	Depth*1			Max. input acc. [Gal]	Number of times	
3D_A01	No defect	0	10	f = 2.78 [Hz] h = 0.0106	20 – 100 (Elastic level)	10	* Penetration of fatigue cracks in longitudinal direction at Elbow1. * A number of small cracks were observed on the inner surface of Elbow2.
					400 – 700	4	
					1400	2	
					1850	14	
3D_C01	Wall thinning at Elbow1& 2	0.48 t	10	f = 2.42 [Hz] h = 0.0121	20 – 80 (Elastic level)	4	* Penetration of a fatigue crack in longitudinal direction at Elbow1. * No crack was observed at Elbow2. * The residual deformation was clearly observed after the test.
					700	1	
					1400	2	
					1850	3	
3D_C02	Wall thinning at Elbow1	0.48 t		f = 2.55 [Hz] h = 0.0131	20 – 80 (Elastic level)	4	* Penetration of fatigue cracks in longitudinal direction at Elbow1. * No crack was observed at Elbow2.
					700	1	
					1400	2	
					1850	3	
3D_C03	Wall thinning at Elbow2	0.48 t		f = 2.62 [Hz] h = 0.0109	20 – 80 (Elastic level)	4	* Penetration of a fatigue crack in longitudinal direction at Elbow2. * No crack was observed at Elbow1.
					700	1	
					1400	2	
					1850	1	
3D_D01	Partial EDM notch at straight pipe	0.49 t	8	f = 2.79[Hz] h = 0.0100	20 – 80 (Elastic level)	4	* Excitation test was ended before the failure occurred. Initial EDM notch did not penetrate after 13 times excitation test.
					800	1	
					1200	13	
3D_D02	Full circle EDM notch at straight pipe	0.5 t		f = 2.75 [Hz]*2 h = 0.00938	20 – 80 (Elastic level)	4	* Full circumferential break occurred at second excitation with elastic-plastic level.
					1850	2	

*1 ‘t’ denotes the thickness at normal part of the pipe

*2 Obtained from a wide band random wave excitation test

Fig.1 Example of initial shape of SCC

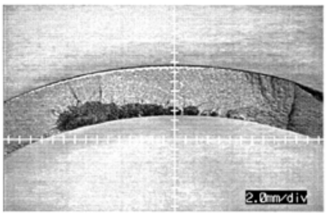
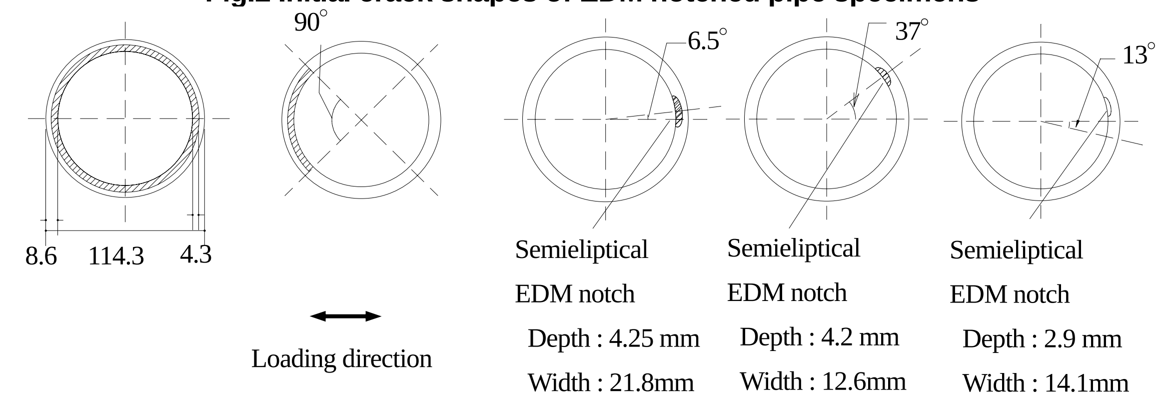
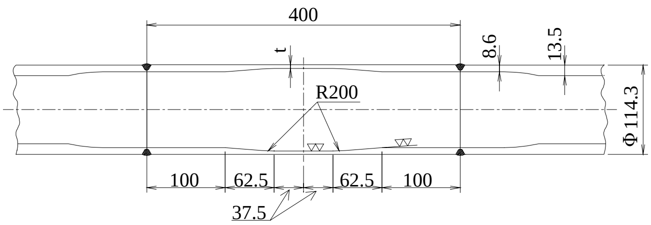


Fig.2 Initial crack shapes of EDM notched pipe specimens



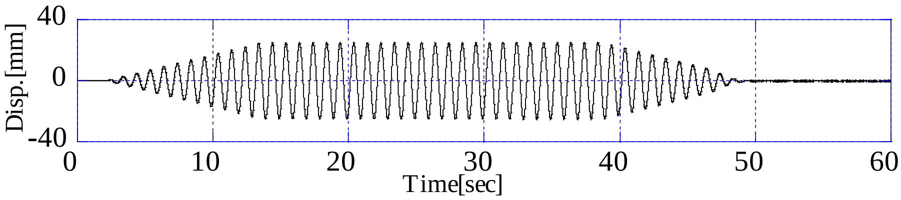
(a) EM01～EM04 (b) EM05, EM09 (c) EM06 (d) EM07 (e) EM08

Fig.3 Geometry of the specimens with wall thinning

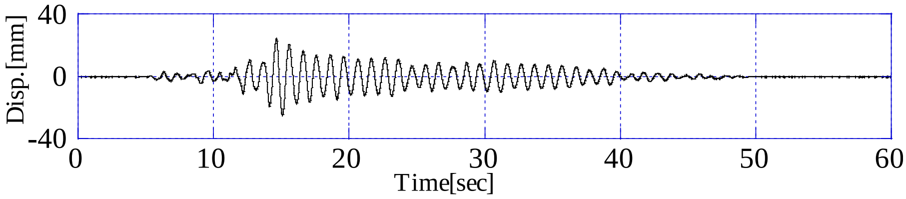


EC01 ～ EC06 : t=4.3mm (50% wall thinning)
EC07 : t=2.15 mm (75% wall thinning)
EC08 : t=6.45 mm (25% wall thinning)
EC09 : t=3.45 mm (60% wall thinning)

Fig.4 Time histories of input displacement



(a) Sinusoidal wave



(b) Random amplitude wave

Fig.5 Typical failure mode of the thinned wall pipe with internal pressure (EC05, 50% wall thinning)

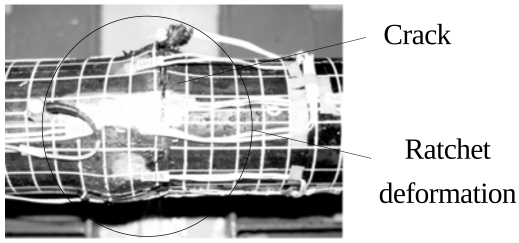


Fig.6 Cross section of thinned wall elbows in longitudinal direction

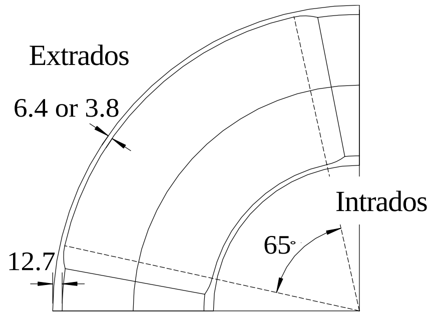
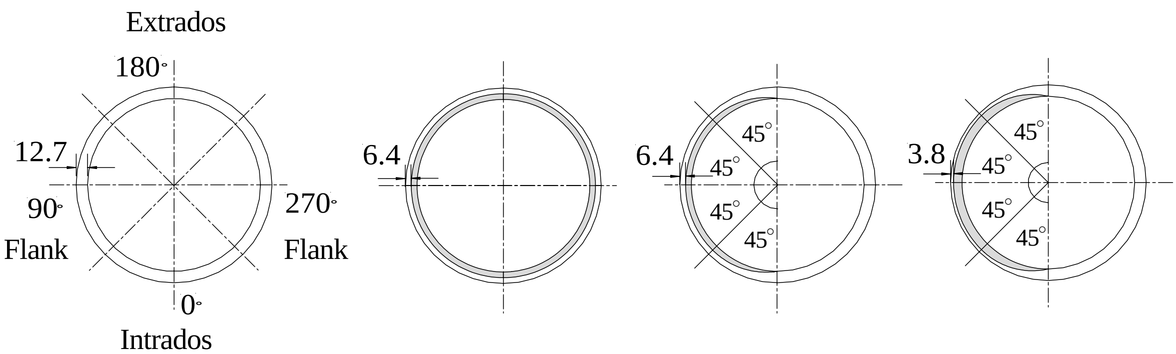


Fig.7 Cross section in circumferential direction



(a) No defect (b) 50% Full circumferential (c) 50% Partial (d) 70% Partial

Fig.8 Time histories of input displacement

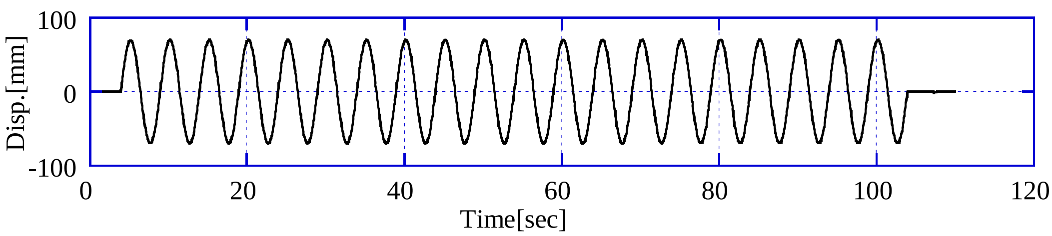
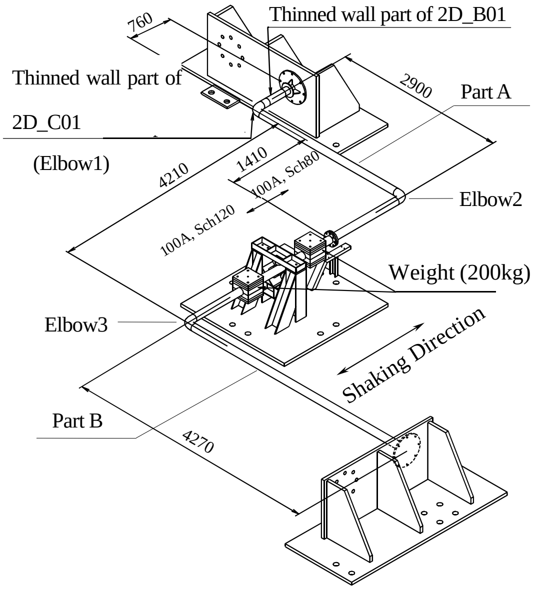
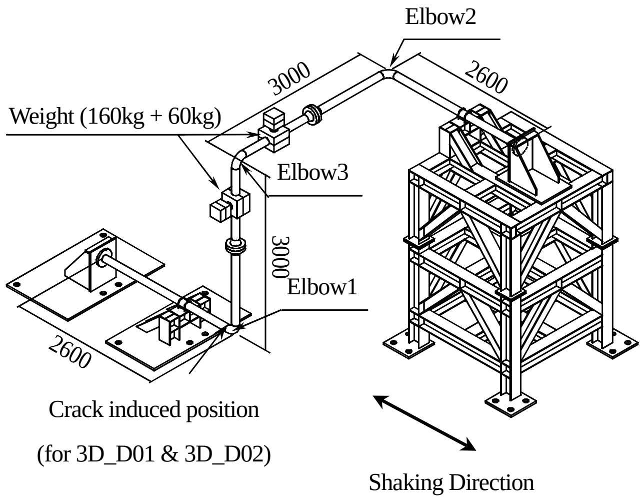


Fig.9 Configuration of test models for piping system tests

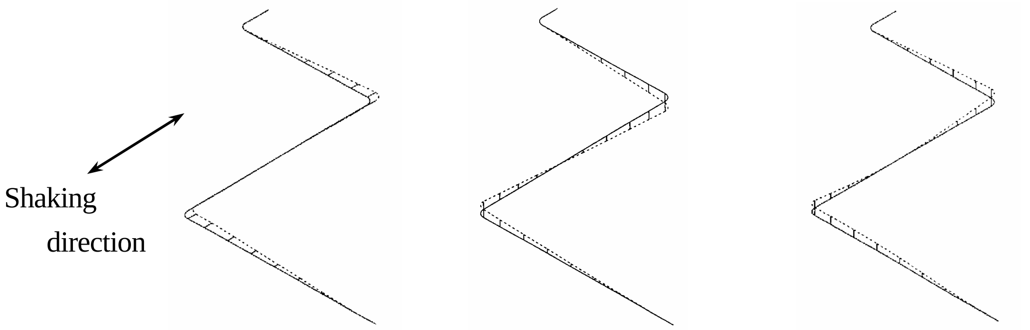


(a) 2-D piping model



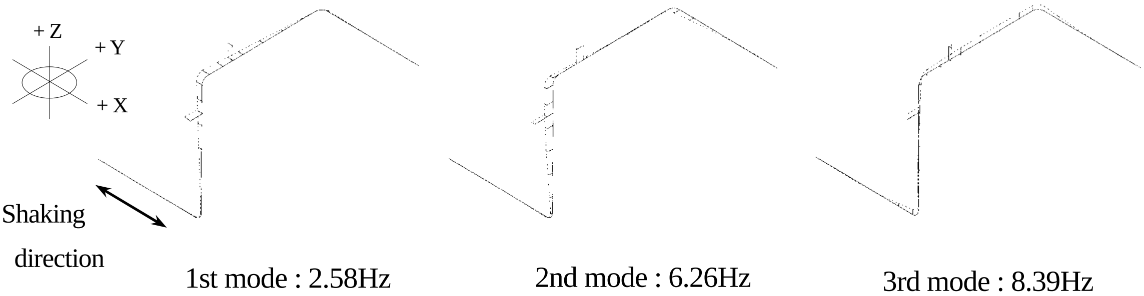
(b) 3-D piping model

Fig.10 Vibration modes and natural frequencies of the test models without defects



1st mode : 3.2Hz 2nd mode : 5.7Hz 3rd mode : 14.3Hz

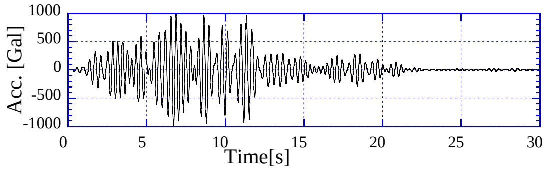
(a) 2-D piping model



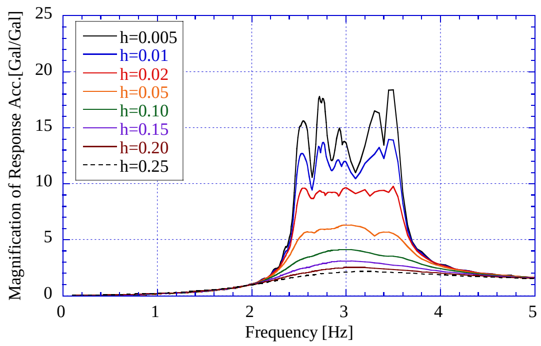
1st mode : 2.58Hz 2nd mode : 6.26Hz 3rd mode : 8.39Hz

(b) 3-D piping model

Fig.11 Narrow band random wave for the tests of 2-D piping model

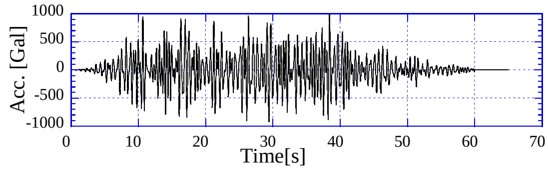


(a) Time history of Input acceleration

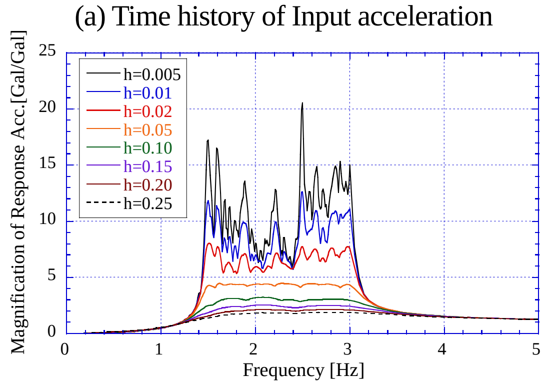


(b) Response spectrum (h: damping ratio)

Fig.12 Narrow band random wave for the tests of 2-D piping model



(a) Time history of Input acceleration



(b) Response spectrum (h: damping ratio)

Fig.13 Fatigue failure at the flank of the elbow

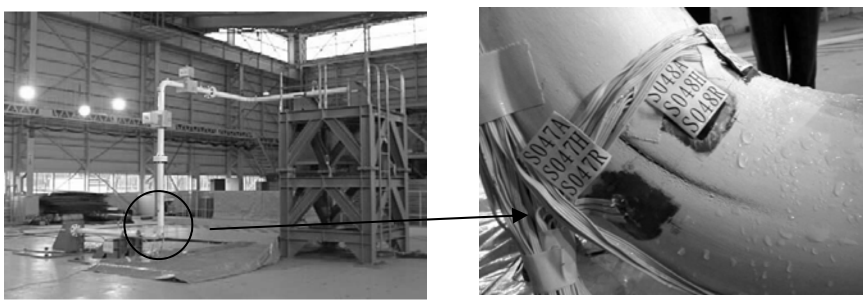


Fig.14 The effect of wall thinning on the estimation of the seismic safety of piping system