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CONSIDERATION ON SEISMIC DESIGN MARGIN OF ELBOW IN PIPING

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ABSTRACT

Elbow is an essential element for three dimensionally arranged piping and it is actually used in most kinds of plants. Many great researches on the flexibility and stress intensity regarding elbow elements have been performed. Moreover, we can greatly benefit from the design code where elbow elements are specified. Our research group also started a research on ultimate strength of piping systems containing elbows in 1997 and we have performed several kinds of elbow element tests and shaking table tests. All experimental results have shown that the failure loads are far higher than those described by the design criteria. The authors have confirmed that the seismic design margin is extremely conservative.

In this paper, the results of shaking table tests of piping, elbow element experiments and the stress calculation for those experiments based on design code are described, their results are compared with the seismic design criteria, and the margin is discussed. The authors point out the necessity of a new design code on the basis of the detail analysis and strain criteria in order to describe more appropriate and reasonable seismic design margin of the piping.

INTRODUCTION

Elbow is generally used for the piping system of nuclear power plant. Regarding elbow or bending pipe, the important researches have been performed since the beginning of 20th century [1],[2],[3]. However the stress distribution of elbow is essentially complicated, the simplified and convenient method to calculate the stress is provided by design code based on previous researches.

Regarding to pipe, pipe fittings and piping system, many researches were performed to verify the ultimate strength against earthquake since the latter half of 1980s [4],[5],[6],[7],[8]. And they show that most of the failures by seismic excitation were low cycle fatigue, except for only a few case of collapse failure. It is described as the seismic load is dynamic reversing load and the inertia force acts in the opposite direction to the deformation direction, then it is caused low cycle fatigue for most of the failures with dynamic reversing load.

Japanese seismic design code [9] was revised in 2008. Based on the consideration that seismic load is the dynamic reversing load, primary stress evaluation for seismic load is not required, but the evaluation with other mechanical load, and fatigue evaluation is required as important evaluation for seismic load.

On ASME code, primary stress evaluation is an important evaluation for seismic load. The difference of both codes is due to the difference of the number of seismic load cycles. The number of seismic load cycles from 60 to 300 is applied to the Japanese seismic design. But that of approximate 20 cycles is applied with ASME code. The difference of evaluation criteria of seismic design is caused by the variation of the number of seismic load cycles between U.S. and Japan.

Elbow is an essential element for three dimensional piping and it is widely used for plants. Many researches on the flexibility and stress intensity of elbow have been performed and we can benefit from the design code. The authors started about a research about failure behavior of piping under seismic excitation from 1997 and we performed several kinds of elbow element tests and shaking table tests. Experimental results provide that the excitation level to reach the failure is so higher than limit level by design code. It is confirmed that the seismic design margin is comparatively large.

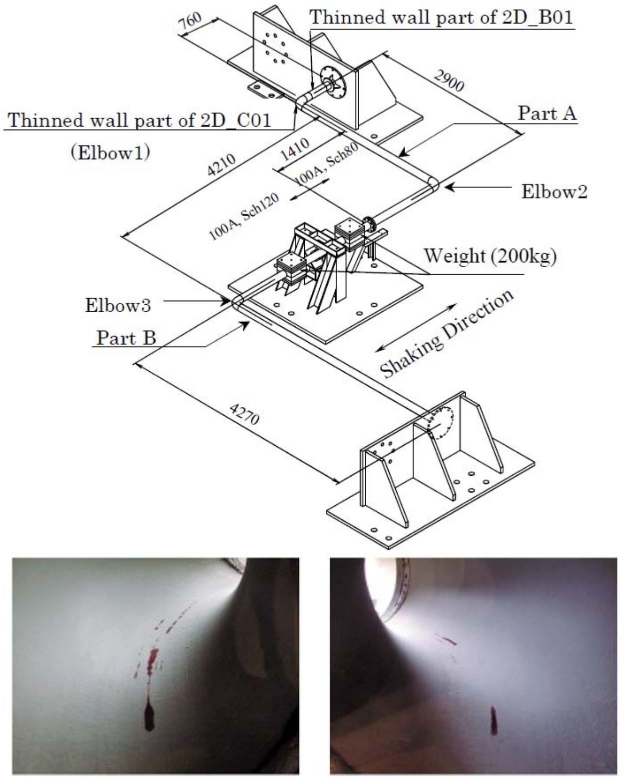
This study focuses on fatigue evaluation because Japanese seismic design considers the dominant failure mode of piping to be fatigue failure. The margin of the fatigue evaluation is investigated by comparing experimental results of elbow fatigue failure to design based evaluation. At first, experimental results of shaking table test are used for the investigation of seismic response variation affecting to primary stress and fatigue evaluation. The plastic deformation brings two kinds of effects which are response reduction and the equivalent cycles decreasing by plastic deformation. The difference of usage factors calculated by the design code and modified response is clarified. Second, the strain range measured by elbow element tests is compared with the strain calculated from peak stress prescribed in the design code.

Now, there are many useful experimental fatigue data for elbow itself. Based on such useful experimental data, more reasonable fatigue evaluation for seismic design is desired. For more reasonable fatigue evaluation of elbow, it could be considered with the combination of the reasonable fatigue curve and the strain range calculated by FEA.

TYPICAL FAILURE OF ELBOW

Regarding to piping system and element, many researches for strength and capacity against seismic force have been performed since 1990s. PFDRP by EPRI [4] is well known as successful research in the United States. NUPEC in Japan performed research programs of “Seismic Proving Test of Ultimate Piping Strength” [6], [7] and “Seismic Proving Test of Eroded Piping” [8] in Japan. The authors also investigated about failure behavior of piping under seismic excitation, “Aged Piping (AP) research”, in which many shaking table tests and piping element tests were performed [10], [11].

Typical failure of elbow was shown in these researches, in which the longitudinal cracks were initiated on the inner surface of flank of elbow, and progressed through to the outer surface. The cracks were caused by local bending at the flank of elbow. Typical examples of the cracks are shown in figure 1 and figure 2.



(a) Crack on side inner surface of Elbow1.

(b) Crack on side inner surface of Elbow2.

Figure 1 Elbow Failure of 2D Piping Model [10]

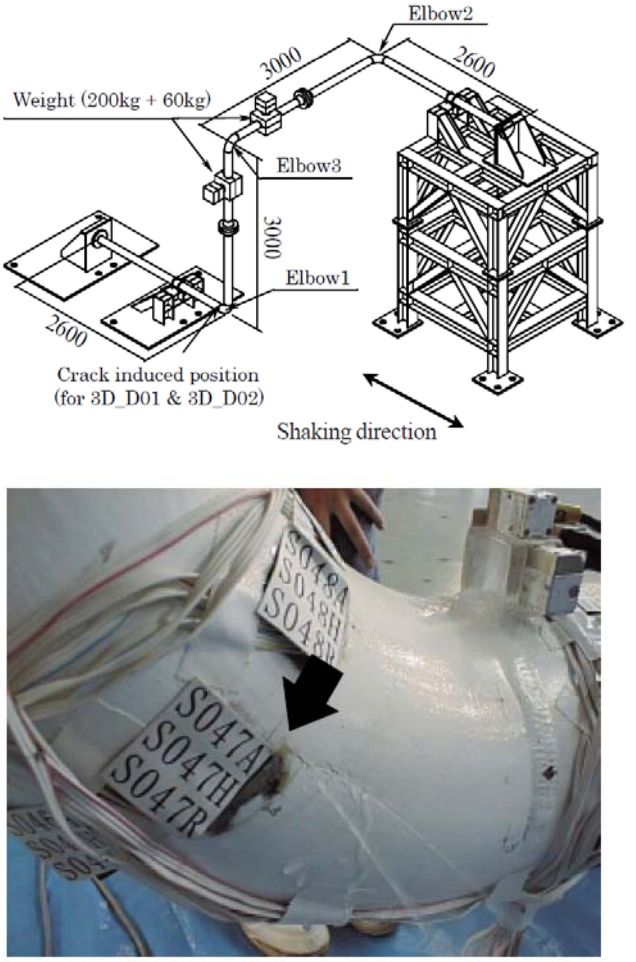


Figure 2 Elbow Failure of 3D Piping Model [11]

FATIGUE EVALUATION FOR PIPING DYNAMIC TEST

Piping Model

To investigate seismic response and failure behavior of eroded piping system under seismic excitation, shaking table tests were performed. The configuration of piping model is shown in figure 3. This piping model has 6 elbows and one tee. Two weights of 795 kg are attached. There are two supports, one is U-plate which restrains piping in one direction and the other is a ball bearing under a weight which supports only upward direction. The piping model contains water and pressurized up to 3 MPa. The actual piping model is shown in figure 4.

Two kinds of models were prepared. One is uniform wall thickness model, which is AP3-A31. The other is thinner wall thickness that has 5 elbows and one tee with thinner wall thickness, which is AP3-C31. The specification of the models is shown in table 1. The vibration modes of AP3-A31 are shown in figure 5. The natural frequency of AP3-C31 is different from the AP3-A31 but vibration mode shapes are almost same. The measured natural frequencies and the damping ratios are shown in table2 and 3.

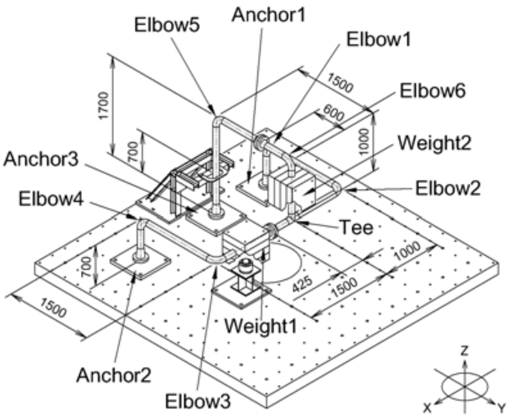


Figure 3 The Configuration of Piping Model

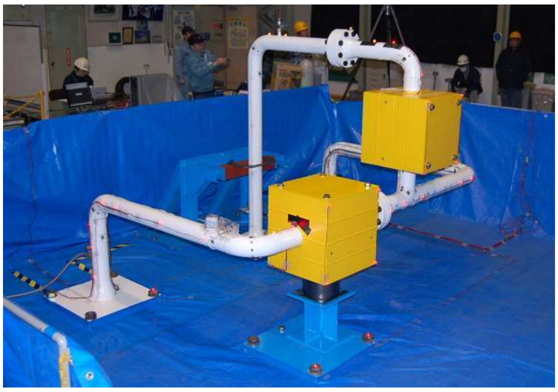


Figure 4 Actual Model on Shaking Table

Shaking Table Test

The random wave excitations and the seismic excitations with levels were performed to clarify the natural frequency and the damping ratio of the models. The seismic excitations and sinusoidal wave excitations were performed to clarify the response in plastic range and the failure mode.

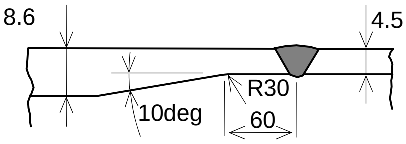
The acceleration time histories of seismic waves are shown in figure 6. And the response spectra calculated from the seismic waves with 0.5% damping ratio are shown in figure 7. The seismic waves were observed by JMA (Japan Meteorological Agency) Suttu as Hokkaido Nansei-Oki earthquake in 1993. The observed seismic wave was selected so that the dominant frequency of the wave was close to the natural frequency of the model and the time length of the wave was comparatively long. These properties cause easily the fatigue failure in the piping models. The wave was modified with 1.5 Hz high pass filter due to the specification of the shaking table.

Test conditions and the calculation results are shown in table 4. Stress levels and usage factors in this table were calculated by the design code [12] and the details of calculations are mentioned after. The waves up to 250% level were excited by 3 directional inputs and the larger waves were excited by only X directional input. The criterion of input direction was due to the specification of the shaking table. The piping models were shaken with sinusoidal wave to make the models failure, because they did not reach the failure with maximum seismic excitation which is 750% X directional seismic excitation. As a result, the longitudinal fatigue crack penetrated at the flank of Elbow3 of AP3-A31. It is shown in figure 8. The in-plane-bending was occurred to the Elbow3 under the response of the model. For the piping model AP3-C31, as shown in figure 9, the circumferential fatigue crack was appeared at Elbow1. The out-of-plane-bending was occurred to Elbow1 under the response of the model. Their detail analyses and evaluation by FEM are presented by the reference [13].

Table 1 The Specification of Piping Models

Model No.	Part	Material (JIS)	Nominal Dimension (mm)	
			Outer Diameter	Thickness
AP3 -A31	Pipe	STPT370	114.3	8.6
	Elbow1-6	PT370		
	Tee			
AP3 -C31	Pipe	STPT370	114.3	8.6 *
	Elbow1-5	FSGP		4.5
	Elbow6	PT370		8.6
	Tee	FSGP		4.5

* The connected part with FSGP was machined as below.



DESIGN BASED STRESS LEVEL

The damping ratio of the piping models specified by Japanese seismic design code is 0.5% [9]. The spectrum modal analysis was performed for each directional response spectrum as shown in figure 7. On actual seismic design in Japan, 10% broadening of response spectrum is applied, but in this study, the response spectrum without broadening was used for analysis. The primary stress and usage factor for Elbow3 of AP3-A31 and Elbow1 of AP3-C31 were calculated for each excitation condition. The primary stress was calculated by equation 1 [12].

$$S = B_1 \cdot \frac{P \cdot D_O}{2 \cdot t} + B_2 \cdot \frac{M}{Z} \qquad (1)$$

$$M = \sqrt{M_x{}^2 + M_y{}^2 + M_z{}^2}\,,\quad B_1 = 0.5,\ \ B_2 = \frac{1.3}{h^{\frac{2}{3}}}$$

$$h = \frac{t \cdot R}{r^2},\quad r = \frac{D_O - t}{2}$$

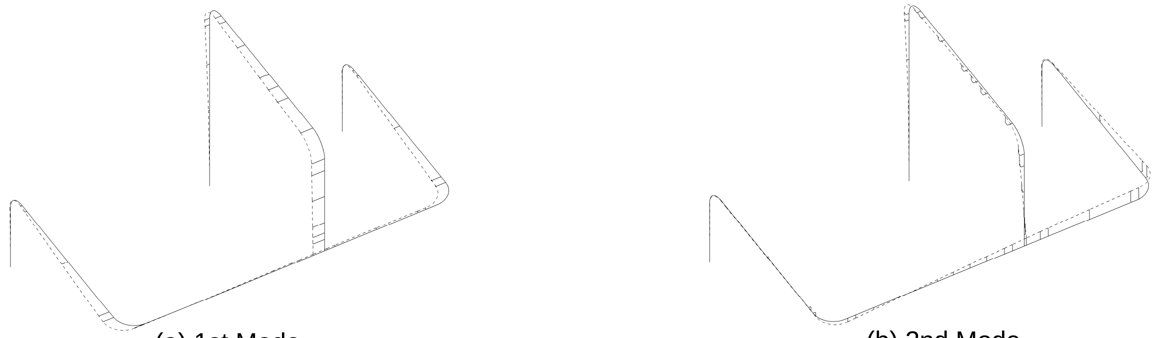
P : Pressure, D_O : Outer diameter, t : Thickness,
M_i : Moment component at the end of elbow,
Z : Section modulus, R : Radius of elbow curvature

Table 2 The Natural Frequency

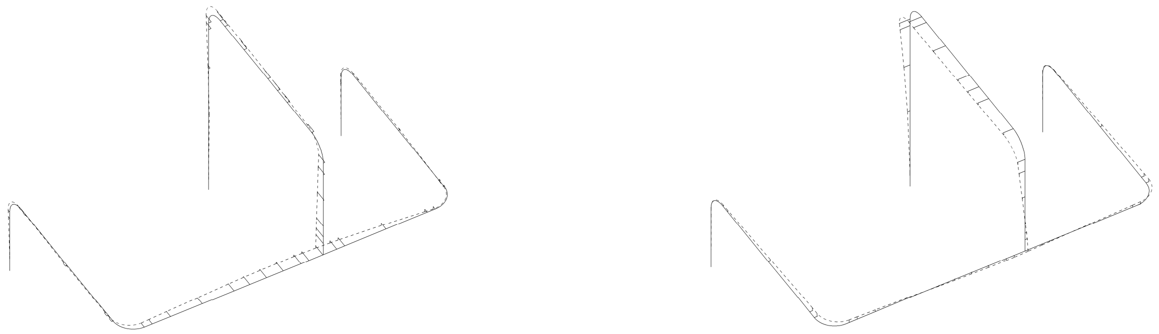
Model No.	Mode	Natural frequency (Hz)				
		Experiment				FEM
		Random wave excitation level				
		0.5m/s^2	1.0m/s^2	1.5m/s^2	2.0m/s^2	
AP3 -A31	1st	6.2	5.7	5.3	5.1	4.6
	2nd	9.0	—	7.9	—	7.5
	3rd	11.5	—	11.6	—	12.1
	4th	17.9	—	17.7	—	19.3
AP3 -C31	1st	4.5	4.2	4.0	—	3.5
	2nd	6.7	6.4	—	—	5.7
	3rd	9.9	9.7	—	—	10.3
	4th	13.0	12.8	—	—	16.4

Table 3 The Damping Ratio

Model No.	Mode	Damping ratio (%)				
		Experiment				Design Code
		Random wave excitation level				
		0.5m/s^2	1.0m/s^2	1.5m/s^2	2.0m/s^2	
AP3 -A31	1st	1.8	1.7	1.2	1.4	0.5
	2nd	13.2	—	2.7	—	
	3rd	1.5	—	0.8	—	
	4th	0.9	—	0.5	—	
AP3 -C31	1st	1.8	0.9	2.2	—	
	2nd	4.4	1.8	—	—	
	3rd	2.0	1.6	—	—	
	4th	0.7	0.7	—	—	



(a) 1st Mode (b) 2nd Mode



(c) 3rd Mode (d) 4th Mode

Figure 5 The natural vibration modes of AP3-A31

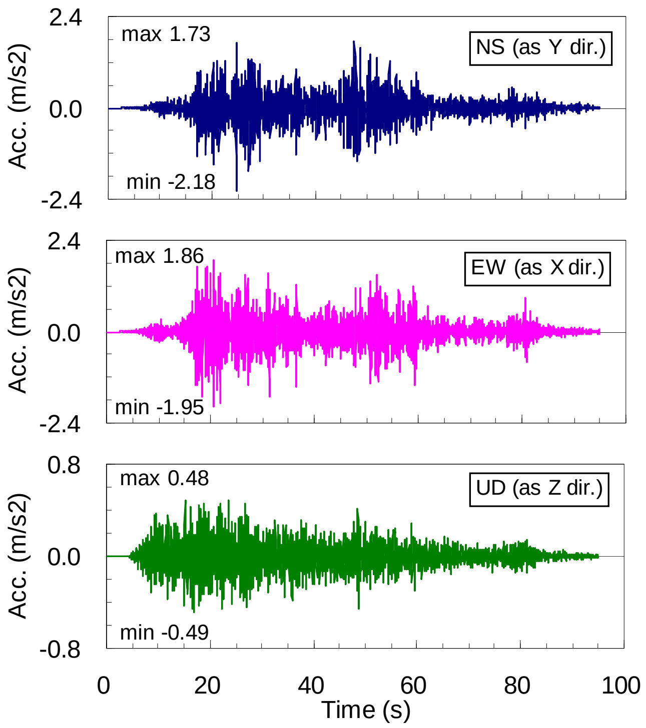


Figure 6 Seismic Waves for the Shaking Table Test (Observed by JMA Suttu, 1993, High Pass Filter 1.5Hz)

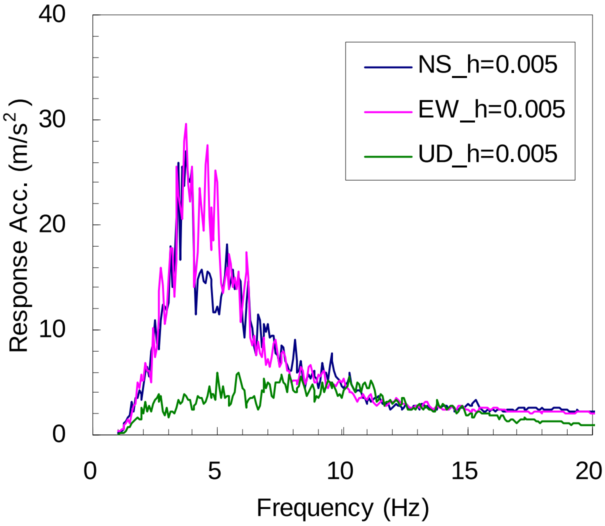
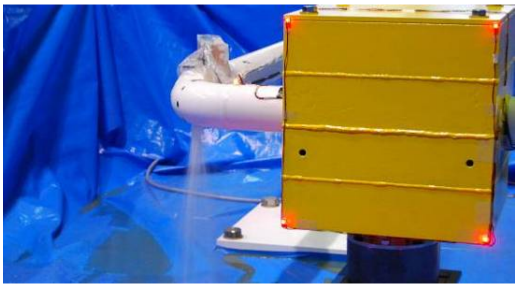
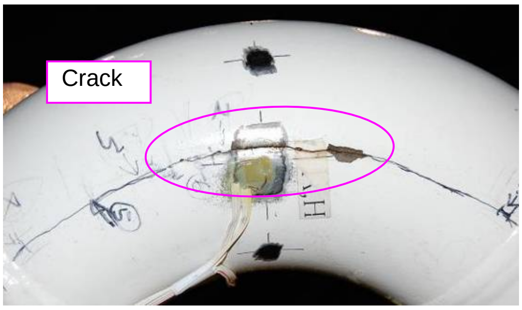


Figure 7 Response Spectra

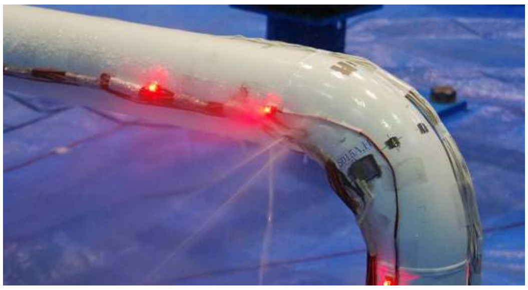


(a)The Leakage from Elbow3

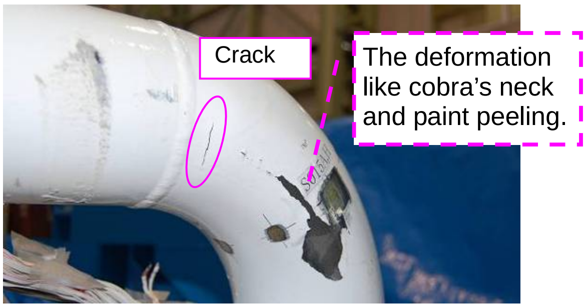


(b) The Axial Crack at the Flank ofElbow3

Figure 8 The Fatigue Crack Penetration in AP3-A31



(a)The leakage from elbow1



(b) The circumferential crack at the edge of elbow1

Figure 9 The Fatigue Crack Penetration in AP3-C31

The Usage factor was calculated with the equivalent cycle of seismic load, the peak stress based on following equations and design fatigue curve [12].

$$
\begin{aligned}
&S_\ell = \frac{K_e \cdot S_p}{2} \qquad (2)\\
&S_p = \frac{K_2 \cdot C_2 \cdot 2 \cdot M}{Z}\\
&\begin{cases} K_e = 1 + (q-1)\cdot\left(1 - \dfrac{3 \cdot S_m}{S_n}\right) & (S_n \geq 3 \cdot S_m)\\ K_e = 1 & (S_n < 3 \cdot S_m) \end{cases}\\
&K_2 = 1.0,\ C_2 = \frac{1.95}{h^{\frac{2}{3}}},\quad q = 3.1
\end{aligned}
$$

In the above expressions, the stress range S_p is calculated by the twice of the moment obtained by response spectrum analysis.

The primary stresses and the usage factors calculated by above method are shown in table 4. In this table, the stress levels are normalized by S_m value of 125 MPa which is provided by the design code [12]. And 60 cycles is used for calculating the usage factor, based on the typical seismic load cycles for BWR plant in Japan. The stress level by sinusoidal wave excitation in table 4 was difficult to obtain by response spectrum analysis. Then it was calculated from the ratio of the weight 2 response displacements by sinusoidal excitation and seismic excitation.

Almost all the primary stresses and usage factors based on the design code in table 4 are extremely large and beyond our engineering common sense. Of course, the limitation of primary stress and usage factor are 3 Sm and 1.0, respectively. The primary stress level by 750% seismic excitation is 7 times of allowable stress 3Sm for AP3-A31 and 19 times for AP3-C31, but no failure was occurred for each test case. Also, the cumulative usage factors are 296 times for AP3-A31 and 2590 times for AP3-C31. These results mean that the design limits are quite different from the actual failures.

INVESTIGATION OF DESIGN MARGIN

The design margin for safety is to be set intentionally, also the concept and necessity should be clarified. It could be said that the stress and usage factor based on the design code in table 4 are conservative but they contain unknown and uncertain factors which are unintentional. To clarify them, it was tried to vary the primary stress and usage factor so as to explain the experimental results.

The maximum response acceleration and displacement measured by shaking table tests are shown in figure 10 and 11 respectively. There are linear relations for low excitation level, while non-linear relations for high excitation level. In high excitation level, the response is relatively smaller than that of linear line. The plastic deformation of piping dissipates the response energy, so the maximum response relatively decreases. Furthermore, the plastic deformation makes the piping models soft and decreases the dominant frequencies of them. It also contributes the maximum response acceleration decrease.

The response reduction rate which is the deviation from the analyzed elastic response with damping ratio 0.5% is shown in figure 12. Increasing the maximum response displacement causes the plastic deformation, it decreases the response. The piping model AP3-C31 response decreases to 23% of the elastic response. The response reduction with plastic deformation is not considered on the Japanese seismic design and it is not intentional design margin. ASME code manages the effect by using 5% damping ratio efficiently. It can be considered that the elastically calculated responses in the plastic region include a kind of analysis error which affects as conservative difference.

The failure mode of collapse is checked here from the experimental results. Figure 13 shows the relation between the maximum response displacement and maximum response acceleration which are the properties of the whole piping model. Figure 10 and 11 obtained by dynamic experiments tend to lead misunderstanding what shows yielding phenomenon. These are due to the response reduction effect by plastic deformation. Figure 13 is corresponding to load-displacement relation and it exactly shows yielding phenomenon. The experimental maximum response correlation data in plastic region deviate from dot and dash lines which mean analyzed elastic responses of the piping models, but the collapse did not occur, because the experimental data are larger than a half of the dot and dash lines.

The fatigue evaluation is affected by the cycles of seismic load and allowable cycles based on the peak stress and design fatigue curve. The equivalent cycle, which is 60 cycles for seismic load, were used for calculating usage factor based on the design. Because the equivalent cycle is affected by the peak stress level on design fatigue curve, the equivalent cycle was calculated by the peak stress level in the range from 10 to 5000 cycles on design fatigue curve, and the average value was adopted.

The issue is that the response of piping is influenced by the change of natural frequency and damping with plastic deformation, which affect the number of equivalent cycles. Figure 14 shows the response change from elastic deformation level to the plastic deformation level. It shows that the high level excitation causes the high damping response with plastic deformation. Regarding to the evaluation about usage factor, the number of equivalent cycles are estimated by high level response which dominates the fatigue damage. The equivalent cycles of the elastic-plastic response were calculated as 24 cycles for AP3-A31 and 13 cycles for AP3-C31. Figure 15 shows the design fatigue curve used for the fatigue evaluation.

The modified primary stresses and usage factors shown in table 4 are evaluated with considering the response reduction effect and the equivalent cycle by elastic-plastic response. The calculated fatigue damage factor is larger than 1.0, it means what the design code is still conservative and have sufficient margin for fatigue crack penetration. The margin may be included in the peak stress and the design fatigue curve.

Table 4 List of Shaking Tests and the Design Stress Level

Model No.	Excitation Condition			Primary Stress Level (x S_m) ***				Usage Factor ****	
				Design Based (Elastic Response)			Modified Response	Design Based (Elastic Response)	Modified Response
	Wave	Dir.	Level **	SP	SW	SD	SD		
AP3 −A31	Random (2-30Hz)	X	0.5～2.0 m/s^2	0.08	0.43	0.03 ～ 0.96	0.03 ～ 0.96	0.00	0.00
		Y							
		Z							
	Seismic* (original)	XYZ	40%			1.11	1.11	0.01	0.00
	Seismic	XYZ	40%			1.11	1.11	0.01	0.00
			60%			1.66	1.66	0.06	0.03
			80%			2.22	2.10	0.21	0.07
			100%			2.77	2.74	0.44	0.17
		X	100%			2.76	2.96	0.43	0.22
		XYZ	150%			4.16	3.41	1.47	0.34
			200%			5.54	4.25	3.15	0.63
			250%			6.93	4.67	5.20	0.81
		X	300%			8.28	4.26	7.68	0.63
			500%			13.8	4.95	22.9	0.94
			750%			20.7	6.06	53.2	1.54
			750%					53.2	1.54
	Sin (4.5Hz, 40sec)	X	9.8 m/s^2			20	5.79	148	10.42
	Cumulative Fatigue Damage Factor							296	17.3
AP3 −C31	Random (2-30Hz)	X	0.5～1.5 m/s^2	0.15	1.16	0.11 ～ 1.65	0.11 ～ 1.65	0.06	0.07
		Y							
		Z							
	Seismic	XYZ	20%			1.49	1.49	0.04	0.01
			40%			2.98	1.94	0.56	0.03
			60%			4.47	3.39	1.80	0.18
			80%			5.96	5.49	3.72	0.67
			100%			7.46	5.30	6.11	0.61
			250%			18.6	8.36	42.9	1.70
			250%					42.9	1.48
		X	750%			55.7	13.6	401	4.79
			750%					401	4.79
			750%					401	4.79
			750%					401	4.30
			750%					401	4.37
	Sin(3.2Hz, 40sec)	X	9.8 m/s^2			42	10.1	487	25.27
	Cumulative Fatigue Damage Factor							2590	53.1

* The original recorded wave without filtering process.

** For seismic excitation, excitation levels are shown as percentage of the amplitude of the wave shown in figure 6.

*** SP,SW and SD mean the stress due to 3.0 MPa internal pressure, dead weight and dynamic inertia force, respectively, divided by S_m which is 125 MPa from JSME S NC1-2005. The stress levels are calculated by eq. (1) at elbow3 for AP3-A31 and elbow1 for AP3-C31 and the stress due to the dynamic inertia force are obtained by modal spectrum analysis with 0.5% damping. The stress level by tri-axial excitation calculated as the SRSS of the values by X, Y and Z excitation. The stress levels are modified by multiplying the response reduction rate in figure 12.

**** Usage factors for design is calculated by eq. (2) using the peak stress calculated by elastic response and 60 cycles. For modified response, the peak stress reduced by the response reduction rate shown in figure 12 and 24 cycles for AP3-A31 and 13 cycles for AP3-C31 as the equivalent cycles.

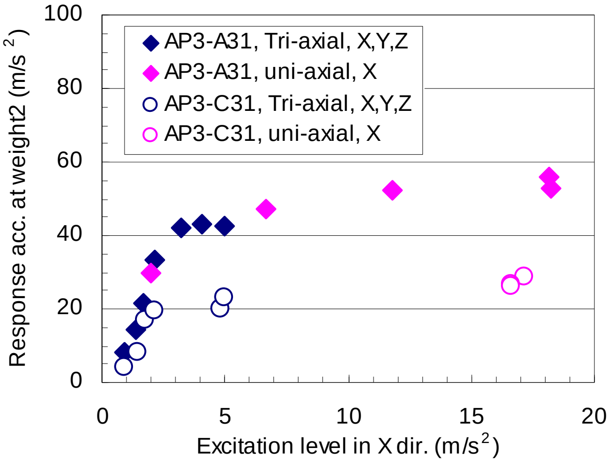


Figure 10 The Maximum Response Acceleration

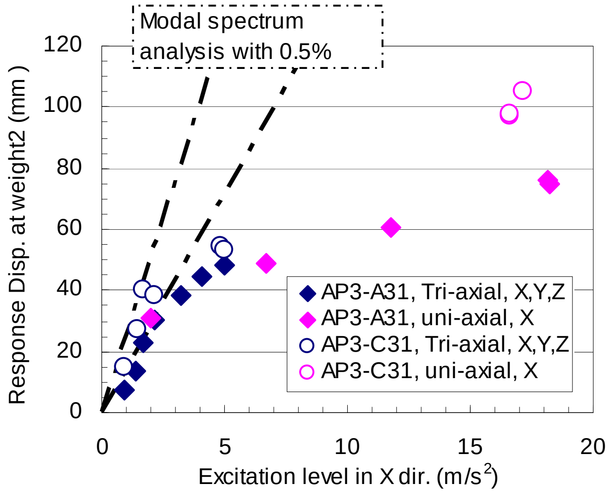


Figure 11 The Maximum Response Displacement

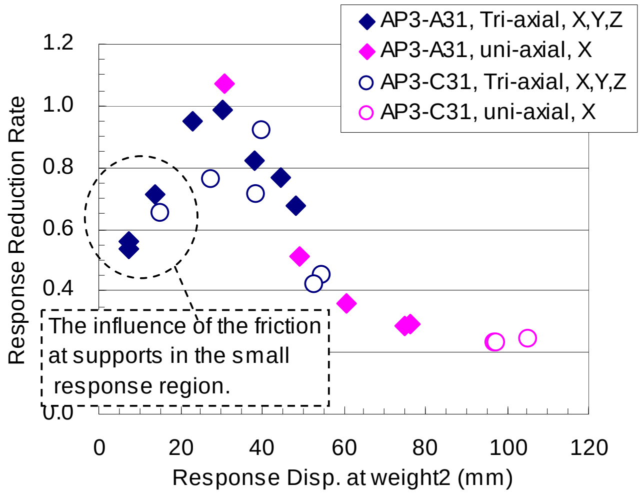


Figure 12 The Response Reduction Effect

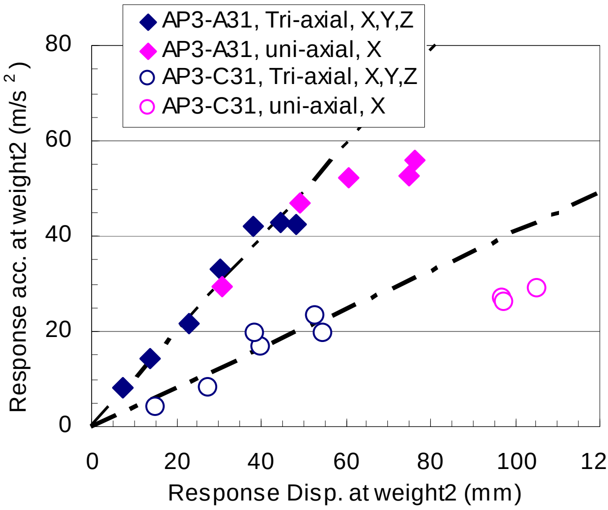
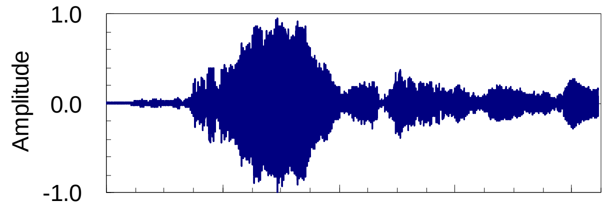
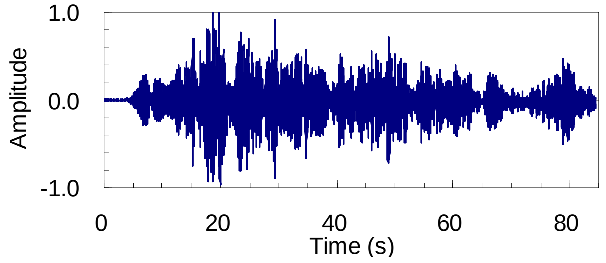


Figure 13 The Equivalent Relation to Load-Displacement Curve



(a) Tri-axial 100% excitation of AP3-A31, n_{eq}=33



(b) Uni-axial 750% excitation of AP3-A31, n_{eq}=24

Figure 14 The Wave Profile Difference

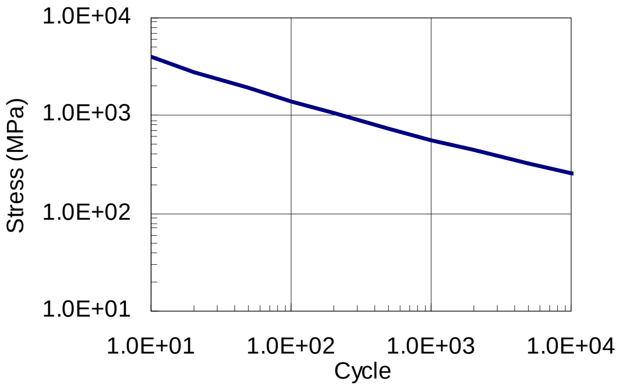


Figure 15 The Design Fatigue Curves used for the Evaluation

FATIGUE EVALUATION OF ELBOW ELEMENT TEST

There is a past research about the fatigue evaluation of elbow. They clarify the design margin which comes from the peak stress calculation and design fatigue curve.

Elbow Element Test Model

The research for failure behavior of elbow was performed in 2001 and 2002 [11]. Elbows for experiment have bending radius as 1.5 times of outside diameter, which is shown in figure 16. And the straight pipes which are 5 times length of outside diameter were connected to the both ends of the elbow. Each test model has outside diameter 216.3 mm and thickness 12.7 mm in straight pipes. The thickness of elbow was thinned by machining as shown in figure 16.

Cyclic In-plane Bending

Two different In-plane bending experiments were performed as shown in figure 17 and 18. The same configurations of test models are used for both experiments which have different support conditions. One experiment has pin-pin support connections and the other is pin-fixed support connections.

The table 5 shows test conditions. The cyclic displacement amplitude is 70 mm for pin-pin type and 185 mm for pin-fixed type. These load conditions are corresponding to collapse load level by $2\tan\theta$ method.

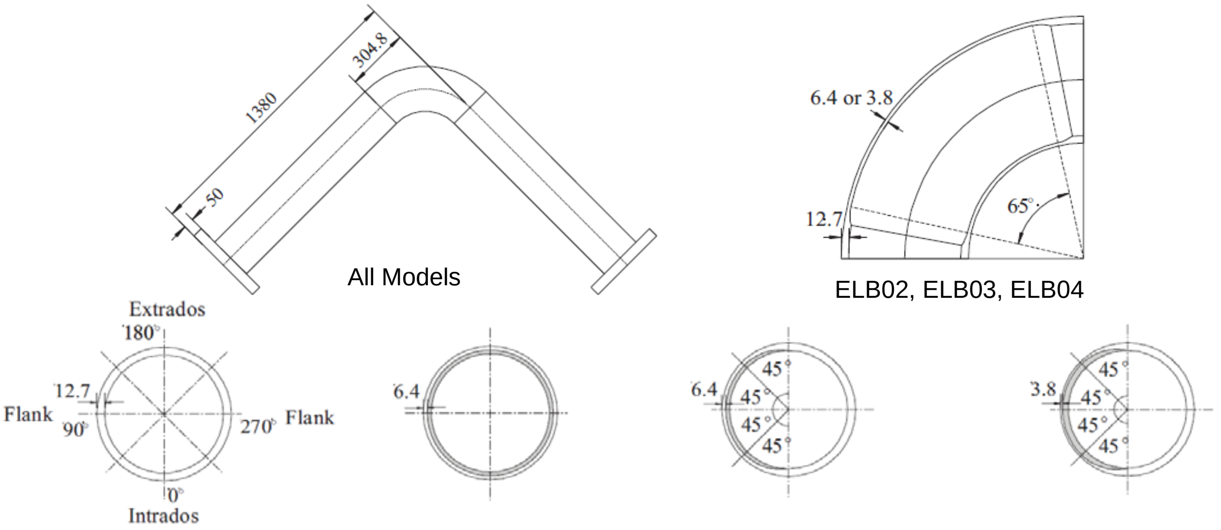
Peak Stress and Usage Factor

The pseudo elastic moment at the end of elbow can be obtained from the applied displacement and the relation between force and displacement. Based on this moment, the peak stresses were calculated from equation (2). The strain range can be calculated as 2 times of the peak stress and divided by Young’s modulus. The design based values and the strain ranges measured on inner surface of the flank of elbow are shown in table 6. The allowable cycles by design curve for fatigue evaluation and the cycles to reach the fatigue crack penetration are also shown in the table 6. The strain ranges based on the design code are more than 1.7 times of the measured strain ranges. The cycles to reach the crack penetration are more than 50 times of the allowable cycles based on the design code.

Table 5 Elbow Element Test Condition

Model No.	Material	Diameter (mm)	Elbow Thickness (mm)	Support Condition	Pressure (MPa)	Cyclic Load (Sinusoidal Wave)	
						Freq. (Hz)	Amp.(mm)
ELB01	Carbon Steel (STS410)	216.3	12.7	Pin-Pin	10	0.2	70
ELB02			6.4		10(～7 *)		
ELB03			6.4 (Partial Thinning)		10		
ELB04			3.8 (Partial Thinning)				
ELBI-01			12.7	Pin-Fixed			185

* Pressure decrease with the ratchet deformation of elbow on cyclic loading



ELB01, ELBI_01 ELB02 ELB03 ELB04

Figure 16 Elbow Element Test Model

Table 6 Fatigue Evaluation of Elbow Element Tests

Model No.	Design Evaluation Based on JSME Code								Experiment	
	Pseudo Elastic Moment (kN-m)	C2	Sn (MPa)	K2	Ke	Sl (MPa)	Strain Range (=2Sl/E)	Allowable Cycle	Measured Strain Range	Cycles to Crack Penetration
ELB01	225	3.76	4330	1.0	2.90	6270	0.062	< 10 (3)	0.032	179 (212 **)
ELB02	130	6.18	7450		2.98	11100	0.110	< 10 (1)	0.022	319
ELB03	169	6.18 *	9700		3.01	14600	0.144	< 10 (0)	0.029	231
ELB04	157	8.90 *	21100		3.06	32200	0.318	< 10 (0)	0.029	177
ELBI-01	322	3.76	6200		2.96	9170	0.090	< 10 (1)	0.047	110

* Stress indices calculated as fully circumferential wall thinning of elbow.
** Including 33 equivalent cycles by the pre-smaller-loadings.

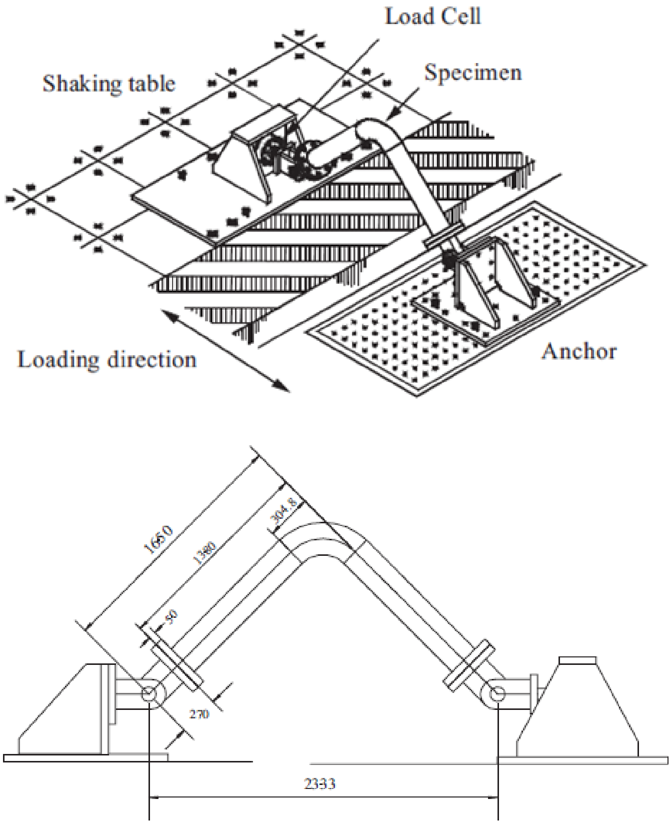


Figure 17 In-plane Bending Test (Pin-Pin)

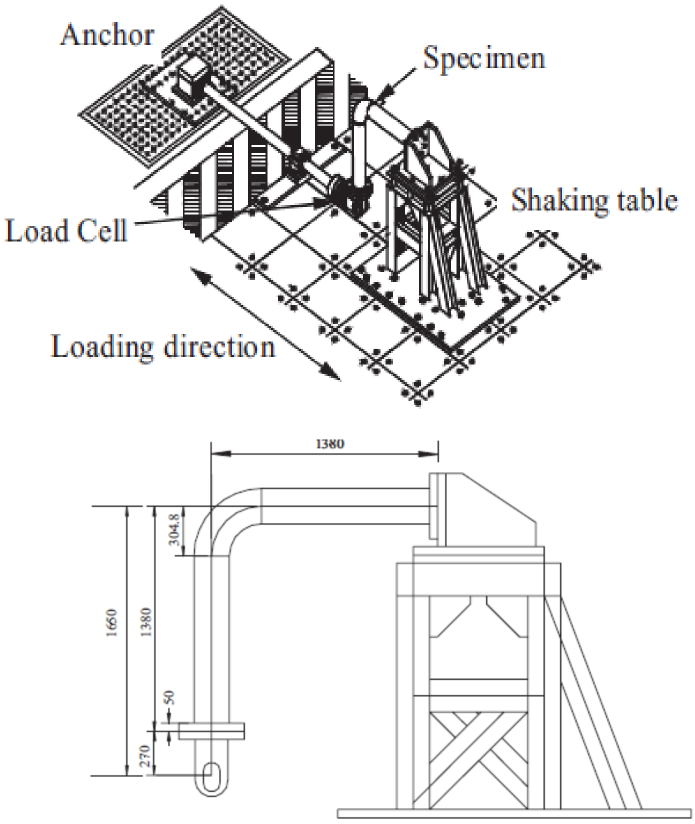


Figure 18 In-plane Bending Test (Pin-Fixed)

CONCLUSION

Many researches verified typical failure mode of elbow is the low cycle fatigue. For investigating the margin of seismic design of piping, the shaking table tests of piping models were performed and the results were compared with the primary stress and usage factor based on the design code. The usage factors based on design code were excessive. The excessive margin can be reduced by considering the response reduction effect by plastic deformation and the reasonable equivalent cycles. The cycles to reach the crack penetrations on the elbow element tests were more than 50 times of the allowable cycles based on the design code. It is known that the design fatigue curve includes the margin of 20 times, the contents are 2.0 times for variance, 2.5 times for scale factor and 4.0 times for environmental, roughness and other factors. This investigation has shown that the fatigue life of the elbow element tests is 2 times longer than the fatigue life without 20 times margin.

The design fatigue curve certainly contains the intentional margin. It is unknown what response reduction effect with elastic-plastic response, equivalent cycles and the difference of the strain ranges between based on the design code and measured are intentional margin. If such item could be estimate more accurately, seismic design of piping would be more reasonable.

The elastic-plastic analysis by FEM could provide detail strain range for fatigue evaluation. Evaluating all piping systems by the detail FEA would not be reasonable, but it could be useful method for severe seismic condition as an alternative evaluation method.

It is known that ratchet strain is difficult to simulate, but the strain range could be simulated precisely by FEM. For evaluating the fatigue evaluation more reasonably, it could be proposed that calculating the strain range by FEM and evaluating the fatigue with NUPEC prediction curve shown in figure 19 [8]. The prediction curve was defined from the pipe and pipe fittings element test results under the hoop stress level was almost $1.0S_m$ [6] [7] [8]. The ratcheting was caused significantly on the tests.

It is known that the fatigue lives are reduced by ratchet deformation, which is called ductility exhaustion [14] [15]. The prediction curve includes the fatigue life reduction because it was defined from the test results with significant ratchet deformation and the ductility exhaustion. Then it could be suggested that the using the prediction curve for fatigue evaluation of pipe and pipe fittings is effective.

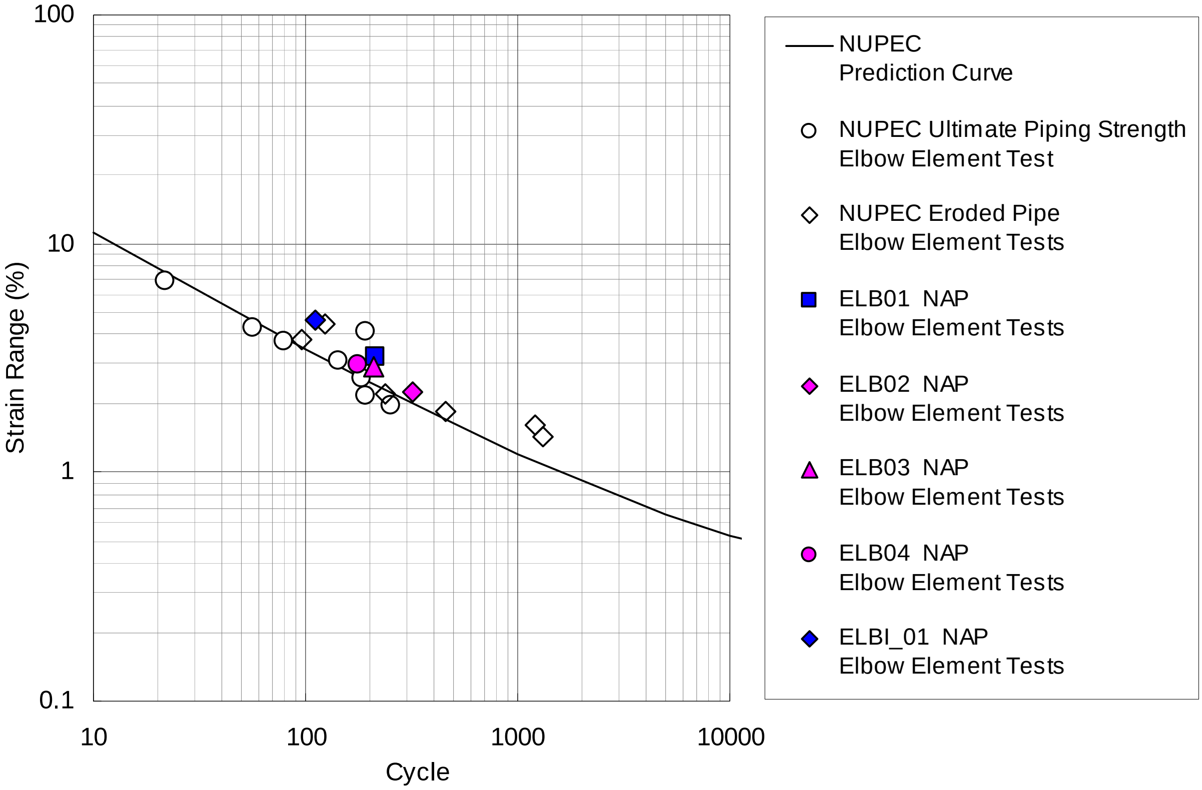


Figure 19 The Prediction Curve and Elbow Element Test Results

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