Seismic Capacity Estimation of Steel Piping Elbow Under Low-cycle Fatigue Loading

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KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

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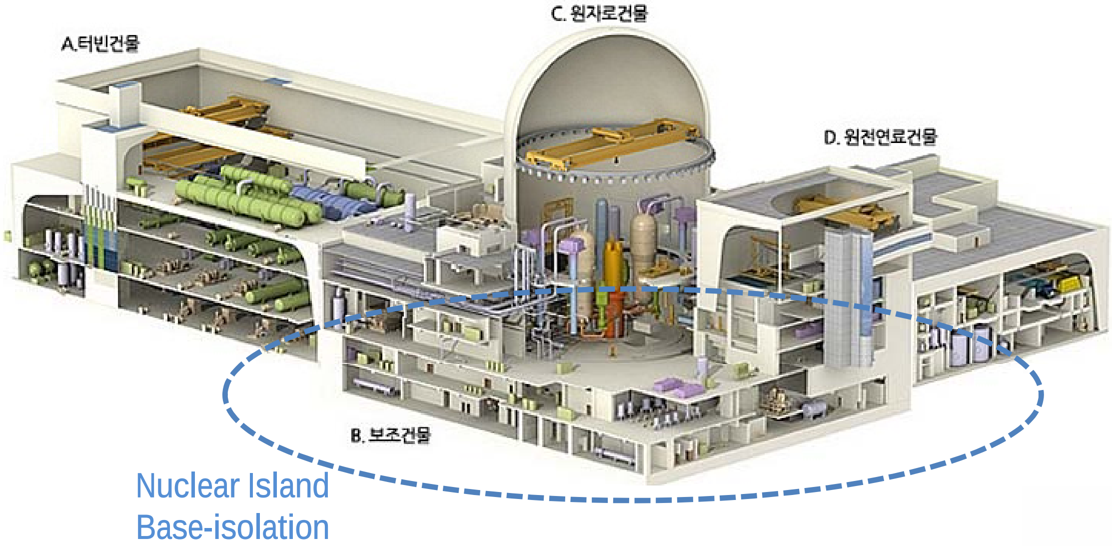
Introduction

APR 1400 with Base Isolation System

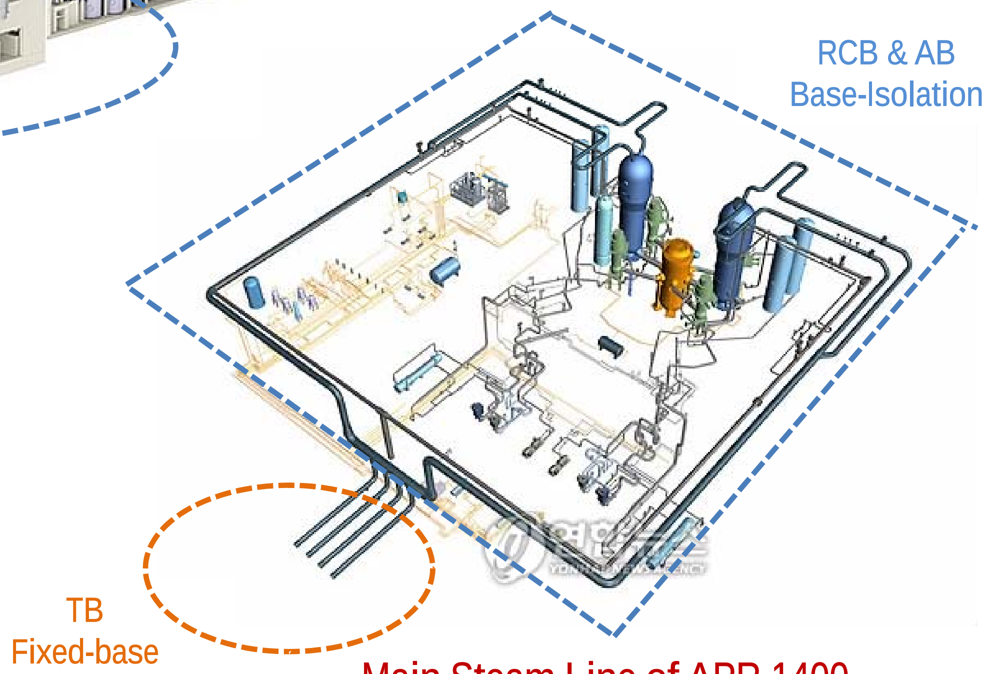


Base isolated pipe

- Critical point is elbow [Touboul et al., 1999]
- Failure
  - Low-cycle fatigue [NUREG, 2010]
  - Leakage by through crack(rupture)
- Failure criteria for fragility analysis was not decided in Korea

Installation of the seismic isolation system

- Installation under the nuclear island
- For seismic performance improvement
- Minimization of design variation
- Possibility of displacement increase
- Seismic risk may increase at some equipments (example : Main Stem Line)

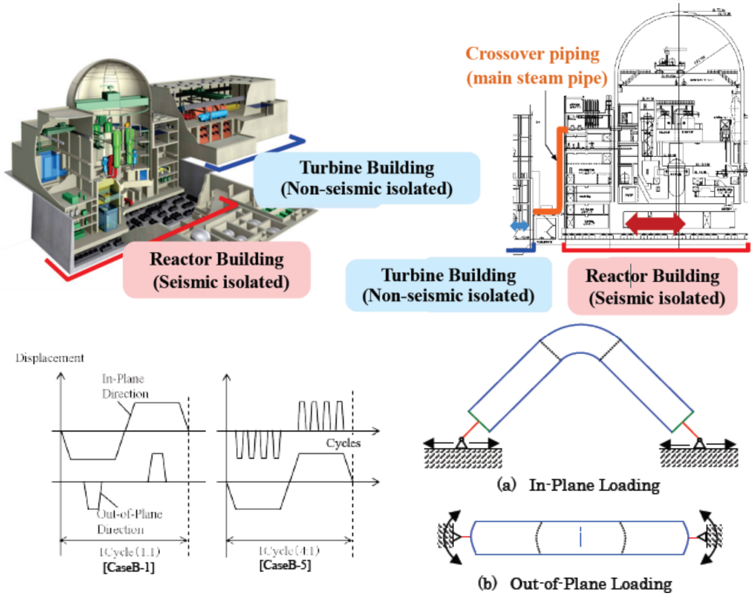


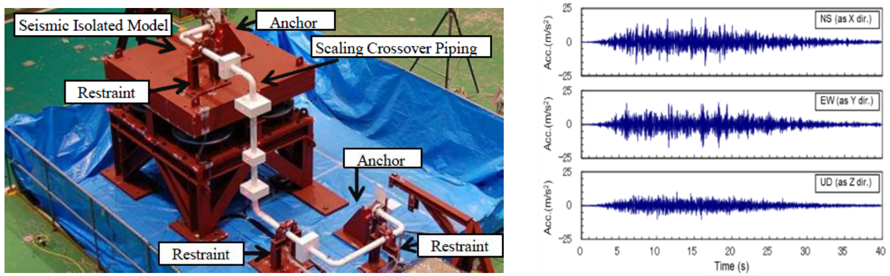
Main Steam Line of APR 1400

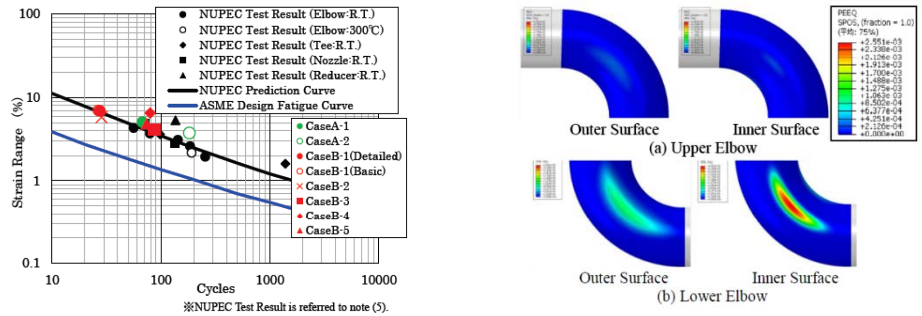
Recent research issues

Development of an Evaluation Method for Seismic Isolation System of Nuclear Power Facilities

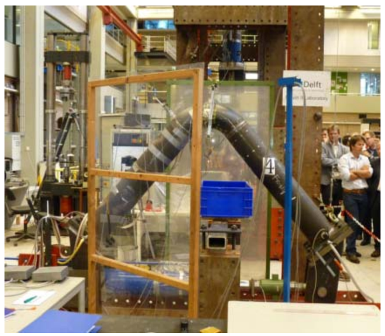
- Fatigue test of the crossover piping [Mizuno et al.]
- Failure behavior of crossover piping seismic isolation system [Otoyo et al.]

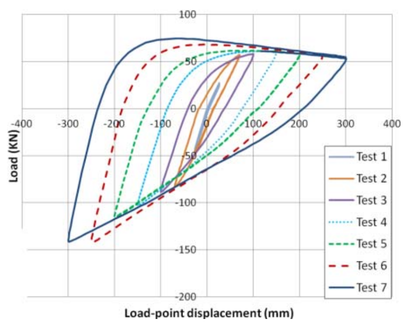


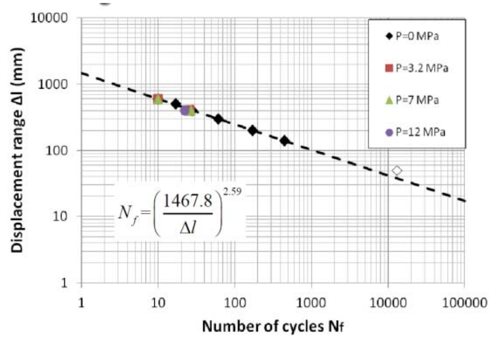




Mechanical Behavior of Steel Piping Components under Severe Loading Conditions [Karamanos]







Recent research issues

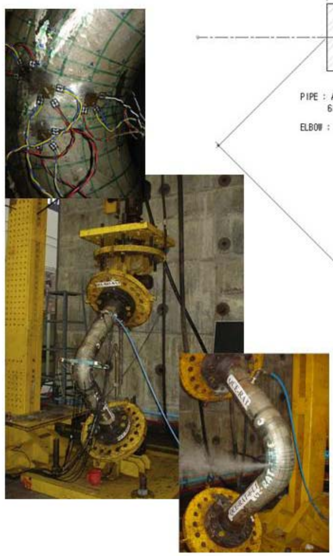
MECOS Program [OECD-NEA]

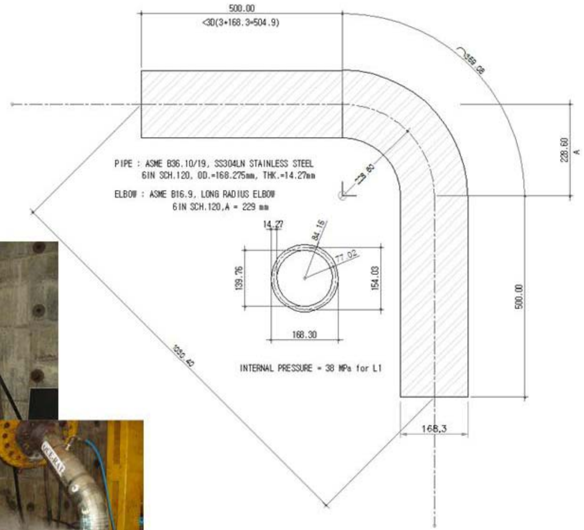
- International program organised under the initiative of OECD-NEA
- Comparison between experimental reference cases and numerical simulations regarding seismic fatigue ratcheting on piping
- Final objective : getting a better appreciation of fatigue ratcheting in design codes

MECOS BENCHMARK 1st WORK SHOP

Numerical Analysis

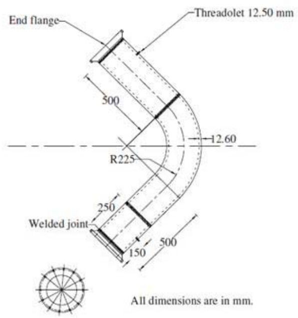
Model description : Pipe size and sectional properties

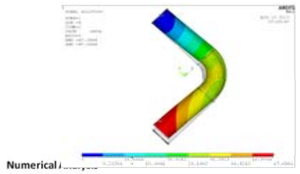


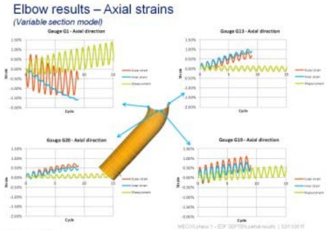


Elbow specimen drawing and sectional properties

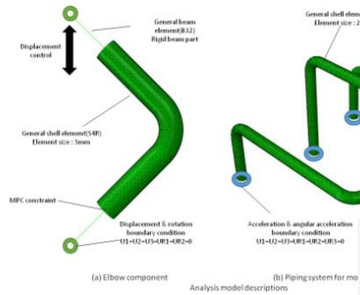
[Specimen drawing by ref. paper]

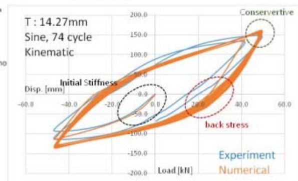


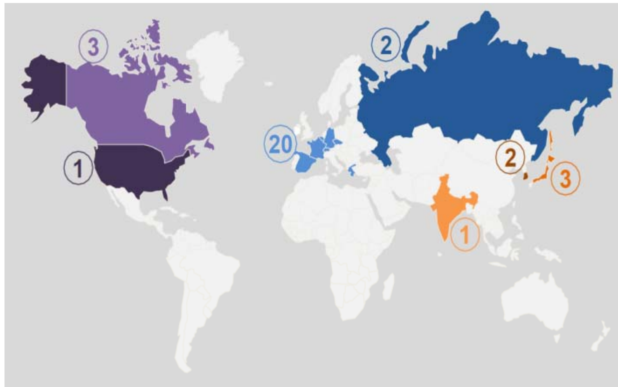




Model description : Elbow and piping system model

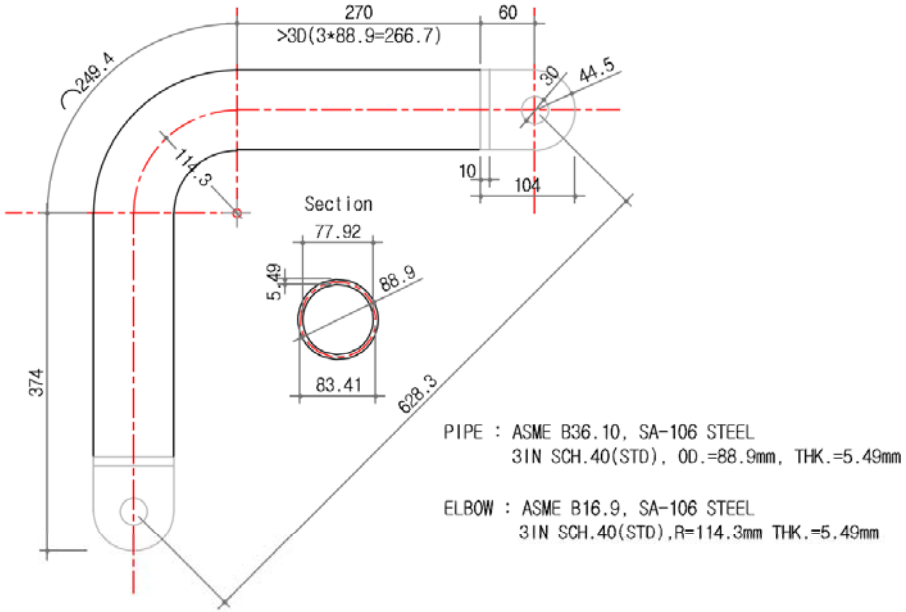




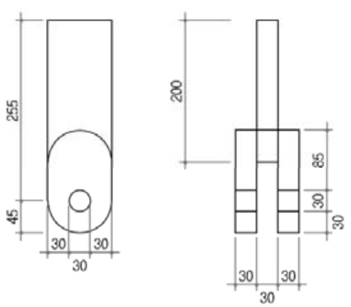


Description of component test

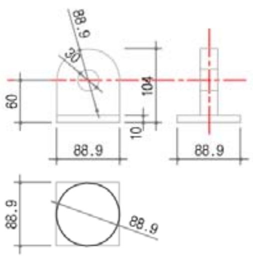
Test specimen description



상,하부 지그 (*2EA)



실험체 지그

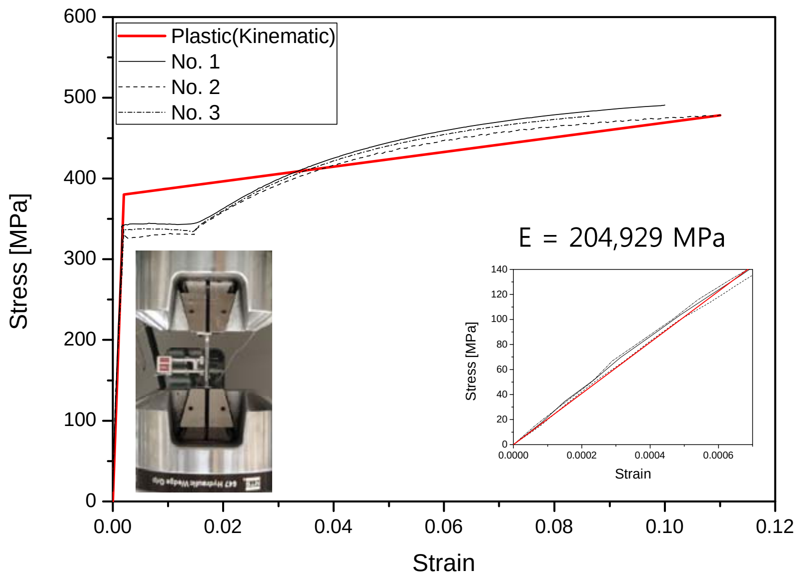


3in. SCH 40 (ASME B36.10M)

- O.D. : 88.9 mm
- t : 5.49 mm
- R : 114.3 mm
- Long elbow, welding connection
- SA-106 steel

Material

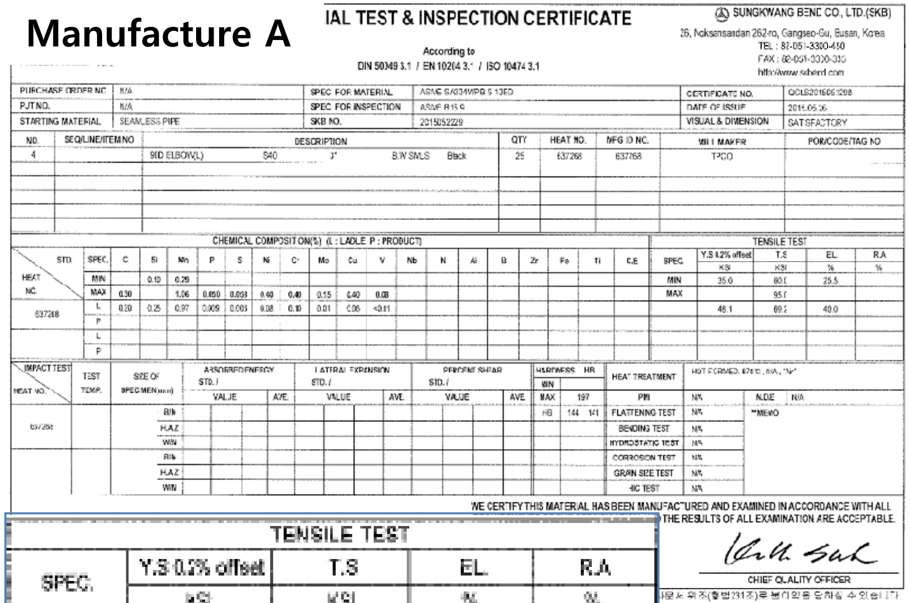
- E : 205 Gpa (estimation by tensile test)
- Nonlinear behavior



Description of component test

Considering The Manufacturing Error

Manufacture A


IAL TEST & INSPECTION CERTIFICATE

SUNGKWANG BEND CO., LTD.(SKB)

According to DIN 50049 3.1 / EN 10204 3.1 / ISO 10474 3.1

PURCHASE ORDER NO.	N/A	SPEC FOR MATERIAL	ASME SA234WPB	CERTIFICATE NO.	
PJT NO.	N/A	SPEC FOR INSPECTION	ASME B16.9	DATE OF ISSUE	
STARTING MATERIAL	SEAMLESS PIPE	SKB NO.		VISUAL & DIMENSION	SATISFACTORY

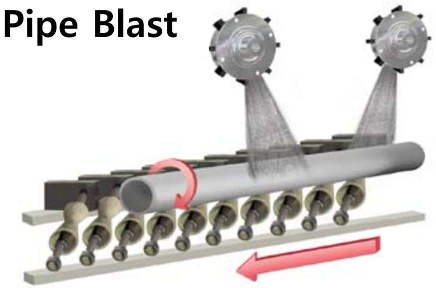
WE CERTIFY THIS MATERIAL HAS BEEN MANUFACTURED AND EXAMINED IN ACCORDANCE WITH ALL THE RESULTS OF ALL EXAMINATION ARE ACCEPTABLE.

CHIEF QUALITY OFFICER

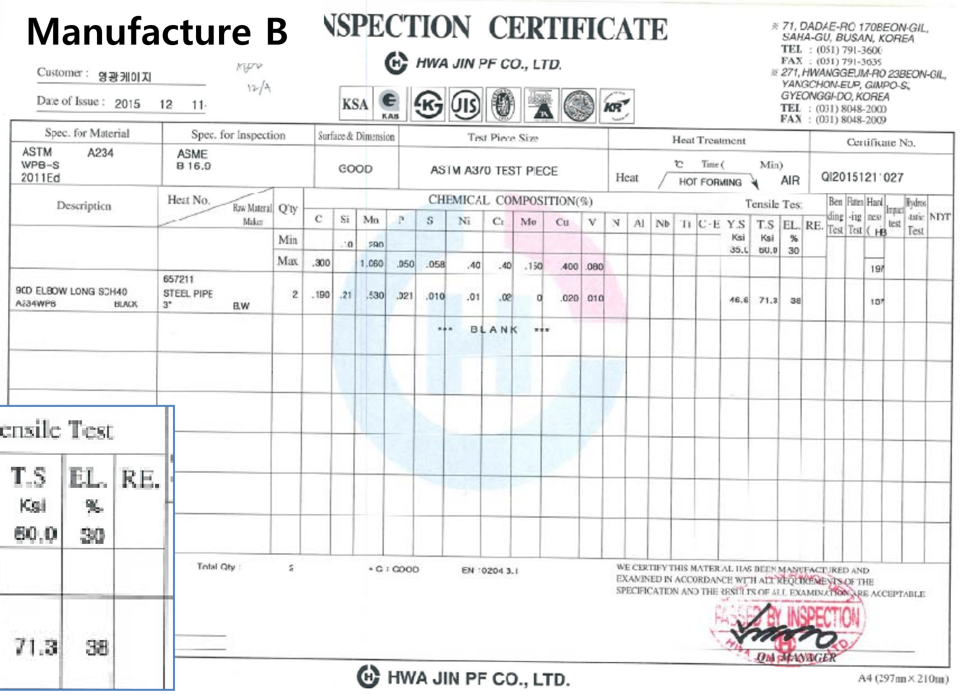
SPEC.	Y.S 0.2% offset	T.S	EL	R.A
	KSI	KSI	%	%
MIN	35.0	60.0	25.5	
MAX		95.0		
	48.1	69.2	40.0	

TENSILE TEST

Pipe Blast



Manufacture B


INSPECTION CERTIFICATE

HWA JIN PF CO., LTD.

Customer : 영광케이지

Date of Issue : 2015 12 11

Spec. for Material	Spec. for Inspection	Surface & Dimension	Test Piece Size	Heat Treatment	Certificate No.
ASTM A234 WPB-S 2011Ed	ASME B 16.9	GOOD	ASTM A370 TEST PIECE	HOT FORMING, AIR	QI2015121 027

Description	Heat No.	Q'ty	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	V	Y.S	T.S	EL.
Max			.300		1.060	.050	.058	.40	.40	.150	.400	.080			
90D ELBOW LONG SCH40 A234WPB BLACK	657211 STEEL PIPE 3" B.W	2	.190	.21	.530	.021	.010	.01	.02	0	.020	.010	46.6	71.3	38

*** BLANK ***

WE CERTIFY THIS MATERIAL HAS BEEN MANUFACTURED AND EXAMINED IN ACCORDANCE WITH ALL REQUIREMENTS OF THE SPECIFICATION AND THE RESULTS OF ALL EXAMINATIONS ARE ACCEPTABLE

PASSED BY INSPECTION

QM MANAGER

HWA JIN PF CO., LTD.

Tensile Test

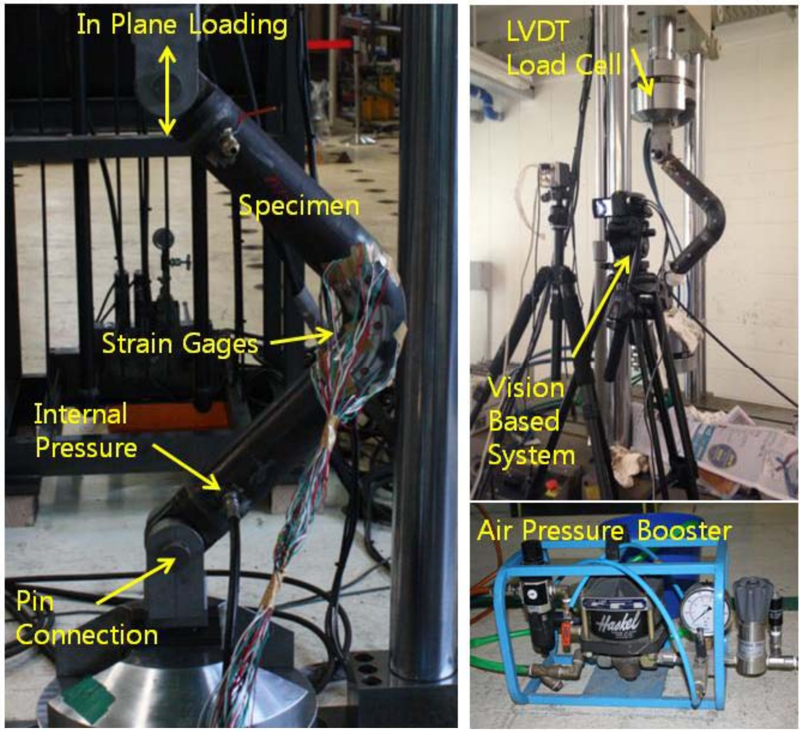
Y.S	T.S	EL.	RE.
Ksi	Ksi	%	
35.0	60.0	30	
46.6	71.3	38	

- Elbow specimen were made by different make for considering the manufacture error.
- 1 case of specimen was under pipe blasting treatment for considering the surface treatment.

Description of component test

Test Plan

Description of component test



In-plane loading
- ±20mm to ±100mm

Internal pressure
- Water pressure booster : 3MPa

Measurement
- Loading force (Load cell)
- Loading displacement (LVDT)
- Strain response (strain gage, vision based system)

Test Specimen	P1-23, 26, 27, 28, 29, 44	P1-24, 25, 30, 31, 45	P1-4, 18, 19, 32, 46	P1-3, 16, 17, 33, 47	P1-1, 10, 12, 15, 34, 48	P1-2, 11, 14, 35, 49	P1-5, 6 13, 36, 39, 50	P1-20, 37, 40, 41, 51	P1-21, 38, 42, 43, 52
Mode	Cyclic mode	Cyclic Mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode
Amplitude	±20mm	±30mm	±40mm	±50mm	±60mm	±70mm	±80mm	±90mm	±100mm
Pressure	3MPa	3MPa	3MPa	3MPa	3MPa	3MPa	3MPa	3MPa	3MPa
Remarks	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage

Test results

Test results of 3 in. elbow specimen component

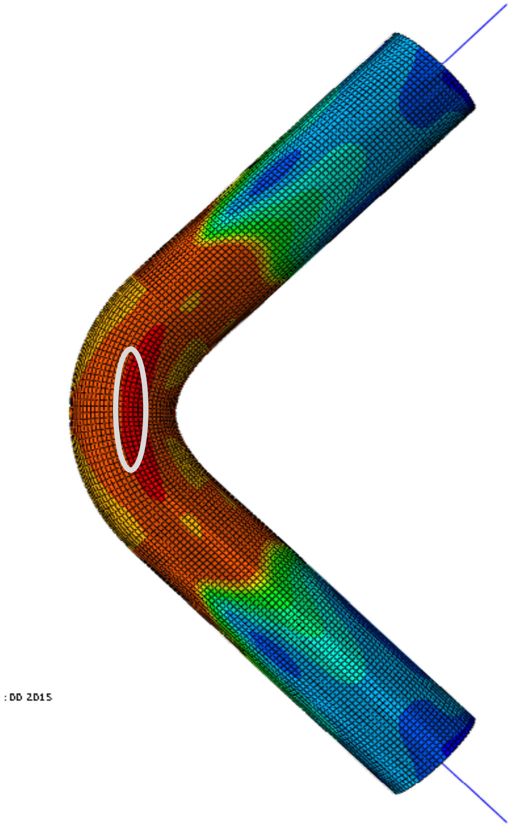
Leakage N^{th} cycle of elbow specimen

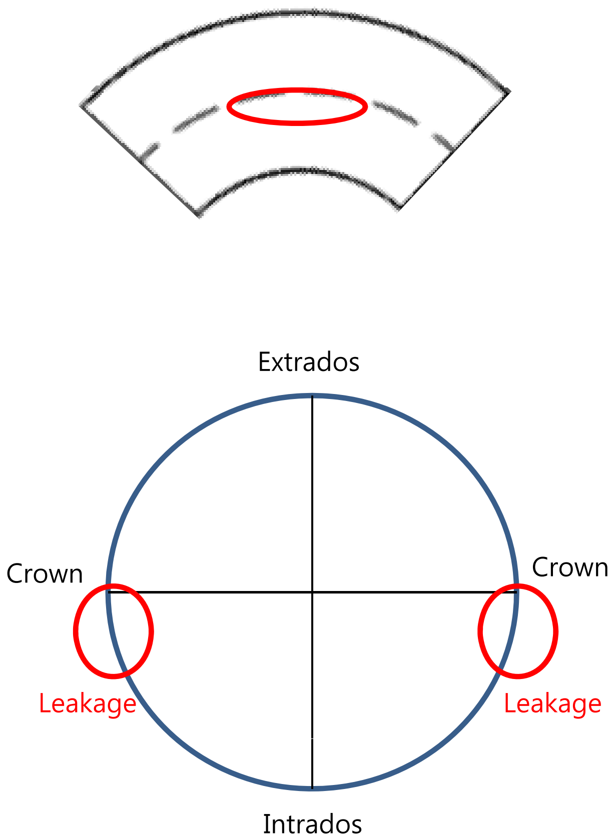
1) ±20mm : 82, 108, 110, 87, 76, 98
2) ±30mm : 45, 46, 29, 29, 38
2) ±40mm : 17, 18, 18, 14, 15
3) ±50mm : 11, 10, 11, 9, 12
4) ±60mm : 6, 6, 8, 8, 8, 8
5) ±70mm : 4, 5, 5, 4, 6
6) ±80mm : 5, 4, 4, 5, 4, 4, 5
7) ±90mm : 4, 4, 4, 4, 4
8) ±100mm : 4, 3, 4, 4, 3

Test results

Leakage Point of Elbow Specimen

- Leakage occurred on the near the crown in intrados direction
- Cracks (ruptures) grew up in axial direction

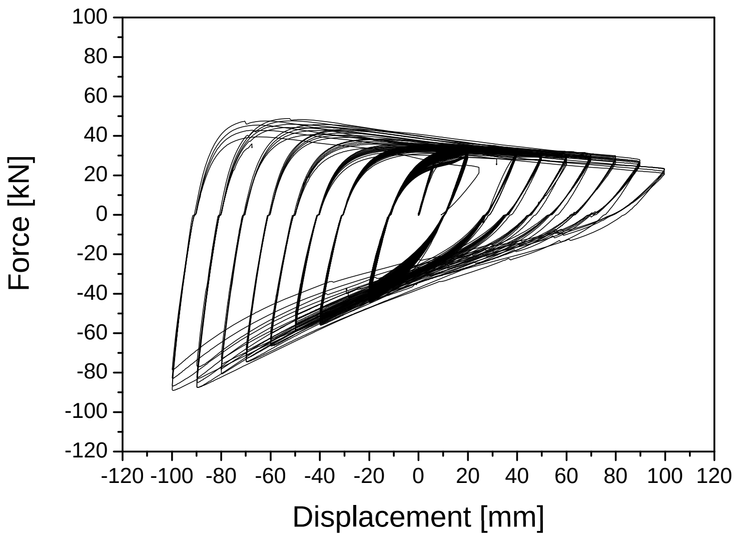




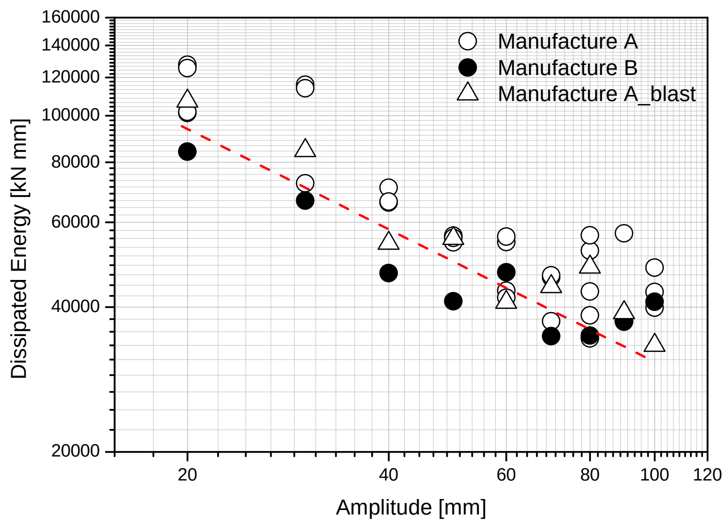
Test results

Test results of 3 in. elbow specimen component

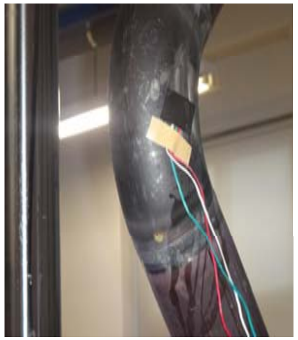
P-D relationship

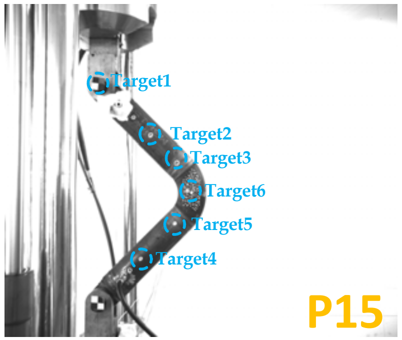


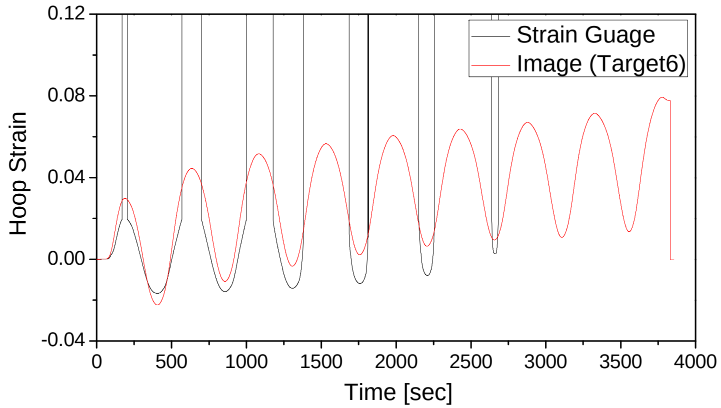
Dissipated energy



Strain response (strain gage and vision based system)



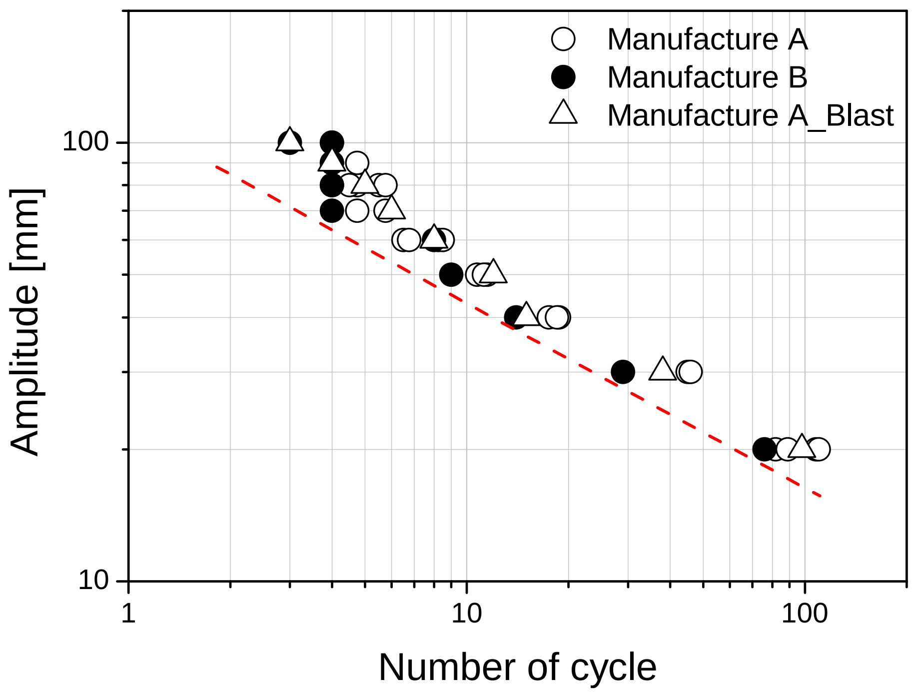




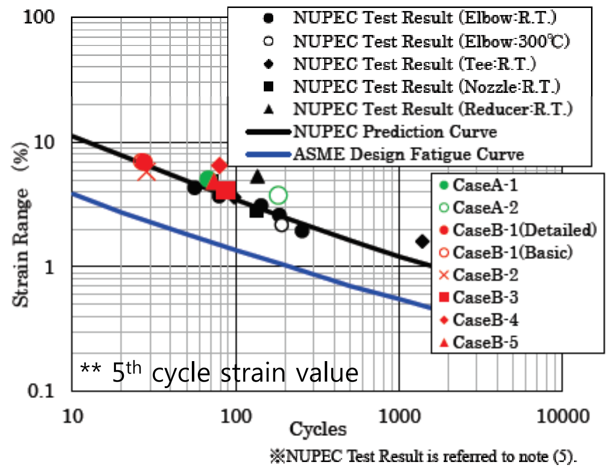
Test results

Fatigue Curve for 3in. SCH40 Steel Pipe Elbow

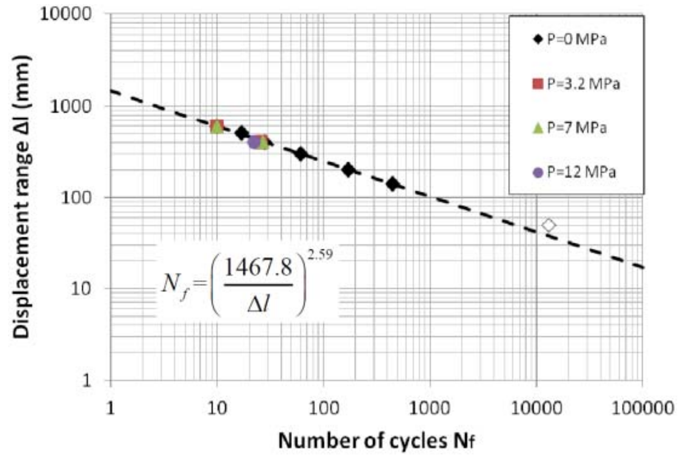
Fatigue curve
- Loading amplitude exponentially decreased as the number of cycles increased
- Use maximum loading amplitude
- Exponential function
- Similar to other research results



[Mizuno et al., 2014]



[Karamanos, 2015]



Numerical model update

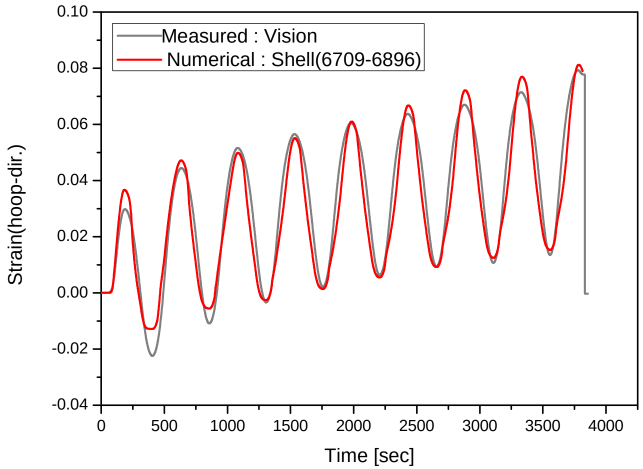
Numerical Model Update

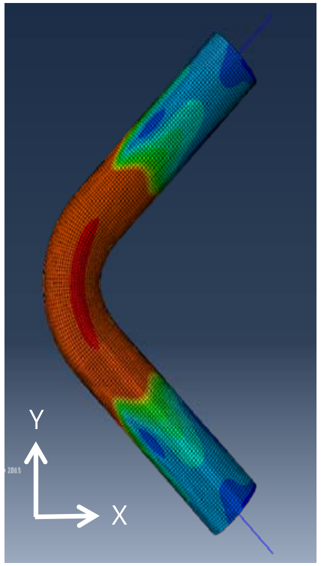
Numerical Analysis

1) Material

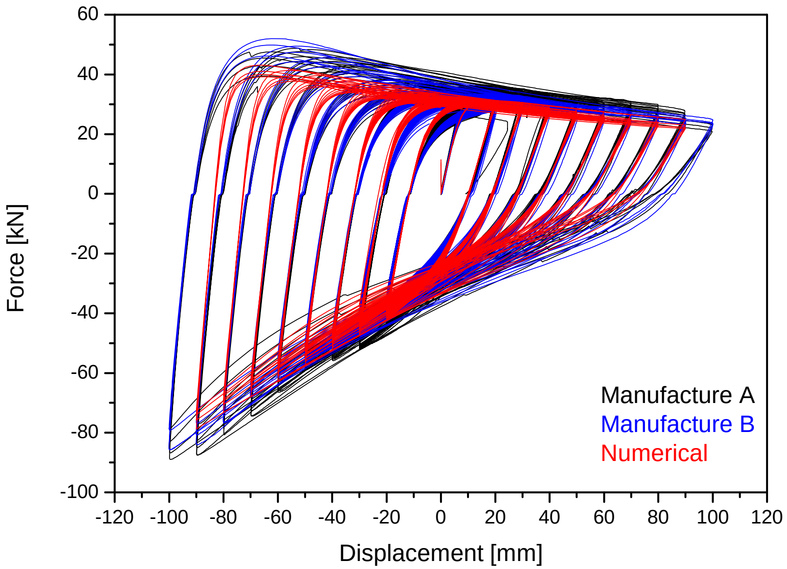
- ABAQUS 6.12
- Young's modulus : 205000 MPa
- Possion’s ratio : 0.3
- Hardening rule : Linear kinematic hardening model
- Displacement control
- Critical direction : Hoop direction [Mizno, 2014]

[Strain comparison for Hoop dir. Of 60 mm case]

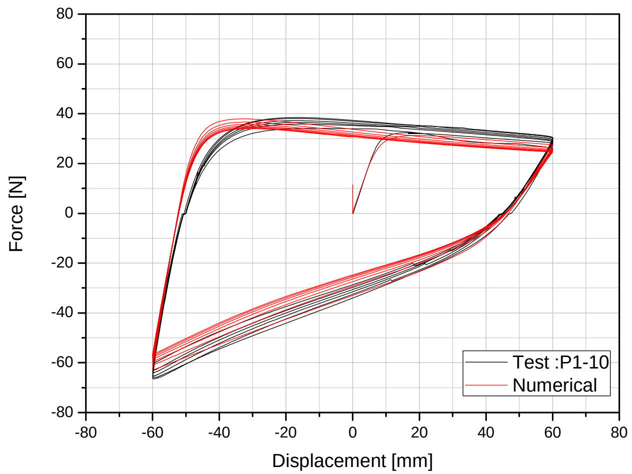




[Comparison of P-D relation ship at 60 mm case]



[Comparison of P-D relation ships]



Estimation of Failure

Estimation of Failure

Suggest the quantitative failure criteria for piping elbow considering the dissipated energy.

- Park and Ang, (1985)

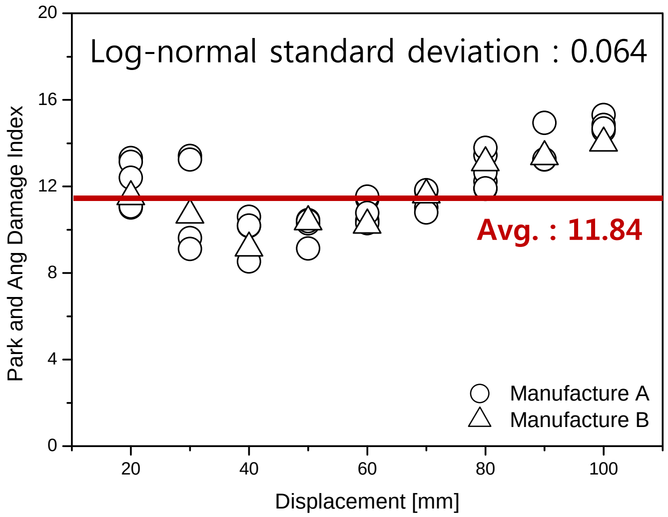
$$D = \max\left(\frac{D_i}{D_y}\right) + b\sum_{i=1}^{N}\left(\frac{E_i}{F_y D_y}\right)$$

D_y : Yield displacement
F_y : Yield force
D_i : ith cycle displacement amplitude
E_i : Dissipated energy [Force-Displacement]

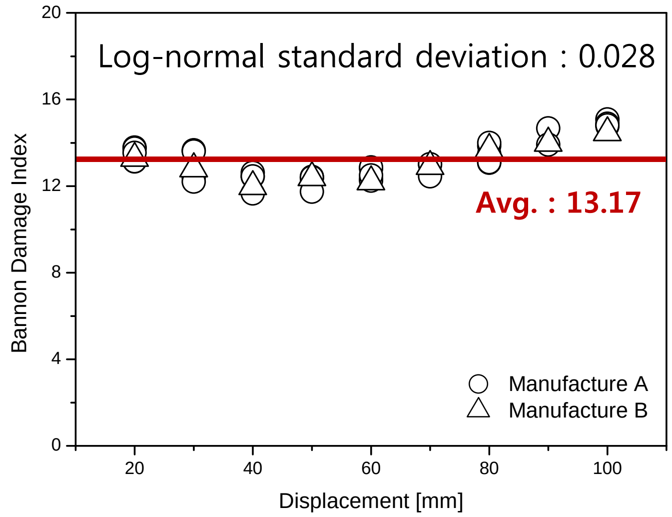
- Banon (1981)

$$D = \sqrt{\left(\max\left(\frac{D_i}{D_y} - 1\right)\right)^2 + \left(\sum_{i=1}^{N} c\left(2\frac{E_i}{F_y D_y}\right)^d\right)^2}$$

b : 0.025 (Cosenza et al., 1993)
c : 1.1 (Castiglioni and Pucinotti, 2009)
d : 0.38



Park and Ang : d=0.025



Banon: c=3.3, d=0.21

Concluding remarks and further study

Concluding Remarks

In-plane cyclic loading tests under internal pressure condition were performed to estimate the failure behavior of the steel piping elbow—a weak component in a piping system under seismic condition.

Leakage phenomenon occurred on and near the crown in piping elbow. Those cracks grew up in axial direction.

The fatigue curve was estimated from test results. In the fatigue curve, loading amplitude exponentially decreased as the number of cycles increased.

A FEM model of piping elbow was modified with test results. The relationships between displacement and force from tests and numerical analysis was well matched. Therefore, failure of piping elbow can be predicted based on numerical analysis.

Suggest the quantitative failure criteria of piping elbow for seismic fragility analysis

Failure criteria of the piping elbow considering the dissipated energy.