Verification of Design Method of Pipeline Crossing Fault with Earthquake Resistant Ductile Iron Pipe Using Large-scale Split-box test

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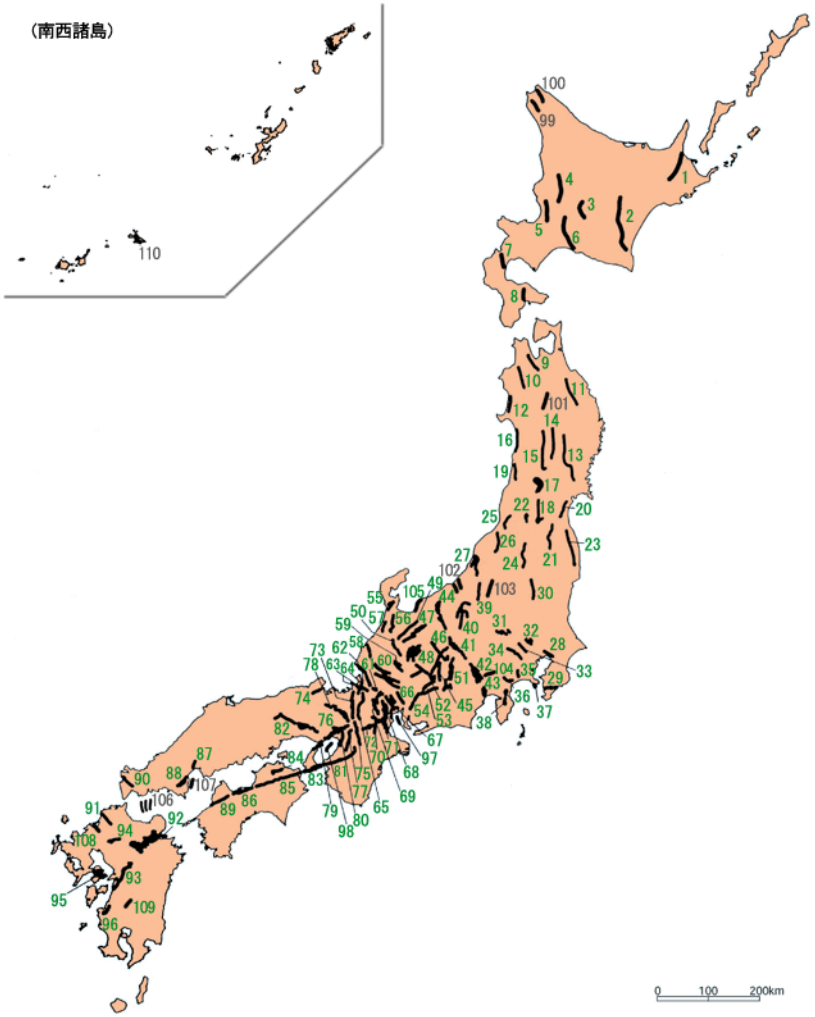
Background

There are approximately 2,000 active fault in Japan

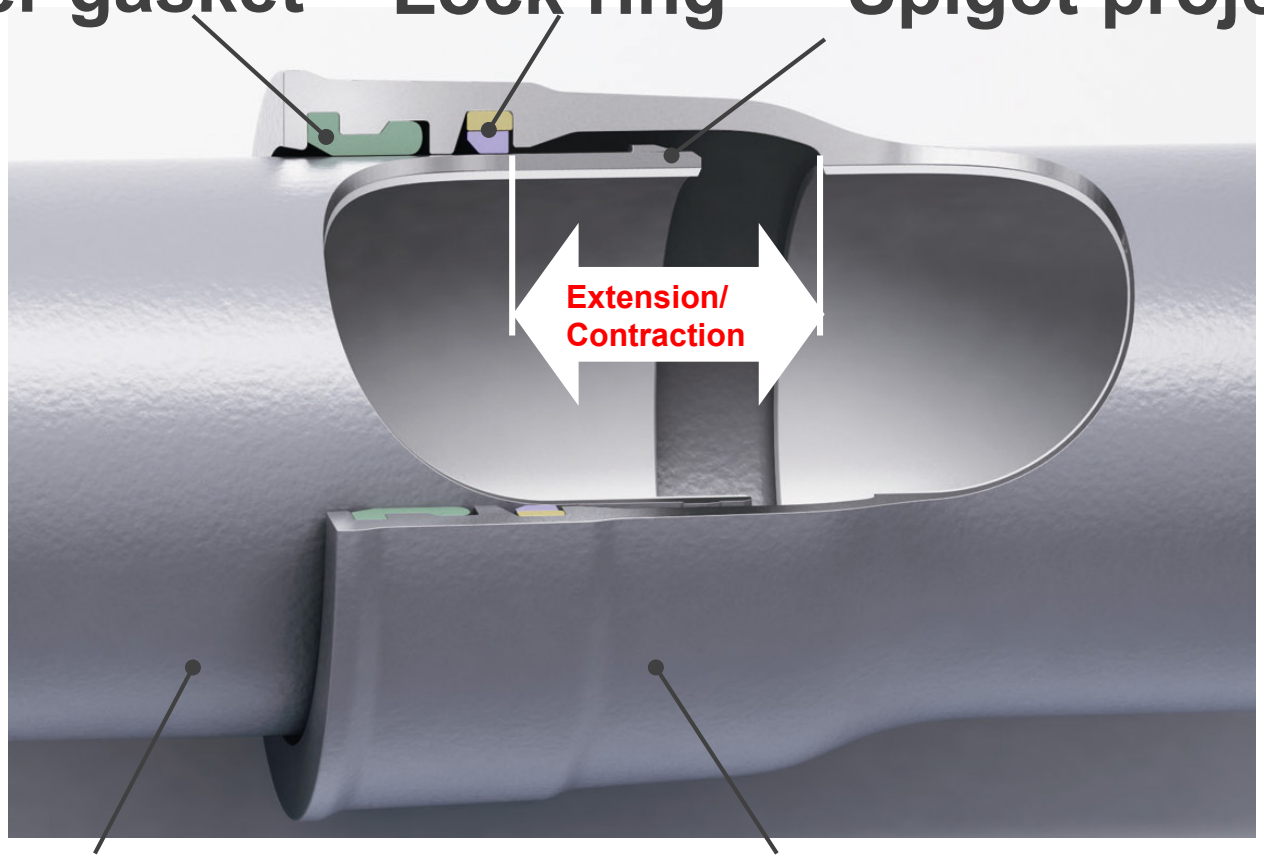


Source: Headquarters for Promotion of Earthquake Research, Japan
Public Works Research Institute, Japan

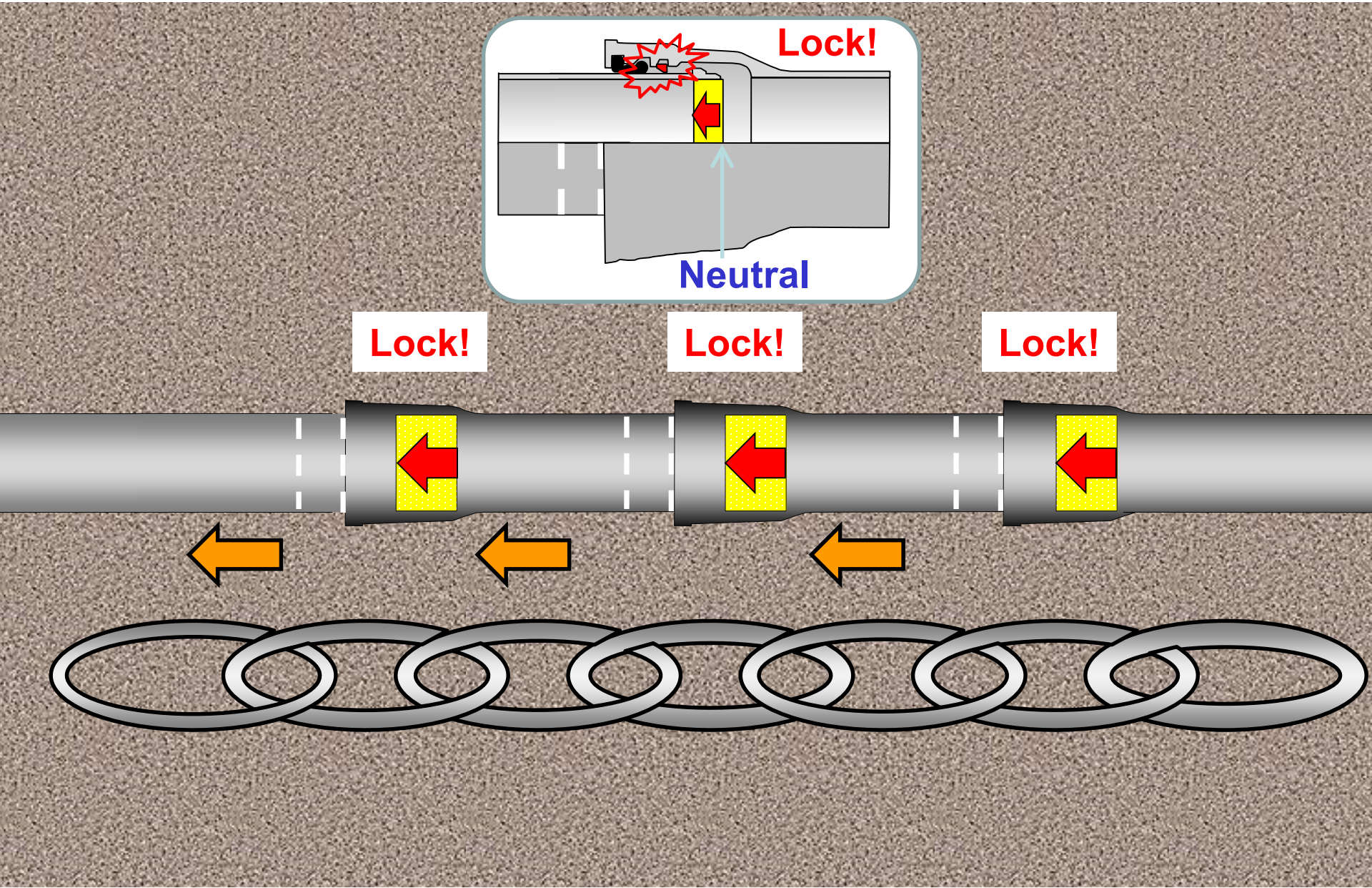
①Subsequent Aftershock of the 2011 Great East Japan Earthquake

② The 2016 Kumamoto earthquake

ERDIP (Earthquake Resistant Ductile Iron Pipe)

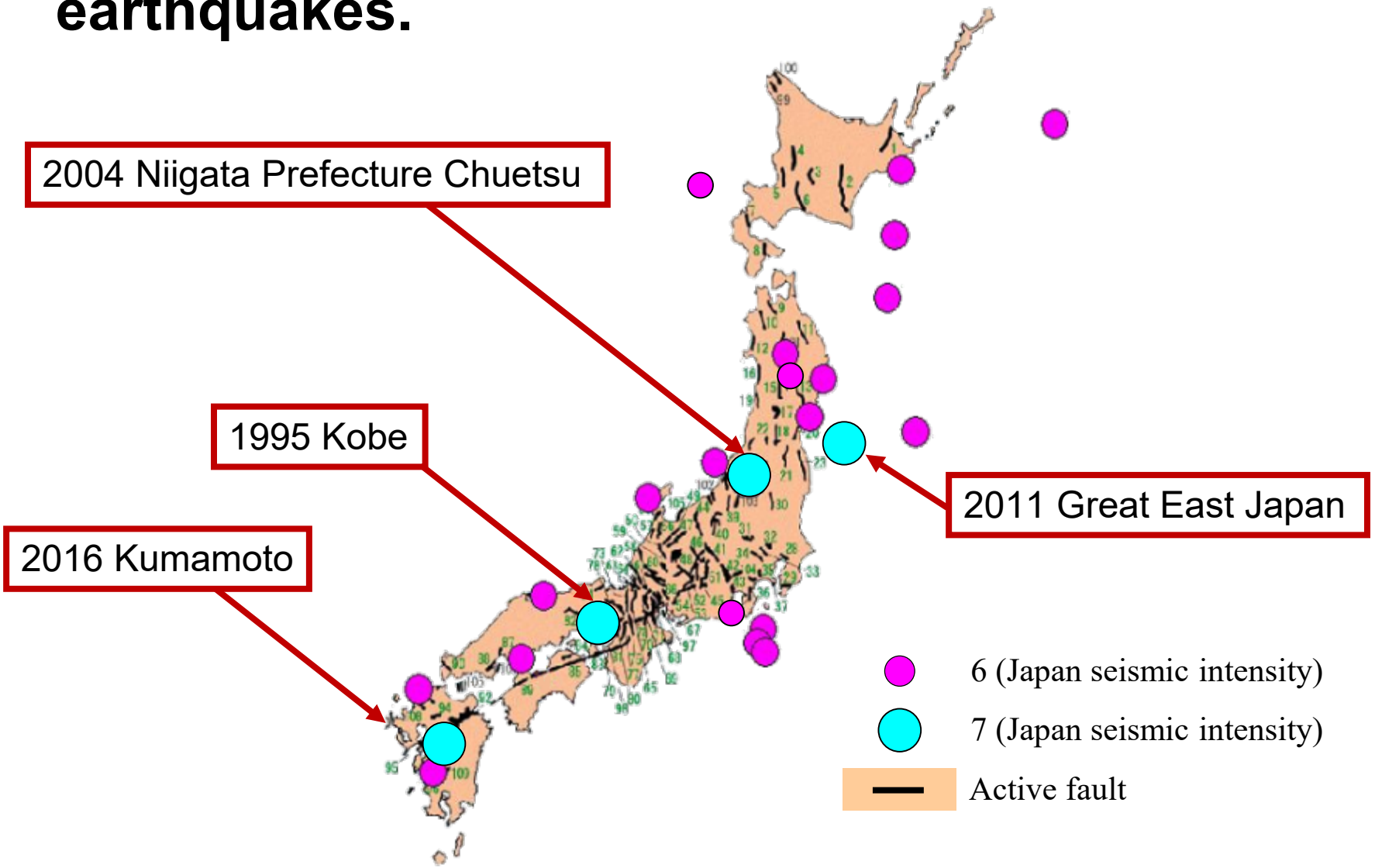


ERDIP (Earthquake Resistant Ductile Iron Pipe)



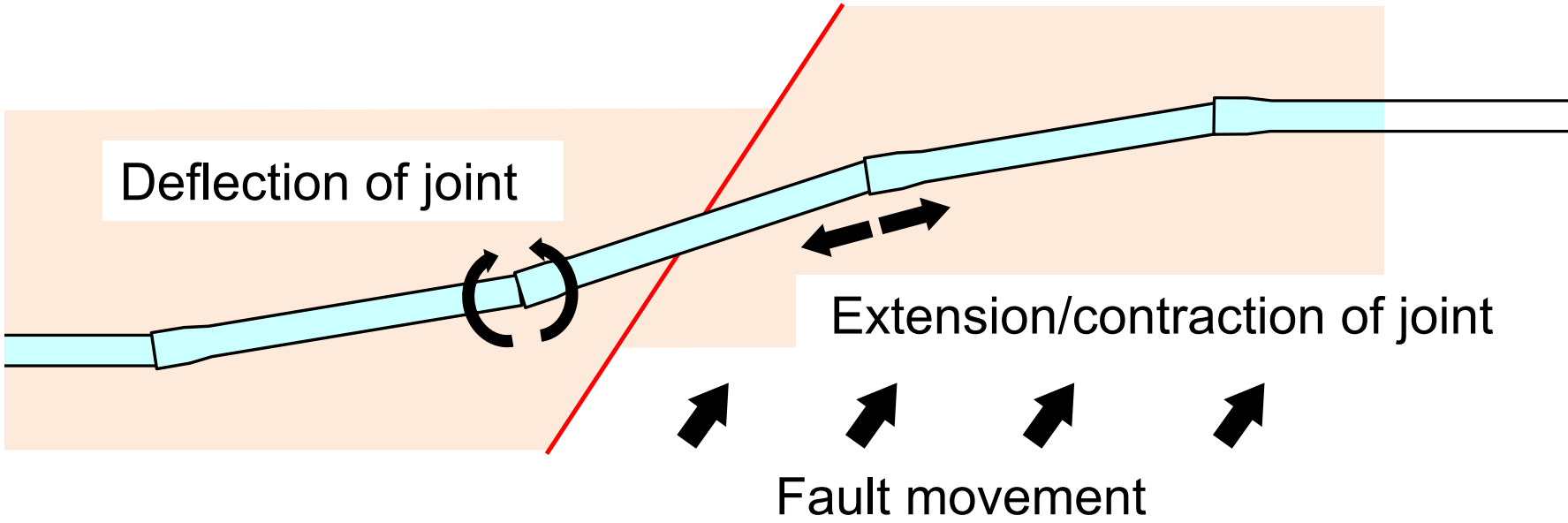
ERDIP (Earthquake Resistant Ductile Iron Pipe)

ERDIP have no documented damages in past earthquakes.



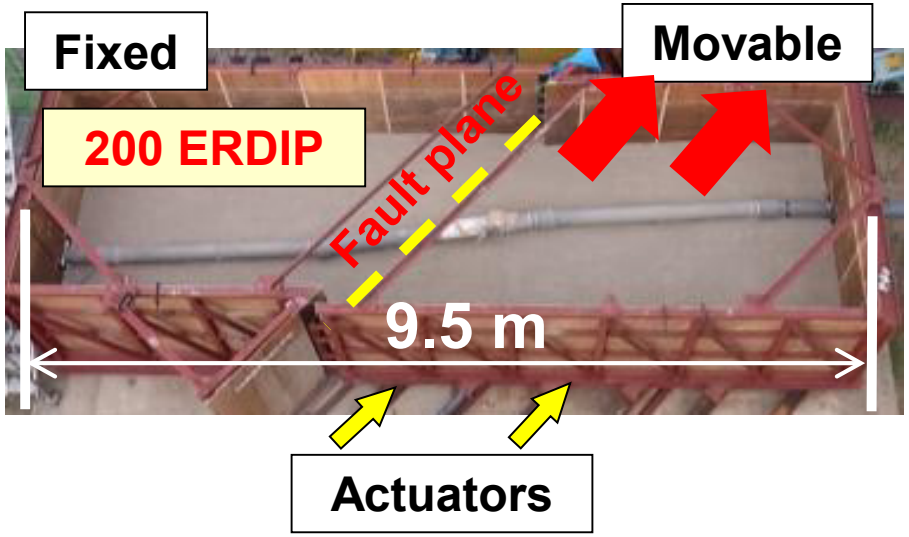
Our goal of research

- To confirm how large can ERDIP pipeline withstand fault displacement.
- To create countermeasures against large displacement.



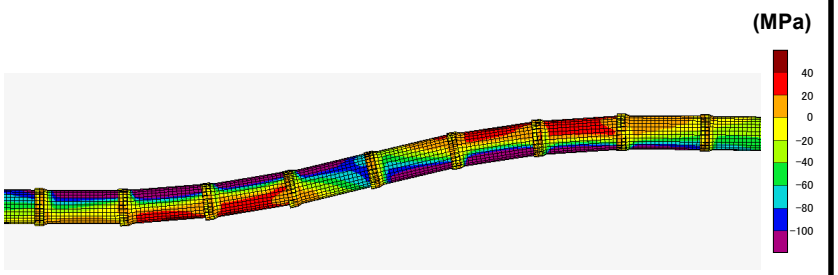
Previous research

Large box experiment



+

FEM analysis



Non-linear FEM analysis using beam or shell model considering geometric and material non-linearity

Items	Criteria
Axial force	< 3D kN D: diameter in mm
Joint deflection angle	< Allowable deflection angle
Stress on pipe body	< Proof stress (270 MPa)

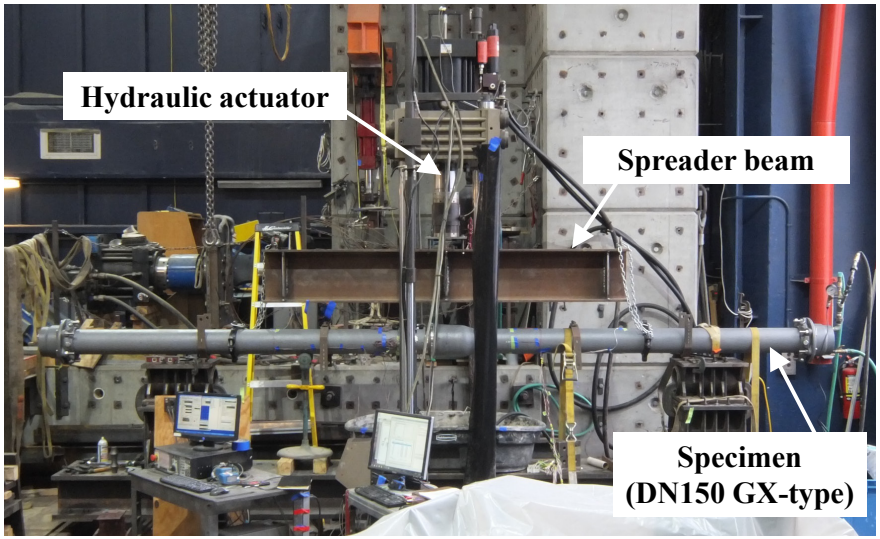
⇨ **No plastic deformation**

Purpose of this study

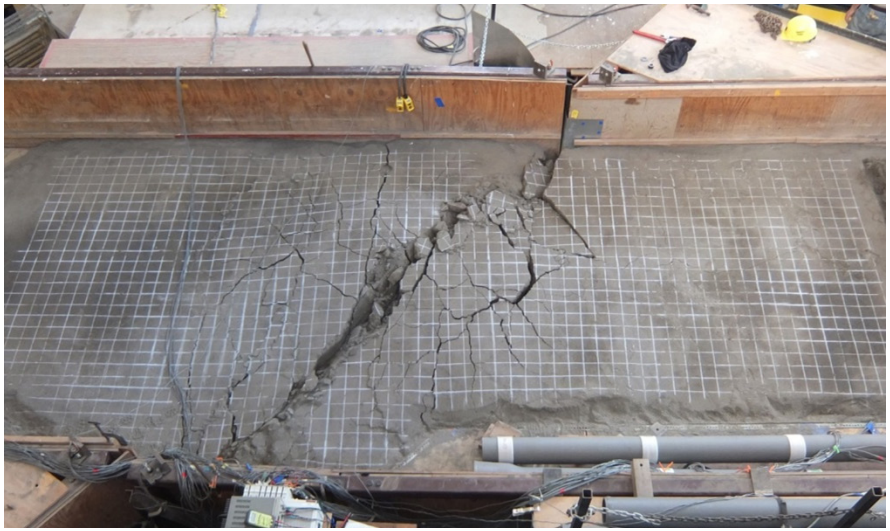
We have to know whether the pipeline behavior during a fault movement becomes more excessive than assumed

Testing under the extreme conditions.

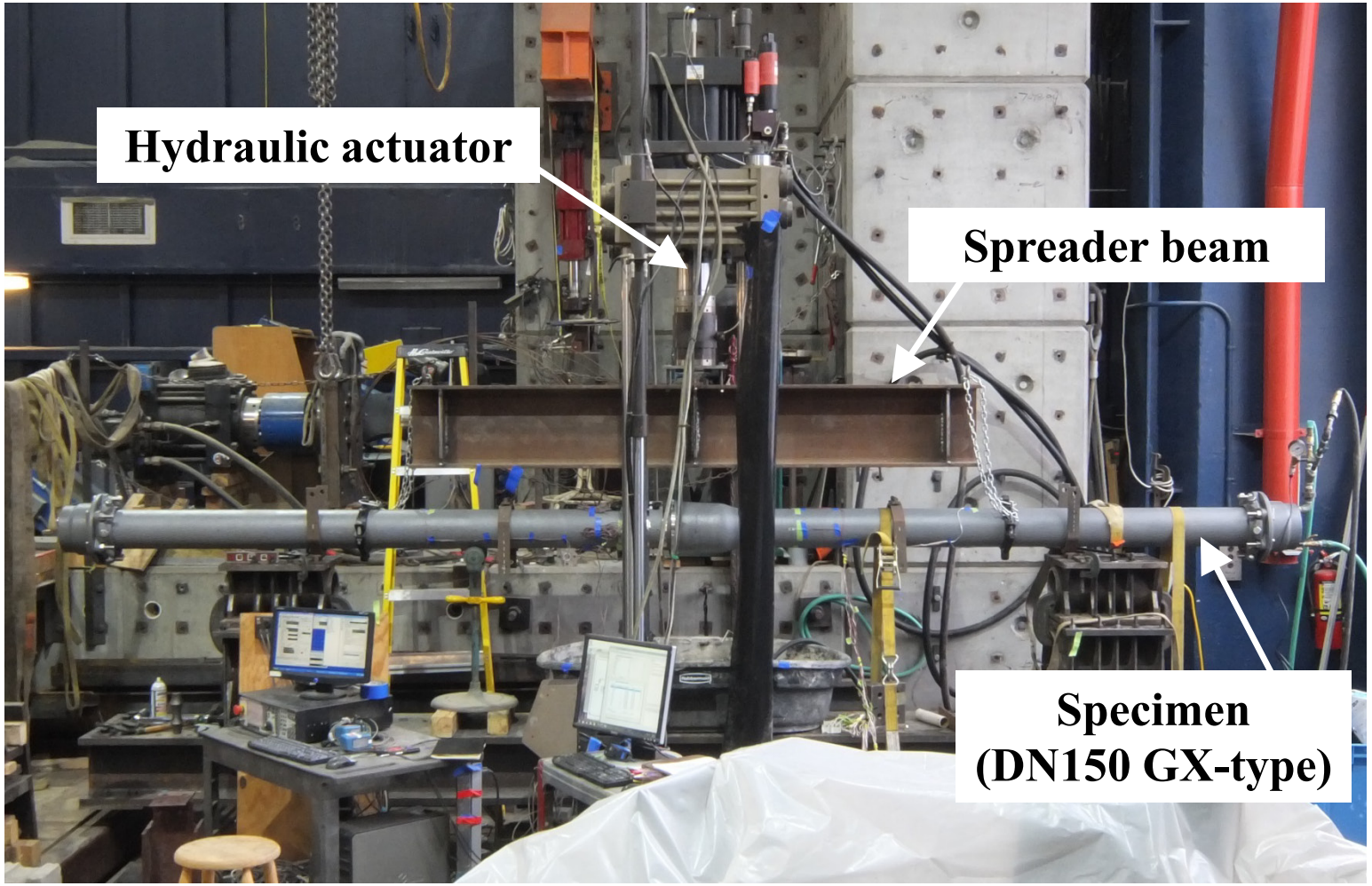
Four-point bending test



Large scale split-box test



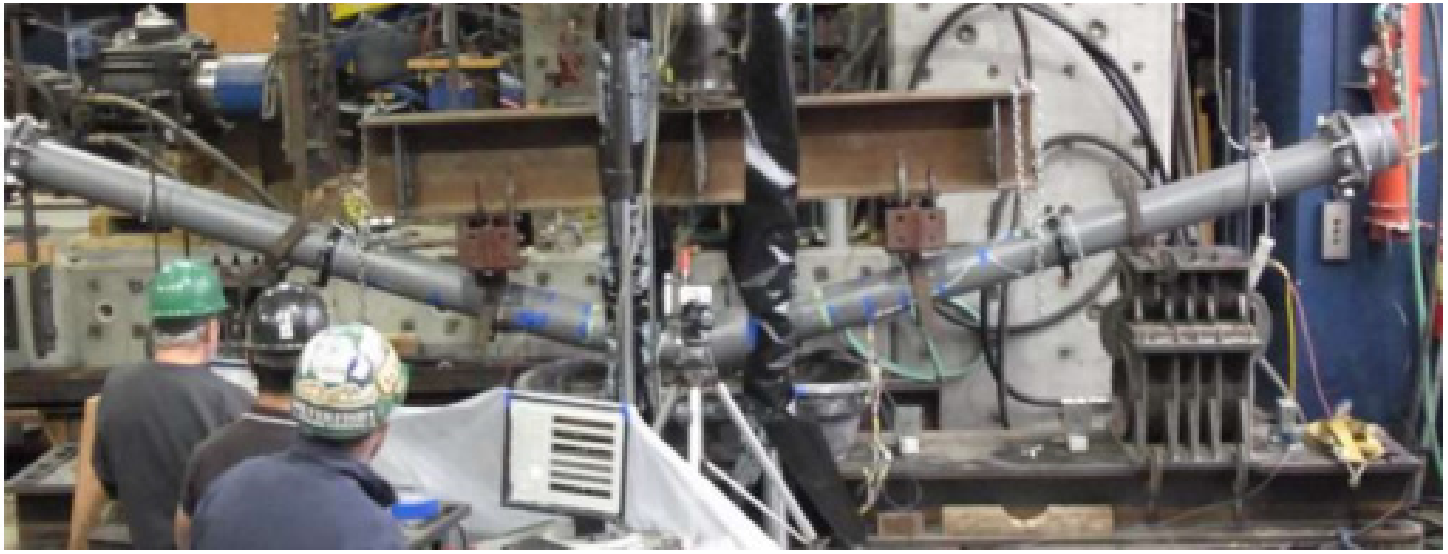
Four-point bending test set-up



Bending specimen during and after the test

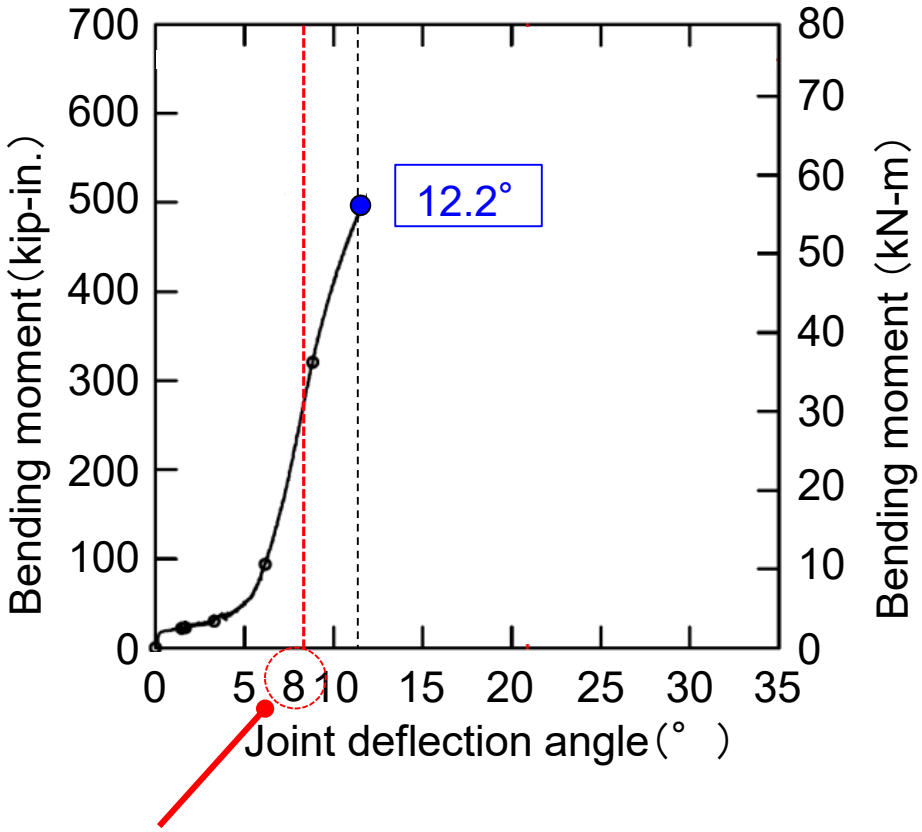
[12.2°]

[32°]



Test result (Joint deflection angle <12.2)

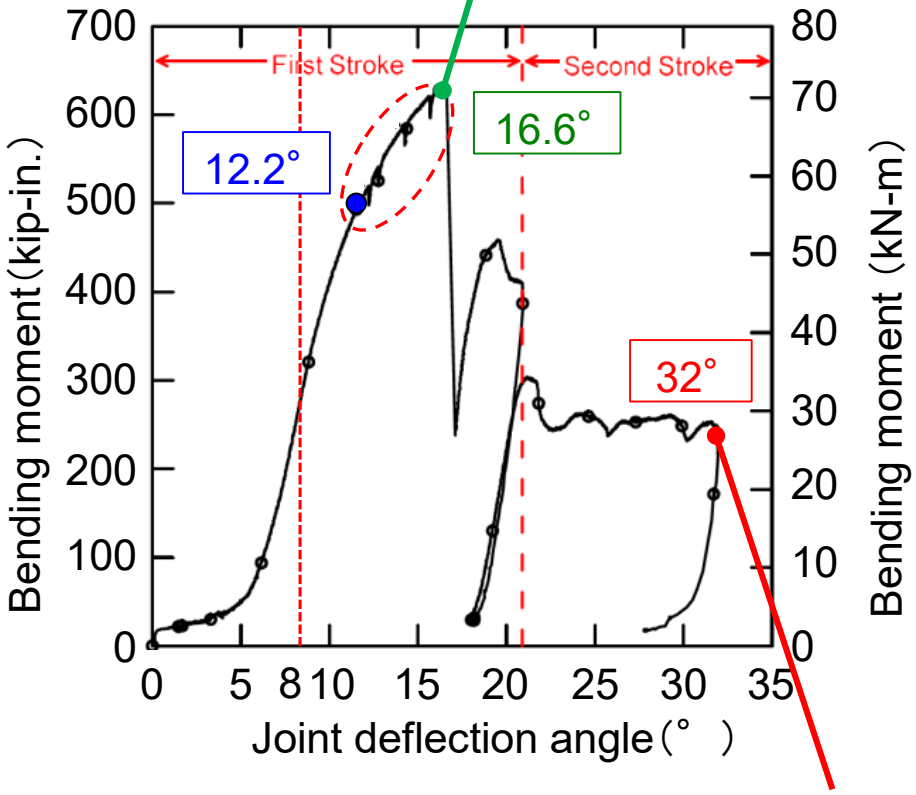
No leakage occurred at 12.2°, which is 1.5 times the performance limit of GX-type joint



The design performance limit of GX-type joint

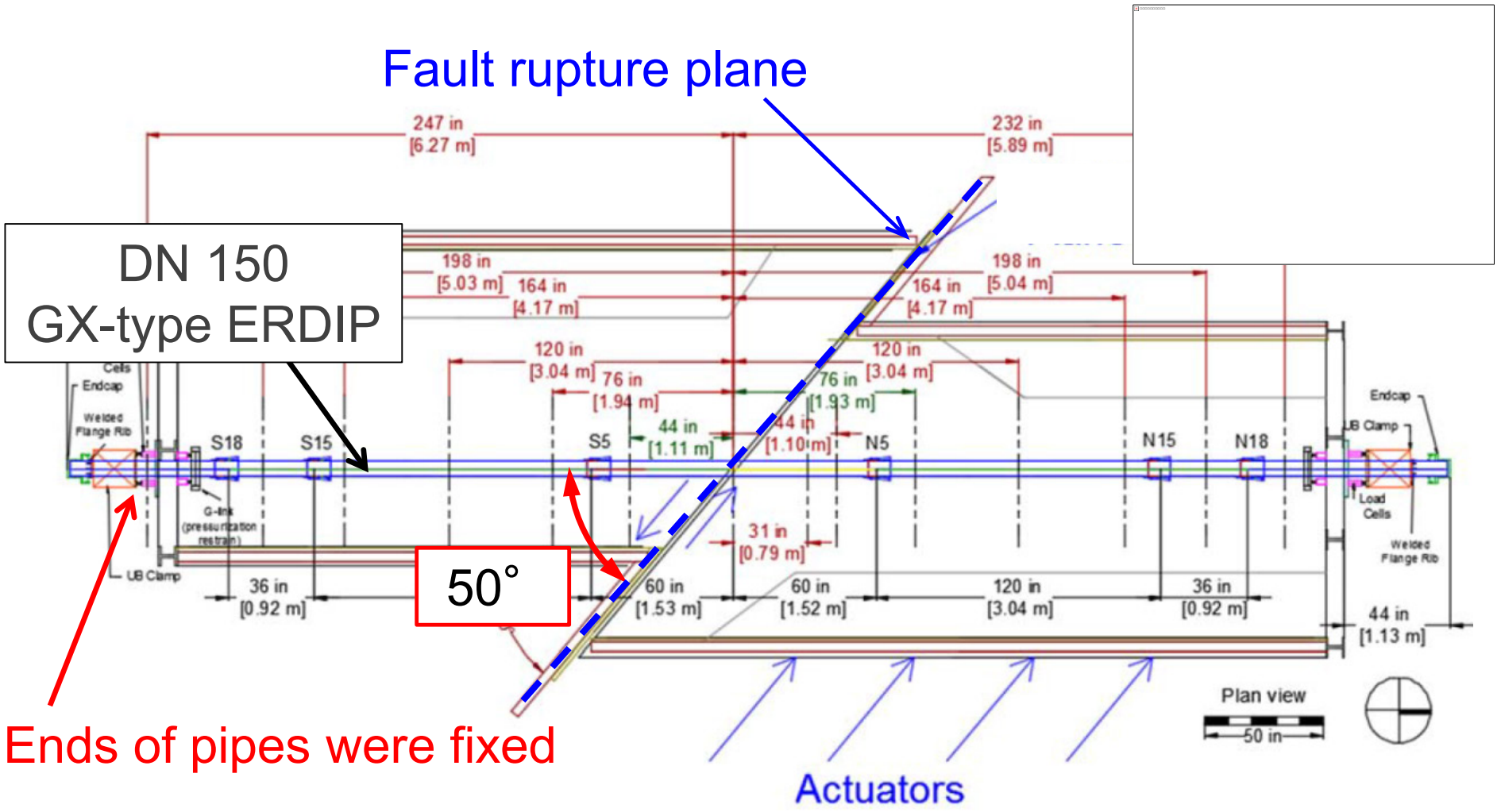
Test result (Joint deflection angle ≧12.2)

The first leakage was observed at 12.2°
The leakage stopped at the deflection of 16.6°



The test was stopped when the joint reached the joint deflection of 32°

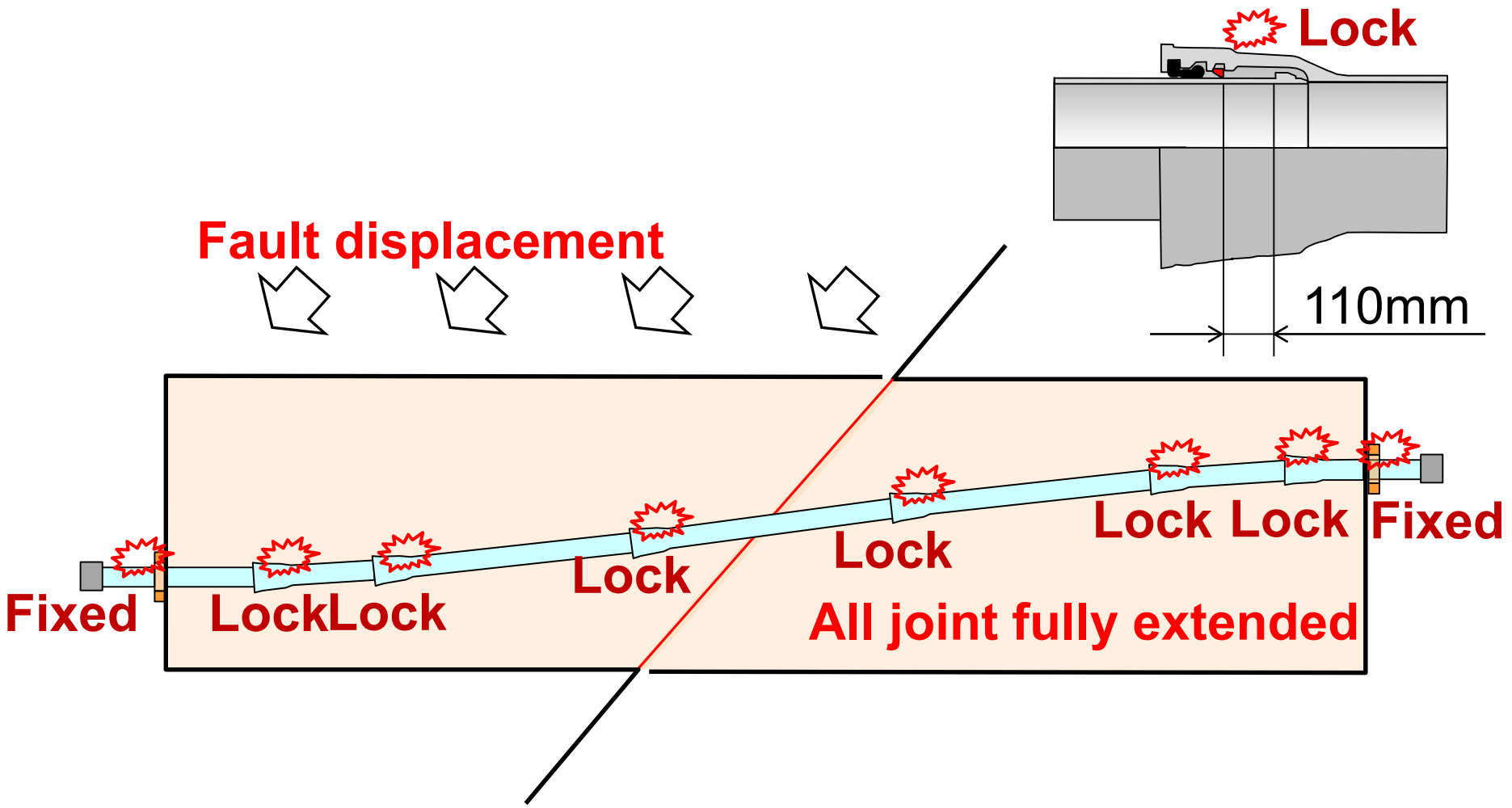
Large scale split-box test set-up



① Pressurized with water to approximately 550 kPa (80 psi)

② Moved one of the two boxes using the actuators

Test procedure

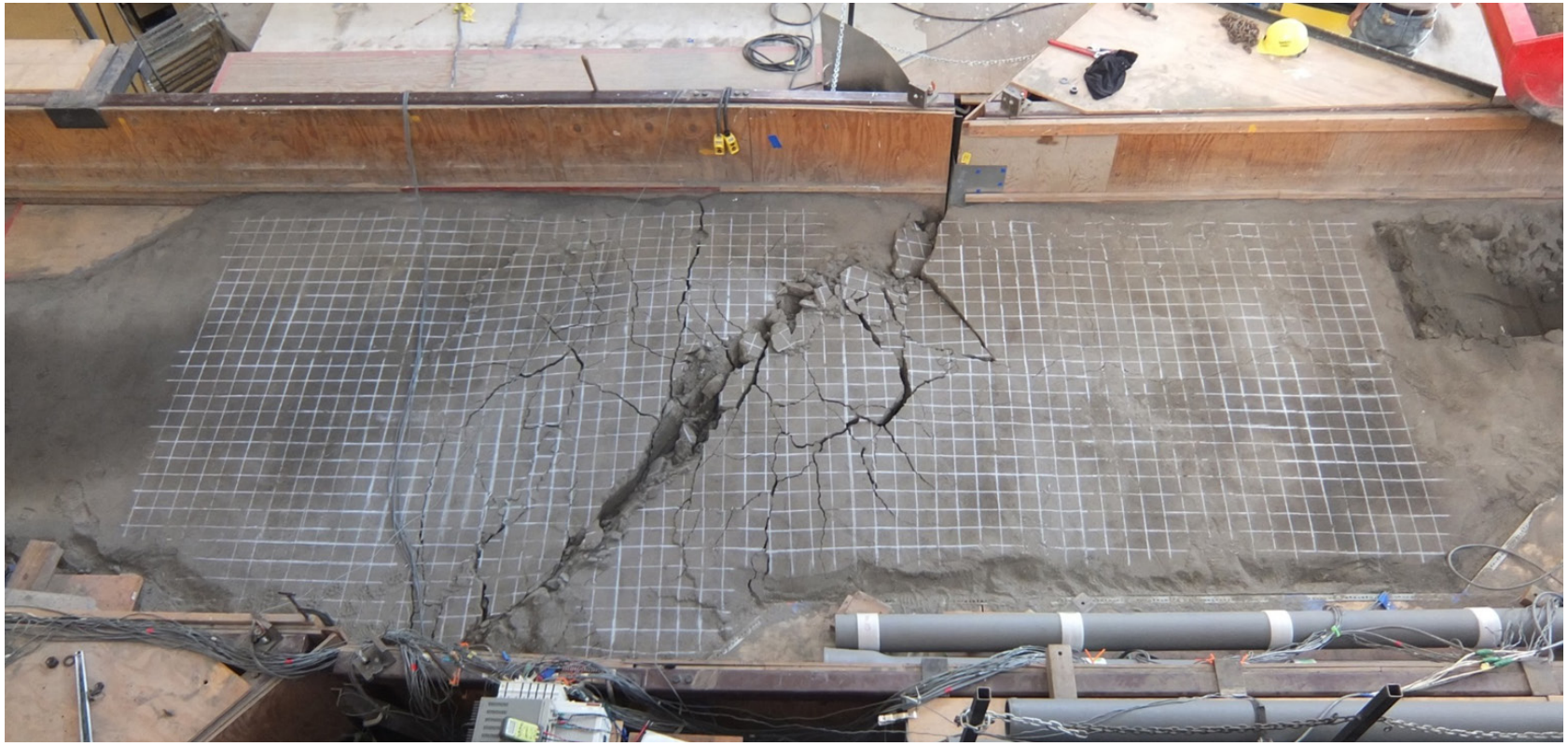


Backfill sand conditions

Items	Conditions
Type	Glacio-fluvial sand
Global average dry unit weight	16.6 kN/m^3 (105.6 lb/ft^3)
Global average moisture content	3.7%
50% particle diameter	0.59 mm
Coefficient of uniformity	3.35
Coefficient of curvature	0.83
Friction angle	42°

Large scale split-box test

Test box after the test



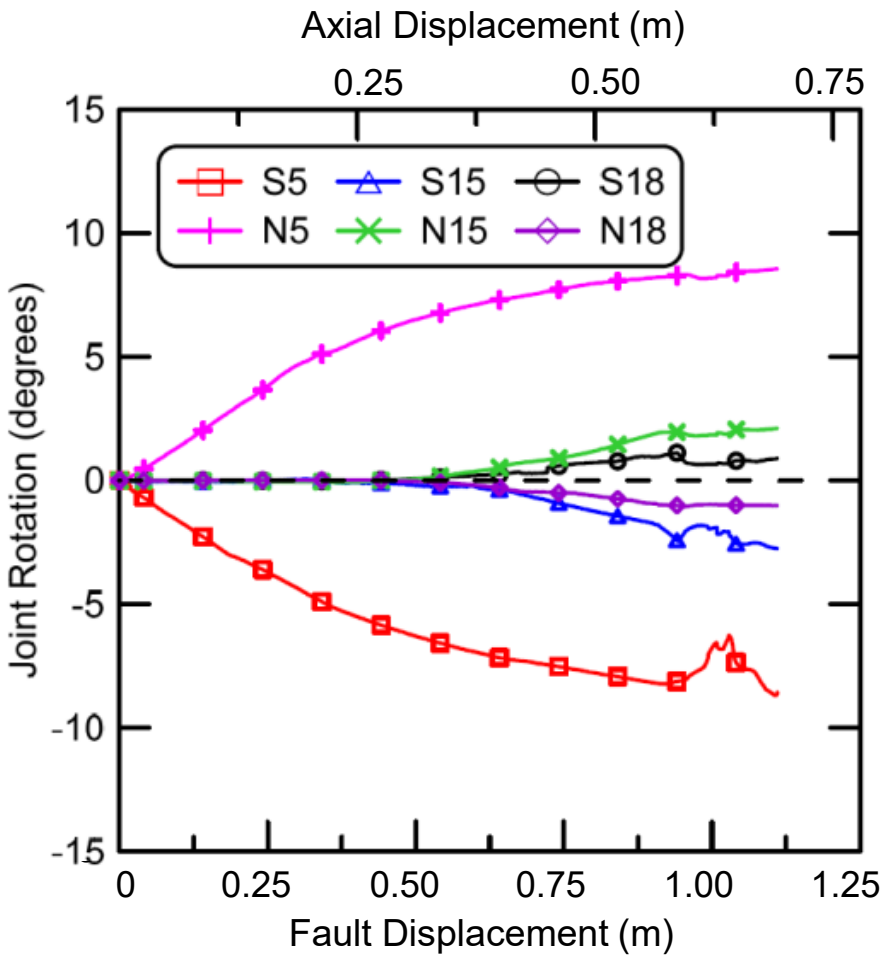
Specimens after the test

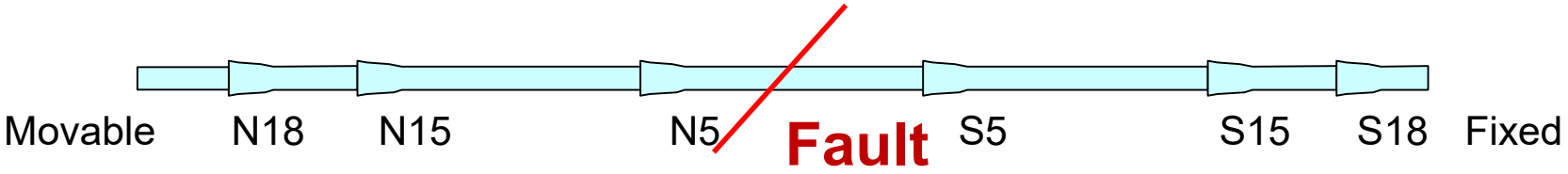
- No leakage immediately occurred even though the fault displacement exceeded 1.1m.
- When the fault displacement was 1.13m, the end of the spigot of joint S5 passed the rubber gasket and leakage occurred.

Leakage from joint S5

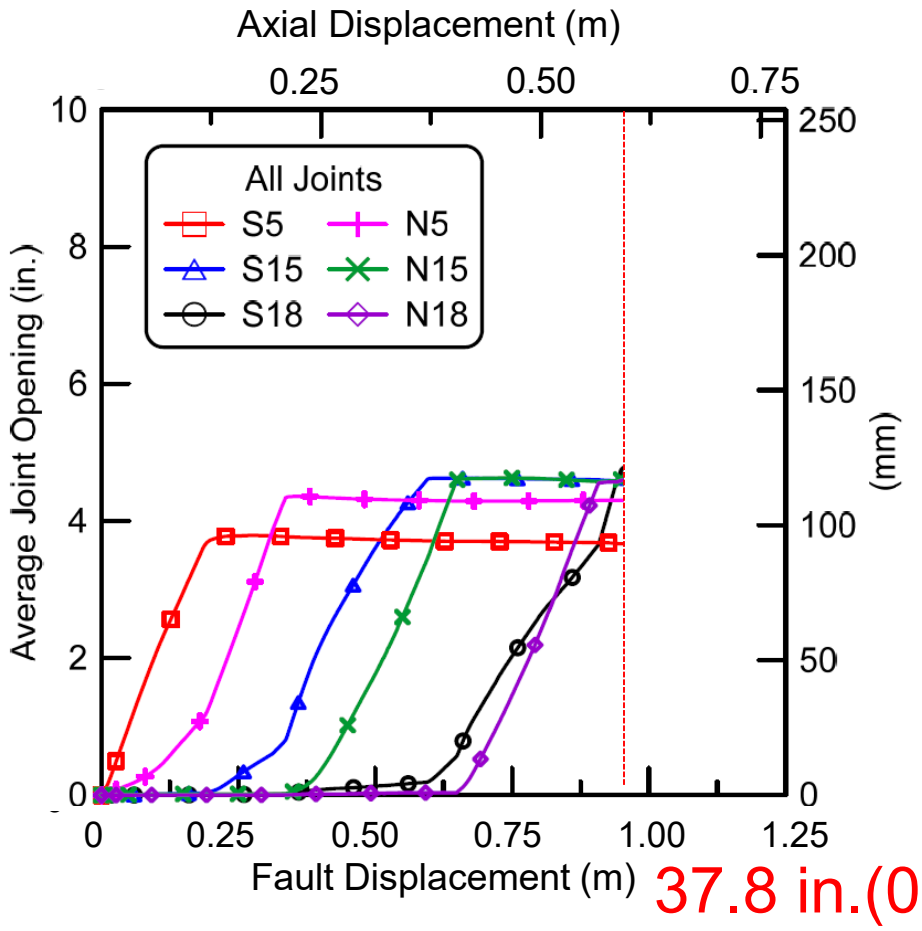
Each joints are deflected and ERDIP pipeline absorb the fault displacement.

Test result of joint deflection angle

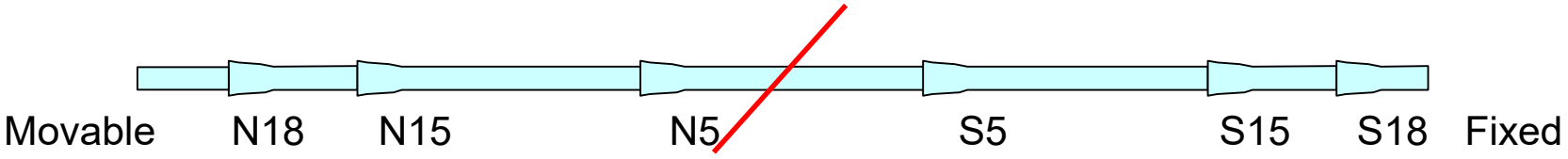




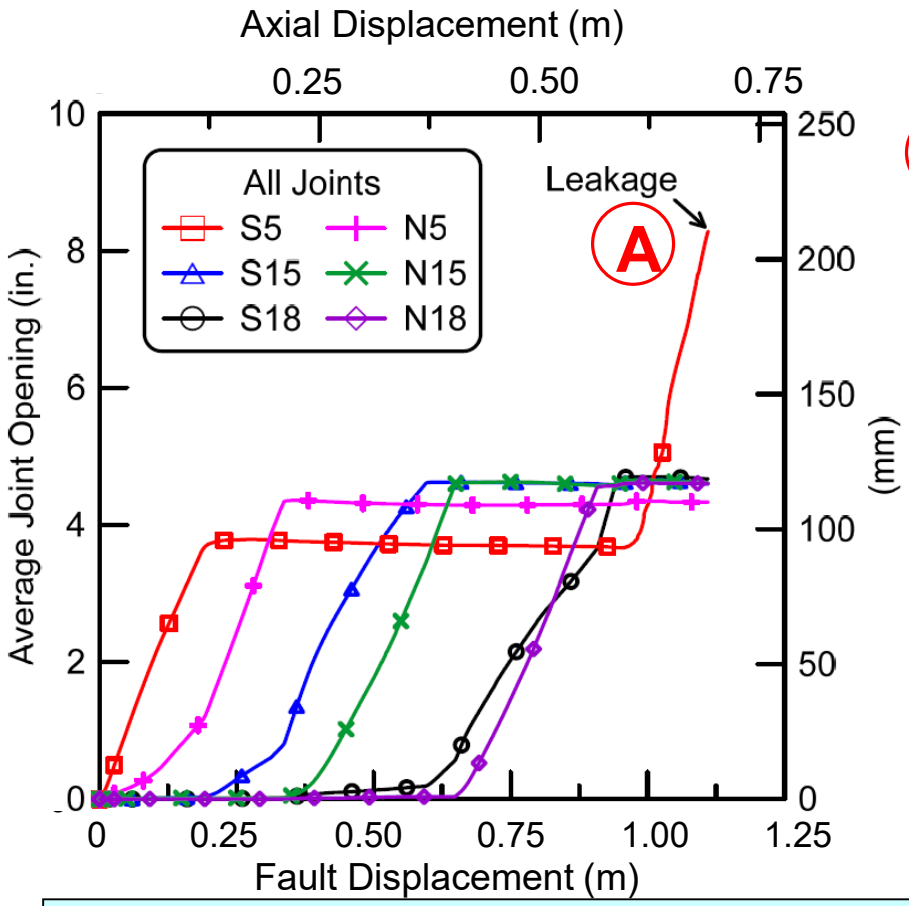
Test result of joint opening

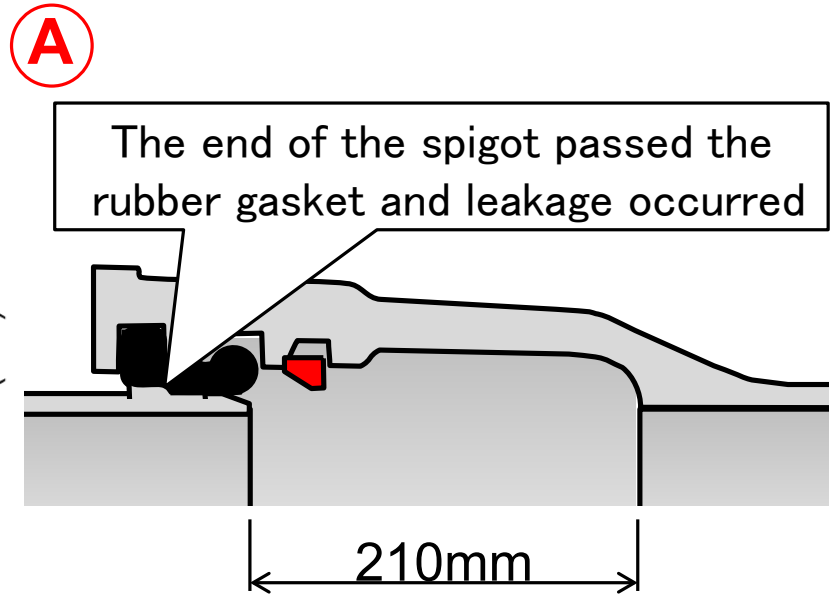


37.8 in.(0.96m)



Test result of joint opening





When the fault displacement was 1.13 m, the amount of extension of joint S5 reached 210 mm.
At this time, the end of the spigot passed the rubber gasket and leakage occurred.

Pipeline behavior exceeding performance limit

Deflection of the joint

No leakage occurred until the joint deflection reached 12.2° (which is approximately 1.5 times larger than the maximum joint deflection i.e., 8°)

Extension of the joint

No leakage occurred until the joint extension reached 210mm (which is approximately twice larger than the limit performance)

Conclusion

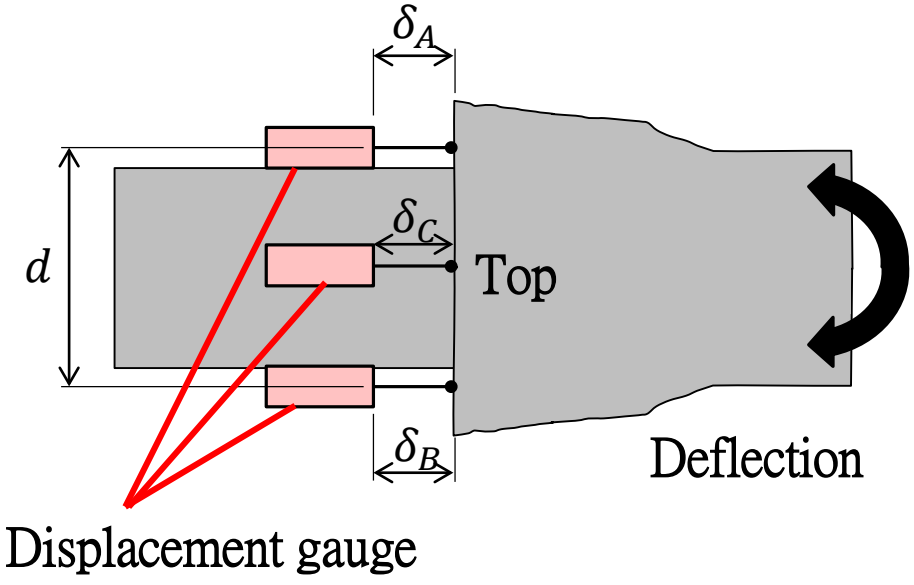
- The ERDIP pipeline could absorb large fault displacement well and no leakage occurred when the joint deflected and extended to a large extent.
- It was not until the joint deflection reached 12.2° which is approximately 1.5 times larger than the maximum joint deflection i.e., 8° that no leakage was visually observed.
- It was not until the joint extension reached 210mm which is approximately twice larger than the limit performance that no leakage was visually observed.

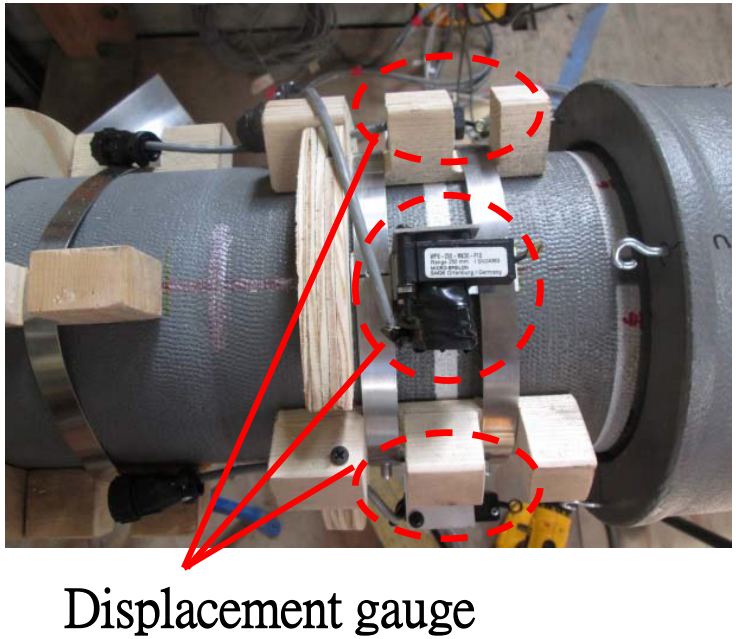
Pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage

Thank you for your attention.

$$Joint\ opening = \frac{(\delta_A + \delta_B + \delta_C)}{3}$$

$$Deflection\ angle = tan^{-1}\frac{(\delta_A - \delta_B)}{d}$$



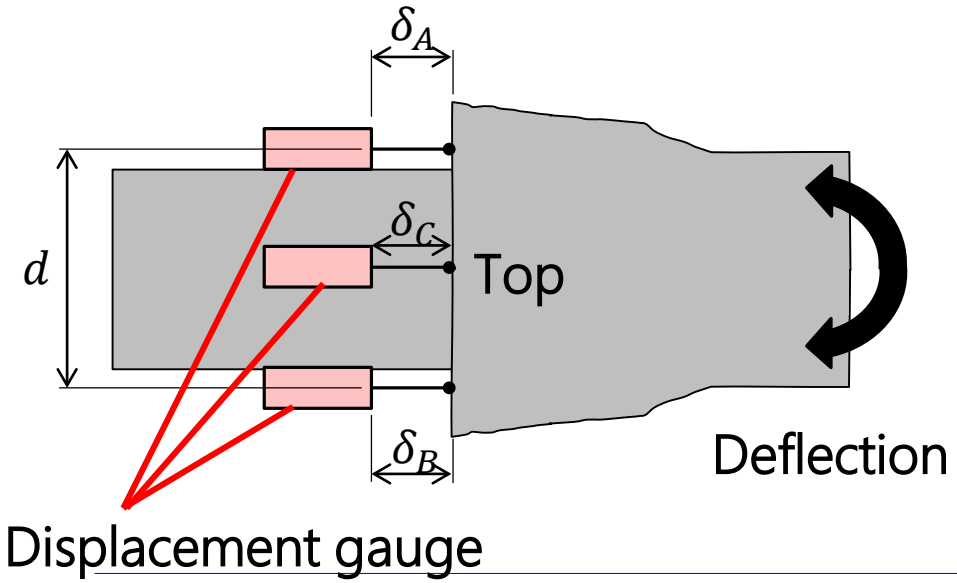


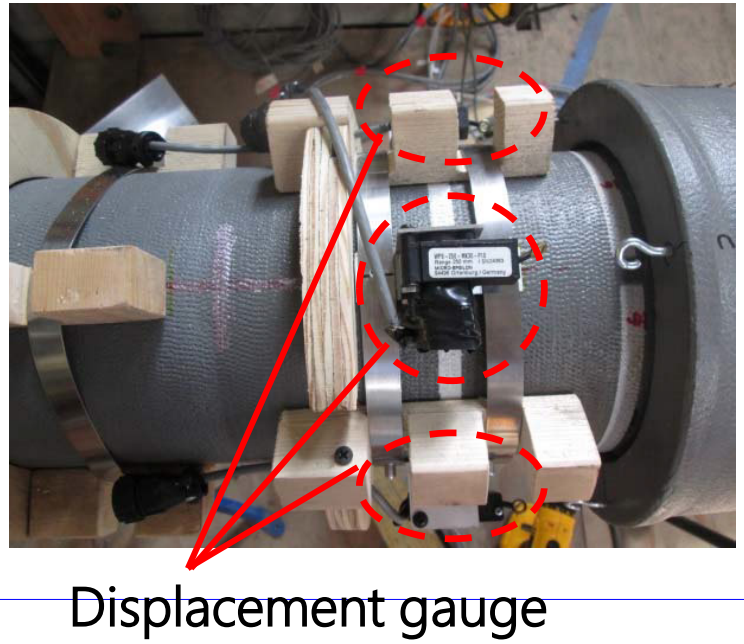
断層実験方法　②測定項目・方法

各継手に取り付けた3個の変位計により、
継手伸縮量および継手屈曲角度を計測した。

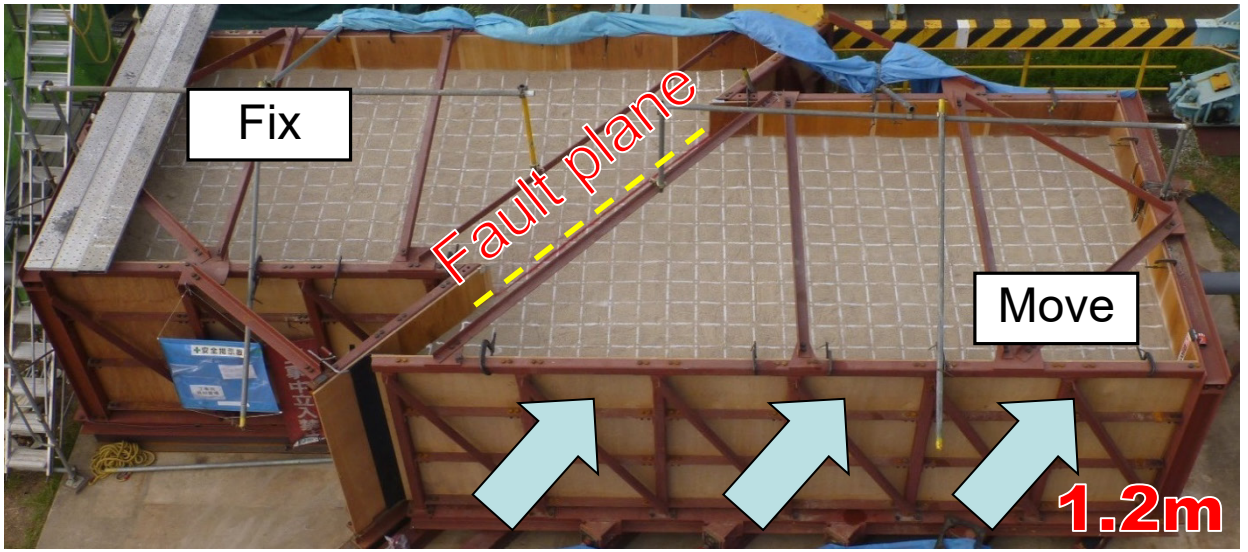
$$Joint\ opening = \frac{(\delta_A + \delta_B + \delta_C)}{3}$$

$$Deflection\ angle = tan^{-1}\frac{(\delta_A - \delta_B)}{d}$$

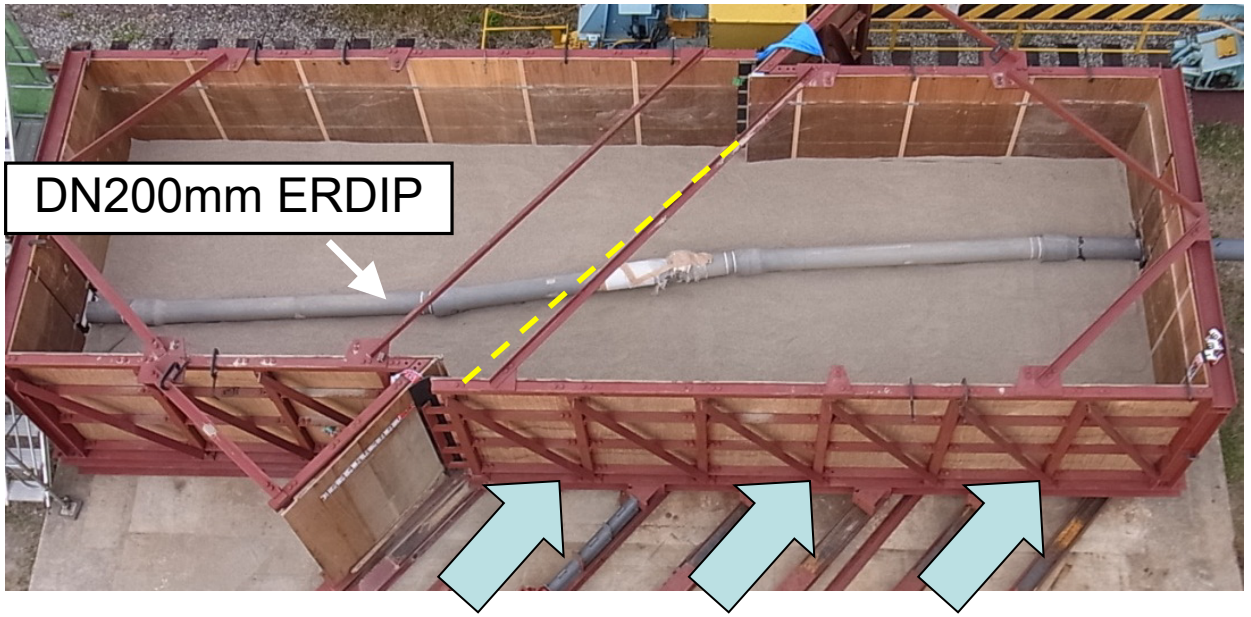




Large scale box experiment

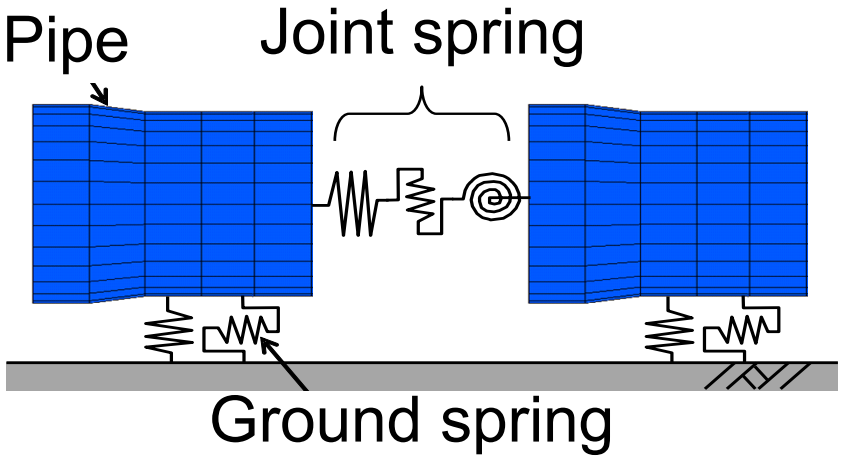


[Before]

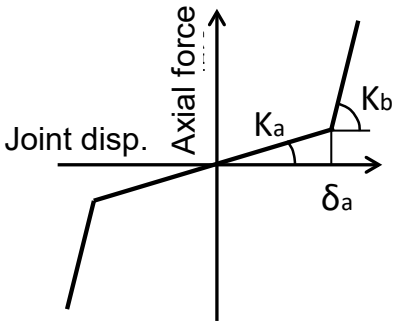
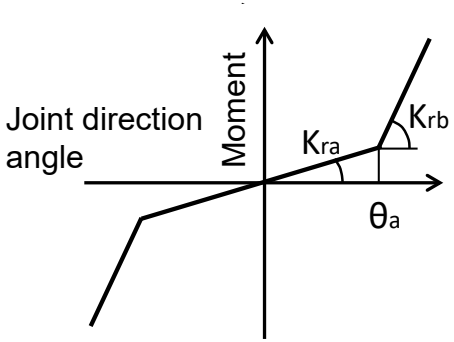
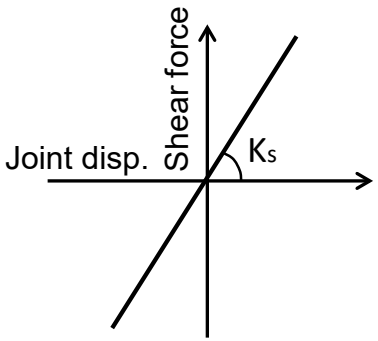


[After]

Analysis model



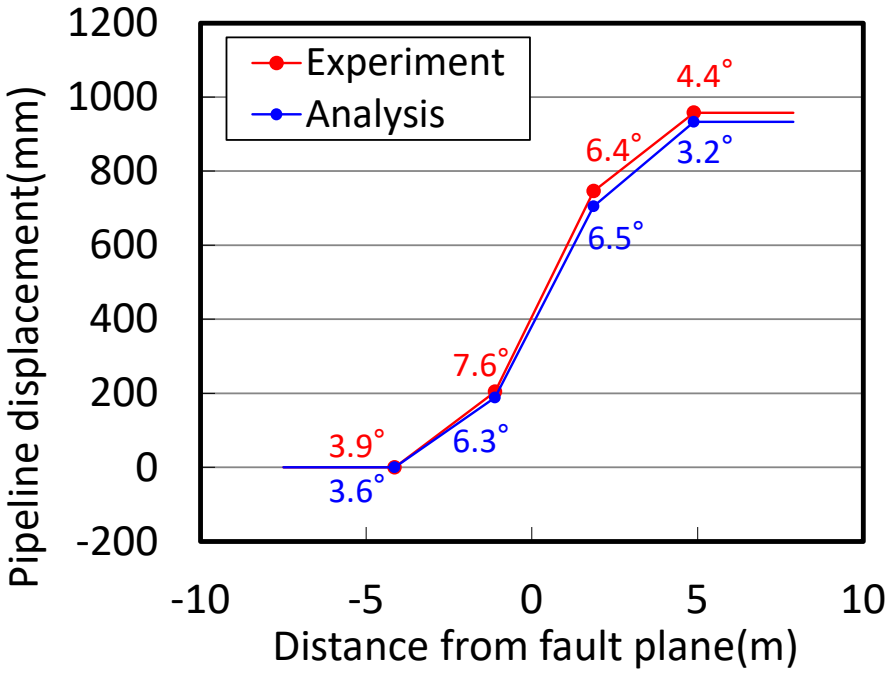
Basic test for rotation spring

Joint spring	Axial direction spring		Rotation spring		Orthogonal direction spring	
						
	K_a	9.20×10^3 (kN/m)	K_{ra}	1.66×10^2(kN · m/deg)	K_s	2.0×10^6 (kN/m)
	K_b	1.98×10^6 (kN/m)	K_{rb}	4.28×10^2(kN · m/deg)		
	δ_a	±0.0475 (m)	θ_a	3.2 (deg)		

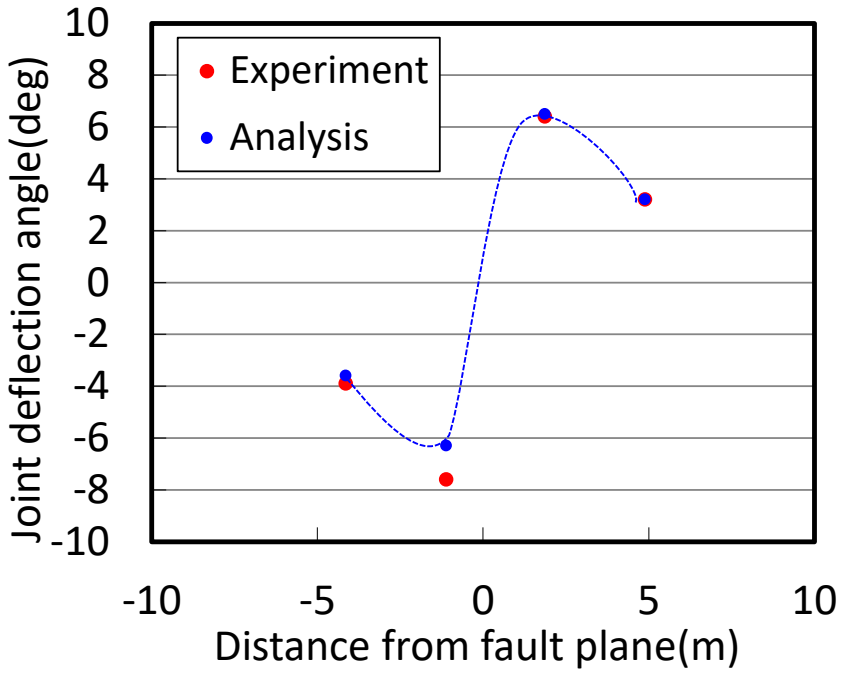
Result comparison

- FEM analysis results were similar to the experiment results.
- FEM analysis can be used for safety assessment of fault crossing pipeline.

Pipeline displacement



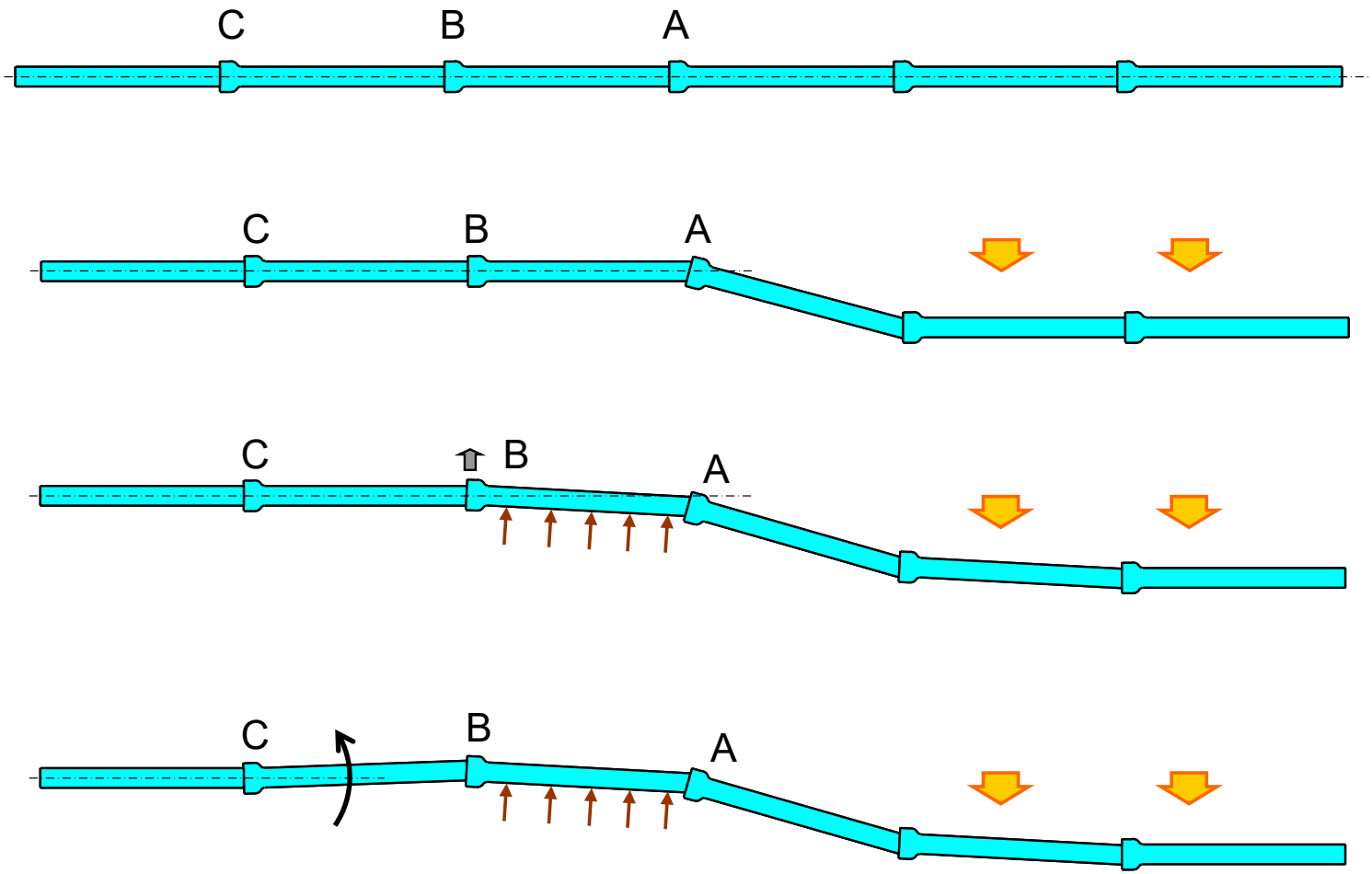
Joint deflection angle



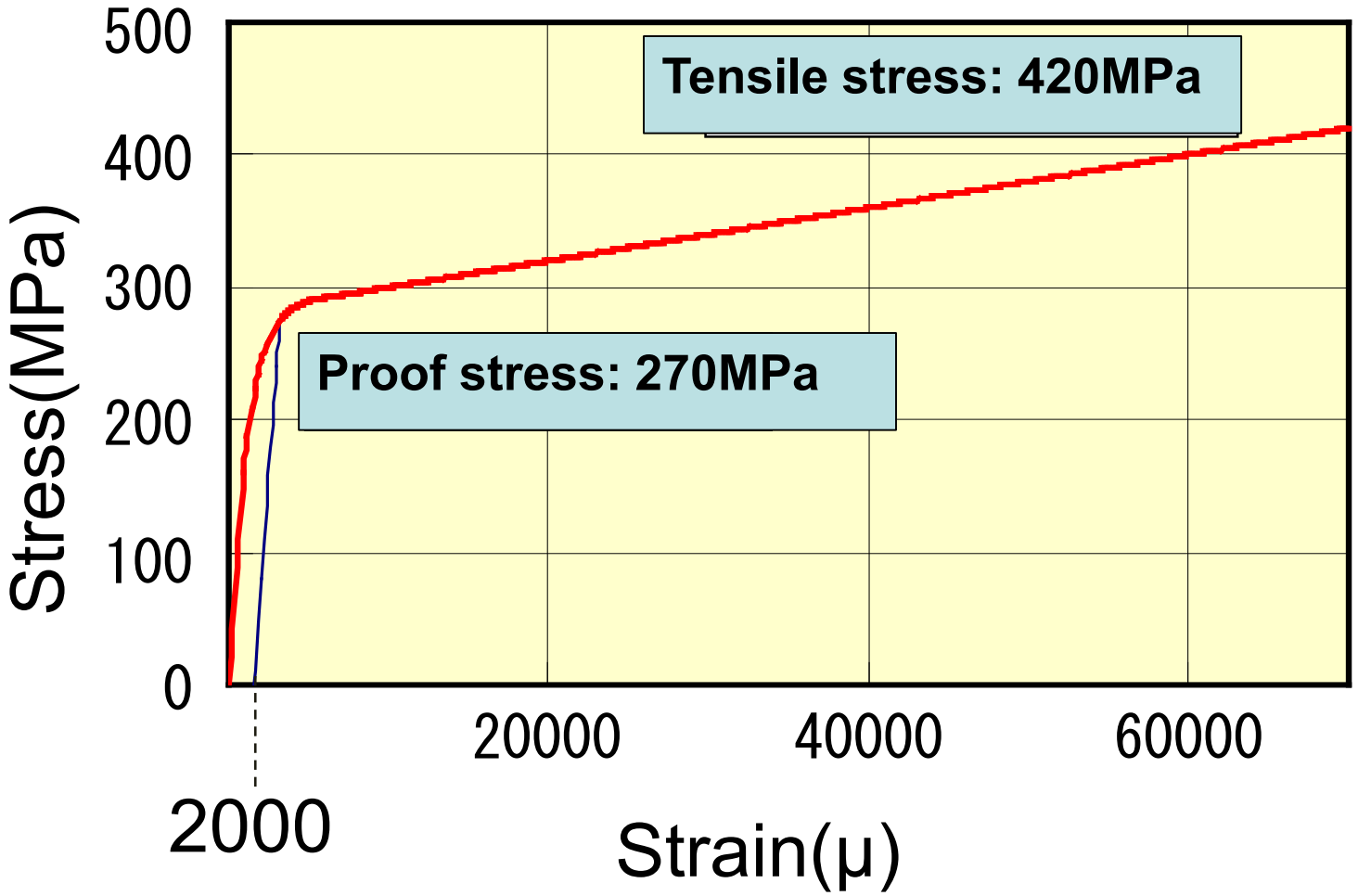
Study of reverse fault

Study of reverse fault

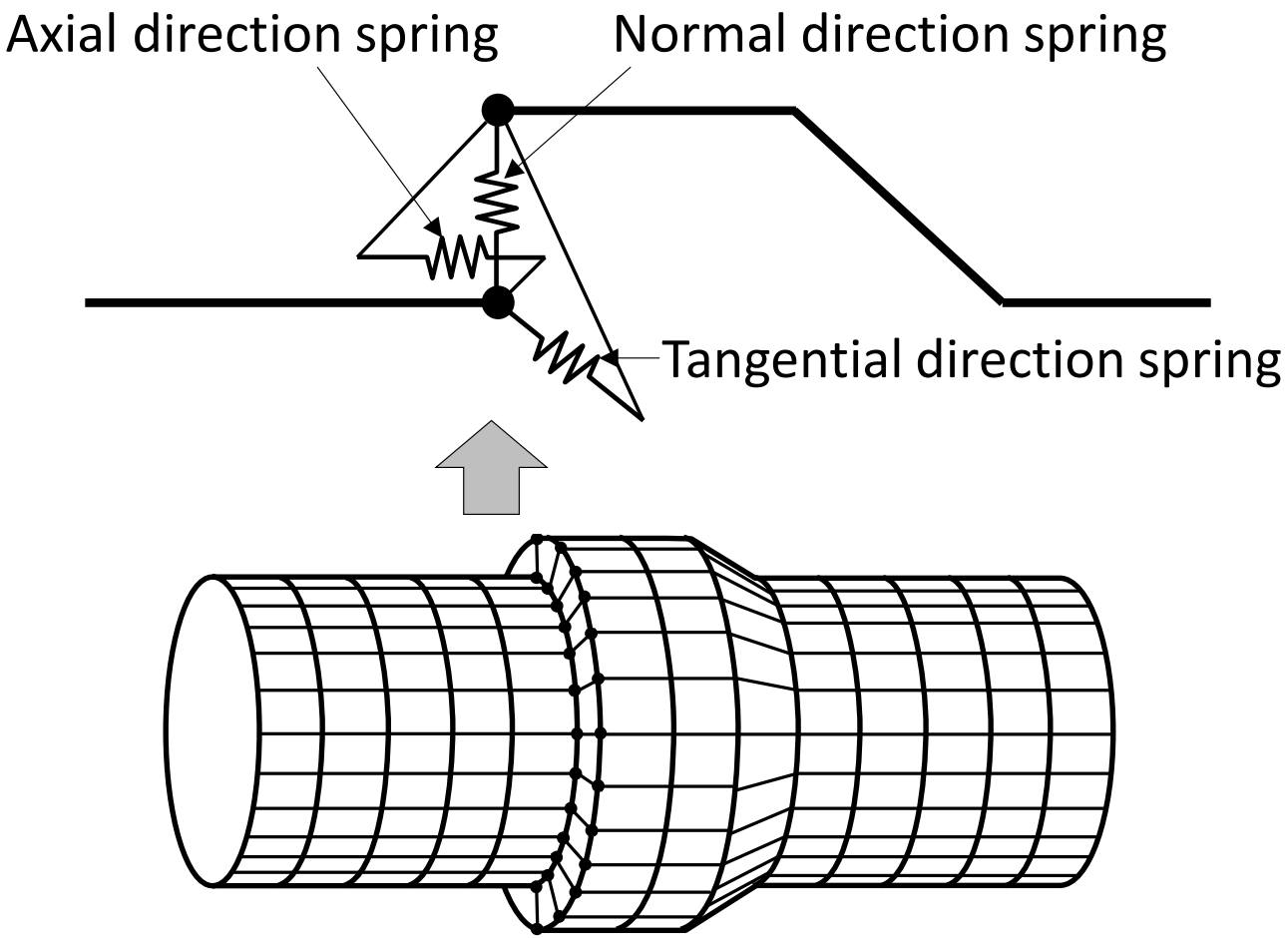
Pipeline movement



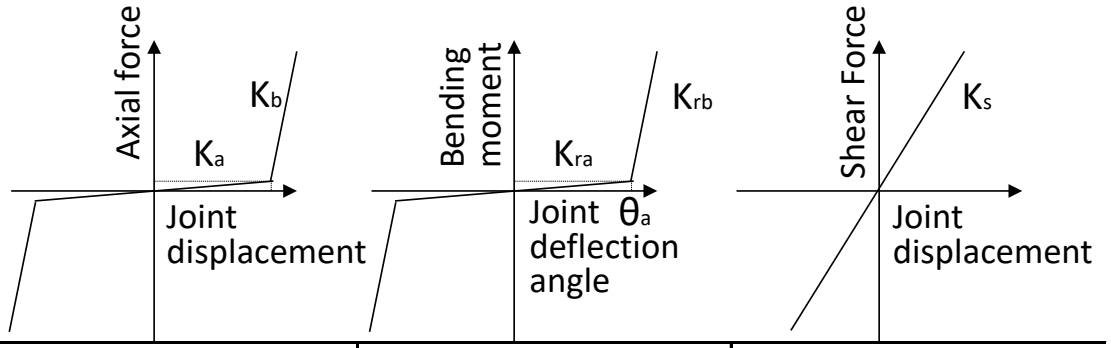
Property of ductile cast iron



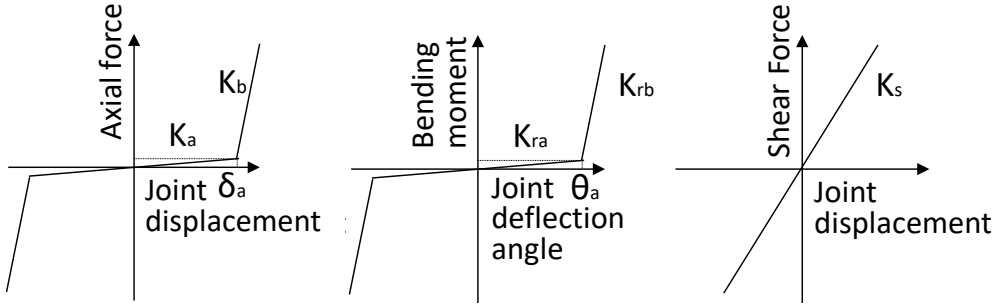
Joint spring for shell element



Spring of unit

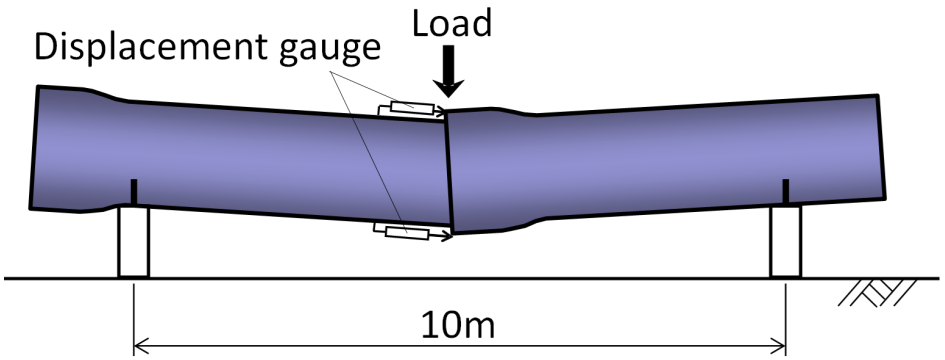


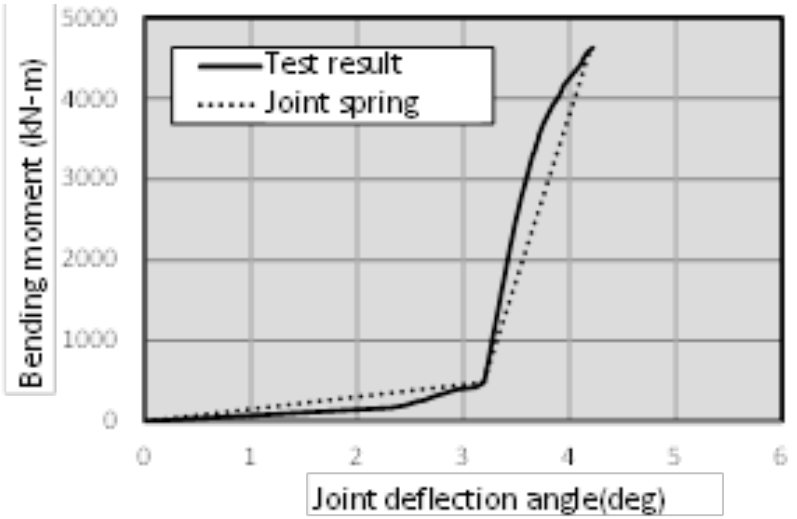
Axial direction spring		Rotation spring		Orthogonal direction spring	
K_a	9.20×10^3(kN/m)	K_{ra}	1.66×10^2(kN-m/deg)	K_s	2.0×10^6(kN/m)
K_b	1.98×10^6(kN/m)	K_{rb}	4.28×10^2(kN-m/deg)		
δ_a	-0.3(m)	θ_a	0.5(deg)		



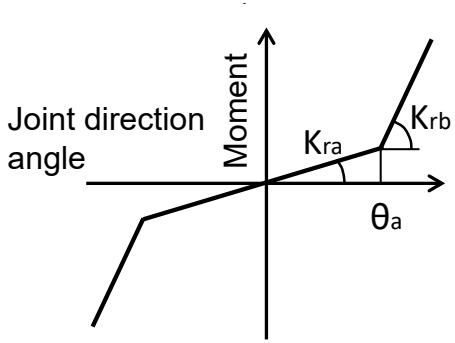
Axial direction spring		Rotation spring		Orthogonal direction spring	
K_a	9.20×10^3(kN/m)	K_{ra}	1.66×10^2(kN-m/deg)	K_s	2.0×10^6(kN/m)
K_b	1.98×10^6(kN/m)	K_{rb}	4.28×10^2(kN-m/deg)		
δ_a	±0.0475(m)	θ_a	3.2(deg)		

Example of a basic test





Rotation spring

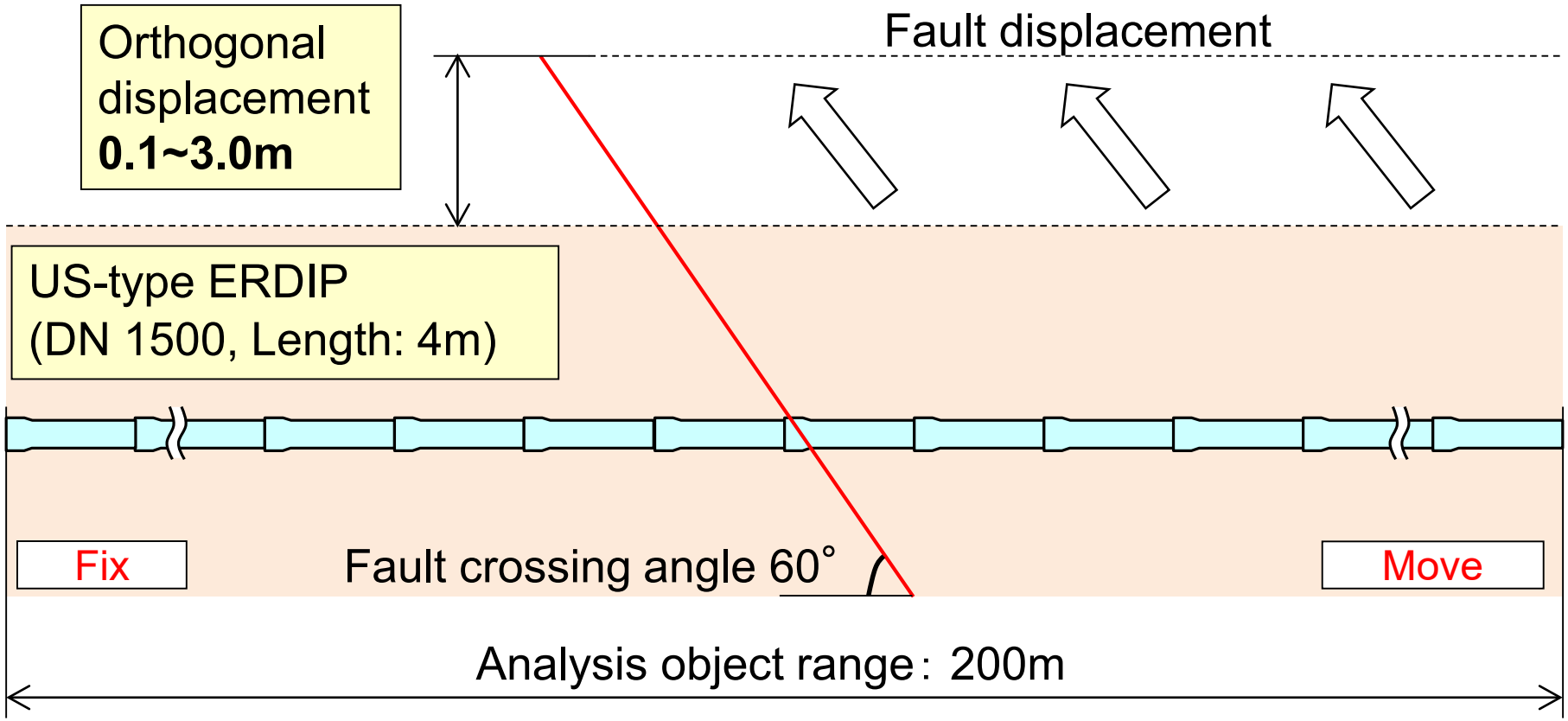


K_{ra}	1.66 ×10²(kN・ m /deg)
K_{rb}	4.28 ×10²(kN・ m /deg)
θ_a	3.2 (deg)

Design of fault crossing ERDIP

(Example：DN1500mm US-type ERDIP)

Analysis conditions



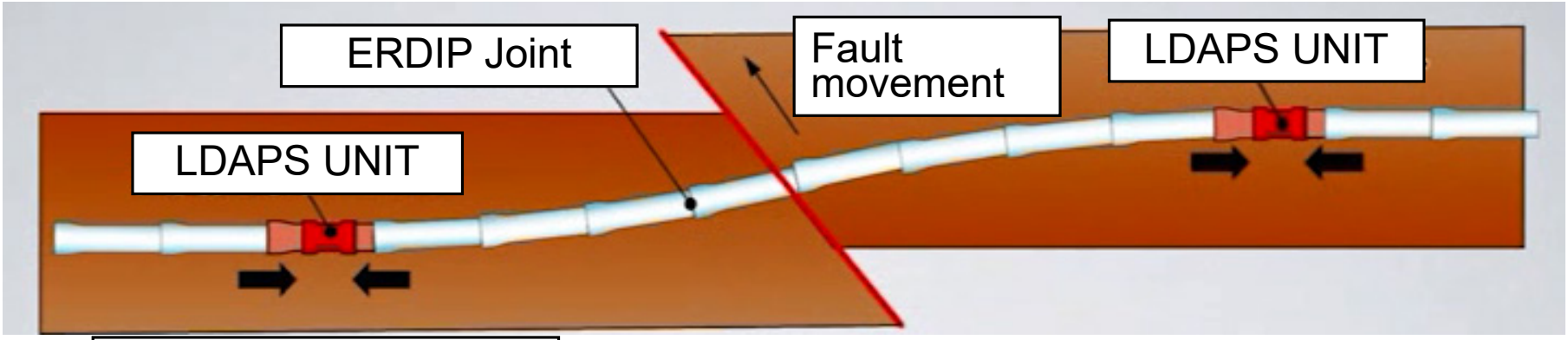
Analysis result

Fault displacement (m)	Axial force (kN)	Stress (MPa)	Joint deflection (deg)
1.0	2,212	25	3.1
1.6	4,314	49	3.7
2.0	5,760	67	4.0
3.0	9,460	111	4.6
Limit value	4,500	270 (Elastic limit)	4.0

Accommodate about 1.6m displacement
(The stress within elastic limit)

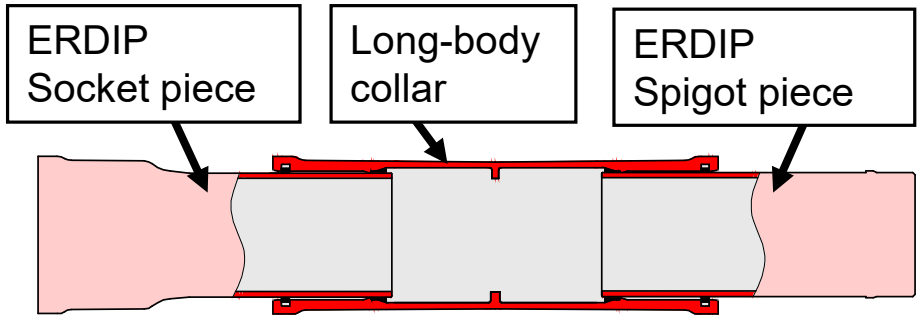
LDAPS（Large Displacement Absorption Pipeline System）

LDAPS･･･ERDIP with multiple LDAPS UNIT



Unit absorbs large fault displacement

Construction of LDAPS UNIT

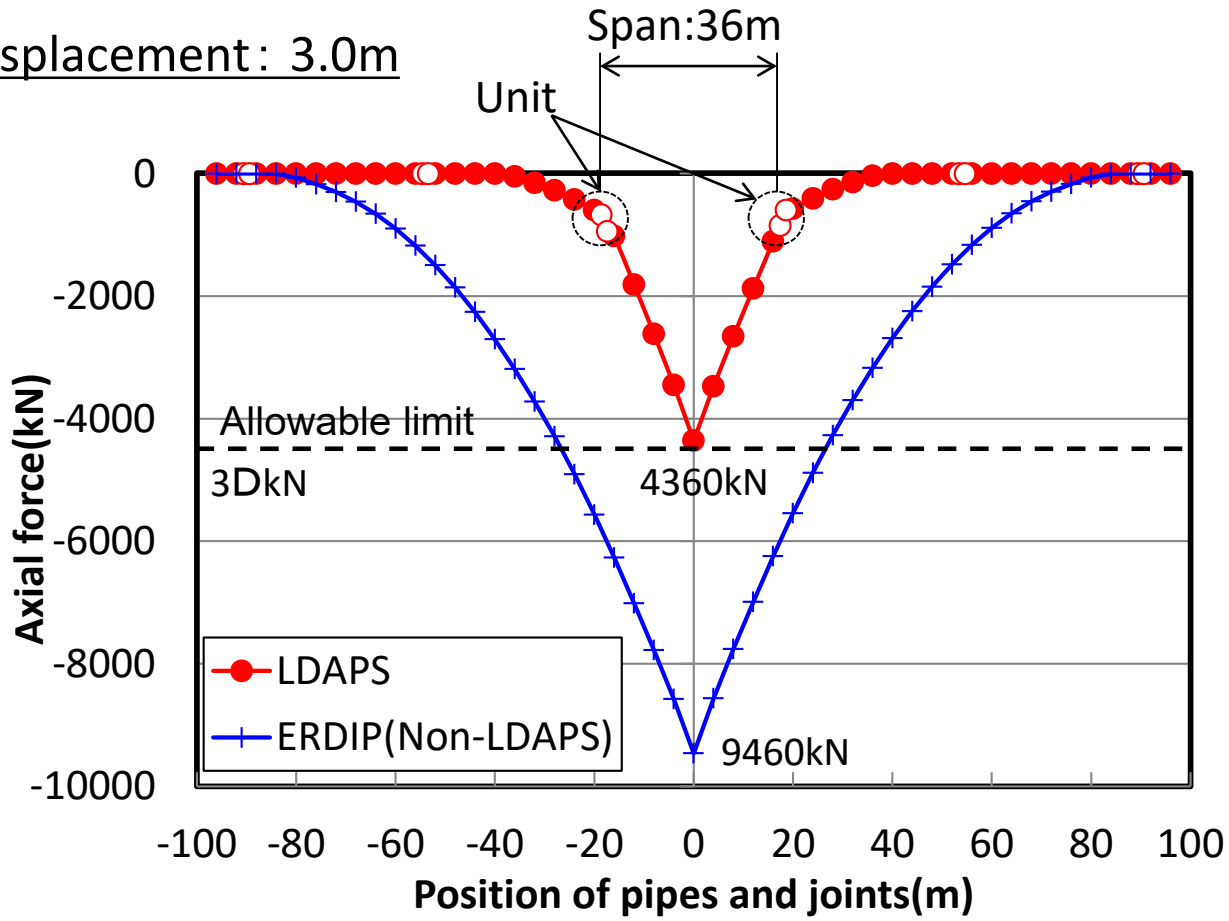


Amount of extension/contraction

Straight pipe socket (mm)	Long-body collar (mm)
±30	±300

Analysis result(1/2) [Axial force]

Fault displacement： 3.0m

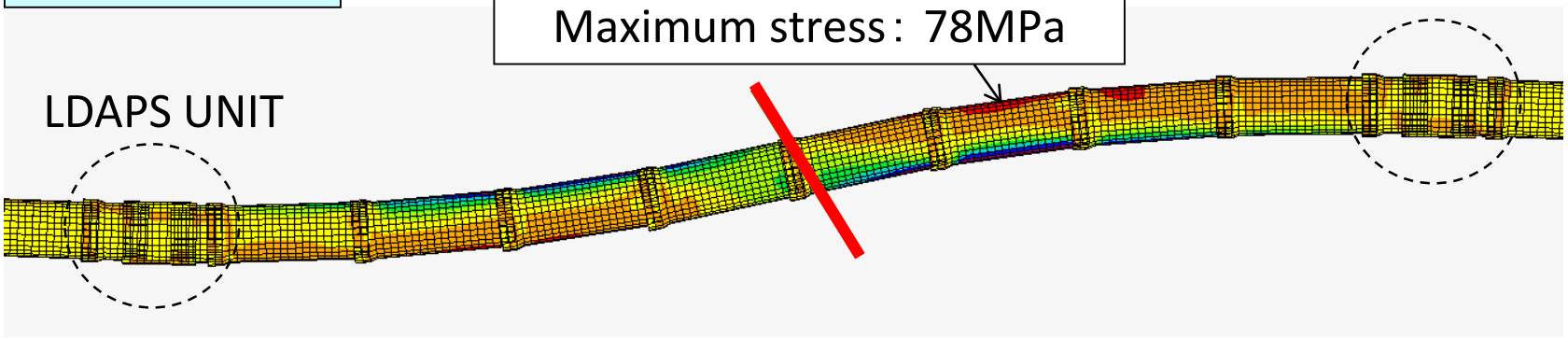


Axial force of LDAPS less than 3DkN（4,500kN）

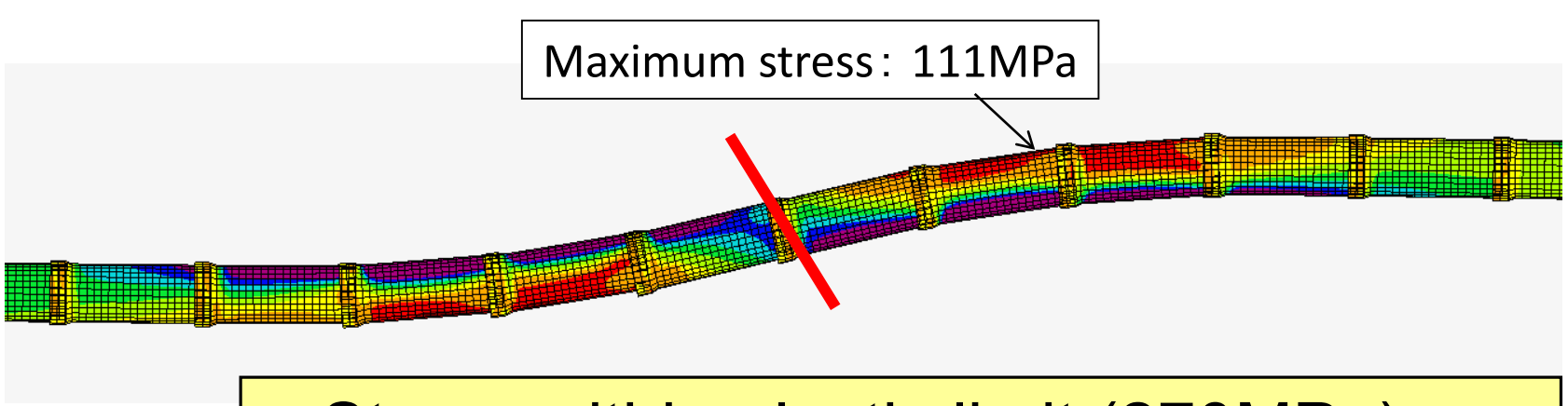
Analysis result(2/2) [Tensile stress]

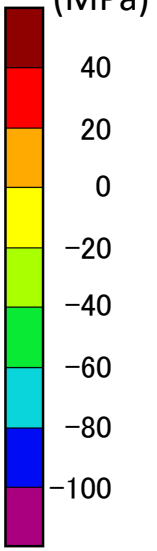
Fault displacement : 3.0m

LDAPS



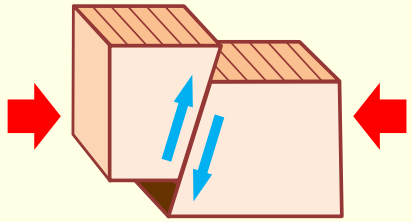
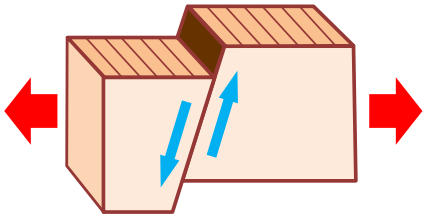
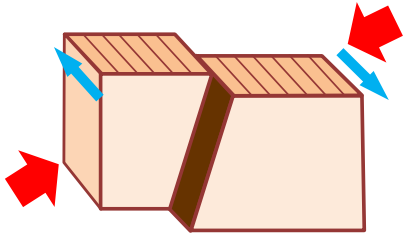
ERDIP (Non-LDAPS)



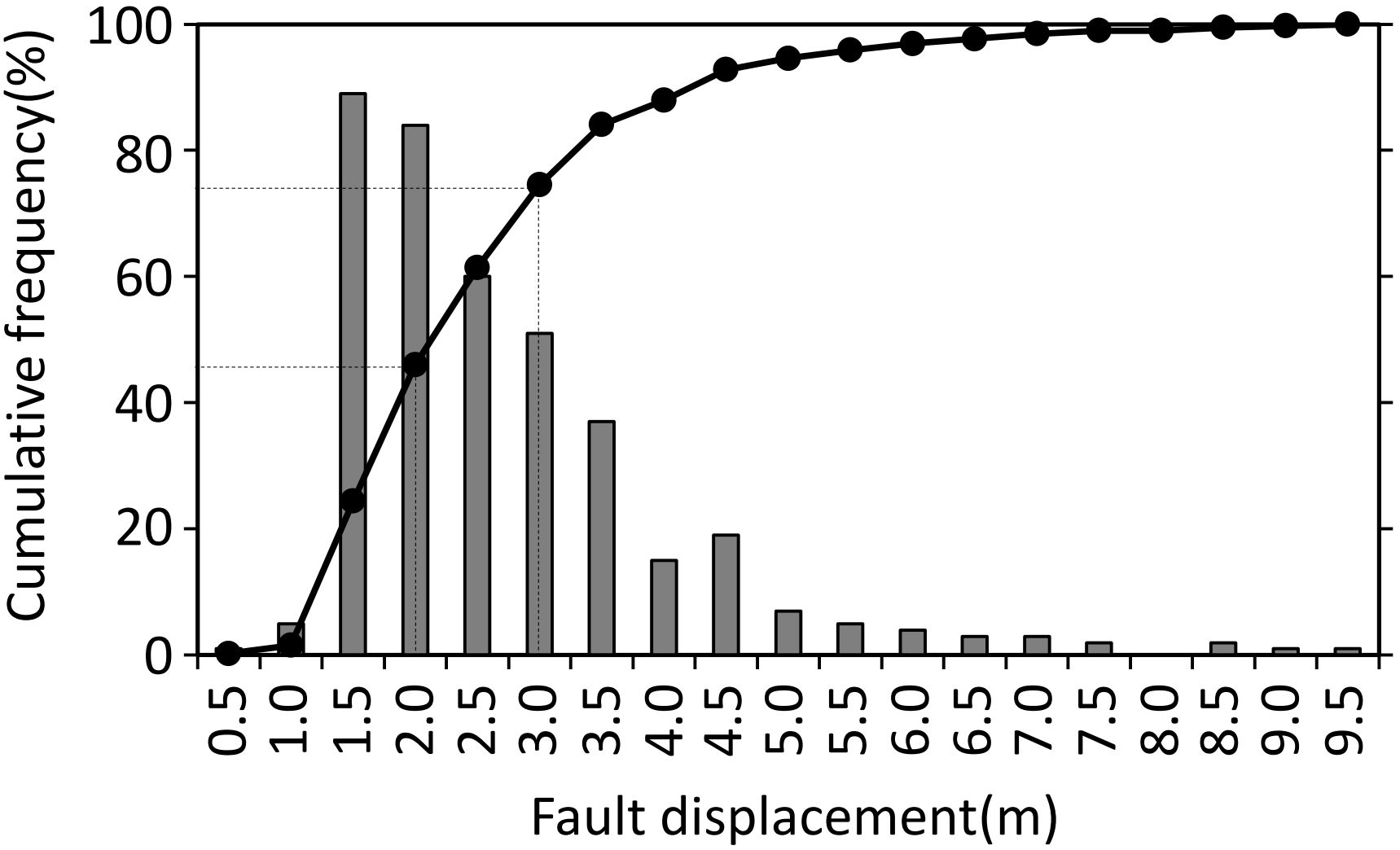


Stress within elastic limit (270MPa)

Fault type in Japan

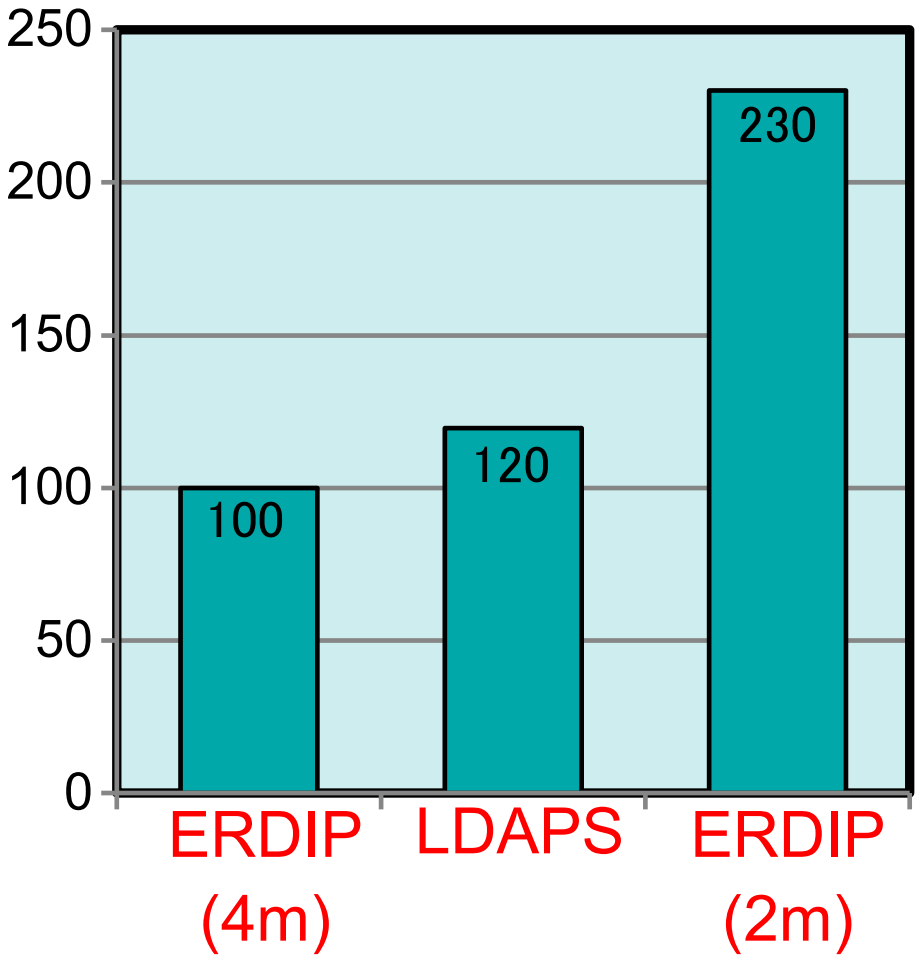
Type	Reverse fault	Normal fault	Strike-slip fault
			
Number	196	28	165

Fault in Japan



Cost effective

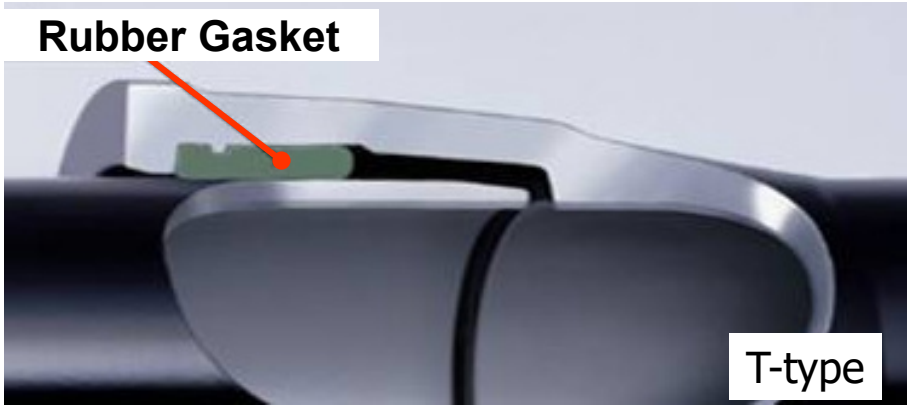
DN1500 US-type joint , pipeline length: 200m



Comparison of Joint Structure

General (Push-on) Joint

(Flexible Joint)

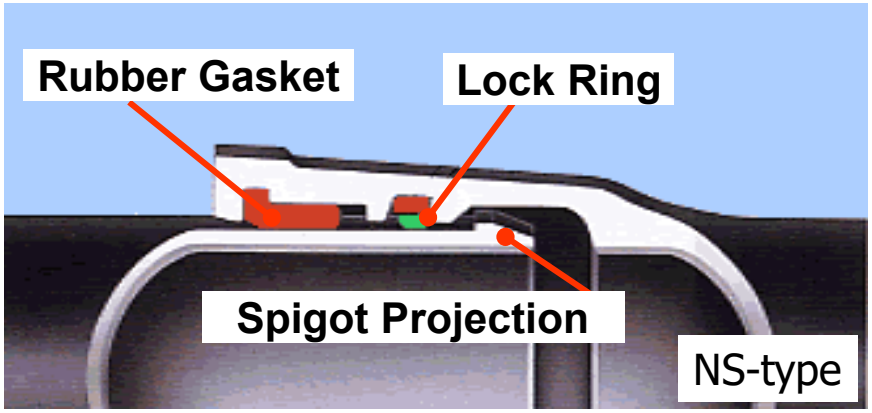


Expand

Deflect

Earthquake Resistant Joint

(Chain structure Joint)



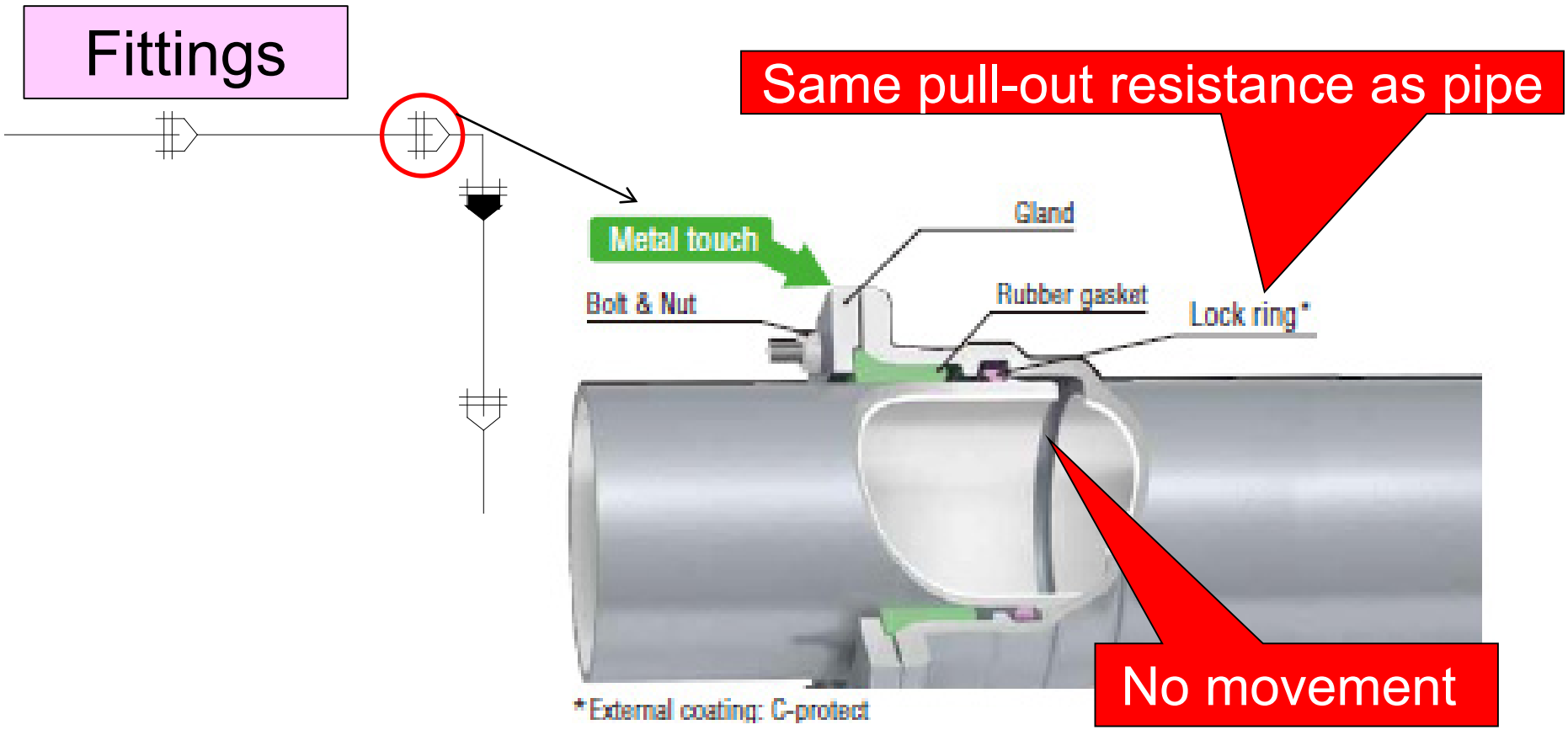
Expand / Contract

Deflect

Lock

Fittings joint of ERDIP

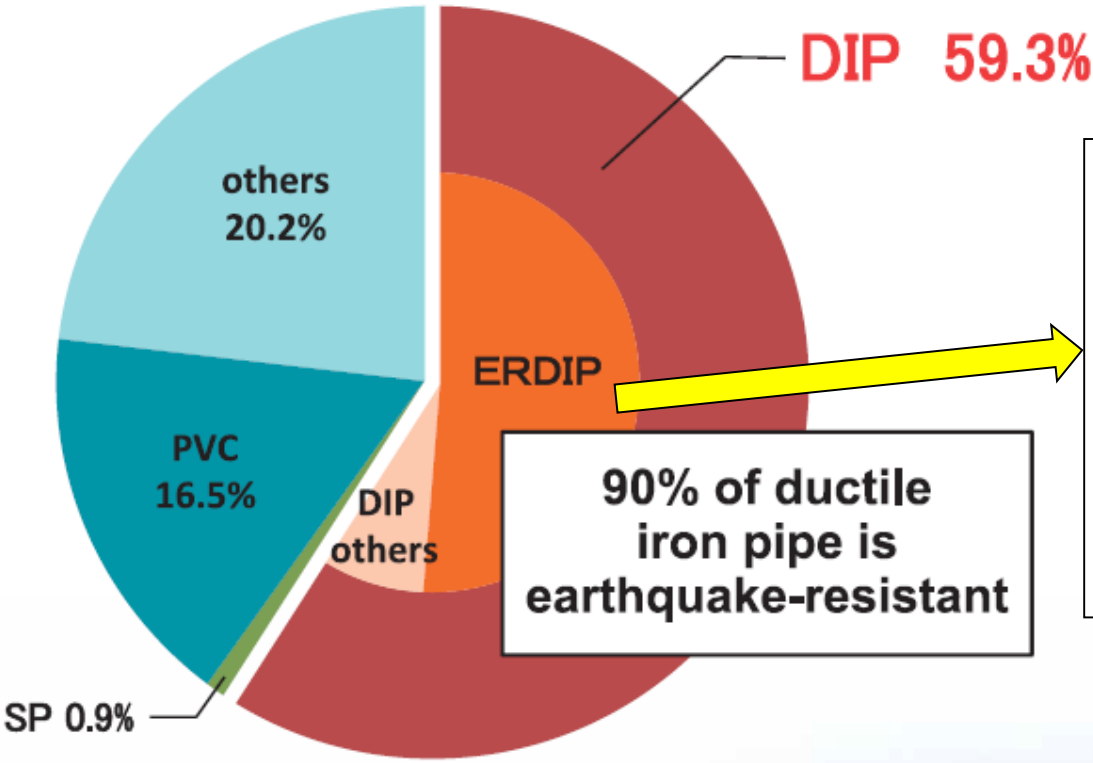
Fittings

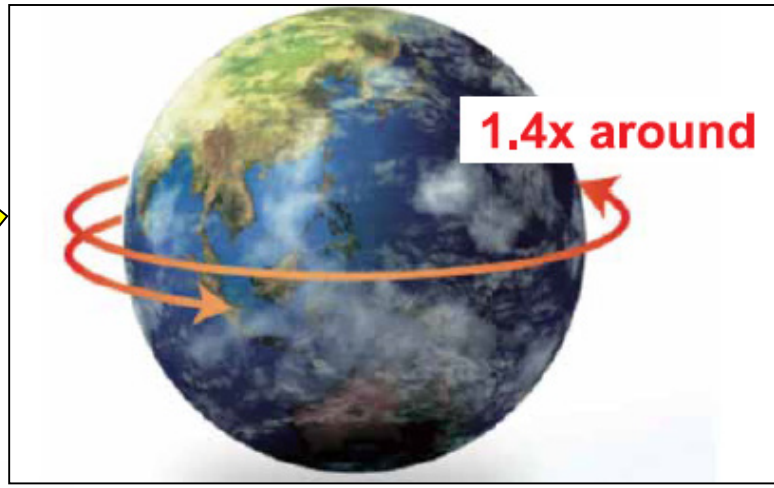


Fitting is provided with restrained joint.

Water pipeline in Japan

Materials used in Pipeline Construction in 2013





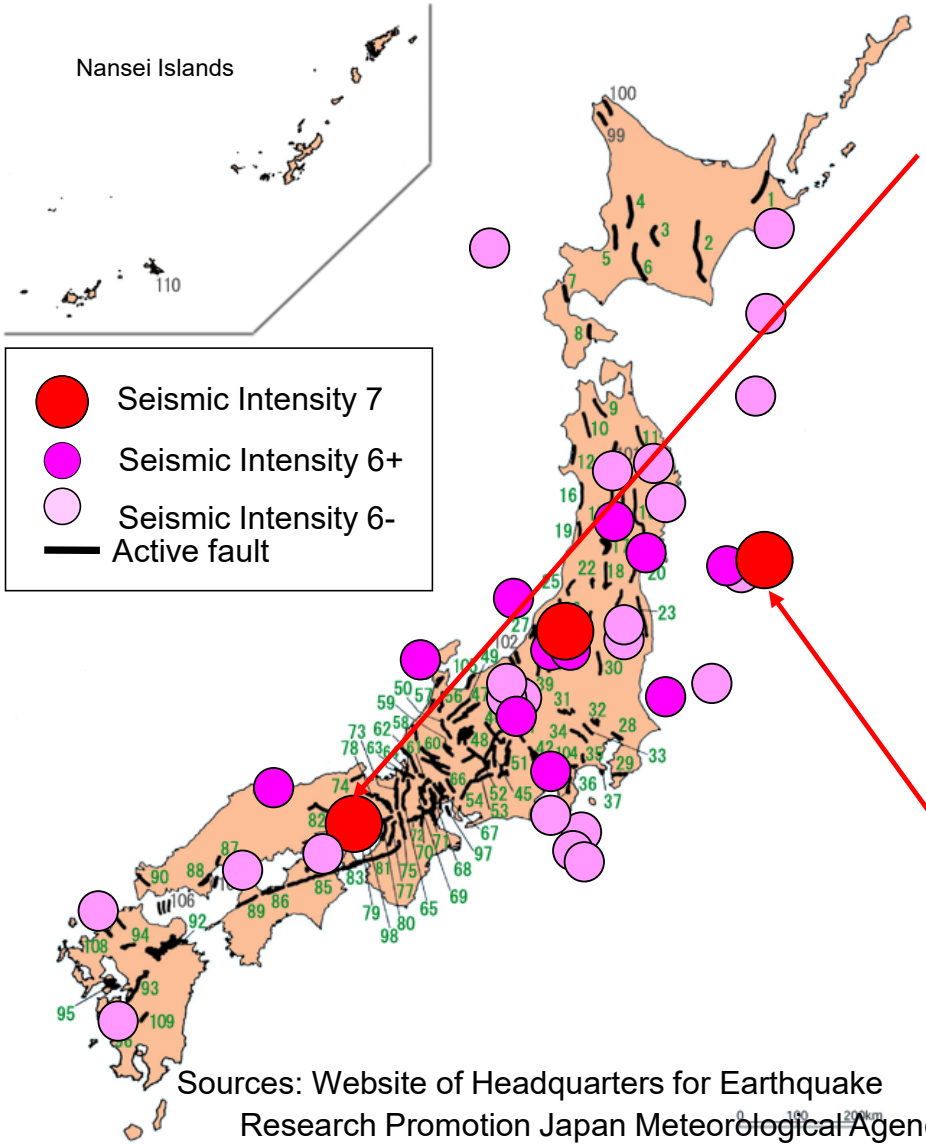
Total: approx. 8,000 miles

35,000 miles (~1.4 around the earth)

of ERDIP installed as of FY2013

Source: Japan Water Works Association (JWWA)

Major Earthquakes after the 1995 Kobe Earthquake



Name	Date	Depth of epicenter	Mg	Max. intensity
1995 the Kobe Earthquake	January 17, 1995	14km	7.3	7
2000 Tottori-ken Seibu Earthquake	October 6, 2000	9km	7.3	6+
(2003 mid Miyagi)	July 26,2003	12km	6.4	6+
2004 the Mid Niigata Prefecture Earthquake	October 23, 2004	13km	6.8	7
(2004 mid Niigata)	October 23,2004	12km	6.0	6+
(2004 mid Niigata)	October 23,2004	14km	6.5	6+
2007 Noto Hanto Earthquake	March 25, 2007	11km	6.9	6+
2007 Niigata Chuetsu-oki Earthquake	July 16, 2007	17km	6.8	6+
2008 Iwate-Miyagi Inland Earthquake	June 14, 2008	8km	7.2	6+
2011 the Great East Japan Earthquake	March 11, 2011	24km	9.0	7
(2011 Ibaraki-oki)	March 11,2011	43km	7.6	6+
(2011 north Nagano)	March 12,2011	8km	6.7	6+
(2011 east Shizuoka)	March 15,2011	14km	6.4	6+
(2011 Miyagi-oki)	April 7,2011	66km	7.2	6+

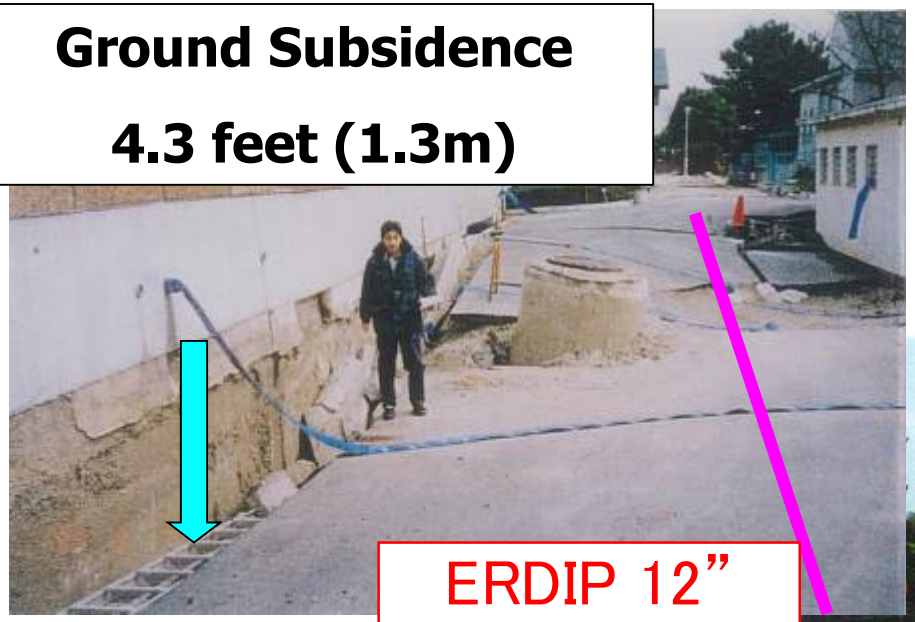
Sources: Website of Headquarters for Earthquake Research Promotion Japan Meteorological Agency

No damage on ERDIP (Large ground deformation)

1995 Kobe Earthquake

Ground Subsidence

4.3 feet (1.3m)



ERDIP 12”

(No damage)

2000 Tottori Earthquake

ERDIP 6”

(No damage)

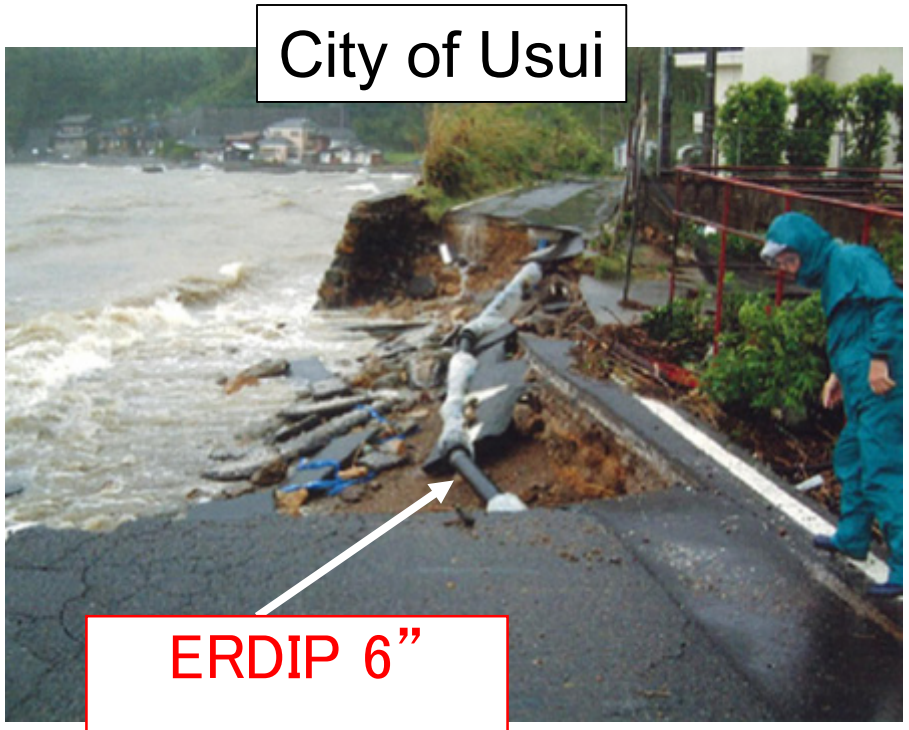
Liquefaction

No damage on 12” ERDIP (Scoured ground by Tsunami)

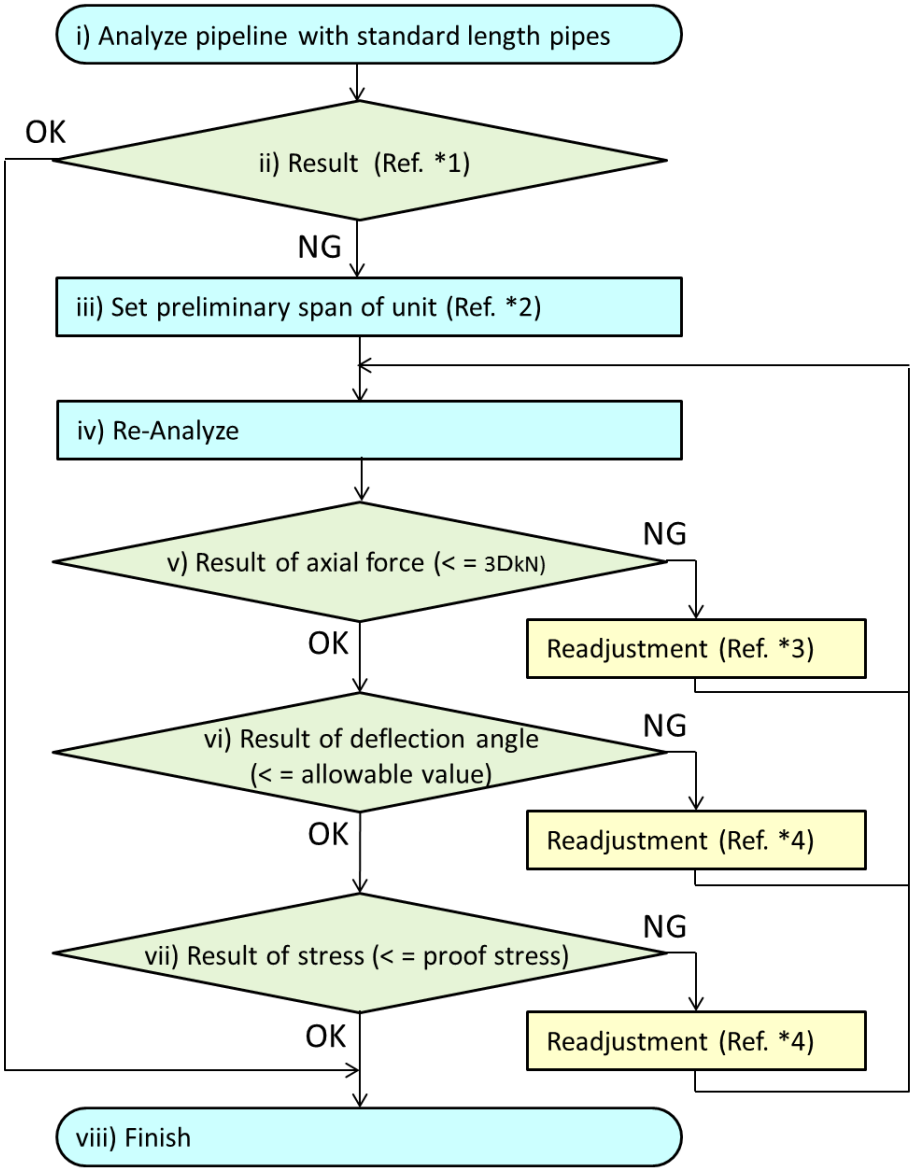
Tsunami at 2011 Great East Japan Earthquake

No damage on 16”(400mm) and 6”(150mm) ERDIP

Landslide caused by heavy rain / typhoon



Design flow



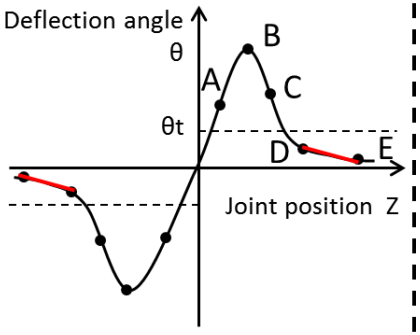
(*1)

Axial force: 3 DkN and under
Joint deflection angle : allowable deflection angle and under
Stress generated on pipe body: Proof stress (270MPa) and under

(*2)

Based on the result of i), set unit location where joint deflection angle is equal or less than threshold value [θt(=1°)]

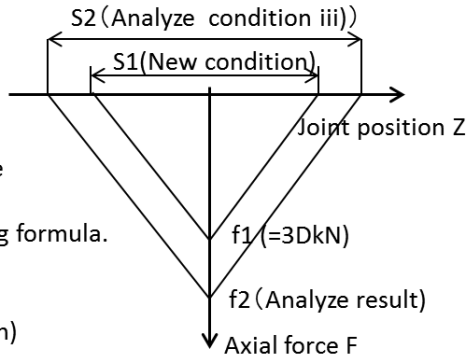
In case of right figure, set unit between D and E.



(*3)

Change span of unit.
S1 : S2 = f1 : f2
(S: span, f: axial force)

Based on the axial force result of iii), calculate S1 as following formula.
S1 < f1/f2 x S2
(S1 is round downed to multiples of pipe length)



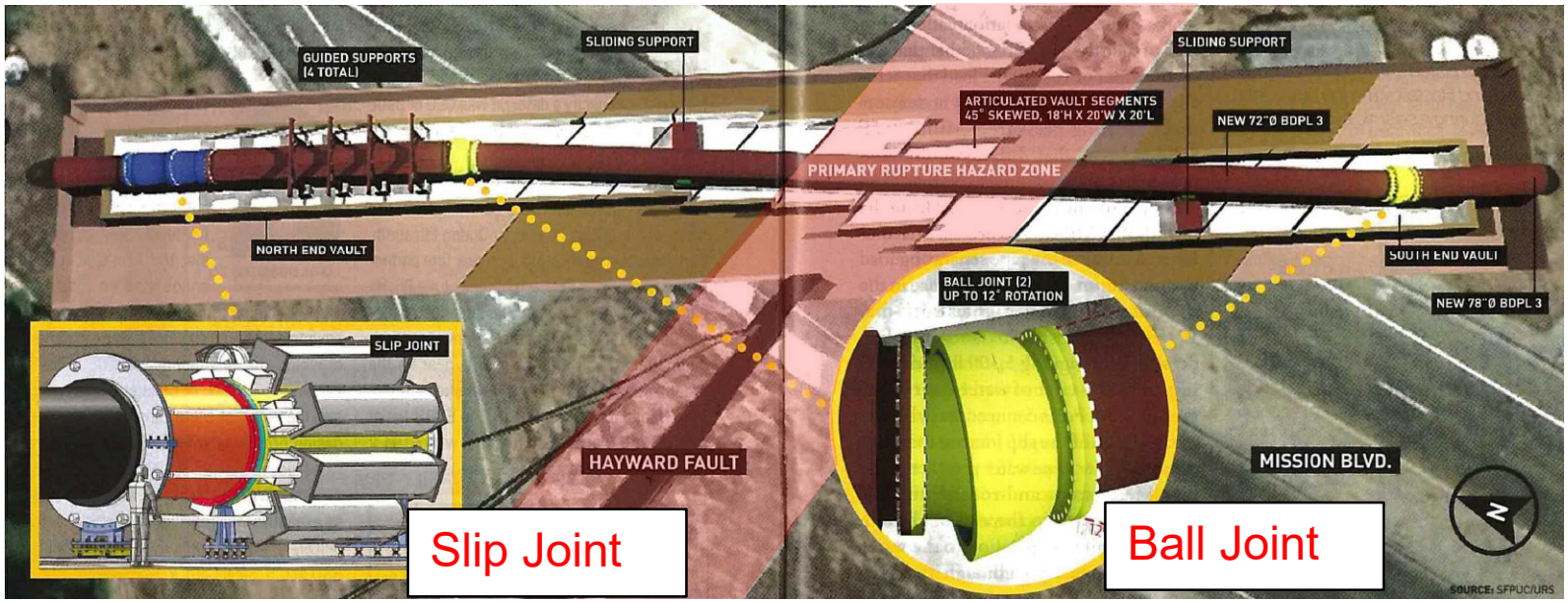
(*4)

(1) Shorten span of unit
(2) Shorten pipe length

Example of design of fault-crossing pipeline

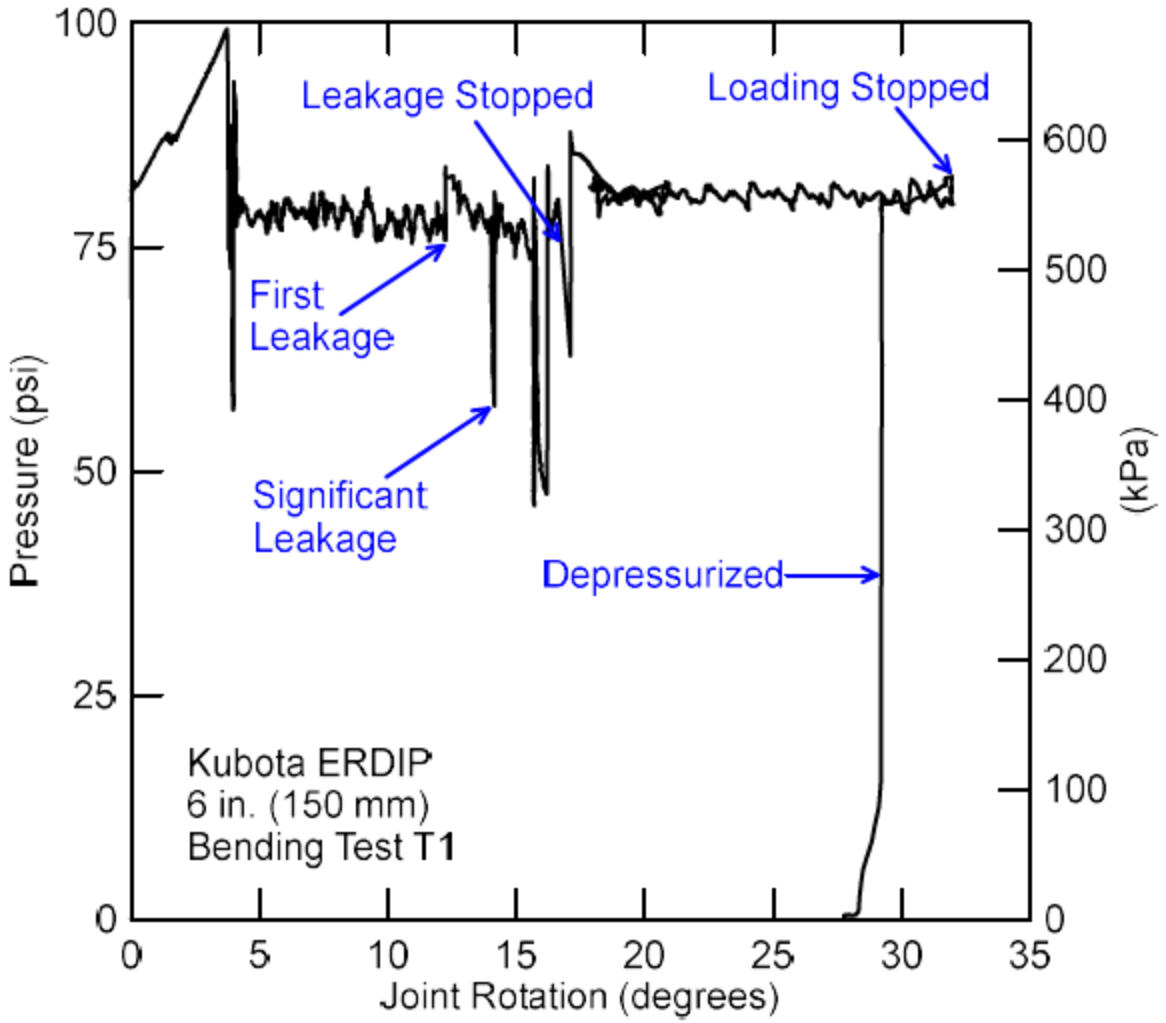
Denali earthquake, 2002, US

Example of design of fault-crossing pipeline

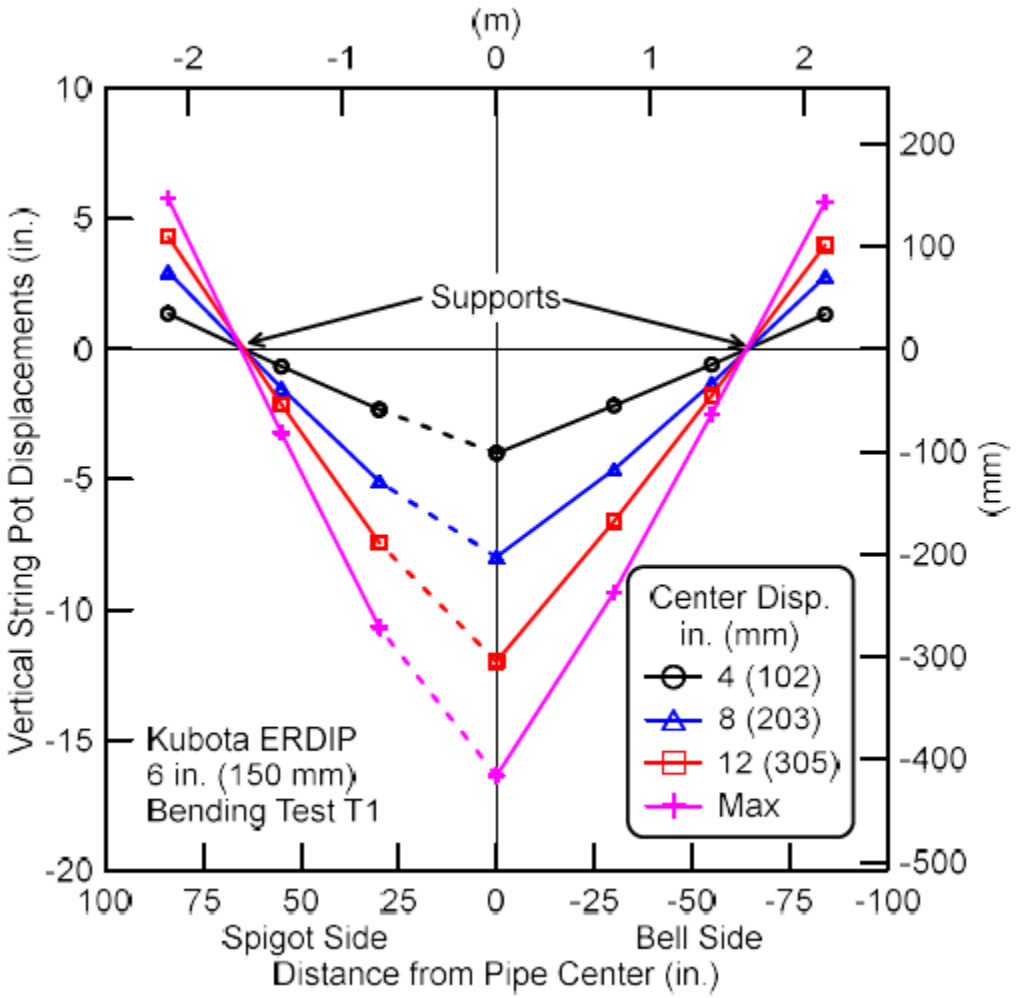


SCOTT BLAIR, PIPELINE TO SURF SEISMIC WAVES(2014)

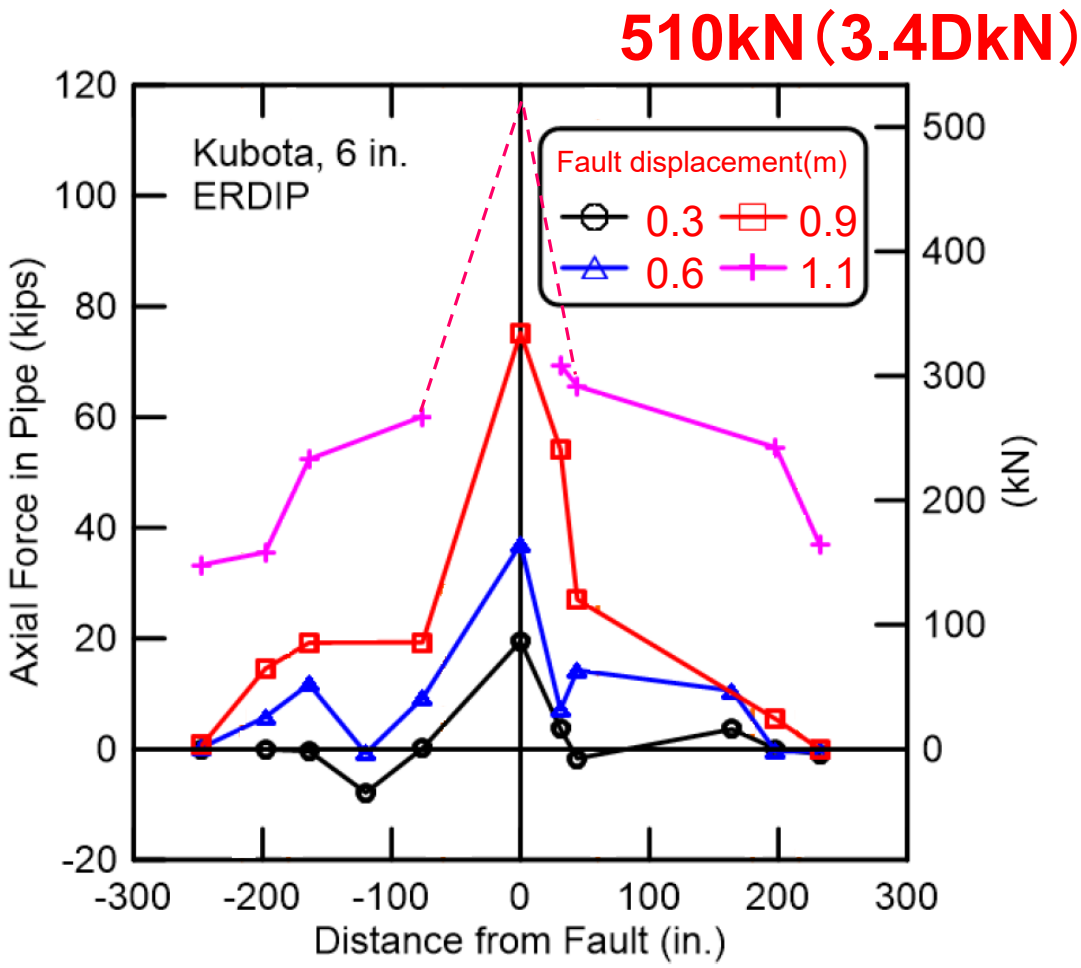
Test result (6 in.)



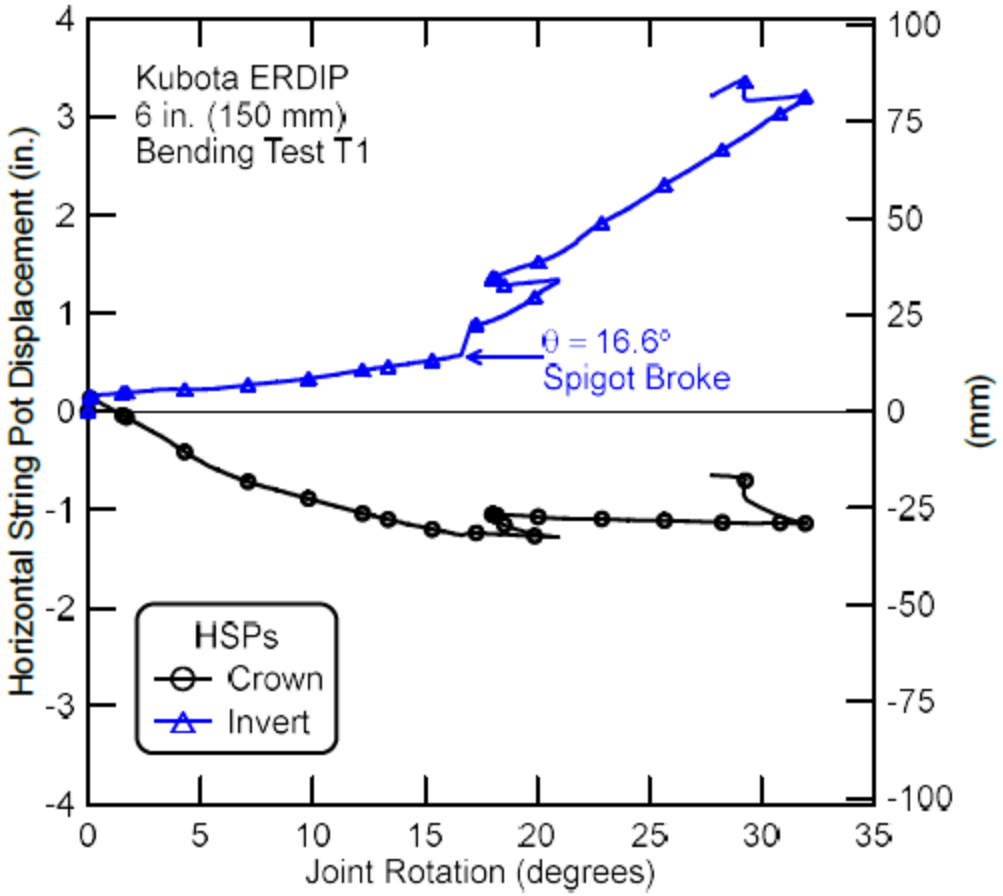
Test result (6 in.)



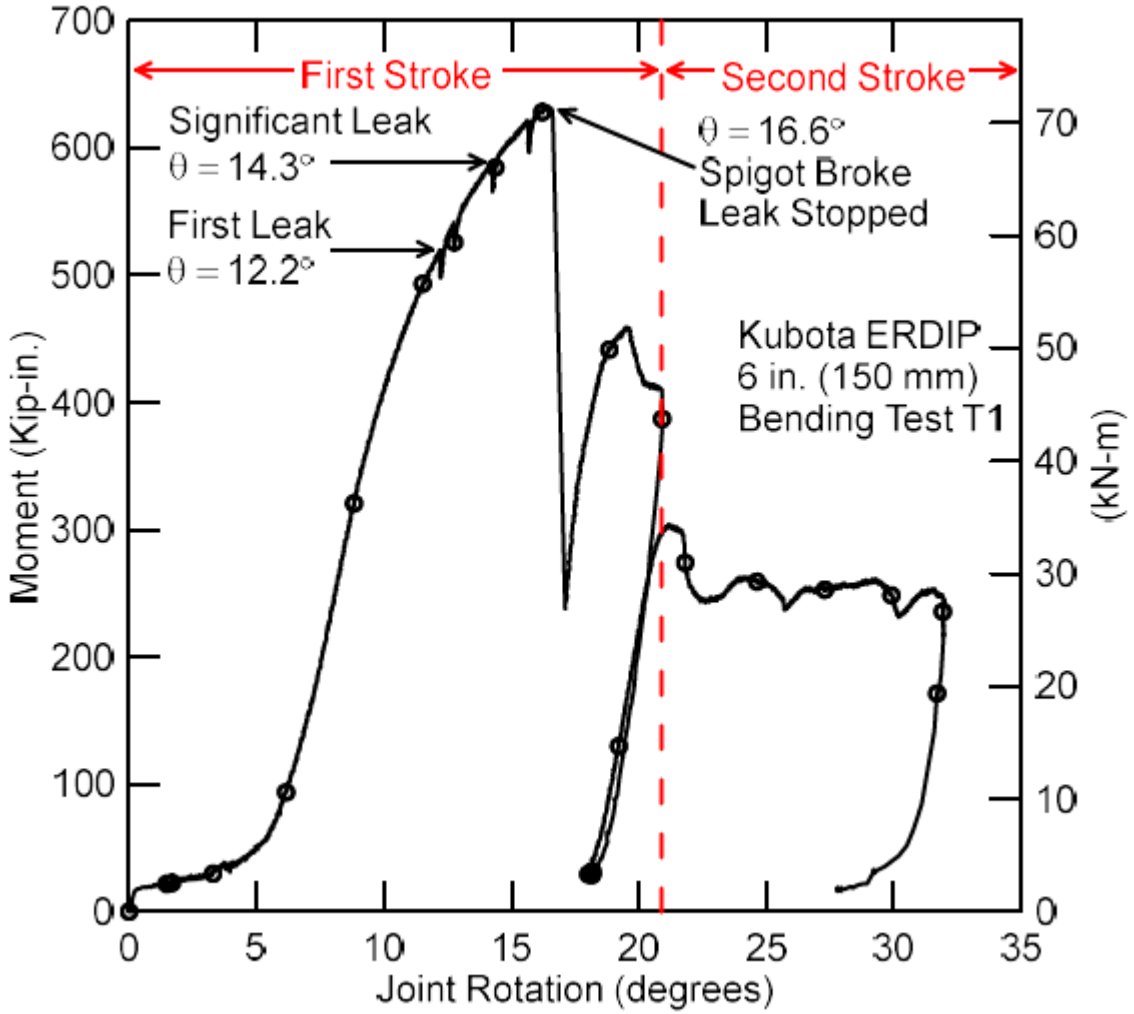
Axial force


510kN（3.4DkN）
Kubota, 6 in.
ERDIP
Fault displacement(m)
0.3
0.9
0.6
1.1
Axial Force in Pipe (kips)
(kN)
Distance from Fault (in.)
120
100
80
60
40
20
0
-20
500
400
300
200
100
0
-300
-200
-100
0
100
200
300

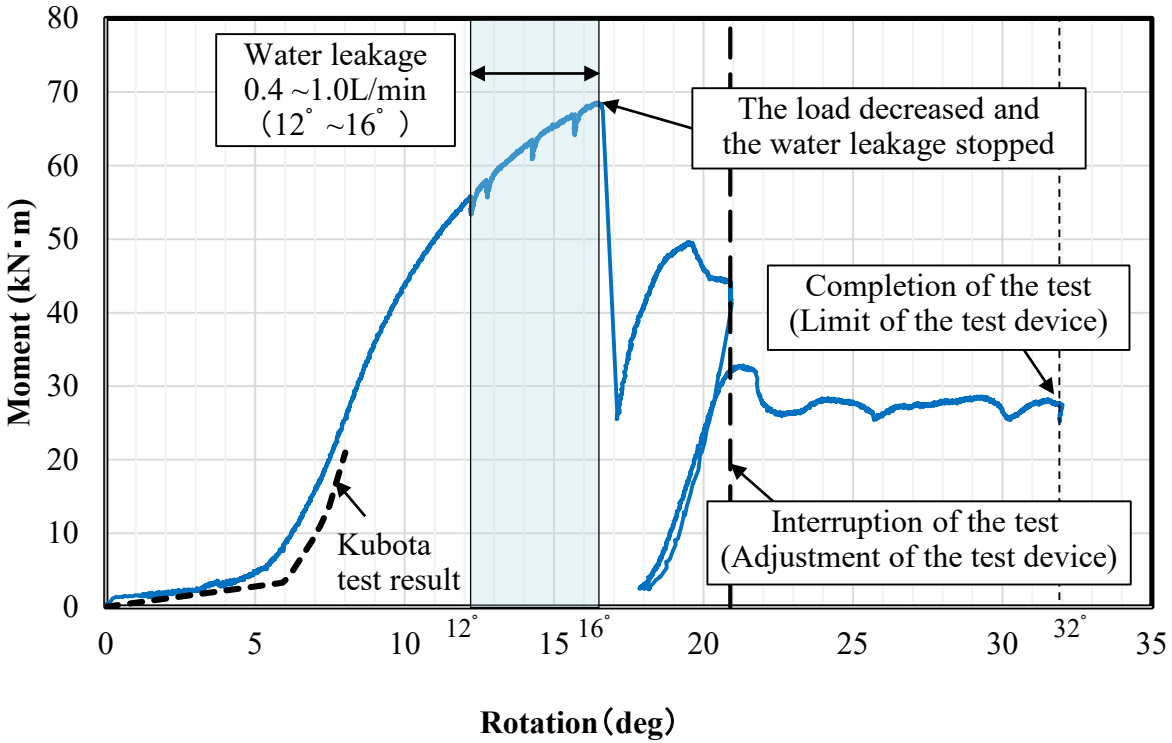
Test result (6 in.)



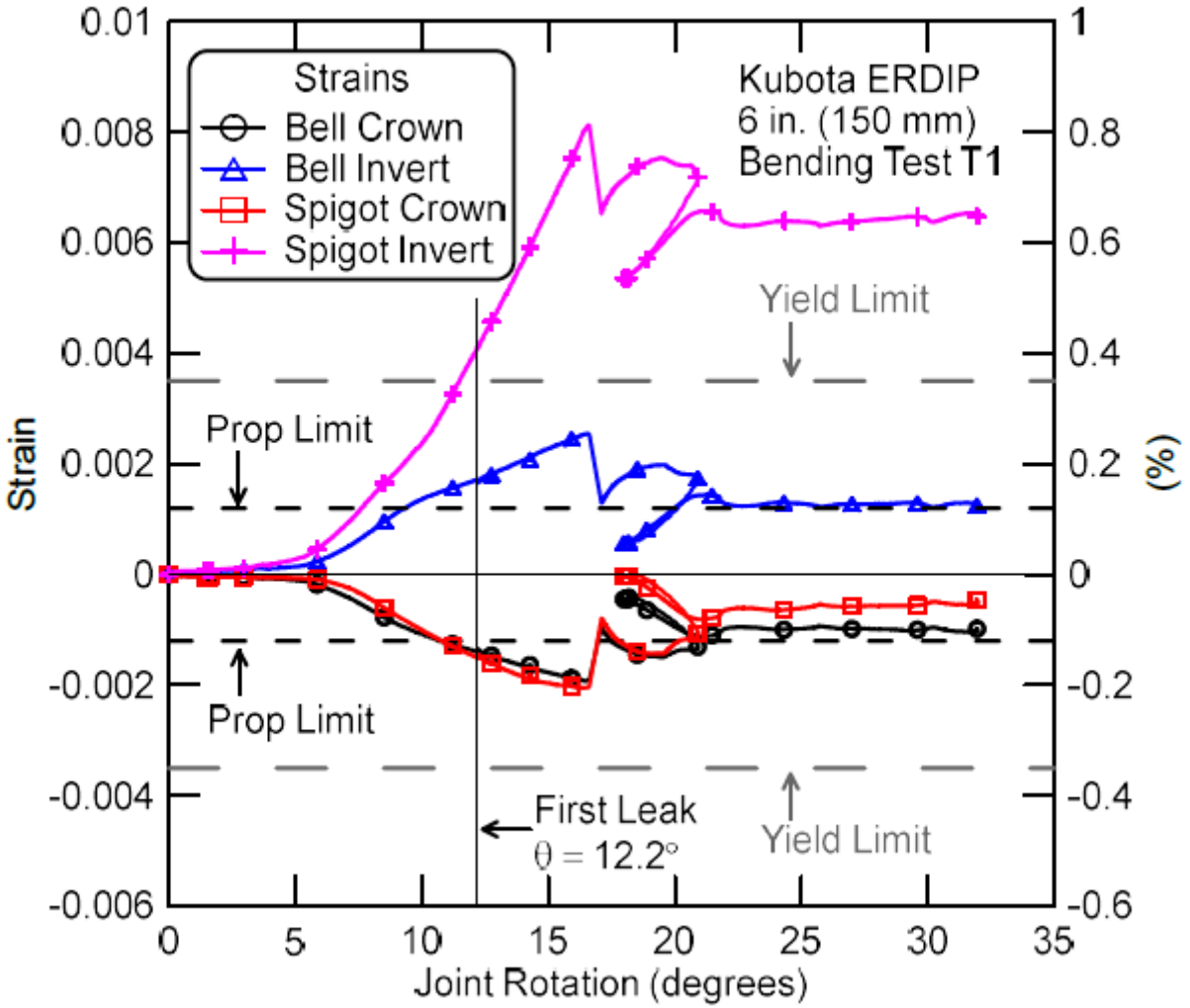
Test result (6 in.)

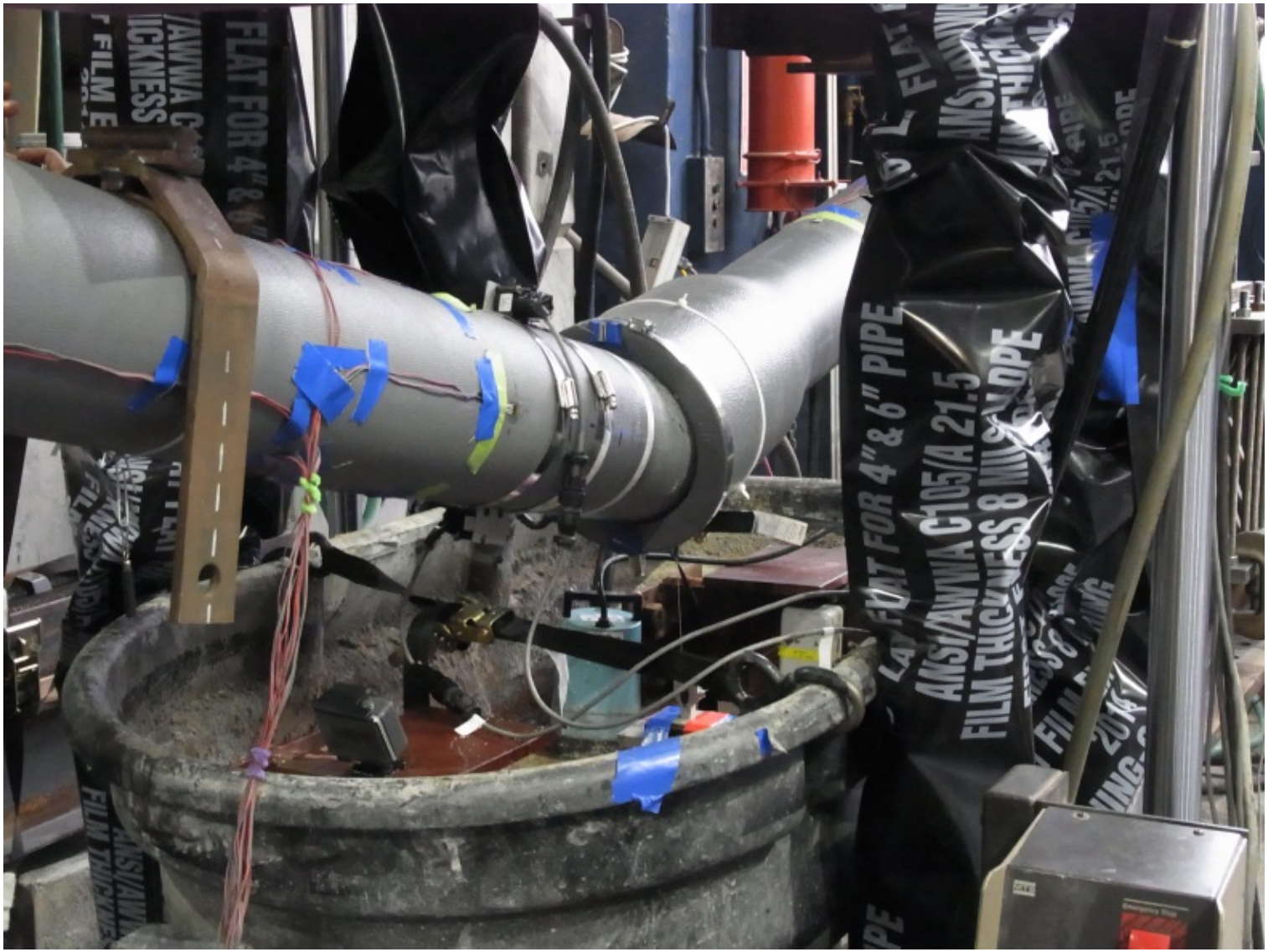


Moment vs. rotation

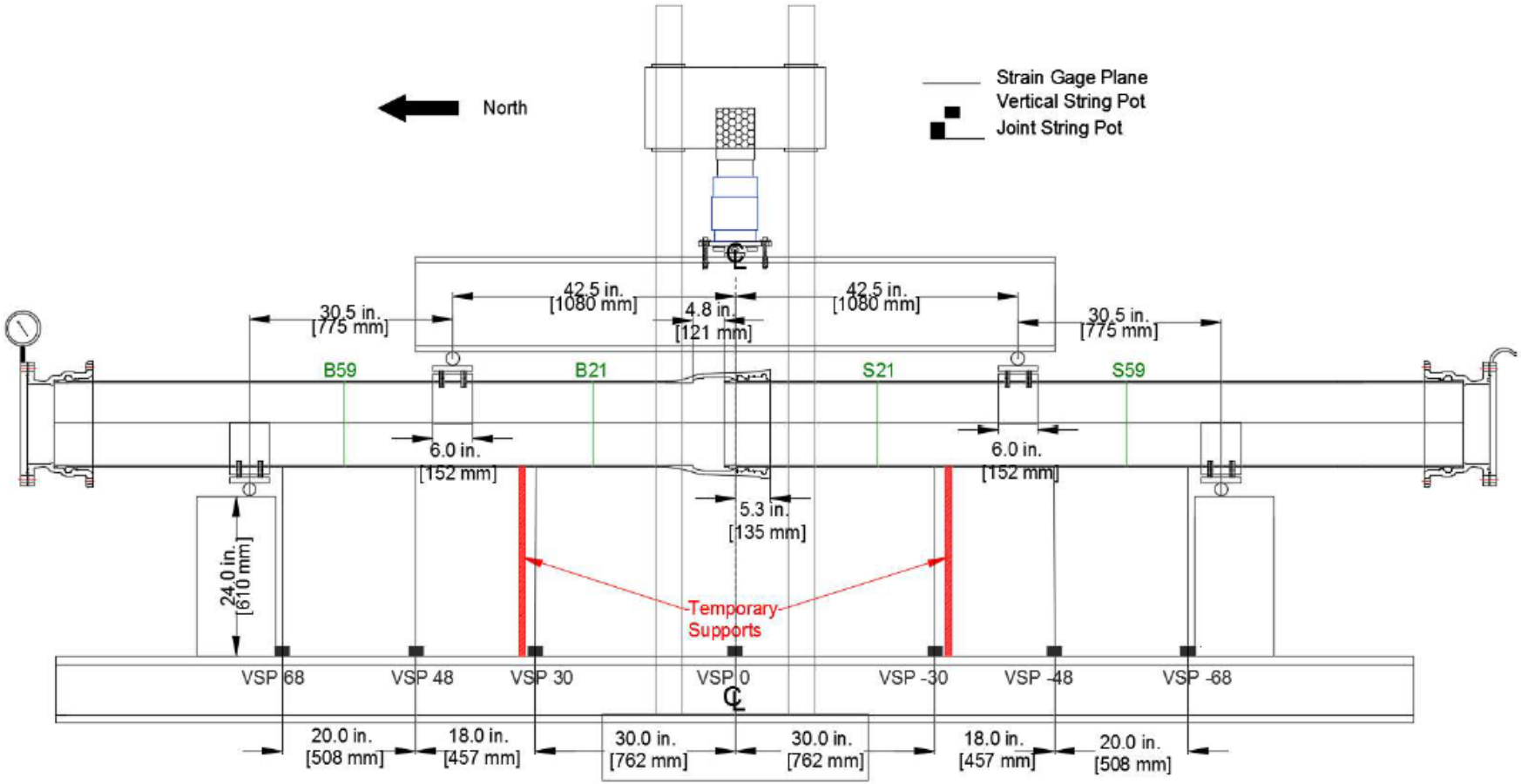


Test result (6 in.)

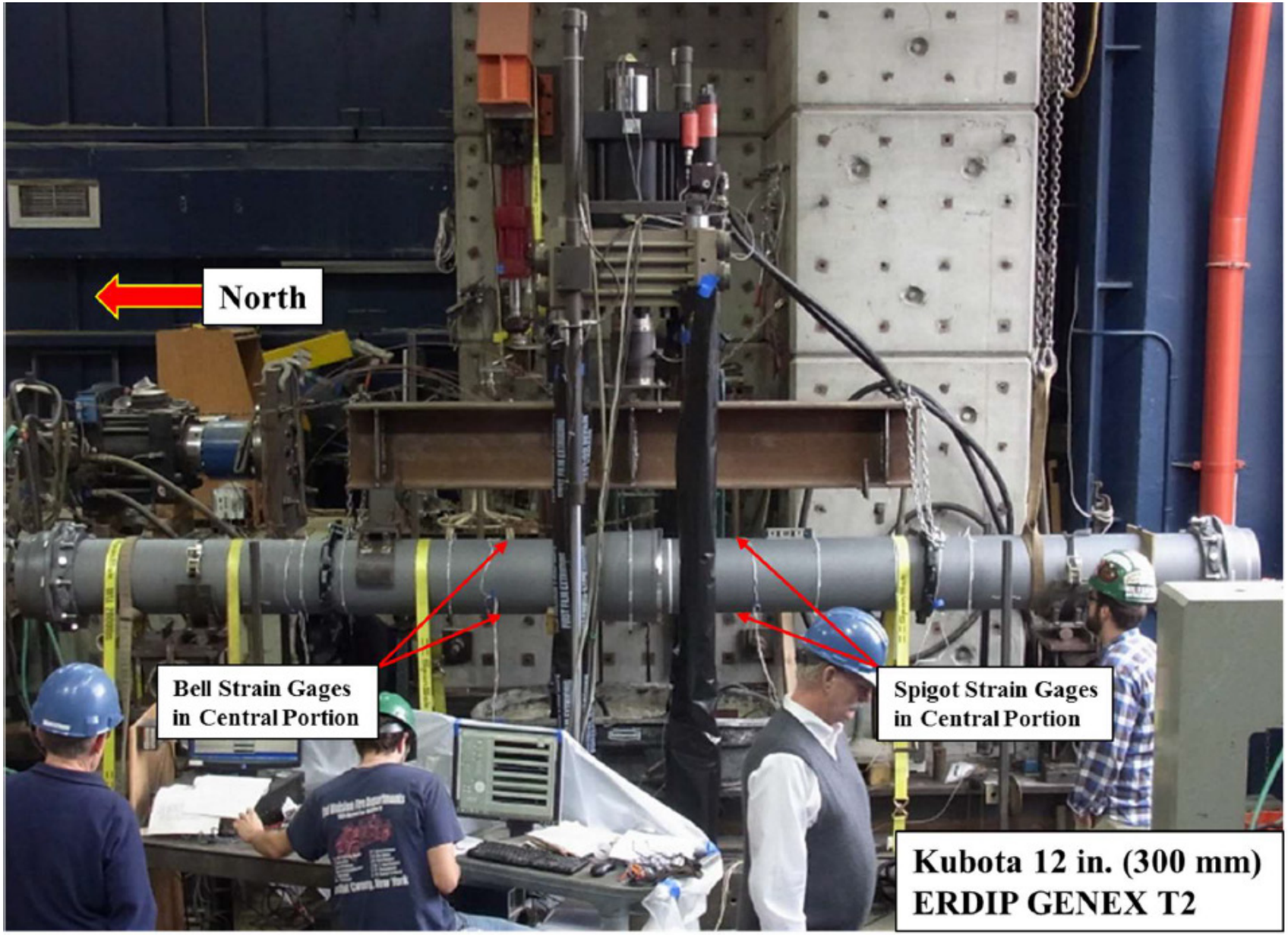



FLAT FOR 4" & 6" PIPE
ANSI/AWWA C105/A 21.5
FILM THICKNESS 8 MIL

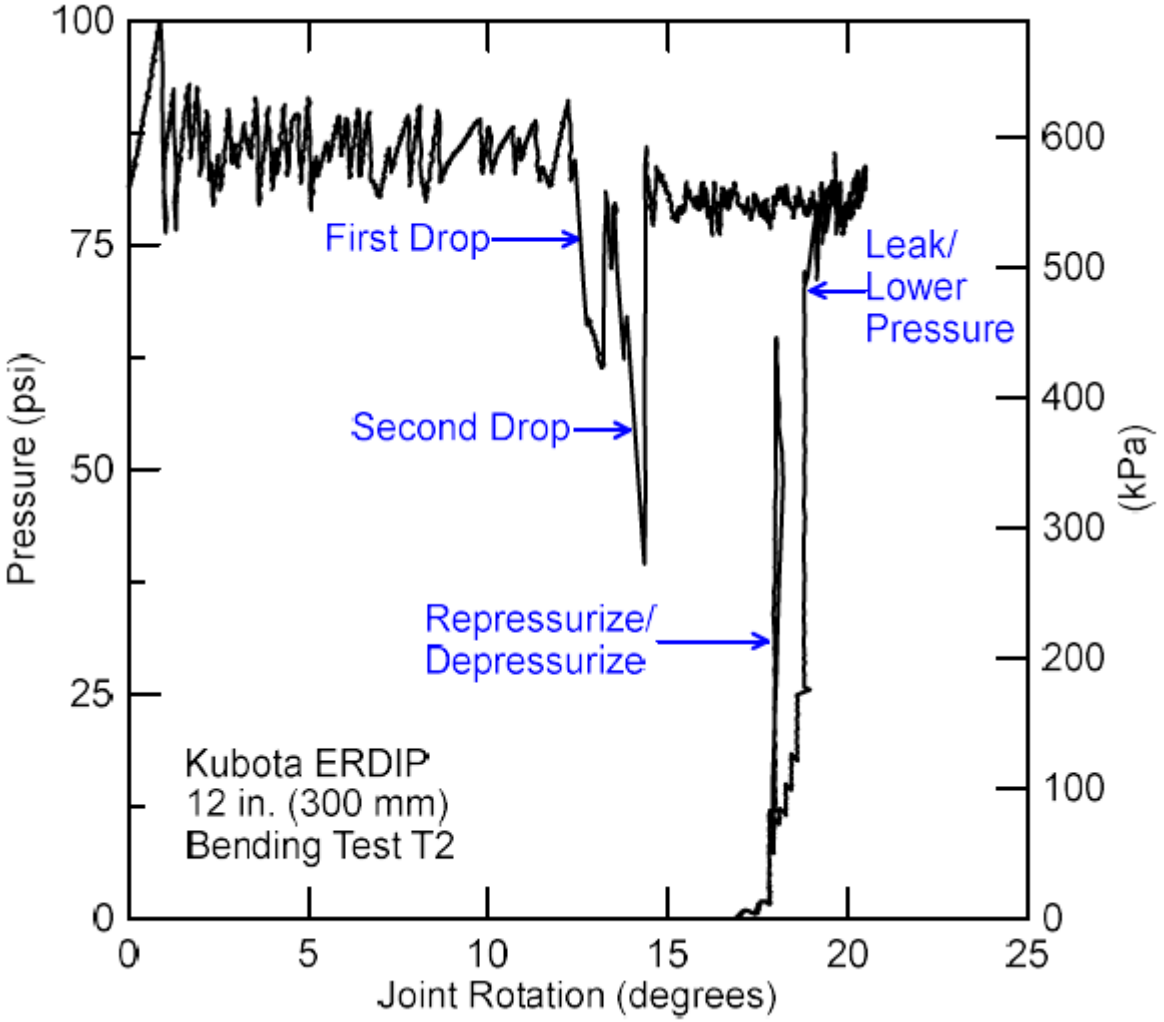
Test set-up (12 in.)



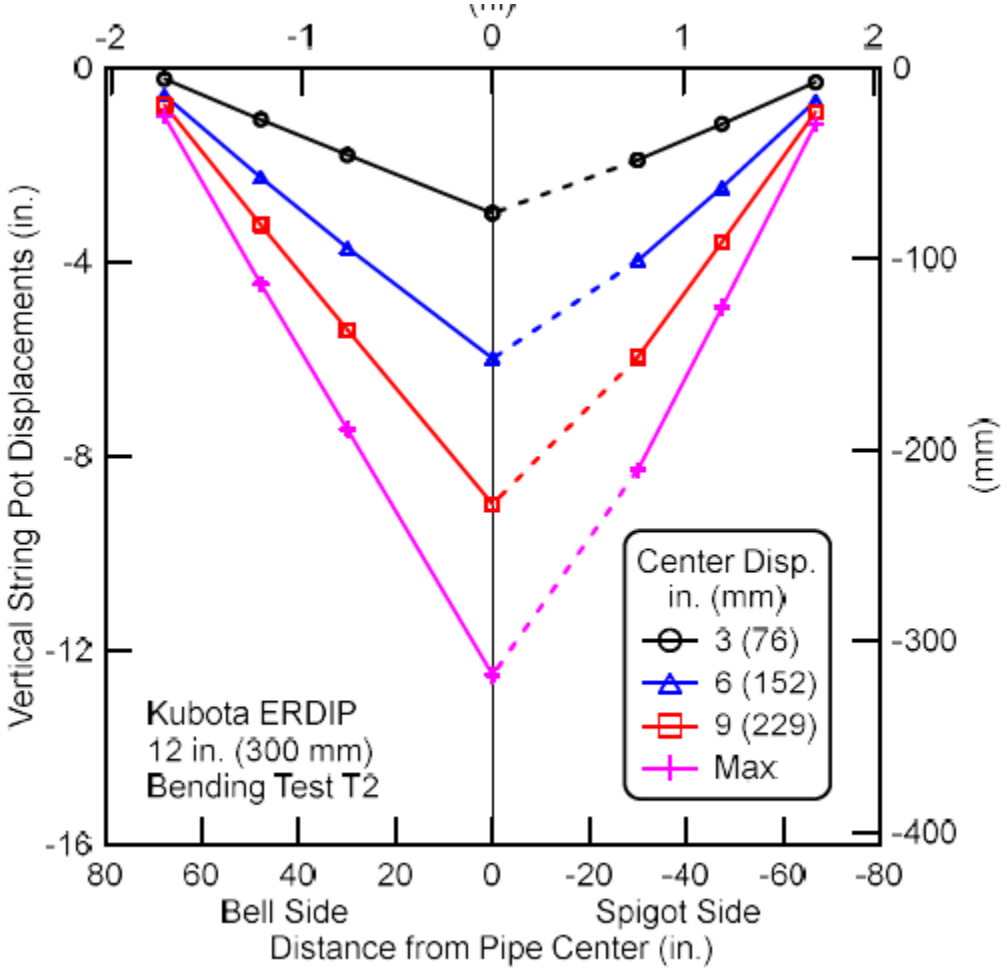
Test result (12 in.)



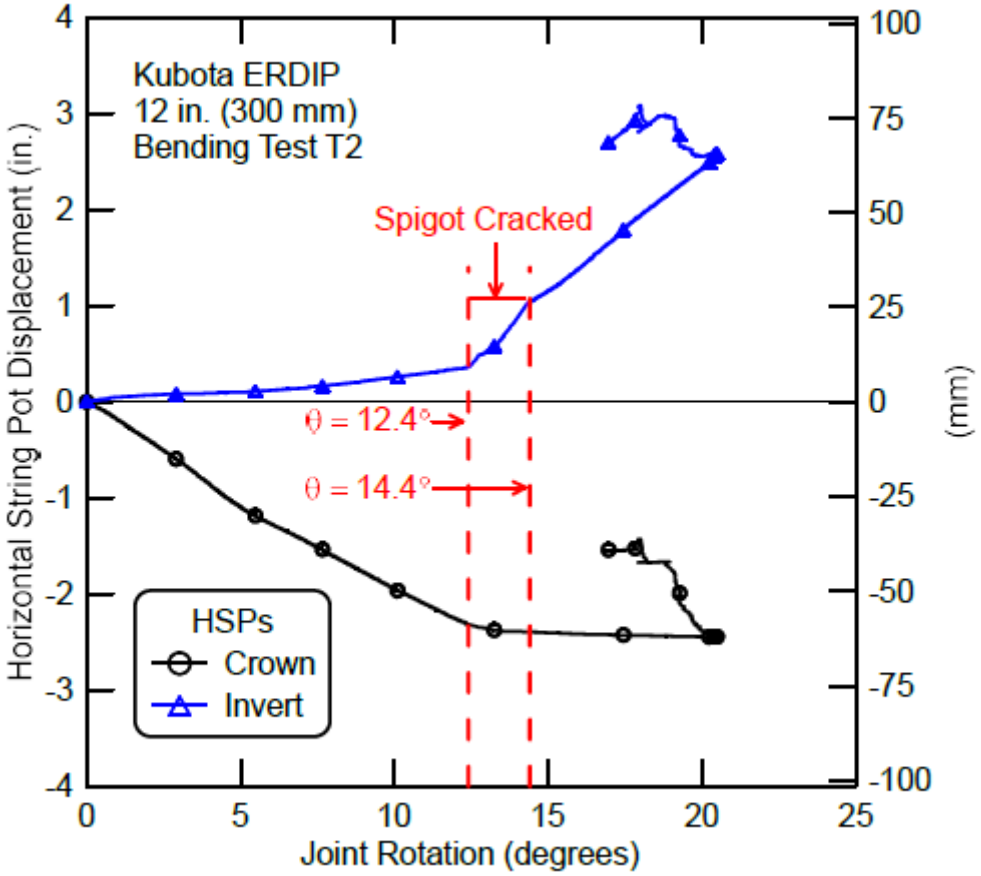
Test result (12 in.)



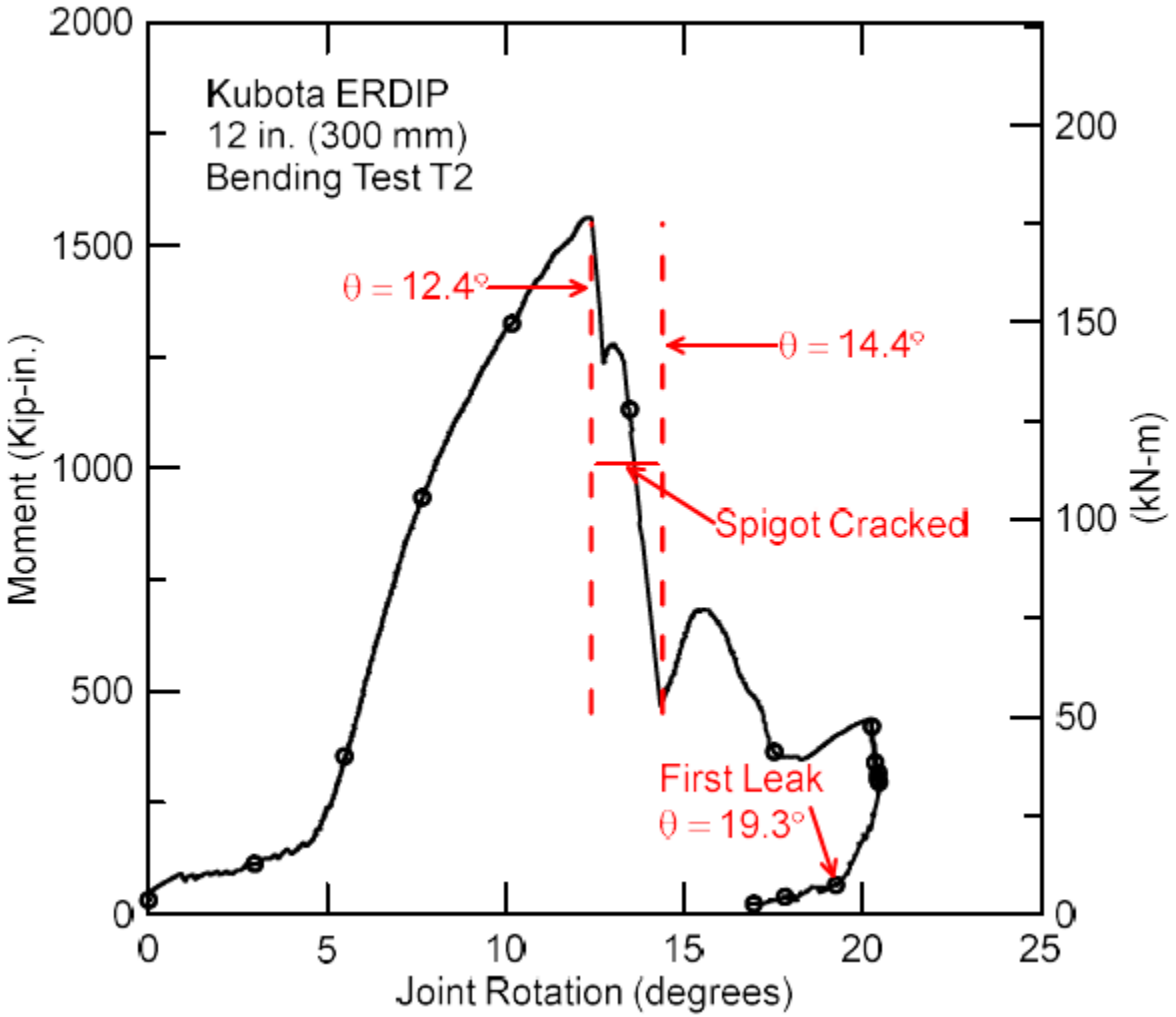
Test result (12 in.)



Test result (12 in.)



Test result (12 in.)



Test result (12 in.)