

# Seismic Integrity of High-Strength Pipelines<sup>†</sup>

SUZUKI Nobuhisa<sup>\*1</sup> IGI Satoshi<sup>\*2</sup> MASAMURA Katsumi<sup>\*3</sup>

## Abstract:

*High-strain linepipes provide excellent strain capacity to withstand axial compression and bending deformation. Assuming the outside diameter, the wall thickness and the design factor of the linepipe as 762 mm, 15.6 mm, and 0.4, respectively, critical compressive strain of the X80-grade linepipe can be estimated to be 2.0% which is approximately 1.5 times larger than that of a conventional X80-grade pipe. The excellent strain capacity enables us to reduce construction costs and ensure integrity of buried pipelines in seismic areas and cold regions.*

## 1. Introduction

The long-distance and high-pressure trends in natural gas pipelines have generated a demand for higher-strength linepipes<sup>1)</sup>. A high-pressure gas pipeline project using X80-grade pipes (API 5L Grade X80) (API: American Petroleum Institute) is now being carried out in Japan.

Seismic design codes in Japan<sup>2,3)</sup> cover pipelines of grade X65 (API 5L Grade X65) and under. In planning a project, it is therefore necessary to verify the strain capacity of X80-grade linepipes. High-strength linepipes such as X80-grade tend to have large yield ratios, and their strain capacity to withstand compression and bending deformation is lower than that of linepipes of grade X65 and under<sup>4,5)</sup>.

The high-strain linepipe (HSLP) is a linepipe with outstanding strain capacity developed to ensure that the high-strength pipeline has an integrity equal to or better than the integrity of pipelines with conventional strength

levels<sup>4-7)</sup>. In order to verify the strain capacity of the high-strain linepipe, buckling tests on actual pipes have also been carried out<sup>6,7)</sup>.

In this paper we outline the general seismic integrity required of high-pressure gas pipelines and the strain capacity required of X80-grade high-strain linepipes (X80-HSLP). The authors also examine cases where X80-HSLP are subjected to bending deformation, and we show the strain capacity on the compression side and the strain capacity of the girth welds on the tension side.

## 2. Seismic Design of High-Pressure Gas Pipelines

### 2.1 Basic Concept of Seismic Design

In general, two types of seismic design code are applied for high-pressure gas pipelines: seismic design codes for high-pressure gas pipelines<sup>2)</sup> (hereinafter referred to as HGPL design codes) and seismic design codes for high-pressure gas pipelines considering liquefaction-induced permanent ground deformation<sup>3)</sup> (hereinafter referred to as L-HGPL design codes). The HGPL design codes are for temporary ground deformation (TGD) and the L-HGPL design codes are for permanent ground deformation (PGD). Both seismic codes are strain based and cover welded pipes of X65 and under<sup>2,3)</sup>.

The HGPL design codes are two-tier seismic design codes for TGD. Basically they ensure the seismic integrity of gas pipelines (to be described later) for Ground Motion Level-1, the TGD that generally will be encountered, and Ground Motion Level-2, a very strong TGD

<sup>†</sup> Originally published in *JFE GIHO* No. 17 (Aug. 2007), p. 14–19



<sup>\*1</sup> Dr. Eng., P.E.,  
Principal Researcher,  
JFE R&D



<sup>\*2</sup> Dr. Eng.,  
Senior Researcher Manager,  
Joining & Strength Res. Dept.,  
Steel Res. Lab.,  
JFE Steel



<sup>\*3</sup> Dr. Eng.,  
Staff General Manager,  
Tubular Products Business Planning Dept.,  
JFE Steel

Table 1 Current seismic design codes in Japan

Ground deformation		Design basis and applications	Number of cycles	Checking criteria
TGD	Level-1	<ul style="list-style-type: none"> <li>· Design</li> <li>· Strain-based</li> <li>· Applications</li> <li>· X65 and lower</li> <li>· Straight, bend, and tee branch</li> </ul>	$N_c = 50$ Low cycle fatigue	1% or $35t/D$ (%)
	Level-2		$N_c = 3-5$ Very low cycle fatigue	3%
PGD	Lateral spread		$N_c = 1/4$ Monotonic deformation	Allowable deformation

(Table 1).

Ground Motion Level-1 normally occurs once or twice during the life cycle of a gas pipeline, whereas Ground Motion Level-2, a very strong TGD, is unlikely to occur at all<sup>2)</sup>. HGPL design incorporates fatigue designs formulated in close consideration of the repetition of ground motions<sup>2)</sup>. The L-HGPL design codes define a lateral spread as an input ground displacement<sup>3)</sup>. A lateral spread is static deformation without repetition, and is characterized by the consideration of extensive pipeline deformation.

**2.2 Required Seismic Integrity and Criteria for Checking**

If the seismic integrity requirements of gas pipelines are met, a Ground Motion Level-1 event will not damage the pipeline or interrupt normal operation (normal operability). In the event of a Ground Motion Level-2 event, there will be no leakage even if deformation is extensive (pressure integrity). If the seismic integrity requirements for liquefaction-induced ground deformation are met, there will be no leakage even after deformation due to Ground Motion Level-2.

The integrity of pipes for axial deformation is checked for TGD, whereas the integrity of pipes for bending deformation is checked for L-TGD. The checking criteria for straight pipes and deformed pipes are shown in Table 1. In Ground Motion Level-1, an allowable strain is a strain amplitude of 1% (number of cycles:  $N_c = 50$ ) or a critical compressive strain of a straight pipe due to axial compression of  $35t/D$  (%) ( $t$ : pipe wall thickness,  $D$ : average pipe diameter). The same value,  $35t/D$ (%), is also applied in the calculation of the critical compressive strain for bending deformation. In Ground Motion Level-2, the local buckling of pipes is allowed and a strain amplitude of 3% ( $N_c = 3$  to 5) is an allowable value. For ground deformation, a safety factor is considered in the pressure integrity limit and an allowable deformation is specified by the bending angle during post-buckling deformation.

**2.3 Checking Criteria on Compressive Deformation**

Equation (1) expresses the critical strains of pipes subjected to axial compression<sup>8)</sup>. When a stress-strain curve of the continuous strain-hardening type is expressed by the power-law hardening of Eq. (2) and substituted into Eq. (1), the critical strain is expressed by Eq. (3).

$$\epsilon_{cr} = \frac{4}{3} \sqrt{\frac{E_T}{E_s}} \frac{t}{D} \dots\dots\dots (1)$$

$$\sigma = A\epsilon^n \dots\dots\dots (2)$$

$$\epsilon_{cr} = \frac{4}{3} \sqrt[n]{n} \frac{t}{D} \dots\dots\dots (3)$$

Where  $\epsilon_{cr}$  is the critical compressive strain,  $E_T$  is the tangent modulus at peak load,  $E_s$  is the secant modulus at peak load,  $t$  is the pipe wall thickness,  $D$  is the average pipe diameter,  $\sigma$  is the nominal stress,  $A$  is the constant,  $n$  is the strain-hardening exponent, and  $\epsilon$  is the nominal stress.

When we substitute a general strain-hardening exponent  $n = 0.11$  in Eq. (3) for pipes of grade X65 and under, the critical compressive strain of pipes becomes  $44t/D$  (%). When a safety factor of 1.25 is considered, we obtain a value of  $35t/D$ (%). This formula expresses the allowable compressive strain of the HGPL design codes (the JGA formula) (JGA: Japan Gas Association). The strain-hardening exponent  $n$ , a function of strain, decreases as strain increases and reaches a constant value in the strain range of not less than 2%. Because the JGA formula is a design formula, small  $n$ -values in the strain range of 3 to 4% are adopted and critical compressive strain is conservatively evaluated.

The  $D/t$  of high-pressure gas pipelines is 50 or so and the critical compressive strain becomes 1% or so. The use of an average  $n$ -value in the range of 1 to 4% is mechanically inappropriate for estimating the critical buckling strain of pipes<sup>5)</sup>. The  $n$ -value in the strain range of 1 to 2% changes extensively, and the estimated critical compressive strain is outside the domain (1 to 4%) and near the lower limit. The analytical solution<sup>5)</sup> given below can be applied for the appropriate estimation of the strain capacity of pipes.

### 3. Local Buckling Characteristics to Withstand Compression and Bending Deformation

#### 3.1 Strain Capacity to Withstand Compression Deformation, in Consideration of Strain Hardening Characteristics

When a stress-strain curve is expressed by the Ramberg-Osgood formula<sup>9)</sup> (the R-O formula) and substituted into Eq. (1), the critical compressive stress can be expressed as given in Eq. (5) and the critical compressive strain can be expressed as given in Eq.(6)<sup>5)</sup>.

$$\epsilon = \frac{\sigma}{E} + \frac{\alpha\sigma_0}{E} \left( \frac{\sigma}{\sigma_0} \right)^N \dots\dots\dots (4)$$

$$\left( \frac{\sigma_{cr}}{\sigma_0} \right)^N = -\frac{1}{2\alpha} \left( 1 + \frac{1}{N} \right) + \frac{4}{3\alpha\sqrt{N}} \frac{E}{\sigma_0} \frac{t}{D} \dots (5)$$

$$\epsilon_{cr} = \frac{\sigma_0}{E} \left( \frac{\sigma_{cr}}{\sigma_0} \right) + \frac{\alpha\sigma_0}{E} \left( \frac{\sigma_{cr}}{\sigma_0} \right)^N \dots\dots\dots (6)$$

Where  $\epsilon$  is the nominal strain,  $\sigma$  is the nominal stress,  $E$  is the Young's modulus,  $\alpha$ ,  $\sigma_0$ ,  $N$  are the constants of the R-O equation,  $\sigma_{cr}$  is the critical compressive stress, and  $\epsilon_{cr}$  is the critical compressive strain.

The critical compressive strain of the usual X65-grade and X80-grade linepipes is calculated by Eqs. (5) and (6) and the allowable compressive strain of the above-described JGA formula is compared. The stress-strain curves of X65-grade and X80-grade pipes are assumed to be as shown in Fig. 1. In both curves, the yield stress is assumed to be a specified minimum yield stress (SMYS) and the tensile strength is assumed to be a specified minimum tensile strength (SMTS). The

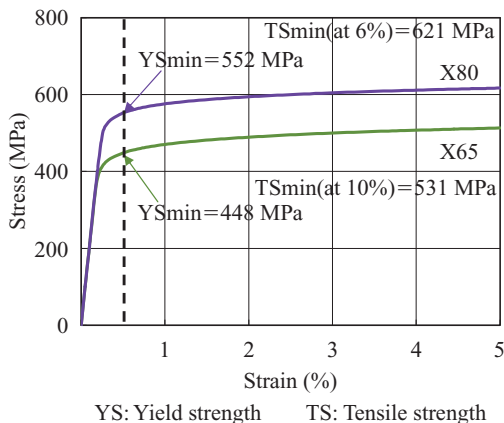


Fig. 1 Stress-strain curves for conventional steel pipe, X65, and X80

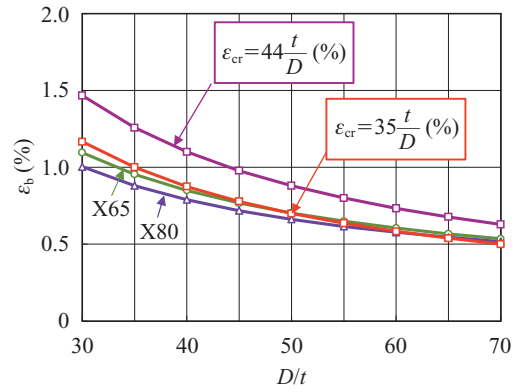


Fig. 2 Strain capacity of conventional steel pipe, X65, and X80

uniform elongation of X65-grade pipes is assumed to be 10%, and the uniform elongation of X80-grade pipes is assumed to be 6%. The yield ratio (YS/TS) of X65-grade pipes becomes 0.84, and that of X80-grade pipes becomes 0.89. When the constants of the R-O formula are found from the stress-strain curves and substituted into Eqs. (5) and (6), the critical compressive strain curves of X65-grade and X80-grade pipes are obtained as shown in Fig. 2.

The critical compressive strain of X65-grade pipes obtained by this calculation is on the same order as that obtained by the JGA formula, as shown in Fig. 2. The critical compressive strain of X80-grade pipes, meanwhile, is on the same order in the  $D/t$  range of not less than 60. Thus, the critical compressive strain of X80-grade pipes obtained by this calculation apparently falls below that obtained by the JGA formula. This calculation example is subject to a special condition where the stress-strain curve is defined by SMYS and SMTS. Nonetheless, it accurately extracts a problem related to the strain capacity of X80-grade pipes subjected to axial compression.

Two alternatives are conceivable as means for solving the above-described problem related to strain capacity. One is to improve the strain capacity of X80-grade pipes to a level equal to or better than that of pipes of X65 and under, for withstanding compressive deformation. This would make it possible to ensure the consistency of seismic integrity of high-pressure gas pipelines independently of the pipe strength. The other alternative is to separately define a JGA formula adaptable to X80-grade pipes, to avoid the daunting challenge of designing X80-grade pipes capable of providing the same strain capacity as pipes of grade X65 and under. One way to approach the first alternative is to control the stress-strain curve. With this approach, there is a chance that a general consensus can be reached. For the second alternative, thorough discussions are clearly necessary.

### 3.2 Strain Capacity to Withstand Bending

Under present circumstances, there are no analytical solutions for determining the critical compressive strain in bending deformation. Some empirical formulas based on bending test data have been proposed<sup>10</sup>. Figure 2 shows the critical compressive strain curves calculated by representative empirical formulas. In the HGPL design codes, the design formulas for the critical strain of compression bending are also applied to bending deformation. The figure also shows the critical compressive strain curves determined by the JGA formula. The data shown are the results of an experiment on pipes of grade X65 and under carried out abroad<sup>10</sup>. The experimental data and empirical formulas do not correspond to each other individually, but each empirical formula can be defined by the corresponding lower bound envelope of every set up the experimental data<sup>10</sup>. Rather than describing each empirical formula, this section offers a general formula to express all of them:

$$\epsilon_{cr} = A \left( \frac{t}{D} \right)^m \dots\dots\dots (7)$$

where, *A* and *m* are a constant and exponent obtained from the experimental data.

Figure 3 compares the critical compressive strains in the *D/t* ratio of 40 to 70. The values of “Classical elastic” are larger than the values obtained by other empirical formulas. The other empirical formulas obtain almost the same values, though with small differences. A comparison of the experimental data at the same *D/t* ratio reveals great differences in the strain capacity. The authors also note that some of the experimental values are smaller than the values obtained by the empirical formulas.

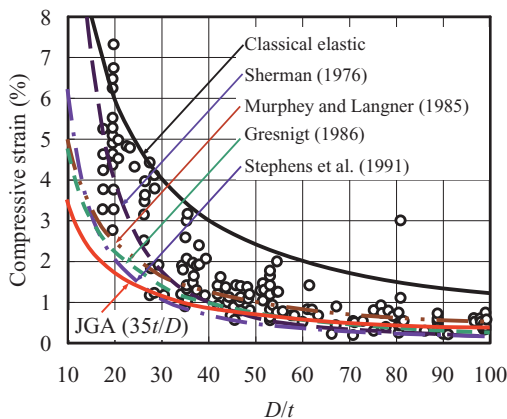


Fig.3 Bending test results and semi-empirical formulas

## 4. Strain-Based Evaluation of Integrity against Bending Deformation (Local Buckling)

### 4.1 Critical Strain of X80 Linepipes

To compare the strain capacity of X80-HSLPs and X80-grade pipes (“X80 Conventional” in Table 2), the material characteristics shown in Table 2 were assumed for both, and critical compressive strain and maximum tensile strain were calculated by finite element analysis (FEA). Each pipe was assumed to have an outside diameter (OD) of 762 mm, a wall thickness (*t*) of 15.6 mm, and OD/*t* ratio of 49. The design factor was set at four levels: 0.00, 0.40, 0.60, and 0.72. The pipes were subject to pure bending deformation, such that tensile strain was produced in the upper portion and compressive strain was produced in the lower portion. Figure 4 shows an FE model in which bending deformation generates a shell wrinkle.

Figure 5 shows the longitudinal strain distribution in a pipe section subjected to bending deformation near

Table 2 Tensile properties of X80 pipes

X80 Steel pipes	Tensile properties		
	YS (MPa)	TS (MPa)	YS/TS (%)
High-Strain	535	696	77
Conventional	552	619	89

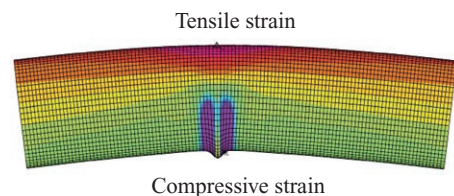


Fig. 4 Longitudinal strain distribution of a steel pipe

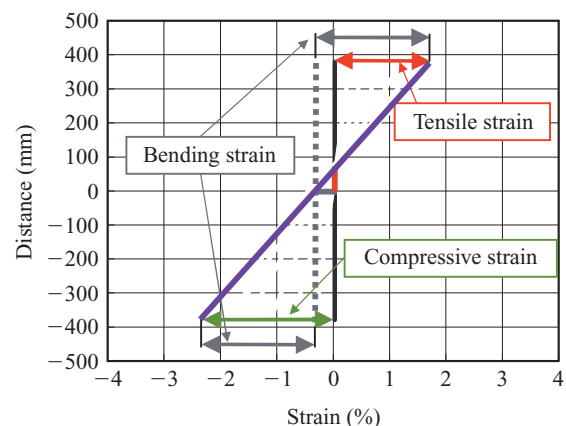


Fig. 5 Longitudinal strain distribution over a cross-section

a shell wrinkle described above. The green line of the figure indicates the longitudinal strain distribution. The neutral axis is shifted toward the tension side due to the effect of interval pressure, and the absolute value of the maximum compressive strain is larger than the maximum tensile strain. The maximum compressive strain at the maximum bending moment is called the “critical compressive strain,” and the maximum tensile strain is called the “critical tensile strain.” The gray lines indicate the bending strain distribution. Bending strain is an average value of compressive strain and tensile strain, and critical bending strain is an average value of critical compressive strain and critical bending strain. This paper makes no reference to the critical bending strain, but rather makes a comparison between the critical compressive strain and critical tensile strain.

**Table 3** shows the average critical compressive strain and average critical tensile strain of X80-HSLP in which geometric imperfections<sup>7)</sup> are considered. **Table 4** shows the same for conventional X80-grade pipes. The average critical compressive strain is obtained by averaging the compressive strain distributed in the longitudinal direction, with the shell wrinkle serving as the center, within the gauge length. The average critical compressive strains over the gauge length are obtained by multiplying the average pipe diameter by 1, 2, and 3 (expressed as  $\epsilon_{1Dcr}$ ,  $\epsilon_{2Dcr}$ , and  $\epsilon_{3Dcr}$ , respectively). The same also applies to the average critical tensile strain.

The average critical compressive strain  $\epsilon_{2Dcr}$  of X80-HSLPs, for example, is 1.87% at a design factor of 0.00, 2.82% at a design factor of 0.72, and progressively higher as the design factor increases. The average criti-

cal tensile strain  $\epsilon_{2Dcr}$ , on the other hand, is 1.16% at a design factor of 0.00, 0.86% at a design factor of 0.72, and progressively lower as the design factor increases. The average critical compressive strain  $\epsilon_{2Dcr}$  and average critical tensile strain  $\epsilon_{2Dcr}$  of conventional X80-grade pipes, meanwhile, show the same tendency as those X80-HSLPs, whereas the average critical strain of conventional X80-grade pipes is smaller than that of X80-HSLPs. From this, we clearly see that the strain capacity of conventional X80-grade pipes is small.

#### 4.2 Examination of Integrity against Local Buckling

To examine the integrity of X80-HSLPs and conventional X80-grade pipes against local buckling, the average critical compressive strain  $\epsilon_{2Dcr}$  is extracted from the calculation results of Tables 3 and 4 (and shown in **Tables 5** and **6**). The figures show the allowable critical compressive strain obtained by dividing the average critical compressive strain  $\epsilon_{2Dcr}$  by a safety factor of 1.25. The allowable strain values calculated by the JGA formula are also shown, for comparison.

The allowable critical compressive strain of X80-HSLPs is 1.50% when there is no internal pressure, increases with increasing design factor, and reaches 2.26% at a design factor of 0.72. The allowable strain calculated by the JGA formula, meanwhile, is 0.71. Therefore, the strain capacity of the X80-HSLPs is apparently larger than the value obtained by the JGA formula. The same applies also to conventional X80-grade pipes, and the allowable critical compressive strain changes from 0.91% to 1.82%. These values are also larger than the value obtained by the JGA formula.

Table 3 Average critical compressive strain and the corresponding tensile strain of the X80 high-strain pipe

OD (mm)	Design factor	$\epsilon_{1Dcr}$ (%)		$\epsilon_{2Dcr}$ (%)		$\epsilon_{3Dcr}$ (%)	
		Comp.	Ten.	Comp.	Ten.	Comp.	Ten.
762	0.00	2.09	1.17	1.87	1.16	1.68	1.16
	0.40	2.14	1.06	2.00	1.04	1.90	1.00
	0.60	2.62	0.96	2.41	0.92	2.25	0.87
	0.72	3.11	0.90	2.82	0.86	2.61	0.80

Table 4 Average critical compressive strain and the corresponding tensile strain of the X80 conventional pipe

OD (mm)	Design factor	$\epsilon_{1Dcr}$ (%)		$\epsilon_{2Dcr}$ (%)		$\epsilon_{3Dcr}$ (%)	
		Comp.	Ten.	Comp.	Ten.	Comp.	Ten.
762	0.00	1.27	0.66	1.14	0.65	1.05	0.65
	0.40	1.45	0.56	1.30	0.54	1.21	0.52
	0.60	1.99	0.56	1.74	0.53	1.59	0.50
	0.72	2.60	0.59	2.27	0.55	2.06	0.51

Table 5 Two times outside diameter average critical compressive strain of the X80 H-S linepipe

OD (mm)	Design factor	$\epsilon_{2Dcr}$ (%)		JGA 35t/D (%)
		Comp.	Comp./1.25	
762	0.00	1.87	1.50	0.71
	0.40	2.00	1.60	
	0.60	2.41	1.93	
	0.72	2.82	2.26	

Table 6 Two times outside diameter average critical compressive strain of the X80 conventional steel

OD (mm)	Design factor	$\epsilon_{2Dcr}$ (%)		JGA 35t/D (%)
		Comp.	Comp./1.25	
762	0.00	1.14	0.91	0.71
	0.40	1.30	1.04	
	0.60	1.74	1.40	
	0.72	2.27	1.82	



Therefore, the strain capacity of conventional X80-grade pipes shown in Table 2 is smaller than that of X80-HSLPs, but larger than that obtained by the JGA formula. Thus, both can be adopted when general seismic integrity is required. In regions requiring an average critical bending strain on the order of 1.5%, however, the high-strain X80-grade pipes must be adopted.

### 5. Strain-Based Evaluation of Integrity against Bending Deformation (Girth Welding)

The linepipe materials now produced have high toughness as well as high strength. These materials are very unlikely to succumb to brittle fracture, even when crack-like damages larger than defects occur in actual construction work. For the major deformation examined in this paper, we therefore speculate that plastic collapse and ductile crack propagation may be more relevant factors than brittle fracture in disallowing service. This chapter therefore focuses on the occurrence of a ductile crack, the initial event leading to the ductile fracture phenomenon. Specifically, we evaluate the integrity under this condition by considering a limit equivalent plastic strain at a notch tip.

#### 5.1 Ductile Crack Initiation Limit in Girth Welding

A steel material equivalent to X80-grade was used as the base metal, and butt joints were prepared by GMAW (gas metal arc welding). For the welding conditions, girth welds of an actual pipeline were simulated and the weld metal was overmatched with the base metal both in YS and TS. The wide plate (WP) test piece shown in Fig. 6 was fabricated from the joint. A semi-elliptical notch of 3 mm in depth, and 70 mm in width, and 5 mm in depth and the same width, was introduced into both the middle portion of the final pass of the weld metal and the CGHAZ (coarse grain-HAZ). The radius at the top of the semi-elliptical notch was 0.1 mm in both

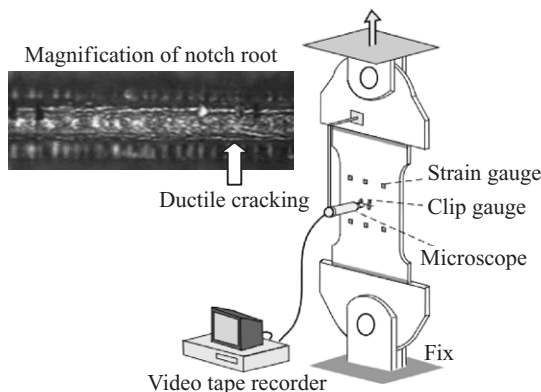


Fig. 6 Wide plate test for ductile cracking evaluation

places. The deepest notch portion was observed under a microscope and the relationship between the initiation of a brittle crack and global strain was monitored.

The test piece shown in Fig. 6 was modeled with 3-D solid elements and studied by FEA. After confirming that the measured values agreed with the results of the FEA on the creep gage displacement and the behavior of global strain, we identified the global strain at the point of ductile crack initiation during the experiment. The equivalent plastic strain at the ductile crack initiation limit of the weld metal used in this experiment was 0.69, and that of the X80-grade steel material used was 1.2.

#### 5.2 Examination of Integrity with Respect to Ductile Crack Initiation Limit in Welds

The tensile stress values for the compressive strain limit in the pipes having an outside diameter of 762 mm are read from the bending deformation analysis of high-strain X80-grade and conventional X-80 grade pipes shown in Tables. 3 and 4. The equivalent tensile stress imposed when the equivalent plastic strain at the notch bottom reached the threshold value was quantified in series in the present analyses, and the values for the local buckling limit on the compression side were compared with those for the ductile crack initiation limit on the tension side.

The results of the comparison are shown in Tables 7 and 8. Difficulties in performing this test compel us to examine the values of equivalent plastic strain related to the ductile crack initiation limit in the HAZ. For the

Table 7 Equivalent plastic strain corresponds to the two times outside diameter average critical compressive strain of the X80 high-strain steel pipe

OD (mm)	Design factor	$\epsilon_{2Der}$ (%)	WM notch		HAZ notch	
		Ten.	$\epsilon_{Ter}$	Ten./ $\epsilon_{Ter}$	$\epsilon_{Ter}$	Ten./ $\epsilon_{Ter}$
762	0.00	1.16	1.65	0.70	3.33	0.34
	0.40	1.04	—	—	2.13	0.49
	0.60	0.92	1.69	0.54	1.83	0.50
	0.72	0.86	1.90	0.45	1.59	0.54

WM: Welded metal

Table 8 Equivalent plastic strain corresponds to the two times outside diameter average critical tensile strain of the X80 conventional pipe

OD (mm)	Design factor	$\epsilon_{2Der}$ (%)	WM notch		HAZ notch	
		Ten.	$\epsilon_{Ter}$	Ten./ $\epsilon_{Ter}$	$\epsilon_{Ter}$	Ten./ $\epsilon_{Ter}$
762	0.00	0.65	0.90	0.72	2.62	0.25
	0.40	0.54	—	—	1.41	0.38
	0.60	0.53	1.13	0.47	1.31	0.40
	0.72	0.55	1.08	0.51	1.21	0.45

present, however, we evaluate the values in terms of the same equivalent strain applied in the base metal on the assumption that the zone has no effect on the inclusions that provide initiation points for the ductile voids, even when the effects of welding heat change the strength properties.

The critical compressive strain of high-strain X80-grade pipes with an outside diameter of 762 mm subjected to bending deformation is 1.87% in the absence of internal pressure, and 2.82% at a design factor of 0.72. The tensile strains under these two conditions are 1.16% and 0.86%, respectively. If we assume from the experimental results of the preceding chapter that the equivalent plastic strain at the ductile crack initiation limit is 0.65 for the weld metal and 1.2 for the base metal and the HAZ, then the tensile strains imposed when the equivalent plastic strain at the notch bottom reaches its threshold value are 1.65% and 1.09% for the notch in the weld metal and 3.33% and 1.59% for the notch in the HAZ.

Therefore, even when a relatively large defect of 70 mm in full length and 3 mm in depth is assumed to be present on the inner surface of the pipe, we can expect the local buckling on the compression side to occur before the initiation of the ductile crack under the conditions applied for this comparison. We can also ascertain that the tensile stress imposed when this compressive strain limit is reached has a safety factor of about double the limit to the tensile strain imposed when a ductile crack appears at the notch bottom.

## 6. Conclusion

This paper has outlined a basic concept for the seismic design of high-pressure gas pipelines in Japan and presented problems with the strain capacity of pipelines made from X80-HSLPs and the like. A general method for improving the strain capacity of linepipes to withstand deformation is to increase the wall thickness of the pipe. This has a disadvantage, however, as an increased

wall thickness drives up the costs of construction.

The high-strain LP has a strain capacity superior to that of the conventional linepipes, with no increase in wall thickness. It was engineered by solving problems with high-strength materials related to strain capacity. The use of the high-strain LP for high-pressure gas pipelines would improve the integrity of pipelines in seismic areas and cold regions while holding rises in construction costs to a minimum.

The authors will be glad if the design concept and strain capacity of the high-strength linepipes described in this report contribute to the basic designs of high-pressure gas pipelines in the future.

## References

- 1) Glover, A. Application of Gade 550 (X80) and Grade 690 (X100) in Arctic Climates. Proc. of Pipe Dreamers' Conference on Application and Evaluation of High-Grade Linepipes in Hostile Environments. 2002.
- 2) JGA (Japan Gas Association). Seismic Design Codes for High-Pressure Gas Pipelines. JGA-206-03, 2004.
- 3) JGA (Japan Gas Association). Seismic Design Codes for High-Pressure Gas Pipelines. considering Liquefaction-Induced Permanent Ground Deformation. JGA-207-01, 2001.
- 4) Suzuki, N.; Endo, S.; Yoshikawa, M.; Toyoda, M. Effect of Strain-hardening Exponent on Inelastic Local Buckling Strength and Mechanical Properties of Linepipes. Proc. of the 20th OMAE. 2001, paper no. OMAE2001/MAT 3104.
- 5) Suzuki, N.; Toyoda, M. Critical Compressive Strain of Linepipes Related to Work-Hardening Parameters. Proc. of the 21st Int. Conf. on OMAE. 2002, paper no. OMAE2002-28253.
- 6) Zimmerman, T.; Timms, C.; Zhou, J.; Glover, A.; Suzuki, N. Local Buckling and Post-Buckling Behavior of High Strength Linepipe. Pipeline Technology Conf. 2004.
- 7) Suzuki, N.; Kondo, J.; Endo, S.; Ishikawa, N.; Okatsu, M.; Shimamura, J. Effect of Geometric Imperfection on Bending Capacity of X80 Linepipe. Proc. of the 6th Int. Pipeline Conf. 2006, paper no. IPC2006-10070.
- 8) Gerard, G. Compressive and Torsional Buckling of Thin Wall Cylinders in Yielded Region. NACA. 1956, TN-No. 3726.
- 9) Ramberg, W.; Osgood, W.R. Description of Stress-Strain Curves by Three Parameters. NACA. 1943, TN. 902.
- 10) Zimmerman, T. J. E.; Stephens, M. J.; DeGeer, D. D.; Chen, C. Compressive Strain Limits for Buried Pipelines. 1995 OMAE. 1995, vol. V, Pipeline Technology, p. 365–378.