NK-Hiper Provides High Performance to Resist Earthquake-induced Ground Deformation

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There is a long history to verity the safety and effectiveness of welded pipelines conveying oil or gas during past earthquakes. Highly pressurized gas pipelines are now required to survive even in strong ground motion after the 1995 Hyogo-ken Nambu earthquake. Moreover additional design codes have been discussed to take liquefaction-induced lateral spreading into consideration. The deformability of pipelines is defined by their inelastic axial and/or bending buckling strength. NKK has developed a new line pipe with higher deformability, NK-Hiper. NK-Hiper provides higher safety compared with conventional pipes of the same specification. This paper describes material properties, inelastic local buckling strength and nonlinear deformation of NK-Hiper against permanent ground displacements and fault movement.

1. Introduction

Basic seismic-resistant performance required of buried pipelines includes flexible deformation responding to various kinds of ground movement resulting from earthquakes, and capability of maintaining transportation function of the pipelines through excellent toughness of the steel pipes even under large deformation.[1)]

From the lessons learned from the 1995 Hyogo-ken Nambu earthquake[2)], the seismic design of buried pipelines adopted the two-stage design method. The design method not only set the earthquake-input by two stages, but also classified the network system of the pipeline concerned into the upstream system of greater importance and other systems. The major pipeline structure of the upstream system requires the basic performance of no leakage even when the pipeline is deformed under a Level 2 ground motion, which is a higher level of motion.

During 1999, there occurred the Kocaeli earthquake in Turkey and the ChiChi earthquake in Taiwan. It is our living memory that both of them caused certain damage to buried pipelines. The main causes of damage to buried pipelines were fault movement and ground liquefaction during the Kocaeli earthquake, and fault movement in the ChiChi earthquake. It is known that the strain and deformation generated in buried pipelines caused by lateral spreading and fault movement of the ground are larger than those caused by Level 2 ground motion. These variables are important load conditions in view of studying the earthquake resistance of buried pipelines. The discussion of lique-

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faction and fault movement in the design remains a future issue to be resolved.

Therefore, to further increase the safety of pipeline systems, NKK developed a new conceptual line pipe, which was introduced in a previous paper.[3)]

For the newly developed NK-Hiper line pipe, a series of evaluation experiments were conducted on the characteristics of the material and on the performance of the pipe under bending load mainly applied to a buried pipeline. Furthermore, detailed effects in the case that the developed material is applied to a piping system were identified through numerical analyses on a combination of bend pipes and straight pipes and on a straight pipe subjected to prescribed displacement caused from ground motion. This paper describes these experiments and numerical analyses.

2. Material characteristics of the line pipe

Previous papers[3),4)] focused on the buckling strength of steel pipes. In this paper, material ductility and toughness were investigated between standard materials and NK-Hiper, as shown in **Table 1**.

Table 1 Mechanical properties of tested pipes

Pipe*1)	YS MPa	TS MPa	YR %	n-value*2)
LN1	481	554	81	0.08
LN2	516	596	87	0.08
LN3	557	637	87	0.07
LN4	578	646	90	0.06
HN1	455	614	74	0.22
HN2	548	724	76	0.16
HN3	553	752	74	0.21
HN4	579	755	77	0.16

*1) Standard : LN1–LN4, Hiper : HN1–HN4
*2) n-value estimated in strain range of 1–4%

2.1 Uniform elongation test

It is thought that characteristics of the material is reflected on those of the steel pipes.[5)] To this point, strip specimens were prepared by cutting them from steel pipe, and the uniform elongation test was carried out.

Fig. 1 shows the geometry of specimen applied to the tension test. Elongation of the specimen after fracture is observed at the local elongation part and at uniform elongation part. Several methods are applicable to determine the uniform elongation, and the Barba's experimental equation (e.q.(1)) is practically used.

$$\varepsilon = \alpha + \beta \{(\sqrt{A}) / l\} \quad \cdots\cdots (1)$$

where, ε is the fracture elongation, α and β are respective constants, A is the original cross sectional area, and l is the gauge length. The uniform elongation α is assumed as an inherent value for the material, and the local elongation is assumed proportional to the square root of the original cross sectional area of the specimen and inversely proportional to the gauge length.

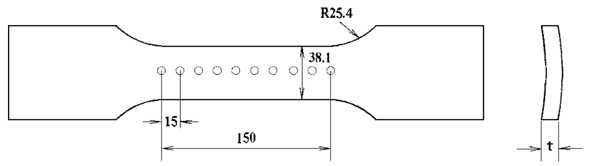

Fig. 1 Geometry of specimen for uniform elongation test

Fig. 2 shows results of uniform elongation test for HN4. **Fig. 3** shows the relation between the material strength and uniform elongation. As shown in these figures, compared with the standard materials, NK-Hiper exhibits increased uniform elongation while increasing in tensile strength. The test results show that NK-Hiper has excellent deformation performance not only to compression load but also to tensile load.

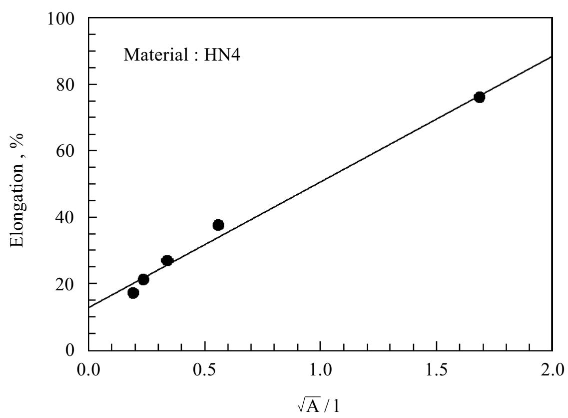

Fig. 2 Results of uniform elongation test (HN4)

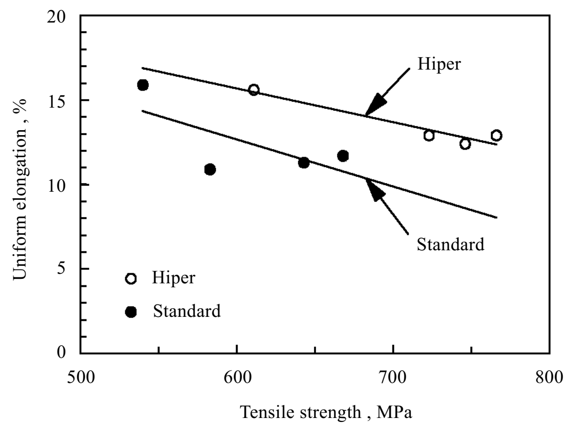

Fig. 3 Relationships between uniform elongation and tensile strength

2.2 Critical strength under multiaxial stress

Since a buried pipeline is subjected to large deformation, the pipe body may be under a multiaxial stress state. In the case that significant unidirectional ground displacement imparts large deformation to the pipe body, the evaluation of the safety margin to fracture may be carried out using the method of Otsuka et al., “the steel fracture evaluation method under multiaxial stress condition”[6),7)].

According to the method of Otsuka et al., a notched round bar specimen shown in **Fig. 4** is prepared, and the fracture ductility of the material is evaluated by varying the stress triaxiality at the most severely deformed part according to the longitudinal curvature (Ro=1.27–6.34 mm) of the notch tip at the cross section of the specimen. **Fig. 5** shows the longitudinal cross sectional view of the notched section after the tensile test. Void occurrence was observed at the center portion of the specimen.

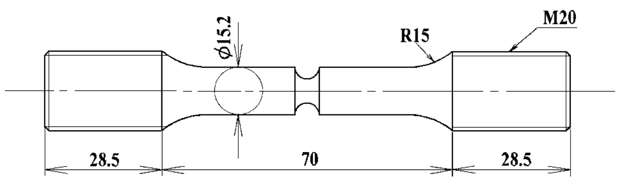

Fig. 4 Geometry of notched round bar specimen for tensile test

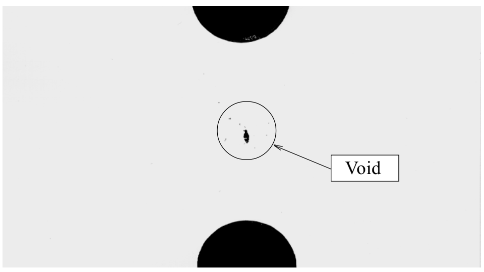

Fig. 5 Appearance of longitudinal cross section of tested specimen

The stress triaxiality and the equivalent stress can be expressed as the following equations, eq.(2) and eq.(3), by Bridgeman’s formulation.

$$\sigma_m / \sigma_{eq} = (1/3) + \ln\{(D/4R) + 1\} \qquad \cdots\cdots (2)$$

$$\varepsilon_{eq} = 2 \ln(D_0/D) \qquad \cdots\cdots (3)$$

where, σ_m is the hydrostatic mean stress, σ_{eq} is the equivalent stress, ε_{eq} is the equivalent strain, D_0 is the cross sectional diameter of notch tip before the test, D is the cross sectional diameter of notch tip after the test, and R is the longitudinal curvature of the notch tip at the cross section after the test.

Fig. 6 shows the fracture initiation curves for standard materials and for NK-Hiper, respectively. Increase in the stress triaxiality decreases the equivalent strain that induces fracture. NK-Hiper, however, exhibits higher ductility on fracture than that of standard materials. This fact suggests that NK-Hiper has larger safety margin than that of the standard materials to the fracture of steel pipe in the case that the steel pipe is subjected to large ground displacement.

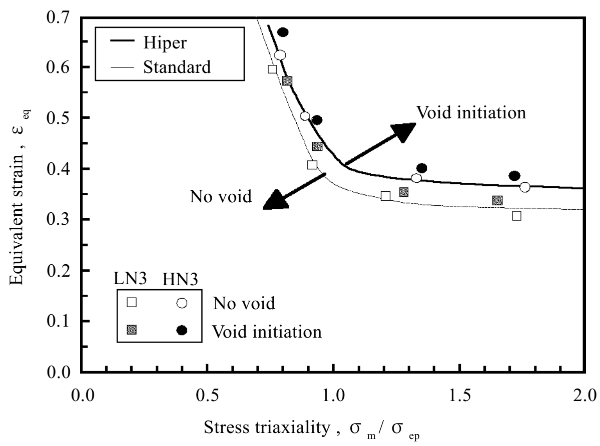

Fig. 6 Comparison of failure initiation curve between NK-Hiper and standard material

2.3 Charpy impact test

In addition to the evaluation of the ductility of steel pipe, which was conducted in previous studies and described in the preceding section of this paper, Charpy impact test was carried out. **Fig. 7** shows the result of Charpy impact tests for the standard materials and NK-Hiper. The test was conducted using full size specimens having 2 mm V notch in accordance with JIS Z2202, at –10°C testing temperature. The test revealed that both the standard materials and NK-Hiper showed 160 J or higher toughness level, which causes no problem in practical use.

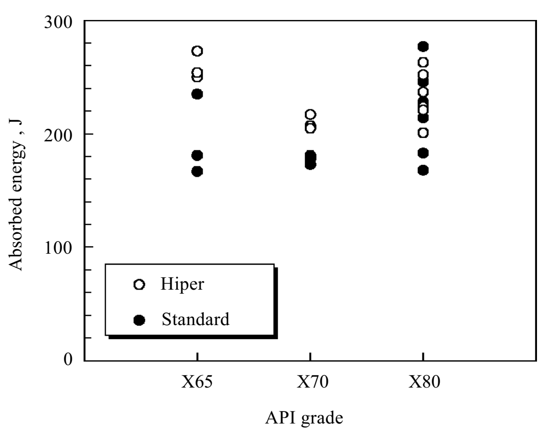

Fig. 7 Results of Charpy impact test

3. Structural strength of line pipe

Regarding bending strength, which is an important evaluation item for assuring seismic resistance, investigation was carried out targeting single straight pipe, combined bend and straight pipes, and pipe buried underground. The determined effect of material characteristics is described below.

3.1 Bending strength

3.1.1 Experimental method

In addition to the bending test without internal pressure, applied in the previous tests, the experiment this time was conducted for straight pipe under 10 MPa of internal pressure. Comparison of the standard materials with NK-Hiper was given with a common specimen size of 610 mm in diameter, 12.7 mm in thickness, and 3300 mm in length. As for the material of the respective specimens, the standard material used LN3 in **Table 1**, and NK-Hiper used HN3.

Fig. 8 illustrates the concept of bending test of a straight pipe. The specimen comprises a testing pipe, a sleeve pipe, and jigs. The bending deformation is applied by prescribed displacement to the edge portion of respective jigs. Strain gauges are attached to the pipe body to determine the local strain appearing on the pipe body during loading. **Photo 1** shows appearance of a specimen after the test. The deformation mode is one that generates buckling deformation at center portion of the specimen.

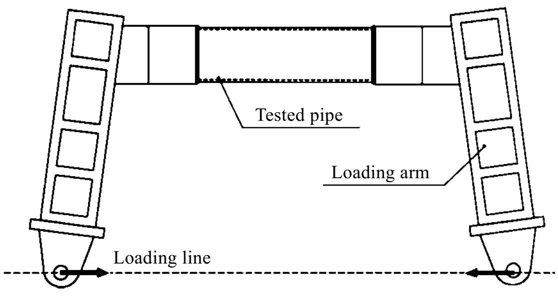

Fig. 8 Geometry of tested pipe for bending

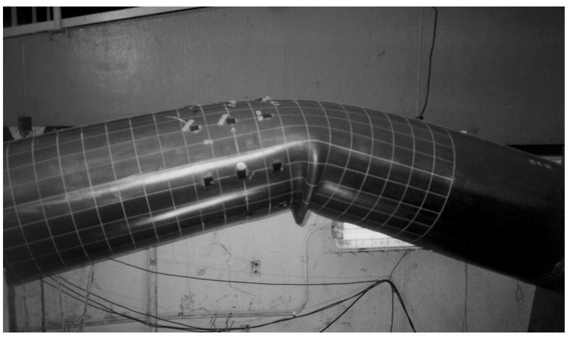

Photo 1 Tested pipe (HN3)

3.1.2 Experimental result

Fig. 9 shows the relation between the bending moment and the bending angle. **Fig. 10** shows the relation between the maximum compressed strain in the axial direction and the bending angle observed during loading. There is a trend that the maximum compressed strain significantly increases as bending buckling appears. **Fig. 11** shows the relation between the bending angle, the local strain, and the strain hardening exponent, at the occurrence of bending buckling. It was experimentally verified that, compared with the standard materials, NK-Hiper gives about 1.5 times the bending buckling strain and bending angle, even under internal pressure as high as 10 MPa. Furthermore, it was confirmed that the bending buckling strain and bending angle depends on the strain-hardening exponent of the material.

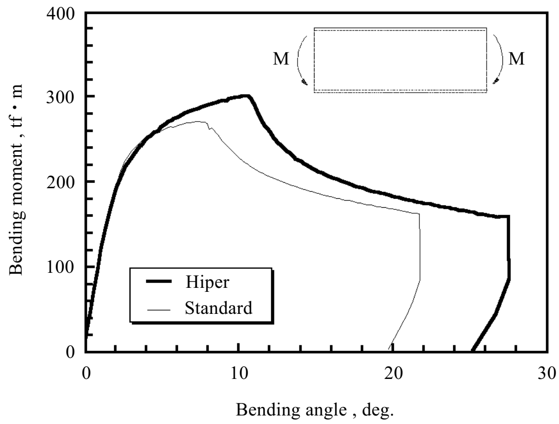

Fig. 9 Bending moment versus bending angle

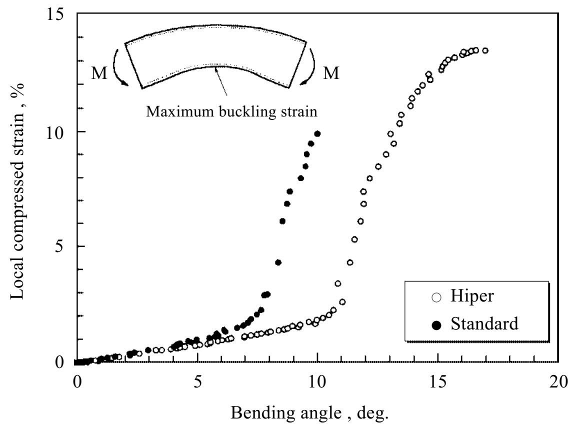

Fig. 10 Local compressed strain versus bending angle

3.1.3 Numerical analysis

Using specimens of HN3 and LN3, a bending analysis for straight pipe was conducted by applying the ADINA[8] 4 node shell elements. **Fig. 12** shows the relation between the bending moment and the bending angle, and **Fig. 13** shows the relation between the maxi-

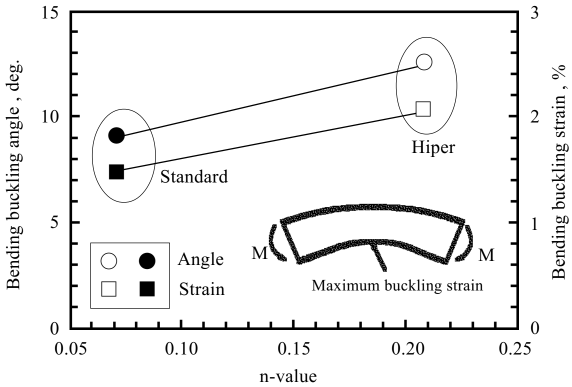

Fig. 11 Bending buckling angle and strain versus n-value

mum compressed strain in the axial direction and the bending angle. Until the start of bending buckling, the load curve of the experiment and that of the numerical analysis showed good agreement to each other. The strain history showed almost the same tendency both in experiment and numerical analysis. **Fig. 14** shows deformation of respective specimens at a bending angle of 12°. The standard material pipe body shows distinctive yield waveforms.

Through the study, it was confirmed that NK-Hiper has a larger safety margin to bending buckling than that of standard materials in view of both the experiment and of numerical analysis.

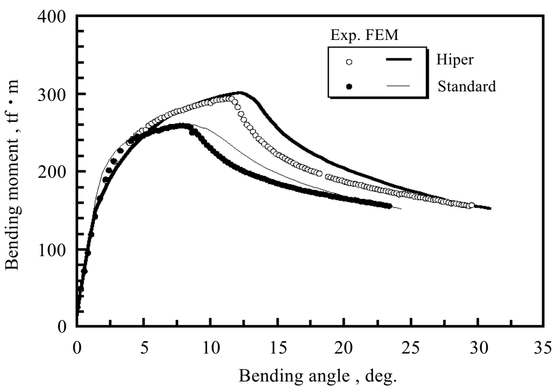

Fig. 12 Comparison of bending moment versus bending angle between exp. and FEM

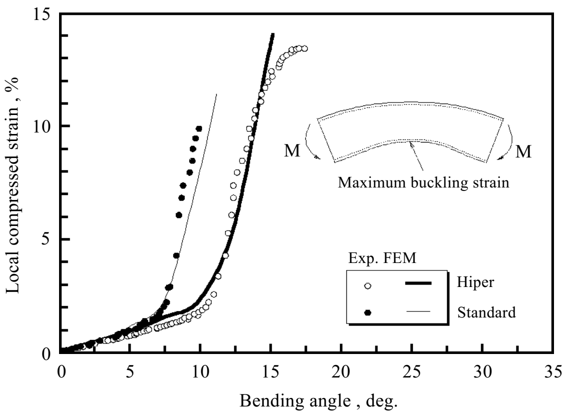

Fig. 13 Comparison of strain versus bending angle between exp. and FEM

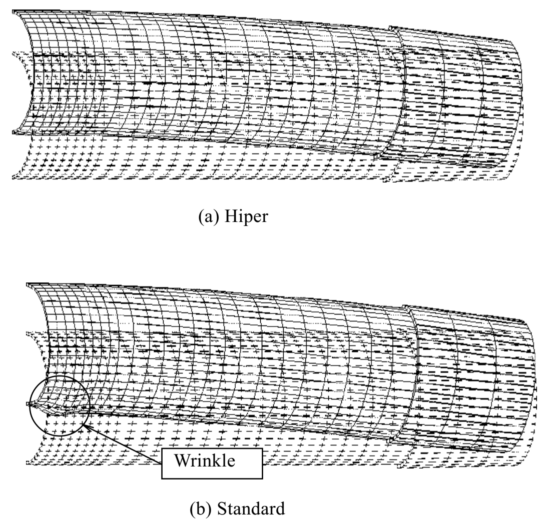

Fig. 14 Deformations of pipes at 12° bending angle by FEM

3.2 Analysis of combined bend pipes and straight pipes

The above-described evaluation on the structural strength to axial compression and bending is for a single straight pipe. This section describes the evaluation of earthquake resistance for the case of combined bend pipes and straight pipes.

3.2.1 Analytical method

Investigation was conducted into the history of maximum strain on the opening mode bending, with the variables of straight pipe material joined to the bend pipe. The opening mode bending means to bend a pipe in the direction to increase the radius of curvature of the bend, as shown in **Fig. 15**.

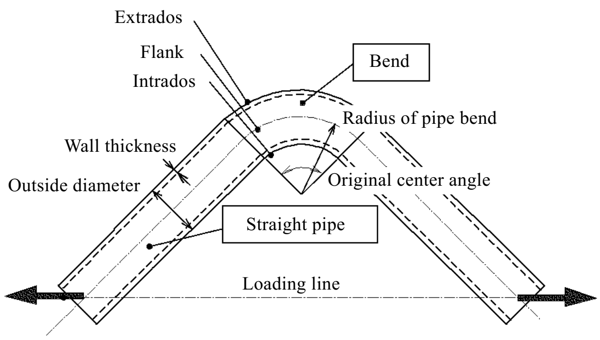

Fig. 15 Schematic figure of opening mode bending

The dimensions for the analytical model was a bend having 610 mm in pipe diameter, 12.7 mm in pipe thickness, 1830 mm in radius of the bend, and 90° in bending angle. **Fig. 16** shows the stress-strain curve of the material of the straight pipe section. The tested materials were, adding to LN3 and HN3, materials having specified minimum yield strength and yield plateau.

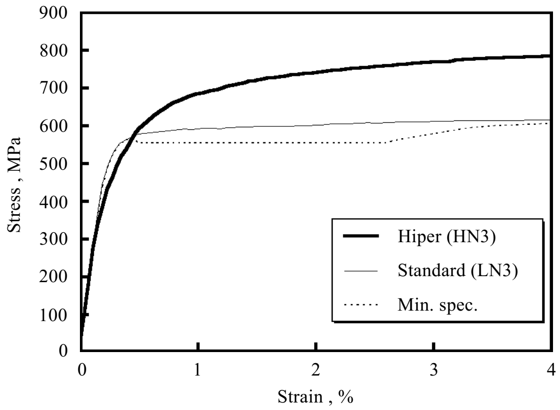

Fig. 16 Stress strain curves

3.2.2 Result of analysis

Fig. 17 shows an example of deformation observed on a standard material at 20° of bending angle. Because the bending rigidity at the bend pipe section increases due to the flattening of cross section of the bend pipe, it is known that the maximum tensile strain occurs in the straight pipe section connected to each end of the bend pipe. The analyses also indicated that the maximum tensile strain appeared in the straight pipe section, as in the case of previous studies.

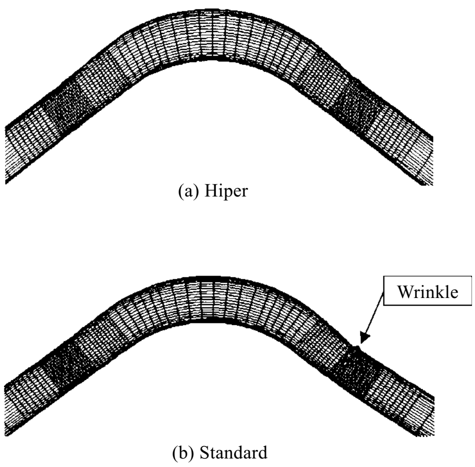

Fig. 17 Deformations of pipes at bending angle 20° by FEM

Fig. 18 shows the relation between the bending moment and bending angle. The figure shows that NK-Hiper gives a larger bending angle that initiates the bending buckling and provides larger deformation performance than that of the standard materials. **Fig. 19** shows the relation between the maximum tensile strain and the bending angle. Compared with the standard materials, NK-Hiper shows a tendency of decreasing the generated strain to the same bending angle due to its strong deformation resistance. Thus, NK-Hiper was confirmed to have the effect of suppressing the generated strain applied to a pipeline system.

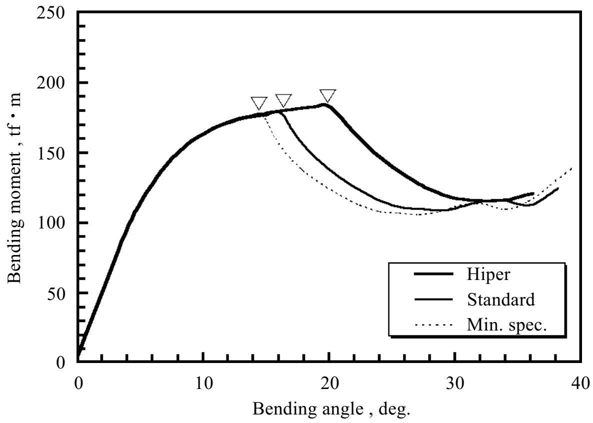

Fig. 18 Bending moment versus bending angle for opening mode bending by FEM

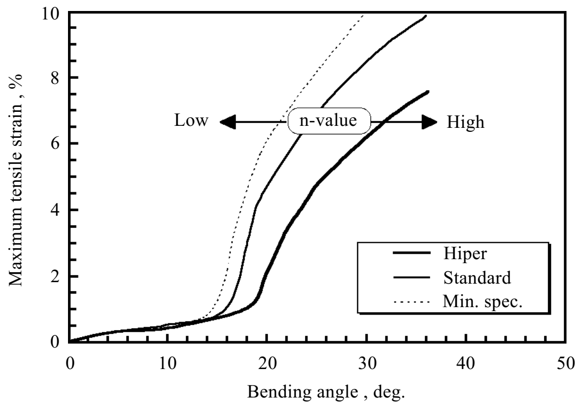

Fig. 19 Maximum tensile strain versus bending angle for opening mode bending by FEM

3.3 Application to buried pipeline

The deformability of buried pipeline against lateral spreading and fault displacement was evaluated on a straight pipe of 610 mm in diameter and 14.7 mm in thickness using FEM. The materials compared were LN1 and HN1 shown in **Table 1**.

3.3.1 Evaluation of earthquake resistance against lateral spreading

To investigate the earthquake resistance of buried pipeline against lateral spreading, a lateral spreading defined by an elliptical domain on the ground surface, illustrated in **Fig. 20**, was established. The pipeline was assumed to be buried along the minor axis of the elliptical domain. Through lateral spreading, the pipeline was assumed to receive a horizontal external force in the lateral direction to the pipe axis.

Fig. 21 shows the pipe-soil interaction of lateral spreading. The model takes into account that the increase in permanent deformation of ground increases the shear deformation, and that the increase in the shear deformation decreases the shear rigidity.

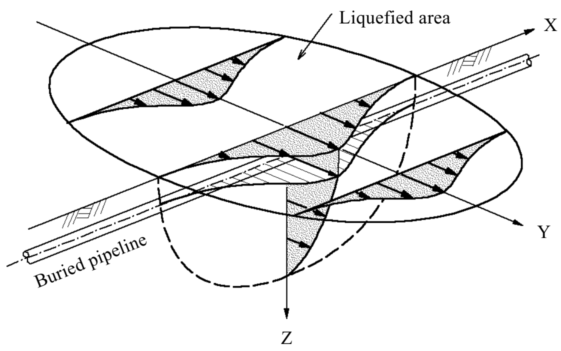

Fig. 20 Deformation of buried pipeline due to lateral spreading

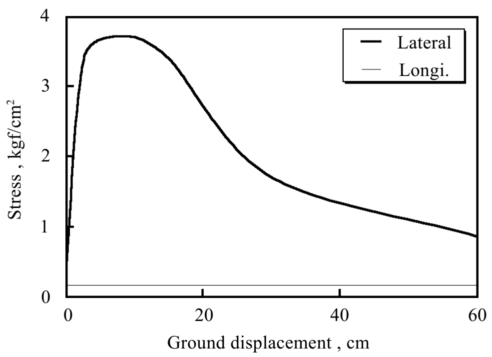

Fig. 21 Pipe-soil interaction (lateral spreading)

Fig. 22 shows the relation between the ratio of maximum compressed strain to the local buckling strain apparent in a pipe and the permanent ground displacement. The chain line indicates that the maximum compressed strain is reached at the local buckling strain. In the region above the chain line, the local buckling initiates. As shown in the figure, the standard material increases in strain ratio according to the permanent ground displacement, and induces local buckling at about 70 cm of maximum ground displacement. In contrast, NK-Hiper gradually increases in strain ratio up to about 150 cm at an increasing rate of about half that of the standard material, and shows the increase in the strain ratio at or above 150 cm of ground displacement.

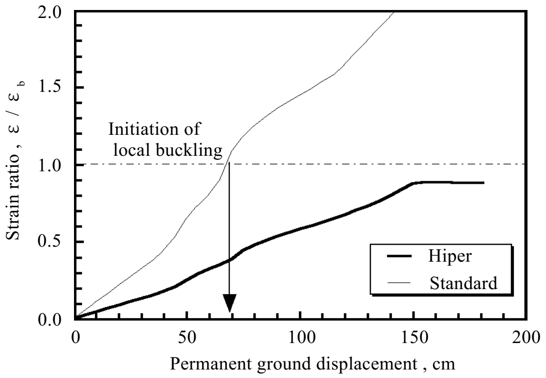

Fig. 22 Relationship between strain ratio and PGD (lateral spreading)

3.3.2 Evaluation of earthquake resistance against the fault displacement

To investigate the earthquake resistance against fault displacement, a right lateral sliding fault model, shown in **Fig. 23**, was established. In this model, the fracture face of the fault is assumed to be a vertical single shear plane, and the buried pipeline is assumed to be lateral to the fault fracture face. **Fig. 24** shows the pipe-soil interaction of fault movement.

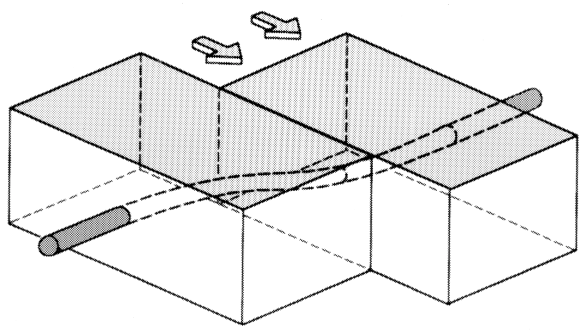

Fig. 23 Deformation of buried pipeline due to fault movement

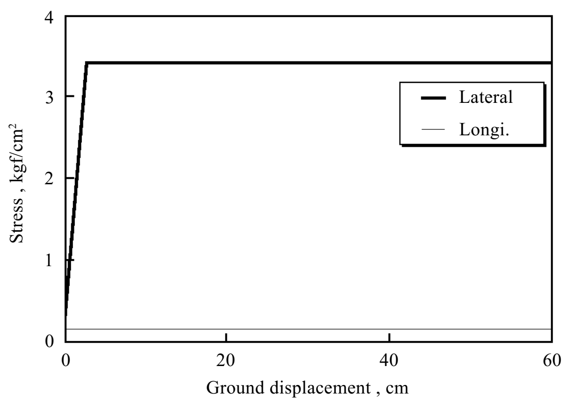

Fig. 24 Pipe-soil interaction (fault movement)

Fig. 25 shows the relation between the maximum compressed strain ratio and the fault displacement. Both the standard material and NK-Hiper increased the maximum compressed strain ratio along with the deformation of fault, similar to the case of lateral spreading (**Fig. 22**). On the standard material, the local buckling initiates at about 1 m of fault displacement. On NK-Hiper, however, the local buckling does not initiate even after the fault displacement reached to 2 m, and the maximum compressed strain remains at about 40% of the local buckling strain.

4. Conclusions

With focus on the high-pressure gas pipelines, the newly developed line pipe of larger n-value type were tested in full-scale steel pipe experiments. At the same

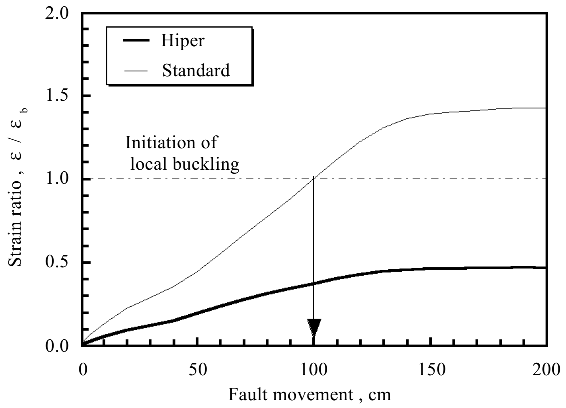

Fig. 25 Relationship between strain ratio and fault movement (strike slip)

time, numerical analyses on a pipeline system of combined bent and straight pipe was performed to conduct evaluation of the structural strength as a pipeline system, and verification of the effect of the buried pipeline system against ground displacement. The investigations revealed the following-described findings.

(1) Compare with the standard materials, NK-Hiper has larger uniform elongation, and is a material that has large deformability against not only to compression but also to tensile load.

(2) Under an internal pressure condition, the bending buckling strain and the bending angle of a straight pipe increase to about 1.5 times as n-value of the steel pipe material increases.

(3) In an opening mode bending analysis applied to a piping system of combined bend and straight pipe, the application of NK-Hiper to the straight pipe section provides increased deformation performance up to the initiation of bending buckling and the suppression of generated strain.

(4) The behavior of buried pipeline against lateral spreading and fault movement was numerically analyzed to confirm that NK-Hiper has an effect to increase the deformation absorption performance compare with the standard materials.

It is expected that the application of the developed steel pipe with improved buckling characteristics contributes to the construction of further safe pipeline system.

We would like to express our appreciation to Professor Masao Toyoda, Osaka University for his advice and cooperation on the development of line pipes having superior earthquake resistance.

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