Paper No. 1783. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ESTIMATION OF THE DEFORMATION BEHAVIOR OF ELBOWS FOR AN EARTHQUAKE-RESISTANT DESIGN

K. YOSHIZAKI and N. OGUCHI

Fundamental Technology Research Laboratory, Tokyo Gas Co., Ltd.,
1-16-25, Minato-ku, Tokyo, 105, JAPAN

ABSTRACT

An analysis method has been established for elbows where deformation and strain are concentrated in buried pipelines during earthquakes. It can accurately predict experimental results not only in the elastic region, but also in the plastic region over 5% of strain. Various dimensions of elbows were analyzed using this method, and as a result, apart from the bending moment, the relationship between the maximum strain and the bending angle is found to be independent of a diameter, a wall thickness and an elbow radius. Furthermore, a buried pipeline including an elbow was analyzed on a supposition of lateral ground displacement, and useful result was obtained for generally estimating the earthquake resistance of typical buried pipelines.

KEY WORDS

Buried Pipeline; Finite Element Analysis; Elbow; Ground Liquefaction; Lateral ground displacement; Elastic-plastic Analysis; Large deformation; Earthquake-resistance.

INTRODUCTION

Ground liquefaction during earthquakes may produce a phenomenon called lateral ground displacement which yields permanent ground deformation at shore walls and so on. For example, in the Hyogoken-Nambu Earthquake (January 17, 1995), shore wall collapse was caused in numerous locations; indeed, it was reported that shore walls surrounding Rokko Island jutted out to sea by an average of 2 m and a maximum of 6.9 m.

In weak earthquakes with small displacement of the ground, buried pipelines including elbows undergo subgrade reactions proportional to the relative displacement of the ground around the pipes. In such cases, straight pipes and elbows support individually the subgrade reactions. It is feared, however, that the deformation concentrates upon the elbow parts due to the initiation of the slide between the straight pipes and the ground around the pipes during strong earthquakes with large displacement of the ground. As a consequence, large level of plastic strain will be induced on those parts.

In this paper, Finite Element Analysis (FEA) method was applied to evaluate the plastic strain of buried pipelines. First of all, an analysis method for evaluating the deformation behavior of elbows, and its validity was verified by a comparison with experimental results. Then we utilized this method to reveal differences in earthquake resistance characteristics of elbows by varying diameter, wall thickness or elbow radius. Furthermore, these results were utilized to obtain the maximum strain of a buried pipeline including an elbow, and useful result was obtained for generally estimating the earthquake resistance of typical buried pipelines.

DEFORMATION BEHAVIOR OF ELBOWS

Previous Work

When an elbow is subjected to a bending moment, the resulting deformation does not follow the simple Bernoulli-Euler bending theory. Rather, the deformation is far greater than that predicted by the theory; and localized strain is also very large. Kármán (1911) has proposed a stress intensification factor and a flexibility factor to express the exact stresses. This approximation method is also used in ASME Sec. III Div. 1 Subsection NB.

However, it is experimentally confirmed that this method is not available in the plastic region. And there have been very few studies on the deformation characteristics of elbows in the region of large deformation. Suzuki *et al* (1990) estimated the deformation behavior of three kind of elbows by experiments and numerical analyses, and express their plastic characteristics as a corrected stress intensification factor. However, general deformation characteristics of various elbows were not obtained sufficiently.

Experiments and Analyses

In-plane bending experiments of elbows were conducted. Pipes for the tests have the diameters of 750mm, 400mm, and 200mm. Fundamental parameters are shown in Table. 1.

Table. 1. Parameters of Pipes used in Bend Testing

	750mmD	400mmD	200mmD
Diameter [mm]	770.2	406.4	216.3
Material	X52	PT38	FSGP
Elbow radius	3DR	1.5DR	1.5DR
Wall thickness [mm]	13.5	8.2	6.9
Yield stress [kgf/mm^2]	40	28	28

Here the case of 750mm-diameter pipe is discussed representatively. The test apparatus with a test specimen is illustrated in Fig. 1. One end was fixed to prevent all motion other than rotation in the plane of bending; the other end was attached to a hydraulic jack for use in loading the specimen. By these procedures, a nearly pure bending moment can be applied to the 90° elbow of the test specimen.

For comparing the experimental results and the numerical ones, the analysis model was prepared as shown in Fig. 2. Linear shell elements were used. Considering into the symmetry of the model, a 1/4 model was created. Dimensional parameters of the model for the analysis were same as the experiment. Mechanical properties were determined as illustrated in Fig. 3, based on the tensile test results. FEM structural analysis code "ABAQUS" was used to accurately handle material and geometrical non-linearity.

The strain distribution at an in-plane inward bending displacement of 280 mm by the analysis is shown in Fig. 4. The strain is associated with von Mises composite strains. As can be seen from Fig. 4, the maximum strain caused at the center of the flank of the elbow.

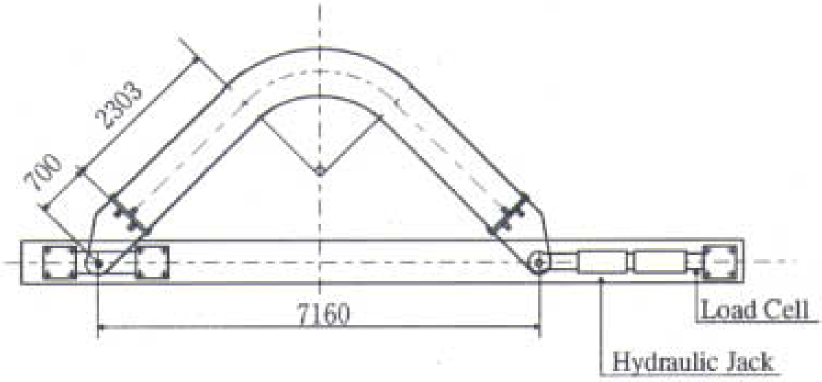


Fig. 1. Test Apparatus

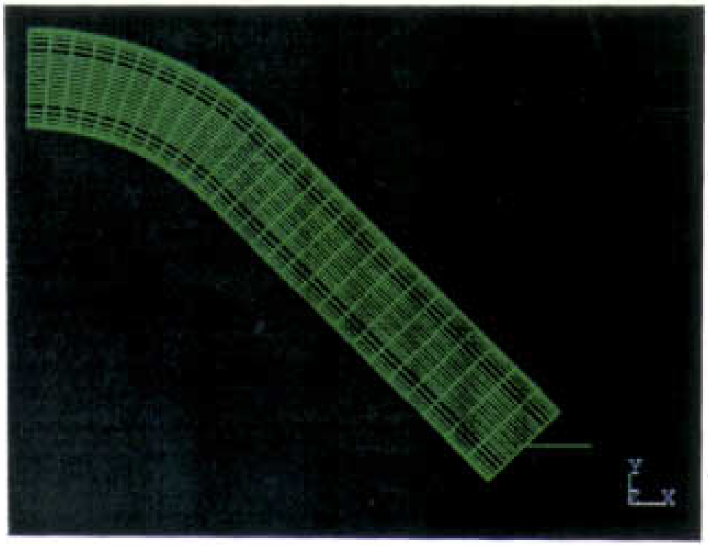
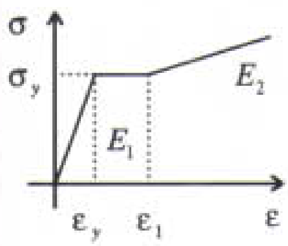


Fig. 2. Analysis Model



$\varepsilon_y = 0.193[\%]$
$\varepsilon_1 = 2.57[\%]$
$\sigma_y = 40[kgf\ /\ mm^2]$
$E_1 = 2.07 \times 10^4[kgf\ /\ mm^2]$
$E_2 = 72[kgf\ /\ mm^2]$

Fig. 3. Mechanical Properties as determined from Stress-strain Curve

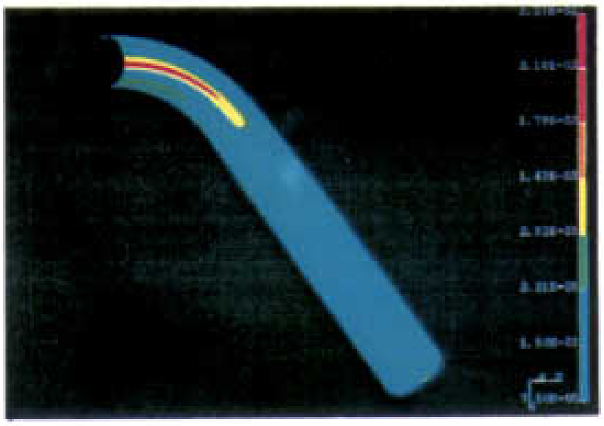


Fig. 4. Strain Distribution

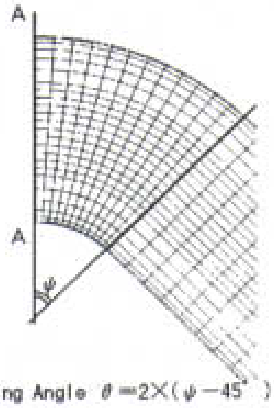


Fig. 5. Definition of Bending Angle θ

We defined a bending angle θ for the elbow as shown in Fig. 5. The relationship between the bending angle and the maximum strain that occurs in the elbow is presented in Fig. 6. The value of maximum strain in Fig. 6 was taken as the largest of the strain components (circumferential direction or axial direction) at the integration point of the elements. Fig. 7 shows the strain distribution along the circumference of section A-A in Fig. 5. In these figures, the solid line indicates the analysis result and the round or square points indicate the experimental data. These figures show a fairly good agreement between the results of analyses using this method and the experimental data. This analysis method can simulate the pronounced localized strain in the plastic region.

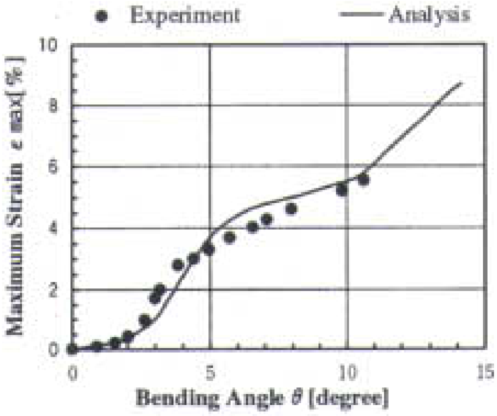
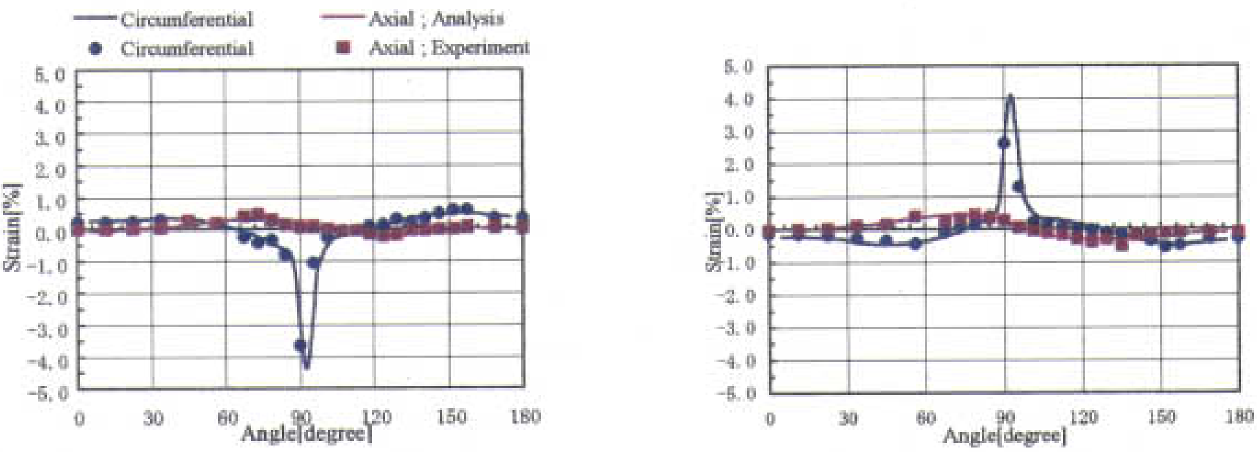


Fig. 6. Relationship between Bending Angle and Maximum Strain



(a) inner surface

(b) outer surface

Fig. 7. Strain Distribution at 280 mm Displacement (plastic region)

Estimation of Deformation Characteristics of Elbows

Similar analyses were performed for various types of elbows;

- diameter ; 100mm, 200mm, 300mm, 400mm, 600mm (1.5DR)
- elbow radius ; 1DR, 1.5DR, 3DR, 5DR (300mmD)
- wall thickness ; 7.9mm, 9.5mm, 12.7mm (600mmD)

The pipe diameter and wall thickness were taken as the normal values of Japanese Industrial Standard. Stress-strain model was similar to Fig. 3. Fig. 8 shows the relationship between the bending angle and the bending moment; Fig. 9 shows the relationship between the bending angle and the maximum strain for various diameters. Similarly, Fig. 10 and Fig. 11 show the effect of elbow radius and wall thickness, respectively. Apart from the value of the moment, the relationships of the maximum strain to bending angle are independent of pipe diameter, wall thickness and elbow radius.

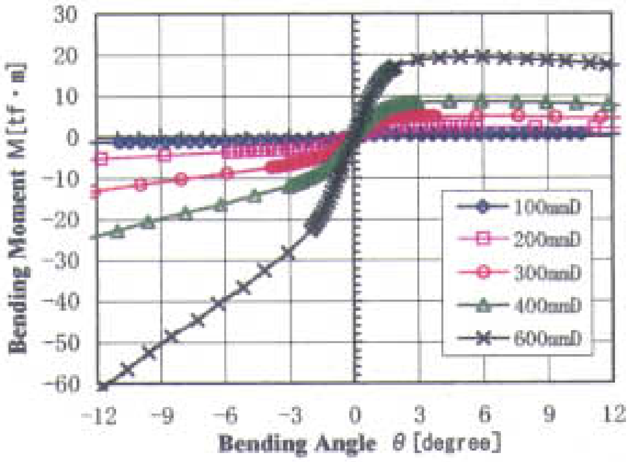


Fig. 8. Relationship between Bending Angle and Bending Moment for Various Diameters

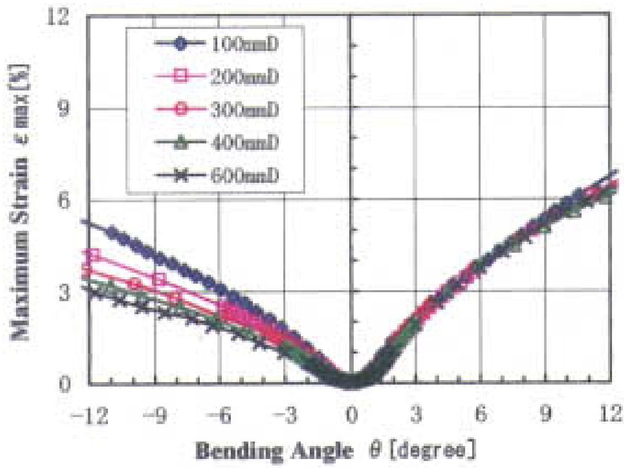


Fig. 9. Relationship between Bending Angle and Maximum Strain for Various Diameters

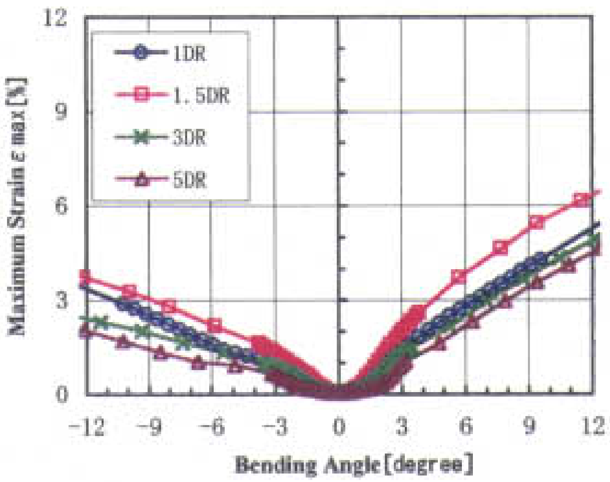


Fig. 10. Relationship between Bending angle and Maximum Strain for Various Elbow Radius (300mmD)

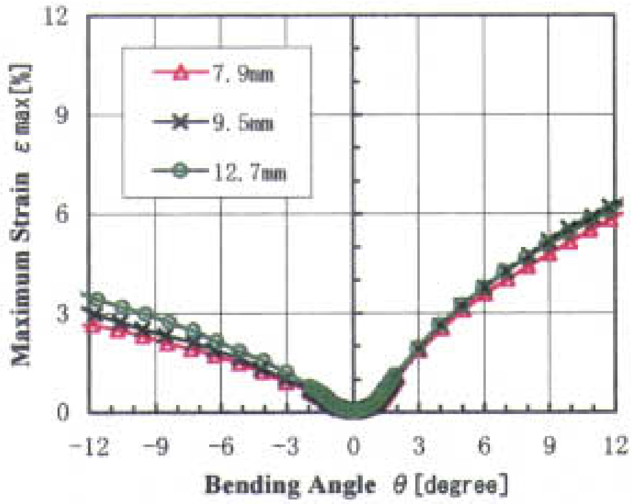


Fig. 11. Relationship between Bending angle and Maximum Strain for Various Wall Thickness (600mmD)

Utilizing the method above mentioned, we conducted deformation analyses relating to the lateral ground displacement for evaluating the earthquake resistance of typical buried pipelines in liquefaction areas. The pipeline used in the analyses is comprised of a 1.5 DR-90° elbow and a 200m length of straight pipes on both sides of the elbow.

.Lateral Ground Displacement and Subgrade reaction

We considered a ground lateral ground displacement in a plane in axial direction of one of the straight pipes and in the normal direction of another one (see Fig. 12). In Fig. 12, we took the following formulation of the lateral ground displacement;

$$Vg(x,0) = \frac{1}{2}\delta\{1+\cos(\frac{2\pi x}{W})\} \tag{1}$$

$$Vg(0,y) = \frac{1}{2}\delta\{1+\cos(\frac{2\pi y}{L})\} \tag{2}$$

,where the width W and the length L of the affected region are both 200 m.

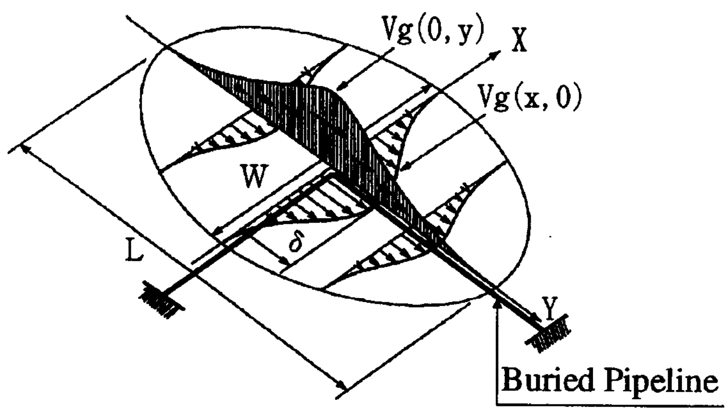
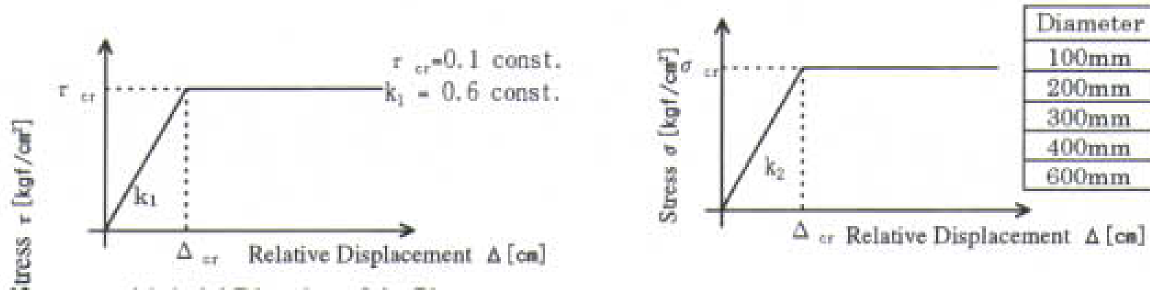


Fig. 12. Lateral Ground Displacement Distribution.

The subgrade reaction acting on the pipe consists of the components in the axial and normal directions of the pipe. Subgrade reaction in the axial direction was based on a model presented in Recommended Practice for Earthquake Resistant Design of High Pressure Gas Pipeline (Japan Gas Association, 1982) and that in the normal direction was based on a model proposed by Trautmann *et al* (1995). Here, we decided to use a model scaled down to 1/10 in relation to the inclination and the maximum subgrade reaction in the analysis of the pipeline, taking account of ground-softening due to liquefaction.



Diameter	σ_{cr}	k_2
100mm	6.5	3.6
200mm	4.9	2.7
300mm	4.1	2.3
400mm	3.5	1.9
600mm	2.7	1.5

(a) Axial Direction of the Pipe

(b) Normal Direction (Trautmann *et al*, 1995)

Fig. 13. Subgrade Reaction Model

Analysis Models

We used the following two modeling methods to create an analysis model to express the pipe.

(A) BEAM MODEL using beam elements only including a special elbow element incorporated with the deformation characteristics obtained from the results of inward/outward bending analysis with shell elements.

(B) HYBRID MODEL using shell elements in the area such as the elbow occurring pronounced localized strain linking with beam elements (Fig. 14). Continuity of deformation between the shell elements and the beam elements is guaranteed by radially-located rigid elements, shown in Fig. 15.

Subgrade reactions were given as non-linear spring elements. The lateral ground displacement shown in Fig. 12 was imposed to those elements. The analyses were carried out until the ground displacement, δ =2m.

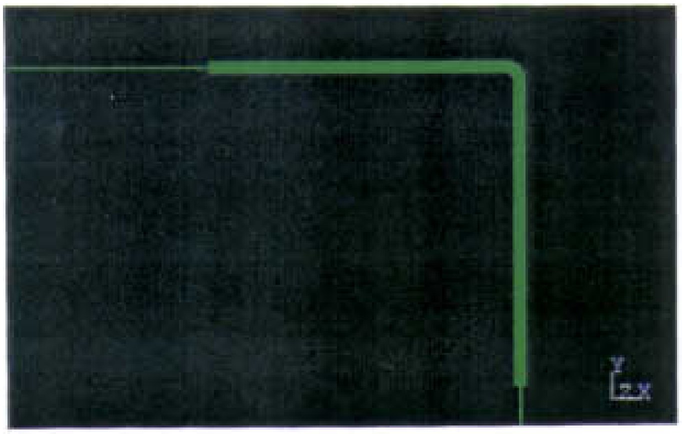


Fig. 14. HYBRID MODEL (Model (B)).

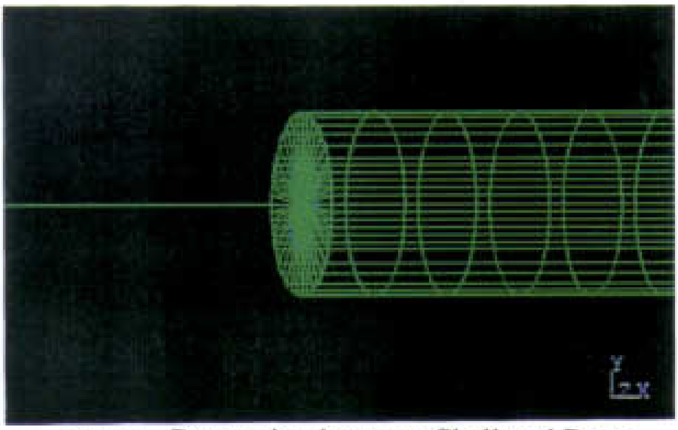


Fig. 15. Connection between Shell and Beam Elements

Analysis Results

Fig. 16 shows the relationship between the maximum strain and the ground displacement for various diameters. As can be seen in the figure, for the same ground displacement, the larger the pipe diameter is, the smaller the value of the maximum strain is. In the case of 300mm-diameter, the comparison of strains obtained by the BEAM MODEL and the HYBRID MODEL is shown in Fig. 17. The BEAM MODEL was found to estimate the maximum strain higher than the HYBRID MODEL. Such trend is considered to be induced by the ovalization of the cross section of straight pipes and the effect of the axial force on the deformation characteristics of elbows.

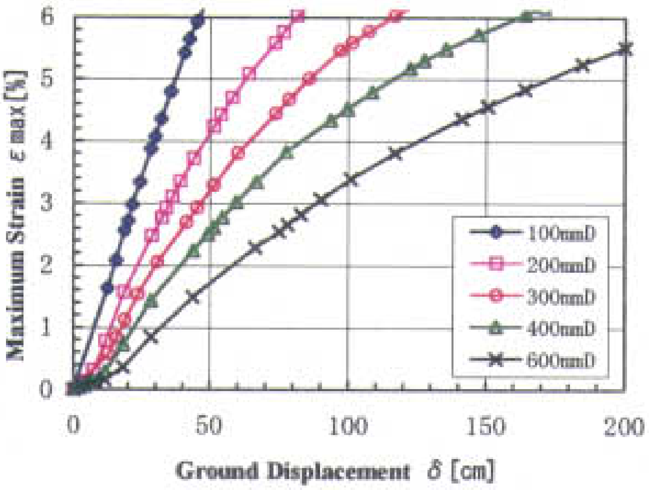


Fig. 16. Relationship between Maximum Strain and Ground Displacement

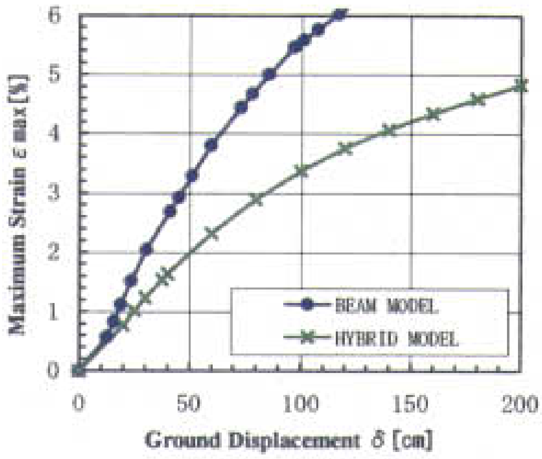


Fig. 17. Difference between BEAM MODEL and HYBRID MODEL

CONCLUSIONS

Numerical analyses based on FEM with shell elements were applied to obtain the deformation characteristics of elbows. Some bending tests for elbows were conducted and the results were compared with the analyses. A fairly good agreement on the bending moments and the maximum strains was obtained even in the range of strain over 5%. The validity of the analysis method was demonstrated. Various dimensions of elbows were analyzed using this method. As a result, apart from the bending moment, the relationship between the maximum strain and the bending angle is found to be independent of a diameter, a wall thickness and an elbow radius. Subsequently, deformation analyses relating to the lateral ground displacement were carried out for estimating the earthquake resistance of typical pipelines in a liquefaction area. As a result, it is found that for the same ground displacement the larger the pipe diameter is, the smaller the value of the maximum strain is. It is found that the BEAM MODEL incorporated with the deformation characteristics of elbows gives a higher level of the maximum strain than the HYBRID MODEL with shell and beam elements. It is considered that the difference is induced by the ovalization of the cross section of straight pipes and the effect of the axial force on the deformation characteristics of elbows.

REFERENCES

ASME. ASME SECTION III DIVISION I - SUBSECTION NB. *3653.2*, SI-13.

Japan Gas Association (1982). Recommended Practice for Earthquake Resistant Design of High Pressure Gas Pipeline.

Kármán (1911). Ueber die Formäderung dünwandiger Rohre. *ZVDI*, Vol. **55**, part 2, pp. 1889-1895.

Suzuki, N. and S. Ohba (1990). Low Cycle Fatigue Strength of Welded Elbows Subject to In-plane Bending, *Journal of Structural Engineering*, Vol. **36A**, pp. 1355-1364.

Trautmann, C. H., T.D. O'Rourke (1995). Lateral Force-Displacement Response of Buried Pipe. ASCE. *Journal of Geotechnical Engineering*, Vol. **111**, No. 9, pp. 1077-1092.