1433

DEFORMATION AND FRACTURE PROPERTIES OF STRAIGHT STEEL PIPE WITH INTERNAL PRESSURE UNDER UNIAXIAL COMPRESSIVE AND BENDING LOAD

Chitoshi MIKI[1], Noritake OGUCHI[2], Takayoshi UCHIDA[3], Atsushi SUGANUMA[4] And Takehiro INOUE[5]

SUMMARY

For the purpose of clarifying the deformation and fracture properties of the pipe with internal pressure under the large displacement, uniaxial compression tests and bending tests of API standard 5L X65 straight steel pipes with the size from 318 to 508 mm outside diameter were performed. Internal pressure using water which induces the hoop stress of 40 percents of the yield stress were applied to the steel pipe. Elasto-plastic stress analysis using finite element method was also performed in order to simulate the large deformation of the pipe. Internal pressure using water which induces the hoop stress of 40 percents of the yield stress were applied to the steel pipe. Elasto-plastic stress analysis using finite element method was also performed in order to simulate the large deformation of the pipe.

Straight pipes with internal pressure have the same deformation and fracture behaviours under uniaxial compressive loading. A few symmetrical plastic bucklings occurred and a through-thickness crack finally initiated at local buckled part. In the case of the pipe without internal pressure, an asymmetrical plastic buckling occurred after the first symmetrical buckling.

Finite element analyses were carried out. FE analytical relationships of load vs. displacement and bending moment vs. curved angle of the pipes with and without internal pressure have good agreements with the experiments. Internal pressure induced the deformation of the pipe to the outside in the buckled part in the analysis.

INTRODUCTION

Liquefacted ground often shows large horizontal displacement in large earthquakes. This displacement causes large deformation of constructions. Buried pipelines in the liquefacted ground are forced large displacement by earthquake which was often seen in southern part of Hyogo Prefecture in Japan in 1995. The knowledge of study and design recommendation related to deformability of the pipe in the liquefacted ground has not been sufficiently provided. A number of studies have been reported concerned about plastic deformation or buckling of straight pipe. Most of them are performance of column pipe without internal pressure. Elastic symmetrical buckling of straight pipes under compressive load is formulated by Timoshenko and Gere [Timoshenko and Gere, 1961] analytically. Battermann solved plastic buckling based on plastic flow theory [Batterman, 1965]. In this report, for the purpose of clarifying the deformation and fracture properties of the pipe with internal pressure under the large displacement, uniaxial compression tests and bending tests of API standard 5L X65 straight steel pipes with the size from 318 to 508 mm outside diameter were performed. Effect of Internal pressure on deformability of pipe is investigated both under compressive or bending load. Elasto-plastic stress analysis using

[1] *Professor of the Dept of Civil Eng, Tokyo Institute of Technology, Tokyo, Japan.. Email: miki@cv.titech.ac.jp*

[2] *Pipeline and Facilities Eng Dept, Tokyo Gas Co. Ltd.,, Tokyo, Japan. Email: yuri_o@tokyo-gas.co.jp*

[3] *Transmission Dept, Osaka Gas Co. Ltd., 4-1-2, Hirano-cho, Chuo-ku, Osaka, Japan. Email: takayoshi-uchida@osakagas.co.jp*

[4] *Distribution Planning and Administration Department, Nagoya, Japan. Email: tatematu@tohogas.co.jp*

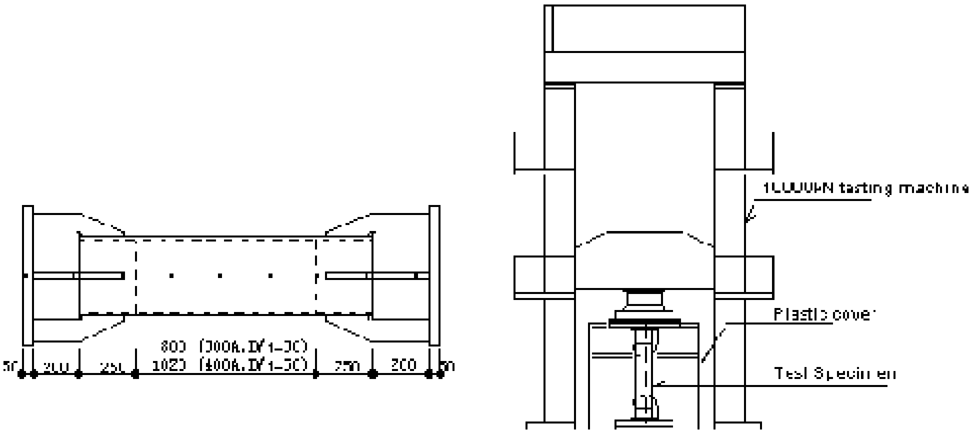
[5] *Steel Research Laboratories, Nippon Steel Corporation,, Chiba, Japan. Email: inoue@atsuita.re.nsc.co.jp*

finite element method was also performed in order to simulate the large deformation of the pipe. The FEM analyses are compared with test results.

PIPE COMPRESSION & BENDING TEST

Test Method

For the purpose of clarifying the deformation and fracture properties of the pipe with internal pressure under the large displacement, uniaxial compression tests and bending tests of API standard 5L X65 straight steel pipes with the size from 318 to 508 mm outside diameter were performed. Test specimens are listed in Table 1. Internal pressure using water which induces the hoop stress of 40 percents of the yield stress were applied to the steel pipe.



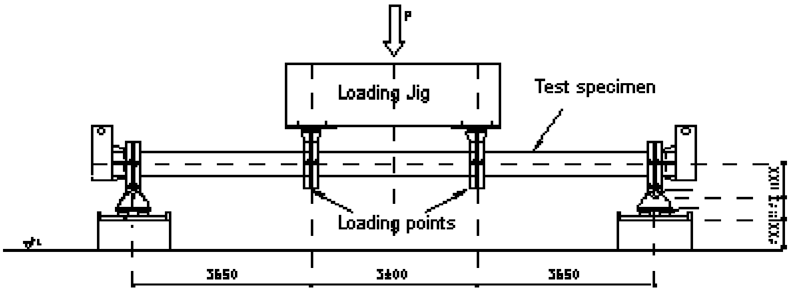
(a) Test specimen **(b) Testing Facilities**

Figure 1: Compression test specimen and testing facilities

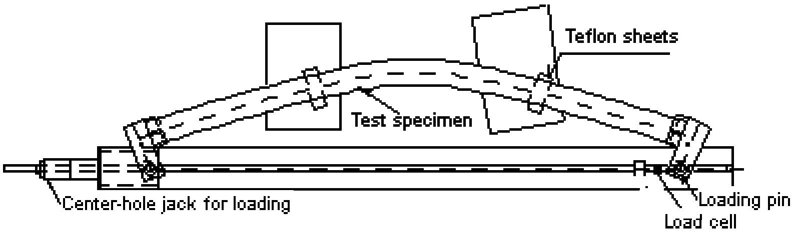
Table 1: Test specimens

No.	Diameter D, mm	Thickness t, mm	D/t	Length L, mm	Loading condition	Remarks
8-1	318.5	7.9	40.3	800	Compression	
8-2	318.5	7.9	40.3	800	Compression	w/o internal pressure
9-1	318.5	7.9	40.3	10700	Bending	
9-2	318.5	7.9	40.3	10700	Bending	w/o internal pressure
9-3	508.0	8.7	58.4	1290	Compression	
10-1	318.5	11.1	28.7	10700	Bending	
10-3	508.0	8.7	58.4	10700	Bending	
10-4	318.5	11.1	28.7	10700	Compression	

Test Facilities for compression test and bending test are in Figure 1 and 2. Bending load was applied by 4 point bending as in Figure 2(a) until bending angle is about 20 degree. Following bending load was applied by compressive load as in Figure 2(b). All specimens were loaded until cracks were grown up and cause leakage of internal pressure except for specimen 9-2. Strain distribution were measured by strain gages during the test.



(a) 4-point bending facilities



(b) Compressive bending facilities

Figure 2: Bending test facilities

Test Results

Table 2 shows test results. Figure 3 shows definition of the angles ω_A and ω_B.
Straight pipes with internal pressure showed the same deformation and fracture behaviours under uniaxial compressive loading. Figure 4 and 5 show the examples of compressed pipe and their section of buckling waves. Figures indicate that a few symmetrical plastic bucklings occurred under compressive load.

Table 2: Test Results

No.	Maximum moment/load	Deformation at maximum moment/load	Deformability	Remarks
8-1	406tonf	11.1mm	566mm	Leak at local buckling
8-2	411tonf	9.1mm	179mm	Leak at local buckling
9-1	36 tonf·m	25°/28°	65°/68°	Leak at local buckling
9-2	32 tonf·m	11°/13°	140°/141°	no crack
9-3	717tonf	7.3mm	416mm	Leak at local buckling
10-1	56tonf·m	50°/55°	99°/103°	Leak at local buckling
10-3	102tonf·m	9°/11°	44°/46°	Leak at local buckling
10-4	534tonf	37mm	512mm	Leak at local buckling

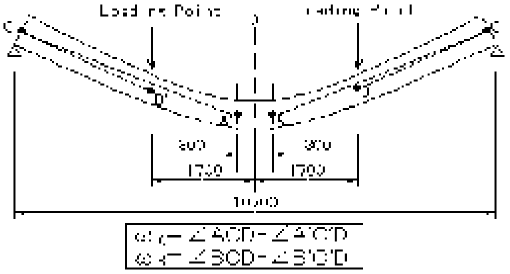


Figure 3: Definition of curved angle ω_A and ω_B.

Figure 4: Deformation pattern of compression test

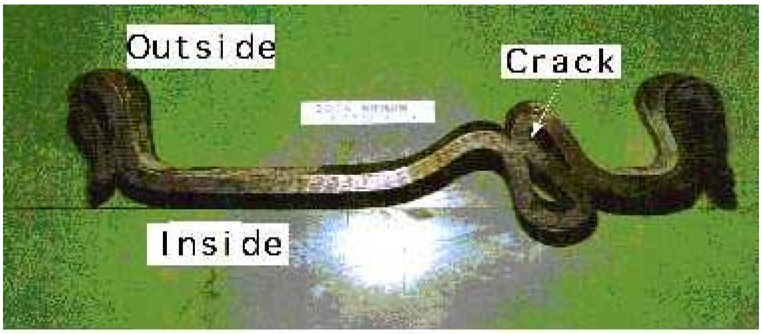


Figure 5: Deformed pipe section of compression test

Figure 6 shows a typical load-displacement curve of the compression test. Load decreases after a symmetrical buckling is formed. The symmetrical buckling is completed by contact of pipe inner surface. This increases compression load until another buckling is formed. After a few bucklings are completed, some difference of each bucking part in the direction of the diameter make the deformed part into the inner of the pipe and its cases tensile stress. A ductile crack is initiated by the tensile stress and grows up to a through thickness crack. Number of buckling wave seems to be independent to pipe size and pipe grade.

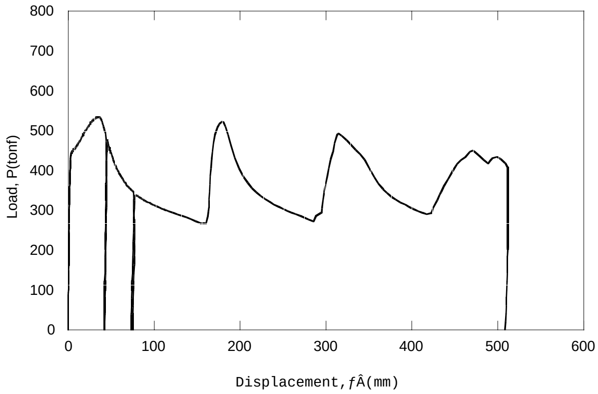


Figure 6: Load-displacement curve of compression test (Specimen 10-4)

Specimen 8-2 is the same grade, geometry and condition as specimen 8-1 except for internal pressure. In the case of the pipe without internal pressure, specimen 8-2, an asymmetrical plastic buckling occurred after the first symmetrical buckling. The maximum load and the displacement at the load of the pipe were independent of internal pressure under uniaxial compressive load. The decrease of compressive load after their maximum values was larger in the pipe without internal pressure than the pipe with internal pressure. Critical deformation until crack penetration of wall thickness in pipe without internal pressure is smaller than one of in pipe with internal pressure. Internal pressure increases critical deformation in compression test by increasing number of symmetric bucklings.

In the bending tests, a local buckling occurred at the inside of the bent pipe. Figure 7 and 8 show the examples of bent pipes and their section of buckling wave. Only a buckling wave is formed under bending moment. Bending moment decreases after the buckling is formed. The buckling is completed by contact of pipe inner surface similar to the case of compression test. The bending moment increases after the completion of buckling. The buckled part was flattened and bent to the one side of the wall and its causes tensile stress. A ductile crack is initiated by the tensile stress and grows up to through thickness crack.

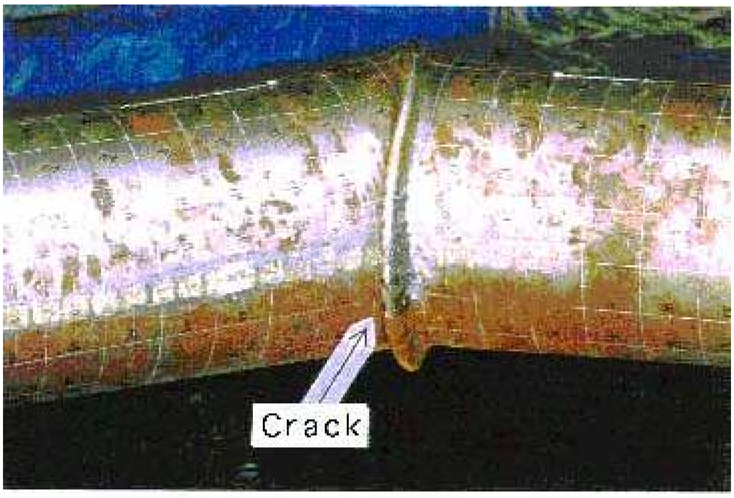


Figure 7: Deformation pattern of bending test

Specimen 9-2 is the same grade, geometry and condition as specimen 9-1 except for internal pressure. In the case of the pipe without internal pressure, specimen 9-2, both of the maximum bending moment and the bent angle at the moment of the pipe with internal pressure were larger than those without internal pressure. The decrease of bending moment after their maximum values was larger in the pipe without internal pressure than the pipe with internal pressure. In bending tests, the shape of cross section of the pipe flattened at the next area to the buckled part and no crack was initiated even at the curved angle of 140 degrees.

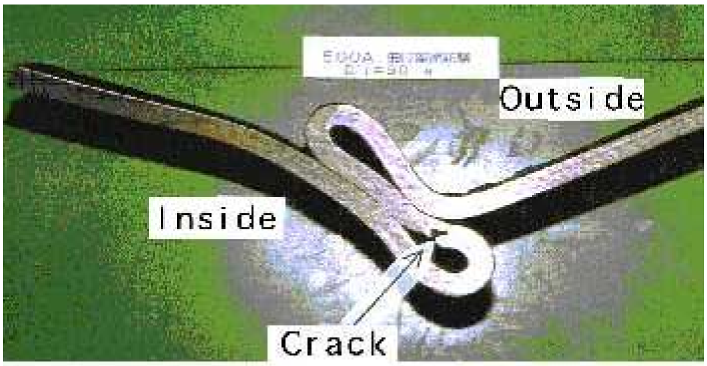


Figure 8: Deformed pipe section of bending test

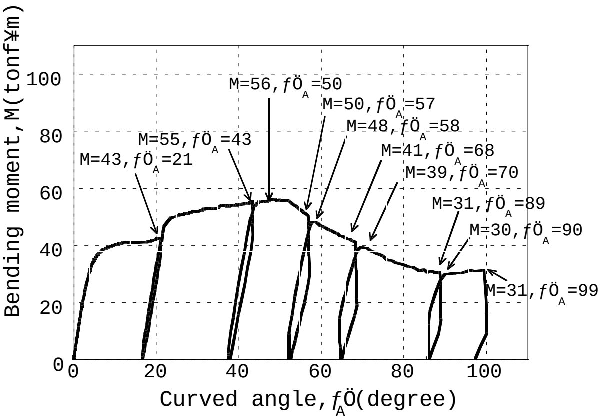


Figure 9: Load-displacement curve of compression test (Specimen 10-1)

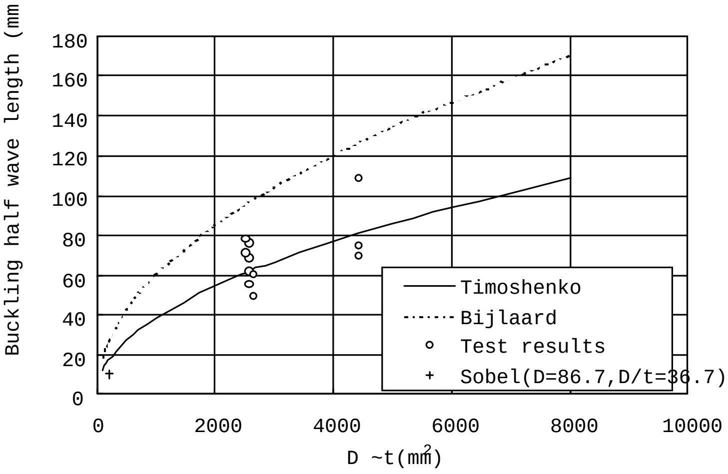


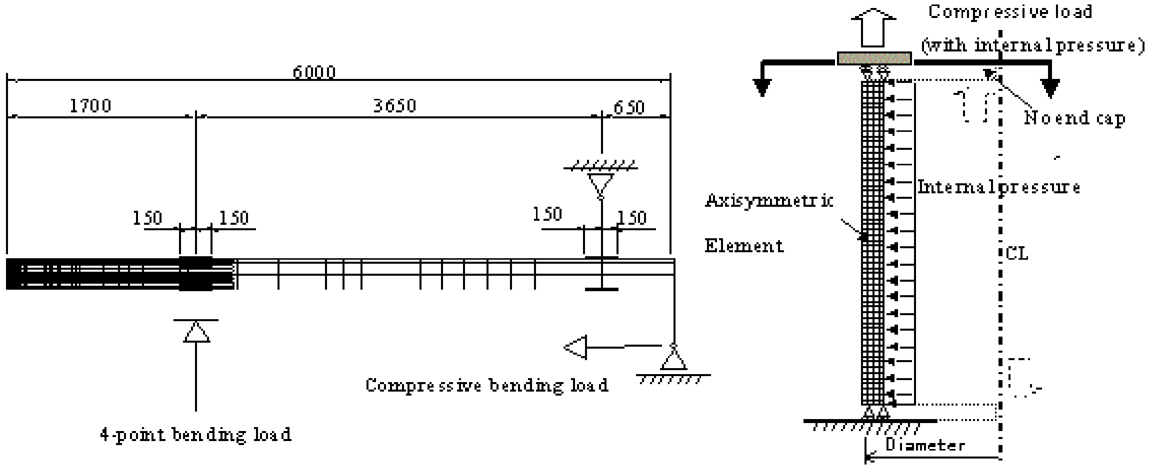
Figure 10: Buckling wave length of the straight pipes

The wavelength of plastic buckling was compared in order to discuss the deformability of the straight pipe up to fracture, because local buckling occurred in all the pipes tested independently of loading mode, size and internal pressure. There are formulae [Timoshenko and Gere, 1961 and Bijlaard, 1949] to estimate buckling wavelength. Figure 10 shows buckling wavelengths comparing to the formula and published data [Sobel and Newmann, 1980]. The wavelength increased with the increase of the outside diameter and the thickness, but was not so much influenced by loading mode and internal pressure. Timoshenko's formula gives good estimation of the buckling wavelength.

FEM ANALYSES

FEM model

Elastic-plastic stress analysis using finite element method was performed in order to simulate the large deformation of the pipe. MARC K6.2 was used with FINITE, LARGEDISP and UPDATE options. FEM model of compression test was two-dimensional axisymmetric model. FEM model of bend test was a quarter model. Figure 10 illustrates FEM models.



(a) Bending test **(b) Compression test**

Figure 11: FEM models

Stress-strain curves are modelled as multi-linear curve in true stress versus true strain from tensile and compression test results from each tested pipe. In compressive test, internal pressure on the end cap is accounting in compressive load. In bending test, two sets of boundary and loading conditions are applied on the models according to 4-point and compressive bending tests.

Diameter distribution was introduced as initial distortion for local buckling. Thickness distribution of pipe specimen was used as amplitude of initial distortion. Timochenko's buckling wavelength was used as wavelength of initial distortion.

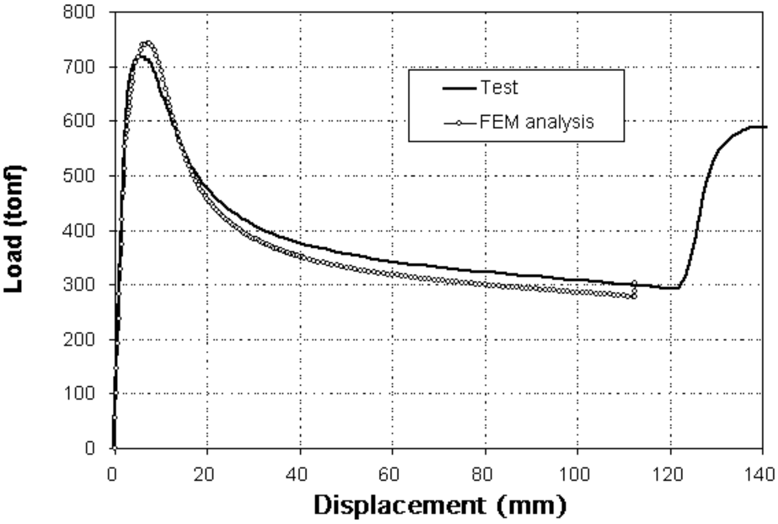


Figure 12: Compressive load versus displacement (Specimen 10-3)

Results of analyses

Figures 12 shows finite element analytical load vs. displacement curve and test results of compression test. Finite element analysis well describes global plastic deformation in compression tests. Figures 13 shows bending moment vs. displacement curve calculated from FEM analysis comparing with one from bending test. Figure 13 indicates that FEM analysis underestimates bending moment in 4-point bending test and well estimates compressive bending test. This underestimation may cause by insufficient modelling of distributed loading caused by fixtures.

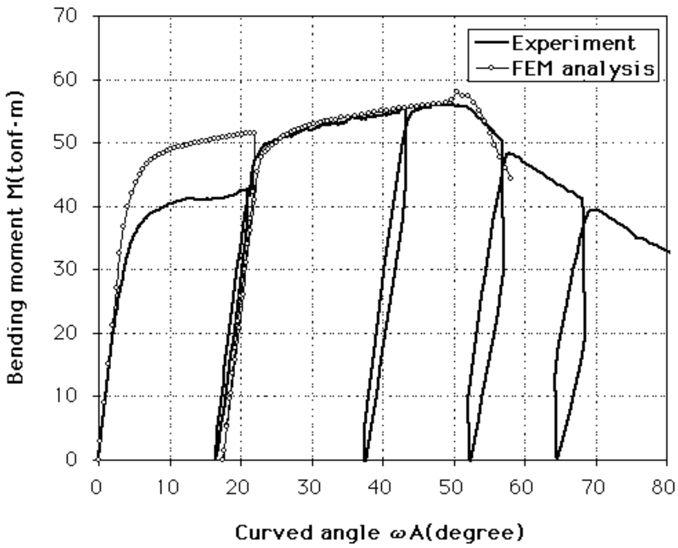


Figure 13: Bending moment versus curved angle (Specimen 10-1)

CONCLUSION

For the purpose of clarifying the deformation and fracture properties of the pipe with internal pressure under the large displacement, uniaxial compression tests and bending tests of API standard 5L X65 straight steel pipes with internal pressure were performed. Elasto-plastic stress analysis using finite element method was also performed in order to simulate the large deformation of the pipe.

1. Deformability of straight pipes is dominated by plastic local buckling. Ductile crack initiates in buckled part and grows through wall thickness.
2. Internal pressure increases deformability of pipe under compressive load. In the other hand, only a bent pipe without internal pressure does not show through thickness crack even at large curved angle such as 140 degrees.
3. Finite element analytical relationships of load vs. displacement and bending moment vs. curved angle of the pipes with and without internal pressure have good agreements with the experiments.
4. The wavelength of plastic buckling increases with the increase of the outside diameter and the thickness, but not so much influenced by loading mode and internal pressure. The wavelength is well estimated by Timoshenko's fomula.

ACKNOWLEDGMENTS

After the 1995 Hyogoken Nanbu Earthquake, the Agency of Natural Resources and Energy, Ministry of International Trade and Industry entrusted the investigation of gas pipe behavior due to liquefaction to the Japan Gas Association. This investigation started in 1996 and will take five years to complete. It is supervised by the committee for investigation of the effect of liquefaction on gas pipelines, chaired by Dr. Tsuneo Katayama, the head of the National Research Institute for Earth Science and Disaster Prevention of the Science and Technology Agency. The authors express their gratitude to all persons concerned at MITI for their permission to publish this paper, and the committee members for their valuable suggestions.

REFERENCES

Timoshenko, S.P. and Gere, J.M.(1961), *Theory of Elastic Stability*, McGraw-Hill

Batterman, S.(1965), "Plastic Buckling of Axially Compressed Cylinders," AIAA Journal, Vol.3, pp.1461-1466

Bijlaard, P.P. (1949), "Theory and Tests on the Plastic stability of Plates and Shells," Journal of the Aerospace Sciences, Vol.16, pp. 529-541

Sobel, L.H. and Newman, S.Z. (1980), Journal of Pressure Vessel Technology, Transactions of the ASME, Vol.102