API-X80 라인파이프의 좌굴 안정성 평가

Buckling Behavior of API-X80 Linepipe

조우연[*] · 안성수[**] · 윤태양[***] · 유장용[****]
Cho. Woo Yeon · Ahn, Seong-Soo · Yoon. Tae-Yang · Yoo. Jang-Yong

ABSTRACT

The objective of this paper is to present the results of an experimental and a finite-element investigation into the behavior of X80 grade pipes subjected to bending. For the pipe specimens comprising the test series, different D/t is applied to be representative of those that can be expected in the field. Results from the numerical models are checked against the observations in the testing program and the ability of numerical solutions to predict pipe moment capacity, curvatures, and buckling modes is established. A finite-element model was developed using the finite-element simulator to predict the local buckling behavior of pipes. The comparison between the numerical and the experimental results demonstrates the ability of the analytical model to predict the local buckling behavior of pipes when deformed well into the post-yield range.

Keywords: *Linepipe, Buckling, Critical Strain, Bending Moment*

1. INTRODUCTION

Buried pipelines are subject to a number of loading conditions. These include internal pressure caused by the action of the fluids they convey, axial forces induced by thermal effects, and bending caused by differential soil movements. Recently, differential soil movements are taken an important consideration in the design and assessment of buried pipelines. When a buried steel pipeline is subject to the increasing curvatures arising from differential geotechnical movements, eventually it will buckle locally. Therefore, recent pipeline design requires that pipeline has the high deformation resistance to local buckling.

Pipe subject to increasing imposed curvature will, sooner or later, buckle locally. Local buckling is associated with a softening moment-curvature response [Korol., 1979]. During the decrease in moment under continuing increase in deformation, the curvatures localize at particular points in the line, resulting in wrinkles at these particular points, while curvatures in adjacent sections of pipe decrease [Dorey et al., 1999]. Because of the localization of deformation, average strain values are misleading indicators of pipe response subsequent to the

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[*] (재)포항산업과학연구원 강구조연구소 토목구조연구실 선임연구원 wycho@rist.re.kr

[**] 포스코 기술연구소 후판연구그룹 책임연구원 virtuor@posco.co.kr

[***] (재)포항산업과학연구원 강구조연구소 토목구조연구실 수석연구원 tyoon@rist.re.kr

[****] 포스코 기술연구소 후판연구그룹 전문연구원 yoojang@posco.co.kr

initiation of pipe wrinkling. Recent studies have shown that it is possible to use a variety of post-buckling deformation measures to establish rational deformation limit states for the pipe. These are generally more permissive than presently used limiting strain values for the onset of local buckling [Mohr, 2002].

A number of factors exist that can influence the onset of local buckling and may have to account for the predictive analyses. One of these factors is the various loading conditions that may occur in field construction. As a representative of field condition, the combination of bending and axial compression is usually considered and their effects on the pipeline have been studied. Especially, in this paper, an experimental testing program to determine the critical compressive strain of pipe in combination of bending and axial force was performed and its result was discussed.

2. BUCKLING BEHAVIOR OF X80 STEEL PIPE

As well known, recent arctic project is known to need linepipe with excellent bending capacity and thus pipeline designer requires the bending capacity data for the high strength linepipe. Responding to the need in the pipeline field, the large scale pipe bending system was installed and the bucking behavior of API-X80 steel pipe manufactured by γ single phase rolling was investigated.

2.1 Test Instrumentation

The experimental set-up, which allowed for independent control of the applied bending and axial force, is shown in Fig. 1. The buckling tests were performed on specimens 4,750 mm long using Universal Testing Machine (UTM) which has a servo-hydraulic load frame capable of 10 MN of tensile or compressive load. Bending was applied using steel moment arms that were bolted to both ends of test specimen and pin connected to the UTM. The moment arms were rotated by forcing the cantilevered ends apart with two hydraulic rams. The seam welding lines of the pipe specimens were located to the perpendicular to the bending plane, so as to avoid the effect from the seam welding line.

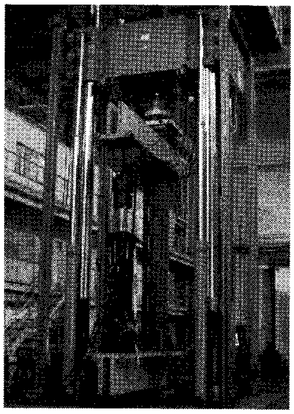


Fig. 1 Pipe Buckling Test System

Table 1. Specimen dimensions and test conditions

Specimen No.	OD	Thickness	D/t	Bending Plane	Loading Condition
A1	28inch (711mm)	19mm	37.4	Seam welding 90°	UTM=const.(100kN) Actuator Bending
A2	28inch (711mm)	19mm	37.4	Seam welding 90°	UTM=const.(100kN) Actuator Bending
B1	28inch (711mm)	19mm	37.4	Seam welding 90°	UTM=const.(9000kN) Actuator Bending
B2	28inch (711mm)	19mm	37.4	Seam welding 90°	UTM=const.(9000kN) Actuator Bending

Each specimen was loaded in bending until the maximum moment capacity of the specimen was exceeded and local buckling on the compression face of the specimen had occurred. Instrumentation consisted of strain gauges to measure local tensile and compressive strains, linear variable differential transformers (LVDTs) to measure longitudinal displacements, clinometers to measure angular displacements, hydraulic ram pressure transducers to allow calculation of the bending strut force, and UTM load and stroke measurement devices. Data was acquired continuously throughout each test for all instruments.

2.2 Test Specimens

The experimental program consisted of testing four pipe specimens with a D/t ratio equal to 37.4. Two specimens among four pipe specimens were tested in pure bending mode with no internal pressure, while the others were tested in complex bending mode with an axial compression force of 9MN so as to find the moment capacity of each pipe under different loading condition. In preparation for testing, flat steel end plates were welded to the ends of each specimen. Because the end plates provided were used to transfer bending forces to the specimen, those plates should be thick enough not to deform during transferring the actuator force. The nominal dimensions and test conditions of X80 steel pipes are shown in Table 1.

2.3 Moment Curvature Relationships

With the assumption of average curvature, global curvature can be defined by dividing the relative rotation by the length of the specimen. However, the distribution of curvature along the length is not uniform after wrinkling is initiated, so the average curvature, which is length-dependent, is not sufficient to explain representative measure on the base pipe properties. In calculating the curvature of the buckled region, some standardized length is important, since in general, a longer gauge length will result in a smaller calculated curvature per unit length. In this study the average curvature over a length (800mm) similar to the pipe diameter (711mm) has been adopted in order to calculate the local curvature for wrinkles. Average compressive strains were calculated as follows [Zimmermann et al., 2004]:

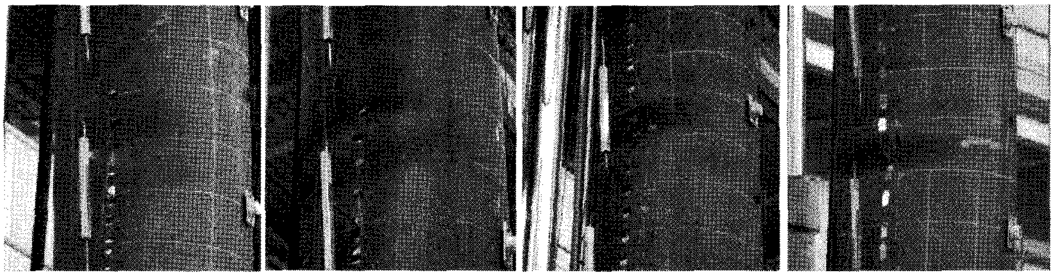
$$\varepsilon_c = \varepsilon_t - KD \qquad (1)$$

Where, ε_c is an average compressive strain over a given gauge length. ε_t is tensile strain measured from strain gauges, K . is curvature for a given gauge length and D is pipe outside diameter.

2.4 Bending Test Results

Fig. 2 presents photographs of the buckled surface of tested specimens. All the deformed shape of A1~B2 showed wrinkling pattern. These patterns are somewhat different from the diamond-shape deformation. Usually, diamond shape buckling occurs in the steel pipe showing the discontinuous yielding in stress-strain curve in longitudinal direction and is very harmful to the structural integrity. The tested pipes were manufactured by γ single phase rolling and fast accelerated cooling and thus had continuous yielding characteristics in longitudinal direction. Therefore, tested pipes soundly buckled by wrinkling pattern.

Fig. 3(a,b) shows the moment vs. compressive strain plots for A1 and A2 tests, in which axial forces of UTM are negligible. In both cases, the bending moment increased through a linear elastic range, past yielded into the in-elastic range, and reached a peak, at which point unloading began to occur due to buckle formation. The compressive strain associated with the peak moment has historically been considered the critical buckling strain value, and this terminology is used here. As shown in Fig.3, the 2nd moments of type-A tests were not so much as 1st moments in both cases, so the total moment changed little.



(a) Specimen-A1 (b) Specimen-A2 (c) Specimen-B1 (d) Specimen-B2

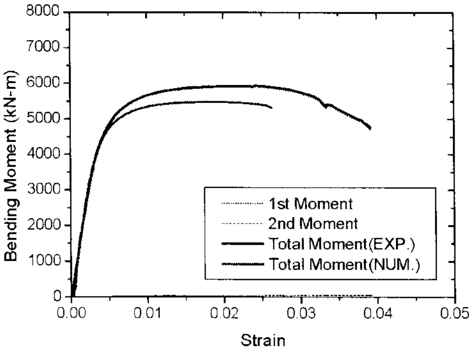
Fig. 2. Deformed shapes of test specimens

While the 2nd moments of type-A tests were not big enough to change the total moment, those of type-B tests were considerably enough to influence the value of critical buckling strain. Fig. 3(c,d) shows the moment vs. compressive strain plot for B1 and B2 tests. The axial forces of both cases were nearly 9MN during the tests. As shown in Fig. 3(c,d), the 2nd moment was nearly half of 1st moment although its amounts are not same. The 2nd moment changed not only the total moment but also the position of maximum moment, of which strain value is the critical buckling strain. Those experimental test results are summarized in Table 2. In type-A tests, the variance of maximum moment and critical strain was insignificant (less than 1%). In type-B tests, the variance was about 35% in maximum moment and 36% in critical buckling strain.

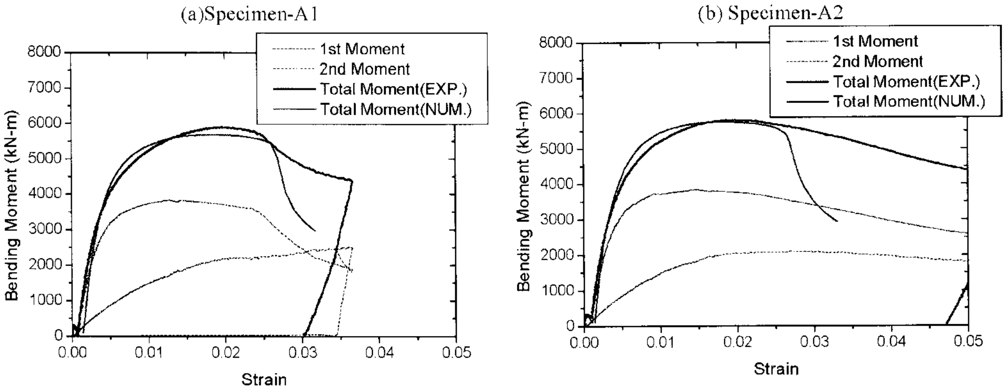
3. NUMERICAL ANALYSIS

For numerical analysis of bending behavior of X80 linepipe ABAQUS 6.3.1, which is the general FE analysis software, is used. Using the post-buckling module (RIKS analysis), the plasticity and nonlinear behavior of X80 grade steel is modeled properly. The pipe body is divided using the element of S4R (number of element is 21,480), which is based on thick shell theory, and the element of longitudinal boundary is chosen B31 (number of element is 234) to stiffen without bothering with boundary effect. As material properties of API X80 steel tested value of specimen is used, from specimen coupon test the exact value of modulus of elasticity, yield strength and tensile strength is obtained. Also, for post-buckling analysis the stress-strain curve which is averaged from the value of 8 specimens are used.

In Fig. 3 the results of numerical analysis are represented comparing with those of experiment. The geometric input of specimen type A is same with type B, only the material properties (elastic modulus, stress-strain curve etc.) are different each other. All the numerical results show the descending pattern after the maximum bending



(a)Specimen-A1 (b) Specimen-A2



(c)Specimen-B1 (d) Specimen- B2

Fig. 3. Compressive Strain and Bending Moment Relation

moments similar to those of experiment but the descending rate is somewhat different each other. The critical compressive strains of experiment and those of numerical analysis are written in Table 2. In numerical analysis, the critical strains of test type A is 5~6% higher than those of type B. It is smaller difference than the behavior of experiment. Considering the small difference of maximum bending moment (within 8%) the numerical analysis can be used to predict the buckling behavior but the difference of critical strain is as big as 17%, so the

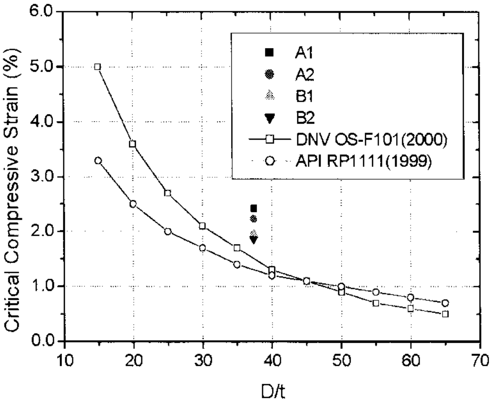


Fig. 4. Critical Compressive Strain and Design Curve

Table 2. Comparison of Strain and Maximum Moment

Specimen No.	Total Moment (Experimental Results)		Total Moment (Numerical Analysis)	
	Critical Compressive Strain (%)	Maximum Moment (kN-m)	Critical Compressive Strain (%)	Maximum Moment (kN-m)
A1	2.42	5,946	2.01%	5,485
A2	2.23	5,408	1.99%	5,318
B1	1.96	5,908	1.92%	5,684
B2	1.86	5,808	1.94%	5,752

numerical procedure and parameter need to be refined to calculate more accurate value of critical compressive strain.

In Fig. 4, critical compressive strain data for four test pipes are plotted with pipeline design codes of DNV OS-F101 and API RP1111. It is well known that DNV code requires high level of deformation capacity, because it regulates offshore pipes, which are severely deformed in construction. As shown in Fig. 4, the critical compressive strain of tested API-X80 steel pipe could meet the DNV code. From this analysis, it is understood that the tested API-X80 pipe had an enough deformation capacity and could meet the current design criterion.

4. CONCLUSIONS

The buckling behavior of newly developed API-X80 steel with good low temperature toughness was investigated through large scale deformation tester. An experimental test to determine the critical compressive strain of pipe in combination of bending and axial force was performed and its result was carefully discussed. The results are summarized as follows.

1) It was found that the developed API-X80 linepipe was within the specification of DNV and API codes in terms of buckling capacity.

2) The compressive axial force had little effect on the peak moment but changed the deformation pattern and state of critical compressive strain of linepipe.

3) The numerical analysis procedure needs to be refined to predict critical strain of buckling behavior

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