Development of a Flexible Pipe for Pipe-in-Pipe Technology

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ABSTRACT Pipe-in-pipe technology has been implemented, whereby pipes of one continuous length are laid individually in the existing submarine pipelines belonging to petrochemical complexes in various locations across Japan to construct renovated networks for fluid transportation. Because the pipelines have a number of sharp bends, development of a new pipe with excellent flexibility and lightweight was required to construct such a network. Thus Furukawa Electric, Nippon Steel, and Idemitsu Kosan have jointly developed the pipe thereby succeeded in acquiring a special certification as a flexible pipe for transportation of high-pressure liquefied petroleum gas. The developed pipe has been successfully laid in the existing submarine pipeline (3.3 km in total length) in the Tokuyama Refinery of Idemitsu Kosan in July 2002.

1. INTRODUCTION

Various submarine pipelines for fluid transportation of petroleum and gas have been laid in petrochemical complexes in different locations across Japan. Some of these pipelines are rather degraded and thus have to be renovated in near future. We have implemented experimentally the pipe-in-pipe technology to reconstruct the degraded pipelines, whereby the existing pipeline is filled with water, in which a new pipe is laid taking advantage of liquid buoyancy to construct a renovated network for fluid transportation. To lay anew a pipe in the existing pipelines of long distance where sharp bends are involved, it is necessary to apply a pipe with excellent flexibility and lightweight.

Meanwhile, Furukawa Electric had made practical applications of a flexible pipe with a composite structure comprising metal reinforcing layers and plastic layers for offshore oil fields [1]. Figure 1 shows the basic structure of the flexible pipe in practical use. The flexible pipe has an established track record overseas in such applications as a riser pipe which transports oil and natural gas mined from the seabed to floating petroleum production facilities or tankers, or as a "flowline" laid on the seabed [2), 3)]. Domestically, however, the pipe has never been applied in pipelines for transportation of high-pressure liquefied petroleum gas, nor has it been laid for long distance in existing pipelines.

Currently the Research Association of Refinery Integration for Group Operation (RING) is promoting an R & D program, under the auspices of the Ministry of Economy, Trade and Industry, to implement "Refining and Petrochemical Complex Renaissance Concept" aimed at strengthening the international competitiveness of domestic petrochemical complexes. As related to this program, the pipe-in-pipe technology was experimentally implemented at the Tokuyama Kombinat centered on the Idemitsu Kosan Refinery.

This report will briefly describe the design and performance verification of a lightweight flexible pipe, which has been carried out jointly by Furukawa Electric, Nippon Steel, and Idemitsu Kosan.

2. DESIGN OF FLEXIBLE PIPE

2.1 Governing Standards

Whereas flexible pipes have established a track record overseas based on the standards stipulated by the

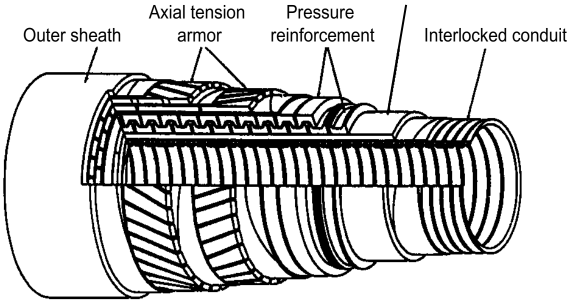

Figure 1 Basic structure of flexible pipe.

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Table 1 Design load and allowable stress of flexible pipe.

Load to be considered		Allowable stress
Primary load (steady load under operation)	Internal pressure	Hoop stress: 40 % or 0.5·(1.6- γ), whichever is smaller, where γ is the ratio of yield stress to tensile strength
		Axial stress: 50 % of yield stress
	Gas weight or external pressure	33.3 % of tensile strength or 66.7 % of yield stress, whichever is greater (applicable to stainless steel)
Secondary load (transient load during installation and the like)	Laying tension	90 % of yield stress

American Petroleum Institute and the like, they lack in domestic records of practical applications. Consequently, the pipe had to undergo examinations by the Performance Evaluation Committee of the High Pressure Gas Safety Institute of Japan to acquire a special certification. We made investigations in compliance with the Security Regulation-Related Standards for Kombinat and the Like (in Japanese, hereafter called Kombinat Standards) in the High-Pressure Gas Security Laws, which are applicable to the existing pipelines.

Table 1 summarizes the loads and allowable stresses specified in the Kombinat Standards that must be taken into account in the design of the flexible pipe. The Kombinat Standards specify the allowable stresses corresponding to specific loading conditions and materials, and the design should be such that the calculated stress under each loading condition does not exceed the allowable stress. While the allowable stress includes suitable safety factors, design standards severer than the API standards are stipulated with respect to internal pressures especially, thereby requiring higher values of design strength than before.

2.2 Study of Pipe Structure

It was feared that, if a pipe with conventional structure is laid in the long-distance pipeline, the laying tension would increase resulting in an excessive stress over the breaking strength of the pipe. Thus, it became an important technological task to reduce the laying tension in order to apply flexible pipes to the pipe-in-pipe technology. Various pipe structures were studied together with preliminary designs, and the result indicated that application of a laying method would be most effective, in addition to reduction of the in-water weight of the flexible pipe, whereby water is poured into the existing pipeline to reduce the laying tension taking advantage of liquid buoyancy. Moreover, it became clear that the pipe should be as flexible as possible to pass the bends smoothly, and that, to this end, the pipe's flexural rigidity and diameter should be as small as possible.

2.2.1 Design Specifications

Design specifications necessitated for structural studies of the flexible pipe are shown below. The laying tension has been estimated, through the study done by Nippon Steel, using a new calculation formula that takes into account the tension increments due to pipe’s flexural rigidity and the contact conditions at bends.

Inner diameter: 5 in
Outer diameter: 7 in approx.
Internal pressure: 2.8 MPa
External pressure: 0.12 MPa
Laying route length (pipe length): 3.3 km
Minimum bending radius: 1450 mm
Number of bends: 5
Laying tension: 80 kN (estimated)
Tensile strength: 320 kN (four times the laying tension)

2.2.2 Design of Pipe Structure

In view of the design specifications mentioned above, a single-layered structure was employed, in place of the double-layered structure conventionally used, for the axial tension armor that takes charge of the laying tension, thereby reducing the weight, flexural rigidity, and outer diameter of the pipe. Moreover, with respect to the single-layered armor, a composite structure comprising steel reinforcements and plastic spacers of small specific gravity was used, and the structure was optimized to minimize the number of steel reinforcements thereby making the stress due to the laying tension lower than the allowable stress, and simultaneously ensuring a tensile strength four times the laying tension.

In terms of the pressure reinforcement layer, given its structural position sandwiched between the two plastic layers together with its use under static environments, it was thought that consideration of wall thickness decrease due to corrosion or abrasion was not necessary. In addition, a steel strip of high precision thickness was used to help optimize the structure to have a tolerance factor of 1.0 over the allowable stress, thus realizing a reduction in both weight and flexural rigidity.

The measures above mentioned enabled to design a flexible pipe with an in-water weight of 0.6 kg/m --an extremely lightweight over the in-air weight of 27 kg/m. Figure 2 shows the structure of the lightweight pipe, and Table 2 the structural specifications and the allowable stresses based on the Kombinat Standards.

2.3 Study of Pipe Strength

Using the optimized lightweight structure, design strengths of the pressure reinforcement layer and the axial tension armor layer were studied with respect to their circumferential and axial stresses due to internal pressure, and it was confirmed that these stresses are below the allowable stress specified in the Kombinat Standards. The design strength of the axial tension armor layer due to laying tension was also confirmed to be below the allowable stress thus posing no problems.

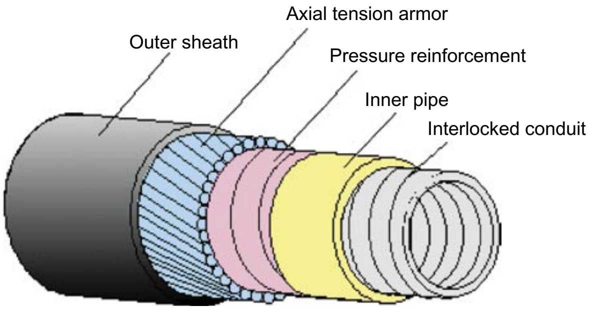

Figure 2 Structure of lightweight flexible pipe.

Table 2 Structural specification and allowable stress of lightweight flexible pipe.

Major layer (Material)	Function	Allowable stress (N/mm^2)	Specification
Interlocked conduit (Stainless steel)	Reinforcement against external and lateral pressures	Primary load: 221 Secondary load: 450	Inner dia.: 127.0 mm Outer dia.: 134.0 mm
Inner pipe (Nylon 11)	Container for fluid	——	Inner dia.: 135.4 mm Outer dia.: 148.8 mm
Pressure reinforcement (Cold-rolled steel strip)	Reinforcement against internal pressure	Primary load: 214	0.5 mmt × 2 Inner dia.: 149.8 mm Outer dia.: 151.8 mm
Axial tension armor (Zn-galvanized steel wire)	Reinforcement against axial force	Primary load: 200 Secondary load: 360	ϕ 7 mm × 15 Inner dia.: 153.8 mm Outer dia.: 167.8 mm
Axial tension armor (Polyester)	Spacer	——	ϕ 7 mm × 52 Inner dia.: 153.8 mm Outer dia.: 167.8 mm
Outer sheath (Polyethylene)	Protection against external damage	——	Inner dia.: 170.7 mm Outer dia.: 183.1 mm
In-air weight			26.9 kg/m
In-water weight			0.6 kg/m
Minimum bending radius			1450 mm
Flexural rigidity			1.2 × 10^4 Nm^2

Below will be described the strength studies with respect to internal pressure, laying tension, and external pressure (hydrostatic pressure).

2.3.1 Study of Pipe Strength against Internal Pressure

1) Pressure Reinforcement Layer

Hoop stress due to internal pressures is taken charge of by the pressure reinforcement layer. The generated stress is given by Equation 1.

$$\sigma = \frac{P(D-t)}{2t\sin\theta} \qquad (1)$$

where: σ is the hoop stress; P is the internal pressure; D is the diameter; t is the thickness; and θ is the winding angle.

Equation 1 gives a hoop stress due to internal pressure of 212 N/mm^2, which is lower than the allowable stress for pressure reinforcement layer of 214 N/mm^2. Because the design is optimized, the tolerance factor over the allowable stress is about 1.0.

2) Axial Tension Armor Layer

Axial stress due to internal pressures is taken charge of by the axial tension armor layer. The generated stress is given by Equation 2.

$$\sigma = \frac{A_p P}{NA\cos\theta} \qquad (2)$$

where: σ is the axial stress; A_p is the inner cross-sectional area of the pipe; P is the internal pressure; N is the number of axial tension rod; A is the cross-sectional area of one axial tension rod; and θ is the winding angle.

Equation 2 gives an axial stress due to internal pressure of 64 N/mm^2, which is lower than the allowable stress for axial tension armor layer of 200 N/mm^2, thus assuring a sufficient strength.

2.3.2 Study of Pipe Strength against Laying Tension

Axial stress generated by laying tension can be obtained, since this is taken charge of by the axial tension armor layer, by replacing numerator $A_p P$ in Equation 2 with laying tension T.

The axial stress due to laying tension thus obtained is 143 N/mm^2, which is lower than the allowable stress for axial tension armor layer of 360 N/mm^2 shown in Table 2, thus assuring a sufficient strength.

2.3.3 Study of Pipe Strength against External Hydrostatic Pressure

Buckling stress of the flexible pipe under hydrostatic pressure against external pressure is taken charge of by the innermost interlocked conduit, and the buckling strength is give by Equation 3.

$$S = \frac{3EI}{R^3} \qquad (3)$$

where: S is the buckling strength against external pressure; E is the elastic constant of the interlocked conduit; I is the geometrical moment of inertia of the interlocked conduit; and R is the winding radius of the interlocked conduit.

Equation 3 gives a buckling strength of the interlocked conduit of 2.39 MPa, which has a safety factor of about 20 over the design external pressure of 0.12 MPa. This is a perfectly problem-free level, since it has been confirmed from the past data that good agreement can be seen between the design and measured values of external pressure buckling.

3. PERFORMANCE VERIFICATION USING PROTOTYPE PIPE

A prototype pipe with an optimized lightweight structure as was designed as stated above was manufactured, and various performance verification tests were carried out to confirm its safety margin and the design validity as mentioned below.

3.1 Airtightness Test

3.1.1 Test Method

To confirm airtightness of the flexible pipe, test end-fittings were assembled on both ends of a specimen 4 m in length, N_2 gas was filled in, the pressure was increased up to the design pressure of 2.8 MPa, and the specimen was maintained for 10 min to check whether any abnormalities such as leaks would occur.

3.1.2 Test Result

No abnormalities such as leaks were found, confirming that the airtightness performance would present no problem.

3.2 Hydrostatic Test

3.2.1 Test Method

To confirm withstand pressure of the flexible pipe, a same specimen as for the airtightness test was used, and water was filled in, then the pressure was increased up to 1.5 times the design pressure (4.2 MPa), and the specimen was maintained for 10 min to check whether any abnormalities such as leaks would occur.

3.2.2 Test Result

No abnormalities such as leaks were found, confirming that the withstand pressure performance would present no problem.

3.3 Burst Pressure Test

3.3.1 Test Method

To confirm internal pressure burst value of the flexible pipe, a same specimen as for the airtightness and hydrostatic tests was used, water was filled in, and then the pressure was increased until the specimen broke down. Photo 1 shows a view of the test.

Photo 1 Burst pressure test.

3.3.2 Test Result

The burst pressure value was 12.6 MPa --more than four times the normal pressure, confirming that it compares favorably with the design value. As shown in Photo 2, the burst occurred in the pressure reinforcement, leaving no breakdown openings in the plastic inner pipe.

3.4 Bending Test

3.4.1 Measurement of Flexural Rigidity

1) Test Method

A hydraulic cylinder and a load cell were attached on both ends of a specimen about 3.5 m in length, on which a bending moment was applied using the hydraulic cylinder, and the bending moment and the bending radius thereby were measured to obtain flexural rigidity EI. Photo 3 shows a view of the test.

2) Test Result

The measured flexural rigidity was 0.9×10^4 Nm^2, somewhat lower than the design value of 1.2×10^4 Nm^2, rendering the pipe to be on the safe side in the aspects of laying work.

3.4.2 Repeated Bending Test

1) Test Method

Assuming a bending history during laying work, a bend was applied to a specimen about 10 m in length using a bending gauge 1400 mm in radius, the specimen was restored to its original position, then a same bend was applied in the reverse direction. After this bending process was repeated five times for 10 bends, the specimen was disassembled to check for any abnormalities. The bending radius corresponds to the severest bend in the laying route, and the number of bending times was given a tolerance factor of 2 over the number of bending the pipe was expected to actually undergo during laying. Photo 4 shows a view of the test.

Photo 2 Burst point due to internal-pressure test.

Photo 3 Flexural rigidity measurement.

Photo 4 Repeated bending test.

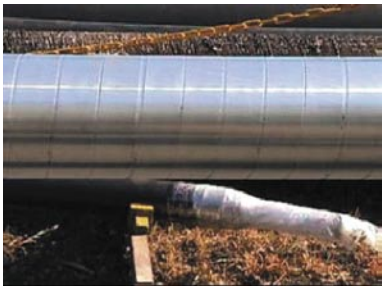

Photo 5 Appearance of pressure reinforcement after repeated bend test.

2) Test Result

Photo 5 shows the result of disassembly. It can be seen that the pipe has no problem in the pressure reinforcement layer and other structures against repeated bends of minimum bending radius, thereby demonstrating its satisfactorily problem-free performance against bending histories expected during laying.

3.5 Tensile Test

3.5.1 Test Method

To test the tensile characteristics of the flexible pipe, testing end-fittings were attached on both ends of a specimen about 4 m in length, a load cell and a hydraulic cylinder were fixed at each end, then a tensile load of 80 kN was applied for 10 min. After the pipe was checked for abnormalities such as fracture, the tension was increased to check the breakdown tension. Photo 6 shows a view of the test.

3.5.2 Test Result

It was confirmed that no abnormalities occurred in the tensile test history of 80 kN for 10 min. The breakdown tension was found to be 321~335 kN, equivalent to the design value, confirming that its actual performance was over four times the laying tension. Photo 7 shows an appearance of the breakdown point.

Photo 6 Tensile test.

Photo 7 Appearance of breakdown point due to tensile test.

Photo 8 Pipe laying test.

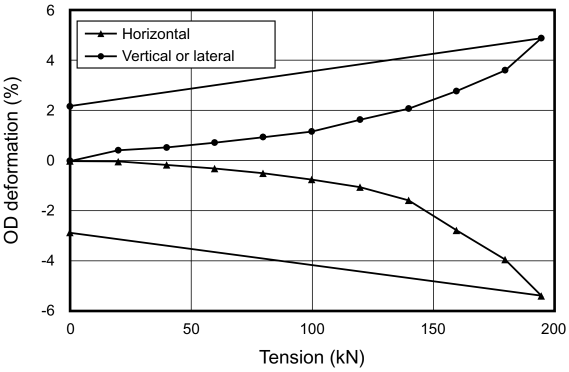

Figure 3 Relationship between tension and outer diameter deformation in laying test.

3.6 Laying Test

3.6.1 Test Method

To confirm the lateral pressure performance and the external damage resistance of the flexible pipe, a laying end-fitting was attached on both ends of a pipe specimen about 12 m in length, the specimen was pulled into a miter bend pipe with a bending radius of 1.5 m, a bending angle of 180°, and a weld bead area that was harsher than the existing pipelines, and then tension was applied between the two end-fittings to provide a lateral pressure history at pipeline bends. Subsequently, under a counteracting tension, the specimen was pulled in using a winch to confirm whether there was buckling in the pipe specimen and to check for external damage. Photo 8 shows a view of the test.

Photo 9 Appearance of outer sheath after laying test.

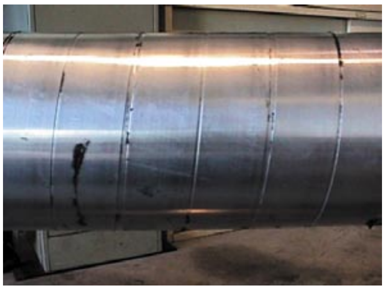

Photo 10 Appearance of pressure reinforcement layer after laying test.

Photo 11 Appearance of interlocked conduit after laying test.

3.6.2 Test Result

Figure 3 shows the relationship between the tension and pipe deformations (horizontal and vertical) at the center of the bend. The relationship is seen to be linear up to about 100~120 kN, posing no problems such as buckling up to a laying tension of 80 kN or so. What is more, a pipe pull-in history with a laying tension in excess of 80 kN was given to the specimen, and the result indicated that no abnormalities such as buckling were observed and that the external damage due to weld beads was insignificant as shown in Photo 9 thus not reaching a problematic level.

As a result of disassembling investigation, it has been confirmed that every reinforcement layer and the inner pipe had no structural abnormalities, achieving sufficient performance in terms of pull-in history. Photo 10 and 11 show the internal pressure reinforcement layer and the interlocked conduit of the disassembled specimen, respectively.

4. SUMMARY OF PERFORMANCE VERIFICATION TESTS

Various tests for performance verification were carried out using a prototype pipe of optimized lightweight structure, and it was demonstrated that there were no problems with respect to the airtightness characteristics, hydrostatic pressure characteristics, burst pressure characteristics, laying tension resistance characteristics, bending characteristics, and pull-in characteristics for laying. Based on these achievements, the flexible pipe developed here has passed the examination by the Performance Evaluation Committee comprised of The High Pressure Gas Safety Institute of Japan and the experts, and thereby has acquired a special certification as a flexible pipe for transportation of high-pressure liquefied petroleum gas.

5. IN CONCLUSION

We have developed, in collaboration with Nippon Steel and Idemitsu Kosan, a lightweight flexible pipe suitable for laying, by means of floating extension method, in long-distance pipelines with severe bends. The pipe developed here was first applied to, after its manufacturing was completed in one continuous length in January 2002, the reconstruction work of the existing submarine pipeline in the Tokuyama Refinery of Idemitsu Kosan in July 2002, and the pipe laying work was accomplished in safety. When the verification test for gas transportation that is currently under way is completed, this will be domestically the first application of a flexible pipe for transportation of high-pressure liquefied gas.

In closing the authors will be most gratified if the flexible pipe developed here can contribute to reconstruction works of petrochemical complexes. We would also like to express our thanks to those who kindly cooperated in this development.

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