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Development of "Steel Pipe for Crossing Fault (SPF)" Using Buckling Pattern for Water Pipelines†

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Abstract:

JFE Engineering has developed "Steel Pipe for Crossing Fault (hereinafter SPF)," which can absorb extremely large fault displacement in order to secure the seismic safety of water pipelines crossing faults. Installation of plural SPF deformation nodes (buckling pattern sections) in straight pipes before and after a fault enables control of the location and mode of deformation in the pipeline when absorbing fault displacement. This function makes it possible to maintain inner section of the pipe, and thereby maintain the water supply with no leakage, even in very large earthquakes with ground transformation of several meters around the fault plane.

1. Introduction

Following the Southern Hyogo Prefecture Earthquake (Kobe Earthquake) in 1995, the Japanese government established the Headquarters for Earthquake Research Promotion in order to promote comprehensive earthquake countermeasures throughout Japan and encouraged scientific research on active faults. According to the results of that research study, the existence of more than 2 000 active faults has been confirmed to date. The length of those faults ranges from several kilometers to several tens of kilometers, and when a slip occurs in a fault, the average fault displacement is assumed to exceed 2 meters.

Steel pipes for water pipelines are used as earthquake-resistant pipes with high seismic safety even against Level 2 earthquakes, particularly in critical trunk pipelines such as conveyance and transmission mains. However, pipelines are subject to buckling deformation at locations where large local displacement of several meters is assumed, for example, in fault plane slips, especially when bending deformation acts on the pipe in the compressive direction, as at reverse faults. When this type of damage occurs, loss of the water supply capability would be a real possibility. Due to the number and length of faults, as described above, it is difficult to lay water pipelines in a way that avoids faults, and until now, no effective countermeasures were available. Thus, at present, virtually no seismic countermeasures have been implemented anywhere in Japan for water pipelines that cross faults. To address this problem, JFE Engineering developed "Steel Pipe for Crossing Fault (SPF)" [1, 2] which makes it possible to maintain the water supply function, without causing cracks or leaks in the pipeline, even if slip displacement occurs at an active fault during an earthquake. This paper presents an outline of SPF and introduces a demonstration experiment and a case study of application.

2. Outline of SPF

2.1 Development Concept

If large fault displacement acts on a water pipeline that crosses a reverse fault, as illustrated in **Fig. 1**, buckling will occur on the two sides of the fault plane[3, 4]. Because this fault displacement acts locally accompanying slip of the fault plane and is also very large, having a scale of several meters, it is difficult to respond with measures that utilize the properties of the pipe, for example, by using high strength steel pipes, etc.

Therefore, the concept adopted here was develop-

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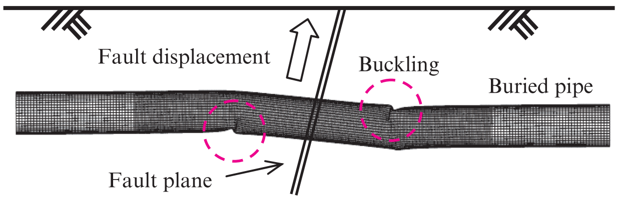

Fig. 1 Deformation of buried pipeline caused by fault displacement

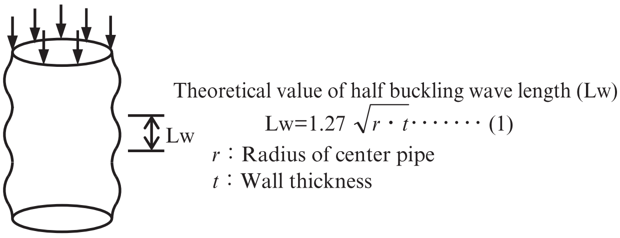

Fig. 2 Deformation mode of cylindrical shell under axial compression

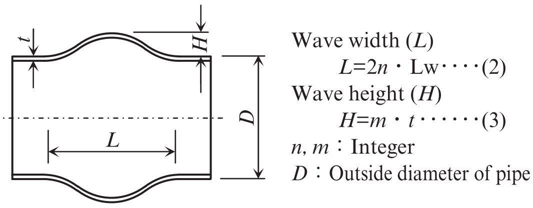

Fig. 3 Specification of designed buckling pattern

ment of a steel pipe for water pipelines which does not depend on the strength of the pipe as a measure against fault displacement, but rather, has a structure that can absorb large displacement by utilizing the elastoplastic deformability of steel.

In setting the seismic performance requirement for SPF, because (1) fault plane slip events have an extremely long recurrence interval on the order of 1 000 years, and (2) the assumed fault displacement is permanent displacement in only one direction, the conditions set here were a maximum of one event requiring a response during the service life of the pipeline, and fault displacement in only one direction (low cycle fatigue was not considered). Furthermore, based on the Guideline for Seismic Design of Water Facilities (Japan Water Works Association, 2009), a pipe that satisfies "the limit condition that leakage does not occur even in case of local plasticization" in a large event due to fault displacement other than ordinary ground motion was assumed. Therefore, in the structure studied here, plastic deformation of the steel pipe is allowable, but the structure must avoid cracking, and it must also be capable of securing a cross sectional area that enables continuity of water supply even if plastic deformation occurs.

2.2 Shape of Buckling Pattern

In axial compressive buckling of a cylindrical shell such as a steel pipe, the effect of initial irregularities (e.g., slight asymmetry, etc.) increases as the wall thickness decreases, and the deformed shape by buckling and the buckling load vary depending on the position and degree of initial irregularities. On the two sides of the reverse fault shown in Fig. 1, the pipeline is subjected to compression and bending deformation, but because the initial irregularities of actual pipes are different in every pipe, it is difficult to predict the position where buckling will occur and the subsequent deformation behavior of the pipe. Conversely, if a shape that allows easier deformation of the pipe is prepared in the pipe as an initial distortion, subsequent deformation can be made to concentrate on that part.

In SPF, a wave-shaped buckling pattern, which is the deformation mode when axial compression is applied to a cylindrical shell, was given as the shape of this initial distortion. The wave width was set as several times of the wavelength obtained from Timoshenko's buckling half-wavelength theory[5]), and the wave height was set as a multiple of the pipe thickness, and the optimum shape was selected based on a finite element method (FEM) analysis (**Figs. 2** and **3**).

2.3 Determination of Shape by FEM Analysis

An FEM analysis was performed in order to confirm the bending deformability of the wave-shaped buckling pattern set as described above and to optimize the shape of the buckling pattern. The optimum shape was obtained as the condition for obtaining the maximum allowable bending angle by performing a parametric study, in which the wave width (L), wave height (H), and wall thickness (t) were examined as variables. The allowable bending angle was obtained based on the following concept. Namely, in the "Seismic design guidelines for high pressure gas pipelines against liquefaction "(Japan Gas Association (2007)[6]), the limit condition for crack initiation is obtained experimentally by forced bending of a straight pipe, as illustrated in **Fig. 4**. Here, the following mechanism was confirmed: First, the inner side of the pipe wall comes into contact at the ridge part that forms as a result of bending. The ridge then begins to collapse as the reaction force increases under progressive bending, and finally, a crack is initiated when collapse proceeds beyond a certain point. Based on this,

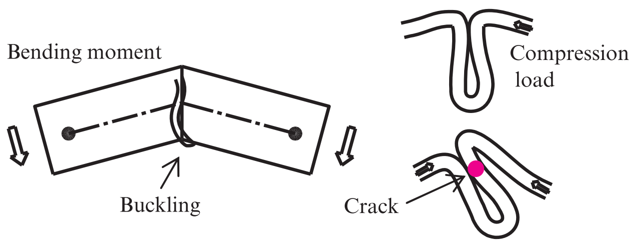

Fig. 4 Crack initiation mechanism of steel pipe bending

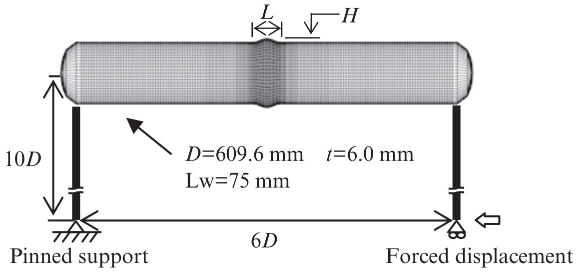

Fig. 5 Analytical model for the selection of the best specification of buckling pattern

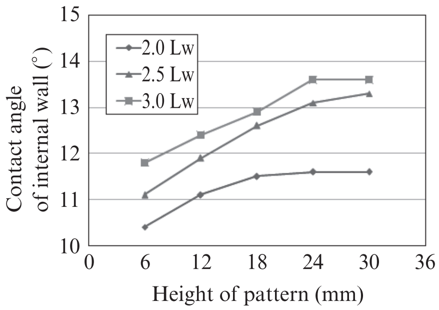

Fig. 6 Calculation results of contact angle for several wave height, H and half wavelength of buckling, Lw

Photo 1 Apparatus of pipe bending test

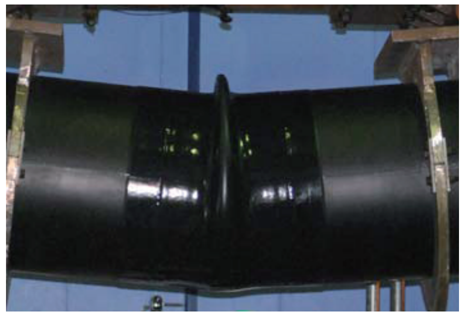

Photo 2 Deformation of test pipe at contact angle of inner wall (θ=12.6°)

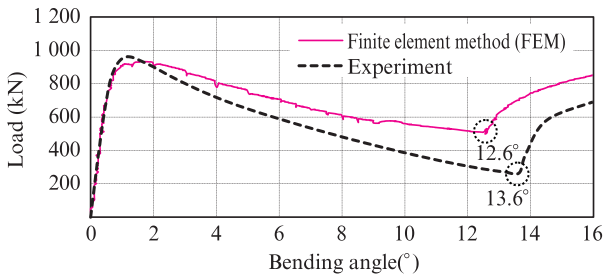

Fig. 7 Relation between bending loads and bending angles

and considering safety, the angle at which contact of the inner surface wall occurs before collapse begins, as shown in Fig. 4, was set as the allowable bending angle.

In the FEM analysis for selection of the optimum shape, a simple bending model was used, as shown in **Fig. 5**, so that only bending acts on the buckling pattern section. The analysis results are shown in **Fig. 6**. From these results, for the wave width, the contact angle of the inner surface wall shows its maximum value in the case of L = 3.0 Lw. For the wave height, although the contact angle of the inner surface wall tends to increase as the wave height increases, this tendency becomes saturated above H = 24 mm (4t). Therefore, L = 3.0 Lw and H = 4t were selected as the optimum specification.

3. Bending Performance Confirmation Test

In order to confirm the deformability of SPF with the optimum specification determined by FEM analysis, a bending test was performed using an actual pipe with an inner diameter of 600A and a wall thickness of 6.0 mm. The test was performed by 4-point bending, using the structural testing machine with a 3 MN capacity shown in **Photo 1**.

The inner surface wall contact angle obtained from the experiment, as shown in **Photo 2** and **Fig. 7**, was 12.6°. The contact angle obtained from an FEM analysis reproducing the experiment was 13.6°. Although the FEM analysis value was slightly larger in comparison with the experimental value, approximate agreement was obtained. Furthermore, the facts that deformation concentrates only on the buckling pattern section and the buckling part forms a bilaterally-symmetric ridge shape were also confirmed.

4. Case Study of Application of SPF

The following presents an outline of a concrete case study of application of SPF in a pipeline crossing a fault.

4.1 Conditions of Case Study

The object fault and the basic conditions of the case study are shown in **Fig. 8** and **Table 1**, respectively.

4.2 Study of Installation Interval

The case in which forcible displacement accompanying slip of a fault plane acts on a straight pipeline crossing the fault plane was assumed. Bending occurs in the pipe, centering on the fault plane, as shown in **Fig. 9**, and as displacement proceeds, the bending moment at

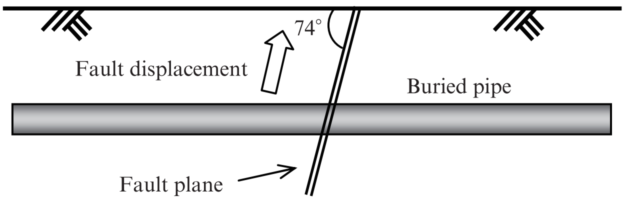

Fig. 8 Model of case study

Table 1 Basic conditions for case study

Steel pipe	Nominal diameter	2 400A
	Wall thickness	21 mm
	Material	SS400
	Young's modulus	2.0×10^5 N/mm^2
	Yield stress	225 N/mm^2
Fault	Fault type	Reverse
	Fault angle	74°
	Fault displacement	1.440 m

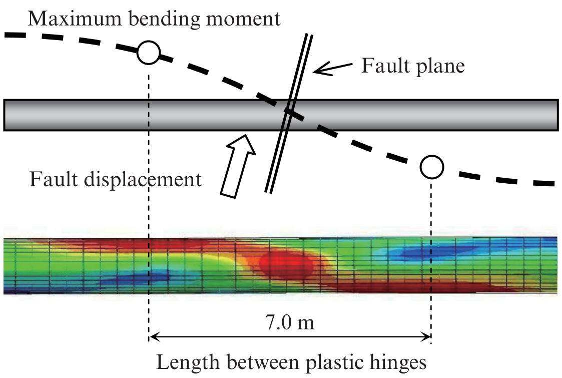

Fig. 9 Plastic hinges on pipe crossing fault

the positions shown by the ○ marks in the figure reaches the fully plastic moment and plastic hinges form. Therefore, SPF is arranged at the positions of the plastic hinges, where the bending moment reaches its maximum, in order to absorb the fault displacement efficiently. The installation interval of the plastic hinges is obtained by FEM analysis.

4.3 Setting Number of Buckling Pattern Waves

The bending angle is calculated from the amount of displacement of the fault, which is given as a fault parameter, and the length between the plastic hinges, which is set as described above. Although the allowable bending angle per 1 buckling pattern wave of SPF varies depending on the relationship between the pipe inside diameter and wall thickness, it is approximately 13°. Therefore, the number of buckling pattern waves of SPF is set assuming an allowable bending angle of 12° as a conservative value. For example, if three buckling pattern waves are installed, the allowable bending angle is 36°.

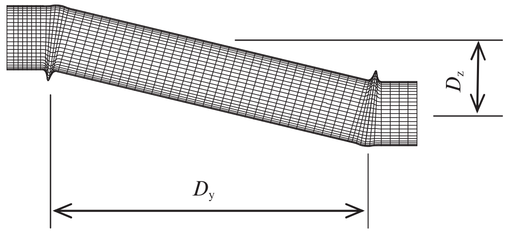

Fig. 10 Design method for the required number of buckling pattern

When the bending angle is calculated from the above-mentioned fault displacement and the length between the plastic hinges, the result is approximately 11°. Since this is smaller than the allowable bending angle (12°), this displacement can be absorbed by one buckling pattern wave (**Fig. 10**).

$$\theta = \tan^{-1}\left(\frac{D_z}{Y_z}\right) \quad (4)$$

where, θ: bending angle (°)
D_y: Length between plastic hinges (7.0 m)
D_z: Vertical fault displacement (1.380 m)

4.4 Performance Confirmation by FEM Analysis

The bending performance of SPF under fault displacement (1.440 m) when one SPF buckling pattern wave was installed at the positions where plastic hinges occur was confirmed by FEM analysis.

In the analysis results, as shown in **Fig. 11**, it can be understood that bending moment acts on the ridge of

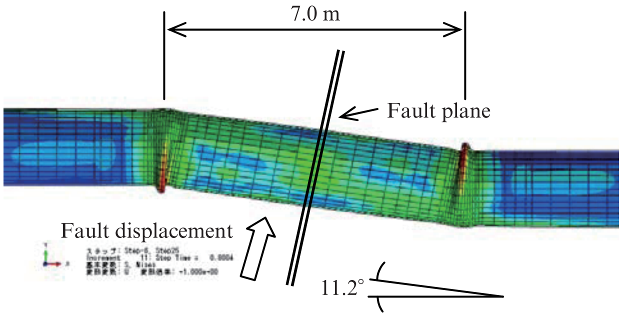

Fig. 11 Deformation of designed buckling patterns in the case study

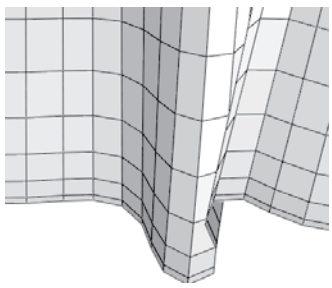

Fig. 12 Deformaition of designed buckling pattern

buckling pattern waves and deformation is concentrated only on the ridges.

As shown in Fig. 11, the bending angle with fault displacement of 1.440 m is 11.2°, and thus is within the allowable bending angle (12°). Furthermore, as shown in **Fig. 12**, this study confirmed that the pipe wall was within the allowable bending angle and did not reach a condition of inner surface contact.

5. Conclusion

In this paper, an outline of "Steel Pipe for Crossing Fault (SPF)," confirmation of the bending performance of the developed pipe in a demonstration experiment, and a case study of application were presented.

By fully utilizing the elastoplastic deformability of steel pipes, SPF can follow extremely large fault displacement, thereby maintaining continuation of the supply of the water lifeline during earthquake disasters. This development is considered to have created an environment where concrete earthquake-resistance countermeasures can be studied, including fault crossing points where positive earthquake-resistant measures had not been feasible in the past. The authors hope that this development will be of assistance in waterworks earthquake-resistance measures, which are now being promoted throughout Japan.

References

1) Hasegawa, N.; Imai, T.; Suzuki, N. Development of high seismic performance pipe for crossing active faults. The 6th Japan-US-Taiwan Workshop on Water System Seismic Practice. 2009.
2) Hasegawa, N.; Imai, T.; Nagamine, H.; Nakajima, Y. Development of steel pipe for crossing fault using buckling pattern. The 46th Meeting for Reading Research Papers. Japan Industrial Water Association. 2011, p. 31–34.
3) Takada, S.; Hassani, N.; Fukuda, K. Proposed design method for fault-crossing buried pipelines. Proceedings of JSCE. 2001, no. 668/I54, p. 187–194.
4) Takada, S.; LI, T.; Liang. J. Earthquake-proof calculation method of an underground conduit crossing a fault. Proceedings of the 24th JSCE Earthquake Engineering Symposium. 2007, p. 969–972.
5) Timoshenko, S. (Namikawa, K.; Naka, T.; Hisada, T., transl.) Zakutsu Riron. Corona Publishing, 1954.
6) Japan Gas Association: Seismic design guidelines for high pressure gas pipelines against liquefaction. 2007.