Performance Test of Steel Pipe for Crossing Fault in United States

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ABSTRACT

This report describes the performance tests of Steel Pipe for crossing Fault (SPF), which is an "on fault earthquake-resistant countermeasure" pipe, conducted at Cornell University. In the test results, despite applying deformation of several times the design value, the pipe did not crack or leak and more than 80% of the pipe cross section where water can pass was secured in all the tests.

I. INTRODUCTION

There are about 2000 faults in Japan. Similarly, there are many huge active faults such as the San Andreas Fault on the West Coast of the United States. Particularly in California, large-scale earthquakes are expected in the future, and since many buried water pipelines cross faults, local water utility companies are studying fault countermeasures for underground waterworks pipelines.

Steel Pipe for crossing Fault (SPF) is a fault countermeasure for buried water pipelines. SPF is manufactured by processing steel pipes for waterworks into a special wavy shape (comparable to the wavy part of a bendable drinking straw) so that the fault displacement which occurs during an earthquake can be absorbed by concentrating the deformation on the wave-shaped section, rather than attempting to resist the deformation. We have conducted tests in Japan, including underground tests, and confirmed the performance of Steel Pipe for Crossing Faults.

This report will give an overview of Steel Pipe for Crossing Fault and describe the performance tests conducted at Cornell University.

II. OVERVIEW OF STEEL PIPE FOR CROSSING FAULT

Damage to Fault Crossing Pipeline

Figure 1 shows an example of damage to a buried steel pipeline (200A diameter steel pipe) crossing a fault in the Taiwan Earthquake of 1999. When a slip occurs at the fault plane, it is likely to be thought that the transverse pipeline undergoes shear deformation at the fault plane due to the shearing force of the ground.

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However, in the actual pipeline shown in Figure 1, bent portions (plastic hinges) formed at positions away from the fault plane, and the whole pipeline exhibited a Z-shaped bending deformation.

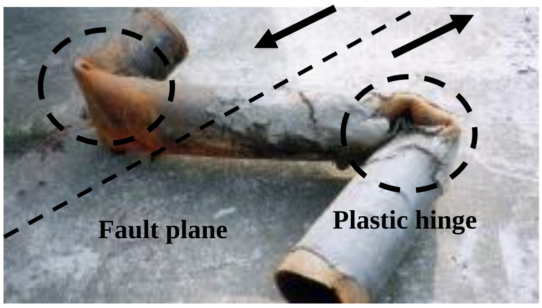


Figure 1. Damage to pipeline in fault cross-section

The pipe damage shown in Figure 1 is an example of damage to a buried steel pipeline crossing a fault. As shown in the figure, the pipe was bent plastically in the shape of the letter "Z." To identify the mechanism of Z-shaped plastic deformation, a finite element analysis of the pipeline-soil system shown in Figure 2 was done. The pipeline and soil were modeled with shell and solid elements, respectively, and forced displacement was given so that fault displacement occurred in the direction indicated by the arrow. In the analysis, as shown in Figure 2, buckling occurred symmetrically on both sides of the fault at a certain distance from the fault plane, and the cross section does not necessarily show deformation at the fault plane. These analytical results were consistent with the observation results shown in Figure 2.

The analytical results indicate that a pipeline will rotate about the fault plane if fault displacement occurs. When this occurs, soil shear force occurs along the fault plane, but since the stiffness of the pipe is sufficiently large compared with the soil shear force, buckling does not occur at the shear plane. However, because of fault displacement, rotating force acts on the pipe so that bending occurs on both sides of the fault plane at points certain distances from the fault plane. When the full plastic moment is reached at the points where the maximum bending moment occurs, buckling begins and plastic hinges are formed. As shown in Figure 2, bending deformation is concentrated only at these plastic hinges. Therefore, it was thought that the most effective countermeasure for fault displacement is to absorb the bending at the position where the maximum bending moment occurs. Based on this concept, we developed “Steel Pipe for crossing Fault,” which fully utilizes the elastoplastic deformability of steel pipes, as a structure that absorbs bending deformation.

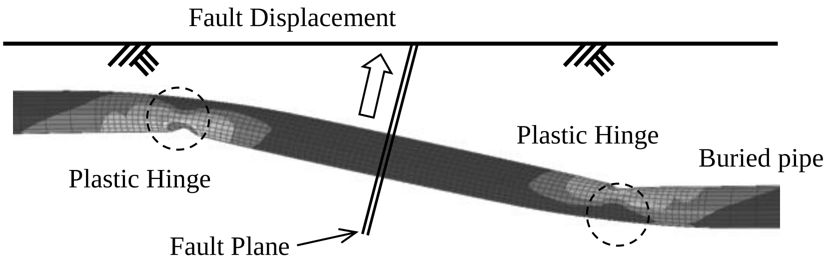


Figure 2. Deformation of buried pipeline caused by fault displacement

Basic Mechanism of Steel Pipe for Crossing Fault

As described above, the damage to a pipeline caused by fault displacement takes the form of concentrated local bending deformation at the positions where plastic hinges are formed. This suggests that the water flow function of the whole pipeline can be maintained if a mechanism which is capable of absorbing bending deformation corresponding to the fault displacement is provided at these positions. Therefore, as shown in Figure 3, short pipes with a convex part (hereinafter referred to as “wave-shaped section”) are prepared in advance as an initial deformation in the steel pipe, and by placing these wave-shaped sections at the positions of the maximum bending moment caused by fault displacement, it is considered possible to control the position of occurrence of deformation and the deformation mode.

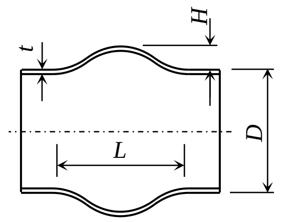


Figure 3. SPF wave-shaped section

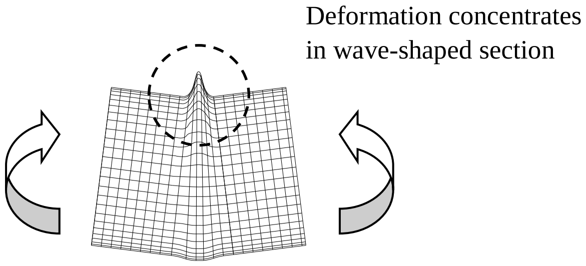


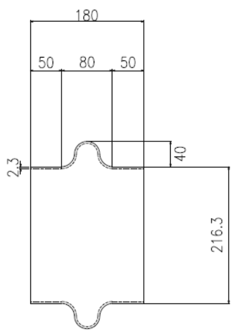
Figure 4. Deformation of wave-shaped section

Figure 4 schematically shows the deformation of the wave-shaped section. The upper side of the pipe (compression side) shows deformation such that the inner walls come into contact with each other when bending deformation occurs, while the lower side of the pipe (tension side) shows deformation in which the wave-shaped section extends and the convex part becomes flat. Since both deformation modes are simple, if the deformation range is restricted, it is possible to prevent the reduction of the water flow function due to blockage of the pipe cross section and cracks due to buckling. Furthermore, because the fault displacement necessarily acts in one direction, there is no concern of cracking due to low cycle fatigue.

Although the steel pipes in the wave-shaped sections deform plastically in order to absorb fault displacement of several meters as bending deformation, the pipeline can still deliver water without leakage after an earthquake. Since the water flow function can be maintained for a certain period of time until more urgent emergency/restoration work is completed, the survey, diagnosis and restoration of the wave-shaped sections can be handled after the disaster.

III. PERFORMANCE TESTS

In order to confirm the performance of Steel Pipe for crossing Fault, we carried out an axial compression test, axial tensile test, bending test and underground test at Cornell University (New York, USA). The geometry of the specimen used in the tests is shown in Figure 3-1.



OD： 213.6 mm

t： 2.3 mm

Material： SS400

Wave height： 40mm

Wave width： 80mm

Figure 3-1. Geometry of Steel Pipe for crossing Fault (SPF) specimen used in tests

Axial Compression Test

The axial compression test was carried out using the test equipment shown in Figure 3-2 to confirm the deformation capacity in the axial compression direction. In order to deform the specimen in the planar direction, a frame was made using molded steel. The specimen and actuator were installed in the frame, and the specimen was subjected to axial compression deformation.

Both ends were joined by flanges to apply pressure (0.55 MPa) to the specimen, and axial compression deformation was applied by using an actuator. The maximum stroke of the actuator was 100 mm, and it was possible to increase the amount of axial compressive deformation by replacing the actuator.

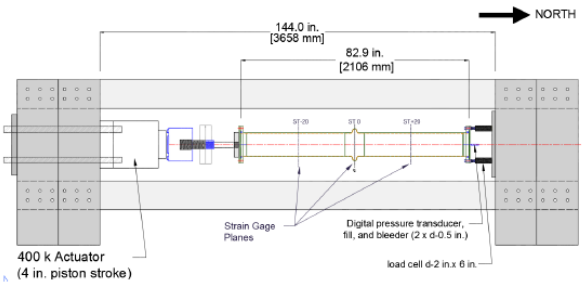


Figure 3-2. Test equipment (axial compression

Figure 3-3 is a deformation image of the allowable displacement of 47.2 mm (at the time of inner surface contact). This deformation is simple deformation in which the wave-shaped section gradually rises, and there were no cracks or leaks.

Figure 3-4 is a deformation image of the displacement of 86.4 mm, which is approximately twice as much as that at inner surface contact. After inner surface contact, the reaction force increased and the straight pipe part began to buckle, but it did not reach cracking and leaking.

Figures 3-5 and 3-6 compare the test results with the results of a FEM analysis. As these figure shows, the deformation is almost the same, and the lateral collapse phenomenon of the wave-shaped section can be reproduced in the FEM analysis.

Figure 3-3. Deformation image (at inner surface contact)

Figure 3-4. Deformation image (final)

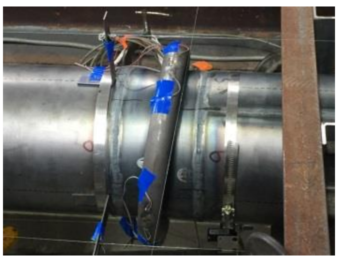


Figure 3-5. Deformation image (at inner surface contact)

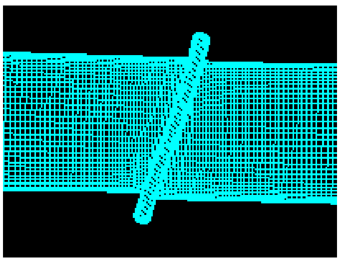


Figure 3-6. Deformation image (final)

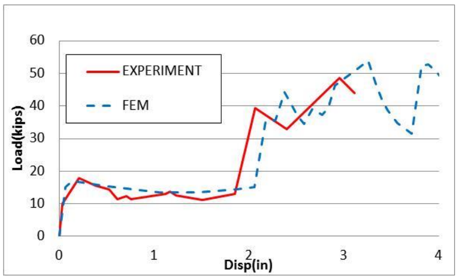


Figure 3-7. Relationship between load and displacement

Figure 3-7 shows the relationship between the load and displacement in the test and in the FEM analysis. The test and FEM analysis results show extremely good agreement. Since Steel Pipe for crossing Fault is made only of a single material (SS400) and the shape is simple, it can be expressed accurately by FEM analysis.

Axial Tensile Test

A demonstration test was carried out to confirm the deformation capacity in the tensile direction. Figure 3-8 shows the test setup. The equipment used in the axial tensile test was basically the same as in the axial compression test, but an adjustment jig was installed at the connection between the specimen and the actuator, and the maximum stroke of the actuator was 100 mm, but could be extended up to a maximum of 400 mm by replacement.

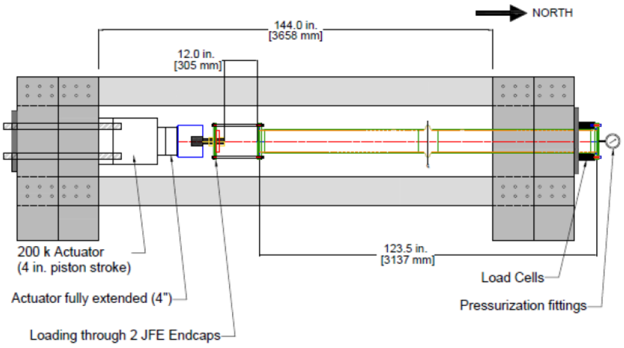


Figure 3-8. Test equipment (tensile

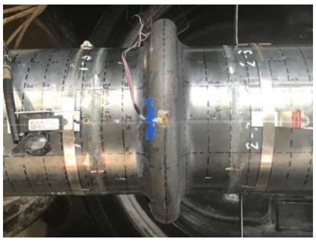


Figure 3-9. Initial state

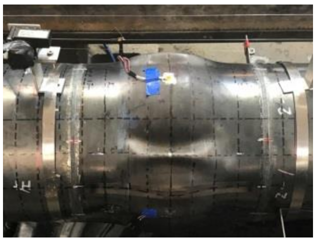


Figure 3-10. Maximum deformation

Figure 3-11. Break (Flange welded part)

The different conditions of the pipe are shown in Figure 3-9 to Figure 3-11. Figure 3-10 shows the final deformation of the wave-shaped section. As shown in the figure, as deformation progresses, the crest height gradually decreases and approaches the straight pipe. Due to the difference in the circumferential lengths of the wave-shaped part and the straight pipe part, creases appear at approximately equal intervals in the peripheral cross section. When pulled further from this state, the deformation in the wave-shaped section dissipates and the deformation moves to the straight pipe part. However, when the straight pipe part starts to expand, the deformation concentrates on the joint (welded part) with the flange. In this test, rupture occurred at the flange welded part on the south side.

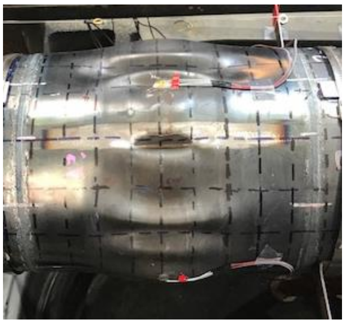


Figure 3-12. After deformation (test)

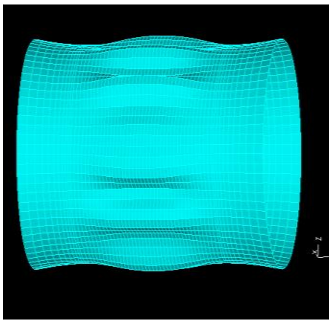


Figure 3-13. After deformation (FEM)

Figures 3-12 and 3-13 are comparisons of the deformation in the test and in the FEM analysis. As the figures show, the deformation is almost the same, and the actual deformation under axial tension can be reproduced sufficiently by FEM. Figure 3-14 shows the *P*-δ curve.

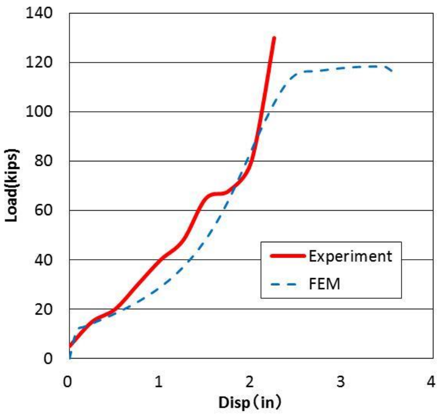


Figure 3-14. *P*-δ curve

Bending Test

In order to confirm the bending deformation capacity of the wave-shaped section, a four-point bending test was performed using the test equipment shown in Figure 3-15. This equipment has a structure in which the outer fulcrum part is movable upward, and all the fulcrums are pin fulcrums and there are no fixed parts. The maximum stroke of the test equipment in one stroke is 300 mm, and replacement is possible when the stroke exceeds this maximum.

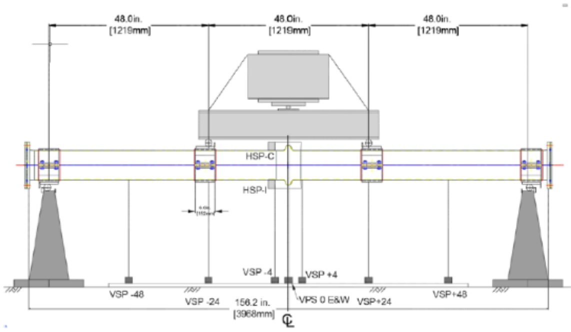


Figure 3-15. Test equipment (bending test)

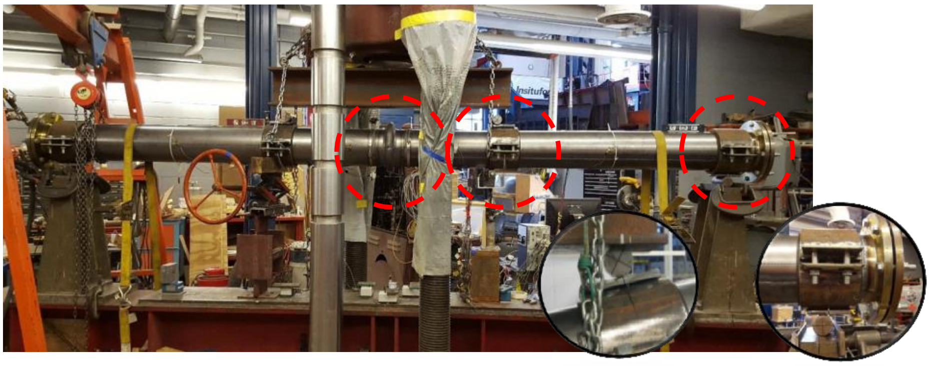


Figure 3-16: Actual setup of test equipment

The test results are shown in Figures 3-17 and 3-18. Figure 3-17 is a deformed image of the pipe with the allowable bending angle (18° at inner surface contact), showing that the upper wave-shaped section rises gradually and deforms uniformly on the left and right. Figure 3-18 shows the deformation at the stroke limit of the test equipment, when the bending angle reached 36.6° (about twice the allowable bending angle). Even in this state, the deformation of the wave-shaped section was almost symmetrical, and no cracks or leaks were found. Figures 3-19 and 3-20 show the deformation image of the FEM analysis. As shown in Figure 3-19, the deformation at the time of contact of the inner surfaces was almost symmetrical, but in the final deformation shown in Figure 3-20, the upper side of the wave-shaped section collapsed and started to deform irregularly.

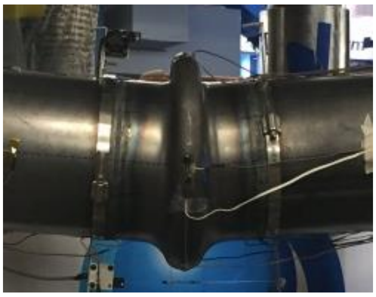


Figure 3-17. Deformation image (at inner surface contact)

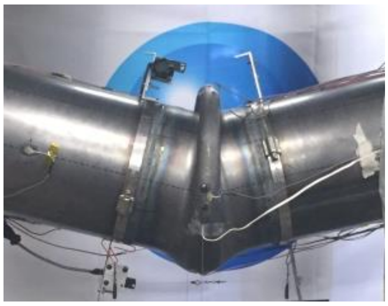


Figure 3-18. Deformation image (final)

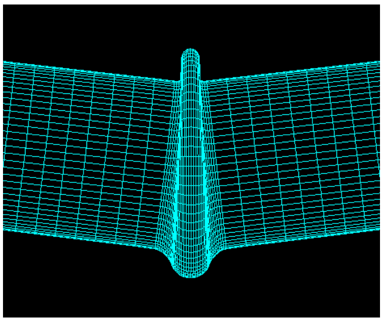


Figure 3-19. FEM deformation image (at inner surface contact)

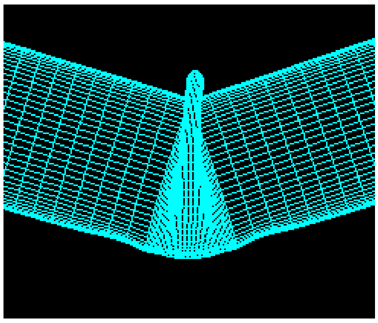


Figure 3-20. FEM deformation image (final)

Figure 3-21 shows the relationship between the bending moment M and bending angle θ. As shown in this figure, the analysis value and the experimental value were almost the same before contact of the inner surfaces, but after contact, the bending moment increased in the FEM analysis but converged to a constant value in the experiment.

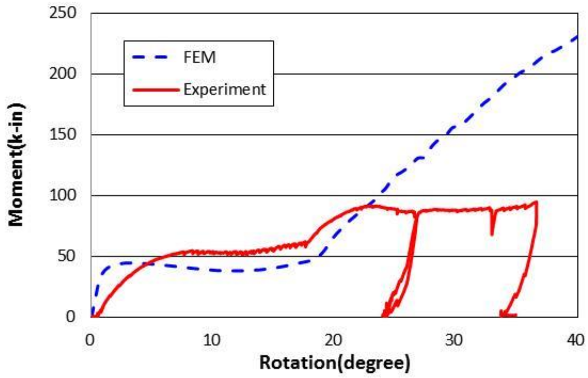


Figure 3-21. *M-θ* curve

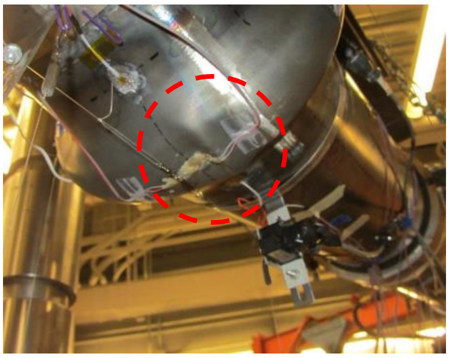


Figure 3-22. Generation of buckle (bending angle 23°)

Underground Test

In order to confirm the deformation capability of the wave-shaped section in the buried condition, an underground test was conducted using the equipment shown in the Figure 3-22. The installation interval of the wave-shaped sections was determined by a FEM analysis, which was carried out beforehand. The test equipment consisted of two soil tanks, one fixed and the other movable, as shown in the figure. Fault displacement (610 mm) was simulated by moving the movable soil tank in the direction of the fault angle (50°) by using actuators.

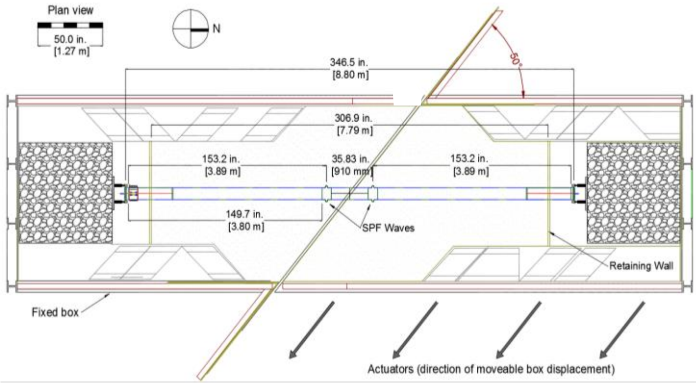


Figure 3-23. Test equipment (underground test)

Figure 3-23 shows the condition of a pipeline installed and backfilled in the test equipment. From this state, fault displacement was given along a fault plane with an angle of 50°.

Figure 3-24 shows the deformed state of the pipeline after applying fault displacement of 610 mm. As shown in figure, the pipeline bent at the wave-shaped sections equidistant from the fault plane and absorbed the fault displacement.

Figures 3-25 and 3-26 show the comparison of the condition before and after deformation. From these figures, it can also be confirmed that the wave-shaped sections absorbed the fault displacement efficiently. The bending angle of the wave-shaped section at final deformation was 42°, and cracks and leaks did not occur even when the pipe was deformed to approximately four times the allowable bending angle (inner surface contact angle of 9°).

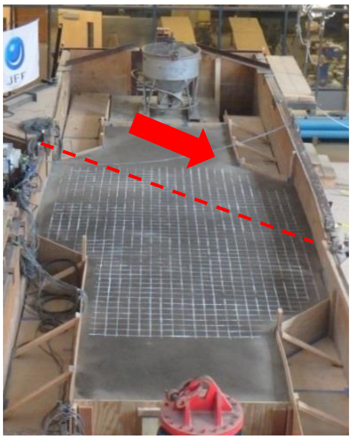


Figure 3-23. Before test

Figure 3-24. After test

Figure 3-25. Before deformation

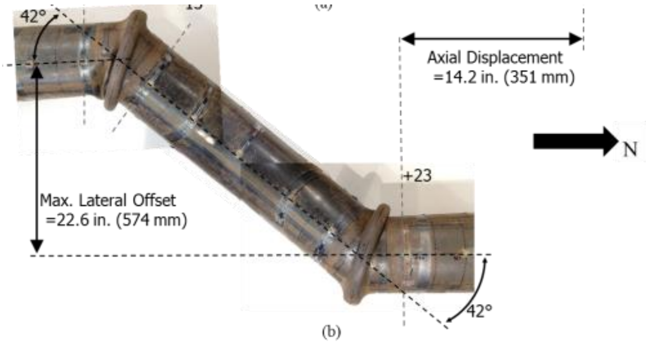


Figure 3-26. After deformation

As shown in Fig. 3-29, although the analytical value was slightly smaller than the experimental value, the first inner surface contact and the second inner surface contact were almost the same, and the curve was roughly traced after that. In analysis including the ground, the analysis value and the experimental value are often inconsistent due to the ambiguity of the ground condition. Here, however, the ground strength was extremely uniform, and the deformation of the pipeline was simple, as only the wave-shaped sections were deformed. This deformation behavior is considered to be a factor in the approximate agreement of the analysis value and the experimental value obtained in this test.

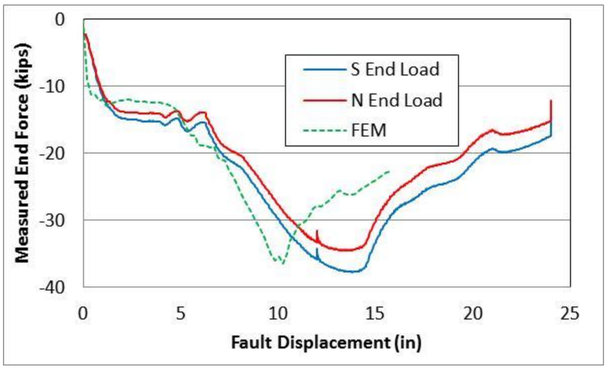


Figure 3-29. Relationship between fault displacement and reaction force

IV. SUMMARY

This report has introduced the results of axial compression, axial tensile, bending and underground tests of Steel Pipe for crossing Fault (SPF), which were conducted at Cornell University in the United States as performance tests of SPF.

In the axial compression test, even though the test pipeline was deformed to about twice the allowable value of inner contact displacement, deformation concentrated only on the wave-shaped section. Complex deformation behavior did not occur, and there were no cracks or leaks.

In the axial tensile test, deformation started in the wave-shaped section, and when the allowable deformation (50 mm) was exceeded, creases (buckling) occurred in the axial direction. However, as the straight pipe part began to elongate under increasing deformation, no cracks or water leakage occurred.

In the bending test, a four-point bending test was performed to an allowable bending angle (inner surface contact angle) of 18° and further to 36.6°, which is about twice the allowable bending angle. No complicated deformation was observed and no cracks or leaks were found.

In the underground experiment, simulated fault displacement of 610 mm was applied to a test pipeline at a fault angle of 50°. In the experimental results, the pipe was deformed to 42°, which was about 4 times the set allowable value of the inner contact angle (9°), but deformation was limited to only the wave-shaped sections, and cracks and leaks were not observed.

From all the test results, no cracks or leakage occurred, even when deformation of several times the allowable axial displacement and bending angle were applied, because the wave-shaped sections were designed with sufficient safety against the set tolerance. Thus, it is considered possible to absorb deformation due to fault displacement, even if unexpected deformation occurs, without failure of the pipeline.

Moreover, in a FEM analysis conducted under the same conditions as the tests, the experimental values and analytical values coincided with very high precision. Therefore, it can be concluded that reproducibility is high even under conditions such as different diameter and pipe thickness.

We hope that this method will be considered one effective option for countermeasures for pipelines crossing faults, and will lead to the construction of earthquake-resistant water pipelines in the United States.

REFERENCE

[1] WSP077-2012 “Steel Pipe for Crossing Fault”, Japan Water Steel Pipe Association, 2012.