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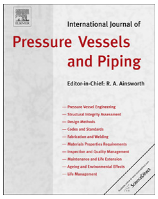

Rupture prediction for induction bends under opening mode bending with emphasis on strain localization

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ABSTRACT

This study focuses on the opening mode of induction bends; this mode represents the deformation outside a bend. Bending experiments on induction bends are shown and the manner of failure of these bends was investigated. Ruptures occur at the intrados of the bends, which undergo tensile stress, and accompany the local reduction of wall thickness, i.e., necking that indicates strain localization. By implementing finite element analysis (FEA), it was shown that the rupture is dominated not by the fracture criterion of material but by the initiation of strain localization that is a deformation characteristic of the material. These ruptures are due to the rapid increase of local strain after the initiation of strain localization and suddenly reach the fracture criterion. For the evaluation of the deformability of the bends, a method based on FEA that can predict the displacement at the rupture is proposed. We show that the yield surface shape and the true stress–strain relationship after uniform elongation have to be defined on the basis of the actual properties of the bend material. The von Mises yield criterion, which is commonly used in cases of elastic–plastic FEA, could not predict the rupture and overestimated the deformability. In contrast, a yield surface obtained by performing tensile tests on a biaxial specimen could predict the rupture. The prediction of the rupture was accomplished by an inverse calibration method that determined the true stress-strain relationship after uniform elongation. As an alternative to the inverse calibration, a simple extrapolation method of the true stress-strain relationship after uniform elongation which can predict the rupture is proposed.

1. Introduction

When installing pipelines in a seismic area prone to soil liquefaction, it is essential to ensure that pipeline deformation does not surpass the predetermined limits. Due to soil liquefaction during landslides pipe deformation may exceed the maximum bending moment and deform under a displacement control condition. Because of this, a rupture that occurs after the peak moment is set as a limit of the pipes [1]. Though many studies [2–4] have been conducted in relation to the deformability of pipes, most have not focused on the rupture but on the peak moment or plastic collapse.

A few studies have proposed methods for evaluating the rupture of pipes under bending deformation. Miyazaki et al. [5] demonstrated that the rupture of straight pipes with local wall thinning under bending can be evaluated by hydrostatic stress. The critical hydrostatic stress was one-third of the true stress at rupture in a uniaxial tensile specimen test. This evaluation method was proposed by Weiss [6]. In contrast, it is well known that the initiation of a ductile fracture can be evaluated by stress triaxiality, which is the ratio of hydrostatic stress to the von Mises equivalent stress and equivalent plastic strain [7]. This evaluation method was proposed by Rice [8] and based on a void nucleation theory. Weiss's criterion does not correspond to the theory for initiation of ductile fractures proposed by Rice. Therefore, while Weiss's criterion would be empirically applicable to evaluate the rupture, it is not based on the actual mechanism. A method for evaluating rupture that is based on the mechanism of the fracture must be established for detailed evaluation of the resistance against soil liquefaction.

Yatabe et al. [9] showed that the rupture of a straight pipe under bending was accompanied by a local reduction of wall thickness, i.e., strain localization by finite element analysis (FEA). This strain localization is also called necking. Though this study could describe the rupture mechanism, its displacement could not be simulated. That is to say, a method for evaluating the deformability that

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represents displacement or bending angle at the rupture of the pipes was not established.

The purpose of this study is to establish a methodology for evaluating the deformability, which represents the deformation at rupture under bending. Induction bends were targeted in this study. There are two bending modes: the opening mode and closing mode. As shown in Fig. 1, the opening mode means deformation outside of the bend; the closing mode is the opposite of the opening mode.

This study focuses only on the opening mode because this mode is more severe than the closing mode when the bend is subjected to landslide by soil liquefaction. Landslide by soil liquefaction cannot be assumed as a load-controlled condition, but can be considered as a displacement-controlled condition [1]. Therefore, the deformation until rupture that occurs after the peak moment can be adopted as a design criterion. Though the peak moment and collapse moment are larger for the opening mode than for the closing mode [1,10,12–14], the deformation until rupture is smaller for the opening mode than for the closing mode [1,11]. Therefore, the induction bend under opening mode bending was adopted as the subject for the present study.

Two bending experiments on induction bends are shown, and the manner of failure of the bends was investigated. Rupture occurred at the intrados of the bends and was accompanied by strain localization. An evaluation method that can predict the displacement at rupture was then proposed based on FEA. The true stress–strain relationship after uniform elongation was determined by the inverse calibration method, and the yield surface was determined by performing tensile tests on a biaxial specimen. The mesh division that can simulate the strain localization was investigated. Finally, input conditions that are essential to simulate the displacement at rupture were parametrically studied. As part of this parametric study, a simple extrapolation method of true stress–strain relationship after uniform elongation that can predict the rupture is proposed.

2. Bending experiment

2.1. Test material and experimental setup

In order to measure the deformation behavior and the deformation at rupture of the bends, bending experiments using API 5L X80 induction bends were performed [11]. The experimental setup is shown in Fig. 1 and Table 1. The name of each part on the test bends is shown in Fig. 2.

The dimensional properties of the test bends are listed in Table 2. The nominal diameters of the test bends were 614.4 mm and the center angles were 45° and 90°. The test bend with the center angle of 45° was labeled Bend-A and that with the center angle of 90° was labeled Bend-B. Wall thickness at the bent part was distributed because the bends were formed by the induction bending process from straight pipe. With respect to the bent part of Bend-A, wall thickness at extrados was 15.7 mm, that at intrados 21.6 mm, and that at neutral axis was 18.0 mm. With respect to Bend-B, the wall thickness at extrados was 14.2 mm, 19.5 mm at the intrados, and that at neutral axis was 16.6 mm. Wall thickness at the straight part, which is shown in Fig. 2, was same as the neutral axis of the bent part in both Bends A and B. The length of the wall thickness transition area, which is shown in Fig. 1, was approximately 100 mm. Two test bends were made by the same process for both of Bends A and B. One of them was used for the bending experiments and the other was used for the uniaxial tensile tests with a round bar specimen. The mechanical properties and chemical composition of the bends are given in Tables 3 and 4, respectively. The nominal stress–strain curves of the bend materials are shown in Fig. 3. The mechanical properties, including the stress–strain curve, depend on the position where the specimens are machined. These positions, extrados or intrados, are shown in Fig. 2. Both specimens were machined in the longitudinal direction of the bends because longitudinal deformation is dominant during bending deformation. The specimens for the tensile tests were round bar with a diameter of 6.4 mm for Bend-A and 6.0 mm for Bend-B.

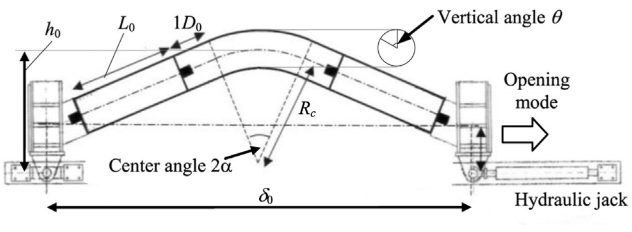

Fig. 1. Schematic illustration of experimental setup.

Table 1
Geometry of experimental setup.

	δ_0 [mm]	h_0 [mm]	L_0 [mm]
Bend-A ($2\alpha_0 = 45$ deg.)	9090	2941	3660
Bend-B ($2\alpha_0 = 90$ deg.)	7974	0	3200

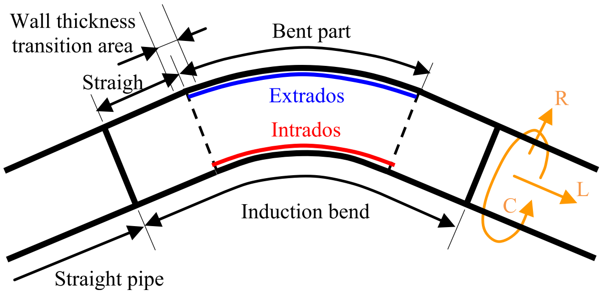

Fig. 2. Schematic illustration of induction bend.

Table 2
Geometrical properties.

	Bend-A	Bend-B
Center angle 2α	44.62°	89.92°
Bend radius R_c	1834.5 mm	1827.0 mm
Outer diameter	613.2 mm	614.3 mm
Wall thickness at extrados	15.7 mm	14.2 mm
Wall thickness at intrados	21.6 mm	19.5 mm
Wall thickness at neutral axis	18.0 mm	16.6 mm

Table 3
Mechanical properties (longitudinal, round bar specimen).

		Bend-A	Bend-B
Extrados	Yield strength	634 MPa	666 MPa
	Tensile strength	708 MPa	734 MPa
	Uniform elongation	7.2%	7.9%
	Elongation	25%	21%
	Y/T	90%	91%
Intrados	Yield strength	644 MPa	627 MPa
	Tensile strength	711 MPa	691 MPa
	Uniform elongation	7.9%	8.1%
	Elongation	25%	23%
	Y/T	91%	91%