A Curvature-ovalization Measurement Apparatus for Circular Tubes Under Cyclic Bending

by W.-F. Pan, T.-R. Wang and C.-M. Hsu

ABSTRACT—In this paper, the authors report the design and construction of a new measurement apparatus, along with the result of its testing. This apparatus can be placed at the midspan of the circular tube specimen and is suitable for simultaneous experimental determinations of the tube curvature and ovalization of the tube cross section. For testing the newly designed apparatus, the tube specimen of AISI 304 stainless steel was bent cyclically. It has been shown that the actual curvature and ovalization of the circular tube subjected to bending can be directly measured by the apparatus.

KEY WORDS—Cyclic bending, curvature, ovalization, inclinometer

Introduction

Proper understanding of the elastoplastic response of circular tubes subjected to pure bending is of importance in many industrial applications, such as offshore pipelines, platforms in offshore deep water, tubular components in nuclear reactors, etc. The deformation characteristics of nonlinear moment-curvature relationship are well known. Ovalization of the tube cross section is known to occur when the tube component is bent into plastic range. Increase in ovalization causes a progressive reduction in the bending rigidity (accumulation of damage) which can result in buckling or fracture of the tube component.[1–4]

In recent years, Kyriakides and coworkers have experimentally investigated the elastoplastic behavior of circular pipes subjected to monotonic or cyclic pure bending. They designed a bending device that can be used for conducting the experiment on circular tubes subjected to cyclic bending[5] to measure the magnitudes of bending moment and tube curvature. For the measurement of ovalization of the tube cross section, Kyriakides and Shaw[6] designed a lightweight instrument which can be placed at the midspan of the test specimen for measuring the ovalization of tube cross section. They studied the inelastic behavior of thin-walled tubes under cyclic bending. These bending test facilities have been used for subsequent experimental studies. For example, Shaw and Kyriakides[7] investigated the inelastic buckling of tubes under cyclic bending, Kyriakides and Shaw[8] performed an experimental investigation on the response and stability of thin-walled tubes under cyclic bending, Corona and Kyriakides[9] studied the stability of long metal tubes subjected to combined bending and external pressure, Corona and Kyriakides[10] discussed the degradation and buckling of circular tubes under cyclic bending and external pressure, and Kyriakides and Ju[11] experimentally investigated the bifurcation and localization instabilities in circular cylindrical shells under pure bending.

Based on the bending facility designed by Kyriakides and coworkers, the magnitudes of the bending moment and ovalization of the tube cross section for a tubular specimen subjected to bending can be directly measured by the load cells, which are connected to the heavy chains of the bending device, and by a self-designed instrument, which is placed at the midspan of the test specimen. However, the measurement of tube curvature is complicated, especially when the tube is bent into plastic range. In these studies,[5–11] a special calibration bending test for each material and each tube size used is performed to obtain a correct value of the effective length. The amount of the effective length is needed for calculating the actual curvature of the tube. Once the magnitude of the effective length is obtained, it can be used to establish the actual curvature for the subsequent cyclic bending.

To avoid a protracted calibration for the curvature of the tube subjected to bending, a new curvature-ovalization measurement apparatus (COMA) is proposed in this paper. This apparatus is a lightweight instrument which can be placed at the midspan of the test specimen. It is suitable for directly measuring the tube curvature and ovalization of the tube cross section. For testing the proposed COMA, a tube specimen of AISI 304 stainless steel was bent cyclically. The bending device used for this test is similar to the device used by Kyriakides and coworkers.[5–11] Experimental data of the tube curvature and ovalization of the tube cross section measured by using the COMA are shown. The curvature-symmetric cyclic bending test was well controlled by the COMA.

Bending Device

The bending device is shown in Fig. 1. It is a four-point bending machine, capable of applying reverse bending (similar to the facilities reported in Refs. 5-11). The device consists of two rotating sprockets resting on two support beams. Heavy chains run around the sprockets and are connected to two hydraulic cylinders and load cells, forming a closed loop. Once either the top or bottom cylinder is contracted, the sprockets are rotated, and pure bending of the test specimen is achieved. Reverse bending can be achieved by reversing the

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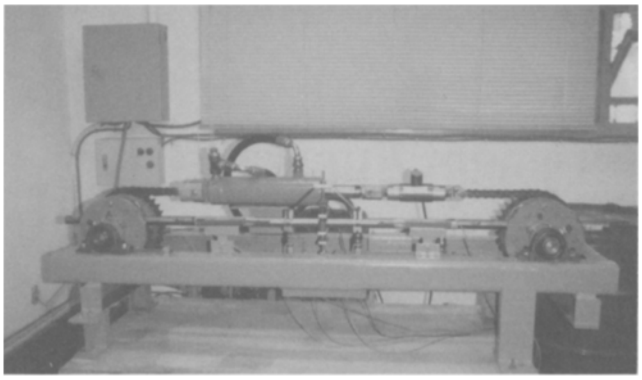

Fig. 1—Pure bending device

direction of flow in the hydraulic circuit. Detailed description of the bending device can be found in several references.[5–7]

The two sprockets rest on two heavy support beams 1.25 m apart. This allows a maximum length of the test specimen to be 1 m. The bending capacity of the machine is 5300 N-m. Each tube is tested and fitted with solid rod extension. The contact between tube and the rollers is free to move along the axial direction during bending. The load transfer to the test specimen is a couple formed by concentrated loads from two of the rollers. The applied bending moment is directly proportional to the tension in the chains. Based on the signal from two load cells, the bending moment M exerted on the tube is calculated as

$$M = FR, \tag{1}$$

where F is the force on the chain, which can be obtained from the pressure and area of the cylinder, and R is the radius of the sprocket.

Curvature-ovalization Measurement Apparatus (COMA)

The curvature-ovalization measurement apparatus (COMA), shown schematically in Fig. 2(a), was designed for directly measuring the tube curvature and ovalization of tube cross section. A picture of the COMA is shown in Fig. 2(b). The COMA is a small lightweight instrument and is mounted close to the tube midspan. It can be used to monitor the changes in major and minor diameters of the tube cross section using a magnetic detector (middle part of the COMA). Simultaneously, it can be used to measure variations in the tube curvature close to the midspan from the signals of inclinometers (inclinometers have also been used by Corona and Ellison[12] for measuring the roll of the cross section and the pitch of the instrument on T-beams under bending).

There are three inclinometers in the COMA. Two of them are fixed on two holders, which are denoted as side-inclinometers 1 and 2, respectively [see Fig. 2(a)]. The holders are fixed on the circular tube before the test begins. The angles of rotation detected by these two side-inclinometers are in the $x - y$ plane, which is the direction of the bending moment (see Fig. 3). To ensure the measurement of these two side-inclinometers in the same plane, a ring with ball bearings is designed which is connected to these two holders by two solid rods. Four railway tracks on the surface of the vertical solid cylinder are used for guiding the movement of the ring. To avoid any deformation of the solid rods, this ring is free to move vertically. The changes in angles of these two side-inclinometers can be detected and transferred into tube curvature. An additional inclinometer (denoted as center-inclinometer) is fixed at the center part of the COMA, as shown in Fig. 2(a). The angle of rotation detected by center-inclinometer is in the $y - z$ plane, which is perpendicular to the plane of the bending moment (see Fig. 3). The center-inclinometer can be used for inspecting the deviation of the plane, in which the aforementioned two side-inclinometers are fixed, from the plane of bending moment ($x - y$ plane).

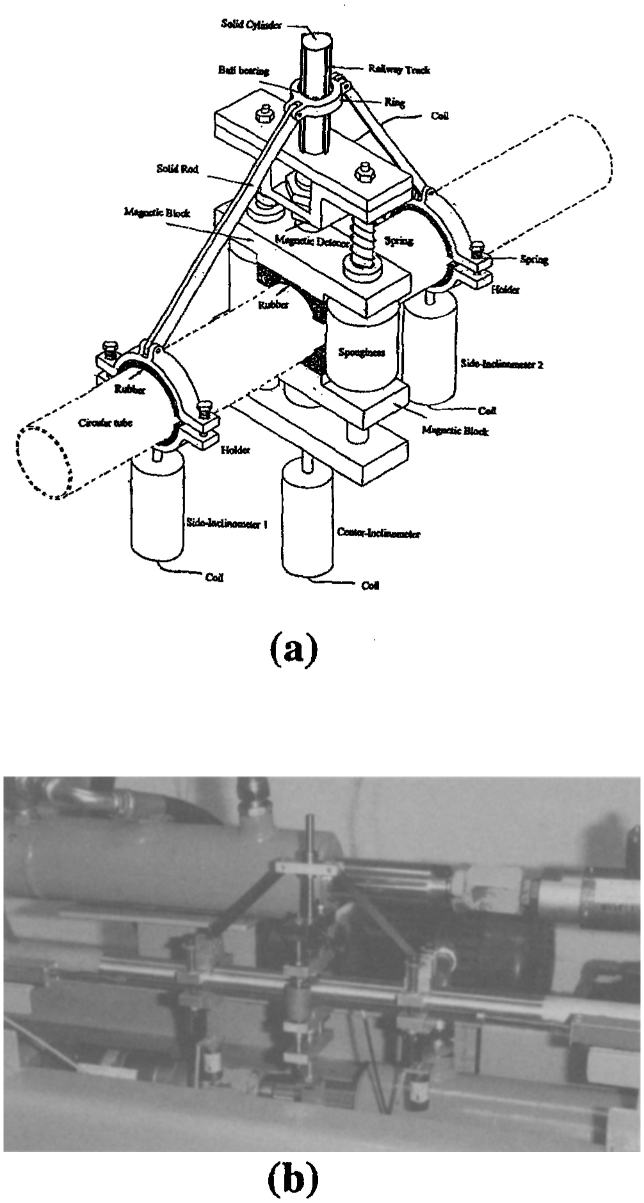

Fig. 2—(a) Schematic drawing of the COMA, (b) a picture of the COMA

Once the two holders are placed and fixed on the circular tube, the distance between the two side-inclinometers is fixed, which is denoted as L_o. Let us now consider that the circular tube is subjected to pure bending, as shown in Fig. 4. The angle changes detected by the two side-inclinometers are denoted as θ_1 and θ_2. Due to the uniform bending in all sections, the circular tube, which is originally straight, is de-

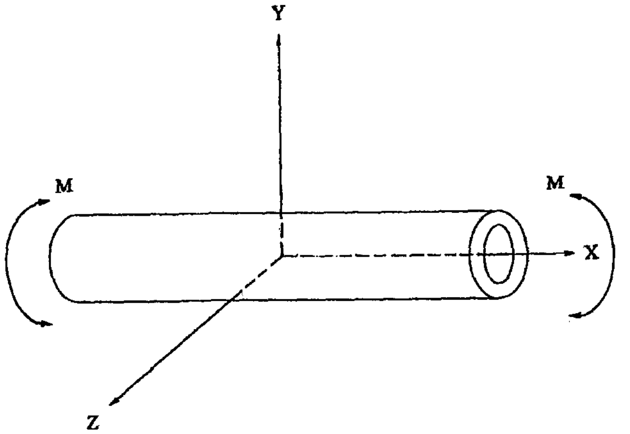

Fig. 3—Coordinate system of the tube specimen under pure bending

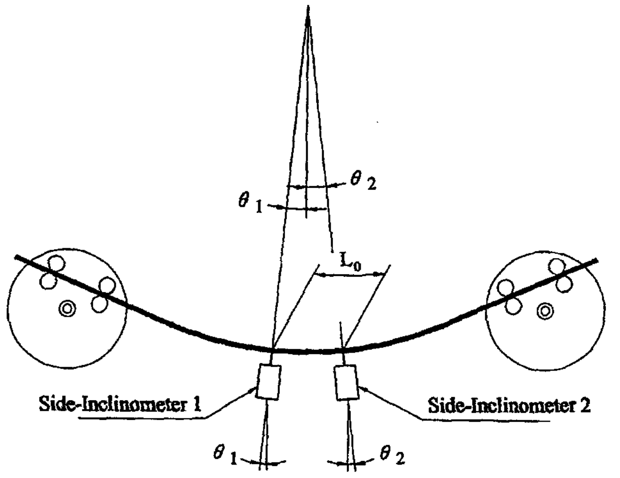

Fig. 4—Angle changes measured by two side-inclinometers under pure bending

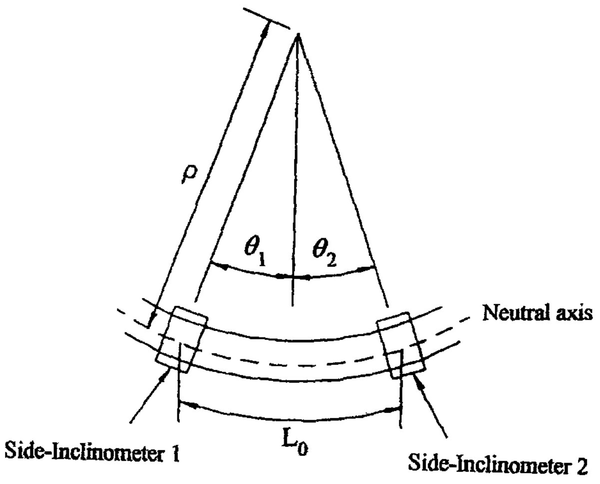

Fig. 5—Longitudinal deformation between two side-inclinometers under pure bending

formed into a circular arc. The distance between the center of this arc and the neutral surface is denoted as ρ (shown in Fig. 5). From Fig. 5, the value of L_o is determined as

$$L_o = \rho(\theta_1 + \theta_2). \tag{2}$$

The curvature of the tube κ is

$$\kappa = \frac{1}{\rho} = \frac{(\theta_1 + \theta_2)}{L_o}. \tag{3}$$

Once the distance between the two side-inclinometers (L_o) is fixed and the angle changes (θ_1 and θ_2) of the two side-inclinometers are detected, the curvature of the tube can be determined from eq (3). It is seen that the COMA can provide a direct measurement of the tube curvature.

Experimental Results

Several bending experiments were performed to examine the elastoplastic response of circular tube under cyclic bending. The specimen was an AISI 304 stainless steel tube with outside diameter D of 38.1 mm and wall thickness t of 1.5 mm ($D/t = 25.4$). The test was a curvature-symmetric cyclic bending test with the curvature amplitude of 0.5 m^{-1}. Figure 6 shows the curvature-time curve under curvature-controlled cyclic bending. The magnitude of the curvature was controlled by the measurements from the COMA. It is demonstrated that curvature-symmetric cyclic bending is successfully controlled using feedback from the COMA. Figure 7 depicts the moment-curvature curve under the curvature-controlled cyclic bending test. Due to the cyclic hardening of AISI 304 stainless steel (observed in cyclic uniaxial strain-controlled tests), similar cyclic-hardening phenomenon is also observed in the present bending test. Figure 8 demonstrates the corresponding ovalization-curvature curve under the curvature-controlled cyclic bending test, where D is the outer diameter and ΔD is the change in the outer diameter. It is demonstrated that reverse bending and subsequent repeated cyclic bending cause a gradual growth of ovalization of the tube cross section. It is also shown in Fig. 8 that when the experiment is tested under curvature-symmetric cyclic bending, the curve for tube ovalization versus tube curvature is not symmetric. The magnitude of tube ovalization for the initial direction of bending is lower than the corresponding magnitude in the opposite direction of bending. Similar results have been observed for 6061-T6 aluminum and 1018 steel tubes tested by Kyriakides and Shaw.[8] Figure 9 shows the angle changes with time measured by the center-inclinometer of the COMA. Based on the magnitudes of the angle change, the plane fixed by two side-inclinometers is almost the same plane of the bending moment.

Conclusion

In this paper, we report the design of a new curvature-ovalization measurement apparatus (COMA) and the results of its testing. This apparatus can be placed at the midspan of the circular tube and is suitable for simultaneous experimental determinations of tube curvature and ovalization of the tube cross section. An AISI 304 stainless steel tube was bent cyclically under pure bending into the plastic range. Based on the signals from the load cell and the COMA, the magnitudes of the bending moment, curvature and ovalization were obtained. It is shown that the COMA can provide direct measurement of the tube curvature. In addition, the

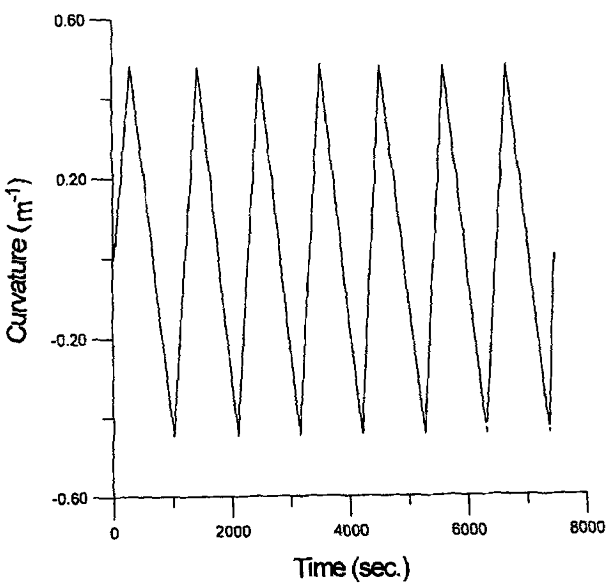

Fig. 6—Cyclic curvature-time curve

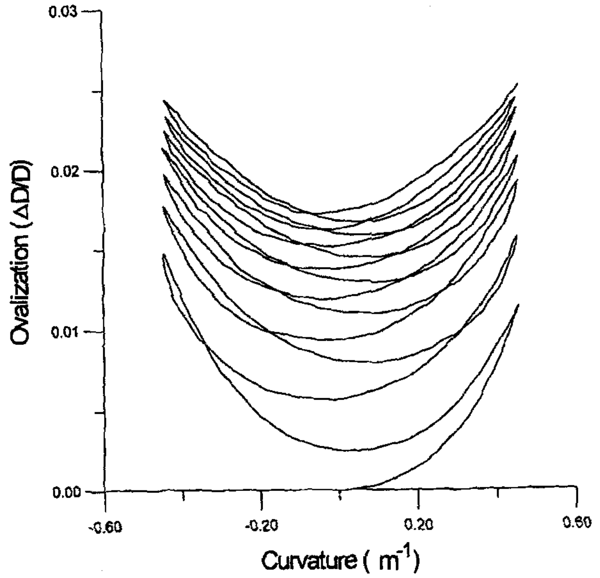

Fig. 8—Cyclic ovalization-curvature curve

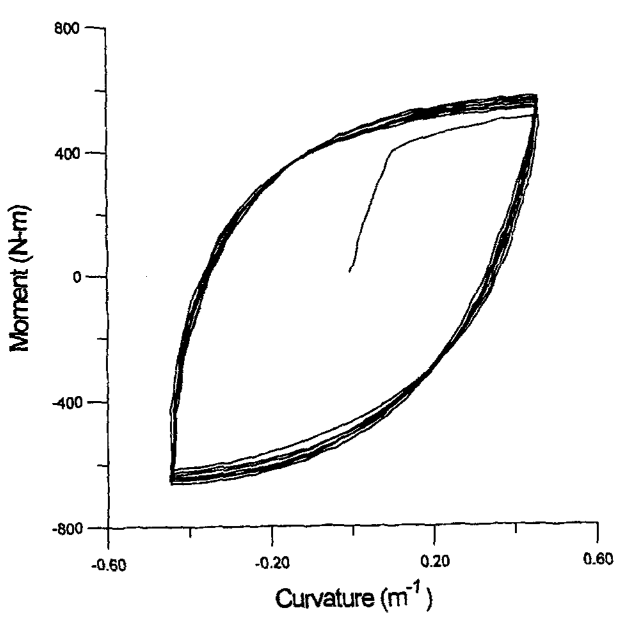

Fig. 7—Cyclic moment-curvature curve

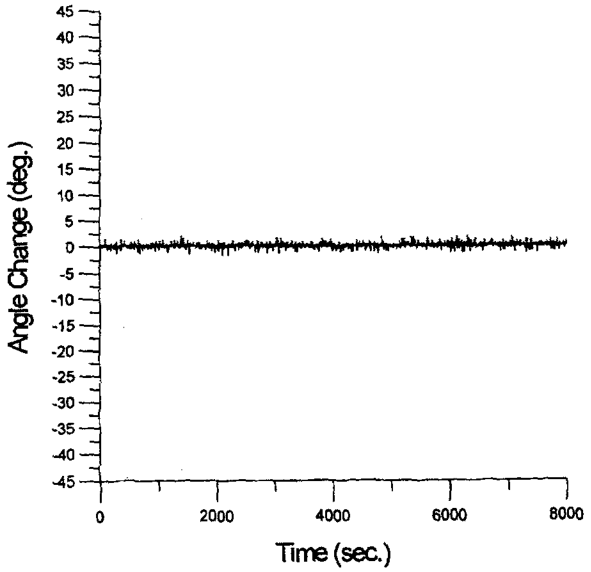

Fig. 9—Angle changes measured by the center-inclinometer

curvature-symmetric cyclic bending was well controlled by the COMA.

Acknowledgments

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