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The Effect of the Curvature-Rate on the Response of Local Sharp-Notched SUS304 Stainless Steel Tubes under Cyclic Bending

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Abstract

In this study, the response of local sharp-notched SUS304 stainless steel tubes with different notch depths of 0.2, 0.4, 0.6, 0.8 and 1.0 mm subjected to cyclic bending at different curvature-rates of 0.0035, 0.035 and 0.35 $m^{-1}s^{-1}$ were experimentally investigated. The tube bending machine and curvature-ovalization measurement apparatus, which was designed by Pan et al. [1], were used for conducting the curvature-controlled cyclic bending. For a constant curvature-rate, the moment-curvature curve revealed that the cyclic hardening and became a steady loop after a few bending cycles; the notch depth had almost no influence on the curves. Moreover, the ovalization-curvature curve increased in an increasing and ratcheting manner with the number of bending cycles. Large notch depths resulted in larger ovalization of the tube cross-section. In addition, for a constant notch depth, higher curvature-rates led to larger cyclic hardening and faster increasing of ovalization.

Keywords: local sharp notch, SUS304 stainless steel tubes, notch depth, curvature-rate, cyclic bending, moment, curvature, ovalization

1. Introduction

It is well known that the bending of circular tubes results in the ovalization (change in the outer diameter divided by the original outer diameter) of the tube cross-section. This ovalization increases slowly during reverse bending and continuous cyclic bending and, in turn, results in the deterioration of the circular tube, which buckles when the ovalization reaches some critical value. The circular tube is severely damaged during buckling and cannot bear the load, which ultimately results in obstruction and leakage of the material being transported. As such, a complete understanding of the response of the circular tube to cyclic bending is essential for industrial applications.

In 1998, Pan et al. [1] designed and set up a new measurement apparatus. It was used with the cyclic bending machine to study various kinds of tubes under different cyclic bending conditions. For instance, Pan and Her [2] investigated the response and stability of 304 stainless steel tubes that were subjected to cyclic bending with different curvature-rates, Lee et al. [3] studied the influence of the D_o/t ratio on the response and stability of circular tubes that were subjected to symmetrical cyclic bending, Lee et al. [4] experimentally explored the effect of the D_o/t ratio and curvature-rate on the response and stability of circular tubes subjected to cyclic bending, and Chang and Pan [5] discussed the buckling life estimation of circular tubes subjected to cyclic bending.

Experimental investigations have shown that some engineering materials, such as 304 stainless steel, 316 stainless steel and high-strength titanium alloy, change mechanical properties (yield strength, hardening, ductility… etc.) under different strain-rates or stress-rates. Therefore, once a tube which is fabricated by aforementioned materials is manipulated under cyclic bending at different curvature-rates, the response and collapse of tubes for each

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curvature-rate are expected to be generated differently. Pan and his co-workers have investigated the influence of curvature-rate on the response and collapse of SUS304 stainless steel tubes (Pan and Her [2]), titanium alloy tubes (Lee and Pan [6]) and 316L stainless steel tubes (Chang et al. [7]) subjected to cyclic bending. However, all of their investigations considered tubes with a smooth surface. If a tube with a notch is considered, the response should be different from a tube with a smooth surface.

In this study, the response for local sharp-notched SUS304 stainless steel tubes subjected to cyclic bending at different curvature-rates is discussed. A four-point bending machine (Shaw and Kyriakides [8], Lee et al. [3]) was used to conduct the cyclic bending test. A curvature-ovalization measurement apparatus (COMA) designed and reported previously by Pan et al. [1] was used to control and measure the curvature. For local sharp-notched tubes, five different notch depths, 0.2, 0.4, 0.6, 0.8 and 1.0 mm, were considered in this study. In addition, three different curvature-rates, 0.0035, 0.035 and 0.35 $m^{-1}s^{-1}$, were controlled. The magnitude of the bending moment was measured by two load cells mounted in the bending device, and the magnitudes of the curvature and ovalization of the tube cross-section were measured by COMA.

2. Experiment

Local sharp-notched SUS304 stainless steel tubes with five different notch depths were subjected to cyclic bending at three different curvature-rates by using a tube- bending device and a curvature-ovalization measurement apparatus in this study. Detailed descriptions of the device, apparatus, materials, specimens and test procedures are given as follows.

2.1. Bending Device

Fig. 1 shows a picture of the bending device. It is designed as a four-point bending machine, capable of applying bending and reverse bending. 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. Each tube is tested and fitted with solid rod extension. The contact between the tube and the rollers is free to move along axial direction during bending. The load transfer to the test specimen is in the form of a couple formed by concentrated loads from two of the rollers. 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 direction of the flow in the hydraulic circuit. Detailed description of the bending device can be found in Shaw and Kyriakides [8] and Lee et al. [3].

Fig. 1 A picture of the bending device

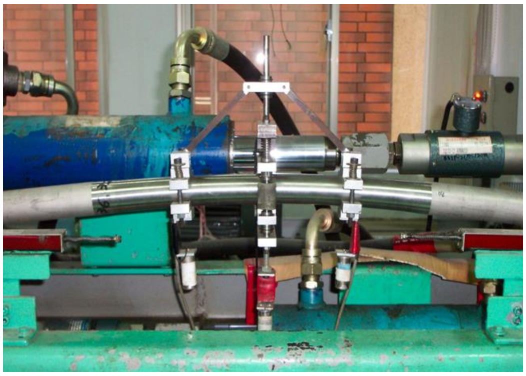


Fig. 2 A picture of the COMA

2.2. Curvature-Ovalization Measurement Apparatus (COMA)

The COMA, shown in Fig. 2, is an instrument used to measure the tube curvature and ovalization of a tube cross-section. It is a lightweight instrument, which is mounted close to the tube mid-span. There are three inclinometers in the COMA. Two inclinometers are fixed on two holders, which are denoted side-inclinometers. These holders are fixed on the circular tube before the test begins. From the fixed distance between the two side-inclinometers and the angle change detected by the two side-inclinometers, the tube curvature can be derived. In addition, a magnetic detector in the middle part of the COMA is used to measure the change of the outside diameter. A more detailed description of the bending device and the COMA is given in Pan et al. [1].

2.3. Material and Specimens

The circular tubes used in this study were made of SUS304 stainless steel. The tubes' chemical composition is Cr (18.36%), Ni (8.43%), Mn (1.81%), Si (0.39%), …., and a few other trace elements, with the remainder being Fe. The ultimate stress, 0.2% strain offset the yield stress and the percent elongation are 626 MPa, 296 MPa and 35%, respectively. The raw smooth SUS304 stainless steel tube had an outside diameter D_o of 36.6 mm and wall-thickness t of 1.5 mm. The raw tubes were machined on the outside surface to obtain the desired local notch depth *a* of 0.2, 0.4, 0.6, 0.8 and 1.0 mm. Fig. 3 shows a schematic drawing of the local sharp-notched tube. According to the drill of the machine, the corresponding surface diameters *b* were 0.6, 1.2, 1.8, 2.4 and 3.0 mm, respectively.

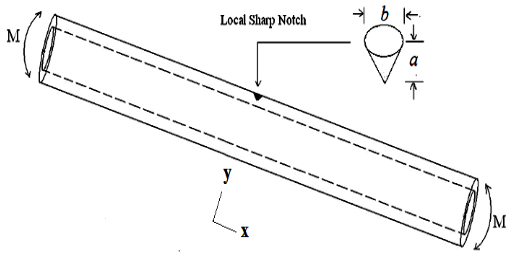


Fig. 3 A schematic drawing of the local sharp-notched tube

2.4. Test Procedure

The test involved a curvature-controlled cyclic bending. The controlled-curvature ranges were from ± 0.015 to ± 0.45 m^{-1} and three different curvature-rates of the cyclic bending test were 0.0035, 0.035 and 0.35 $m^{-1}s^{-1}$. The magnitude of the bending moment was measured by two load cells mounted in the bending device. The magnitudes of the curvature and ovalization of the tube cross-section were measured by the COMA.

3. Results and Discussion

Fig. 4 shows a typical set of experimentally determined moment (M) - curvature (κ) curve for local sharp-notched SUS304 stainless steel tubes, with notch depth of *a* = 0.2 mm, subjected to cyclic bending under the curvature-rate of 0.0035 $m^{-1}s^{-1}$. The tubes were cycled between κ = ± 0.3 m^{-1}. However, the tube exhibits cyclic hardening and becomes stable after a few cycles. Since the notch is small and local, the notch depth has almost no influence on the M-κ curve. Therefore, the M-κ curves for different values of *a* are not shown in this paper.

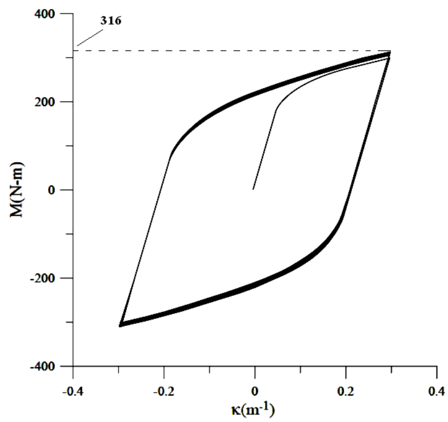
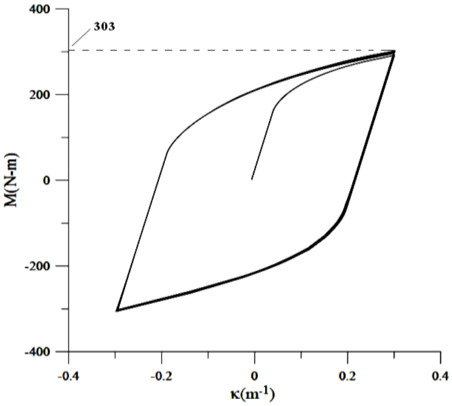
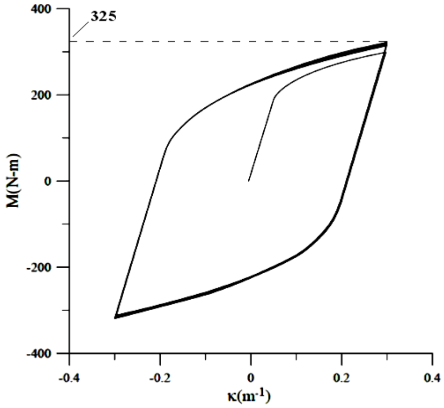


Fig. 4 Experimentally determined moment (M) - curvature (κ) curve for local sharp-notched SUS304 stainless steel tube, with notch depth of *a* = 0.2 mm, subjected to cyclic bending under the curvature-rate of 0.035 $m^{-1}s^{-1}$

Figs. 5(a)-(b) present experimentally determined moment (M) - curvature (κ) curve for local sharp-notched SUS304 stainless steel tubes, with notch depth of *a* = 0.2 mm, subjected to cyclic bending under the curvature-rate of 0.0035 and 0.35 $m^{-1}s^{-1}$, respectively. It is evident that the M-κ curves shown in Figs. 4, 5(a) and 5(b) are very similar. However, higher curvature-rates lead to higher magnitude of the maximum moment at the maximum curvature. The maximum moments of 303, 316 and 325 N-m correspond to the curvature-rates of 0.0035, 0.035 and 0.35 $m^{-1}s^{-1}$, respectively. The highest and lowest curvature-rates have 100 times difference. But, the maximum moment only increases 7.3%. Due to similar phenomenon, the experiment results of the M-κ response for local sharp-notched SUS304 stainless steel tubes with *a* = 0.4, 0.6, 0.8 and 1.0 mm under cyclic bending at the curvature-rates of 0.0035, 0.035 and 0.35 $m^{-1}s^{-1}$ are omitted in this paper.



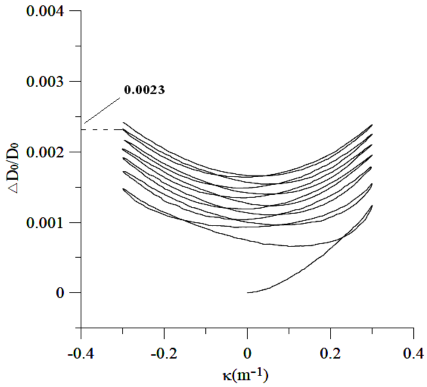
(a)



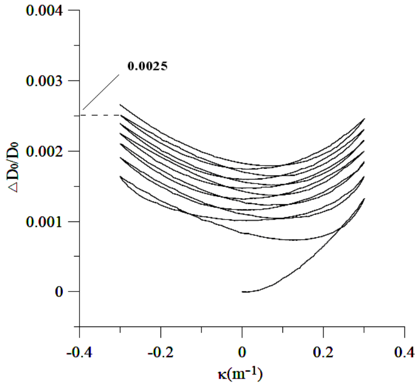
(b)

Fig. 5 Experimentally determined moment (M) - curvature (κ) curve for local sharp-notched SUS304 stainless steel tubes, with notch depth of a = 0.2 mm, subjected to cyclic bending under the curvature-rates of (a) 0.0035 and (b) 0.35 $m^{-1}s^{-1}$

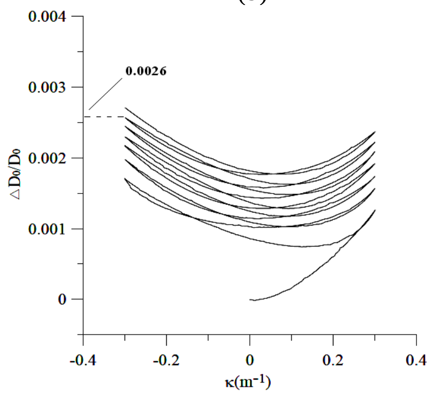
Figs. 6(a)-(e) depict the experimentally determined ovalization of the tube cross-section ($\Delta D_o/D_o$) versus the applied curvature (κ) for local sharp-notched SUS304 stainless steel tubes, with notch depths a of 0.2, 0.4, 0.6, 0.8 and 1.0 mm, respectively, subjected to cyclic bending at the curvature-rate of 0.035 $m^{-1}s^{-1}$. The ovalization is defined as $\Delta D_o/D_o$ where D_o is the outside diameter and ΔD_o is the change in the outside diameter. It can be seen that the ovalization increases in a ratcheting manner with the number of bending cycles. Higher a of the notch tube leads to a more severe unsymmetrical trend of the $\Delta D_o/D_o$-κ curve. In addition, higher a of the notch tube causes greater ovalization of the tube cross-section. The maximum ovalizations of 0.0023, 0.0025, 0.0026, 0.0027 and 0.0028 for the curvature of -0.3 m^{-1} at the 6th cycle correspond to notch depths a of 0.2, 0.4, 0.6, 0.8 and 1.0 mm, respectively.



(a)

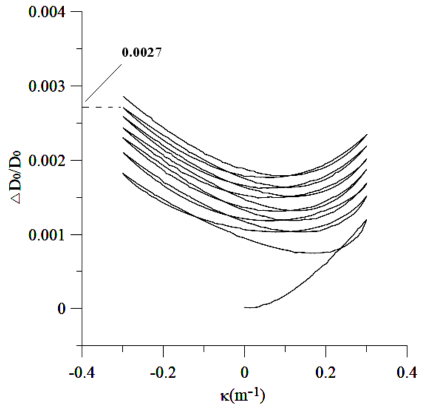


(b)

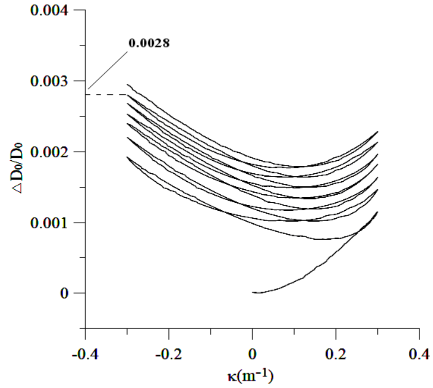


(c)

Fig. 6 Experimentally determined ovalization of the tube cross-section ($\Delta D_o/D_o$) versus the applied curvature (κ) for local sharp-notched SUS304 stainless steel tubes, with notch depths of a = (a) 0.2, (b) 0.4, (c) 0.6, (d) 0.8 and (e) 1.0 mm, subjected to cyclic bending under the curvature-rate of 0.035 $m^{-1}s^{-1}$ (continued)



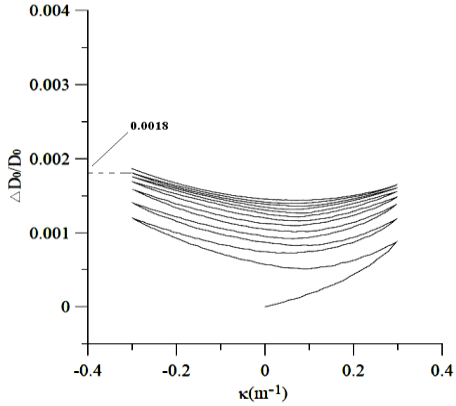
(d)



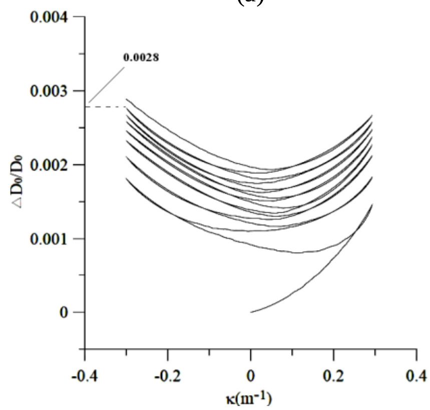
(e)

Fig. 6 Experimentally determined ovalization of the tube cross-section ($\Delta D_o/D_o$) versus the applied curvature (κ) for local sharp-notched SUS304 stainless steel tubes, with notch depths of *a* = (a) 0.2, (b) 0.4, (c) 0.6, (d) 0.8 and (e) 1.0 mm, subjected to cyclic bending under the curvature-rate of 0.035 $m^{-1}s^{-1}$

Figs. 7(a)-(b) depict the experimentally determined ovalization of the tube's cross-section ($\Delta D_o/D_o$) versus the applied curvature (κ) for local sharp-notched SUS304 stainless steel tubes, with notch depth of *a* = 0.2 mm, subjected to cyclic bending under the curvature-rates of 0.035 and 0.35 $m^{-1}s^{-1}$, respectively. It can be noted that a higher degree of ovalization can be noticed under higher curvature-rates. The maximum ovalizations of 0.0018, 0.0023 and 0.0028 for the curvature of -0.3 m^{-1} at the 6th cycle correspond to the curvature-rates of 0.0035, 0.035 and 0.35 $m^{-1}s^{-1}$, respectively. The highest and lowest curvature-rates have 100 times difference. But, the maximum moment increases 55.6 %. It is concluded that the curvature-rate has a strong influence on the $\Delta D_o/D_o$-κ curve. Again, due to similar results, the experimental results of the $\Delta D_o/D_o$-κ response for local sharp-notched SUS304 stainless steel tubes with notch depths of 0.4, 0.6, 0.8 and 1.0 mm under the curvature-rates of 0.0035 and 0.35 $m^{-1}s^{-1}$ are omitted in this paper.



(a)



(b)

Fig. 7 Experimentally determined ovalization of the tube cross-section ($\Delta D_o/D_o$) versus the applied curvature (κ) for local sharp-notched SUS304 stainless steel tubes, with notch depths of *a* = 0.2 mm, subjected to cyclic bending under the curvature-rate of (a) 0.0035 and (b) 0.35 $m^{-1}s^{-1}$

4. Conclusions

The response of local sharp-notched SUS304 stainless steel tubes with different notch depths subjected to cyclic bending at different curvature-rates was experimentally investigated in this study. Based on the experimental results, the following important conclusions can be drawn:

(1) It is found from the M-κ curves that the local sharp-notched SUS304 stainless steel tubes with any notch depth at any curvature-rate exhibits cyclical hardening and gradually steady after a few cycles under symmetrical curvature-controlled cyclic bending.

(2) It can be seen that a higher curvature-rate leads to a higher magnitude of the moment. In addition, the curvature-rate has a slight influence on the M-κ curves (Figs. (4), 5(a) and 5(b)).

(3) It is observed from the $\Delta D_o/D_o$-κ curves that the ovalization of the tube cross-section increases in an unsymmetrical and ratcheting manner with the number of cycles. Higher *a* leads to more severe unsymmetrical trend of the $\Delta D_o/D_o$-κ curve.

(4) It can be seen that a higher curvature-rate leads to a greater ovalization of the tube cross-section. In addition, the curvature-rate has a strong influence on the $\Delta D_o/D_o$-κ curves (Figs. 6(a), 7(a) and 7(b)).

Acknowledgement

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