Structural Engineering and Mechanics, Vol. 34, No. 3 (2010) 367-376 367
DOI: http://dx.doi.org/10.12989/sem.2010.34.3.367

Mechanical behavior and buckling failure of sharp-notched circular tubes under cyclic bending

Kuo-Long Lee†

Department of Computer Application Engineering, Far East University, Tainan, Taiwan 701, R.O.C.

(Received October 24, 2008, Accepted November 13, 2009)

Abstract. In this paper, an experimental investigation of the mechanical behavior and buckling failure of sharp-notched circular tubes subjected to cyclic bending is discussed. The unnotched and sharp-notched circular tubes of SUS 304 stainless steel were tested under symmetric curvature-controlled cyclic bending. It was found from moment-curvature curves that the loops show cyclic hardening and gradually steady after a few cycles for all tested tubes. The ovalization-curvature curves show an unsymmetric, ratcheting and increasing manner with the number of cycles. In addition, it was found that six almost parallel lines corresponding to unnotched and five different notch-depth (0.2, 0.4, 0.6, 0.8 and 1.0 mm) tubes were noted from the experimental relationship between the cyclic controlled curvature and the number of cycles necessary to produce buckling on a log-log scale. An empirical formulation was proposed so that it could be used for simulating the aforementioned relationship. By comparing with the experimental finding, the simulation was in good agreement with the experimental data.

Keywords: mechanical behavior; buckling failure; sharp-notched circular tubes; cyclic bending; moment; ovalization; number of cycles to produce bucking.

1. Introduction

The bending of circular tubes leads to the ovalization of the tube cross-section (the change of the outside diameter (D_o-D) divides by the original outside diameter (D_o) shown in Fig. 1). Reverse bending and subsequent repeated cyclic bending may cause a gradual growth in ovalization. The increasing ovalization causes a progressive reduction in the bending rigidity of the tube. The tube will buckle when a critical magnitude of ovalization is reached. It is therefore of great importance to understand the response and buckling of circular tubes under cyclic bending in many industrial applications.

Beginning in the 1980, Kyriakides and his co-workers designed and constructed the tube cyclic bending machine, as shown in Fig. 2, and conducted a series of experimental and theoretical investigations. Kyriakides and Shaw (1982) examined the response and stability of elastoplastic pipes under monotonic bending and external pressure. Shaw and Kyriakides (1985) researched inelastic behavior of 6061-T6 aluminum and 1018 steel tubes subjected to cyclic bending. Kyriakides and Shaw (1987) extended the analysis of 6061-T6 aluminum and 1018 steel tubes to

† Associate Professor, E-mail: lkl@cc.feu.edu.tw

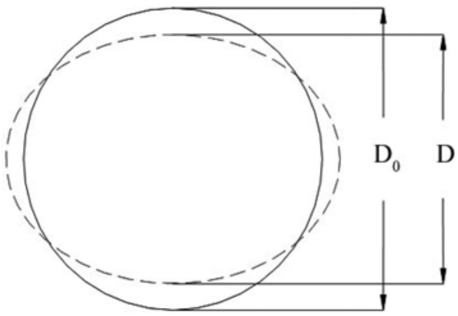

Fig. 1 Definition of the ovalization

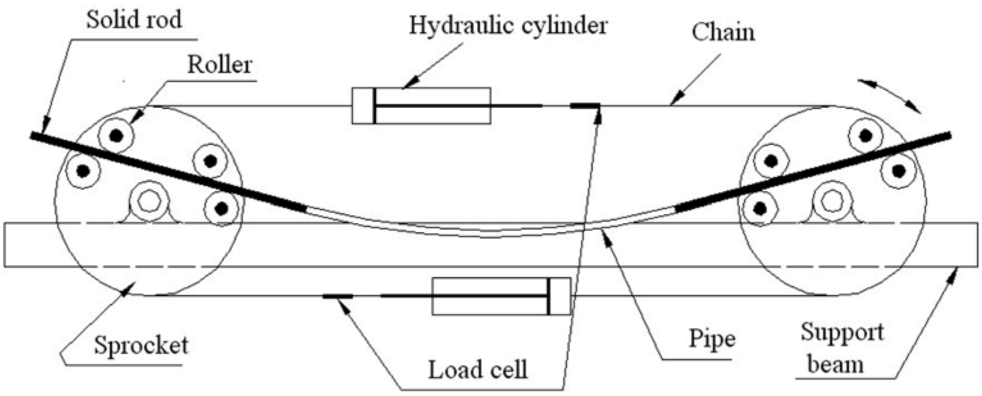

Fig. 2 Schematic drawing of the bending device

the stability conditions under cyclic bending. Corona and Kyriakides (1988) investigated the stability of 304 stainless steel tubes subjected to combined bending and external pressure. Corona and Kyriakides (1991) studied the degradation and buckling of 6061-T6 aluminum and 1020 carbon steel tubes under cyclic bending and external pressure. Corona and Vaze (1996) studied the response, buckling and collapse of long, thin-walled seamless steel square tubes under bending. Vaze and Corona (1998) experimentally investigated the elastic-plastic degradation and collapse of steel tubes with square cross-sections under cyclic bending.

Recently, Pan and his co-workers also constructed a similar bending machine with a newly invented measurement apparatus, which was designed and set up by Pan *et al*. (1998), to study various kinds of tubes under different cyclic bending conditions. Pan and Fan (1998) studied the effect of the prior curvature-rate at the preloading stage on the subsequent creep (moment is kept constant for a period of time) or relaxation (curvature is kept constant for a period of time) behavior. Pan and Her (1998) investigated the response and stability of SUS 304 stainless steel tubes subjected to cyclic bending with different curvature-rates. Lee *et al*. (2001) studied the influence of the diameter-to-thickness ratio (D_o/t ratio) on the response and stability of circular tubes subjected to symmetrical cyclic bending. Lee *et al*. (2004) 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. Chang *et al.* (2008) studied the mean moment effect on circular thin-walled tubes under cyclic bending.

In addition, Elchalakani *et al.* (2002) experimentally conducted tests on the different D_o/t ratios of grade C350 steel tubes under pure bending, and proposed two theoretical simulation models. Jiao and Zhao (2004) tested the bending behavior of very high strength (VHS) circular steel tubes, and proposed their plastic slenderness limit. Elchalakani *et al.* (2004) experimentally investigated the inelastic flexural behavior of concrete-filled tubular (CFT) beams, which were made of cold-formed circular hollow sections filled with normal concrete.

Until now, all investigations on tubes considered the smooth surface without any notch. However, in practical industrial applications, the tubes are constantly under the sea. The salt water may corrode the tube surface and produce a sharp-notch on the tube surface. Once a notch exists, the mechanical behavior and buckling failure of a notched tube differ from the tube with a smooth surface. Therefore, a study on the behavior of sharp-notched tubes subjected to cyclic bending is of importance for industry.

In this study, the unnotched and five different sharp-notched (notch depths of 0.2, 0.4, 0.6, 0.8 and 1.0 mm) SUS 304 stainless steel tubes were investigated. A four-point bending machine (Shaw and Kyriakides 1985, Corona and Kyriakides 1991, Pan *et al.* 1998, Lee *et al.* 2001) was used to conduct the tests. The curvature-ovalization measurement apparatus (COMA) designed and reported previously by Pan *et al.* (1998) was used to collect the data of the curvature-controlled cyclic bending tests. The magnitude of the bending moment was measured with two load cells mounted in the bending device, and the magnitudes of the curvature and ovalization of the tube cross-section were measured with the COMA.

It was found no matter whether the tubes were with or without a notch, the experimental moment-curvature curves show a cyclic hardening trend. The loops will gradually steady after a few cycles. However, the ovalization-curvature curves display an unsymmetric, ratcheting and increasing manner with the number of cycles. The deeper notch-depth leads to a faster increase in ovalization and more severe unsymmetric trend of the ovalization-curvature curve. In addition, it can be noted that although the unnotched and five different notch-depth (0.2, 0.4, 0.6, 0.8 and 1.0 mm) tubes were tested, six almost parallel lines can be seen on the log-log scale describing the relationship between the curvature and the number of cycles necessary to produce buckling. The empirical formulation proposed by Kyriakides and Shaw (1987) was modified so that it could be used for simulating the aforementioned relationship. It was found the simulation is in good agreement with the experimental data. Moreover, the relationship between the ovalization at buckling and the sharp-notch depth was also constructed.

2. Experimental facility, material, specimens and test procedures

2.1 Bending device

A schematic drawing of the bending device is shown in Fig. 2. The device is designed as a four-point bending machine, capable of applying reverse cyclic bending. The device consists of two rotating sprockets resting on two support beams. Heavy chains run around the sprockets resting on two heavy support beams 1.25 m apart. This allows for a maximum length of 1 m for the test specimen. The bending capacity of the machine is 5300 N-m. Each tested tube is fitted with solid rod extensions that engage the rollers. The rods can be freely moved along the axial direction during bending. Once either the top or bottom cylinder is contracted, the sprockets rotate, and bending of the test specimen is achieved. Reverse bending can be achieved by reversing the flow direction in the hydraulic circuit. A detailed description of the bending device can be found in several references (Kyriakides and Shaw 1987, Corona and Kyriakides 1991, Pan *et al.* 1998, Lee *et al.* 2001).

2.2 Curvature-ovalization measurement apparatus (COMA)

The COMA, shown schematically in Fig. 3, 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 as side-inclinometers (see Fig. 2). 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 in the outside diameter. A more detailed description of the bending device and the COMA is given in Pan *et al.* (1998).

2.3 Material and specimens

Circular tubes made of SUS 304 stainless steel were used in this study. The tubes' chemical compositions were 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 was 626 MPa, the yield stress was 296 MPa, and the percent elongation was 35%.

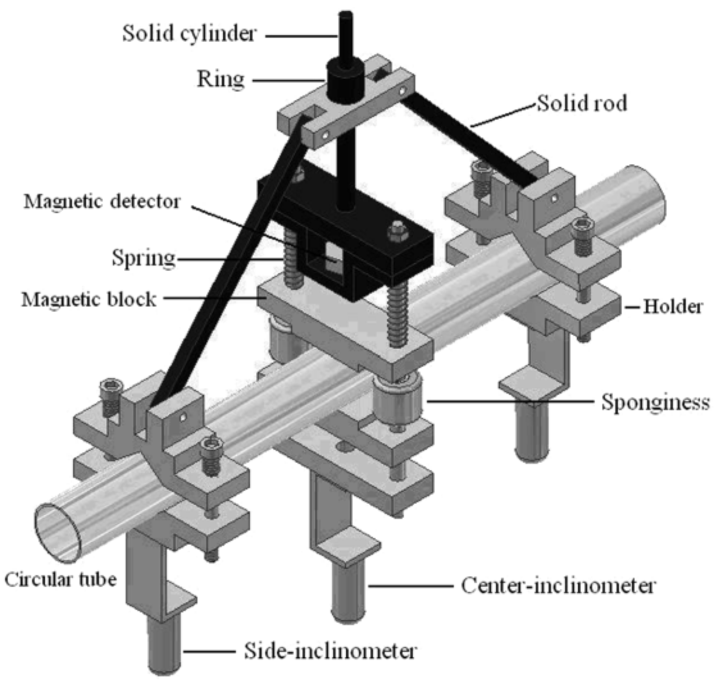

Fig. 3 Schematic drawing of the COMA

Fig. 4 A picture of the sharp-notched tubes

The raw unnotched SUS 304 stainless steel tube had an outside diameter D_o of 31.8 mm and wall-thickness t of 1.5 mm. The raw tubes were machined on the outside surface to obtain the desired notch depth a of 0.2, 0.4, 0.6, 0.8 and 1.0 mm. Because the notch wide does not influence the behavior of the tube under cyclic bending, the notch wide was machined to be 1.0 mm for all notched tubes. Fig. 4 shows a picture of the sharp-notched tubes.

2.4 Test procedures

The test was a curvature-controlled cyclic bending. The controlled-curvature ranges were from ±0.05 to 0.4 m^{-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 controlled and measured by the COMA. In addition, the number of cycles necessary to produce buckling and the ovalization at buckling were also recorded.

3. Experimental result and discussion

3.1 Mechanical behavior of notched SUS 304 stainless steel tubes under curvature controlled cyclic bending

Figs. 5(a)-(f) show the experimentally determined cyclic moment (M)-curvature (κ) for SUS 304 stainless steel tubes with a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm, respectively. Note that the amount of a = 0.0 mm represents the unnotch and smooth tube. The curvature range is from +0.1 to −0.1 m^{-1}. The M-κ curve for all tubes with or without a notch shows that the SUS 304 stainless steel tube cyclically hardened and become stable after a few cycles. A tube with a higher value of a has a smaller wall-thickness. Thus, a lower magnitude of the moment is needed when the tube bends to the maximum curvature.

Figs. 6(a)-(f) show the corresponding ovalization ($\Delta D_o/D_o$) - curvature (κ) results. The ovalization is continuously changing. On first loading, the ovalization grows to a maximum value at the maximum curvature. On unloading to zero curvature, some permanent deformation of the tube cross section is observed. Continuous reverse bending to the minimum curvature causes the

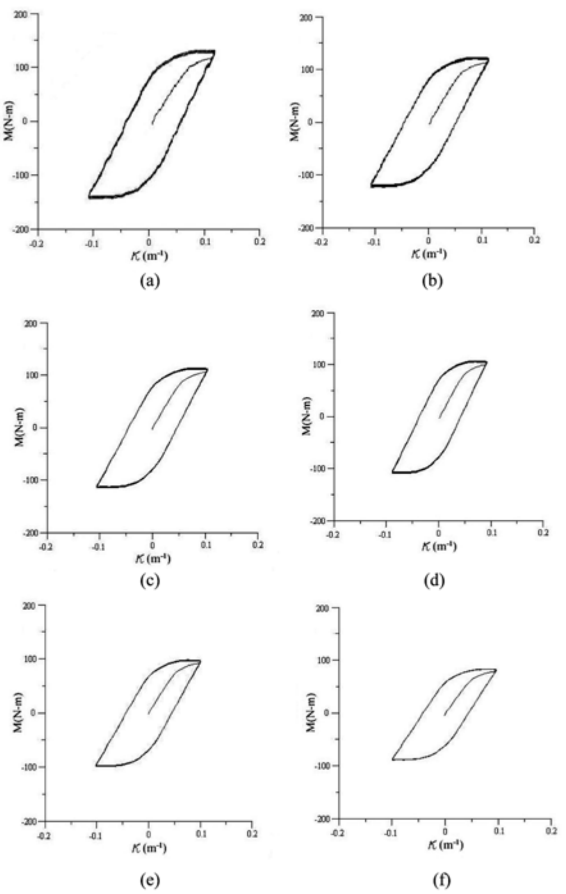

Fig. 5 Experimentally determined moment (M)-curvature (κ) graphs for tubes with a = (a) 0.0, (b) 0.2, (c) 0.4, (d) 0.6, (e) 0.8 and (f) 1.0 mm

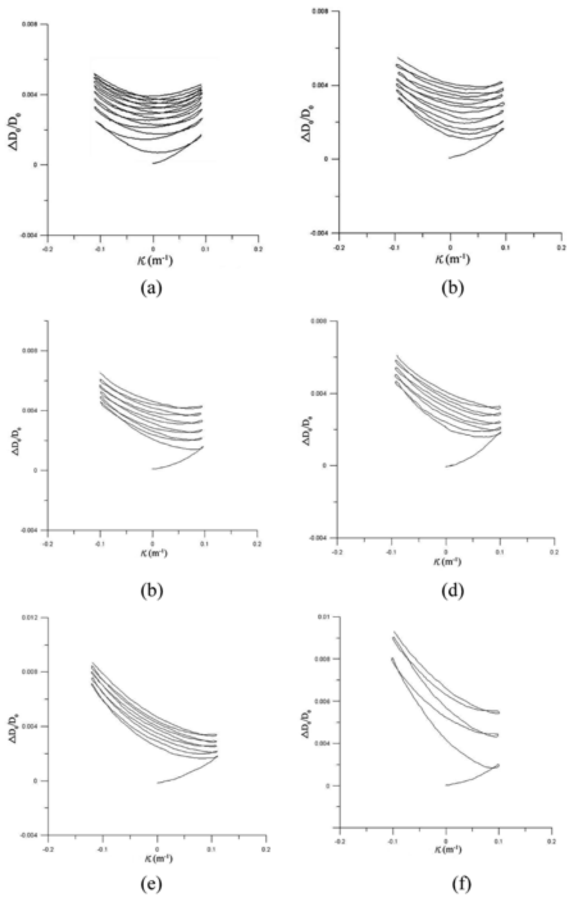

Fig. 6 Experimentally determined ovalization (ΔD_o/D_o)-curvature (κ) graphs for tubes with a = (a) 0.0, (b) 0.2, (c) 0.4, (d) 0.6, (e) 0.8 and (f) 1.0 mm

ovalization to again increase. The ovalization increases in a ratcheting manner with the number of bending cycles. The ovalization continues to progress until a certain critical value is reached at which the tube buckles. It was also found that the $\Delta D_o/D_o$-κ curve exhibits a symmetric increasing manner for a = 0.0 mm. Once the notch exists, the $\Delta D_o/D_o$-κ curve shows an unsymmetric increasing manner. Higher a of the notch tube leads to more a severe unsymmetric trend of the $\Delta D_o/D_o$-κ curve. In addition, higher a of the notch tube causes higher ovalization of the tube's cross-section.

3.2 Buckling failure of notched SUS 304 stainless steel tubes under curvature controlled cyclic bending

Fig. 7 shows the experimental results of the cyclic curvature (κ_c) versus the number of cycles necessary to produce buckling (N_b) for tubes with the value a of 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm.

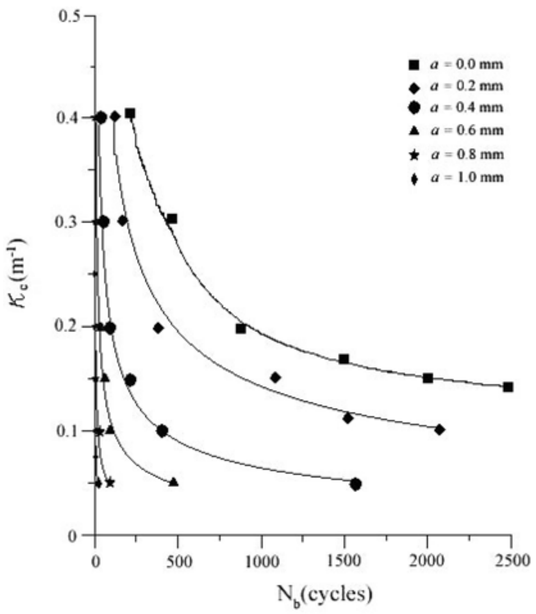

Fig. 7 Experimental results of the cyclic curvature (κ_c) versus the number of cycles necessary to produce buckling (N_b) for tubes with a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm

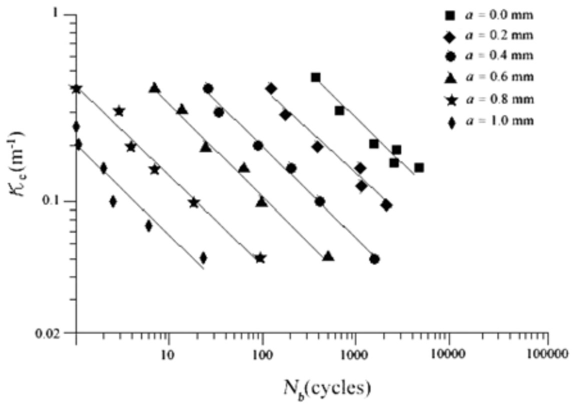

Fig. 8 Experimental results of the cyclic curvature (κ_c) versus the number of cycles necessary to produce buckling (N_b) for tubes with a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm on a double logarithmic scale

For each tube size, six specimens were carefully tested. For a given curvature, the tube with a higher value of a displays a lower number of cycles necessary to produce buckling. The results of Fig. 7 are plotted on a double logarithmic scale in Fig. 8. The six straight lines in this figure are least square fits of the data. The six fits are almost parallel straight lines.

Kyriakides and Shaw (1987) proposed the relationship between the κ_c and N_b to be

$$\kappa_c = C\,(N_b)^{-\alpha} \tag{1}$$

where C and α are material parameters, which are related to the material properties and the D_o/t ratio. The constant C is the magnitude of cyclic curvature at N_b = 1 and α is the slope of the log-log plot. Eq. (1) has been widely used for simulating curvature-controlled cyclic bending tests. Since the six straight lines are almost parallel to one another, the value of α is determined to be 0.12. Based on the experimental data, six quantities of C were determine for a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm, respectively. Based on these results, the following relationship is proposed

$$C = C_o e^{-\beta\left(\frac{a}{t}\right)} \quad \text{or} \quad \ln C = \ln C_o - \beta\left(\frac{a}{t}\right) \tag{2}$$

where C_o and β are material parameters. Fig. 9 shows the relationship between value of ln C and a/t. The magnitudes of C_o and β can be determined to be 8.248 and 5.331, respectively. The simulated and experimental results in Fig. 10 are included where they fit the data quite well. The empirical formulation of Eq. (2) was built based on the experimental result. The equation can be

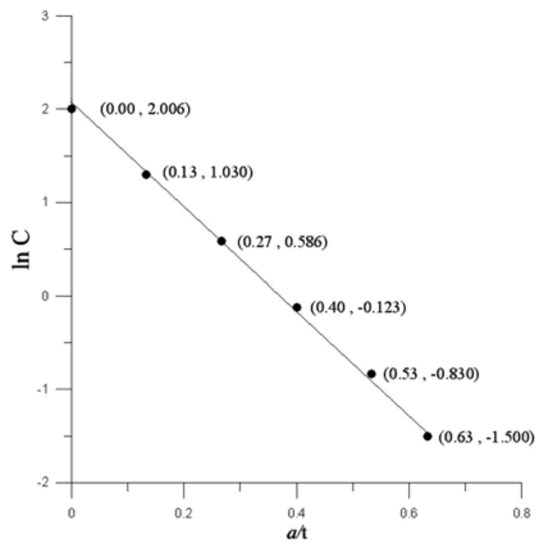

Fig. 9 Relationship of ln C and a/t

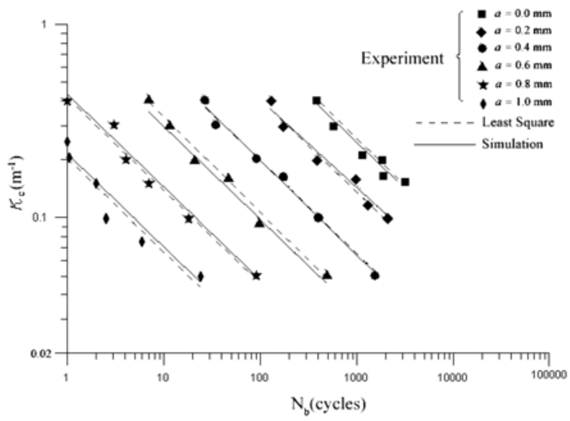

Fig. 10 Experimental and simulated results of the cyclic curvature (κ_c) versus the number of cycles necessary to produce buckling (N_b) for tubes with a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm on a double logarithmic scale

used for predicting the number of cycles to produce buckling for sharp-notched tubes with different sizes of the crack depth under cyclic bending.

3.3 Ovalization at buckling of notched SUS 304 stainless steel tubes under curvature controlled cyclic bending

Fig. 11 shows the relationship between the ovalization at buckling $(\Delta D_o/D_o)_b$ and cyclic curvature (κ_c) for a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm. It can be seen that for a certain amount of a, the quantity $(\Delta D_o/D_o)_b$ is almost a constant. The phenomenon for a = 0.0 (unnotched tube) is the same as previous investigations of curvature-controlled symmetric cyclic bending tests (Kyriakides and Shaw 1987, Pan and Her 1998, and Lee *et al.* 2001). However, it can be found that the notched tube with a higher a leads to a lower amount of $(\Delta D_o/D_o)_b$.

If we plot the data of $(\Delta D_o/D_o)_b$ vs. a, the data points almost fall on a straight line shown in Fig. 12. For simulating the relationship between $(\Delta D_o/D_o)_b$ and a, an empirical formula was proposed as

$$(\Delta D/D)_b = c(a/t) + d \qquad (3)$$

where c and d are material parameters, which can be determined from the straight line in Fig. 12 to be –0.0339 and 0.0454, respectively. The empirical formulation of Eq. (3) was built based on the experimental result. The equation can be used for predicting the ovalization at buckling for sharp-notched tubes with different sizes of the crack depth under cyclic bending.

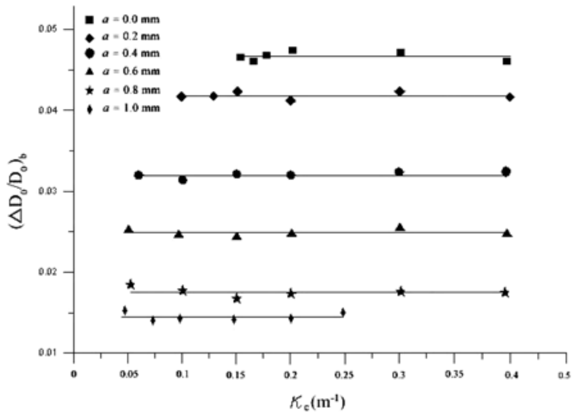

Fig. 11 Experimental data of ovalzation at buckling $(\Delta D_o/D_o)_b$ and cyclic curvature (κ_c) for tubes with a = 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm

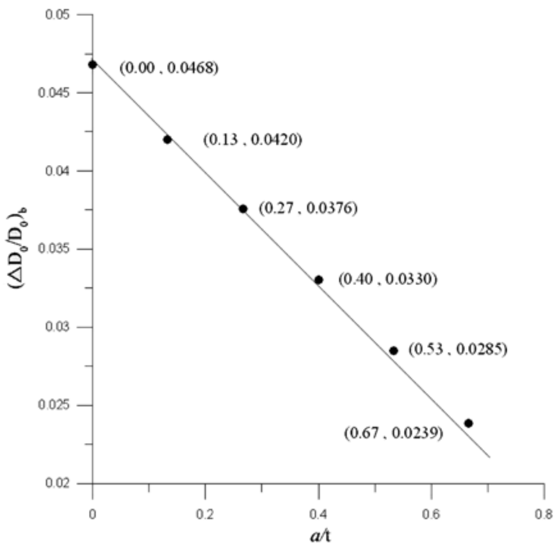

Fig. 12 Relationship of $(\Delta D_o/D_o)_b$ and a/t

4. Conclusions

In this study, the mechanical behavior and buckling failure of sharp-notched SUS 304 stainless steel tubes subjected to cyclic bending is discussed. Based on the experimental and simulated results, the following important conclusions can be drawn from this investigation:

(1) For symmetric curvature-controlled cyclic bending, the M-κ loop of the SUS 304 stainless steel tube with or without a notch shows cyclic hardening. However, the loops gradually steady after a few cycles.

(2) For symmetric curvature-controlled cyclic bending, the $\Delta D_o/D_o$-κ curve shows an increasingly ratcheting form as the number of cycles increases. Tube with a sharp-notch leads to unsymmetric $\Delta D_o/D_o$-κ curve. Higher value of a may produce more severe unsymmetry. Moreover, persistent cycling eventually leads to buckling.

(3) Although the six groups of tested tubes had six different sharp-notch depths of 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 mm, six almost parallel straight lines are seen on the log-log scale of κ_c and N_b. An empirical relationship of Eqs. (1) and (2) was proposed to simulate these curves. Based on the experimental data obtained for sharp-notched SUS 304 stainless steel tubes, the material parameters C_o and β were determined to be 8.248 and 5.331, respectively. The empirically determined relationship and experimental results were shown to be in good agreement.

(4) The $(\Delta D/D)_b$-κ_c plot (Fig. 11) demonstrates that for a certain amount of a, the value of $(\Delta D/D)_b$ is a constant for symmetric curvature-controlled cyclic bending. The specimen with a higher value of a leads to a lower amount of $(\Delta D/D)_b$. The $(\Delta D/D)_b$-(a/t) plot (Fig. 12) displays that the data fall on a straight line. A simple empirical formulation of Eq. (3) was proposed to fit the data. The material parameters c and d in Eq. (3) were determined to be −0.0339 and 0.0454, respectively.

Acknowledgements

The reported experimental work was carried out by using the bending facilities developed by Professor Wen-Fung Pan (Department of Engineering Science, National Cheng Kung University). Their supports are gratefully acknowledged.

References

Chang, K.H. and Pan, W.F. (2008), "Mean moment effect of thin-walled tubes under cyclic bending", *Struct. Eng. Mech.*, **28**(5), 495-514.

Corona, E. and Kyriakides, S. (1988), "On the collapse of inelastic tubes under combined bending and pressure", *Int. J. Solids Struct.*, **24**(5), 505-535.

Corona, E. and Kyriakides, S. (1991), "An experimental investigation of the degradation and buckling of circular tubes under cyclic bending and external pressure", *Thin Wall. Struct.*, **12**, 229-263.

Corona, E. and Vaze, S. (1996), "Buckling of elastic-plastic square tubes under bending", *Int. J. Mech. Sci.*, **38**(7), 753-775.

Elchalakani, M., Zhao, X.L. and Grzebieta, R.H. (2002), "Plastic mechanism analysis of circular tubes under pure bending", *Int. J. Mech. Sci.*, **44**, 1117-1143.

Elchalakani, M., Zhao, X.L. and Grzebieta, R.H. (2004), "Concrete-filled circular tubes subjected to constant amplitude cyclic pure bending", *Eng. Struct.*, **26**, 2125-2135.

Jiao, H. and Zhao, X.L. (2004), "Section slenderness limits of very high strength circular steel tubes in bending", *Thin Wall. Struct.*, **42**, 1257-1271.

Kyriakides, S. and Shaw, P.K. (1982), "Response and stability of elastoplastic circular pipes under combined bending and external pressure", *Int. J. Solids Struct.*, **18**(11), 957-973.

Kyriakides, S. and Shaw, P.K. (1987), "Inelastic buckling of tubes under cyclic loads", *ASME J. Press. Vessel Technol.*, **109**, 169-178.

Lee, K.L., Pan, W.F. and Hsu, C.M. (2004), "Experimental and theoretical evaluations of the effect between diameter-to-thickness ratio and curvature-rate on the stability of circular tubes under cyclic bending", *JSME Int. J. Series A*, **47**(2), 212-222.

Lee, K.L., Pan, W.F. and Kuo, J.N. (2001), "The influence of the diameter-to-thickness ratio on the stability of circular tubes under cyclic bending", *Int. J. Solids Struct.*, **38**, 2401-2413.

Pan, W.F. and Fan, C.H. (1998), "An experimental study on the effect of curvature-rate at preloading stage on subsequent creep or relaxation of thin-walled tubes under pure bending", *JSME Int. J. Series A*, **41**(4), 525-531.

Pan, W.F. and Her, Y.S. (1998), "Viscoplastic collapse of thin-walled tubes under cyclic bending", *J. Eng. Mat. Tech.*, **120**, 287-290.

Pan, W.F., Wang, T.R. and Hsu, C.M. (1998), "A curvature-ovalization measurement apparatus for circular tubes under cyclic bending", *Exp. Mech.,* **38**(2), 99-102.

Shaw, P.K. and Kyriakides, S. (1985), "Inelastic analysis of thin-walled tubes under cyclic bending", *Int. J. Solids Struct.*, **21**(11), 1073-1110.

Vaze, S. and Corona, E. (1998), "Degradation and collapse of square tubes under cyclic bending", *Thin Wall. Struct.*, **31**, 325-341.