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Cyclic Bending Failure of Local Sharp-dented 6061-T6 Aluminum Alloy Tubes

Kuo-Long Lee, Wen-Fung Pan

Abstract— **This study presents an experiment for examining the degradation and failure of local sharp-dented 6061-T6 aluminum alloy tubes submitted to cyclic bending. The dent depths of circular tubes were considered from very trivial to approximately 0.6 times the tube's wall thickness. The moment-curvature response revealed an almost stable and closed hysteresis loop. The dent depths had almost no influence on the loop configuration. The ovalization-curvature behaviour demonstrated an asymmetrical and ratcheting trend along with the number of bending cycles. Furthermore, the deeper dent depths led to larger ovalizations. The relationship between the controlled curvature and the number of bending cycles required to ignite failure on a log-log scale displayed five nonparallel straight lines for five different dent depths. Finally, an empirical formula was introduced to simulate the relationship between the controlled curvature and the number of bending cycles required to produce failure. As a result, the experimental and analytical data were found to agree well.**

Index Terms— **local sharp-dented 6061-T6 aluminum alloy tubes, cyclic bending, moment, curvature, ovalization, failure.**

I. INTRODUCTION

The bending of a circular tube causes the ovalization of the tube cross-section. Ovalization is the change in the outer diameter divided by the original outer diameter, which gradually increases for reverse bending and subsequent cyclic bending. The ovalization phenomenon leads to the degradation of the tube's rigidity. The circular tube buckles or fractures (failure) when the ovalization reaches a crucial value. The buckling or fracturing is a severe damage on the tube. The tube cannot support the load. The obstruction or leakage of the material being carried also happens. Therefore, a complete understanding of the degradation and the failure of the circular tube submitted to cyclic bending is very important for industrial applications.

In 1987, Prof. Kyriakides and his research team designed a bending machine and began a series of experimental and theoretical studies on tubes submitted to monotonic or cyclic bending with or without external or internal pressure. Kyriakides and Shaw [1] then extended the aforementioned research to evaluate the buckling failure of tubes under cyclic bending. They suggested an empirical form to describe the controlled curvature and the number of cycles required to produce a buckling relationship. Meanwhile, Corona and Kyriakides [2] experimentally investigated the behavior of tubes subjected to cyclic bending with some external pressure. They discovered that the accumulation of ovalization was accelerated by applying some external pressure. Vaze and Corona [3] employed a similar bending machine to examine the deterioration and collapse of square steel tubes submitted to cyclic bending. They discovered that the tubes deteriorated because of the growth of periodic deflections in the flanges. Moreover, Corona and Kyriakides [4] studied the tube's buckling under bending with external pressure. In their work, 304 stainless steel tubes exhibited the angle buckling oriented at 20-45° to the direction of the bending moment. Similarly, Corona et al. [5] investigated the anisotropy of the plastic deformation for tubes submitted to bending. The material anisotropy behavior at the pre-buckling, post-buckling, and bifurcation stages was simulated by flow and deformation theories. Limam et al. [6] experimentally and theoretically discussed the inelastic collapse of tubes subjected to bending with some internal pressure. They employed the shell model in the finite element method to evaluate tube wrinkling and localization. Limam et al. [7] also examined the response and collapse of local-dented tubes undertaking pure bending with some internal pressure. The dent processing, tube pressurization, and tube bending to collapse were described through the finite element method. Bechle and Kyriakides [8] experimentally investigated the localization of NiTi tubes submitted to bending. In addition, the influence of the texture-driven and material asymmetry on the tube structure was studied.

In 1998, Pan et al. [9] designed a new measurement apparatus that can simultaneously measure the curvature and ovalization of tubes subjected to bending. This apparatus was then used with a tube-bending machine to investigate tubes submitted to different loading paths of bending. Accordingly, Pan and Her [10] experimentally investigated the viscoplastic collapse of SUS304 stainless steel tubes under cyclic bending at different curvature rates. Lee et al. [11] evaluated the influence of the D_o/t ratios on the response and collapse of circular tubes submitted to cyclic bending. Chang and Pan [12] proposed an empirical formulation to estimate the buckling life of circular tubes subjected to cyclic bending.

Circular tubes are often used in harsh environments in real industry applications. The materials in the environment may corrode the tube surface and create a notch on the surface. In 2010, the research team of Prof. Pan began to experimentally and theoretically investigate the response and the collapse of sharp-notched circular tubes submitted to cyclic bending. Lee et al. [13] experimentally studied the relationship between the variation of ovalization and the number of bending cycles for sharp-notched circular tubes subjected to cyclic bending. They discovered that the aforementioned relationship could be clearly divided into three stages, namely initial, secondary, and tertiary. In addition, Lee et al. [14] evaluated the viscoplastic response and buckling of sharp-notched SUS304 stainless steel circular tubes undertaking cyclic bending. Both the different notch depths and curvature rates were examined.

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They observed that the cyclic controlled curvature and the number of bending cycles required to produce buckling relationships on a log-log scale revealed parallel lines for every notch depth for a certain curvature rate. Chung et al. [15] investigated the response and stability of sharp-notched 6061-T6 aluminum alloy tubes under cyclic bending. The cyclic controlled curvature and the number of bending cycles required to produce buckling relationship exhibited marked differences from the corresponding relationship observed in the cyclic-bended sharp-notched SUS304 stainless steel tubes tested by Lee et al. [13]. However, the sharp notch for the aforementioned investigations was a circumferential sharp notch.

A tube will produce a dent from the external impact or pressure when it is under transportation, erection, or use. The dent depth can be very shallow or close to the wall thickness. The response should be different from that of a tube with a smooth or a notched surface when a tube with a dent is subjected to cyclic bending. In 2012, Limam et al. [7] experimentally and theoretically examined the response of local-dented tubes submitted to bending and some internal pressure. In their study, dented 321 stainless steel tubes were internally pressurized and bent to collapse. They discovered that the defect had a severe influence on the bending rigidity. They also used the finite element method to simulate the processes of the tube denting, internal pressurization, and bending. Although Limam et al. first investigated local-dented tubes under bending, the bending mode was a monotonic bending. Tubes are known to be constantly subjected to cyclic bending. In addition, Limam et al. used local round-type dents. In contrast, the present study uses local sharp dents. As we know, a sharp dent is more common, and its damage to the tube is relatively large. Therefore, the degradation and the failure of local sharp-dented circular tubes submitted to cyclic bending are investigated.

Local sharp-dented 6061-T6 aluminum alloy tubes with different dent depths submitted to cyclic bending were experimentally studied herein. Experimental tests were conducted using a tube-bending machine and a curvature-ovalization measurement apparatus. The bending moment, curvature, and ovalization were measured using sensors on the testing facilities. In addition, the number of bending cycles required to produce failure was recorded.

II. Experiments

A. Tube-bending Machine

Fig. 1 schematically shows the experiments executed by a specially built tube-bending machine. This facility was set up to conduct monotonic, reverse, and cyclic bending tests. A detailed explanation of the experimental facility can be found in many papers (Pan et al. [9], Pan and Her [10], Lee et al. [11]). Pan et al. [9] designed a new light-weight apparatus to measure the curvature and the ovalization of the tube shown in Fig. 2. Two side-inclinometers in the apparatus were used to detect the tube's angle variation during cyclic bending. The tube curvature can be determined by a simple calculation according to the angle changes. In addition, the tube ovalization can be measured in the center part of the apparatus that included a magnetic detector and a magnetic block.

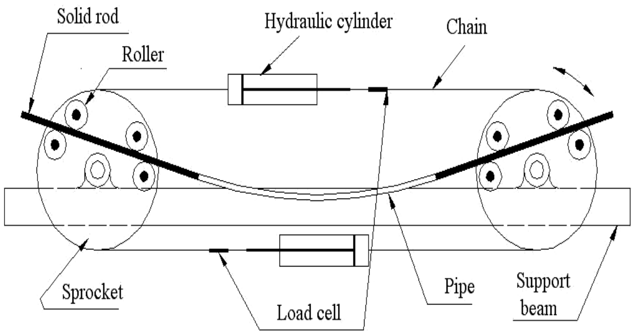


Fig. 2 A schematic drawing of the tube bending machine

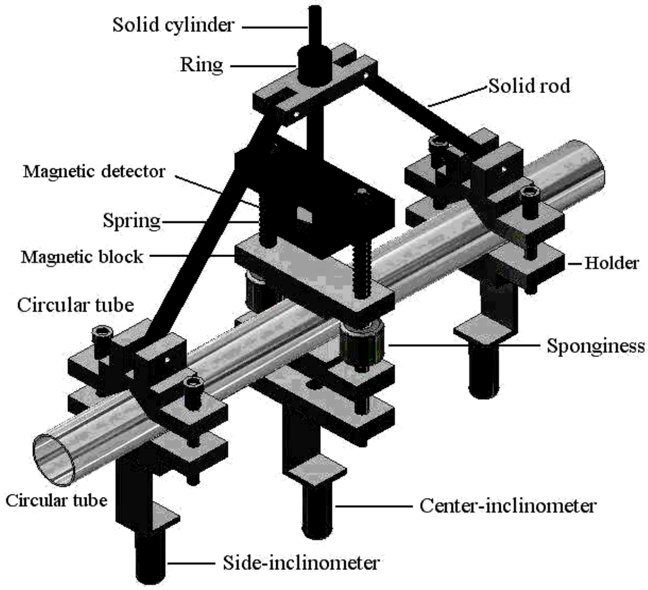


Fig. 3 A schematic drawing of the curvature-ovalization measurement apparatus

B. Material and Specimens

6061-T6 aluminum alloy tubes were used for the experimental testing. Table 1 depicts the chemical composition (weight %) of the tested material. The mechanical properties were 0.2% offset yield stress (σ_o) = 166 MPa, ultimate stress (σ_u) = 258 MPa, and percent elongation ($\%\varepsilon_f$) = 23%.

Table 1 Chemical composition of 6061-T6 aluminum alloy (weight %)

Chemical Composition	Al	Mg	Si	Ti	Fe
Proportion (%)	98.096	0.937	0.535	0.012	0.139
Chemical Composition	Mn	Zn	Cr	Ni	
Proportion (%)	0.022	0.0983	0.022	0.005	

The original tubes with an outside diameter D_o of 33.0 mm and a wall thickness t of 2.0 mm were processed on the outside surface to create the expected dents. Figs. 3 and 4 show a picture and a schematic drawing of the dent production, respectively. The indenter contacted the outside surface and exerted a force F to create a dent. Four different dent depths (a) were considered herein: 0.3, 0.6, 0.9, and 1.2 mm.

Fig. 3 A picture of processing a sharp dent on the 6061-T6 aluminum alloy tube

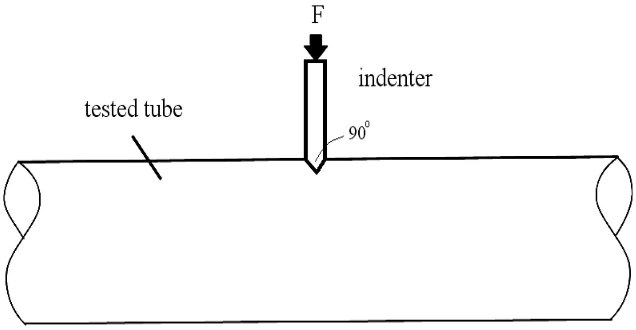


Fig. 4 A schematic drawing of processing a sharp dent on the 6061-T6 aluminum alloy tube

C. Test Procedures

The cyclic bending tests were performed under curvature-controlled conditions. The curvature rate for the test was 0.03 m^{-1}/s. The bending moment of the tube was measured by two load cells set up in the tube-bending machine, as shown in Fig. 1. The curvature and the ovalization were measured by the light-weight instrument, as shown in Fig. 2. The number of bending cycles required to produce failure was also recorded.

III. Experimental Results

A. Mechanical Response

Fig. 5 depicts the experimental relationship between the moment (M) and the curvature (κ) for a local sharp-dented 6061-T6 aluminum alloy tube with a = 0.6 mm subjected to cyclic bending. The tubes were cycled between curvatures of +0.4 m^{-1} to -0.4 m^{-1}. The M-κ relationship was found to be a closed and stable hysteresis loop from the first bending cycle. The dent depth had almost no influence on the M-κ relationship because the sharp dent was small and local. Therefore, the M-κ relationships for different as were not shown herein.

Figs. 6(a)-(e) depict the experimental relationships between the ovalization ($\Delta D_o/D_o$) and the curvature (κ) for a = 0.0, 0.3, 0.6, 0.9, and 1.2 mm, respectively. The tubes were also cycled between curvatures of +0.4 m^{-1} to -0.4 m^{-1}. Note that a = 0.0 mm stands for the smooth tube surface. The $\Delta D_o/D_o$-κ relationships exhibited a ratcheting and an increasing trend with the number of bending cycles. A larger a led to a more asymmetrical appearance of the $\Delta D_o/D_o$-κ relationship. Moreover, a larger a of the dented tubes caused a larger ovalization.

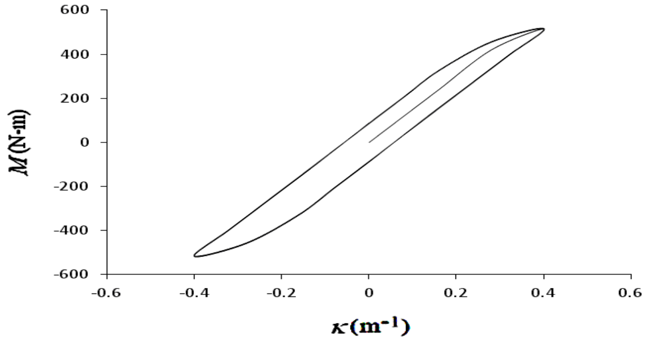
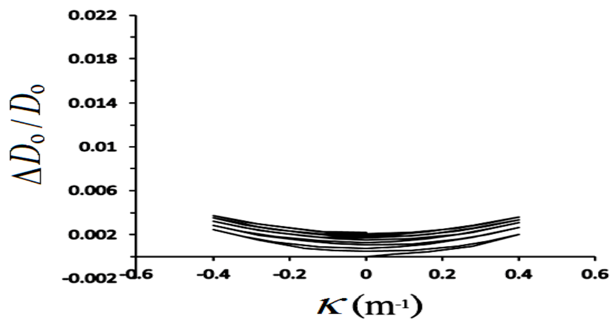
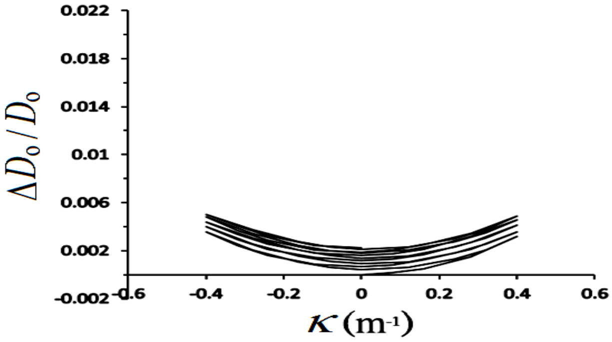


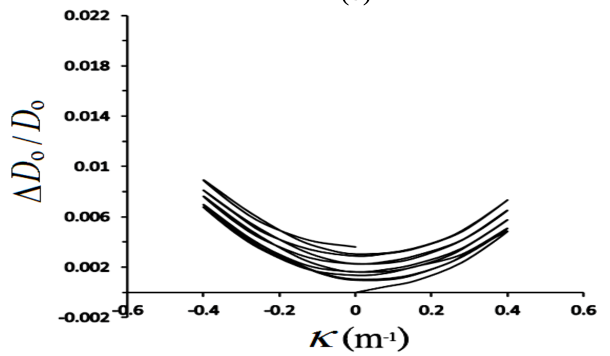
Fig. 5 Experimental moment (M) - curvature (κ) curves for a local sharp-dented 6061-T6 aluminum alloy tube with a = 0.6 mm under cyclic bending



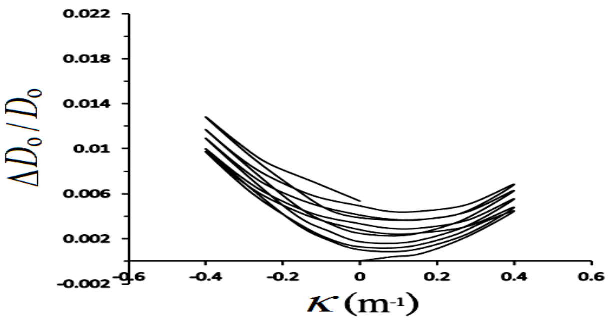
(a)



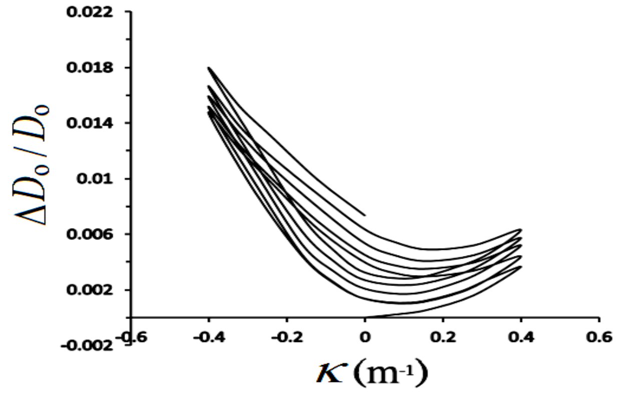
(b)



(c)



(d)



(e)

Fig. 6 Experimental ovalization ($\Delta D_o/D_o$) - curvature (κ) curves for local sharp-dented 6061-T6 aluminum alloy tubes with a = (a) 0.0, (b) 0.3, (c) 0.6, (d) 0.9 and (e) 1.2 mm under cyclic bending

B. *Failure*

Fig. 7 presents the experimental data of the cyclic curvature (κ_c/κ_o) versus the number of bending cycles required to ignite failure (N_f) for the local sharp-dented 6061-T6 aluminum alloy tubes submitted to cyclic bending with different *a*s. Note that the tube's curvature was normalized by $\kappa_o = t/D_o^2$ (Corona and Kyriakides [2]). The tubes with a larger a led to a lower N_f for a fixed κ_c/κ_o. Subsequently, the experimental data in Fig. 7 were plotted on a log-log scale, and five straight lines were observed in Fig. 8. Note that the lines were determined by the least square method.

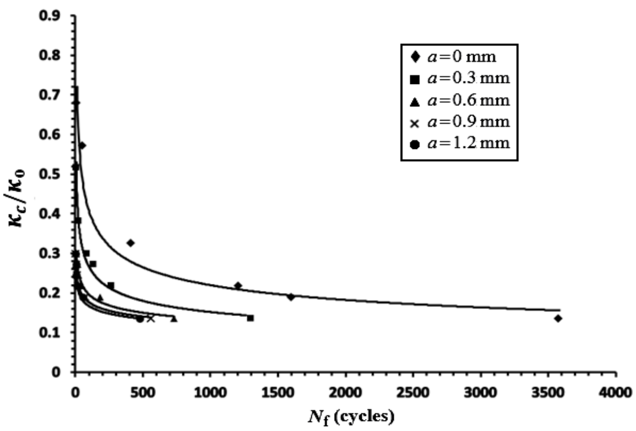


Fig. 7 Experimental cyclic curvature (κ/κ_o) versus the number of bending cycles required to ignite failure (N_f) for local sharp-dented 6061-T6 aluminum alloy tubes with different *a*s on decimal coordinates

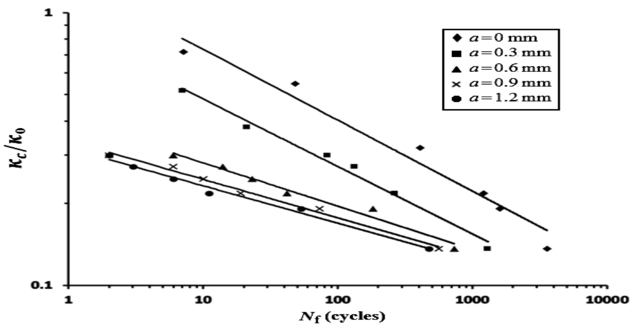


Fig. 8 Experimental cyclic curvature (κ/κ_o) versus the number of bending cycles required to ignite failure (N_f) for local sharp-dented 6061-T6 aluminum alloy tubes with different *a*s on double logarithmic coordinates

In 1987, Kyriakides and Shaw [1] proposed an empirical formulation to describe the relationship between κ_c/κ_o and the number of bending cycles required to ignite buckling (N_b):

$$\kappa_c/\kappa_o = C\,(N_b)^{-\alpha} \;\text{ or }\; \log \kappa_c/\kappa_o = \log C - \alpha \log N_b, \quad \text{(1a, b)}$$

where C and α are the material parameters. In our study, the failure types were buckling for a = 0.0 mm and fracture for $a \neq$ 0.0 mm. Thus, the empirical formulation of Eq. (1) was modified to become:

$$\kappa_c/\kappa_o = C\,(N_f)^{-\alpha} \text{ or } \log \kappa_c/\kappa_o = \log C - \alpha \log N_f. \quad \text{(2a, b)}$$

The C value is the quantity of κ_c/κ_o by letting $N_f = 1$, while the α value is the slope of the line on the log-log plot. Five amounts of C and α were obtained for a = 0.0, 0.3, 0.6, 0.9 and 1.2 mm from Eq. (2b) based on the experimental data in Fig. 8 (Table 2).

Table 2 Experimental determined C and α for different *a*s

a (mm)	0.0	0.3	0.6	0.9	1.2
a/t	0.0	0.15	0.3	0.45	0.6
C	1.33	0.82	0.40	0.32	0.31
α	0.27	0.26	0.16	0.12	0.12

The following formulation was proposed by considering the linear distribution of the experimental relationship between $C^{1/4}$ and $(a/t)^{1/2}$ in Fig. 9:

$$C^{1/4} = \beta\,(a/t)^{1/2} + C_o, \quad (3)$$

where β and C_o are material parameters. From Fig. 9, β and C_o were determined to be -0.64 and 1.08, respectively. The following formulation was proposed by observing the linear distribution of the experimental relationship between $\alpha^{1/2}$ and a/t in Fig. 10:

$$\alpha^{1/2} = \gamma\,(a/t) + \alpha_o, \quad (4)$$

where γ and α_o are material parameters. From Fig. 10, γ and α_o were determined to be -0.27 and 0.73, respectively. Finally, using Eqs. (2), (3) and (4), the simulated relationship between κ_c/κ_o and N_f for local sharp-dented 6061-T6 aluminum alloy tubes with different *a*s under cyclic bending is demonstrated in Fig. 11. It can be seen that the simulated result correlates well with the experimental finding.

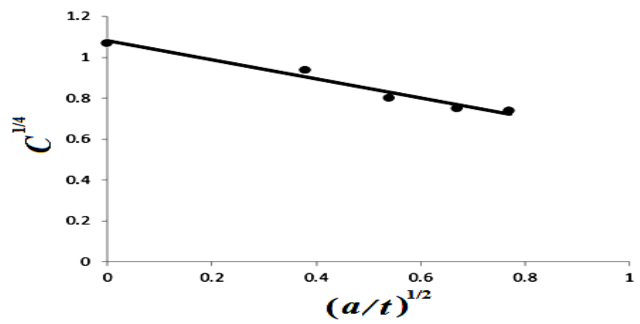


Fig. 9 Relationship between $C^{1/4}$ and $(a/t)^{1/2}$

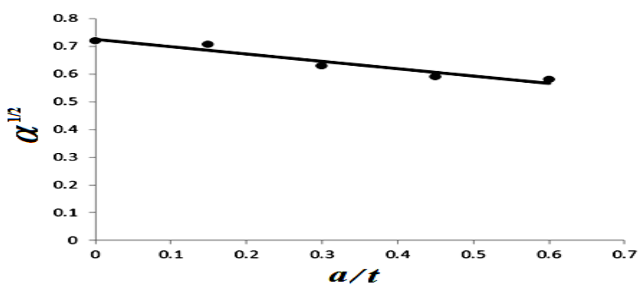


Fig. 10 Relationship between $\alpha^{1/2}$ and a/t

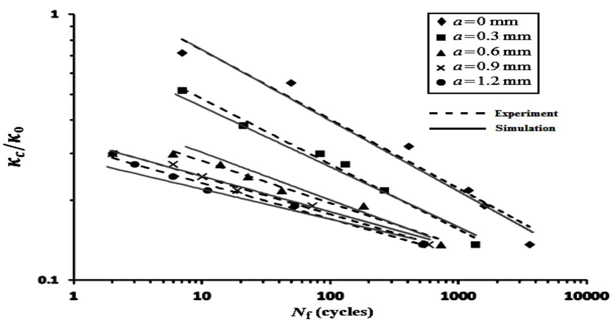


Fig. 11 Experimental and simulated cyclic curvature (κ/κ_o) versus the number of bending cycles required to ignite failure (N_f) for local sharp-dented 6061-T6 aluminum alloy tubes with different *a*s on double logarithmic coordinates

IV. Conclusions

This study investigated the response of the local sharp-dented 6061-T6 aluminum alloy tubes with different *a*s submitted to cyclic bending. Some important conclusions are sorted as follows according to the experimental and simulated results:

(1) The experimental *M*-κ relationship for the local sharp-dented 6061-T6 aluminum alloy tubes with any *a* displayed a closed and stable hysteresis loop from the first bending cycle. In addition, the *M* magnitudes were almost equal to each other at the maximum and minimum controlled curvatures for any *a*. The sharp dent was small and local. Hence, the dent depth had almost no influence on the *M*-κ relationship.

(2) The experimental $\Delta D_o/D_o$-κ relationship for the local sharp-dented 6061-T6 aluminum alloy tubes with any *a* revealed an increasing and ratcheting trend with the number of bending cycles. The $\Delta D_o/D_o$-κ relationships were symmetrical for $a = 0.0$ mm, but asymmetrical for $a \neq 0.0$ mm. In addition, the tubes with a larger *a* led to more asymmetrical trend and a larger ovalization.

(3) The empirical formulation of Eq. (1) proposed by Kyriakides and Shaw [1] was modified in Eq. (2) to simulate the κ/κ_o-N_f relationship for the local sharp-dented 6061-T6 aluminum alloy tubes with different *a*s submitted to cyclic bending. The formulation of the material parameters, *C* and α, were proposed in Eqs. (3) and (4), respectively, according to the experimental data. The simulated results by Eqs. (2)-(4) were in good agreement with the experimental findings (Fig. 11).

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