Response and Fracture of EMT Carbon Steel Round-Hole Tubes with Different Hole Orientations and Different Hole Diameters under Cyclic Bending

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Abstract: This paper aims to investigate the response and fracture of EMT carbon steel round-hole tubes (EMT carbon steel RHTs) under cyclic bending loads. The study considers four different hole orientations (0°, 30°, 60°, and 90°) and five distinct hole diameters (2, 4, 6, 8, and 10 mm). The results reveal that hole orientation and diameter exert a minimal impact on the moment-curvature relationship, leading to the formation of stable loops. The ovalization-curvature graphs demonstrate a trend of asymmetry, serration, and growth with an increasing number of bending cycles. Additionally, larger hole orientations or smaller notch diameters result in reduced ovalization. Furthermore, the double logarithmic coordinates of the controlled curvature–number of cycles required to induce fracture reveal five parallel lines for different hole diameters when the hole orientation is fixed. Finally, in adopting the formulas for smooth tubes and for 6061-T6 aluminum alloy round-hole tubes (6061 aluminum alloy RHTs), this study adjusts the related material parameters. These modifications effectively describe the controlled curvature–number of cycles required to induce fracture for EMT carbon steel RHTs with different hole orientations and diameters under cyclic bending, demonstrating reasonable agreement with the experimental results.

Keywords: EMT carbon steel RHTs; hole orientations; hole diameters; moment; curvature; ovalization; cyclic bending; number of cycles required to induce fracture

1. Introduction

A round-hole tube (RHT) is a tube with a circular cross section and a hole in the center. It has many applications in the engineering field, such as noise reduction, pipeline transportation, pressure control, thermal equipment, motor transportation, machinery industry, petroleum geological drilling, measuring instruments, flow regulation, and other purposes. Given that round-hole tubes (RHTs) are frequently subjected to cyclic bending loads for various purposes, it is necessary to explore their related material properties and mechanical behaviors. Therefore, the requirements for mechanical design, structural design, and performance of RHTs should be mastered to achieve the highest benefit and ensure the safety of the product.

In an industrial environment, RHTs are often subjected to cyclic bending loads. The ovalization becomes evident in RHTs. The degree of ovalization of the RHT increases proportionally with the number of bending cycles. Ultimately, when the ovalization exceeds a critical threshold, the RHT fractures. Therefore, understanding the response and fracture mechanisms of RHTs under cyclic bending loads is crucial for enhancing product durability and safety in various industrial applications.

Many researchers have investigated the bending behavior of smooth tubes. Kyriakides and Shaw [1] developed a device capable of performing both monotonic and cyclic bending tests on tubes, with or without external pressure. This equipment has been
extensively utilized in the study of tubes made from various materials, including 6061-T6 aluminum alloy, 304 stainless steel, 1018 steel, 1020 steel, and NiTi smooth tubes [1–9].

Several researchers have made notable contributions to the study of tube behavior under various bending conditions. For instance, Yuan and Mirmiran [10] focused on the buckling behavior of concrete-filled fiber-reinforced plastic tubes subjected to bending. Elchalakani et al. [11] conducted explorations into the slenderness limit of cold-formed hollow sections through cyclic bending tests. Additionally, Elchalakani and Zhao [12] studied the cyclic bending performance of concrete-filled cold-formed steel tubes, while Zhi et al. [13] examined the stability and instability of cylindrical shells under earthquake conditions. In a separate study, Yazdani and Nayebi [14] analyzed the damage sustained by pipelines when bending under stable internal pressure. Guo et al. [15] focused on studying the bending behavior of thin-walled hollow tubes, whereas Elchalakani et al. [16] established novel ductile slenderness limits based on strains for concrete-filled tubes through bending tests.

Other researchers have explored various aspects of tube behavior, including instability following non-proportional paths [17], the effect of corrosion on the bending performance of curved tubes [18], and local buckling behavior under bending and axial loads [19]. Additionally, Silveira et al. [20] demonstrated the applicability of the constructal law in evaluating the mechanical geometry of materials engineering systems. He et al. [21] proposed the relationship between the bending angle and the length of the transition section formation zone through experiment and simulation verification. Wang et al. [22] conducted a four-point bending experimental study on the bending response of square steel tube concrete reinforced by internal angle steel. Meanwhile, Wu et al. [23] explored the response and damage of stacked sequentially braided composite pipes with 45° and 60° braids under three-point bending.

In 1988, Pan et al. [24] developed a device enabling the measurement of curvature and ovalization of tubes during bending. Their research encompassed a variety of bending experiments on smooth tubes, including cyclic bending experiments, pure bending creep experiments, and cyclic bending experiments with varying curvature ratios. From 2016 onwards, Pan et al. shifted their focus to investigate the behavior of notched tubes under bending loads. For instance, they conducted cyclic bending tests on tubes featuring circumferential sharp notches [25], as well as cyclic bending tests on tubes incorporating localized sharp cuts [26].

Although Lee et al. [27] conducted relevant research on the response and fracture of 6061-T6 aluminum alloy RHTs with different hole orientations and hole diameters under cyclic bending loads, one question that arises is whether the observed behaviors—such as moment-curvature, ovalization-curvature, and the relationship between controlled curvature and the number of cycles required to induce fracture—are consistent with those of other materials. Furthermore, this paper will delve into a thorough discussion on the applicability of the theory proposed by Lee et al. [27] to other materials, building upon their research on 6061-T6 aluminum alloy RHTs.

Carbon steel tubing is known for its durability and ability to withstand pressure and environmental conditions. It is an ideal material for structural applications and is the most commonly used tube in industrial applications. Carbon steel tubing has high strength, good toughness, good resistance to stress and impact, as well as tightness, good plasticity, easy welding and heat processing, thin wall thickness, and it saves metal. However, its corrosion resistance is poor, and appropriate anti-corrosion measures are required. Due to functional requirements, carbon steel tubes may undergo various machining processes, including drilling, grooving, and circumferential cutting. Consequently, this study aims to investigate the response and fracture of EMT carbon steel RHTs with different hole orientations and hole diameters under cyclic bending.
2. Experiments

2.1. Experimental Devices

In this study, cyclic bending tests were performed on EMT carbon steel RHTs using a pure bending (four-point bending) machine, illustrated in Figure 1. The test setup includes two sprockets mounted on beams and a strong chain running around them, capable of accommodating tube specimens up to 1 m in length. To facilitate testing, each tube is fitted with solid rod extensions. During the bending process, the interaction between the tube and the roller allows for free axial movement. The applied load is generated by two concentrated loads from a pair of rollers. Retraction of the upper or lower cylinder initiates sprocket rotation, enabling pure bending of the test tube. Reverse bending is achieved by reversing the hydraulic circuit’s flow direction. For a more comprehensive understanding of the machine, readers are directed to the detailed exposition by Pan et al. [24].

![Figure 1. Schematic diagram of the tube-bending machine.](image)

The Curvature and Ovalization Measurement Apparatus (COMA), developed by Pan et al. [24] and depicted in Figure 2, is a valuable tool for assessing tube curvature ($\kappa$) and ovalization ($\Delta D/D_0$), a crucial parameter in this study. Positioned near the mid-span of the tube, the COMA utilizes a fixed distance between two side-inclinometers and their angular change to accurately calculate $\kappa$. For a more detailed understanding of the COMA, readers are referred to the comprehensive exposition by Pan et al. [24].

![Figure 2. Schematic diagram of the COMA.](image)

2.2. Material and Specimens

In this study, circular tubes made of EMT carbon steel were used. These tubes were purchased from Kounan Steel Co., Ltd., Kaohsiung, Taiwan. The chemical composition of the tubes includes Fe (98.74%), C (0.15%), Mn (0.6%), P (0.03%), S (0.05%), Si (0.35%), and some other trace elements (0.08%). The material properties are as follows: a density of
7850 kg/m³, Young’s modulus of 206 GPa, Poisson’s ratio of 0.29, yield strength of 270 MPa, and ultimate strength of 460 MPa. The initial raw EMT carbon steel tube had a $D_0$ of 31.8 mm and a wall thickness ($t$) of 1.5 mm. To introduce local round holes, the raw tubes underwent drilling on the outside surface to achieve desired hole diameters ($d$) of 2, 4, 6, 8, and 10 mm. Figure 3 depicts the schematic drawing of the RHT, and Figure 4 provides a visual representation of the EMT carbon steel RHTs.

![Figure 3. Schematic diagram of the RHT.](image)

Since the round hole is local, the orientation ($\phi$) of the round hole is expected to influence the response and fracture of the EMT carbon steel RHTs. Therefore, $\phi$ must be taken into consideration. In Figure 5, orientations of $\phi$ at $0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$, $120^\circ$, $150^\circ$, and $180^\circ$ were examined. Since the bending moment is exerted in the z-direction, similar responses are expected to be observed for $\phi = 0^\circ$ and $\phi = 180^\circ$, $\phi = 30^\circ$ and $\phi = 150^\circ$, and $\phi = 60^\circ$ and $\phi = 120^\circ$ when subjected to cyclic bending loads. Consequently, this study focused solely on four orientations, specifically $\phi = 0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$.

![Figure 5. Schematic diagram of the RHT with a round hole at different $\phi$.](image)

### 2.3. Test Procedures

EMT carbon steel RHTs were subjected to curvature-controlled cyclic bending at a curvature rate of $0.03 \, \text{m}^{-1} \, \text{s}^{-1}$. The bending moment ($M$) was determined by using load cells in the bending machine, as depicted in Figure 1. The $\kappa$ and $\Delta D/D_0$ were measured by
using the COMA shown in Figure 2. The number of cycles required to induce fracture \((N_f)\) was recorded.

3. Experimental Results and Discussion

3.1. \(M-κ\) Relationships

Figure 6 shows the \(M-κ\) relationship of the EMT carbon steel RHT under cyclic bending with \(ϕ = 0^\circ\) and \(d = 2\) mm. The controlled curvature ranges from \(-0.3\) m\(^{-1}\) to \(0.3\) m\(^{-1}\). The experimental results indicate that in the initial stage of loading, the EMT carbon steel RHT undergoes elastic deformation, presenting a linear trend in the \(M-κ\) relationship. However, upon entering the plastic region, the \(M-κ\) relationship becomes nonlinear, with the slope of the curve gradually decreasing, and the EMT carbon steel RHT undergoes permanent plastic deformation. When the curvature reaches the control peak value of \(0.3\) m\(^{-1}\), the bending test machine initiates reverse bending, reducing the curvature from the peak value of \(0.3\) m\(^{-1}\) to \(-0.3\) m\(^{-1}\). In the initial stage of the unloading process, the linear \(M-κ\) relationship is parallel to the linear \(M-κ\) relationship in the initial elastic range. Subsequently, the later part of the negative bending is similar to the positive bending, with the slope of the curve gradually decreasing, exhibiting a nonlinear trend as it enters the plastic range. After completing the first cycle, the \(M-κ\) relationship graph shows a loop, and with an increase in cycles, the loops almost overlap. Because the holes are small and localized, the \(M-κ\) relationships for different values of \(ϕ\) and \(d\) are nearly identical. Therefore, only the \(M-κ\) relationship for the case of \(ϕ = 0^\circ\) and \(d = 2\) mm is presented in this study. This phenomenon aligns with the experimental findings of Lee et al. [27] on 6061-T6 aluminum alloy RHTs under cyclic bending loads, where stable loops remain unaffected by \(ϕ\) and \(d\).

![Figure 6. \(M-κ\) relationship of the EMT carbon steel RHT under cyclic bending with \(ϕ = 0^\circ\) and \(d = 2\) mm.](image)

3.2. \(ΔD/D_o-κ\) Relationships

Figure 7a–e, respectively, depict the \(ΔD/D_o-κ\) relationships of EMT carbon steel RHTs under cyclic bending with a fixed \(ϕ = 0^\circ\) and different \(d\) values: 2, 4, 6, 8, and 10 mm. The controlled curvature ranges from \(-0.3\) m\(^{-1}\) to \(0.3\) m\(^{-1}\). The experimental results show that regardless of deformation in the elastic or plastic range, the \(ΔD/D_o-κ\) curve exhibits a nonlinear trend. When the EMT carbon steel RHT is loaded, \(ΔD/D_o\) shows an increasing trend, reaching its peak when the curvature is \(0.3\) m\(^{-1}\). Subsequently, in the unloading phase, \(ΔD/D_o\) shows a decreasing trend, and when the curvature reaches \(0.0\) m\(^{-1}\), \(ΔD/D_o\) is not zero, indicating plastic deformation in the EMT carbon steel RHT. During the reverse loading phase, \(ΔD/D_o\) shows an increasing trend again, reaching its peak when the curvature is \(-0.3\) m\(^{-1}\). Then, in the unloading phase, when the curvature returns to \(0.0\) m\(^{-1}\), \(ΔD/D_o\) increases slightly. Through repeated cyclic loading, the \(ΔD/D_o-κ\) curve exhibits an
increasing, serrated, and bowtie trend. In addition, no matter what \(d\) is, the \(\Delta D/D_o-\kappa\) relationship shows an asymmetric pattern, and the larger \(d\) is, the more serious the asymmetry is. It is observed that as \(d\) increases, the growth of \(\Delta D/D_o\) also increases. This phenomenon is consistent with the experimental results of Lee et al. [27].

![Figure 7](image)

**Figure 7.** \(\Delta D/D_o-\kappa\) relationships of EMT carbon steel RHTs under cyclic bending with \(\phi = 0^\circ\) and \(d = (a) 2, (b) 4, (c) 6, (d) 8, (e) 10\ mm.**

Figure 8a–d, respectively, illustrate the \(\Delta D/D_o-\kappa\) relationships of EMT carbon steel RHTs under cyclic bending with different \(\phi\) values: \(0^\circ, 30^\circ, 60^\circ, 90^\circ\) and a fixed \(d = 10\ mm.\) It can be observed that a smaller \(\phi\) leads to a larger \(\Delta D/D_o.\) In addition, it can be observed that \(\Delta D/D_o-\kappa\) relationships are asymmetrical for small values of \(\phi,\) but \(\Delta D/D_o-\kappa\) relationships are symmetrical for large values of \(\phi.\) This phenomenon is consistent with the experimental results of Lee et al. [27].

![Figure 8](image)

**Figure 8.** \(\Delta D/D_o-\kappa\) relationships for EMT carbon steel RHTs under cyclic bending with \(\phi = (a) 0^\circ, (b) 30^\circ, (c) 60^\circ, (d) 90^\circ\) and \(d = 10\ mm.\)
3.3. Controlled Curvature ($\kappa_c/\kappa_o$–$N_f$) Relationships

Figure 9a–d illustrate the experimental $\kappa_c/\kappa_o$–$N_f$ relationships for EMT carbon steel RHTs under cyclic bending with $\phi = 0^\circ$, 30°, 60°, 90°, and different $d$. Here, $\kappa_o$ is used to nondimensionalize $\kappa_c$, calculated as $\kappa_o = t/D_o^2$. The experimental results indicate that, for fixed values of $\phi$ and $d$, larger values of $\kappa_c/\kappa_o$ correspond to a reduced $N_f$. Similarly, when $\phi$ and $\kappa_c/\kappa_o$ are fixed, larger values of $d$ result in a decreased $N_f$. Meanwhile, for fixed values of $d$ and $\kappa_c/\kappa_o$, larger values of $\phi$ lead to an increased $N_f$. Figure 10a–d depict the same data as Figure 9a–d using double logarithmic coordinates, with straight lines representing the results of least squares fitting. This phenomenon is consistent with the experimental results of Lee et al. [27]. However, an inconsistency arises. For a certain $\phi$, Lee et al. [27] showed five almost-parallel straight lines, while this study found five non-parallel straight lines.

Figure 9. Experimental $\kappa_c/\kappa_o$–$N_f$ relationships for EMT carbon steel RHTs under cyclic bending with $\phi = (a) 0^\circ$, (b) 30°, (c) 60°, (d) 90° and different $d$.

Figure 10. Experimental $\kappa_c/\kappa_o$–$N_f$ relationships for EMT carbon steel RHTs under cyclic bending on double logarithmic coordinates with $\phi = (a) 0^\circ$, (b) 30°, (c) 60°, (d) 90° and different $d$. 
In 1987, Shaw and Kyriakides [1] proposed the \( \kappa_s/N_i \) relationship for smooth circular tubes under cyclic bending as follows:

\[
\frac{\kappa_s}{\kappa_o} = C(N_i)^{-\alpha} \quad \text{or} \quad \log \frac{\kappa_s}{\kappa_o} = \log C - \alpha \log N_i
\]  

(1)

where \( C \) and \( \alpha \) are material parameters associated with the mechanical properties of the material and the geometric shape. The value of \( \alpha \) represents the slope of the double logarithmic coordinate line's relationship between \( \kappa_s/\kappa_o \) and \( N_i \) while \( C \) indicates the corresponding value of \( \kappa_s/\kappa_o \) when \( N_i = 1 \). However, this formula cannot cover the \( \kappa_s/\kappa_o-N_i \) relationship for 6061-T6 aluminum alloy RHTs under cyclic bending with different \( \phi \) and \( d \). Therefore, Lee et al. [27] proposed that \( C \) is a function of \( d/t \) as

\[
\log C = -\beta(d/t) + C_o
\]  

(2)

where \( \beta \) and \( C_o \) are material parameters. Through experimental data in Figure 10a–d, the \( \log C \) versus \( d/t \) relationships for different \( \phi \) are shown in Figure 11a. The straight lines are obtained by the least squares method. It can be found that \( \beta \) represents the slope of the straight line in Figure 11a, while \( C_o \) denotes the intercept of this straight line. Based on the straight lines depicted in Figure 11a, the corresponding values of \( \beta \) and \( C_o \) for each \( \phi \) are determined. These values are then plotted in Figure 11b,c, respectively. Since they are all linear relationships, this study proposes the following equation to express the relationships between \( \beta \) and \( \phi \) and \( C_o \) and \( \phi \):

\[
\beta = b_1\phi + b_2, \quad 0 \leq \phi \leq \pi/2, \quad (3)
\]

and

\[
C_o = c_1\phi + c_2, \quad 0 \leq \phi \leq \pi/2, \quad (4)
\]

where \( b_1, b_2, c_1, \) and \( c_2 \) are material constants and can be obtained as 0.0777, 0.2823, 0.006 and 0.0219, respectively, according to Figure 11b,c.

![Figure 11. (a) Relationships between logC and d/t for different \( \phi \), (b) relationship between \( \beta \) and \( \phi \), and (c) relationship between \( C_o \) and \( \phi \).](image)

Next, this paper continues to discuss the form of \( \alpha \). Lee et al. [27] found that for a specific \( \phi \), the \( \kappa_s/\kappa_o-N_i \) relationship on double logarithmic coordinates showed five almost-parallel straight lines. Based on this observation, they proposed the form of \( \alpha \) to be

\[
\alpha^{1/3} = a_1\phi + a_2, \quad 0 \leq \phi \leq \pi/2
\]  

(5)

where \( a_1 \) and \( a_2 \) are material parameters. However, the \( \kappa_s/\kappa_o-N_i \) relationship on double logarithmic coordinates showed five non-parallel straight lines in this study. Therefore, this study attempts to establish the relationship between \( \alpha \) and \( d/t \). From experimental data in Figure 10a–d, the relationship between \( \alpha \) and \( d/t \) for different \( \phi \) can be obtained, as shown in Figure 12a. Thus, the following proposal is made:

\[
\log \alpha = -\gamma(d/t) + \alpha_o
\]  

(6)
where \( \gamma \) and \( \alpha_o \) are material parameters. The straight lines in Figure 12a are obtained by the least squares method. According to the corresponding \( \gamma \) and \( \alpha_o \) from the straight lines in Figure 12a, the relationships between these values and \( \phi \) are plotted in Figure 12b,c, respectively. Since they are all linear relationships, this study proposes the following:

\[
\gamma = g_1 \phi + g_2, \quad 0 \leq \phi \leq \pi/2
\]

(7)

and

\[
\alpha_o = a_1 \phi + a_2, \quad 0 \leq \phi \leq \pi/2
\]

(8)

where \( g_1, g_2, a_1, \) and \( a_2 \) are material constants and can be obtained as \(-0.0255, -0.4554, -0.0001\) and \(0.00108\), respectively, according to Figure 12b,c. Figure 13a–d illustrate the experimental and theoretical \( \kappa_c/\kappa_o-N_f \) relationships for EMT carbon steel RHTs under cyclic bending on double logarithmic coordinates with \( \phi = 0^\circ, 30^\circ, 60^\circ, 90^\circ \) and different \( d \). The comparison results demonstrate that the theoretical predictions reasonably describe the experimental results.

4. Conclusions

This study primarily investigates the response and fracture of EMT carbon steel RHTs under cyclic bending with different \( \phi \) of \( 0^\circ, 30^\circ, 60^\circ \), and \( 90^\circ \) and different \( d \) of 2, 4, 6, 8, and 10 mm. The behavior of 6061 aluminum alloy RHTs under cyclic bending with
different $\phi$ and $d$ tested by Lee et al. [27] is compared. Based on tested, analyzed, and compared data, the following conclusions can be drawn:

1. From the experimental $M$–$\kappa$ relationships, it is observed that as the $\kappa$ increases, the $M$ also increases. Under cyclic bending loads, the $M$–$\kappa$ relationship exhibits a stable loop until eventual buckling failure. Results also indicate that for different $\phi$ and $d$, the $M$–$\kappa$ relationships show similar loops. This phenomenon is consistent with the experimental results of Lee et al. [27].

2. In the experimental $\Delta D/D_o$–$\kappa$ relationships, higher $\kappa$ leads to increased $\Delta D/D_o$. Larger $d$ or smaller $\phi$ values correspond to increased $\Delta D/D_o$. This phenomenon is consistent with the experimental results of Lee et al. [27]. Additionally, under cyclic bending loads, the $\Delta D/D_o$–$\kappa$ relationships exhibit a ratcheting, unsymmetrical, bowtie, and growing trend. The larger $d$ or smaller $\phi$ is, the more serious the asymmetry is. This phenomenon is consistent with the experimental results of Lee et al. [27].

3. The experimental $\kappa_o/\kappa_o$–$N_t$ relationships reveal that, when $\phi$ and $d$ are fixed, larger $\kappa_o/\kappa_o$ leads to fewer $N_t$. Fixing $\phi$ and $\kappa_o/\kappa_o$ larger $d$ results in fewer $N_t$. Conversely, when fixing $d$ and $\kappa_o/\kappa_o$ larger $\phi$ leads to more $N_t$. When $\phi$ is fixed, the relationships of $\kappa_o/\kappa_o$–$N_t$ for five different $d$ on double logarithmic coordinates exhibit five straight lines. This phenomenon is consistent with the experimental results of Lee et al. [27]. However, for a certain $\phi$, they show almost-parallel lines, while we found non-parallel lines.

4. This study adopts the formula (Equation (1)) proposed by Kyriakides and Shaw [1] to describe the $\kappa_o/\kappa_o$–$N_t$ relationships. The formulation of the material parameter $C$ in Equation (2), proposed by Lee et al. [27], was used in this study. The material parameters $\beta$ and $C_o$ were derived from Equations (3) and (4), respectively. Additionally, the material parameter $\alpha$ (Equation (5)) was newly proposed based on the experimental data. The material parameters $\gamma$ and $\alpha_o$ were derived from Equations (6) and (7), respectively. The theoretical equations (Equations (1)–(4) and (5)–(7)) were employed to describe the $\kappa_o/\kappa_o$–$N_t$ relationships for EMT carbon steel RHTs under cyclic bending with $\phi = 0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$ and various $d$ (dashed lines in Figure 13a–d), and the results of experimental and theoretical analyses are reasonably consistent.

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