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Finite Element Analysis on the Response for Circular Tubes under Pure Bending Creep or Relaxation

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Abstract – **In this paper, by using adequate stress-strain relationship, mesh, boundary condition and loading condition, the finite element ANSYS was used to analyze the response for circular tubes subjected to pure bending creep or pure bending relaxation. Experimental data tested by Pan *et al.* [1] for SUS304 stainless steel tubes were compared with the ANSYS analysis. The response include the moment-curvature and ovalization - curvature relationships for the preloading pure bending stage, curvature-time and ovalization-time for preloading pure bending and subsequent pure bending creep stages and moment-time and ovalization-time for preloading pure bending and subsequent pure bending relaxation stages. It has been shown that the analysis is in good agreement with the experimental data.**

Keywords – **Circular Tubes, Finite Element ANSYS Analysis, Pure Bending Creep, Pure Bending Relaxation.**

I. INTRODUCTION

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

As part of the earliest research on this issue, Kyriakides' research team began a series of experimental and theoretical studies on tubes submitted to monotonic or cyclic bending with or without external or internal pressure. Shaw and Kyriakides [2] investigated the elastic-plastic response of thin-walled tubes under cyclic bending. They also showed that a gradual increase of the tube's ovalization for reverse and continuous cyclic bending. Corona and Kyriakides [3] experimentally investigated the weakening and failure of tubes undertaken cyclic bending with external pressure. In their research, the effects of the cyclic bending path with or without external pressure on the ovalization's accumulation-rate and the timing of buckling were examined. Furthermore, Corona and Kyriakides [4] investigated the failure of tubes subjected to bending with or without external pressure. The asymmetric imperfections and buckling were theoretically evaluated through a previously derived form. Similarly, Corona *et al.* [5] discovered that the tubes displayed the plastic anisotropy, and described this anisotropy by using Hill's yield criterion. By including the material anisotropy, the prebuckling, postbuckling, and bifurcation were evaluated by the flow and deformation theories, respectively. Limam *et al.* [6] investigated the failure of local-dented tubes undertaken pure bending with internal pressure. By using the finite element models, the dent's processing, tube's pressurization, and tube's bending to collapse were properly described. Bechle and Kyriakides [7] examined the localization of NiTi tubes submitted to bending. The influence of the texture-driven and material asymmetry on the tube's structure was studied.

Pan *et al.* [8] 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 [9] investigated the response and stability of 304 stainless steel tubes that were subjected to cyclic bending with different curvature-rates, Lee *et al.* [10] studied the influence of the D_o/t ratio on the response and stability of circular tubes submitted to symmetrical cyclic bending, Lee *et al.* [11] 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.* [12] studied the mean moment effect on circular, thin-walled tubes undertaken cyclic bending, and Chang and Pan [13] discussed the buckling life estimation of circular tubes subjected to cyclic bending.

In practical industrial applications, tubes are under the hostile environment, so the material in the environment may corrode the tube surface and produce notches. Additionally, a tube in the working condition often involves some notches. The mechanical behavior and buckling failure of a notched tube differs from that of a tube with a smooth surface. In 2010, Lee *et al.* [14] studied the variation in ovalization of sharp-notched circular tubes subjected to cyclic bending. Lee [15] investigated the mechanical behavior and buckling failure of sharp-notched circular tubes under cyclic bending. Lee *et al.* [16] experimentally discussed the viscoplastic response and collapse of sharp-notched circular tubes subjected to cyclic bending. Later, Lee *et al.* [17] investigated the response of SUS304 stainless steel tubes subjected to pure bending creep and pure bending relaxation.

In 1998, Pan *et al.* [1] started to experimentally investigate the response of SUS304 stainless steel tubes subjected to pure bending creep or pure bending relaxation. The pure bending creep is to bend the tube to a desire moment and then hold that moment for a period of time. The pure bending relaxation is to bend the tube to a desire curvature and hold that curvature for a period of time. It is known that the pure bending creep leads to the buckling of the tube, but the pure bending relaxation produces the only moment relaxation. In addition, their responses are time-related. Faced with such complex behaviors, experimental and theoretical analysis is necessary.

In this study, by using adequate stress-strain relationship, mesh, boundary condition and loading condition, the finite element ANSYS was used to simulate the response of SUS304 stainless steel tubes subjected to pure bending creep or pure bending relaxation. Finally, experimental data tested by Pan *et al.* [1] were used for comparison.

II. FINITE ELEMENT ANALYSIS

In this study, the response of circular tubes submitted to pure bending creep or pure bending relaxation was also analyzed numerically using finite element code ANSYS. The response is the correlation among the moment, curvature, ovalization and time. The elastic-plastic stress-strain response, mesh, boundary condition and loading condition are explained as follows.

A. Elastic-plastic Stress-Strain Curves

A uniaxial stress (σ) - strain (ε) curve was constructed multi-linearly in ANSYS according to the tested uniaxial stress (σ) - strain (ε) curve for SUS304 stainless steel shown in Fig. 1. In addition, the kinematic hardening rule was selected in this study.

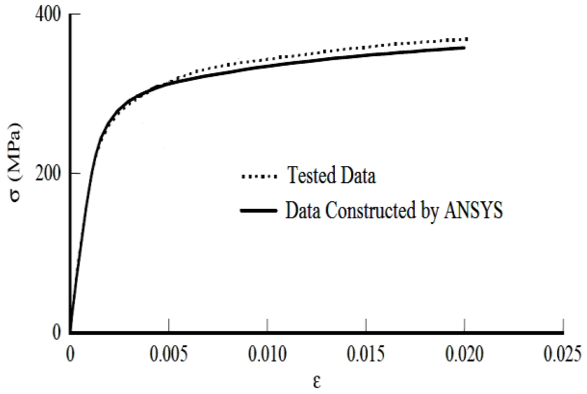

Fig.1. Tested and ANSYS constructed data of the uniaxial stress-strain curve for SUS304 stainless steel.

B. Mesh

Due to the three-dimensional geometry and elastoplastic deformation of the tube, the SOLID 186 element was used in the related analysis. This element is a tetrahedral element built in ANSYS and is suitable for analyzing plastic and large deformations. In particular, this element is adequate for analysis of shell components under bending. The tube geometry from the experimental data from [1] is the outside diameter D_o of 30.3 mm, wall thickness t of 0.76 mm and tube length L_o of 388 mm. Fig. 2 shows the mesh constructed by ANSYS for half tube according to the geometry of the tested tubes.

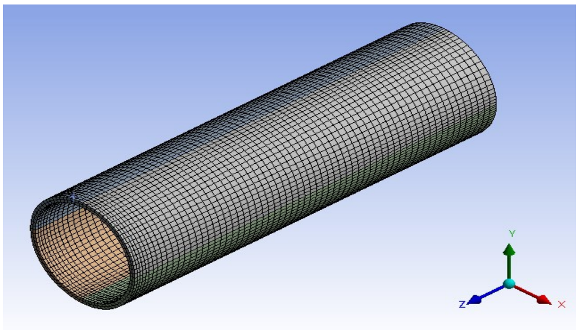

Fig.2. Mesh constructed by ANSYS for the circular tube.

C. Boundary Condition

Fig. 3 shows the restrictions on the symmetrical plane (central cross-section), constructed by ANSYS for a tube subjected to cyclic bending. Since the tubes were bent in the z-direction only, the frictionless roller support was fixed to the symmetrical plane and the displacement in the z-direction of this plane was set to zero.

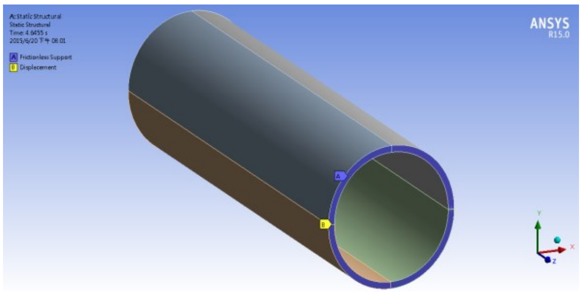

Fig.3. Boundary condition of a tube under pure bending constructed by ANSYS

D. Loading Condition

Fig. 4 shows the loading condition constructed by ANSYS on the basis of the tube bending device [1]. As the figure shows, the remote displacement of the solid rod in the z-direction was unrestricted, i.e., the rotation was free to move in the z-direction. In addition, the bending moment was applied only in the z-direction and hence, the rotations in the x- and y-directions were set to zero.

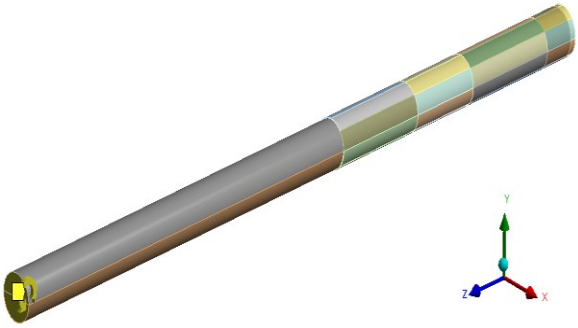

Fig. 4. Loading condition constructed by ANSYS.

Fig. 5 depicts a tube is subjected to pure bending. The rotating angle θ was employed as the input data for curvature-controlled cyclic bending. The curvature κ is

$$\kappa = 1/\rho = 2\theta/L_o \qquad (1)$$

where ρ is the radius of curvature and L_o is the original tube length.

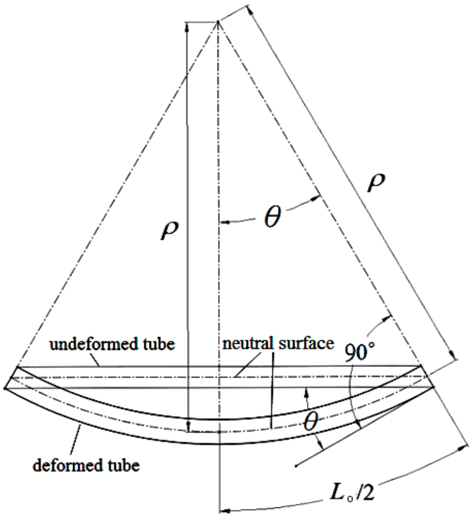

Fig.5. Relationship between rotating angle θ and curvature κ for a tube under pure bending.

III. COMPARISON OF EXPERIMENTAL AND ANSYS ANALYSIS RESULTS

A. Preloading Pure Bending Stage

Fig. 6 shows the experimental and ANSYS simulated moment (M) - curvature (κ) curves for SUS304 stainless steel circular tube subjected to pure bending. The controlled maximum value of curvature was +0.6 m^{-1}. It is observed that the M-κ curve exhibits linear in the elastic deformation stage and gradually becomes nonlinear in the plastic deformation stage. The M is around 224 N-m when the κ reaches +0.6 m^{-1}.

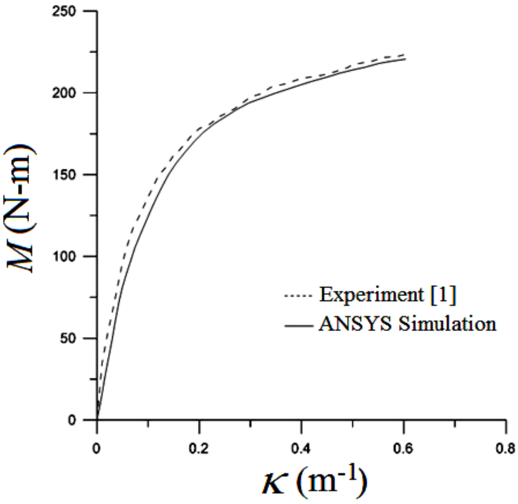

Fig.6. Experimental and ANSYS simulated moment (M) - curvature (κ) curves for SUS304 stainless steel tube subjected to pure bending.

Fig. 7 shows the experimental and ANSYS simulated ovalization ($\Delta D_o/D_o$) - curvature (κ) curve for SUS304 stainless steel tube subjected to pure bending. 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. The controlled maximum value of curvature was still +0.6 m^{-1}. It is seen that the ovalization increases in a nonlinear way along with the increase of curvature. The $\Delta D_o/D_o$ is around 0.022 when the κ reaches +0.6 m^{-1}.

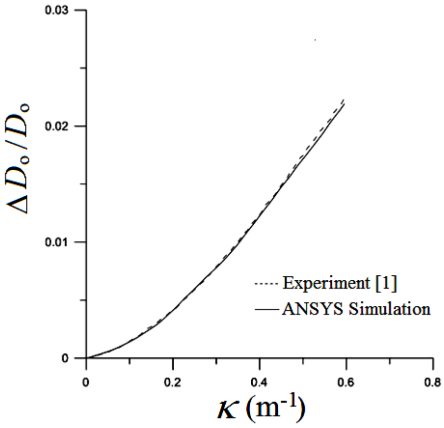

Fig.7. Experimental and ANSYS simulated ovalization ($\Delta D_o/D_o$) - curvature (κ) curves for SUS304 stainless steel circular tube subjected to pure bending.

B. Subsequent Pure Bending Creep Stage

Fig. 8 depicts the experimental and ANSYS simulated curvature (κ) - time (t) curves for SUS304 stainless steel circular tube subjected to the preloading pure bending and subsequent pure bending creep. The starting and buckling points of the pure bending creep stage are mark "$*$" and "x", respectively. The starting pure bending creep stage is at 170 N-m. It can be seen that as soon as the pure bending creep is started the magnitude of the curvature quickly increases. Owing to the continuously increasing curvature at the creep stage, the tube buckles eventually.

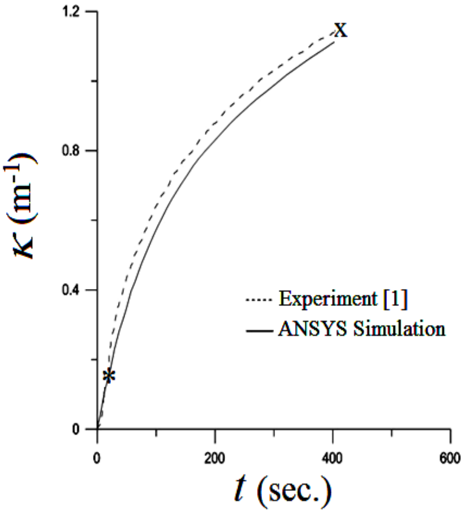

Fig.8. Experimental and ANSYS simulated curvature (κ) - time (t) curves for SUS304 stainless steel tube subjected to preloading pure bending and subsequent pure bending creep.

Fig. 9 shows the experimental and ANSYS simulated ovalization ($\Delta D_o/D_o$) - time (t) curves for SUS304 stainless steel circular tube subjected to the preloading pure bending and subsequent pure bending creep. The starting pure bending creep stage is still at 170 N-m. It can be seen that once the pure bending creep is started the magnitude of the ovalization quickly increases also. The tube buckles when the $\Delta D_o/D_o$ reaches 0.061.

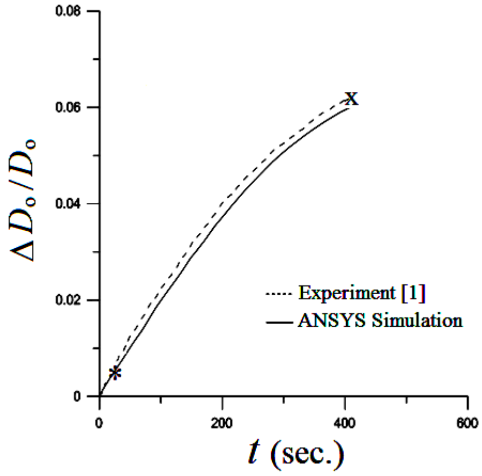

Fig.9. Experimental and ANSYS simulated ovalization ($\Delta D_o/D_o$) - time (t) curves for SUS304 stainless steel tube subjected to preloading pure bending and subsequent pure bending creep.

Fig. 10 depicts the moment (M) - time (t) curves for SUS304 stainless steel tube subjected to preloading pure bending and subsequent pure bending relaxation. The starting point of the pure bending relaxation stage is mark "∗". The starting pure bending relaxation stage is at 0.6 m^{-1}. It can be seen that as soon as the pure bending relaxation is started the magnitude of the moment (223 N-m) quickly decreases and approaches to a fixed amount (82 N-m).

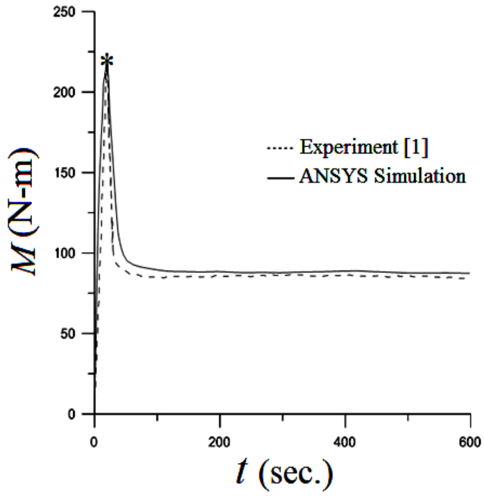

Fig.10. Experimental and ANSYS simulated Moment (M) - time (t) curves for SUS304 stainless steel tube subjected to preloading pure bending and subsequent pure bending relaxation.

Fig. 11 shows the experimental and ANSYS simulated ovalization ($\Delta D_o/D_o$) - time (t) curves for SUS304 stainless steel circular tube subjected to the preloading pure bending and subsequent pure bending relaxation. The starting pure bending relaxation stage is also at 0.6 m^{-1}. It can be seen that as soon as the pure bending relaxation is started the magnitude of the ovalization (0.022) quickly approaches to a fixed value (0.0235). Owing the constant ovalization, the tube doesn't buckle.

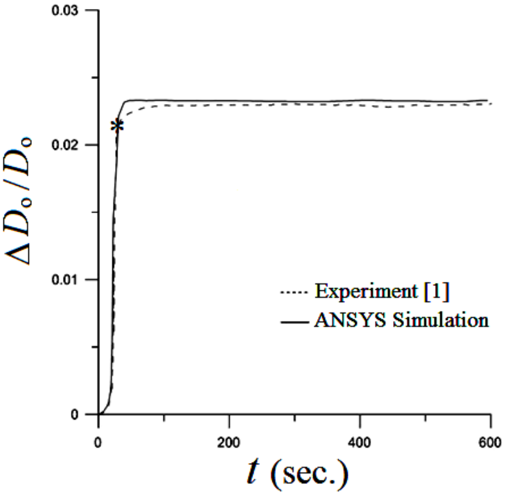

Fig.11. Experimental and ANSYS simulated ovalization ($\Delta D_o/D_o$) - time (t) curves for SUS304 stainless steel tube subjected to preloading pure bending and subsequent pure bending relaxation.

IV. CONCLUSIONS

In this study, by using adequate stress-strain relationship, mesh, boundary condition and loading condition, the finite element ANSYS was used to simulate the response of circular tubes subjected pure bending creep or pure bending relaxation. The experimental data of SUS304 stainless steel tubes tested by Pan *et al.* [1] were used for comparison with the ANSYS analysis. The experimental and ANSYS simulated results include the M-κ and $\Delta D_o/D_o$-κ relationships for preloading pure bending stage (Figs. 6-7), the κ-t and $\Delta D_o/D_o$-t relationships for preloading pure bending stage and subsequent pure bending creep stage (Figs. 8-9), and the M-t and $\Delta D_o/D_o$-t relationships for preloading pure bending stage and subsequent pure bending relaxation stage (Figs. 10-11). A good agreement between the experimental finding and the ANSYS analysis has been achieved.

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