An Experimental Study on the Effect of Curvature-Rate at Preloading Stage on Subsequent Creep or Relaxation of Thin-Walled Tubes under Pure Bending*

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Pure bending with a constant curvature-rate followed by creep (hold constant moment for a period of time) or relaxation (hold constant curvature for a period of time) tests were conducted to investigate the effect of prior curvature-rate at preloading stage on the subsequent creep or relaxation behavior. Thin-walled tubes of 304 stainless steel were used in this investigation. The curvature-ovalization measurement apparatus, designed by Pan et al.\(^1\), was used for conducting the present experiments. It has been found that the curvature-rate at the preloading stage has a strong influence on the subsequent creep or relaxation deformation under pure bending.

**Key Words**: Thin-Walled Tube, Pure Bending, Curvature-Rate, Creep, Relaxation

1. Introduction

Industrial thin-walled tubular components such as offshore pipelines, platforms in offshore deep water, nuclear reactors, etc., are generally subjected to bending loads. Most of the loads exceed the elastic limit that causes plastic deformation. Nonlinear moment-curvature curve and ovalization of tube cross-section (Brazier effect\(^2\)) can be observed. The magnitude of tube ovalization increases when the magnitude of the bending moment increases. Such increase in ovalization of tube cross-section causes a progressive reduction in its bending rigidity (accumulation of damage) which can ultimately result in buckling of the tube (Fabian\(^3\); Reddy\(^4\); Gellin\(^5\)). Therefore, the study of the response of thin-walled tubes subjected to bending is very important for many industrial applications.

In recent years, studies have been made on circular tubes subjected to monotonic or cyclic pure bending with or without external pressure. Kyriakides and Shaw investigated the response and stability of elastoplastic pipes under combined bending and external pressure\(^6\). After that, Shaw and Kyriakides extended the analysis of the inelastic tubes subjected to cyclic bending\(^7\); and investigated the response and stability of thin-walled tubes under cyclic bending\(^8\). Corona and Kyriakides investigated the stability of long metal tubes subjected to combined bending and external pressure\(^9\); as well as the degradation and buckling of circular tubes under cyclic bending and external pressure\(^10\). Kyriakides and Ju\(^11\),\(^12\) experimentally and theoretically studied the bifurcation and localization instabilities in circular cylindrical shells under pure bending; and Corona and Vaze\(^13\) experimentally investigated the response, buckling and collapse of long, thin-walled, seamless steel square tubes under pure bending.

In these studies\(^6\)\(^13\), a special calibration bending test for each material and each tube size used is performed first to obtain a correct value of the effective length which is needed for calculating the actual curvature of the tube for the subsequent cyclic bending. To avoid a protracted calibration for this value, Pan et al.\(^1\) designed a new curvature-ovalization measurement apparatus (COMA). This apparatus is a lightweight instrument which can be placed at the mid-span of the test specimen. It is suitable for measuring directly the tube curvature and ovalization of the tube cross-section. For testing the proposed
COMA, tube specimen of AISI 304 stainless steel was cyclically bent.

It has been known that engineering alloys, such as 304 and 316 stainless steel as well as high-strength titanium alloys, exhibit viscoplastic behavior. If the constant loading-rate (strain-rate or stress-rate) straining followed by creep or relaxation is considered, the strain or stress amplitude and the loading-rate are found to have strong influence on the subsequent creep or relaxation deformation. Kujawski and Krempel conducted an experiment of the relaxation deformation in 10 min. and subsequent reloading at various strain-rates on Ti-7Al-2Cb-1Ta titanium alloy. They discovered that the total stress drop and the relaxation rate were dependent on the strain-rate preceding the relaxation deformation. Xia and Ellyin conducted constant strain-rate plastic straining followed by creep tests to investigate the effect of prior plastic straining on the subsequent creep behavior of 304 stainless steel. They found that the plastic strain and plastic strain-rate had a strong influence on the subsequent creep deformation. Wu and He conducted the transient creep tests on 304 stainless steel with carefully monitored precreep loading stage, at either a prescribed constant strain-rate or a constant stress-rate. They discovered that the creep strain was strongly influenced by the stress-rate or strain-rate at the preloading stage. Therefore, if a thin-walled tube is bent by a constant loading-rate (curvature-rate or moment-rate) followed by creep (hold constant moment for a period of time) or relaxation (hold constant curvature for a period of time) deformation, the curvature or moment amplitude and the loading-rate should have strong influence on the subsequent creep or relaxation deformation. Based on this recognition, an experimental investigation on the effect of curvature-rate at preloading stage on creep and relaxation behaviors of thin-walled tubes under pure bending was carried out in this study.

In the present study, a four-point bending machine (similar to the facilities reported in previous studies) was used for conducting the pure bending tests. The material of the thin-walled tube chosen for this study was AISI 304 stainless steel. The curvature-ovalization measurement apparatus (COMA), designed by Pan et al., was used. Based on the capability of the bending machine, three curvature-rates, viz. $3 \times 10^{-2}$, $3 \times 10^{-3}$ and $3 \times 10^{-4} \text{m}^{-1} / \text{sec}$, were employed at the preloading stage of the tube. The subsequent creep and relaxation deformation were controlled by the load cell and the COMA, respectively. The magnitudes of curvature and ovalization of the tube cross-section were simultaneously measured by the COMA. The magnitude of the bending moment was obtained from the two load cells, mounted in the bending machine. It was observed from the experimental result that due to the hardening of the metal tube under higher curvature-rates, a larger magnitude of moment is required to bend the specimen at the preloading stage. However, the ovalization of tube cross-section increases when the applied curvature-rate increases. For the subsequent creep deformation, it is found that the creep curvature is larger with a higher constant curvature-rate at the preloading stage than that with a lower one. A similar result has been found in the tube ovalization curves. Furthermore, for the subsequent relaxation deformation, the moment curve decreases faster with a higher constant curvature-rate at the preloading stage than that with a lower one. Owing to the constant curvature in the subsequent relaxation test, the magnitude of the tube ovalization was kept at a constant for each constant curvature-rate at the preloading stage.

2. Experimental Facility

A bending test facility was developed and used to carry out a number of experiments on thin-walled tubes. The facility consists of a pure bending device and a curvature-ovalization measurement apparatus (COMA). Further description of the test facility is made in the following.

2.1 Bending device

Figure 1(a) shows a schematic drawing of the bending device, and Fig. 1(b) shows a picture of the bending device. It was designed as a four-point bending machine, capable of applying bending. Similar devices were reported by Kyriakides and coworkers. The device consists of two rotating sprockets, about 30 cm in diameter, symmetrically resting on two support beams of 1.25 m apart. The maximum length of the test specimen allowed is 1 m.
The sprockets support two rollers which apply point loads in the form of a couple at each end of the test specimen. Heavy chains run around these sprockets and are connected to two hydraulic cylinders and load cells forming a closed loop. Once either the top or bottom cylinder contracts, the sprockets rotates, and pure bending of the test specimen is achieved. 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 the two rollers. Detailed description of such a bending device can be found in literature.  

2. 2 Curvature-ovalization measurement apparatus (COMA)

The curvature-ovalization measurement apparatus (COMA), as shown in Fig. 2(a), is a lightweight instrument, mounted close to the tube's mid-span. A picture of the COMA used in this study is shown in Fig. 2(b). Using a magnetic detector (middle part of the COMA), it can monitor the changes in the major and minor diameters of the tube cross-section (the ovalization of tube cross-section). Simultaneously, it can measure variations in the tube curvature close to the mid-span from the signals of inclinometers. There are three inclinometers (side-inclinometer 1, side-inclinometer 2 and center-inclinometer) in this COMA (see Fig. 2(a)). Based on the fixed distance between the two side-inclinometers and the angle changes detected by the two side-inclinometers, the tube curvature can be obtained.

The angle of rotation detected by the center-inclinometer is in the plane, which is perpendicular to the plane of the bending moment. The center-inclinometer can be used for inspecting the deviation of the plane, in which the aforementioned two side-inclinometers are fixed, from the plane of the bending moment. Detail description of the COMA can be found in the work by Pan et al.  

3. Experimental Investigation

Experiments have been conducted to obtain data showing the dependence of creep curvature and relaxation moment upon the curvature-rate at the preloading stage. Specimens and the test procedures are given below:

3.1 Material and specimens

The material used in this study was AISI 304 stainless steel, with chemical composition: Cr 18.36, Ni 8.43, Mn 1.81, Si 0.39, C 0.05, P 0.28, S 0.004 and Fe remainder. To obtain the desired ratio of outer diameter D to wall thickness t(D/t), the tubes originally with D=31.8 mm and t=1.5 mm (D/t=21.2) were slightly machined on the outer surface. Figure 3 shows the dimensions of the test specimen. The outer diameter, wall thickness and gauge length are 30.33, 0.76 and 388 mm, respectively, i.e. D/t is approximately equal to 40.

3.2 Test procedures

The bending test was conducted by using the bending device described in Section 2.1. The magnitudes of the curvature and curvature-rate were controlled and measured by the COMA which also measured the ovalization of tube cross-section. The bending moment can be calculated from the signals detected by the two load cells, mounted in the bending device. Based on the capability of the bending
machine, three different curvature-rates, viz, $3 \times 10^{-1}$, $3 \times 10^{-2}$ and $3 \times 10^{-3} \text{m}^{-1}/\text{sec}$, were employed at the preloading stage.

In the subsequent creep test, the specimen was bent in the curvature-controlled mode (controlled by the COMA) at the preloading stage while the computer monitored the magnitude of the moment. As soon as the moment magnitude reached the preset creep holding moment, the loading process stopped. The test system was programmed to switch to the moment-controlled mode (controlled by the load cells) instantaneously and the moment was kept at this constant magnitude, while the creep curvature and ovalization were being recorded. In the subsequent relaxation test, the specimen was bent in the curvature-controlled mode at the preloading stage while the computer monitored the magnitude of the curvature. As soon as the curvature magnitude reached the preset relaxation holding curvature, the loading process stopped. The test system was programmed to keep the curvature at this constant magnitude, while the relaxation moment and ovalization were being recorded.

4. Results and Discussion

In this section, the experimental data of thin-walled tubes for AISI 304 stainless steel under different curvature-rates at preloading stage and subsequent creep or relaxation deformation are discussed. Note that creep deformation is to hold a constant moment for a period of time and relaxation deformation is to hold a constant curvature for a period of time.

4.1 Preloading stage

Figure 4 presents the moment ($M$)-curvature ($\kappa$) curves of the thin-walled tubular specimen under three different curvature-rates at preloading stage. It can be seen that the moment-curvature curves are sensitive to the magnitude of curvature-rate. The higher the applied curvature-rate, the greater the degree of hardening for tubular specimen is. Figure 5 shows the corresponding ovalization of tube cross-section as a function of the applied curvature. The ovalization of tube cross-section is defined by $\Delta D/\bar{D}$ where $D$ is the outer diameter and $\Delta D$ is the change in outer diameter. It can be noted that the ovalization of tube cross-section increases when the applied curvature increases. The higher degree of the ovalization of tube cross-section can be observed under higher curvature-rates.

4.2 Creep stage

Figure 6 depicts the curvature ($\kappa$)-time ($t$) profiles of the whole creep process under pure bending (the loading stage and the creep stage). The starting and buckling points of the creep stage are marked by "*" and "×", respectively. The profiles confirm the constant curvature-rate control of each curve prior to reaching the hold moment. Although the magnitude of the moment just prior to creep stage are almost the same (170 N·m), the creep curves for three curvature-rates at preloading stage are quite different. It could be seen that as soon as the creep is started the magnitude of the tube curvature quickly increases. The initial creep-rate of the creep test with fast curvature-rate preloading is large, and the corresponding creep curvature is larger than that of the creep test with a slower curvature-rate preloading.
Owing to the continuously increasing curvature at the creep stage, the tube specimen buckles eventually. Figure 7 demonstrates the ovalization-time profiles of the whole creep process under pure bending at same holding moment of 170 N·m (the loading stage and the creep stage). The starting and buckling points of the creep stage are also marked by "*" and "X", respectively. It is shown that the ovalization curves are also strongly influenced by the curvature-rate at the preloading stage and the ovalization of the tube cross-section increases faster with a higher constant curvature-rate preloading than that with a lower one.

4.3 Relaxation stage

Figure 8 depicts the moment-time profiles of the whole relaxation process under pure bending (the loading stage and the relaxation stage). The starting point of the relaxation stage is marked by "*". Owing to constant curvature-rate control at the preloading stage, the profiles are not straight lines prior to reaching the hold curvature. It could be seen...
that as soon as the relaxation is started the magnitude of the bending moment quickly relaxes. Although the magnitude of the curvature just prior to creep stage are almost the same (0.6 m⁻¹), the relaxation curves for three curvature-rates at preloading stage are quite different. The initial relaxation-rate of the relaxation test with fast curvature-rate preloading is large, and the corresponding relaxation moment is larger than that of the relaxation test with a slower curvature-rate preloading. Owing to constant curvature at the relaxation test, the ovalization of the tube cross-section vs. time curves for various constant curvature remains constant as shown in Fig. 9. The starting point of the relaxation stage is also marked by “*”.

5. Conclusions

The effect of curvature-rate at preloading stage on creep and relaxation behaviors for thin-walled tubes under pure bending is investigated in this study. A bending machine and a curvature-ovalization measurement apparatus (COMA) were used for conducting the present experimental tests on thin-walled tubular specimens of 304 stainless steel. The following important conclusions can be drawn from this investigation:

(1) The thin-walled tube hardens when curvature-rate increases. The higher the applied curvature-rate, the greater the degree of hardening of the tube is. The ovalization of tube cross-section increases when the curvature-rate increases. The higher the applied curvature-rate, the greater the degree of ovalization of tube cross-section is.

(2) For the subsequent creep stage, the creep curvature is larger with a higher constant curvature-rate at the preloading stage than that with a lower one. The creep ovalization of tube cross section increases faster with a higher constant curvature-rate at the preloading stage than that with a lower one.

(3) For the subsequent relaxation stage, the relaxation moment decreases faster with a higher constant curvature-rate at the preloading stage than that with a lower one. Owing to constant curvature in this stage, the ovalization of tube cross section remains constant for any constant curvature-rate preloading.

(4) It is shown that the creep or relaxation deformation of thin-walled tube subjected to pure bending is strongly influenced by the loading-rate at the preloading stage.

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