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On the response of dented stainless-steel pipes subject to cyclic bending moments and its prediction

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ABSTRACT

In this paper, the effect of initial dent depth on the response of pipes subjected to cyclic bending loads with relatively large magnitudes is investigated experimentally. The initiation and propagation of the resulting cracks in the damaged region of the pipe are found to cause fatigue failure, augmented by the progressive accumulation of the cross-section ovalization during the cyclic loading. The empirical formula proposed by Kyriakides and Shaw [1] is modified based on the experimental results, in order to predict the number of cycles causing the local instability of pipe's cross-section. Moreover, it is shown that the experimental curve of the ovalization and the number of cycles necessary to produce buckling can be divided into three stages: initial, secondary and tertiary stages. Finally, an empirical equation, similar to the Bailey–Norton creep relationship, is proposed for simulating the initial and secondary stages of the aforementioned curve. The results produced by the proposed empirical relationship are found to be in good agreement with the experimental data.

1. Introduction

Pipes are used in various industrial applications, such as nuclear reactors, offshore and onshore oil and gas transport systems, offshore platforms, and power plants heat-exchange systems. Pipes often experience cyclic bending loads. The ovalization of a pipe's cross-section (i.e., change in the outside diameter to the original outside diameter, $\frac{\Delta D_o}{D_o}$, after application of loading), could occur due to bending loads. Reversal (i.e., tension–compression) bending loading cycles and also any subsequent repeated bending cycles result in a gradual increase in the ovalization. The increase in ovalization would in turn degrade the bending rigidity of the pipe. Once a critical magnitude of ovalization is reached, the pipe would locally buckle. Therefore, understanding the variation in ovalization of pipes subjected to cyclic bending load is critical and of paramount in most industrial applications.

In searching for relevant literature, it was discovered that there are essentially two groups of researchers that have extensively studied the response of pipes to cyclic loading; nonetheless, the number of studies on this topic is relatively scarce.

The response of circular tubes under monotonic or cyclic bending (with or without external pressure) have been extensively investigated by Kyriakides and coworkers. For instance, Kyriakides and Shaw [2] studied the response and stability of elastoplastic pipes under combined bending and external pressure conditions. They reported the maximum moment capacity and curvature, as a function of the material parameters, geometric features, and applied external pressure. The inelastic behavior of circular tubes with respect to cyclic bending was studied by Shaw and Kyriakides [3]. They reported that reverse bending and any repeated cyclic bending would result in a gradual growth of ovalization of the cross-section. Further, they extended their analysis to characterize the stability of circular tubes under cyclic bending [1]. They observed that a tube would progressively ovalize to a critical value when subjected to a curvature-symmetrical loading, and would finally buckle. The critical ovalization value of a pipe was observed to be approximately equal to the value of ovalization corresponding to that observed just prior to the onset of buckling in the pipe under monotonic bending. Furthermore, Corona and Kyriakides [4] analyzed the stability of circular tubes under combined bending and external pressure. In their study, the curvature–pressure interaction collapse scenarios were generated for two different loading paths involving bending, followed by application of external pressure and subsequent bending. Also, the specimens' response was observed to be strongly affected by the loading path. Corona and Kyriakides [5] also investigated the degradation and buckling of circular tubes subjected to cyclic bending and external pressure. In their study, the effects of the cyclic bending and external pressure on the rate of accumulation of ovalization and the onset of instability were also investigated.

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Recently, experimental and theoretical studies have been carried out to analyze the response and stability of circular tubes under monotonic and cyclic bending. For instance, using the endochronic theory, Pan and Leu [6] investigated the collapse of thin-walled tubes subjected to bending. They compared their theoretical results with experimental data obtained through testing 6061-T6 aluminum and 1018 steel tubes under cyclic bending also tested by Kyriakides and Shaw [1]. The effects of the rate of curvature at the preloading stage on the subsequent creep (i.e. while pipes were subjected to a constant bending moment for a period of time) and curvature's relaxation were investigated by Pan and Fan [7]. They used thin-walled 304 stainless steel tubes, and found that under the application of pure bending, the curvature rate at the preloading stage strongly influences the subsequent creep or relaxation behavior. Further, the response and stability of 304 stainless steel tubes subjected to cyclic bending with different curvature rates was studied by Pan and Her [8]. They found that the degree of hardening of the metal tubes increased when the applied loading rate increased. Moreover, they observed that by increasing the applied curvature rate, the ovalization of cross-section increases accordingly.

The influence of diameter-to-thickness ratio $\frac{D_o}{t}$ on the response and stability of circular tubes subjected to cyclic bending was studied by Lee et al. [9]. By maintaining the inside diameter of their SUS 304 stainless steel tubes constant, they machined the outside surface of the tubes to obtain the required $\frac{D_o}{t}$ ratio, in order to highlight the influence of $\frac{D_o}{t}$ ratio on their pipes' response. Their work was therefore restricted to investigating varying $\frac{D_o}{t}$ ratios (i.e. 30, 40, 50, and 60) with a fixed inside diameter. They observed that the specimens with smaller outside diameters endured less number of cycles before the onset of buckling than those with larger outside diameters.

Another notable study is that conducted by Rhaman et al. [10] who investigated the experimental ratcheting responses of straight pipes subjected to cyclic bending and steady internal pressure. In their study, the response of the pipes was also simulated numerically using ANSYS finite element code, incorporating several well-known cyclic plasticity models. However, none of the models could simulate the simultaneous variations in the moment–rotation, diameter change ratcheting, and circumferential strain ratcheting responses accurately. They then incorporated more sophisticated cyclic plasticity models (i.e., the modified Chaboche, Ohno and Wang, Abdel Karim and Ohno, and modified Ohno–Wang models). Nonetheless, they discovered that even these sophisticated models could not produce results with acceptable accuracy. Vishnuvardhan et al. [11] conducted an experimental investigation on the fatigue ratcheting response of TP304 LN stainless steel straight pipes, subjected to a steady internal pressure and four point cyclic bending. The pipes were first filled with water and pressurized upto 35 MPa till the first through-thickness crack was observed. The pipes were subsequently subjected to various magnitudes of cyclic bending loads. The load, load-line displacement, and deflections at three locations along the pipe were continually monitored during each test; as well, the number of cycles corresponding to through-thickness crack/s and final failure of the component were recorded. Pipes' ratcheting response included local bulging (13–19% with respect to the original diameter along the gauge length portion), which caused thickness thinning of 8–16%, as well as ovalization of the pipe cross-section. While continuous ratcheting was observed on pipes' mid-section, no shakedown effect was evident during the experiments.

In another study, Zakavi and Nourbakhsh [12] investigated the ratcheting behavior of four pairs of stainless steel elbows using finite element method in which Armstrong and Frederick's nonlinear kinematic hardening model was considered. To calibrate the model and obtain the hardening coefficients, they conducted uniaxial plasticity test on several cylindrical bars until necking, under symmetric strain-controlled experiments with different strains. They compared their numerical results with the experimental ones reported by Yahiaoui et al. [13]. Their FE models included the same loading conditions tried experimentally (i.e., subjecting the elbows to two different steady internal pressures, followed by dynamic conditions that induced out-of-plane external moments at frequencies typical of seismic excitations). The ratcheting rate in their study was observed to depend significantly on the magnitude of the internal pressure, dynamic bending moment and the nonlinear kinematic hardening model's constant parameters. Although the strain ratcheting rates obtained by their FE model agreed well with experimental results, their FE model overestimated the other ratcheting results when compared to the experimental data.

According to the reported experimental studies, some engineering materials, such as 304 stainless steel, 316 stainless steel and high-strength titanium alloys are classified as rate dependent. As a result, the response and failure modes of tubes made of such materials would be different when subjected to cyclic bending at different curvature-rates. Pan and co-workers analyzed the influence of curvature-rate on the response and failure mode of tubes made of different alloys subjected to cycling flexural loading condition. In their studies, tubes made of 304 stainless steel (Pan and Her [8]), titanium alloy (Lee and Pan [14]) and 316L stainless steel (Chang et al. [15]) were considered. However, in all the cases, the considered tubes had a smooth surface. According to Lee [16], the failure modes of the tubes with smooth surfaces are different from those of the ones that host any surface defects.

Fatigue response of offshore pipelines hosting plain (smooth) dents under cyclic pressure has been investigated both experimentally and numerically by Fowler [17]. In that study, a longitudinal wedge shaped denting tool was used to create a dent on 12 in. diameter steel pipes, with dent depths ranging between 5% and 20% of pipes' diameter.

Recently, a multi-industry joint project used the existing experimental and numerical results to assess the effect of various defects (i.e. gouges, manufacturing or weld defects, and corrosion) on the structural integrity of pipelines [18–20].

As is evident, although several researchers have investigated the ultimate capacity, or the fatigue strength of healthy, defected and damaged pipelines, there is still a clear lack of studies on characterization of low cycle fatigue response of pipes under bending loads. The present study, therefore investigates the response of TP316L stainless steel pipes hosting a plain dent with dent ratios ranging from 10% to 20%, subjected to bending loads. The focus has been on the evaluation of the reduction of structural capacity in dented pipes under cyclic bending loads with the aim of estimating their remaining operating life and development of a criterion that identifies the onset of ovality in pipes. Detailed descriptions of the test procedures, set up, instrumentation, specimens and materials properties are described in the following sections.

2. Experimental set up and procedure

To carry the quasistatic cyclic bending tests on the dented pipes, the specimens were first dented using a 10 mm diameter spherical indenter. The pipes were subsequently subjected to symmetric tension–compression bending cycles under a displacement-controlled scheme until fatigue cracking was observed within the dented region. Each pipe was supported by a