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On the ratcheting response of circular steel pipes subject to cyclic inelastic bending: A closed-form analytical solution

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ABSTRACT

The current paper deals with the cyclic plastic response and strain ratcheting of circular steel tubes under repeated inelastic pure bending. A closed-form solution is proposed for the problem. The cyclic softening/hardening behaviour of the material is modelled using a combined bilinear kinematic/nonlinear isotropic hardening rule. The relative hardening modulus in each half-cycle is considered as an extra state variable to account for the non-fading memory characteristics of the material. The cycle by cycle growth (creep) in the ovalisation of the cross-section is modelled using a modified version of the Bailey–Norton creep law. The solution considers the material nonlinearity, the cyclic plasticity effects and the geometrical nonlinearity due to the ovalisation of the cross-section. The model predictions are examined against a number of available test data on the inelastic monotonic and cyclic bending of tubes and reasonable agreements are observed.

1. Introduction

Steel tubulars are frequently used in engineering applications, for instance in offshore platforms, offshore pipelines, heat exchangers, reactors' components, space frames, etc. Extreme events, such as earthquakes, collisions and other hostile conditions may produce inelastic bending and ovalisation in a steel tubular. Subsequent cycling causes extended and repeated excursions into the plastic range [1]. This could lead to a gradual growth of ovalisation and strains in the tube, in propagation of plastic strains, degradation and failure of the structure [2].

The cycle by cycle progressive increase in the plastic strains is called strain ratcheting or cyclic creep. The plastic strain continuously accumulates with an increasing number of loading cycles and may eventually cause failure [3]. The ratcheting response is significantly influenced by the stress history, which depends on the external loads, as well as the geometry [4]. Preventing ratcheting is very important in the design of components subject to cyclic loading in the inelastic domain.

The response of circular tubes to inelastic cyclic bending has already been addressed by a number of researchers. Shaw and Kyriakides [1] showed in their experiments that cyclic inelastic bending results in a gradual growth of ovalisation in the tube cross-section. Under a curvature-symmetrical cyclic bending the tube reportedly buckles, when the ovalisation growth in the tube comes close to the critical ovalisation under monotonic bending. Corona et al. [5] conducted inelastic cyclic bending tests on metallic tubes to investigate the progressive accumulation of ovalisation of the tube cross-section. The aim was to evaluate the effects of the cyclic bending history and the external pressure on the ovalisation rate and on the onset of instability. It was found that moment-controlled bending about a mean moment leads to ratcheting in curvature as well as in ovalisation. Similarities were observed between the response and onset of instability in the monotonic bending case and all cyclic bending cases. For a group of 20 tubes, instability was found to occur when the ovalisation of the cross-section reached a critical value. The critical value was almost independent of the bending history.

Using the endochronic theory, Pan et al. [6] proposed a theoretical model for the collapse of thin-walled tubes subjected to inelastic bending. The results were compared with experimental data obtained on metallic tubes under cyclic bending. Pan et al. [7] studied the effect of curvature rate on the response and stability of stainless steel tubes subjected to cyclic bending. Lee et al. [8], studied experimentally the influence of the diameter-to-thickness (D_o/t) ratio on the response and stability of circular tubes subjected to symmetrical cyclic bending. Raw 316L stainless steel circular tubes were slightly machined on the outside surface to obtain the desired D_o/t ratios. It was observed that at a certain amount of controlled curvature, specimens with smaller outside diameters have a few number of cycles to produce buckling as

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compared to those with larger outside diameters. An empirical relationship, proposed by Kyriakides and Shaw [9], was then modified to give a relationship between the controlled curvature and the number of cycles to failure for different D_o/t ratios.

Elchalakani et al. [10] reported experiments on cold-formed circular hollow section (CHS) beams to determine new section slenderness limits suitable for the design and construction of seismic resisting structural systems. The section slenderness ratios (D_o/t) were ranging from 13 to 39. Limit point moments in the cyclic tests were compared with those obtained in monotonic tests and also with design moments predictions from a number of steel specifications. The deformation ductility demand was determined and used to derive new fully ductile section slenderness limits suitable for seismic design.

Kyriakides et al. [11] studied experimentally the plastic bending of steel tubes with the diameter-to-thickness (D_o/t) ratio of 18.8 exhibiting Lüders bands. Elchalakani et al. [12] conducted variable amplitude cyclic pure bending tests to determine fully ductile section slenderness limits for cold-formed CHSs. Rahman et al. [13] experimentally examined the ratcheting responses of circular tubes under steady internal pressure and cyclic bending. The experiments were also numerically simulated using the ANSYS finite element code. They utilised different cyclic plasticity models and reported that none of the models could satisfactorily simulate the simultaneous variations in the moment–rotation, diameter change ratcheting, and circumferential strain ratcheting.

Chang et al. [14] conducted cyclic bending tests to investigate the degradation and buckling of circular tubes. The specimens' fabrication and testing were similar to those in Lee et al. [8]. Some modifications were made to the empirical formulation proposed by Lee et al. [8] to provide a better relationship between the curvature range and the number of cycles to failure. An empirical relationship, analogous to the Bailey–Norton creep formulation, was also suggested for the tube ovalisation against the number of cycles to failure. The proposed relationship was reportedly in good agreement with the experimental data.

Vishnuvardhan et al. [15] studied experimentally the fatigue ratcheting response of stainless steel tubes under steady internal pressure and pure cyclic bending. Jiao and Kyriakides [16] conducted a set of experiments on super-duplex tubes with D/t of 28.5. The tubes were first internally pressurised and then axially cycled under stress-controlled schemes about a compressive mean stress. Simultaneous ratcheting in the hoop and axial directions as well as a gradual growth of the wrinkles were observed. The rate of ratcheting and the number of cycles to failure reportedly depend on the initial compressive pre-strain, the internal pressure and the stress cycling parameters. Shariati et al. [17] investigated the softening and ratcheting behaviour of SS316L cantilevered cylindrical shells under cyclic bending. The effects of displacement amplitude, mean force, loading history and cut out position were studied.

Azadeh and Taheri [18] studied experimentally the response of dented stainless-steel tubes subject to cyclic bending moments. They modified the empirical formula proposed by Kyriakides and Shaw [9] in order to predict the tolerated number of cycles in damaged tubes. Based on modified Bailey–Norton creep relationship they also provided predictions for the initial and secondary stages in the "ovalisation-curvature" curve.

A number of constitutive models were already employed to simulate the ratcheting response. With the so called coupled models [19], the plastic modulus calculation was coupled with a kinematic hardening rule through the yield surface consistency condition [20]. Lourenço and Netto [20] used three coupled models proposed by Armstrong and Frederick [21], Chaboche [22] and Bari and Hassan [19] to simulate the strain ratcheting of corroded pipes under typical operational load conditions.

It should be noted that the ratcheting of pipes under cyclic pure bending varies from that under cyclic bending involving shear and internal pressure. In spite of this, the behaviour of circular steel pipes under pure bending, in the absence of internal pressure, remains still an ongoing active research topic (see as examples [14,18,23–34]). This is partly because the application of circular hollow sections (CHS) is not in practice strictly limited to pipelines. Steel CHSs are used extensively in the field of the mechanical and construction engineering.[35] Sample applications include tubular buildings [36] which are required to survive earthquakes; offshore structures in extreme weather conditions; nuclear reactor components in off-design conditions [11], offshore cranes, wind turbine towers [31], monopole structures, floating offshore wind farms [37], space frames, lattice towers, high rise buildings, industrial structures, piles, bridge piers [38], modern bridges [39], aerospace, shipbuilding and automotive industries [40], etc. Offshore pipelines themselves do experience inelastic bending without internal pressure during their lay down. The CHS elements in many of aforementioned structures need to withstand inelastic monotonic and cyclic bending in the absence of the internal pressure.

Moreover, ratcheting is a very complex and nonlinear phenomena. Even advanced finite element analysis with the state-of-the-art constitutive models fall short to consistently simulate the ratcheting response of the tubes even under simple pure bending or uniaxial stressing, both at the structural (ΔD or wrinkling) and material (strain) levels. Rahman et al. [13] utilised a number of cyclic plasticity models to numerically simulate the ratcheting response of the steel tubes under cyclic bending. They reported that none of the models could satisfactorily simulate the simultaneous variations in the moment–rotation, the ΔD ratcheting, and circumferential strain ratcheting. They concluded that, despite the considerable advancements in cyclic plasticity modelling, they still are not robust enough to simulate structural responses when model parameters are determined from material responses only. For this reason, there exists still a demand for reliable numerical/analytical solutions even for the baseline ratcheting problems under cyclic bending or uniaxial loading.

On the other hand, a number of previous studies tried to tackle the problem of ratcheting in circular tubes by decoupling the actual loads to a number of independent components (e.g. pure bending) to get a better insight to the phenomenon. This seems to be another motivation for the ongoing researches on the ratcheting of circular steel pipes under pure bending.

The current study incorporates and modifies a number of existing analytical frameworks and concepts and successfully provides a consistent model for the monotonic and cyclic responses of the steel tubulars both at the structural (ΔD) and material (strain) levels. The analytical formulation incorporates a bilinear kinematic hardening model and a nonlinear isotropic hardening model. In addition, modified Bailey–Norton creep equation is used in the formulation. Based on the experimental data from other researchers, a novel semi-empirical formulation is proposed which can trace the ovalisation-curvature path under cyclic bending. The idea of using the relative hardening modulus as a state variable to account for the non-fading memory characteristics of the material in the ratcheting response of the steel tubes is also new and has significantly improved the model predictions. The predictions from the current analytical formulation, despite its relative simplicity, are interestingly comparable with the experimental data for the ratcheting response of circular steel pipes under pure bending.

The introduction of the paper is followed by Section 2 which deals with the monotonic inelastic bending of circular steel tubes. Basic assumptions are presented. The governing equation for the elasto-plastic "moment–curvature" of the tube under monotonic