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A closed-form analytical solution for the ratcheting response of steel tubes with wall-thinning under inelastic symmetric constant amplitude cyclic bending

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ABSTRACT

Metallic tubes experiences a progressive accumulation of ovalisation, or ratchet, under cyclic inelastic bending. During their life time, the tubes may also suffer from different types of mechanically and/or chemically originated defects. The current paper discusses a closed-form solution for the response analysis of defective circular steel tubes under monotonic and cyclic inelastic bending. The defect in the tube is idealised as a uniform patch type wall thinning.

The material model considers the cyclic hardening/softening features based on a combined non-linear hardening law. To account for the non-fading memory characteristics of the steel material, the hardening modulus in each half-cycle is introduced as a state variable. A modified version of the Bailey–Norton law is used for the cyclic growth (cyclic creep) in the ovalisation of the cross-section. In overall, the solution considers the geometrical non-linearity due to the ovalisation as well as the hysteresis effects.

The study also includes monotonic and cyclic inelastic bending experiments on small-scale, thick-walled, high strength, low alloy carbon steel defective tubes. The analytical solutions for the inelastic monotonic and cyclic bending of the tubes are validated against these experimental data and reasonable agreements are noticed and reported.

1. Introduction

Steel tubulars have widespread engineering applications, for instance in offshore pipelines, offshore platforms, heat exchangers, pressure vessels, reactors, space frames, etc. Extreme loads, such as earthquakes, collisions, high temperature, high pressures and flow induced vibrations may generate inelastic bending in a steel tubular. Subsequent cycling causes extended and repeated excursions into the plastic range [1]. This could lead to gradual growth of ovalisation, accumulation of plastic strains and structural degradation [2–4].

During their life time, steel tubes may also experience different types of mechanically and/or chemically originated defects. For example the material loss caused by corrosive fluid inside an offshore steel pipeline and by the surrounding seawater can lead to corrosion and wall thinning with variable size and depth in the inner and/or the outer surface of the pipeline. These defects in combination with structural overloads may elicit detrimental effects on the strength, serviceability and mechanical integrity of the pipeline.

The cycle by cycle progressive accumulation of the plastic strains in a structural component is called strain ratcheting and may eventually cause failure [5]. Ratcheting is significantly influenced by the stress history, which depends on the external loads, as well as the geometry of the structure. Preventing ratcheting is very important in the design of components subjected to cyclic loading in the inelastic domain [6–8].

Strain ratcheting in perfect metallic circular tubes under inelastic cyclic bending has already been experimentally studied by a number of researchers [1,4,9–19]. Inelastic cyclic response and strain ratcheting of defective steel tubes have been the subject of several recent studies. Miyazaki et al. [20] investigated the fracture strength and behaviour of carbon steel pipes (grade 100A) with local wall thinning under cyclic pure bending. Shariati and Hatami [21] experimentally studied SS304L cylindrical shells with cut-outs under uniaxial cycling. Zeinoddini et. al [22] and Zeinoddini and Peykanu [2] experimentally and numerically modelled the ratcheting behaviour of *X*52 steel tubes with rectangular defects under inelastic uniaxial cycling. Ratcheting behaviour of corroded pipes under cyclic bending and internal pressure was investigated

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Nomenclature

A	area
a, a_o, a_c	semi-empirical coefficient of ovalization
a_{el}	$= (1-\nu^2)^2/16$
$2a$	extrados ellipse larger diameter
$2a'$	intrados ellipse larger diameter
$2b$	extrados ellipse smaller diameter
$2b'$	intrados ellipse smaller diameter
b	isotropic hardening parameters
C	non-dimensional coefficient
d	defect depth
D	nominal diameter
D_o	outer diameter
E_T	hardening modulus of the material
E	modulus of elasticity
e	monotonic strain
$\bar{e}$	normalised monotonic strain
e_{pr}	monotonic proportional limits of the strain
$\bar{e}_1$	normalised strain at the outermost fibres in defected area
e_o	maximum strain at $k = 0$
G_k	relative hardening modulus in kth half-cycle
G_T	relative hardening modulus of the material
k	number half-cycle
m, n	material constants
M	bending moment
$\overline{M}$	normalised moment
M_{pr}	elastic moment
M_o	$= \sigma_o D_o^2 t$
p, p_1	geometrical ratios defind in Eq. (9)
p_k	accumulated plastic strain
p_o	width of the stress-strain loop in $k = 0$
q, q_1	geometrical ratios defind in Eq. (9)
Q	isotropic hardening parameters
R	initial section external radius
R'	initial section internal radius
R_k	isotropic variable
$\bar{S}_k$	normalised cyclic stress in kth half-cycle
S_k	cyclic stress in kth half-cycle
$S_{pr,k}$	stress proportional limit in kth half-cycle
$\bar{S}_{pr,k}$	normalised stress proportional limit in kth half-cycle
t	wall thickness
$\bar{t}$	Newtonian time
x, y	coordinate components
α	geometrical ratio defind in Eq. (9)
β	$= R'/R$
$\Delta D/D_o$	ovalisation ratio
Δ	neutral axis normalised eccentricity
δ_k	accumulated residual ovalisation at half-cycle k
η	normalised coordinate component
ε_k	cyclic strain in kth half-cycle
$\bar{\varepsilon}_k$	normalised cyclic strain in kth half-cycle
ε_c	creep strain
φ	angle of defect
γ, γ_o, γ_c	semi-empirical coefficient of ovalization
κ	curvature
κ_c	cycling extreme curvature
κ_o	$= t/D_o^2$
ζ	kinematic hardening constant
λ_k	cyclic hardening at an infinitesimal strip in the half-cycle k
ν	poisson's ratio
ρ	curvature radius
σ	monotonic stress
$\bar{\sigma}$	normalised monotonic stress
σ_{pr}	monotonic proportional limits of the stress
σ_o	maximum stress at $k = 0$
$\bar{\Theta}$	relative angle of cross-section's rotation

by Lourenco and Netto [23]. The corrosion was modelled by machining elliptical defects with differing depths. They reported that under some load combinations, the intact areas remained elastic but the defective region showed strain ratcheting. Zeinoddini et al. [5,24] studied effects of denting on the uniaxial monotonic and cyclic behaviour of X80 steel pipes. Azadeh and Taheri [8] experimentally studied the response of dented stainless-steel tubes under cyclic bending moments. An empirical expression proposed by Kyriakides and Shaw [9] was reformulated and used in order to estimate the number of cycles to failure in the damaged tubes. Based on a modified Bailey–Norton creep relationship they also provided predictions for the initial and secondary paths in the "ovalisation-curvature" curve.

Chen et al. [25] studied the ratcheting deformation of pressurised Z2CND18. 12 N stainless steel 90° elbow pipes with local wall thinning subjected to constant internal pressure and reversed bending using finite element analysis. Talebi, et al. [26] reported inelastic uniaxial cyclic creep and incremental collapse experiments on API X80 steel pipes with corrosion exposure. Kiran et al. [27] carried out experimental and numerical studies on inelastic behaviour of thin walled elbows and tee joints under incremental seismic loads, with an emphasis on fatigue-ratcheting.

The current paper offers a closed-form analytical solution for the ratcheting response of defective steel tubes under inelastic cyclic bending. The defect in the tube is idealised as a patch type uniform wall thinning. The current study can be regarded as continuation of a previous work [28] which provided analytical solutions for the ratcheting response of the perfect steel circular pipes subjected to cyclic inelastic bending. It tries to expand the previous solution to defective steel tubes. The paper also includes the results of an experimental study on the monotonic and inelastic cycling of steel tubes with wall thinning. The experimental data were used for the validation of the analytical model.

The paper is organised as follows. Section 2 briefly describes the test setup and the specimens' geometry and fabrication. In Section 3 the governing equations for the elasto-plastic "moment-curvature" of the defective tubes under monotonic pure bending are presented and validated against the experimental data. Section 4 deals with the cyclic inelastic bending of circular defective steel tubes. The solution obtained in Section 3 is utilised to derive the tube response in individual half-cycles of the cyclic loading. Taking into account the material hysteresis behaviour and the geometrical non-linearity due to changes in the shape of the cross-section, the governing equations for the cyclic inelastic bending of circular steel tubes are obtained. The solution is then examined against test data on the inelastic cyclic bending of defective tubes and reasonable agreements are observed.

2. Experimental study

Inelastic monotonic and cyclic bending tests were carried out on a number of defective steel tubes. The experimental results are used for validation of the analytical model proposed in the current study. The materials, specimens' geometry, experimental setup and procedures are described here.

2.1. Materials

The tubular specimens were made of high strength low alloy X80 carbon steels [29]. The elemental chemical composition of the steel materials (in wt%) was determined by glow discharge spectroscopy and