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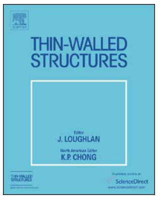

Full length article

Axial and hoop ratcheting assessment in pressurized steel elbow pipes subjected to bending cycles

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ABSTRACT

The present study evaluates ratcheting response of pressurized elbow pipes made of three steel alloys of austenitic stainless steel, 1020 steel, and 304L stainless steel subjected to external bending under load-controlled conditions by means of the Ahmadzadeh-Varvani (A-V) hardening rule. The model enabled ratcheting assessment of elbows in different directions mainly due to parameters implemented in the dynamic recovery term. The internal variable $\bar{b}$ in the model calibrated the backstress evolution over stress cycles and along with Macaulay functions controlled non-proportionality, directionality, and plastic shakedown over ratcheting progress in elbow pipes. A finite element model was employed to evaluate stress components at various positions on the elbow midsection. Experimental ratcheting data measured by strain gauges at different elbow positions of crown, intrados, and extrados closely agreed with those of ratcheting strains predicted based on the A-V model.

1. Introduction

For a reliable design of load-bearing components and structures, service loads, elastic-plastic deformation, materials characterization, and geometric complexities are critically assessed. Of examples of complex loading conditions are those pressurized pipes and vessels subjected to internal pressure and external bending loads [1–4] leading to damage accumulation and failure over loading cycles. Asymmetric stressing beyond yield stress accumulates plastic strain over cycles referred as materials ratcheting. The complexity of geometry and loading in structures sophisticates ratcheting assessment as stress distribution varies over elements of structures in-service. The evidence of ratcheting in materials has been first reported over a century ago when Bairstow [5] tested iron and steel samples and recorded the progressive hysteresis loops over stress cycles. Among earliest classical ratcheting investigations on pipes subjected to internal pressure and repeated external stresses were those reported by Weill and Rapasky [6], Miller [7], and Sah et al. [8]. They related ratcheting through microscopic observation to dynamic recrystallization, a mechanistic limitation to time dependent deformation as cyclic stress level increased. A simplified ratcheting map was developed by Bree [9] on the basis of inelastic analysis of a pressurized thin-walled tube under thermal cyclic gradient through the wall thickness. Bree's attempt was to demark the boundaries between progressive damage and no-damage zone where the hysteresis loops fully reversed within elastic zone. These boundaries set the transition of the load combinations between shakedown and ratcheting. Ratcheting boundary proposed by Bree further contributed to construct ASME code in pressure vessels and pipelines [10] for practical design purposes. Yamamoto and coworkers [11] employed a procedure to assess ratcheting boundary developed in Japanese committee for 3D elastic-plastic finite element analysis in which elastic-perfectly plastic model was used. In another effort [12] ratcheting shakedown and boundaries of 3D structures were evaluated through FE method and elastic-plastic analysis while components undergoing varying plastic strain amplitudes. Moreton et al. [13] and Gao et al. [14] interpreted the ratcheting boundaries using measured ratcheting strains. The intercept of the straight line from ratcheting data with the corresponding bending load at zero ratcheting rate in Moreton and Gao experiments were taken as points to construct the ratchetting boundary. The lower bound formulation in shakedown on the basis of Melan's theorem [15] was further developed by Adibi-Asl and Reinhardt [16,17]. Their proposed method determined shakedown-ratcheting boundary without employing cyclic history. For ratcheting evaluation of structures at high temperature, British Energy Generation Ltd has implemented integrity assessment procedure referred as R5 [18]. This procedure offered a simplified solution to determine shakedown on the basis of elastic materials response. To improve conservative results through R5 procedure, the Linear Matching Method (LMM) was developed to evaluate the plastic deformation and creep response of machinery parts based on linear solutions along with FE analysis [19].

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Nomenclature

$\bar{a}$	Backstress
$\bar{b}$	Internal variable
$d\bar{a}$	Increment of backstress
dp	Accumulated plastic strain increment
$d\bar{\varepsilon}^p$	Plastic strain increment
E	Modulus of elasticity
f	Yield surface function
H_p	Plastic modulus function
$\bar{n}$	Unit exterior normal to the yield surface
γ_1, γ_2, δ	Materials constants
ν	Poisson's ratio
$\langle\rangle$	Macualay brackets
σ_0	Size of yield surface
m	Materials constant
d_0, L	External radius and pipe straight length
R	Bending radius

The applicability of these approaches in assessing ratcheting and shakedown is highly affected by such parameters as loading type and distribution, structural geometry, complexity of procedure and analysis. While ratcheting simulation of pressurized mild steel elbows subjected to external bending was studied earlier [20] and authors reported some promising results, a hardening rule to comprehensively identify parameters affecting ratcheting of elbow pipes at various directions and positions is yet to exist.

Internal pressure in elbows with double curve configurations induces rather more damage and failure in piping systems subjected to external loads in their services as compared to pipes with straight geometries. This makes elbows more prone to damage and ratcheting deformation as load-bearing structural parts used in power plants, gas and petroleum, pressure vessels and boiler industries and particularly when ratcheting is coupled with fatigue cycles under complex repeated loads. Different positions on the elbow section correspond to different accumulated plastic strain over stress cycles resulting in the elbow to ovalize at which crown and intrados positions always show the highest ratcheting as compared with extrados position on the elbow [21–26].

The stress distribution over three-dimensional configuration of elbow, the influence of internal pressure, and the applied external loads challenges the ratcheting assessment at various positions on the elbow pipe section. The current study intends to assess ratcheting of pressurized elbows subjected to external bending loads at different positions of crown, intrados, and extrados on the elbow circumference. Ratcheting strain data over loading cycles along axial and hoop axes are evaluated by means of a newly developed kinematic hardening rule of Ahmadzadeh-Varvani (A-V) [27–32] for three different steels alloys. The A-V model enables to assess ratcheting along both axial and hoop directions through its dynamic recovery parameters. Furthermore, the internal variable in the model controls ratcheting direction and backstress evolution as stress cycles progress. Both predicted and experimental ratcheting strains over stress cycles in steel elbows were found in close agreements at different elbow circumferential positions.

2. Stress components on midsection of elbow and the hardening rule formulation

2.1. Stress components in the midsection of elbow pipe through FE analysis

Stress components at mid-section of an elbow pipe where intrados, extrados, and crown positioned are subjected to steady internal pressure P and external bending cycles and are calculated through an elastic-plastic finite element model by means of ANSYS 17.1 [33]. Fig. 1 presents the schematic of the elbow pipe and the finite element model. Internal pressure was applied to the elbow inner surface and the reversed bending load in z-direction was impressed at the central point of the pipe end. The second degree brick-shaped element SOLID185 with eight nodes was chosen. For symmetric geometry of pipe, one quarter of the pipe was modeled. Mesh analysis was carried out on the pipe while the free end of the pipe was kept the plane section during loading and a uniform axial thrust was applied to the end of the pipe for a closed-end boundary condition. A refined mesh was used on the pipe midsection.

Terms d_0, R, L, and F respectively correspond to external radius, bending radius, pipe straight length, and force applied to ends of the elbow pipe presented in Fig. 1. Angle θ in this figure varies for different positions of extrados, intrados, and crown. Axial, hoop, and shear stresses are calculated through elastic-plastic FE analysis for pressurized elbow pipes in this study and are listed in Table 1. These values were employed to assess ratcheting at different circumferential positions on the elbow pipes.

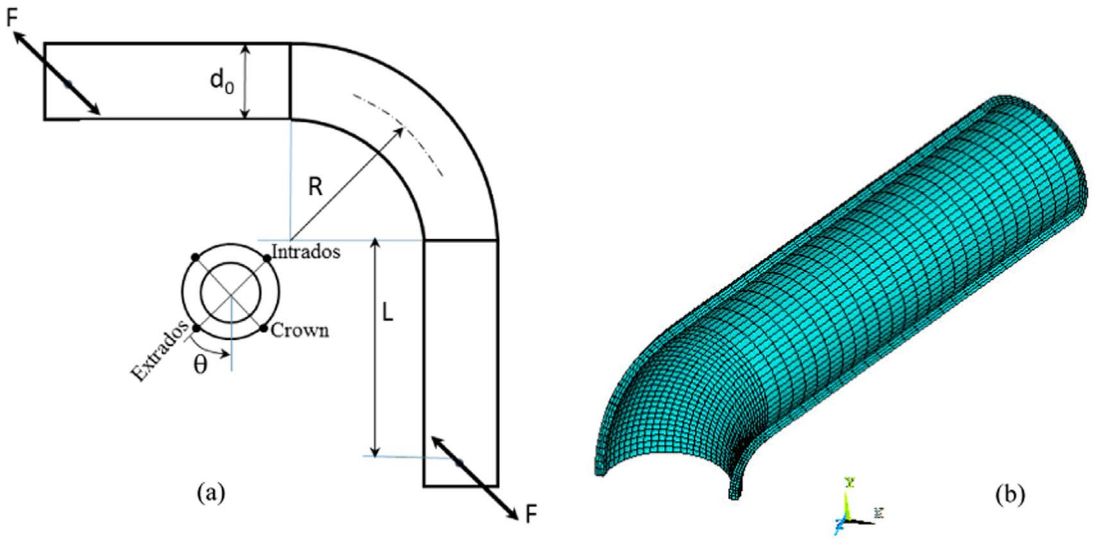

Fig. 1. (a) Elbow pipe: geometry and positions, and (b) finite element model.