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Buckle Propagation and Fracture in Pipelines

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ABSTRACT

The objective of this paper is to derive analytical solutions for buckle propagation and fracture of a pipeline subjected to hydrostatic pressure. Rigid-plastic approximations are used to determine the plastic deformation of the pipeline. Because the transition zone of buckle propagation occurs over a finite region, the plastic collapse of a pipeline of finite length is first considered. The deformation model for the finite-length pipe is then extended to buckle propagation in pipelines of infinite length. Closed-form solutions for the steady-state buckle propagation pressure are derived by considering plastic work dissipation due to both circumferential bending and longitudinal stretching. Analytical predictions of the propagation pressure are within 5% of the experimental data on mild steel pipes. The present model is an improvement over previous analytical solutions, in which the longitudinal stretching resistance of the pipeline was ignored. It has been found that the plastic work due to longitudinal stretching accounts for 20% to 30% of the propagation pressure in the pipelines considered in this study. Finally, approximations of the maximum strains are made from the assumed deformation field. Fracture criteria based on the uniaxial rupture strain or the combinations of biaxial rupture strains are suggested to predict cracks in the pipe.

NOTATION

D : pipeline diameter
E : Young's modulus
h : pipeline thickness
L : pipeline half-length
M : bending moment per unit length
M_o : $\sigma_o H^2/4$, fully plastic bending moment per unit length
N : membrane force per unit length
N_o : $\sigma_o H$, fully plastic membrane force per unit length
p_c : elastic buckling pressure
p_o : hydrostatic pressure
p_p : propagation pressure
R : pipeline radius
u : axial deformation
v : circumferential deformation
w : radial deformation
$\dot{W}_{ext}$: external work rate
x : longitudinal coordinate
z : through-thickness coordinate
β, ϕ : hinge angles
γ : rotation of collapsing quadrant
$\dot{\Gamma}$: rate of plastic work dissipation
$\dot{\Gamma}_b$: plastic bending work rate
$\dot{\Gamma}_{br}$: plastic bending work rate per unit length
$\dot{\Gamma}_m$: plastic membrane work rate
δ : midline deflection, i.e., $\omega(x = 0, \theta = 0)$
ΔA : change in cross-sectional area
ε : strain
ε_{ij}^o : middle surface strain
ε_{ij}^m : maximum strain '#ÜX9J
θ : circumferential coordinate
κ : curvature
ν : Poisson's ratio
ξ : length of transition zone (propagating buckled region)
ρ : radius of curvature of transition zone
σ_o : flow stress
ω : deformation
ω_o : centerline deflection, i.e., $\theta = 0$
$\omega_{\pi/2}$: outer lobe deflection, i.e., $\theta = \pi/2$
$(\dot{\ })$: $\dfrac{\partial}{\partial t}$

INTRODUCTION

When damaged locally by dropped anchors and other offshore drilling equipment, a pipeline may experience buckle propagation at hydrostatic pressures that are lower than the elastic buckling pressure for a perfect cylinder. As the pipeline buckles into a circumferential dog-bone pattern, it undergoes large plastic deformation. Plastic strains at the outer lobes of the buckled pipeline may be very high, exceeding the fracture strain, and result in cracks or leaks in the pipeline. Pipeline rupture due to a propagating buckle is referred to as a wet buckle (Kyriakides and Babcock, 1980).

Because the cleaning and repairing processes after wet buckling are costly and time-consuming, several steps have been taken to design pipelines against propagating and wet buckles. For instance, buckle arresters reduce the extent of pipeline damage by propagating buckles. Furthermore, underwater pipelines are manufactured seamless in order to avoid fracture at longitudinal welds where the fracture resistance may be lower than the base metal. However, thicker and larger-diameter pipelines are needed for drilling at greater depths, i.e., beyond 3,000 ft. It is difficult and costly to manufacture large-diameter, seamless pipelines and most will be made with longitudinal welds. Deep-water, welded pipelines will therefore be susceptible to fracture at longitudinal welds, should buckle propagation occur.

The problem considered in this paper concerns pipeline buckle propagation and fracture. Although buckle propagation has been studied extensively, analytical predictions of the propagation pressure (Palmer and Martin, 1975; Chater and Hutchinson, 1983; Kyriakides et al., 1984; Croll, 1985; Wierzbicki and Bhat, 1986) have consistently underpredicted experimental results. Kamalarasa and Calladine (1988) attributed the difference

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KEY WORDS: Rigid-plastic, pipeline, buckle propagation, fracture.