Plastic Failure of Pipelines

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ABSTRACT

The objective of this paper is to derive analytical solutions for the indentation, buckle propagation, and fracture of a plastically deforming pipeline. Rigid-plastic approximations are used to find the plastic deformation of a collapsed pipeline. Circumferential bending and longitudinal stretching are the only two dominant load resisting mechanisms considered in evaluating the rate of plastic work dissipation. The load-deformation response of the pipeline is characterized by a bending term which is independent of the deformation and a membrane term which increases linearly with pipeline deformation. It is shown that very long pipelines are susceptible to buckling, while longitudinal stretching resistance stabilizes plastic collapse in short pipelines. A closed-form solution for the steady-state buckle propagation pressure of an infinitely long pipeline is derived from this model. Analytical predictions of the propagation pressure are within 5% of the experimental data. The plastic work due to longitudinal stretching accounts for 20-30% of the propagation pressure, and the present model is an improvement of previous approximations which ignored longitudinal stretching. Finally, approximations of the maximum strains are made from the deformation field and a fracture criterion based on a critical rupture strain is used to predict fracture of a steel pipeline.

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

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 cylinder. As the pipeline buckles into a circumferential "dogbone" 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 a crack or leak in the pipeline. Pipeline rupture due to a propagating buckle is often referred to as "wet buckle" (Kyriakides and Babcock, 1980).

The cleaning and repairing processes after wet buckling are costly and time-consuming, and 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 is usually lower than the base metal. However, thicker and larger pipelines are needed for drilling oil at greater depths, i.e., beyond 3,000 ft. These large pipelines can no longer be manufactured seamless and have to be made with longitudinal welds. Very deep water pipelines will therefore be susceptible to fracture at the longitudinal welds should buckle propagation occur.

The problem considered in this paper is concerned with pipeline indentation, buckle propagation and fracture. We first consider the plastic deformation of a fixed-end pipeline of finite length when it is subjected to hydrostatic pressure. This solution will provide a theoretical foundation for carefully-controlled experiments to determine fully-plastic fracture criteria of the pipeline. The rigid-plastic model is then extended to a pipeline of infinite length. A closed-form solution for the steady-state buckle propagation pressure is derived. Unlike previous solutions for the propagation pressure, the plastic work due to longitudinal stretching as the buckle propagates down the pipeline is considered. Finally, the rigid-plastic structural model is combined with fully plastic fracture mechanics to determine plastic fracture in a collapsing pipeline. Conventional fracture mechanics criteria, which are based on linear or non-linear elastic material response, cannot be used to predict crack initiation and growth in a deforming pipeline that is experiencing large-scale plasticity. An alternative fracture criterion based on a critical strain or combination of bi-axial strains is used for predicting fracture.