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Numerical investigation of ductile tearing in surface cracked pipes using line-springs

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Abstract

Accurate prediction of crack-driving force equations is important in any pipeline fracture assessment program. In highly ductile materials, such as pipeline steel, a considerable amount of stable crack growth can be tolerated before the failure of the structure. The existing methods use simplified analytical procedures to account for ductile tearing, and they often result in conservative critical crack sizes. Further, none of the published numerical tools for modelling crack growth is suitable for engineering applications. This work describes a simple method for simulating through-thickness ductile tearing in surface cracked pipes, using line-spring finite elements. The crack growth resistance curve is used to advance the crack front. The line-spring results are verified using crack growth simulations employing the Gurson damage model. Finally, a detailed parametric study is carried out to examine the effect of ductile tearing on crack driving force relationships in circumferentially surface cracked pipes. The results demonstrate that considering ductile tearing is important in fracture assessment procedures for pipelines.

Keywords: Ductile crack growth; Surface cracked pipes; Line-spring method; Structural integrity

1. Introduction

Surface flaws such as welding defects, cracks and damage due to corrosion, etc., are common in girth welded offshore pipelines. For highly ductile materials such as pipeline steels, considerable amount of crack

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growth can be tolerated before the catastrophic failure of the structure. The present methodologies (for example BS7910:1999) for fracture assessment of pipelines employ simplified analytical procedures to include ductile tearing. This usually leads to stringent critical flaw size limits and excessive installation costs. A simple tool that can accurately predict crack-driving force relations in surface cracked pipes by simulating ductile tearing is demanded.

Several crack growth simulation procedures such as the Gurson model (Tvergaard and Needleman, 1984), the cohesive zone model (Besson et al., 2001), cell models (Xia and Shih, 1995), are published in the literature. However, these models require several model parameters to be identified, which is one of the main difficulties in applying them to structures. Further, these procedures are computationally expensive, and may cause numerical difficulties when applied to extensive problems, such as surface cracked pipes.

The line-spring finite element, initially proposed by Rice and Levy (1972) and later extended by Lee and Parks (1995), provides a simple approach to model surface cracks. Incorporating this line-spring technology, a new software, $\text{LINK}_{\text{pipe}}$ ($\text{LINK}_{\text{pipe}}$, 2003), that is tailormade for pipeline applications, has been developed using a co-rotated kinematic description of the ANDES shell and line-spring finite elements (Skallerud and Haugen, 1999; Skallerud, 1999). Numerical aspects and implementation of $\text{LINK}_{\text{pipe}}$ are described by Skallerud et al. (2005). Recently, Jayadevan et al. (2005) and Skallerud et al. (in press) have verified the accuracy of the line-spring method and its usefulness as an efficient computational tool for surface cracked pipes. An attractive feature of the line-spring element is that it easily facilitates the simulation of crack growth.

A ductile crack growth model using the line-spring finite element was proposed by Lee and Parks (1998a,b) for fully plastic, quasi-static through-thickness crack growth in surface cracked shell structures. They employed the plane-strain sliding-off and cracking model of McClintock et al. (1995) to obtain the instantaneous crack-tip opening angle in terms of the material parameters and the instantaneous slip-line angle and stress triaxiality at the crack-tip. However, this approach is not straightforward and it requires the determination of some model parameters from experiments. A more simplistic approach to propagate the crack in the line-spring model is to use the traditional material crack growth resistance curve. This is in accordance with the established use (BS7910:1999) of the resistance curve to account for ductile tearing. This also means that the constraint correction of the resistance curve (Nyhus et al., 2002) can be easily included in the simulations since the T-stress is readily available from the line-spring element.

The objective of this study is to demonstrate that line-spring finite element model is a simple and accurate procedure to investigate the ductile tearing in surface cracked pipes. The quasi-static stable crack growth is simulated using material tearing data. Since experimental ductile tearing data on surface cracked pipes is limited, the line-spring model is verified using continuum simulations of ductile crack growth. Using the line-spring model, a detailed parametric study on ductile tearing in surface cracked pipes along the through-thickness direction is performed. Then a range of crack depth and crack length values and diameter-to-thickness ratios of the pipe are considered under different loading conditions. The results show that the ductile tearing strongly influences the crack-driving force relations in surface cracked pipes. The study demonstrates the usefulness of parametric investigations in comparison to the underlying principles.

1.1. Line-spring theory

With the line-spring model, a surface cracked pipe is represented by a shell structure with a through slit. The stiffness from the ligament of the part-through crack is accounted for by introducing line-springs in the through slit, as schematically illustrated in Fig. 1. The local compliance of a spring connecting one point of the slit to the corresponding point on the other side is calculated based on known solutions of single edge notch (SEN) specimens under plane strain conditions. Thus, knowing the local compliance of a spring,