PIPE RUPTURE SIMULATIONS FOR TWO-PHASE CO2-MIXTURE

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Abstract

Control of ductile fracture propagation to ensure arrest is an essential element of design of pipelines transporting natural gas and other fluids such as dense-phase CO_2. Full-scale pipe rupture simulations have been carried out using Finite Element Analysis (FEA). The simulations captured an accurate pressure loading profile behind the crack tip resultant from the escaping fluid. Results for loading profiles representative of both natural gas and a CO_2 mixture are compared, the difference being that the CO_2 mixture can exist as a two-phase fluid (liquid and gas) compared to the single-phase natural gas.

1. Introduction

Existing crack arrest methodologies are based on Charpy absorbed energy and are well known to under-predict requirements for current high-toughness steels. Consequently, a more accurate method to predict fracture arrest in pipelines is required. To this end, the current work focuses on modeling full-scale pipe rupture. Accurately modeling pipe rupture requires an accurate description of both ductile fracture and of the pressure loading on the pipe due to the escaping fluid, which will be referred to as ‘flap pressure’.

To model crack growth in FEA pipe rupture simulations, cohesive zone models, damage models, and the Crack-Tip Opening Angle (CTOA) have all been used to model ductile fracture. The current work compares crack growth based on a constant CTOA nodal release algorithm with growth based on element deletion at a critical plastic strain that is a function of stress triaxiality and Lode angle. A difference between the two models is that the critical CTOA is a single fracture parameter determined by small-scale Drop Weight Tear Tests, whereas damage models require extensive calibration of several model parameters based on small-scale testing and simulation of notched specimens.

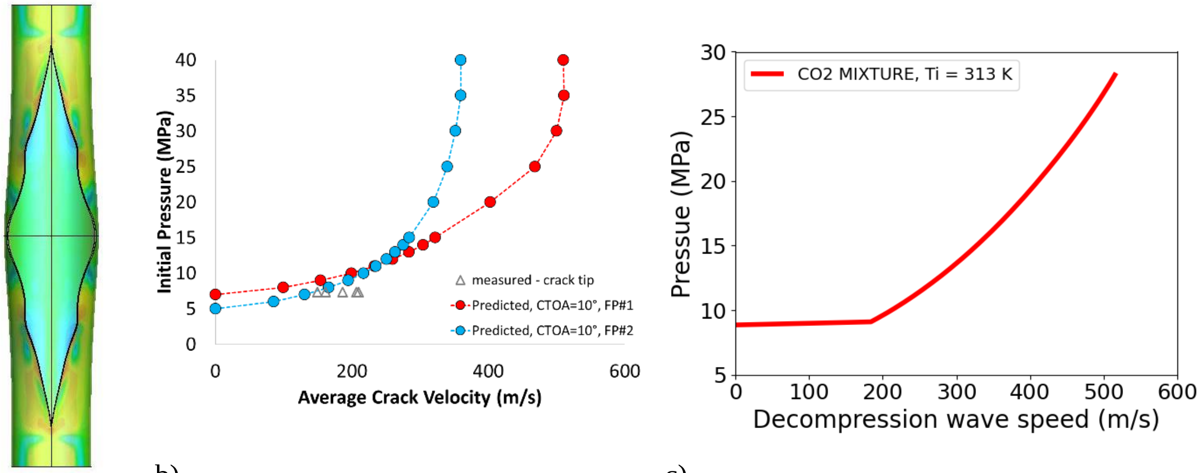
Descriptions that have been used to capture the flap pressure include:

a. a constant pressure applied a specified distance behind the crack-tip after which the pressure drops to zero
b. a linear pressure drop model, which does not vary circumferentially
c. a pressure that drops exponentially with distance behind the tip and varies around the circumference of the pipe

Two factors that control crack arrest are fracture resistance and pressure decompression due to the escaping fluid. Current methodologies treat the fracture resistance curve and the gas decompression curve as completely uncoupled. In reality, the curves are coupled in that the resistance curve is dependent on the decompression curve. Complicating the issue is that some fluids, such as a CO_2 mixture, require a two-phase description (liquid and gas). Computational Fluid Dynamics (CFD) can be used to predict the decompression pressure versus wave speed of the fluid. However, CFD will not capture the deformation of the flaps and the deformation profile must be assumed in the CFD simulations. Consequently, researchers have employed Fluid-Structure Interaction (FSI) methods in the study of pipeline rupture. Iterative CFD/FEA methods have been used to study pipe rupture. Another FSI technique, known as the Coupled Eulerian-Lagrangian (CEL) simulation method in Abaqus/Explicit has also been used for pipe rupture. In the current work, WARP3D was used to model the pipe fracture in FEA with a representative flap pressure of a CO_2 mixture. The flap pressure profile was determined from CFD simulations performed using an assumed deformed pipe geometry. The Equation of State (EOS) required for the fluid was calculated using the GERG-2008 EOS via the software NIST REFPROP and validated using shock-tube simulations. Progress towards a fully integrated CFD/FEA model will be discussed.

2. Results

An example of a single FEA simulation of a pipe rupture simulations is shown in Fig. 1a. Several simulations were performed by varying only the initial pipeline pressure and the resultant steady-state crack velocity was calculated. The pressure versus crack velocity response predicted for two flap pressure profiles is shown in Fig. 1b (each point indicates a simulation result). Fig. 1c shows the pressure versus decompression wave speed of the fluid predicted by CFD from a shock-tube simulation based on the Equation of State of a CO_2 mixture. The flat pressure plateau seen in the figure is due to a two-phase (liquid and gas) region which influenced the subsequent flap pressure profile used in FEA.



a) b) c)

Figure 1: a) WARP3D simulation of pipe rupture, b) pressure vs. crack velocity for two flap pressure profiles and c) pressure vs. decompression wave speed response from shock tube simulation using fluid properties of CO_2 mixture

3. Conclusions

It was found that to accurately simulate pipe rupture it is important to apply an accurate decay pressure response on the flaps behind the crack front. Both CTOA and damage models accurately captured pipe rupture. The resultant profile from FEA represents the fracture resistance curve that is often required to assess crack arrest. The second curve is based on the decompression response of the escaping fluid. The complex interaction between the escaping fluid and fracturing pipe should be further developed using an iterative CFD/FEA approach.

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