Tensile Fracture of Wrinkled Cold Bend Pipe under Monotonic Loading Condition

Nima Mohajer Rahbari¹, J.J. Roger Cheng¹, and Millan Sen²

¹Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada
²Enbridge Pipeline Inc., Edmonton, Alberta, Canada

ABSTRACT

In this article, ductile fracture on the tensile side of wrinkled cold bend pipes under monotonic combined loading condition is investigated through an experimental and analytical study. Two cold bend pipe specimens made of API X65 steel material were tested at the University of Alberta under increasing bending curvature with and without internal pressure. It was found that the pressurized pipe ruptured on the tensile side of the bulging wrinkle location, whereas, no fracture was captured for the unpressurized specimen. Numerical analysis is conducted by employing finite element simulation and the concept of damage mechanics to study the deformational behaviour and final failure modes of the pipe specimens. Comparison between analytical models and experimental data shows that the utilized cumulative damage approach could acceptably predict the final fracture of the pressurized cold bend pipe. Internal pressure is shown as the most critical factor in triggering the tensile fracture of wrinkled pipes.

KEY WORDS: Ductile Fracture; Wrinkling; Steel Pipe; Cold Bend; Combined Loads.

INTRODUCTION

Energy pipelines transport oil and gas from remote production sites to consumption units. Along their route, frequent horizontal and vertical changes in the direction of line are dictated by change in the topography of terrain and the geometry of the trenches. Cold bend pipe segments are necessary to make the pipeline conforming to these changes. It has been empirically observed that the wrinkle formation and fractures are most likely to happen in the location of cold bends. Pipelines are subjected to various loading conditions due to ground movements that could be sufficient to cause a catastrophic failure. In this regard, any possible failure scenarios due to combined loading conditions should be well understood and taken into a merit considerations by design engineers. Therefore, many research works have been conducted to understand different failure mechanisms of steel pipelines and develop suitable design limit states (e.g. critical buckling strain and rupture strain).

Fracture of steel pipe on the tensile side of wrinkled cross-section has been reported by (Tajika et al., 2011; Igi et al., 2011) for straight pipes of API X80 material with D/t ratio of 55.4 and pressurized to 60% of the SMYS which had been initially designed to study the tensile rupture strain due to flaws caused by welding process. Tajika et al. (2011) tested two high-stain and one conventional line pipes under monotonically-increasing curvature. The Y/T ratio of the high-stain pipes and conventional pipe were about 80% and 90% respectively. It was found that the conventional pipe starts to wrinkle at much lower curvature due to the highest value of Y/T ratio and finally ruptured on its tensile side of the buckling wrinkle. Igi et al. (2011) tested a girth-welded line pipe specimen with Y/T equal to 80% under monotonically-increasing curvature. A large artificial notch with length of 80mm and depth of 20% of wall thickness was introduced on the outer surface on the tensile side of girth weld’s heat affected zone (HAZ) region, since it was known from previous studies (Igi et al., 2010) that the HAZ is more vulnerable to tensile fracture than the weld material itself. It was found that after a certain deformation value, a periodic compressive strain and several small wrinkles developed in the vicinity of the girth weld. One of the wrinkles located about one wavelength far from the girth weld began to swell and finally an unexpected tensile rupture occurred on the tensile side of the wrinkled region 400mm away from the artificial notch and HAZ in the base material without any initial defects, although, the crack growth from the artificial notch propagated to 40% of the wall thickness. This obviously reveals the importance of the tensile fracture of wrinkled steel pipes under monotonic loading condition as one of the significant design limit states, since the rupture occurred at wrinkle location in spite of existence of a relatively large notch in the HAZ of the girth weld. That is, the critical tensile strain limit of wrinkled cross-section overcomes the tensile strain limit of defect and triggers the rupture of tensile side in the opposite location of wrinkle. Igi et al. (2014) used the porous plasticity model to conduct the finite element (FE) simulation of the ductile fracture for the latter case.

Herein, two pressurized and unpressurized cold bend pipe specimens with outside diameter (D) to thickness (t) ratio of 93 and made of API X65 steel material are investigated under monotonic combined loading conditions. The internal pressure in the pressurized specimen was corresponding to 80% of specified minimum yield strength (SMYS) hoop stress in the pipe’s wall. Initial intention of the test program was to study the critical buckling strain (Sen, 2006; Sen et al., 2004; Cheng et al., 2004; Sen and Cheng, 2010) and the mechanical properties (Sen et al., 2008) of the cold bend pipes. However, for the pressurized specimen, an unexpected rupture was observed on the tensile side of the wrinkled region in the post-buckling loading path. The objective of the current study is to develop a methodology for