

Key Design Variables Responsible for the Rupture of Buckled Pipes

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A rupture of buckled steel pipes on the tensile side of a cross-section is studied in this paper as the most plausible case of ultimate failure for the pressurized buried pipelines under monotonically increasing curvature. Finite element simulation of full-scale bending tests on two pressurized X80 pipes with different yield-to-tensile strength (Y/T) ratios were conducted. The Y/T ratio and internal pressure were identified as the crucial factors that have a coupled effect on the ultimate failure mode of buckled pipes. That is, the high values of Y/T ratio and internal pressure mutually trigger the rupture of buckled pipes on the opposite side of the wrinkling.

INTRODUCTION

Steel pipelines are so ductile and can accommodate a large amount of post-buckling deformations while preserving their operational safety and structural integrity. To benefit from this outstanding quality and prevent the buckled (wrinkled) pipelines from premature rupture, the postbuckling behavior of the steel pipes should be well understood.

Rupture is one of the major failure limits to the integrity of pipelines that endangers the environment as well as the public safety and property. Comprehensive experimental and numerical studies on the fracture of buckled steel pipes (Das, 2003; Sen, 2006; Mohajer Rahbari, 2017) show that under increased monotonic curvature, successive buckles (wrinkling) are formed on the compressive side of the wall, and the occurrence of rupture at the wrinkling location is unlikely because of the ductile nature of steel material. Rupture of wrinkling can occur once buried pipelines are subject to a very rare and changing boundary conditions accompanied by extremely large plastic deformations toward tearing the wrinkled wall (Ahmed, 2011). However, experiments have shown that the increasing curvature can easily trigger the postbuckling rupture of the tensile wall on the opposite side of the wrinkling (Sen, 2006; Mitsuya et al., 2008; Tajika and Suzuki, 2009; Igi et al., 2011; Tajika et al., 2011; Mitsuya and Motohashi, 2013; Mitsuya and Sakanoue, 2015). This mode of failure seems very likely to be the rupture limit of the wrinkled pipes, as it occurs following the same regime of monotonic bending deformations that have previously made the pipe buckle.

Tajika et al. (2011) tested two high-strain pipes and one conventional line pipe under monotonically increasing curvature while pressurized up to 60% of the specified minimum yield strength (SMYS) as hoop stress. All three pipe specimens had the same geometry with the D/t ratio of 54 and were made of X80 steel grade. However, the yield-to-tensile strength (Y/T) ratios for the material of the high-strain pipes and the conventional pipe were roughly 83% and 90%, respectively. It was found that the conventional pipe (with a higher Y/T ratio) started to wrinkle at a much lower curvature and finally ruptured on its tensile side of

the buckling region. A more than 7% tensile strain was captured by strain gauges at the rupture. Igi et al. (2011) tested a girth-welded X80 line pipe specimen with a Y/T ratio of 80% and the D/t ratio of 55 under a constant internal pressure corresponding to 60% of the SMYS hoop stress and a monotonically increasing curvature. A large artificial notch (20% of wall thickness) was introduced on the outer surface of the tensile side of girth weld's heat-affected zone to study the tensile fracture of pressurized steel pipes due to weld flaws under bending curvature. However, an unexpected rupture occurred on the tensile side of the wrinkled cross-section, which not only did not have any initial defects but also was 400 mm away from the artificial notch. The crack growth from the artificial notch was propagated up to 40% of the wall thickness, but no rupture occurred at that location. Investigation of the fracture surface revealed a decreased wall thickness as a result of necking, which clearly indicates the occurrence of ductile fracture phenomenon in the steel material. Tajika and Suzuki (2009) tested three line pipe specimens with a D/t ratio of 32 and made of X65 steel grade with a Y/T ratio of 88%. The first, second, and third specimens were tested under increasing curvature while being pressurized by three different internal pressure levels equal to 40%, 60%, and 66% of the yield pressure, respectively. It was found that the specimen with the highest internal pressure failed in rupture on the opposite side of the bulging buckle while experiencing postbuckling deformations. Excessive distortion of the buckled cross-section without any leakage was reported as the failure mode of the other two specimens, which had the lower rate of internal pressure.

To the best of the authors' knowledge, two similar failures have been reported in the literature for the case of buckled cold bend pipes. One of the pressurized cold bend pipe specimens of Sen (2006) tested at the University of Alberta unexpectedly ruptured on the tensile side of the buckled region because of an increased postbuckling bending. This pipe had the D/t ratio of 93 and was made of steel grade X65 with a Y/T ratio of 94%. The rupture occurred under an internal pressure corresponding to 80% of SMYS hoop stress and a monotonic increase of closing curvature. A small necking of pipe wall (reduced wall thickness) was observed at the tensile fibers of the cross-section where the fracture initiated. Mitsuya et al. (2008), Mitsuya and Motohashi (2013), and Mitsuya and Sakanoue (2015) conducted experimental research on pressurized cold bend pipes under both closing and opening monotonic curvature to study the rupture limit state of the buried pipelines as a result of liquefaction. The specimens were made of X80 steel grade with the Y/T ratio of about 90% and

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