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Experimental investigation of pipes with flexible joints under fault rupture

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ABSTRACT

Objective of the present study is the experimental investigation and comparison of the response of continuous pipes and pipes with internal flexible joints under imposed transverse displacement, modeling seismic fault rupture. Three-point bending tests were performed modeling the deformation of buried pipes subjected to fault offset. The introduction of flexible joints between adjacent pipeline parts is proposed as an alternative protection measure to reduce developing strains due to such offsets. Indeed, experimental results confirmed very significant contribution of flexible joints in strain reduction, thus providing strong promise of effective protection of buried pipes from the principal failure modes occurring in such cases, i.e. local buckling of pipe wall and tensile fracture of girth welds between adjacent pipeline segments. Experimental results have been sufficiently reproduced by numerical simulation accounting for geometric and material nonlinearities and incorporating longitudinal residual stresses due to seam weld. The numerical analyses and corresponding results are also presented in detail.

1. Introduction

Onshore buried steel fuel pipelines extend over long distances and when seismic areas are traversed, crossing tectonic faults might be inevitable. Fault offset is considered to be the major cause of pipeline failure due to seismically induced actions [1]. Due to the hazardous nature of pipelines, there is an ongoing effort to propose effective measures for pipeline protection against the consequences of faulting. Pertinent efforts focus on reducing the risk of local buckling of pipe wall and tensile fracture of girth welds, which are the two principal failure modes in such case. Various mitigating measures have been implemented by the industry, such as increasing the pipe wall thickness, upgrading the steel grade and wrapping the pipe with geotextiles in order to reduce pipe-soil friction [2], embedding the pipeline in soft soil, choosing appropriate angle of pipe - fault crossing, introducing bends (e.g. elbows) at some distance from the fault zone to enhance flexibility, etc.

The present work is part of a feasibility study of a new mitigating measure, namely introducing flexible joints between adjacent pipe parts, following the ideas of Bekki et al. [3]. The aim is to concentrate the developing strains at the joints and retain the pipe steel parts virtually undeformed and consequently unstressed [4]. Flexible joints are used in industrial piping networks to absorb thermal expansion, thrust and machinery vibration.

Strength and deformation capacity of pipes has been experimentally investigated for over five decades. The mechanical behavior of buried pipes subjected to permanent ground displacements (PGDs) is a complex pipe – soil interaction problem, given that the pipe is forced to follow the PGDs by developing excessive deformation. Thus, when the surrounding soil is incorporated in an experimental investigation, numerous constructional, cost and time consuming issues emerge. The experimental investigation of pipes can therefore be roughly divided into two main categories: (i) Pipes without surrounding soil. The tests are usually three- or four-point bending tests with simple boundary conditions (e.g. cantilever, clamped beam, etc.) and simple or combined external loading (e.g. bending, axial force, internal pressure). The major objective of these experiments is the estimation of pipe bending capacity, pre- and post-buckling behavior and critical compressive buckling strain. (ii) Pipes with surrounding soil, where the experimental set-up is usually a shear-box or a centrifuge, used to assess the behavior of a pipe subjected to faulting, soil liquefaction or settlement by considering the effect of various relevant parameters (e.g. soil characteristics, pipe diameter and wall thickness, burial depth, etc.).

Literature on the topic of experimental investigation of pipes without surrounding soil is broad. Experimental studies on the strength and deformation capacity of tubes and pipes have been presented in [5,6,7,8]. In the middle of the 1980's, Gresnigt [9] published the results of an extensive experimental study of pipes in a prominent textbook, focusing on the plastic design of pipes subjected to permanent ground displacements. Then, important experimental studies have been also presented by Yoosef-Ghodsi et al. [10], Murray [11] and Gresnigt et al. [12,13]. Recently, Dame et al. [14] performed full-scale four-point bending tests of API5L Grade B pipes with external diameter of 24in to study

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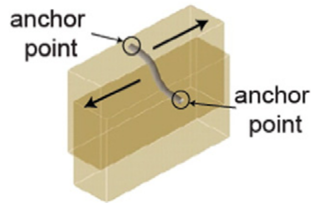

Fig. 1. Schematic illustration of pipeline deformation subjected to strike-slip fault offset.

the structural behavior of pipes under bending and internal pressure. Thinvongpituk et al. [15] experimentally investigated steel pipes with diameter over thickness (D/t) ratio ranging from 21.16 to 42.57 under pure bending to validate a proposed analytical methodology for the estimation of pipe cross-section ovalization. Then, Gresnigt and Karamanos [16] presented a study on previous experimental results, focusing on the elastoplastic local buckling of pipes and the effect of the manufacturing process on the pipe ultimate capacity and local buckling. Mason et al. [17] were the first to perform tensile tests of full-scale API5L Grade B pipes with welded slip joints (WSJ) to investigate the strength of joints. Chen et al. [18] performed full-scale experiments of 40in diameter X70 pipes under bending, compression and internal pressure to assess their strength. Later, Ferino et al. [19] carried out experiments on full-scale X80 pipes (D/t ratio from 50 to 65) to examine the critical buckling strain of high-strength steel pipes. Recently, Kristoffersen et al. [20] presented experimental results from three-point bending tests of in-scale offshore X65 pressurized pipelines under transverse and axial forces and internal pressure to investigate the relationship between axial load, bending capacity and cross-sectional distortion. Experimental results have been used to formulate the provisions of pertinent codes and standards regarding the strength and deformation capacity of onshore and offshore pipes, e.g. API [21], ASME [22,23], CSA [24,25], DNV [26].

Experimental tests of buried pipes with surrounding soil are quite limited in the literature. Abdoun et al. [27] used a centrifuge to investigate in-scale HDPE pipes subjected to strike-slip faulting focusing on the fault offset rate, the backfill soil moisture content, the burial depth and the pipe diameter. A year later, Ha et al. [28] used the same centrifuge to experimental investigate HDPE pipes in order to compare the obtained results to those reported after the failure of a major water pipeline in Izmir (Turkey), caused by the 1999 Kocaeli earthquake [29]. A major finding was that the locations where local buckling occurred, acted as “flexible joints” in case of increasing fault offset. Then, Rofooei et al. [30] utilized a shear box in order to rigorously model the response of an API5L Grade B pipe with 4in diameter subjected to reverse faulting. The reverse faulting caused inelastic pipe local buckling both in the fault footwall and hanging wall part. Moradi et al. [31] used a centrifuge to investigate the behavior of stainless steel pipes under normal faulting, considering the relationship between axial and bending strains and the effects of burial depth and fault offset magnitude. Very recently, in the final report of the RFCS project GIPIPE [32], results of small-scale experiments of pipes under faulting (normal of reverse) using a shear box were presented and were used to calibrate numerical models. Additionally, in the same study, axial pulling tests were performed in order to evaluate the developing pipe – soil friction and full-scale tests were executed, simulating the imposed ground displacement due to landslide or faulting. Experimentally obtained pipe strains were compared to code-based predictions and the locations of strain concentration were investigated.

Experimental investigation on the efficiency of alternative mitigating measures against the consequences of faulting on pipelines is however quite limited until now. Hedge et al. [33] tested small diameter PVC pipes embedded in geocell reinforced sand beds in order to investigate the efficiency of geocells in terms of protecting buried pipelines. The experimental set-up consisted of a test tank filled with sand, where the pipeline was placed at the bottom and force was applied on the top soil surface through a hydraulic jack. Sim et al. [34] performed shaking table tests of small diameter pipes crossing a vertical fault to investigate the performance of tyre-derived aggregate (TDA) backfill in terms of protecting buried pipelines against vertical faulting and shaking. The obtained experimental results showed that TDA backfill contributes to pipe bending moment reduction. Monroy-Concha [35] carried out tests of pulling pipes embedded in sand backfill so as to examine the effect of covering trench's walls with geotextiles on the buried pipe protection. Finally, experimental investigation of flexible joints as individual components, i.e. without considering them as part of a piping network, have been primarily conducted to determine the mechanical properties of the joint [36,37].

Seismic fault activation is associated to PGDs and thus the problem under investigation is displacement-controlled and consequently strain-controlled rather than stress-controlled. Extensive yielding is expected to take place due to faulting, while the corresponding strains might remain below a limit that is associated to failure, i.e. concentration of tensile strains is associated with tensile rupture at girth welds, while compressive strains with local buckling of the pipeline wall. Pertinent structural codes for the design of buried pipes at fault crossings provide strain-limit expressions for both compressive and tensile strains (e.g. [38,39]).

The objective of the experimental investigation presented here was to study the efficiency of flexible joints integrated in tubes under transverse imposed displacement, modeling fault movement, in terms of reducing longitudinal strains and consequently preventing tube failure. Unpressurized continuous tubes and a tube with internal flexible joints were tested and the obtained results were compared to identify the repercussions of joints in the overall tube response. Special focus was paid on comparing the developing strains in light of the pipeline strain-based design rules. Then, the experimental results were compared to corresponding numerical ones, obtained from nonlinear analyses of finite element models. Details of both the tests and the corresponding numerical modeling are presented in the following sections.

It must be noted that the examined application of flexible joints has not been so far used in practice. In the present study some aspects of the joints' efficiency in protecting buried pipes from fault activation are investigated. However, considerable constructional and practical issues have to be tackled in addition, before practical application can actually be implemented, which are beyond the scope of this paper. Such issues include bellow protection against corrosion, pipe – bellow proper welding, bellow isolation from the surrounding soil and bellow long-

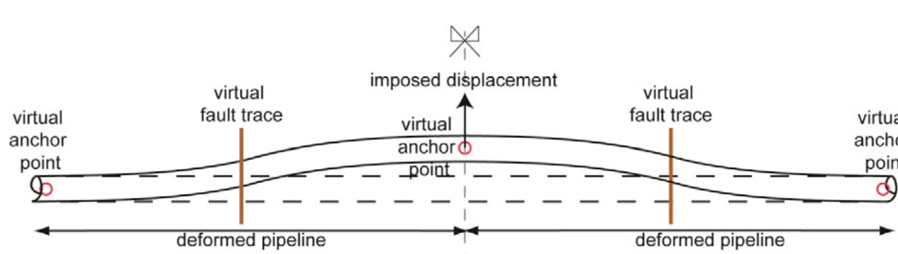

Fig. 2. Schematic illustration of the experimental concept.