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FAILURE MITIGATION OF BURIED STEEL PIPELINE UNDER STRIKE-SLIP FAULT OFFSET USING FLEXIBLE JOINTS

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Abstract: Oil and gas onshore steel buried pipelines are hazardous structures, thus mitigating their potential failure due to faulting is a research topic of significant interest. Conventional preventive measures that are currently used in practice aim at reducing pipe – soil friction, so that the pipeline is more free to deform within the soil and occurring tensile and compressive strains do not exceed certain limits. In the present study a different approach is examined, namely the introduction of flexible joints between adjacent pipeline steel parts in the vicinity of fault crossing, in order to concentrate strains at these joints and drastically reduce developing strains on steel pipe parts. Advanced numerical models are adopted to investigate the behavior of continuous pipelines and pipelines with flexible joints under strike-slip fault offset. Numerical results highlight the effectiveness of flexible joints in terms of reducing resulting strains, while a parametric study on pipe – fault crossing angle indicates the angle range within which flexible joints are effective.

Introduction

Onshore buried steel pipelines cover long distances to supply costumers with oil and oil products. Thus, crossing seismic areas that incorporate active tectonic faults is often inevitable. In such case, potential fault activation may endanger the pipeline integrity with potential leakage and associated devastating consequences to the environment and nearby populated areas, as well as economic losses. Extensive studies after past severe earthquake events have indicated that seismic damages to pipelines have been mainly caused by permanent ground displacements, such as landslide, liquefaction-induced lateral spread and fault movement (O'Rourke and Liu, 1999). The latter was the main conclusion after the 1971 San Fernando earthquake (Jennings, 1971), the 1995 Kobe earthquake (Nakata and Hasuda, 1995) and recently the 1999 Kocaeli (EERI, 1999) and the 1999 Chi-Chi earthquake (Takada *et al.*, 1999).

Buried pipeline – fault crossing has been thoroughly investigated both analytically and numerically during the past decades. Newmark and Hall (1975) were the pioneers of such pertinent work and presented an analytical model to assess the integrity of a buried pipeline crossing a ruptured fault. They modeled the pipeline as a long cable undergoing small displacements and considered the fault as a planar surface separating two rigid bodies, which are subjected to relative motion. Kennedy *et al.* (1977) extended this analytical model by incorporating the lateral pipe – soil interaction, while Kennedy and Kincaid (1983) considered also the soil friction nonlinearity. This approach was adopted by Weng and Yeh (1985) who incorporated pipeline bending stiffness. Later, Takada *et al.* (2001) proposed a simplified model to estimate maximum axial strain by taking into account cross-section distortion, while Karamitros *et al.* (2007, 2011) extended the previous analytical methodologies for strike-slip and normal faulting by combining the model of beam on elastic foundation and the elastic beam theory to estimate maximum strains by incorporating geometric and material nonlinearities. Trifonov and Cherniy (2010) proposed a semi-analytical methodology for pipeline stress analysis. From the point of view of numerical simulation, Ariman and Lee (1991) introduced the finite element method to evaluate pipeline strain, while Karamitros et al. (2007, 2011) simulated the pipeline with shell elements and the surrounding soil with springs to evaluate their proposed analytical methodology. Then, Kokavessis and Anagnostidis (2006) presented a finite element model for assessment of

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pipeline behavior under ground-induced actions, using contact elements to simulate pipe – soil interaction, while Vazouras *et al.* (2010, 2012) presented advanced numerical simulations by meshing the pipeline with shell elements and the surrounding soil with 3D-solid elements. Recently, Trifonov (2015) extended the continuum models by considering trench dimensions and paying special attention to fault discontinuity modeling. Furthermore, experimental studies on the effects of strike-slip offset on buried HDPE pipelines have been reported by Ha *et al.* (2008) and Abdoun *et al.* (2009) based on centrifuge tests. They examined the impact of the fault type, the fault dip angle, the burial depth, the pipeline diameter and the moisture continent on pipeline response due to faulting.

In the present study, the behavior of pipelines due to strike-slip movement is investigated, assuming that the pipeline deformation takes place within a horizontal plane. Pipeline deformation due to strike-slip faulting is schematically illustrated in Figure 1, and causes bending and tension. The dominant failure modes in such case are located in areas of high curvature and are associated with local buckling of the pipeline wall due to compressive strains or tensile fracture due to tensile strain concentration, especially in girth welds between adjacent pipeline parts, which are thus identified as the most vulnerable part of the structure.

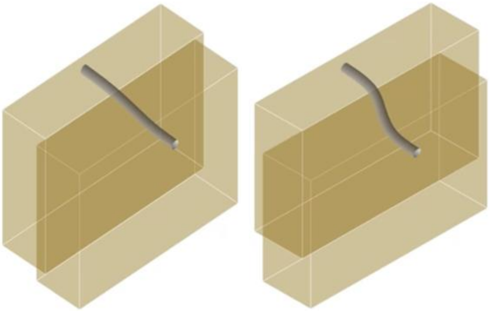

Figure 1. Schematic deformation of a continuous pipeline due to strike-slip faulting

Several preventing measures have been proposed, nowadays, to minimize the impact of fault offset on pipelines (Karamanos *et al.*, 2014). Among such measures, the usual design approach is based on the idea of reducing pipe – soil friction by embedding pipeline in a shallow, sloped-wall trench with cohesionless backfill soil, allowing the pipeline to deform over a more extended length, thus developing more distributed strains with smaller peak values, ensuring that pipe rupture is prevented. Another approach is to wrap the pipeline with friction-reducing geotextile to prevent the development of extensive strains (Gantes and Bouckovalas, 2013). In the present work, the idea of Bekki *et al.* (2002) is adopted, namely integrating flexible joints between pipeline adjacent parts around the fault zone. This design concept aims at concentrating strains at the joints and retain pipe steel parts virtually undeformed (Melissianos and Gantes, 2014). The work described in the present paper is a research effort to highlight the effectiveness of the proposed mitigating approach by comparing numerical results for continuous pipelines and pipelines with flexible joints. Additionally, the effect of pipe – fault crossing angle is investigated regarding the effectiveness of their joints, and their location on the pipeline with reference to fault trace is optimized.

Introduction of flexible joints

Flexible joints are commercial products and are usually referred as expansion joints. The most common type of joints is bellows, which are used in industrial facilities’ piping systems to absorb thermal expansion and pressure thrust. There are two main types of joints: (i) the single expansion type with axial, lateral and angular deformation capacity and (ii) the hinge expansion type with angular deformation capacity only, while axial and lateral deformations are constrained by means of a pivot (Figure 2). The hinged type is selected for transmission pipe – fault crossing applications, acknowledging the fact that the axial and lateral stiffness of single-type joints are insufficient to resist large movements due to fault offset. Additionally, transmission pipelines operate under high pressure that may deform the single-type joint, unlike the hinged-type joint, which absorbs internal pressure within the joint.

Comparing the proposed mitigating measure with friction-reducing approaches, two main differences can be identified: (i) in friction-reduction design, large strains and permanent deformations are allowed within certain limits, provided that pipe pressure boundary is maintained. On the other hand, the introduction of flexible joints aims at preventing pipe failure by concentrating strains at the joints and retain the pipeline steel in the elastic range, and (ii) flexible joints are part of the structural system, which minimizes the necessity for additional special constructional requirements.

Figure 2. Schematic drawing of hinged flexible joint

Two approaches for bellow numerical modeling have been proposed by Peng and Peng (2009): (i) bellow modeling as a general beam finite element with its stiffness matrix constructed from the spring rates provided by the manufacturer, and (ii) bellow modeling as a generic flexible joint represented by a rotational spring at the centre point, without considering bellow length. In the present study, the simulation approach of a rotational spring is adopted by modeling the hinge bellow as an elastic rotational spring with stiffness 0.0088kNm/deg, while relative axial and lateral movements at the two ends of the bellow are restrained. Also, given that bellow torsional movement is not accepted, rotation about the longitudinal axis is restricted through appropriate constraints.

Pipeline – fault crossing numerical simulation

The structural response of buried pipelines subjected to fault movement is directly related to soil nonlinear behavior, while pipe – soil interaction conditions increase the complexity of the physical problem. Thus, advanced computational tools by implementing the finite element method are deemed as appropriate for dealing with the complexity of the problem. The beam-type model is employed to simulate the mechanical behavior of the pipeline and the surrounding soil. According to this modeling technique, the pipeline is meshed with beam-type finite elements that can assess its bending and axial deformation and additionally provide strains and stresses. The soil is represented by a series of mutually independent translational uniaxial springs in three directions, while soil behavior is considered to be nonlinear according to ALA (2001) provisions. The adopted finite element model is schematically illustrated in Figure 3.

Axial springs simulate pipe – soil friction and their properties are related to backfill soil properties and pipeline coating material. Lateral springs (transverse horizontal) simulate the soil resistance to any horizontal transverse movement of the pipeline in the trench. Vertical upward and downward springs model the vertical movement of the pipeline in the trench, but their properties differ significantly, as backfill soil above the pipe has very low stiffness, unlike the native soil under the pipe that resists downward movement. Additionally, strike-slip fault offset is considered in the analysis as a quasi-static process by applying the imposed displacement on the corresponding “ground” nodes of springs at a sufficiently slow rate that excludes any potential dynamic effects.

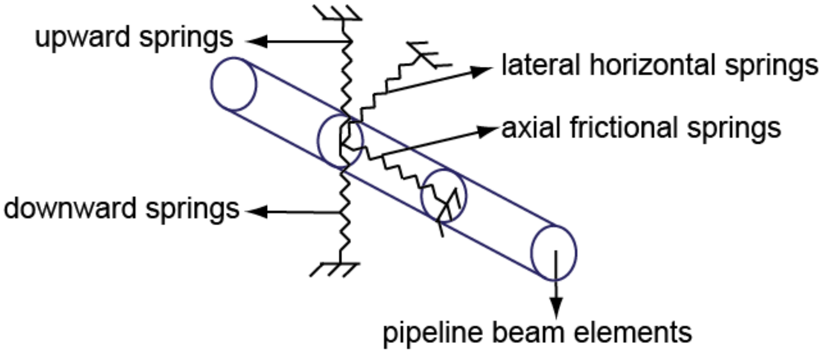

Figure 3. Beam-type finite element model

However, using beam-type finite elements does not allow the direct assessment of neither local buckling, nor tensile fracture. Thus, these failure modes are evaluated by comparing developing strains to upper bound limits suggested by codes. In ALA (2001) provisions the tensile strain limit $\varepsilon_{t,c}$ to prevent tensile failure and the compressive strain limit $\varepsilon_{c,c}$ to avoid local buckling are proposed:

$$\varepsilon_{t,c} = 2\% \tag{1}$$

$$\varepsilon_{c,c} = 0.50\left(\frac{t}{D'}\right) - 0.0025 + 3000\left(\frac{pD}{2Et}\right)^2, \text{ with } D' = \frac{D}{1-3\frac{D-D_{\min}}{D}} \tag{2}$$

where t is the pipeline wall thickness, D the pipeline external diameter, D_{min} the pipeline internal diameter, p the internal pressure and E the pipeline steel Young's modulus. The compressive strain limit of Equation 2 includes a term for internal pressure, which acts as a relief against the external earth pressure on the pipeline. So, considering a less favorable situation, e.g. the pipeline being under maintenance and not pressurized, in the present study the internal pressure is not taken into account and the pertinent term of Equation 2 is neglected.

In Figure 4, the pipeline – fault crossing site is illustrated in plan view, where the fault is assumed to be planar and thus appears on the ground surface as a straight line. The strike-slip offset is defined by fault component Δ_1, which is parallel to the fault trace, while the imposed ground displacements on the pipeline, Δ_x and Δ_y are estimated through the pipe – fault crossing angle β:

$$\Delta_x = \Delta_1 \sin\beta \text{ and } \Delta_y = \Delta_1 \cos\beta \tag{3}$$

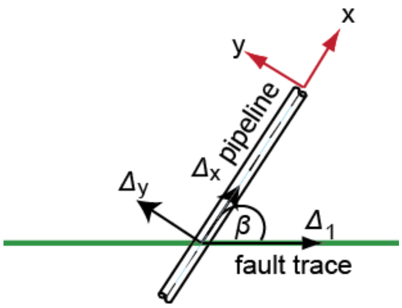

Figure 4. Pipeline – fault crossing plan view

Numerical model

A straight pipeline segment with total length of L=1000m is considered for the purposes of the present research, featuring a cross-section with diameter D=914mm and wall thickness

t=12.7mm, while the fault is assumed to intercept the pipeline at its middle. The modeled pipeline segment is considered to be straight, for computational simplicity but also in accordance to good engineering practice, to avoid bends in fault crossings, as additional forces may be imposed due to pipe route change. Steel is of type API5L-X65 with Young's modulus E=210GPa, yield stress f_y=448.5MPa, ultimate stress f_u=510MPa, ultimate strain ε_u=4% and is considered as elastic-plastic with isotropic hardening. The pipeline is meshed with PIPE elements and discretized per 0.5m, after a mesh density sensitivity analysis was carried out to establish the appropriate mesh size. The pipe is assumed to be coated with coal tar and embedded under 1.3m of granular loose sand with cohesion c=0, unit weight γ=18kN/m^3 and internal friction φ=36^o. Pipeline – soil interaction is modeled using spring elements and soil springs' force – displacement curves are obtained according to ALA (2001) provisions. Strike-slip fault offset is considered to be Δ_1=1.5m, while the pipe – fault angle is varied from β=20^o to β=90^o. Numerical modeling is carried out using the commercial software ADINA (2008), considering geometrical nonlinearity, as well as pipeline steel and soil nonlinear properties. The finite element model consists of 2000 pipe elements, 8004 spring elements, 10005 nodes and 18018 degrees of freedom.

Numerical results

The bending moment and axial force distributions of the continuous pipeline are depicted in Figure 5 for varying pipe – fault angle β, indicating that the decrease of pipe – fault angle results in bending moment decrease and axial force increase. Additionally, the decrease of angle β leads to further extension of axial force along the pipeline, while maximum and minimum bending moment values tend to appear closer to the fault intersection.

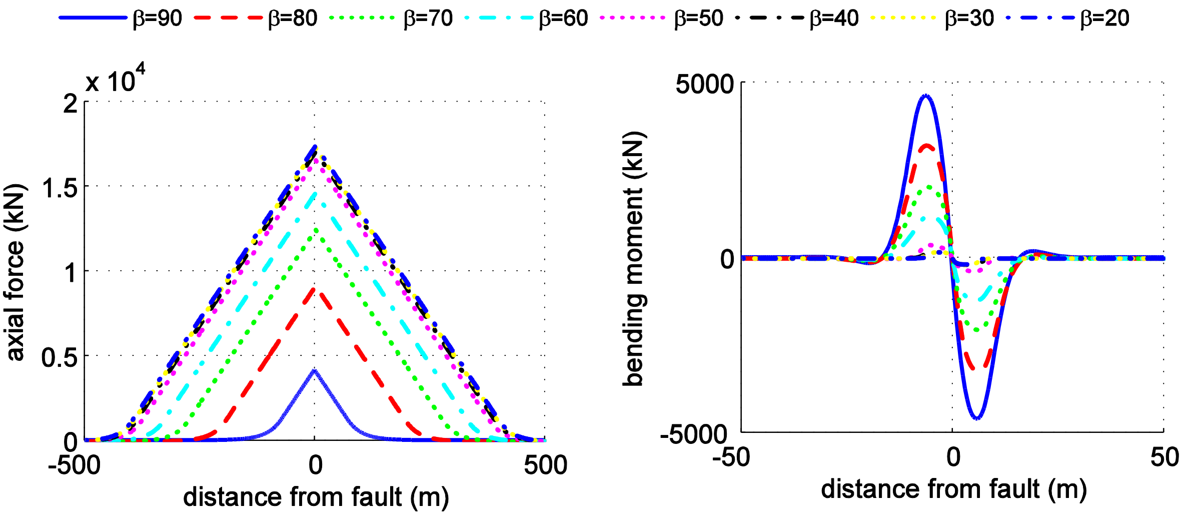

Figure 5. Axial force and bending moment distributions of continuous pipeline for various pipe – fault crossing angles

The effectiveness of flexible joints is then investigated for all cases of pipe – fault angle. In each case, the selection of the flexible joints' positions is based on the location of the maximum and minimum bending moment of the continuous pipeline, abbreviated as CP. Three flexible joints are integrated into the pipeline, now abbreviated as PFJ, one on the fault, one on the footwall part and the third on the hanging wall part of the fault. Then, the efficiency of the joints is demonstrated by comparing the stress state of CP vs. PFJ in terms of axial force, bending moment and developing longitudinal stresses and strains. Such comparison is presented, due to limited space, for pipe – fault angles equal to β=90^o, β=50^o and β=20^o only, which represent three characteristic cases, i.e. for β=90^o the pipe intercepts the fault line perpendicularly, for β=20^o the pipe tends to be parallel to the fault line, while angle β=50° represents an intermediate case. In Figure 6 the deformation of the continuous pipeline and the pipeline with flexible joints due to strike-slip movement are presented. CP deformation is a smooth curved line, while PFJ deformation approximates a polyline with straight segments around the fault. In Figure 7 the bending moment and axial force distributions along the pipeline are depicted, indicating a major decrease in the bending moment and a minor increase in the axial force of the pipeline with joints. Additionally, the effectiveness of joints in terms of decreasing bending moment is reduced as angle β decreases, even though such decrease leads to limited increase of the axial force.

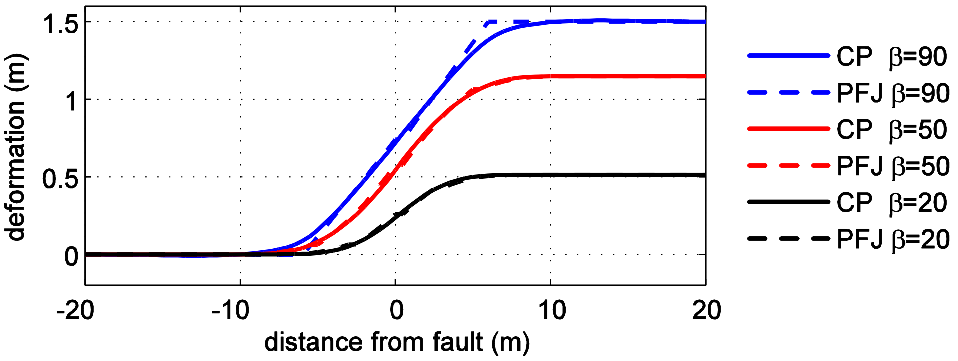

Figure 6. Deformation of continuous pipeline and pipeline with flexible joints for various pipe – fault crossing angles

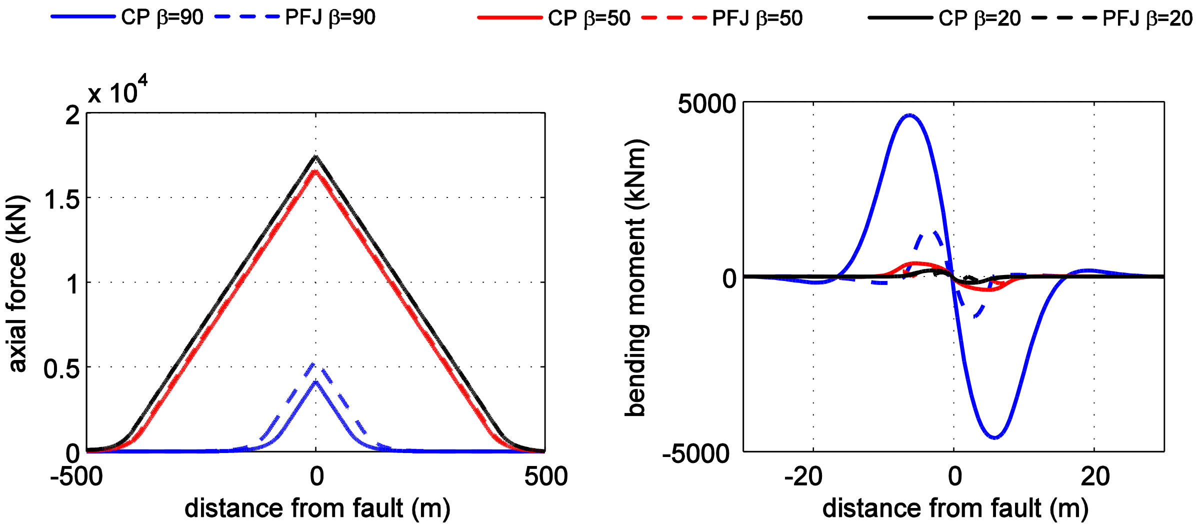

Figure 7. Axial force and bending moment distributions of continuous pipeline and pipeline with flexible joints for various pipe – fault crossing angles

The distributions of maximum longitudinal strains, as presented in Figure 8, highlight the efficiency of joints in terms of redistributing developing strains, as strain peaks are concentrated at the flexible joints, while much lower strains develop on pipe steel parts. Thus, the risk of local buckling or tensile rupture is significantly reduced. However, considering that the flexible joints, having much lower bending stiffness than pipe sections, virtually act as internal hinges and reduce the developing bending moments and consequently the bending strains, and taking into account that the decrease of pipe – fault angle results to reduction of bending and corresponding increase of tension, the effectiveness of the joints gradually decreases with angle decrease. The latter is assisted by the fact that the bellow's axial stiffness is high due to the pivot of the bellow.

The bending moment distributions for a pipeline with flexible joints for various pipe – fault angles are shown in Figure 9, confirming the previous findings of this study. The decrease of angle *β* results to a decrease of the developing bending moment, while the maximum bending moment is located closer to the fault. Additionally, based on the expected fault offset and the angle *β* that is defined by the route selection procedure, a more detailed analysis is necessary towards the optimization of the flexible joints' number and position on the pipeline.

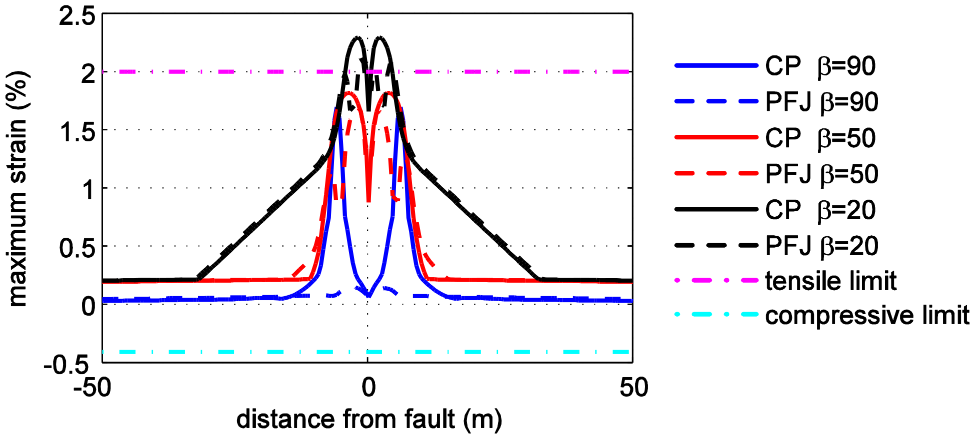

Figure 8. Maximum longitudinal strain distributions of continuous pipeline and pipeline with flexible joints for various pipe – fault crossing angles

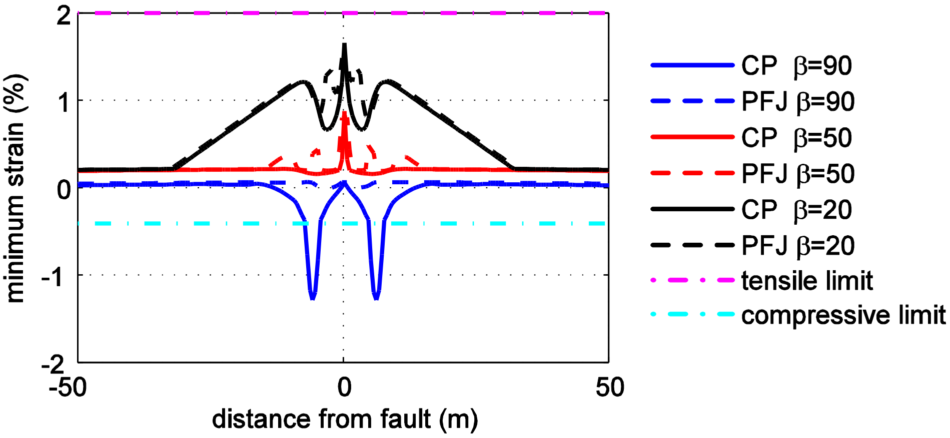

Figure 9. Minimum longitudinal strain distributions of continuous pipeline and pipeline with flexible joints for various pipe – fault crossing angles

The maximum and minimum longitudinal stress distributions along the pipeline depicted in Figure 10 indicate the steel yielding for CP in the close vicinity of the fault, both in tension and compression. On the other hand, the introduction of flexible joints does not substantially modify stress distributions, which are not of great concern for steel pipelines, as the structural integrity can rely on the post-yielding strength of steel.

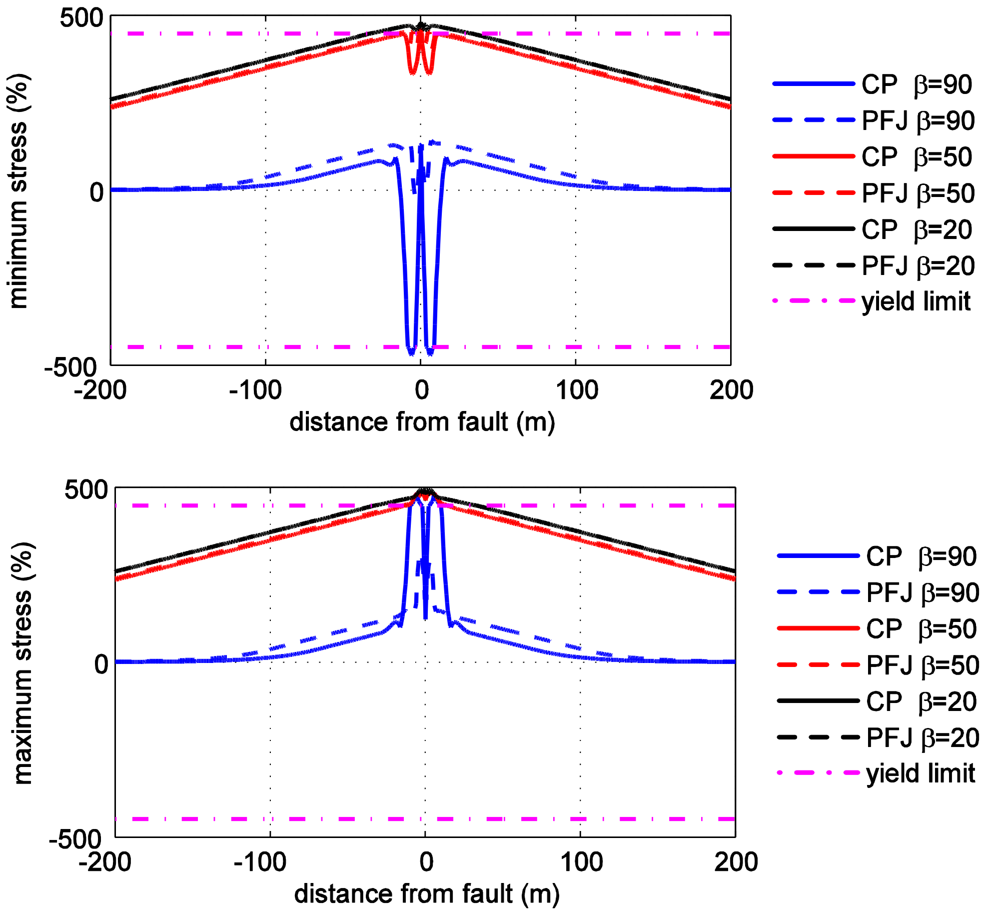

Figure 10. Longitudinal stresses distribution of continuous pipeline and pipeline with flexible joints for variable pipe – fault crossing angle

Conclusions

The response of continuous buried pipelines subjected to strike-slip fault movement was investigated and compared to the one of the same pipelines incorporating flexible joints. Advanced numerical simulation with beam-type finite element models was implemented and nonlinear analyses were performed to investigate the efficiency of flexible joints, as innovative mitigating measures against the principal failures in such cases, namely local buckling of the pipeline wall and tensile fracture of girth welds. The pipeline under investigation was an API5L-X65 typical large-diameter transmission pipe considered to be deeply buried. The proposed introduction of joints between adjacent pipe parts transformed the continuous structural system to a segmented one, as joints act as internal hinges concentrating strains and allowing steel parts to remain virtually straight. On the basis of the obtained results, the flexible joints tended to significantly reduce the developing bending moment and longitudinal strains, even though a minor increase in axial force was reported. Moreover, the location of joints along the pipe was selected based on the location of the maximum developing moment of the continuous pipe. However, the pipe – fault crossing angle was identified to play a major role on pipeline response and thus a parametric study was carried out. As pipeline tends to be parallel to the fault line, resulting bending moments decrease, while axial forces increase. Thus, the more perpendicular to the fault line the pipeline crosses the fault, the more efficient the use of joints is, as bending dominates the behavior. In conclusion, the findings of the present paper are supportive towards the efficiency of flexible joints against the impact of strike-slip offset on buried steel pipelines, provided that the pipe crosses the fault line close to perpendicularly.

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