Numerical evaluation of the effectiveness of flexible joints in buried pipelines subjected to strike-slip fault rupture

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ABSTRACT

Buried steel pipelines transport large amounts of fuel over long distances and inevitably cross active tectonic seismic faults when seismic areas are traversed. Eventual fault activation leads to large imposed displacements on the pipeline, which may then fail due to local wall buckling or tensile weld fracture, having grave financial, social and environmental consequences. In this paper, flexible joints are evaluated as an innovative mitigating measure against the consequences of faulting on pipelines. Joints are introduced in the pipeline in the fault vicinity, aiming at absorbing the developing deformation through relative rotation between adjacent pipeline parts, which then remain relatively unstressed. The effectiveness of flexible joints is numerically evaluated through advanced 3D nonlinear finite element modeling. Extensive parametric analysis is carried out to determine the effect of pipeline – fault crossing angle, fault offset magnitude, joint angular capacity, burial depth and diameter over thickness ratio on the joint efficiency. The uncertainty regarding the fault trace is also addressed.

1. INTRODUCTION

Onshore buried steel pipelines with girth-welded joints are used in the energy industry to transport large amounts of fuel over long distances. Permanent ground displacements (PGD), such as those due to fault rupture, ground settlement or sloping ground failure, have been identified as the dominant causes of catastrophic pipeline failure due to earthquake induced actions after past major earthquake events [1] (e.g. the 1995 Kobe [2], the 1999 Kocaeli [3] and the 1999 Chi-Chi [4] earthquakes). A potential failure of pipelines (e.g. fuel leakage, explosion) can have significant environmental and financial consequences. Fault offset is the result of earth plate's relative movement and its consequences on pipeline performance can be severe. The principal failure modes in this case are directly related to the extensive deformation of pipelines due to faulting causing local buckling/wrinkling due to compressive strains or tensile weld fracture due to tensile strains.

Analytical or numerical approaches have been applied to assess the pipe stress-state due to faulting. Newmark and Hall [5] analytically calculated the pipeline wall stress-state, considering the pipeline as a long cable undergoing small displacements that intercepts a planar fault. Kennedy et al. [6],[7] extended previous work [5] by incorporating lateral soil interaction and pipe – soil friction nonlinearity. Wang and Yeh [8] integrated the pipe bending stiffness in the established analytical models. The pipe model of elastic beam was adopted by Vougioukas et al. [9] to account for the vertical and horizontal fault movements. Wang and Wang [10] modeled the pipe as a beam on elastic foundation, while Takada et al. [11] proposed a more accurate model by relating the cross-sectional deformation and the pipe bending angle to calculate the maximum strain. Recently, Karamitros et al. [12],[13] improved the previous analytical approaches by combining the model of a beam on elastic foundation and the elastic beam theory to estimate the maximum strains due to strike-slip and normal faulting. Trifonov and Cherniy [14],[15] presented a semi-analytical methodology for pipeline stress – strain analysis by considering the contribution of transverse displacements to the axial elongation.

The analytical approach remains a helpful tool during the preliminary design stage of a pipeline project. The pipeline – soil interaction complexity, however, requires the implementation of advanced numerical models that are capable of considering all pertinent parameters, such as geometrical and material nonlinearity, cross-section ovalization and complex soil properties. The finite element method was initially introduced [16] to evaluate the developing strains and nowadays two categories of numerical models are available:

- The first is the so-called beam-type model, where the pipeline is meshed with beam-type finite elements that can model the axial, shear and bending deformation and can provide stresses and strains at cross-section integration points along the pipe. The surrounding soil is modeled using a series of nonlinear translational springs in four directions (axial, transverse horizontal, transverse vertical upward and downward), based on the Winkler soil approach. However, trench dimensions and native soil properties cannot be directly encountered in the analysis. Additionally, the used of beam-type finite elements does not allow the direct estimation of local buckling, cross-section ovalization and detailed stress-strain distributions around the circumference of the pipe. Thus, checks on failure modes are carried out by comparing the maximum developing tensile and compressive strains obtained from the integration points to the corresponding strain limits provided by pertinent standards. The beam-type model is extensively used by researchers to verify the pipeline safety at active fault crossings. Joshi et al. [17] employed this model to investigate the pipe behavior due to reverse faulting. Uckan et al. [18] presented a simplified beam-type model as a useful tool to calculate the pipe critical length and established a methodology to formulate pipe fragility curves. This model is also adopted by worldwide Standards and Regulations such as Eurocode 8 [19], ALA [20] and ASCE [21] as a reliable and computationally efficient modeling approach.
- The second approach is the so-called continuum model, where the pipeline is discretized into shell finite elements and the surrounding soil into 3D solid elements. The pipe – soil interaction is modeled with contact elements. This approach severely increases modeling complexity, nonlinearity and computational effort in terms of solution time requirements,

boundary conditions, resulting degrees of freedom, convergence difficulties, fault rupture modeling and particularly the introduction of contact elements. The initial attempts to employ the continuum model by considering pipe – soil contact issues were presented in [22],[23]. Recently, Vazouras et al. [24],[25],[26] presented a rigorous finite element model for pipeline – strike-slip fault crossing by considering soil parameters, pipe – fault crossing angle and pipeline mechanical characteristics to come up with a simplified expression for critical buckling strain. This model was then adopted in [27],[28] to consider the effects of trench dimensions, native soil properties and fault motion simulation. As an alternative, nonlinear translation springs can be used for soil modeling instead of 3D-solid elements to avoid the numerical difficulties related to the use of contact elements between the pipeline and the soil [12],[13],[29],[30].

Avoiding pipeline failure is the major priority in pipeline design against faulting. A set of different seismic countermeasures are thus employed in engineering and constructional practice to minimize the developing strains on pipe walls, mainly by reducing pipe – soil reaction forces. The commonly adopted measures are:

- Pipeline embedment in a shallow, sloped-wall trench with loose backfill to reduce soil resistance and allow the pipeline deformation to take place over a longer length. Development of large strains and permanent deformations is allowed, as long as pipe failure is prevented [30],[31].
- Pipe wall thickness increase or steel grade upgrade to reduce developing strains and pipe curvature by increasing pipe stiffness [30],[31].
- Avoidance of sharp bends that increase constraints to axial displacements and may impose additional forces on the pipeline [19],[20],[30].
- Pipeline wrapping with friction-reducing geotextile to reduce pipe – soil friction and increase the anchor length, thus reducing the developing longitudinal strains [30].
- Pipeline wrapping with composite FRP wraps to increase strength and the critical fault movement that causes failure [32].

- Pipeline placement within buried concrete culverts. Culverts are sacrificed during the fault movement to retain the pipeline unstressed. The lack of backfilling drastically reduces friction-induced strains on the pipeline.
- Use of geocells and geogrids in the trench above the pipeline to reduce pipe deformation [33].
- Backfill pipe trench with tyre derived aggregate surrounded by sand to reduce pipe bending moments [34].

Various parameters, such as the fault offset magnitude and constructional issues, can limit the efficiency of these measures. Monroy [35] for example, suggests that wrapping the pipeline with a double layer geotextile is effective only if the distance between pipeline and trench wall is less than half the pipeline diameter.

Research presented in the present paper focuses on the use of innovative materials or commercial devices/products that could be integrated in the pipeline in the fault vicinity in order to reduce the developing strains. Segmented pipelines have been used in the piping industry for decades, but mainly for water or sewage transmission under low pressure. The joints used in these pipelines (slip and spigot-bell joints) do no ensure the continuity of the structure in terms of axial, shear and/or rotational deformations, depending on the type of joint, and thus extensive research has been carried out on investigating the integrity of segmented pipelines under permanent ground displacements based on the joints' properties [36]-[44], investigating among others the potential of joint pull-out failure. The mitigation measure proposed in the present study follows the suggestions of Bekki et al. [45] in introducing flexible joints between the adjacent pipeline parts in the fault crossing area. The principal objective is to concentrate strains at the joints and retain the steel parts almost undeformed [46],[47]. This concept introduces a different design approach for reducing the risk of local buckling or tensile failure, by transforming the pipeline structural system from continuous to segmented, so as to concentrate strains at the joints, instead of reducing the soil friction.

Flexible joints are widely used in the piping industry, for example to absorb thermal expansion, thrust and machinery vibration or as joints between the adjacent parts of segmented pipelines. A major advantage is that flexible joints are commercial products, thus they can be either readily available or also customized with respect to diameter, internal pressure and allowable deformations. Among the available flexible joints, namely slip joints, spigot-bell joints and bellows, it was concluded that the appropriate type for buried pipe applications that operate in high pressure is the hinged metallic bellow (Fig. 1), which is capable of undergoing angular deformation only, as lateral and axial movements are restrained. The selection is based on the following criteria: (i) availability in the market and production upon request, (ii) contribution to developing longitudinal strain reduction, (iii) ease of construction in the field, (iv) compliance with pipe flow, (v) operability of pipeline after fault rupture and (vi) full structural cooperation between the pipe and the flexible joint, i.e. avoidance of joint pull-out failure. Focus on the latter is important due to the fact that bellow-type joints are welded between the pipeline segments and thus continuity of the structure is ensured. It is also noted that the integrated joints are expected to undergo large rotations due to fault offset and thus joint rotations have been quantified for a wide range of values of the involved parameters, indicating that there are commercially available bellow-type joints with sufficient rotational capacity to accommodate the required rotation for very large offsets, in the order of 3 to 4 pipe diameters. Almost all alternative protection measures are not effective for such large offsets.

Transmission pipelines operate usually under very high pressure (e.g. 8 MPa) that may deform heavily a single joint in normal operation, while hinged joints can withstand high pressure. It is noted that hinged metallic bellows have not been used until now in high-pressure buried pipeline – fault crossing applications. In the market, however, hinged joints for high pressure are available. Therefore, the use of expansion joints in such applications has to be accompanied by special procedures and precautions regarding pipe – joint welding, joint corrosion, thermal insulation, joint protection against external damage, compliance with the pipe flow process, avoidance of obstructing the normal pipeline inspection procedures (e.g. in-line inspection with pigs) and joint angular capacity with respect to the expected fault offset magnitude.

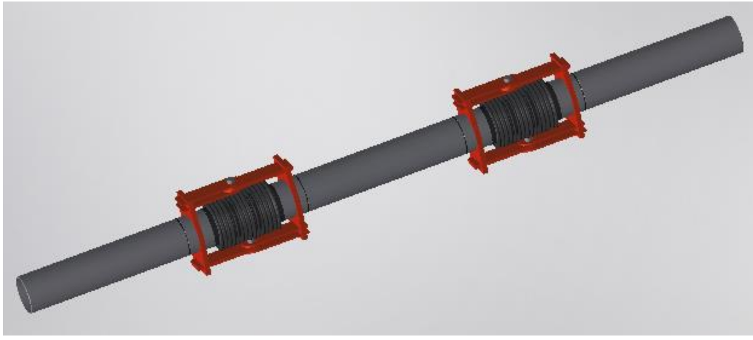


Figure 1: Schematic illustration of the introduction of hinged flexible joints in a pipeline

The research objective of this paper is the evaluation of the mechanical behavior of buried pipelines with flexible joints subjected to fault rupture and the demonstration of the advantages of flexible joints as mitigating measures against the consequences of faulting in terms of reducing the risk of pipe failure, provided that the technological and practical aspects of such joints are solved. Pipelines with flexible joints behave as segmented pipes under fault rupture and the response is characterized by rotations at the joints and small deformation of the parts between the pipes. However, the relative values of pipe – joint – soil stiffness render their actual response unknown and thus different parameters affecting the mechanical behavior due to faulting are examined, to identify the optimum range within which joints reduce the risk of pipeline failure. The study is carried out numerically through advanced nonlinear analyses.

2. PIPELINE – FAULT CROSSING

2.1 Details of pipeline finite element model

Among the two alternative pipeline modeling techniques, i.e. beam-type and continuum model, the beam-type model is more appropriate for practical applications, taking also into account the fact that several fault crossings will be encountered by a single pipeline traversing a seismic area, hence a large number of analyses will be required. Time and computational cost requirements can be significant parameters determining the acceptability of the continuum model by design engineers. The beam-type model is adopted hereinafter to investigate the mechanical behavior of continuous pipelines and pipelines with flexible joints to demonstrate the effectiveness of flexible joints in protecting buried pipelines against PGD.

The behavior of pipelines subjected to strike-slip fault movement is addressed, hence the pipeline deformation is assumed to take place within a horizontal plane. Schematic illustration of two successive stages of pipeline deformation subjected to strike-slip faulting is presented in Fig. 2. A planar fault with zero thickness is considered in the analysis, crossing a straight pipeline segment at the middle of its modeled length. The pipeline stress-state is directly related to the pipe – fault crossing angle β whose selection is related among others to the route selection procedure, seismological and geotechnical aspects of the seismic fault and the expected fault offset. Crossing angles $\beta \leq 90^o$ lead to pipeline bending and tension, while angles $\beta > 90^o$ lead to bending and compression [48] and their effect will be discussed later. Fault displacement Δ is parallel to the fault trace and is decomposed to the imposed pipeline displacements with respect to the crossing angle β: Δ_x along the pipeline axis and Δ_y perpendicular to the pipeline axis (Fig. 3).

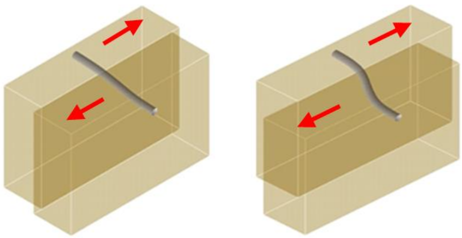


Figure 2: Schematic illustration of two successive stages of pipeline deformation due to strike-slip faulting

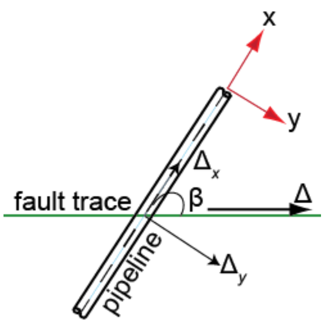


Figure 3: Pipeline – fault crossing site plan view

Pipeline numerical modeling is carried out using the general purpose finite element software ADINA [49]. The pipe is discretized into PIPE elements that are Hermitian 2-node beam-type finite elements with extra degrees of freedom to account for cross-section ovalization. A longitudinal mesh density equal to 0.25 m is selected after a mesh density sensitivity analysis is performed to define the optimum length of pipe elements with respect to accuracy and computational cost efficiency. Geometrical nonlinearity is considered in the analysis to account for the second order effects resulting from potential fault activation in the order of meters and cross-section ovalization. Soil modeling is carried out using discrete springs after ALA [20] provisions (Fig. 4). Elastic – perfectly plastic soil springs are modeled in ADINA using nonlinear SPRING elements that exhibit stiffness only in the local axial direction and connect pipe nodes to “ground” nodes. Soil “ground” nodes on the fault footwall are considered fixed, while the corresponding ones on the fault hanging wall are subjected to the imposed displacement caused by the fault movement. Non-seismic and in service actions (e.g. internal pressure, corrosion, overburden soil weight, hydraulic transient actions, etc.) are not considered in the present study.

Flexible joints can be modeled either as a general beam-type finite element with its stiffness matrix being constructed from the spring rates provided by the manufacturer, or as a generic flexible joint, represented by a rotational spring at the center point, without considering the joint length [50]. The second modeling approach for the joint has been adopted in the present study, namely by simulating the joint with a rotational spring, while the joint lateral and axial relative movements at the two ends are restrained. The joint torsional movement is generally prohibited by the manufacturers [51] and thus rotation about the longitudinal axis is restricted through appropriate constraints.

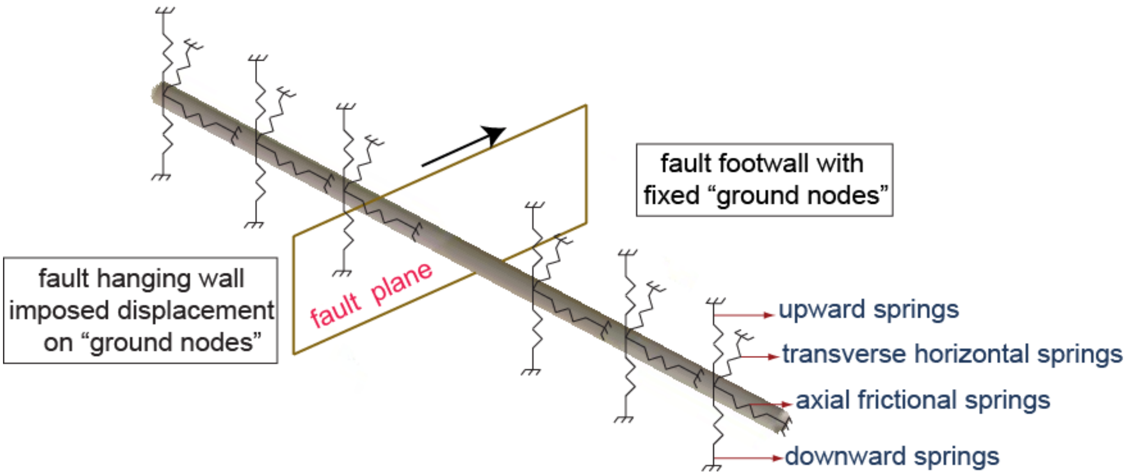


Figure 4: Beam-type finite element model of pipeline – fault crossing

The imposed displacements caused by fault movement evolve at an adequately slow rate that allows the engineer to neglect any dynamic phenomena, considering the fault offset as a quasi-static process [19],[20], [48]. Accordingly, fault rupture is treated herein is a static phenomenon. The problem’s inherent nonlinearity is handled through the implementation of the Newton-Raphson or Arc-Length solution algorithms [52]. Numerical convergence and smooth displacement application are achieved by selecting a proper number of analysis steps so that the external loading application follows closely the response evolution.

A typical high-pressure, large diameter natural gas pipeline is considered as a case study. The pipe’s modeled length is 1000 m, following a sensitivity analysis to define a sufficient length within which the soil reactions have vanished. The cross-section is of diameter D = 914 mm (36 in) and thickness t = 12.7 mm (0.5 in). Material nonlinearity is considered through an elastic – plastic bilinear law with isotropic hardening. Steel is of type API5L-X65 with the properties listed in Table 1. While pipeline steel is commonly modeled via the Ramberg-Osgood formula, in the present study nonlinear material modeling is actually of very minor importance, taking into account that the response of buried pipelines with flexible joints is well into the elastic range, as will be shown in the subsequent sections.

Table 1: API5L-X65 steel properties

Property	Value
Elastic Young's modulus (GPa)	210
Plastic Young' modulus (GPa)	0.464
Yield stress (MPa)	448.5
Yield strain (%)	0.214
Failure stress (MPa)	510
Failure strain (%)	18

The pipeline is assumed to be coal-tar coated and embedded under 1.30 m of granular loose sand with unit weight γ = 18kN/m^3, cohesion c = 0 and internal friction angle φ = 36°. The corresponding soil spring properties are estimated according to ALA provisions [20] and are listed in Table 2. Finally, flexible joints introduced in the pipeline exhibit rotational stiffness equal to 100 kNm/rad and angular capacity equal to 40° (e.g. [53],[54]). Note that in case of large diameter and high-pressure pipeline, excessive flexible joint rotation may be undesirable, as it may cause flow disruption.

Table 2: Soil spring properties

Spring type	Yield force (kN/m)	Yield displacement (mm)
Axial (friction)	40.69	3
Transverse horizontal	320.07	23
Vertical (upward displacement)	45.46	4.6
Vertical (downward displacement)	1493.65	114

2.2 Pipeline failure modes

Pipeline design against permanent ground displacements is carried out in strain terms, rather than stress terms. Strain Based Design (SBD) is the appropriate design approach in cases where stresses and strains are expected to exceed the proportional limit and the external loading is displacement-controlled. The SBD possesses a major advantage: when strain and stress are not proportional, stress-based methods may become very sensitive to the details of the material stress – strain behavior and to any safety factors. Codes and standards therefore adopt strain limits to evaluate the potential of the two main pipe failure modes:

(a) Tensile strains may rupture the pipeline wall at areas of strain concentration or defected locations. Areas of great concern are the girth welds between the adjacent pipeline parts, given that the pipeline is corrosion and defect free. Eurocode 8 [19] suggests a tensile limit of 5%, while ALA [20] an operable limit of 2% and a pressure integrity limit of 4%. However, taking also into account the concern regarding the integrity of girth welds and their capability to develop such high strains due to the metallurgical alterations induced by the steel heat-affected zone during the welding procedure, a suggestion in engineering practice is to further lower the tensile limit conservatively to 0.5% [30]. In the present study the code-based tensile limit of 2% by ALA is adopted.

(b) Compressive strains can cause local buckling of the pipeline wall and consequently lead to leak or rupture. Strain concentration leads to the formation of a wrinkle that extends over a short pipe length. The wrinkle then evolves to a local buckle as compression increases. Local buckling is handled by codes and standards as an ultimate limit state and compressive strain limit expressions are provided to avoid this critical condition. The ALA [20] operable limit is adopted here:

$$\varepsilon_c = 0.50\left(\frac{t}{D'}\right) - 0.0025, \text{ with } D' = \frac{D}{1 - 3\dfrac{D - D_{\min}}{D}} \tag{1}$$

where t is the pipe wall thickness, D the external diameter, E the pipe steel elastic modulus and $D_{\min}$ the pipe minimum inside diameter. The compressive strain limit equals 0.39%, after Eq. (1), for the pipeline under investigation.

3. NUMERICAL ANALYSIS RESULTS

3.1 Investigation of optimum number and locations of flexible joints

The primary consideration in adopting flexible joints as mitigating measures is to determine the optimum number and locations of the joints that minimize the cost and maximize the efficiency in terms of preventing failure through strain reduction. The joint locations are initially selected based on the bending moment distribution of the continuous pipeline caused by faulting, given that joints act as internal hinges in the structural system. Specifically, primary candidate locations for joints are the sections of maximum bending moment of the continuous pipeline on either sides of the fault trace. The distance between the maximum bending moment location and the fault trace is defined as L_j (Fig. 5). In strike-slip fault type the bending moment distribution is antisymmetric due to the symmetric lateral soil resistance. At this stage the uncertainty regarding the fault trace is disregarded.

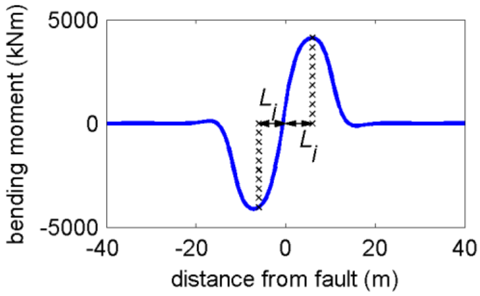


Figure 5: Definition of L_j length in bending moment distribution of a continuous pipeline

To investigate the best combination of joints, six different cases of pipes with joints are investigated with respect to length L_j (Table 3). Throughout this study, the continuous pipeline is abbreviated as CP and the pipeline with flexible joints as PFJ. The pipelines are assumed to intercept a strike-slip fault with crossing angle β = 90° and subjected to fault offset magnitude of Δ/D = 2. In the case under investigation the distance L_j equals 6.5 m.

Table 3: Cases of pipelines with flexible joints under investigation

Case	**Number of joints**	**Joints location**
2PFJ	2	$-L_j$, $+L_j$
3PFJ	3	$-L_j$, 0, $+L$
4PFJ(1)	4	$-L_j$, $-L_j/2$, $+L_j/2$, $+L_j$
4PFJ(2)	4	$-2L_j$, $-L_j$, $+L_j$, $+2L_j$
6PFJ(1)	6	$-3L_j/2$, $-L_j/2$, $-L_j$, $+L_j/2$, $+L_j$, $+3L_j/2$
6PFJ(2)	6	$-2L_j$, $-L_j$, $-L_j/2$, $+L_j/2$, $+L_j$, $+2L_j$

The effectiveness of flexible joints for very significantly decreasing the bending moment in all PFJ cases is demonstrated in Fig. 6. It is noted that, for this crossing angle β = 90°, the pipeline behavior is predominantly flexural, corresponding to optimum conditions for hinge-type flexible joints, as pipe axial strains are practically zero. The bending moment reduction with respect to the continuous pipeline is also quantified in Table 4, accompanied also by the maximum rotations of all joints for all PFJ cases. The maximum moment reduction is reported in 4PFJ(1), 6PFJ(1) and 6PFJ(2) cases, while cases 2PFJ, 3PFJ and 4PFJ(2) exhibit smaller reduction. In cases 4PFJ(2), 6PFJ(1) and 6PFJ(2) the joints that are located beyond L_j distance (±2L_j and ±3L_j/2) exhibit almost zero rotation, while joints located at L_j/2 in 4PFJ(1), 6PFJ(1) and 6PFJ(2) cases exhibits the same rotation, as well as joints at L_j in 2PFJ and 4PFJ(2) cases. Hence, the optimum case is 4PFJ(1), as joints located beyond L_j distance nearly do not rotate (shown also in Fig. 6) and consequently they are inactive. The case 4PFJ(1) of the pipeline with four joints located at distances L_j and L_j/2 on each side of the fault trace (abbreviated in the following for simplicity as PFJ) is hence adopted hereinafter to further investigate the parameters affecting the joint's efficiency.

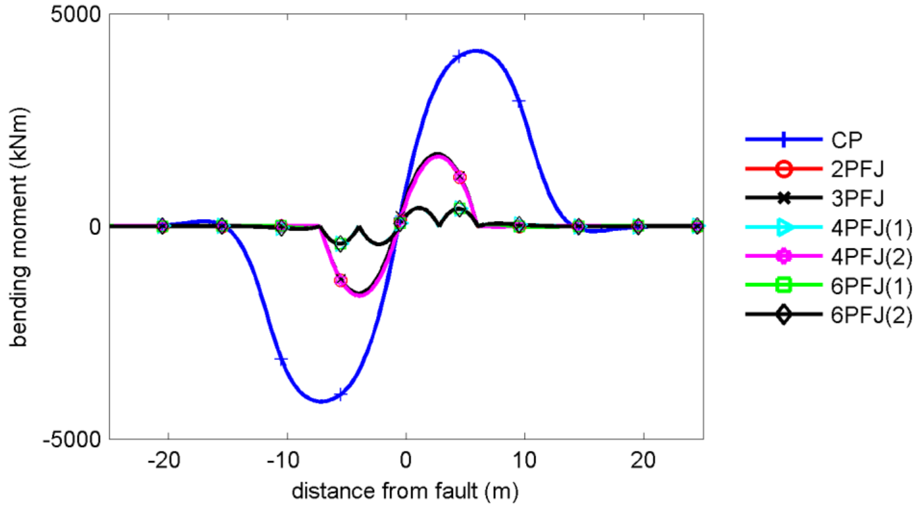


Figure 6: Bending moment distributions of continuous pipeline and pipelines with flexible joints subjected to strike-slip faulting

Table 4: Maximum bending moment reduction with respect to the continuous pipeline and joint rotation in all cases of pipelines with flexible joints

Case	**Number of joints**	**Bending moment reduction (%)**	**Maximum joint rotation (º)**
2PFJ	2	60.29	8.39
3PFJ	3	59.86	8.24
4PFJ(1)	4	89.64	8.10
4PFJ(2)	4	60.29	8.39
6PFJ(1)	6	89.64	8.10
6PFJ(2)	6	89.64	8.10

3.2. Response features of pipeline with flexible joints

The introduction of flexible joints in a buried steel pipeline modifies the structural system from continuous to segmented. In order to evaluate and quantify this effect, the continuous pipeline (CP) and the pipeline with four flexible joints (PFJ), as obtained from section 3.1, are examined in more detail. The pipeline displacements are plotted in Fig. 7, indicating a smooth curved shape for CP, while PFJ follows a piece-wise linear shape. Furthermore, axial forces and bending moments are compared in Fig. 8.

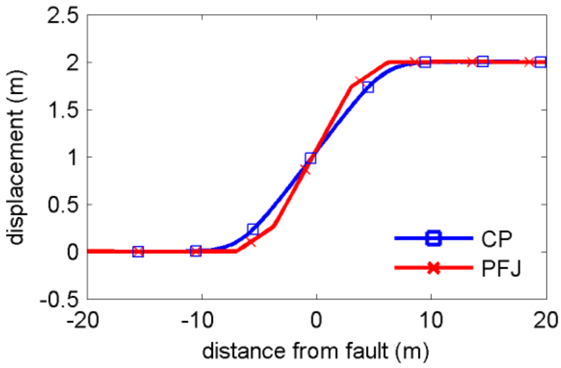
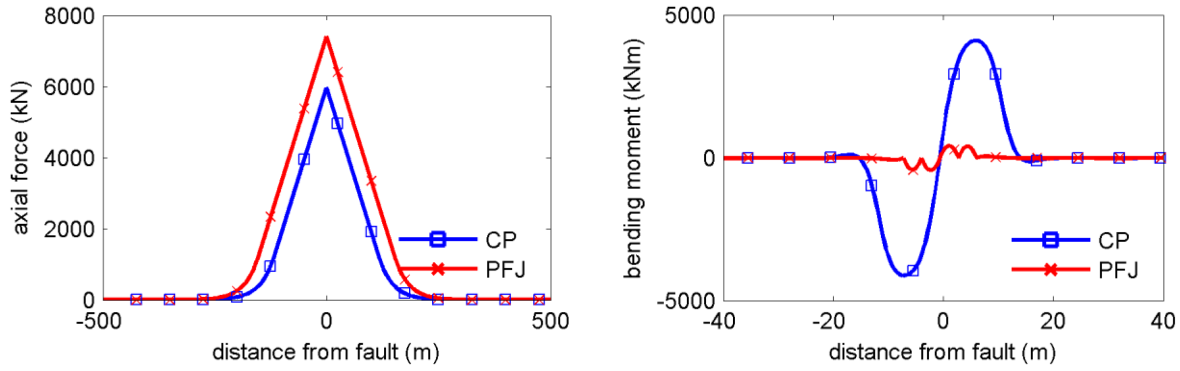


Figure 7: CP and PFJ displacements

It is observed that the implementation of flexible joints leads to a very significant decrease of bending moment (Fig. 8b), while a minor increase in axial force is observed (Fig. 8a). The pipeline response is dominated by bending and thus the hinged joints reduce bending moment, while the axial force is marginally increased. The introduction of flexible joints also leads to an important reduction of longitudinal maximum effective stresses, as shown in Fig. 9. The stress distribution along the pipeline is symmetric around the fault trace, given the strike-slip faulting and the symmetric soil response to any lateral pipeline movement in the trench.



(a) (b)

Figure 8: (a) Axial force and (b) bending moment distributions of CP and PFJ

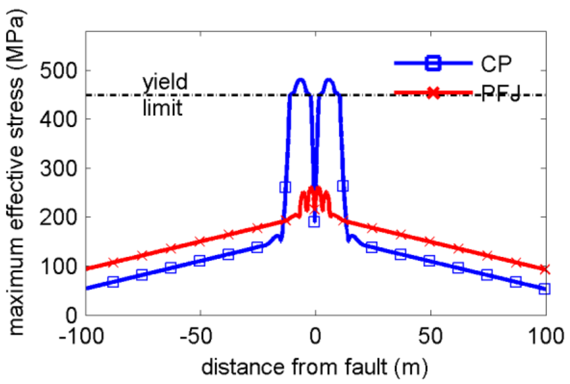
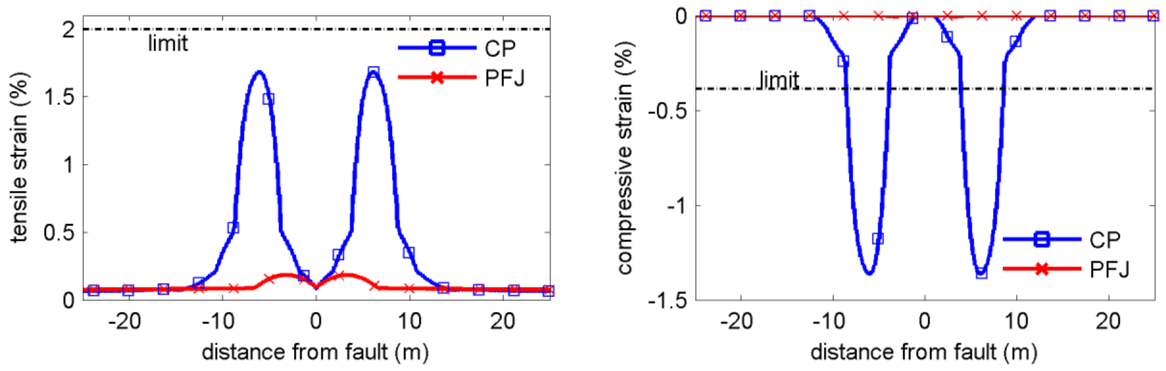


Figure 9: Maximum effective stress distributions along CP and PFJ

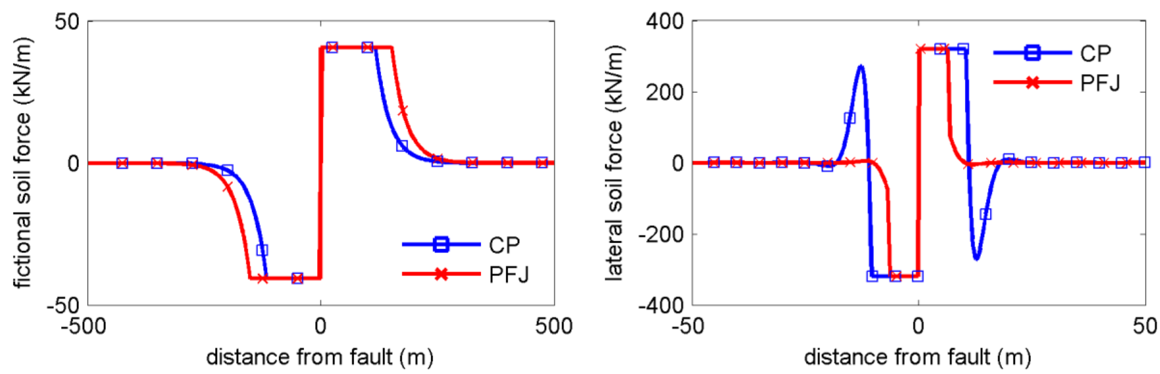
As the pipeline design against permanent ground displacements is carried out in strain terms, it is crucial to identify the PFJ response in terms of developing longitudinal strains, which are the summation of axial and bending strains. The longitudinal tensile strains are illustrated in Fig. 10a and the compressive strains in Fig. 10b, respectively, both indicating that the flexible joints contribute decisively to a sharp decrease of strains, thus minimizing the potential of pipeline failure due to either tensile fracture or local buckling. The compressive strains are particularly reduced, practically vanishing. The strain reduction is explained by the structural system's modification from continuous to segmented, as strains are concentrated at the joints, retaining the steel pipe parts nearly undeformed. The longitudinal strain distributions (Fig. 10) in combination with axial force (Fig. 8a) and bending moment (Fig. 8b) distributions lead to the conclusion that bending strains are much higher than axial strains and thereby hinged joints are the appropriate joint type for strike-slip faults.



(a) (b)

Figure 10: Longitudinal (a) tensile and (b) compressive strain distributions along CP and PFJ

The modification of the pipeline deformed shape due to faulting effected by the integration of flexible joints (Fig. 7) has also some effect on the soil response due to pipeline movement in the trench. This is depicted by the frictional soil force distribution along CP and PFJ (Fig. 11a), showing a minor increase in the soil plastification length around the fault vicinity, while increase of the soil plastification length regarding the lateral soil response is observed for PFJ in Fig. 11b.



(a) (b)

Figure 11: (a) Frictional soil force and (b) lateral soil force distributions along CP and PFJ

4. PARAMETRIC STUDIES

4.1 Pipeline under bending and tension

The pipeline – fault crossing angle β is a dominant parameter of the pipeline mechanical behavior due to strike-slip faulting. The major effect of angle β is its influence on the relationship of pipe developing tension and bending moment with respect to the fault movement magnitude. When angle β tends to 90º, the pipeline intercepts the fault plane nearly perpendicularly and bending dominates the response. Tension is the primary stress-state when angle β is lower, as the pipeline tends to become parallel to the fault trace. It is thus essential to investigate the impact of the crossing angle β on the response of pipelines with flexible joints. The integrated joints act as internal hinges in the structural system and consequently their efficiency depends on the degree of flexural versus axial response. Within this framework, a continuous pipeline and the corresponding pipeline with four flexible joints are investigated. The joints are located in each case according to the procedure described in section 3.1. Three characteristic crossing angles are considered, namely β = 50º, β = 70º and β = 90º. The maximum fault movement is assumed equal to Δ/D = 4.

The displacements of the continuous pipeline (CP) and the pipeline with four flexible joints (PFJ) are illustrated in Fig. 12, where on the horizontal axis the distance from the fault trace is presented and on the vertical axis the normalized pipeline displacement with respect to pipe diameter is shown. Three indicative cases regarding the fault displacement are illustrated, namely Δ/D = 0.5, Δ/D = 2 and Δ/D = 4, to demonstrate the effect of the fault offset magnitude. In all cases the joint angular demand is well below the 40º capacity, as the highest joint rotation reported equals 8.10º. Increasing fault offset and decreasing angle β lead to more intense pipe tension than bending and consequently the differences between the CP and the PFJ deformations tend to be negligible.

The effect of angle β on the pipe response is clearly demonstrated through the comparison of developing axial forces and bending moments on CP and PFJ in Fig. 13 and Fig. 14, respectively. The maximum developing axial force (N_{max}) with respect to the fault offset (Δ/D) is depicted in Fig. 13 for three different crossing angles β. The major outcome is that N_{max} is proportional to fault offset. Additionally, as angle β increases to β = 90º, more tension is developed in PFJ than in CP. The maximum developing bending moment (M_{max}) with respect to the fault offset (Δ/D) is illustrated in Fig. 14 for three different crossing angles β. The efficiency of the integrated hinged joints increases as angle β increases and the pipeline crosses the fault trace close to perpendicularly. Another aspect is that the increasing fault offset leads to the decrease of the difference between the M_{max} of the CP and the PFJ. At the same time, as angle β decreases, tension dominates the pipe behavior and this difference is almost eliminated.

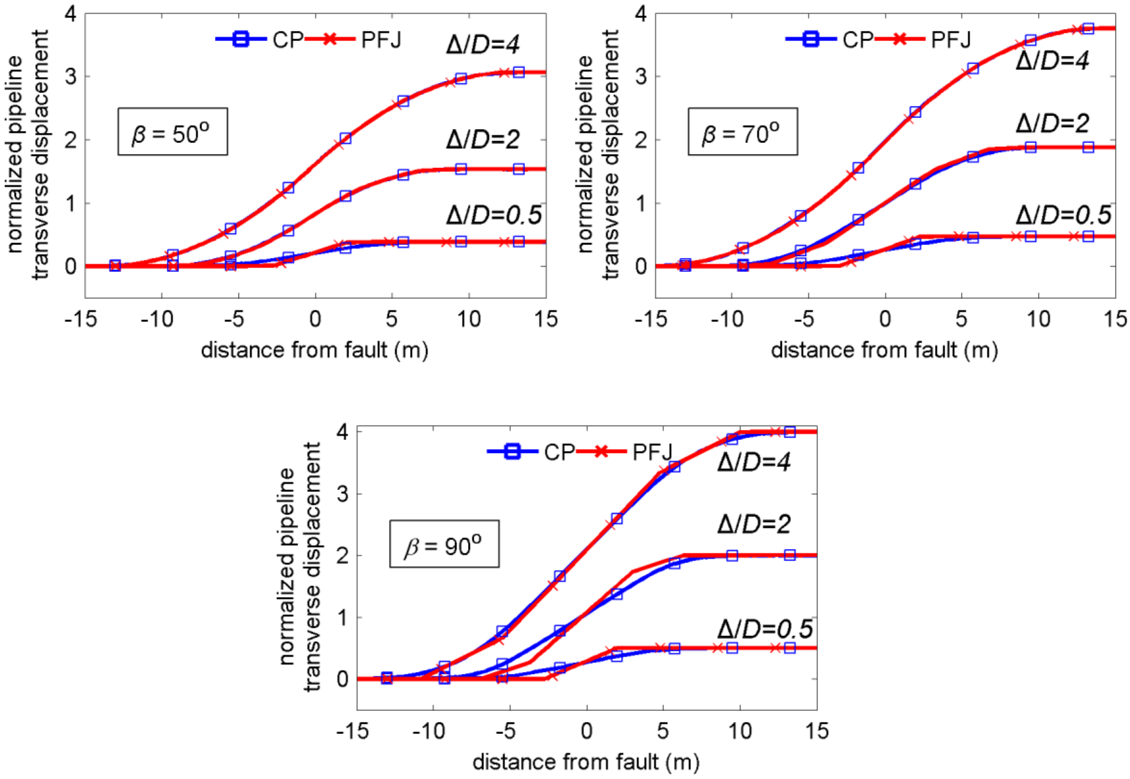


Figure 12: CP and PFJ displacements for β = 50°, β = 70° and β = 90°

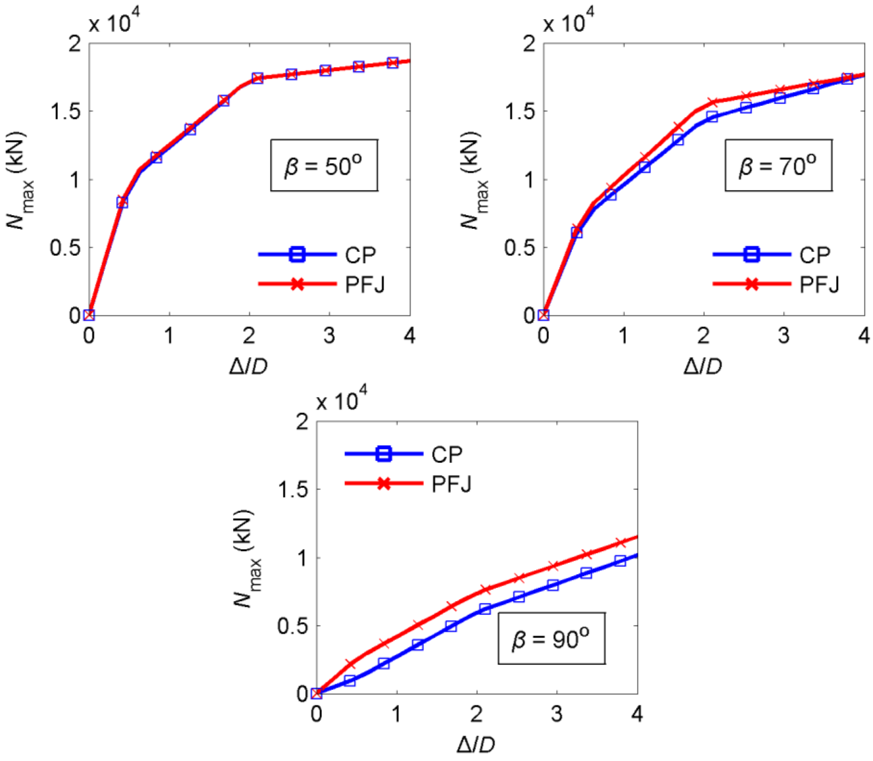


Figure 13: Maximum axial force (N_{max}) of CP and PFJ with respect to fault offset (Δ/D) for $\beta = 50^{o}$, $\beta = 70^{o}$ and $\beta = 90^{o}$

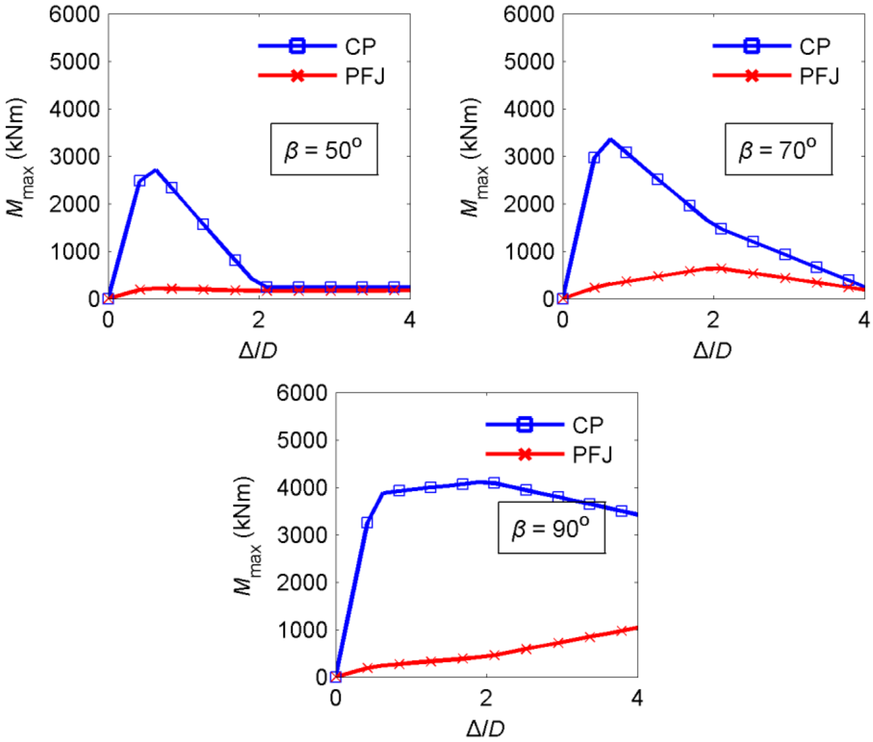


Figure 14: Maximum bending moment (M_{max}) of CP and PFJ with respect to fault offset (Δ/D) for $\beta = 50^{o}$, $\beta = 70^{o}$ and $\beta = 90^{o}$

The maximum developing longitudinal tensile strain ($\varepsilon_{t,\max}$) of CP and PFJ with respect to the fault offset (Δ/D) is shown in Fig. 15 for the three different crossing angles β. The tensile strain limit of 2% is also presented with a dashed straight line. The development of tensile strains is directly dependent on the crossing angle β. Thus, the decrease of β increases the importance of tension and thereby in case of β = 50º, joints do not provide strain reduction. It is noted that within a range of fault displacement ($0.5 \leq \Delta/D \leq 2$), the rate of strain increase (for both CP and PFJ) is very low due to the transition from dominant flexural to axial pipe behavior, i.e. the bending strains decrease and the axial strains increase with their summation being more or less constant. In the intermediate case of β = 70º, joints sufficiently prevent tensile fracture by "keeping" strains below the code-based limit, up to $\Delta/D \approx 3$. For larger imposed displacements the pipe stretching dominates and the entailing tension cancels the joint's efficiency in strain reduction. The maximum tensile strain decrease is achieved for β = 90º, which is in general the most desirable case for a safe and economically efficient design of a pipeline – fault crossing. The maximum developing compressive strains ($\varepsilon_{c,\max}$) of CP and PFJ with respect to fault offset are presented in Fig. 16 for the same three cases of angle β. Results reveal that pipelines with flexible joints develop very low, almost negligible, compressive strains, hence the potential of local buckling is avoided in all cases.

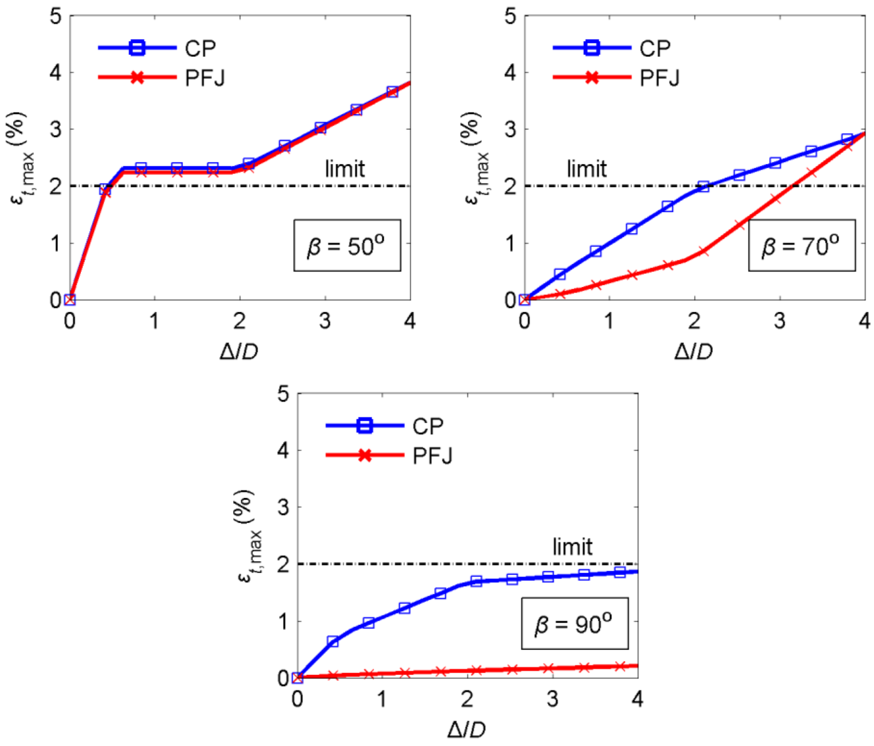


Figure 15: Maximum longitudinal tensile strain ($\varepsilon_{t,\max}$) of CP and PFJ with respect to fault offset (Δ/D) for β = 50°, β = 70° and β = 90°

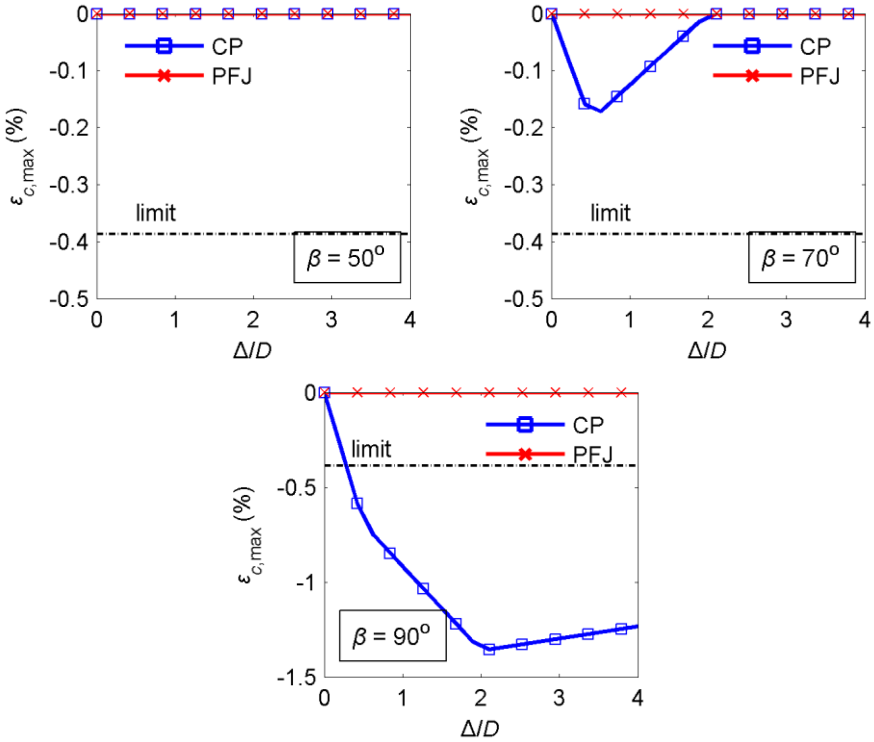


Figure 16: Maximum longitudinal compressive strain ($\varepsilon_{c,\max}$) of CP and PFJ with respect to fault offset (Δ/D) for β = 50°, β = 70° and β = 90°

The numerical evaluation of pipelines with flexible joints crossing a strike-slip fault with angle β equal or lower to 90º indicates that the introduction of joints is in most cases a very effective countermeasure that can notably protect a buried steel pipeline against the consequences of faulting. The joints performance is directly related to the pipe – fault crossing angle. The strain reduction is maximized when the pipeline crosses the fault plane close to β = 90º. For β < 70º in combination with higher fault displacements, joints tend not to contribute to the pipe protection in terms of strain reduction. In such cases, the use of joints that are capable of undergoing some axial displacement, in addition to rotation, would be more beneficial.

4.2 Pipeline under bending and compression

While in case of tension pipe integrity can rely on the steel post-yielding strength, in case of compression local buckling can lead to pipe failure at much lower absolute strain levels. Pertinent standards and provisions, as well as engineering practice, suggest to avoid crossing angles β > 90º, which would result in the development of bending and excessive compression along the pipe. Crossing angles β > 90º might, however, be unavoidable due to limitations encountered in the route selection procedure, or it might occur unintentionally, due to insufficient data regarding the fault behavior. The repercussions of such values of angle β on the pipeline response are again investigated through the numerical evaluation of a continuous pipeline (CP) and a pipeline with four flexible joints (PFJ). The pipes are assumed to intercept the fault plane with angles β = 100º, β = 110º and β = 120º, selected in light that β > 90º is an undesirable design approach and thus higher values would be unrealistic in common design practice. The maximum fault offset is assumed to be Δ/D = 2.

Indicative results regarding the CP and PFJ displacements for all crossing angles are illustrated in Fig. 17, where the distance from the fault trace is presented on the horizontal axis and the normalized transverse pipe displacement on the vertical axis. The comparison of pipe displacements between cases of β < 90º and β > 90º reveals that compression magnifies the difference between CP and PFJ displacements due to pipe shortening and intense joint rotation. The intense PFJ displacement compared to CP is the cause of the effectiveness of joints in all cases of β > 90º, as will be shown later. The maximum joint rotation reported in the results equals 39.9º and consequently the PFJ is severely deformed, having practically encountered global instability. It is therefore necessary to pay special attention to the angular capacity of the joint in terms of providing rotational capacity "overstrength".

The introduction of flexible joints leads in general to a significant decrease of the pipe stress-state in terms of developing axial forces, bending moments and longitudinal strains for the crossing angles β = 100º, β = 110º and β = 120º under consideration. In more details, the maximum developing compressive force ($N_{\max}$) with respect to the fault offset is depicted in Fig. 18. Axial compressive forces of PFJ are much lower than CP due to the pipe deformation. The maximum developing bending moments ($M_{\max}$) with respect to the fault offset (Δ/D) are presented in Fig. 19, illustrating that bending moments of PFJ are several times lower than those of CP. Coming to the safety checking, the maximum tensile strains ($\varepsilon_{t,\max}$) and compressive strains ($\varepsilon_{c,\max}$) of CP and PFJ with respect to fault offset (Δ/D) are shown in Fig. 20 and Fig. 21, respectively, along with code-based strain limits. Tensile strains increase as the fault offset increases, but in general they decrease as the crossing angle increases due to the higher compression. In either case, tensile strains of PFJ are almost negligible, thus ensuring the integrity of girth welds. Regarding, then, the compressive strains, one can notice (Fig. 21) that the CP is going to suffer severe damage, mainly due to local buckling, even for relatively small fault offset (Δ/D < 0.5). Developing compressive strains of CP for Δ/D > 0.5 are too high in practice to be fairly compared with the corresponding ones of PFJ in the same chart for $0 \leq \Delta/D \leq 2$. It then follows that flexible joints in buried pipelines with β > 90º can very efficiently protect the pipe against local buckling in all cases under consideration.

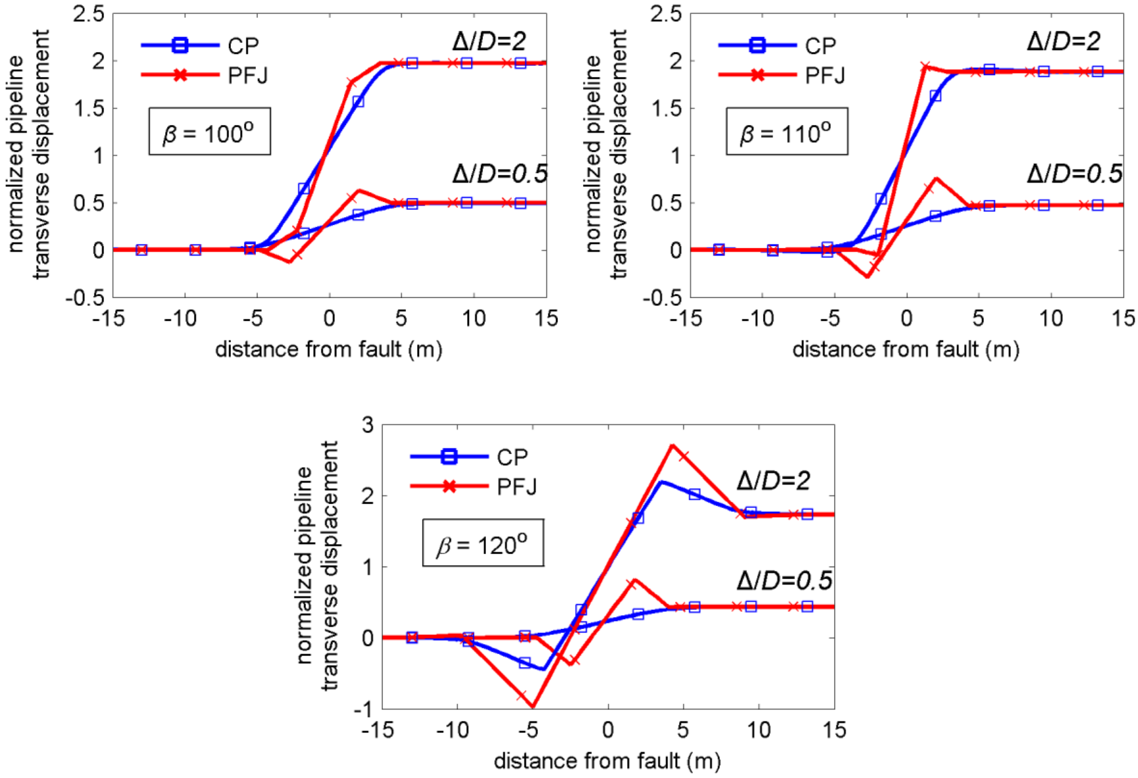


Figure 17: CP and PFJ displacements for β = 100°, β = 110° and β = 120°

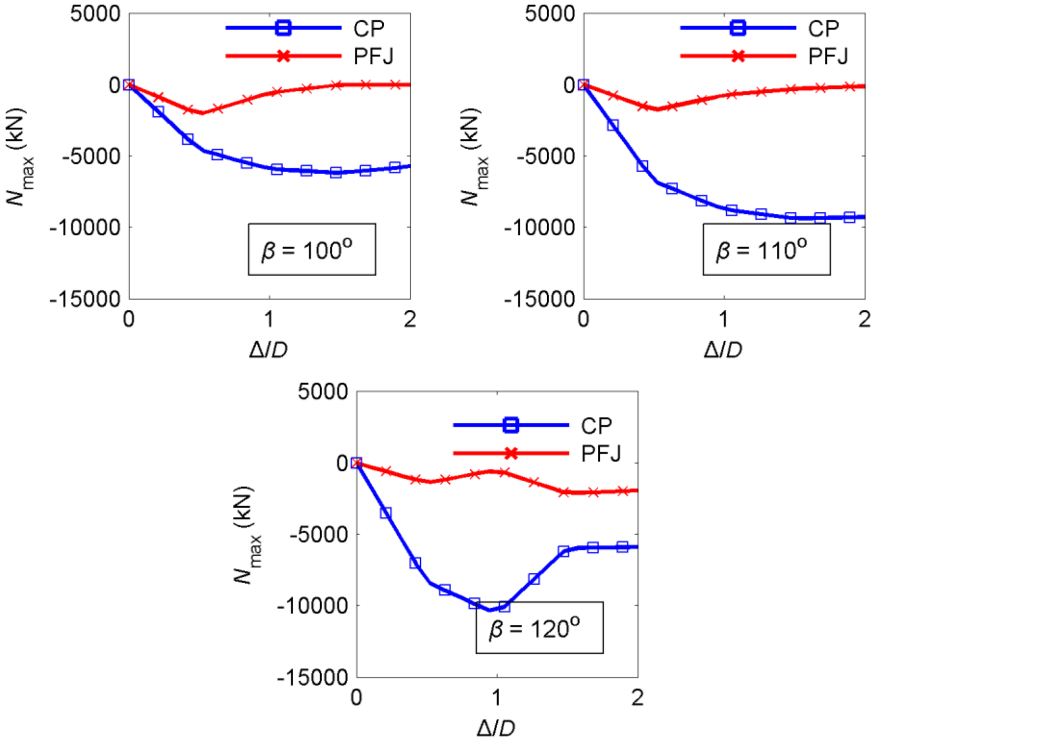


Figure 18: Maximum axial force (N_{max}) of CP and PFJ with respect to fault offset (Δ/D) for β = 100°, β = 110° and β = 120°

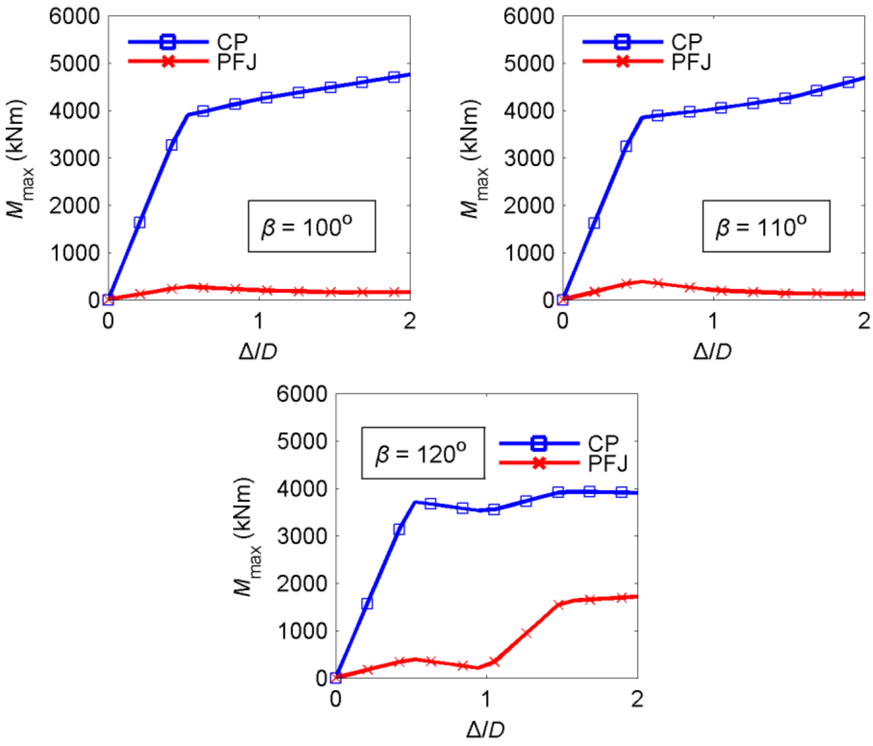


Figure 19: Maximum bending moment ($M_{\max}$) of CP and PFJ with respect to fault offset (Δ/D) for $\beta = 100^{o}$, $\beta = 110^{o}$ and $\beta = 120^{o}$

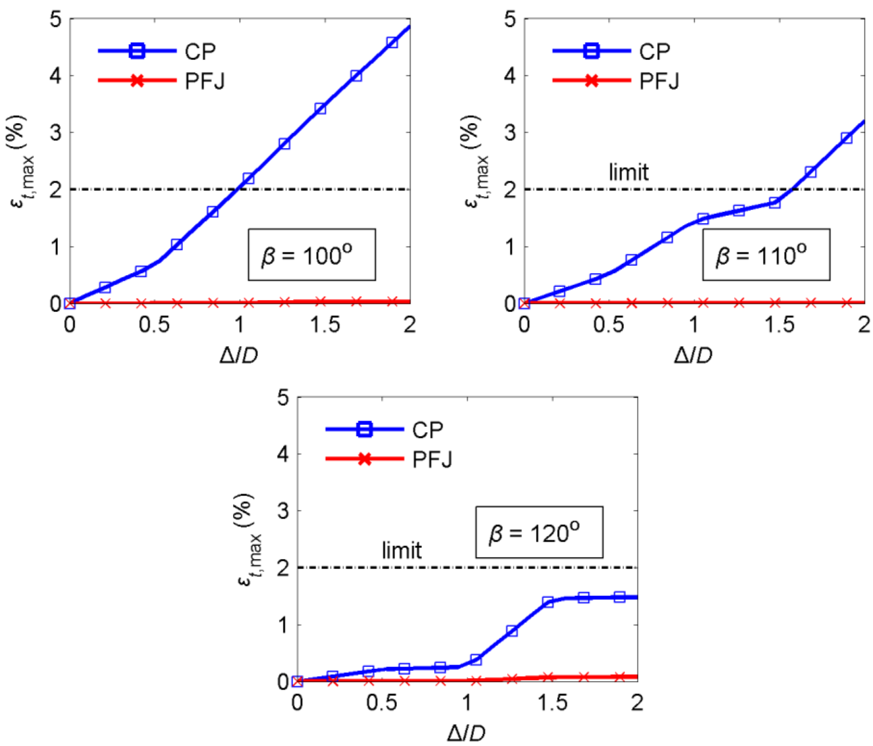


Figure 20: Maximum longitudinal tensile strain ($\boldsymbol{\varepsilon}_{t,\max}$) of CP and PFJ with respect to fault offset (Δ/D) for $\beta = 100^{o}$, $\beta = 110^{o}$ and $\beta = 120^{o}$

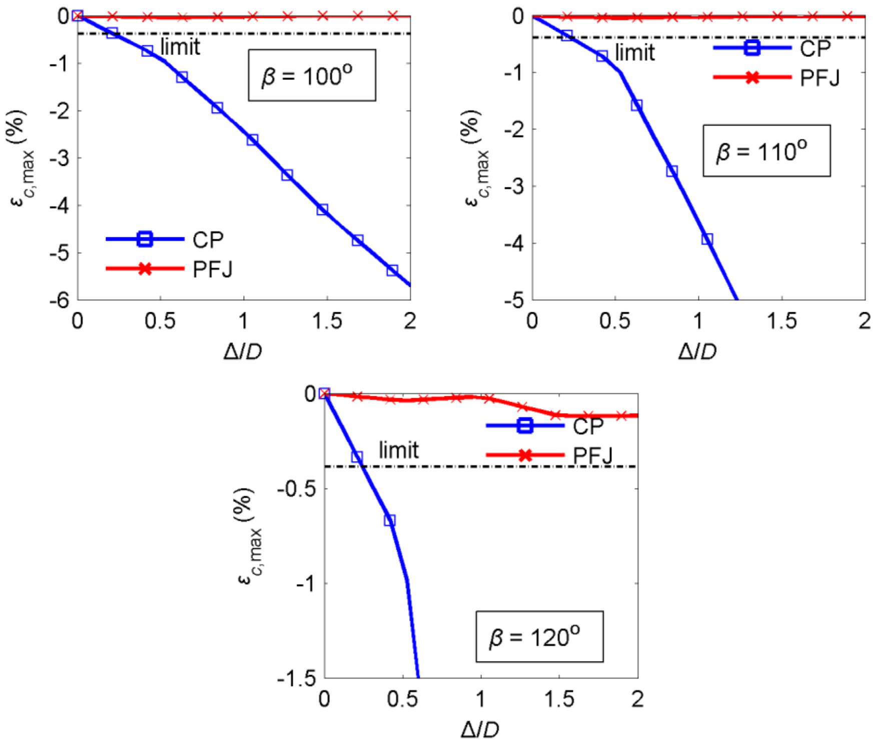
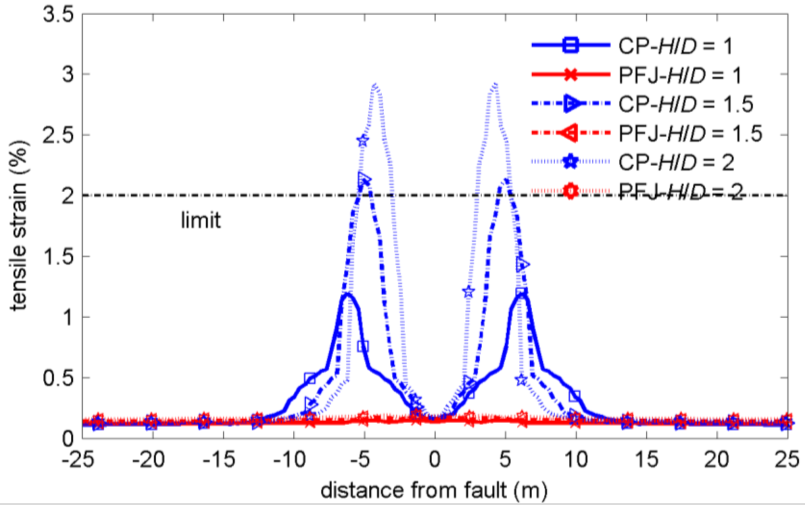


Figure 21: Maximum longitudinal compressive strain ($\varepsilon_{c,\max}$) of CP and PFJ with respect to fault offset (Δ/D) for β = 100°, β = 110° and β = 120°

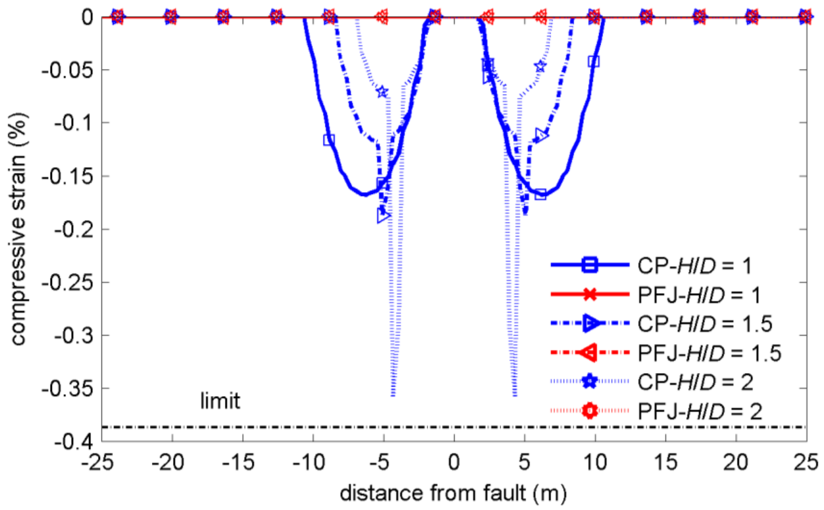
4.3 Effect of burial depth

Oil and gas pipelines are usually embedded in a trench to be protected against corrosion and third party damage. Soil response to any pipe movement in the trench is related to the pipe burial depth that defines the level of soil pressure acting on the pipe. In numerical modeling, increase of burial depth leads to stiffer soil springs and consequently pipeline movement in the trench becomes more difficult, thus the pipe developing stress-state is higher. It is therefore meaningful to investigate the effect of burial depth on the strain reduction efficiency of flexible joints. Engineering and constructional practice suggest that the burial depth equals about one to two times the pipe diameter in fault crossings. The pipeline under investigation is considered to intercept a strike-slip fault with crossing angle β = 70° and subjected to Δ/D = 1 of fault offset, representing a typical case. Three cases of burial depths for the continuous pipeline (CP) and the corresponding pipeline with flexible joints (PFJ) are considered, namely H/D = 1, H/D = 1.5 and H/D = 2, where H is the soil height above the top of the pipe.

Pipeline response is examined through the longitudinal tensile and compressive strain distributions (Fig. 22). The increase of burial depth leads to strain increase for the continuous pipeline, as expected due to stiffer soil springs, and threatens its integrity in terms of exceeding code-based tensile strain limit. On the contrary, nearly negligible differences are reported for PFJ cases regarding the strain reduction on the steel pipe parts due to the integration of flexible joints. The effect of burial depth on joints efficiency can be thus described as negligible.



(a)



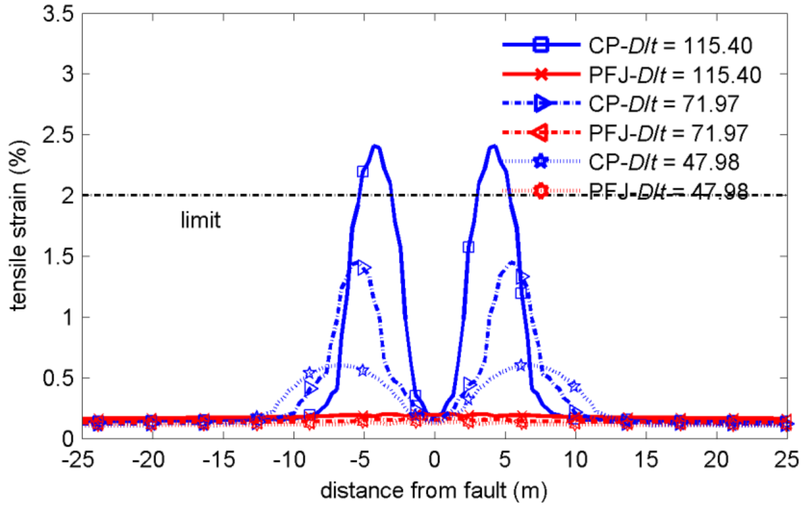
(b)

Figure 22: (a) Tensile and (b) compressive strain distributions of CP and PFJ for various burial depths (*H*/*D*)

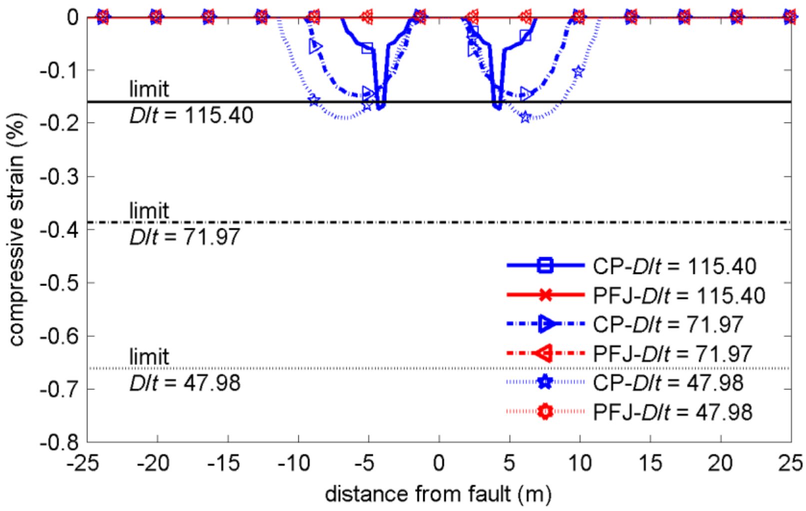
4.4 Effect of *D*/*t* ratio

The geometry of the pipeline cross-section is defined though the process analysis of the pipeline system and in particular pipe diameter (*D*) and wall thickness (*t*) are related to operating flow, temperature, pressure, etc. The diameter over thickness ratio (*D*/*t*) plays a dominant role in the pipeline response and especially on buckling behavior, as it defines the pipe slenderness. Shallowly buried pipelines with low *D*/*t* under compression may buckle upwards as a beam, while deeper buried pipes with higher *D*/*t* tend to buckle locally [55]. The *D*/*t* ratio is therefore a significant parameter, whose effect on pipelines with flexible joints is hereafter examined by considering CP and PFJ crossing a strike-slip fault with angle β = 70º and subjected to $\Delta/D = 1$ of fault movement. Pipe diameter is considered to be constant *D* = 914mm, while three cases of commercial thickness values are considered, namely *t* = 7.92mm, *t* = 12.70mm and *t* = 19.05mm. The corresponding ratios are then *D*/*t* = 115.40, *D*/*t* = 71.97 and *D*/*t* = 47.98.

The tensile and compressive strain distributions for all cases are illustrated in Fig. 23. The first important observation for CP is that higher *D*/*t* ratios increase the structure's slenderness and consequently higher strains are developed due to reduced stiffness. The integration of flexible joints between the pipe adjacent parts transforms the structural system from continuous to segmented and the effect of ratio *D*/*t* is almost eliminated. The latter is verified by the strain distributions of PFJs that indicate almost no interaction between the ratio *D*/*t* and flexible joints effectiveness in terms of reducing strains.



(a)



(b)

Figure 23: (a) Tensile and (b) compressive strains distributions of CP and PFJ for various *D*/*t* ratios

5. UNCERTAINTY REGARDING FAULT TRACE

The analysis of buried pipeline – fault crossing is usually based on the assumption of a planar fault, intercepting the pipeline at a specific location. Optimum locations of hinged joints have then been defined in the previous sections with respect to this assumption. These approaches, however, can be violated in nature by the native soil conditions. Soil stratigraphy may affect the direction of rupture propagation to the surface. In case the native soil conditions are rocky, the rupture propagation from the underlying bedrock to the ground surface may not be disturbed and thus the planar fault assumption is sufficiently accurate. Nevertheless, the upper soil layers are usually earth fill with inhomogeneous properties (e.g. alluvial deposits) that can alter the rupture propagation to the surface. This can result to a shift of the fault trace from where it is expected to appear on the ground surface. The fault trace uncertainty is not usually considered in the pipe – fault crossing analysis, and in practice design engineers deal with the fault trace uncertainty by applying seismic countermeasures over the entire pipe length, in which the fault trace may be encountered. The latter is estimated by seismological, geological and geotechnical surveys and can range from a few meters to a few hundred meters. Regarding, then, the application of flexible joints as mitigating measures by considering the fault trace uncertainty, this same approach has to be adopted. The important question that arises is regarding the optimum configuration of flexible joints, assuming that joints shall be integrated in the pipeline at equal distances for practical and constructional reasons. In order to address this task, the following procedure is proposed:

- Estimation of the length over which the fault may “appear” on the ground surface.
- Analysis of a continuous pipeline subjected to the maximum fault offset, as defined by relevant geological and seismological studies of the area, by assuming the theoretical fault trace being located at the middle of the length of uncertainty.
- Plot of the bending moment distribution of the continuous pipeline and estimation of distance L_j (Fig. 6), which is the distance between the assumed fault trace location and the maximum bending moment location.
- Integration of a flexible joint at the theoretical fault trace location and consequently at distances equal to L_f on each side of the fault trace, as schematically illustrated in Fig. 24. Additionally, two joints are introduced outside the “borders” of uncertainty area, in order to address the worst case scenario of the fault being activated at the margins of the uncertainty area.

– Estimation of the optimum distance L_f, by considering the fault trace being located either between two flexible joints or closer to a joint.

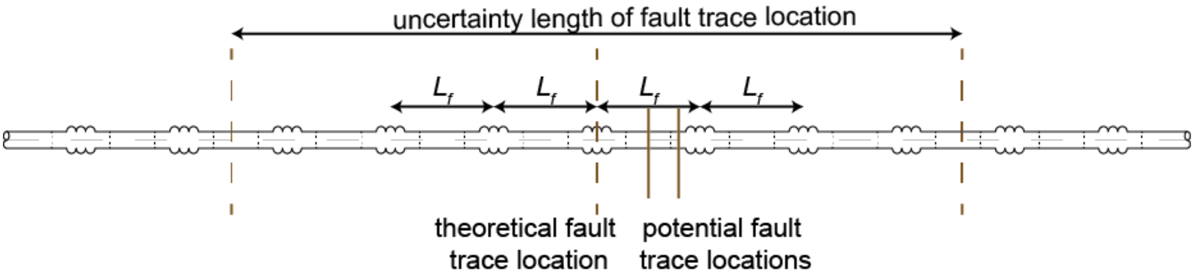
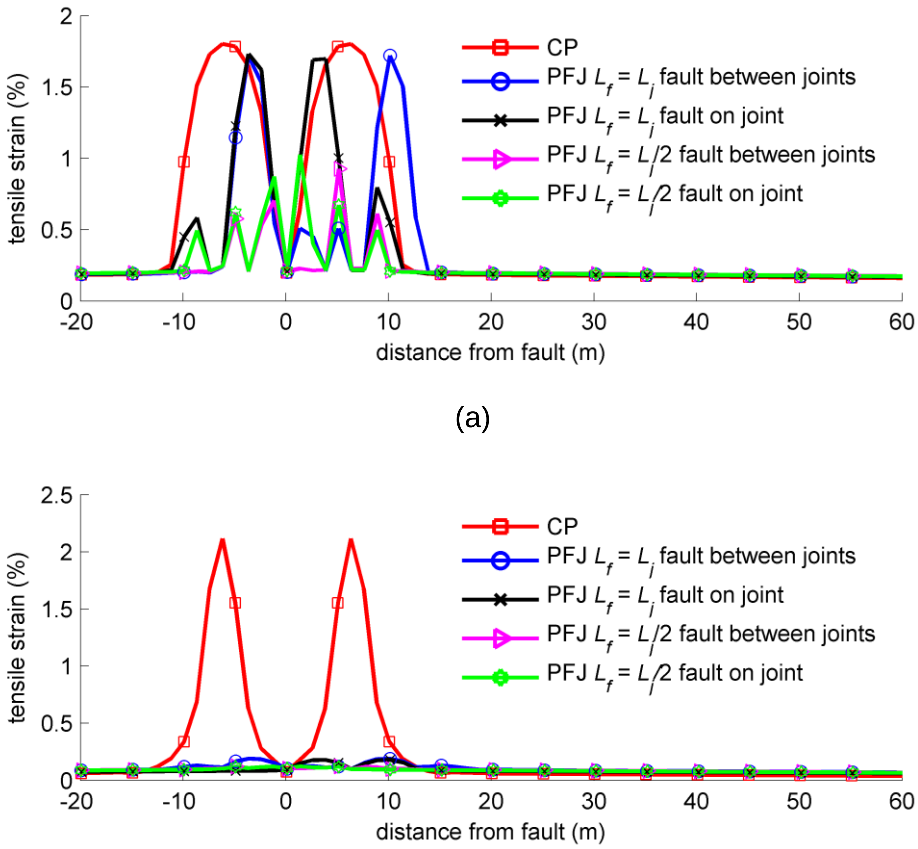


Figure 24: Configuration of flexible joints over the length of fault trace uncertainty and potential fault trace locations

An essential part of the procedure regarding the integration of flexible joints over the length of fault trace uncertainty is the estimation of distance L_f. Taking into account that the optimum configuration of joints for a given fault trace location is at distance $L_j/2$ between two joints and the fault trace, analyses are carried out consequently, assuming that $L_f = L_j/2$ or $L_f = L_j$. The potential fault trace locations for each case are depicted in Fig. 24. The pipeline with flexible joints (PFJ) is subjected to strike-slip fault offset of magnitude Δ/D = 2 and the pipeline – fault crossing angle is assumed to be equal to β = 70° and β = 90°. The continuous pipeline (CP) is also considered for reference. The distributions of tensile strains along the pipeline are depicted in Fig. 25. It is observed that regardless of the fault trace location, the optimum configuration of flexible joints in terms of reducing the developing tensile strains is at distance $L_f = L_j/2$ for crossing angle β = 70°. On the contrary, for β = 90° it is observed that both configurations, namely $L_f = L_j$ and $L_f = L_j/2$, are roughly equally efficient and thus for pipeline – fault crossing close or equal to perpendicularity it is suggested that joints are integrated at distance $L_f = L_j$ in order to minimize the cost. It is noted that if there is uncertainty regarding the pipe – fault crossing angle β, then joints should be integrated at distance $L_f = L_j/2$ in order to address the worst case scenario.



(a)

(b)

Figure 25: Tensile strain distributions for crossing angle (a) β = 70º and (b) β = 90º considering different configuration of flexible joints and fault trace being located either between two adjacent joints or at a joint

6. SUMMARY AND CONCLUSIONS

Buried steel pipelines with flexible joints subjected to strike-slip fault offset have been investigated using advanced numerical modeling and nonlinear analysis, employing the beam-type model. The flexible joints of hinged bellow-type are proposed as innovative mitigating measures against the consequences of faulting on the pipeline. They are introduced in continuous pipes to concentrate strains at the joints and retain the steel pipe parts virtually unstressed. The presented numerical study stands as a preliminary feasibility study of the effectiveness of joints in terms of reducing the developing longitudinal tensile and compressive strains and consequently reducing the risk of pipe failure. Taking also into account that hinged bellow-type flexible joints have not been used before as seismic countermeasures in buried pipes subjected to fault rupture, it is emphasized that technological and practical aspects of such joints must be solved before actual application. Thus, by demonstrating and quantifying the structural advantages of the proposed approach, the present study aims at motivating further industrial research towards addressing these practical aspects.

The optimum number and location of flexible joints on the pipeline were examined in case of strike-slip faulting, while the main parameters affecting their efficiency were investigated, namely pipeline – fault crossing angle, fault offset magnitude, burial depth and ratio D/t. Additionally, the uncertainty on fault trace was addressed and suggestions were formulated for practical applications. The main conclusions of the present study can be summarized as follows:

1. Metallic hinged bellow-type flexible joints are the appropriate type of commercial flexible joints for buried pipeline – fault crossing applications. Such joints exhibit low rotational stiffness, while the axial and lateral relative movements are constrained, to withstand large internal pressure and pipe movements due to faulting.
2. The introduction of flexible joints transforms the pipeline structural system from continuous to segmented. Numerical results indicated significant strain reduction due to the integration of joints, as imposed deformation is now absorbed by rotation at the joints.
3. Parametric studies carried out showed that the joints' efficiency is maximized for crossing angles β closer to 90°, where bending moment dominates the pipeline behavior. As angle β decreases and fault offset increases, tension dominates the pipe behavior and joints' contribution to strain reduction deteriorates. Thus, use of commercial hinged flexible joints is recommended for crossing angles β larger than 70°.
4. For crossing angle $\beta > 90°$ joints can ensure the pipe integrity. The extensive deformation relieves the pipe from the compressive axial force. However, special attention has to be paid on the joint's angular capacity, as very high rotation is expected.

5. The performance of flexible joints in reducing longitudinal tensile and compressive strains has been shown to be independent of *D*/*t* ratio and burial depth *H*, as joints' efficiency is independent of pipe cross-section geometry and soil properties.
6. Geological conditions and soil properties at the fault crossing site may introduce an uncertainty regarding the fault trace location on the ground surface. To account for this uncertainty, joints should be integrated along the entire pipeline length, where fault trace might appear on the ground surface, which is also the case when other mitigating measures are used. For angle β near 90^o the optimum distance between joints is equal to distance L_j between the assumed fault trace and the location of maximum bending moment in a continuous pipeline. For smaller angles β approaching 70^o, smaller distance between joints is recommended, in the order of $L_j/2$.

In conclusion, the introduction of commercial hinged bellow-type flexible joints in continuous buried steel pipes has been shown leading to significant strain reduction and consequently protection of the pipeline from fault offset. Hinged joints were examined in case of strike-slip faulting, but the encouraging results indicate their potential applicability in cases of normal or reverse faulting as well. As a final comment, fault offset is in nature three-dimensional and in such case hinged joints with biaxial angular capability (Gimbal type joint) should be implemented.

ACKNOWLEDGMENTS

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