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Contribution to the damage analysis of pipeline cracking under high pressure

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Abstract:

Introduction/purpose: This study aims to contribute to the prediction of pipeline damage caused by cracking in hydrocarbon-transport pipelines, subjected to high internal pressures, in response to the growing demand in industrialised countries.

Methods: To achieve this objective and analyse crack propagation in terms of Stress Intensity Factor (SIF) evaluation, the Finite Element Method (FEM) was employed. The study considers the effects of the transported medium's internal pressure on the one hand, and external stresses caused by natural phenomena such as earthquakes, landslides, and others, on the other. These external stresses are represented by tensile and compressive forces. Particular attention was given to the propagation of three types of cracks: circumferential, longitudinal, and mixed-mode cracks.

Results: The affected tubular structure zone is highly susceptible to mode I cracking. In contrast to the two initial types of cracking defects, an oriented crack at an angle of π/4 with respect to the pipeline's longitudinal axis develops nearly equally in modes I and II. Its growth kinetics are closely linked to its size, internal pressure, and the intensity of external forces.

Tensile forces promote the opening of circumferential cracks, the closure of longitudinal cracks, and mixed-mode (I and II) propagation of oriented cracks. Conversely, compressive forces favour the closure of *circumferential and oriented cracks while encouraging the opening of longitudinal cracks.*

Conclusion: The study reveals that, under identical loading conditions, longitudinally initiated cracks pose the greatest danger in terms of mode I crack growth. The risk of pipeline rupture is particularly high along the pipeline, and it increases significantly with higher internal pressure.

Key words: Pipeline, pressure, external forces, Finite Element Method (FEM), crack, Stress Intensity Factor.

Introduction

Pipelines are structures designed exclusively for the transport of hydrocarbons. For instance, liquid petroleum and gases are often conveyed over long distances via pipelines. The mixture of oil and natural gas extracted from a well must be transported as a two-phase flow through pipelines to processing facilities, where the oil can be separated from the gas. Predicting rupture and ensuring the reliability of these structures in various practical applications is crucial, given their economic and safety implications (De Barros et al, 2020; Nikhil et al, 2021; Barsoum & Yurindatama, 2020; Zheng et al, 2021).

Pipeline cracking presents a serious threat to the integrity, safety, and longevity of hydrocarbon and fluid transport systems (Mechab et al., 2011; 2014). It may result from material fatigue, stress corrosion cracking, or fluctuations in mechanical and environmental conditions, often leading to failures ranging from minor leaks to catastrophic ruptures (Qin & Cheng, 2021; Ma et al, 2024). To mitigate these risks, implementing robust preventative strategies is essential. These include regular inspections, the use of corrosion-resistant materials, the application of protective coatings, and the integration of advanced monitoring technologies. Such measures not only help detect early signs of degradation but also enhance the reliability and service life of pipeline infrastructure.

Numerous authors have studied the fracture behaviour of pipelines through numerical simulations, aiming to assess their mechanical integrity while considering different crack configurations (Fezazi et al, 2020; Mechab et al, 2018; Mechab et al, 2020; Metehri et al, 2024; Salem et al, 2019; Wu et al, 2022; Zhou et al, 2025; Zhou et al, 2020; Chattopadhyay et al, 2014; Weltevreden et al, 2021).

The parameters related to the ductile fracture mechanics of cracked pipelines under high internal pressure are critical for evaluating the integrity of damaged structures (Muthanna et al, 2021). Rahman (1995) analysed the behaviour of short cracks initiated in pipelines subjected to internal pressure and bending loads, where one key observation was that for through-thickness cracks, the effect of internal pressure was significant for structures made from high work-hardening materials, but negligible for materials with the opposite behaviour.

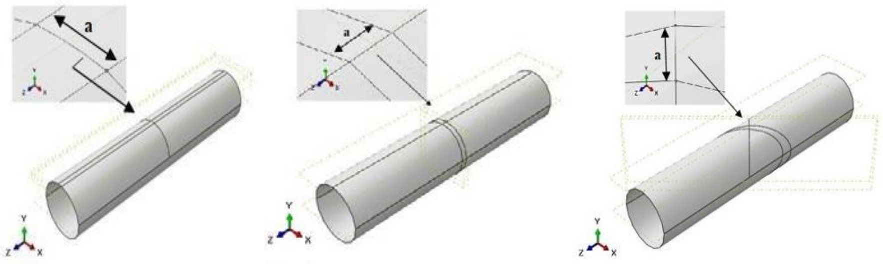
In this work, the Finite Element Method (FEM) was employed to analyse the propagation of cracks initiated in pipelines under high internal pressure. This behaviour was assessed in terms of variations in the Stress Intensity Factor. The crack propagation criterion was evaluated based on crack size, location, and the pressure of the transported medium. To this end, the computational software Abaqus 6.14 was used. This software suite provides powerful engineering simulation capabilities based on the finite element method.

Developed models and results

To achieve this objective, a three-dimensional model was developed. This model consists of a tubular structure (pipeline) with a length of 5000 mm, an external diameter of 1000 mm, and a wall thickness of 30 mm, containing a crack of size "a". The structure is subjected to internal pressures. For this purpose, three models were developed (Figure 1), differing only in the nature of the crack defect: a model containing: a circumferential crack (Figure 1a), a longitudinal crack (Figure 1b), and a mixed crack, i.e., oriented at 45° (Figure 1c). To simulate extreme conditions, an elastic approach was adopted for this study. The growth of these cracks was analysed in terms of the variation of the Stress Intensity Factor in opening mode (the most critical mode) and shear mode.

In order to optimize the transport of hydrocarbons through pipelines and meet the ever-increasing demand for this type of energy, it is necessary to significantly increase the pressure of the transported medium (oil or gas). To withstand such pressures and meet this growing demand, it is essential to increase the flow rate, and consequently the pressure, of the transported medium. However, such pressures pose a risk of pipeline rupture. To minimize this risk, it is preferable to use pipelines with larger dimensions (both diameter and wall thickness).

The pipeline used in this analysis is made of SA312TP304 steel, defined by its characteristics (Table 1) and dimensions, characterised by the R/t ratio (where R is the radius and t is the wall thickness).



a) b) c)

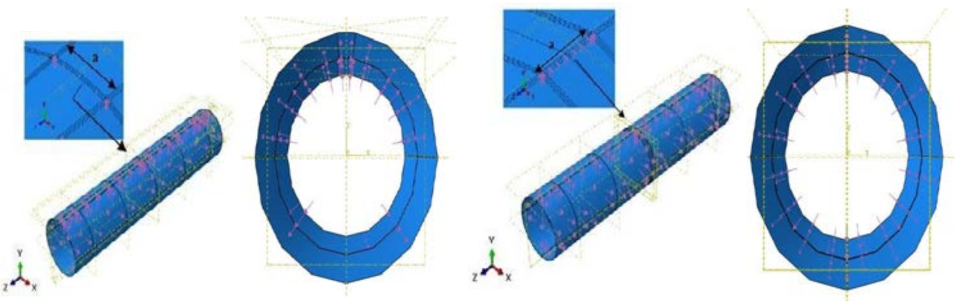
Figure 1 - Pipeline containing a crack: (a) circumferential, (b) longitudinal, (c) mixed (45° orientation)

Table 1 – Mechanical properties of SA312TP304 steel (Kim et al, 2002)

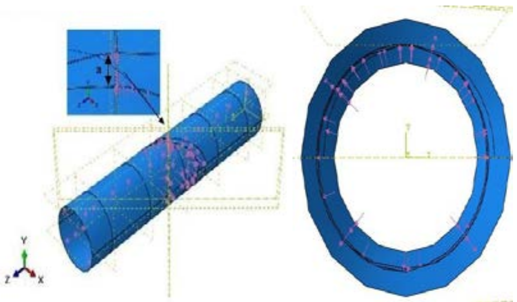
Material	Young's modulus E (MPa)	Poisson's Ratio ν	Tensile strength σu (MPa)	Tensile yield stress σy (MPa)	α	n
SA312TP304	204330	0.3	550.5	268.91	7.33	3.52

Pressure–crack interaction

The interaction between internal pressure and the presence of cracks is a key parameter in determining the survival of these tubular structures (gas and oil pipelines). This interaction enables the analysis of the ultimate pressure in order to minimise the risk of pipeline rupture and prevent disasters associated with such damage. The boundary conditions imposed on the cracked pipelines are illustrated in Figure 2.



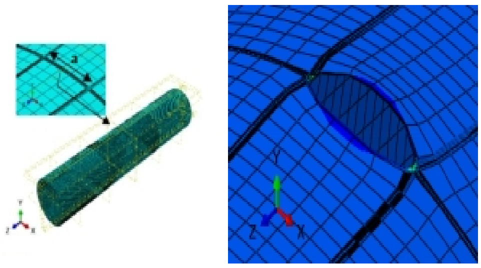
a) Circumferential crack *b) Longitudinal crack*



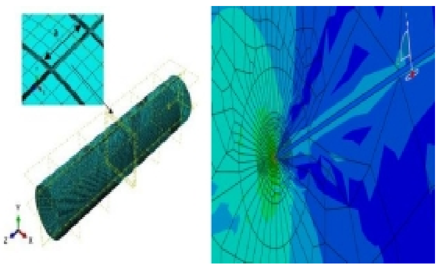
c) *Mixed crack*

Figure 2 - Boundary conditions applied to the cracked pipeline under internal pressure

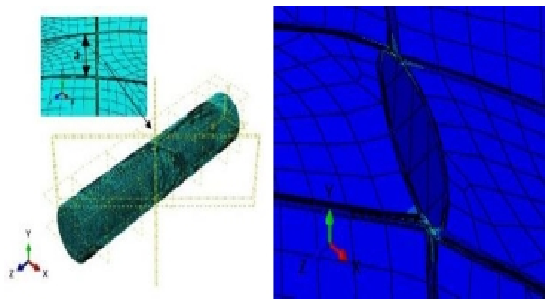
Finite element modelling requires a full meshing of the structure using linear S4 elements with four nodes, with a total of 55168 elements (Figure 3). For reasons of reliability and reproducibility of the results, the mesh was particularly refined in the vicinity of the crack front (Figure 3).



a) Circumferential crack



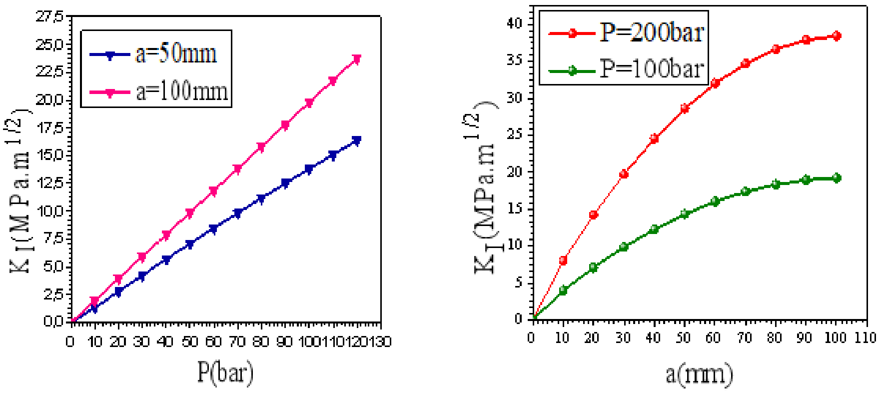
b) Longitudinal crack



c) *Mixed crack*

Figure 3 - Mesh of the analysed structure

Pressure–circumferential crack interaction



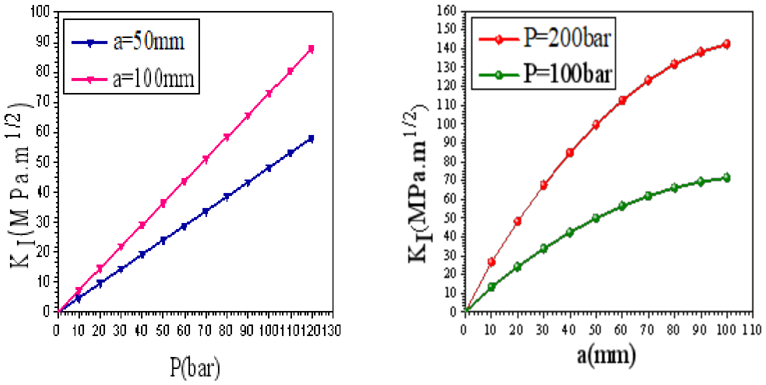
a) *b)*

Figure 4 - Effect of Pressure and Circumferential Crack Size on its Propagation Kinetics in Mode I

This interaction is illustrated in Figure 4. Analysis of this figure clearly shows that a circumferential crack becomes increasingly unstable as the internal pressure rises (Figure 4a). This behaviour is even more pronounced when the cracks are longer (Figure 4b). The instability is characterised here in terms of the evolution of the Stress Intensity Factor in Mode I. It is important to note that the difference between the fracture criterion for short cracks and that for long crack fronts becomes increasingly significant as the internal pressure within the pipeline increases (Figure 4).

Pressure–longitudinal crack interaction

The cracked pipeline is subjected to pressures exerted by the transported medium, which increases the risk of instability of the initiated longitudinal crack, as shown in Figure 5. This risk is characterised here by an intensification of the Stress Intensity Factor in Mode I. These figures show that the propagation kinetics of such a crack increase significantly with higher internal pressures (Figure 5a). This behaviour becomes even more pronounced as the crack length grows (Figure 5b).

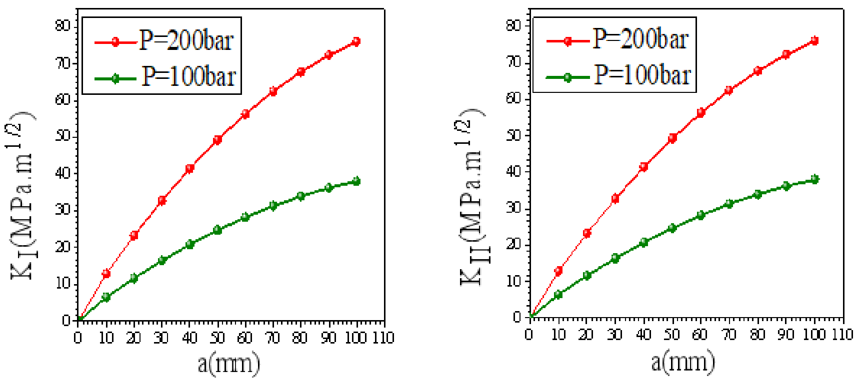


a) b)

Figure 5 - Effect of Pressure and Longitudinal Crack Size on its Propagation Kinetics in Mode I

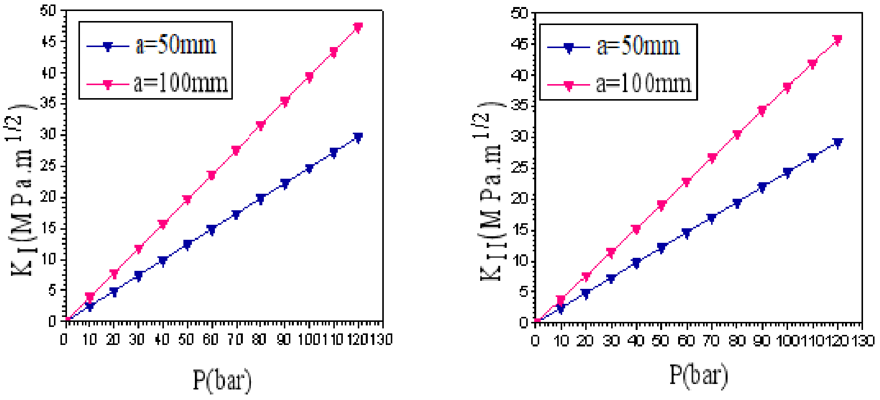
Pressure–crack interaction for a crack oriented at 45°

The results obtained are illustrated in Figures 6 and 7. These figures show that an oriented crack propagates almost equally, under the effect of internal pressure, in mixed Modes I and II. The propagation kinetics increase significantly with crack length, regardless of the mode of growth. The instability of cracks in Modes I and II becomes more likely as internal pressures rise (Figure 6). Thus, pipelines subjected to high internal pressures are particularly prone to cracking damage (Figure 7). Longer cracks exhibit a higher propagation rate in both opening (Mode I) and shear (Mode II) modes. This propagation behavior is distributed almost equally between Mode I and Mode II. The Stress Intensity Factor in Mode I is consistent, in terms of magnitude, with that observed in Mode II.



a) b)

Figure 6 - Behaviour of a Crack of Size "a" Oriented at 45° in Modes I and II



a) *b)*

Figure 7- Effect of Internal Pressure on the Mode I and Mode II Behaviour of a Crack Oriented at 45°

Interaction between external forces and cracks

These types of forces, whether tensile or compressive, generally represent the effects resulting from natural disasters such as earthquakes, landslides, or other phenomena. To simulate such loadings, longitudinal displacements "U" were imposed on the pipeline.

Interaction between external forces and circumferential cracks

The imposed tensile displacements (U > 0) (Figure 8) increase the risk of instability in the opening mode of an initiated circumferential crack. These displacements generate stresses that act as crack-opening forces. Positive values of the Stress Intensity Factor (SIF) are characteristic of such crack opening (Figure 9). In the case of long crack fronts, the fracture resistance of the pipeline can be exceeded for any imposed displacement greater than 3.5 mm. In such cases, sudden crack propagation becomes inevitable. It should be noted, however, that even in the absence of internal pressure from the transported medium, this type of loading alone may be fatal to the tubular structure, leading to catastrophic rupture. Conversely, an imposed compressive displacement (U < 0) applied to the pipeline enhances the mechanical behavior of the cracked zone through a crack-closing mechanism (Figure 10). The compressive stresses generated by this type of displacement act as stabilizing (closing) forces on the crack.

Negative values of the Stress Intensity Factor are indicative of this crack closure behavior (Figure 11). It is important to note that, compared to internal pressure, and under our simulation conditions, the effect of external loadings is much more significant in terms of the evolution of the Stress Intensity Factor in opening mode. This clearly demonstrates that natural disasters can cause pipeline rupture through the initiation and propagation of circumferential cracks.

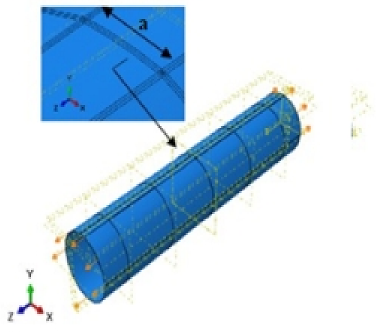


Figure 8 - Boundary conditions for a pipeline with a circumferential crack subjected to tensile forces (U > 0)

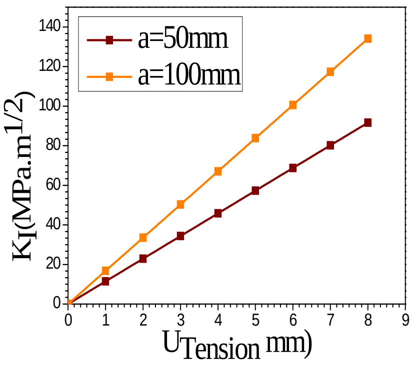


Figure 9 - Effect of Imposed Displacement U on Mode I Propagation of a Crack (U > 0, Tension)

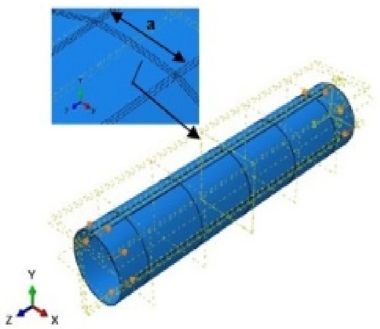


Figure 10 - Boundary conditions for a pipeline with a circumferential crack subjected to compressive forces (U < 0)

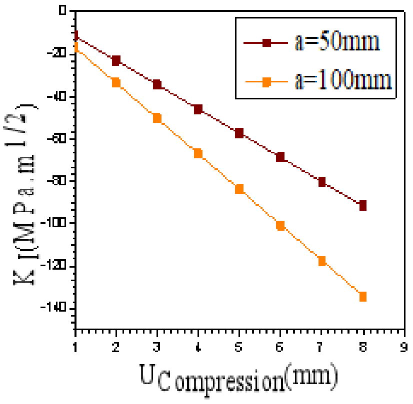


Figure 11 - Effect of Imposed Displacement U on Mode I Propagation of a Crack (U < 0, Compression)

Interaction between external forces and longitudinal cracks

Interaction between external forces and cracks

These types of forces, whether tensile or compressive, generally represent the effects resulting from natural disasters such as earthquakes, landslides, or other phenomena. To simulate such loadings, longitudinal displacements "U" were imposed on the pipeline.

Interaction between external forces and circumferential cracks

The imposed tensile displacements (U > 0) (Figure 8) increase the risk of instability in the opening mode of an initiated circumferential crack. These displacements generate stresses that act as crack-opening forces. Positive values of the Stress Intensity Factor (SIF) are characteristic of such crack opening (Figure 9). In the case of long crack fronts, the fracture resistance of the pipeline can be exceeded for any imposed displacement greater than 3.5 mm. In such cases, sudden crack propagation becomes inevitable. It should be noted, however, that even in the absence of internal pressure from the transported medium, this type of loading alone may be fatal to the tubular structure, leading to catastrophic rupture. Conversely, an imposed compressive displacement (U < 0) applied to the pipeline enhances the mechanical behavior of the cracked zone through a crack-closing mechanism (Figure 10). The compressive stresses generated by this type of displacement act as stabilizing (closing) forces on the crack. Negative values of the Stress Intensity Factor are indicative of this crack closure behavior (Figure 11). It is important to note that, compared to internal pressure, and under our simulation conditions, the effect of external loadings is much more significant in terms of the evolution of the Stress Intensity Factor in opening mode. This clearly demonstrates that natural disasters can cause pipeline rupture through the initiation and propagation of circumferential cracks.

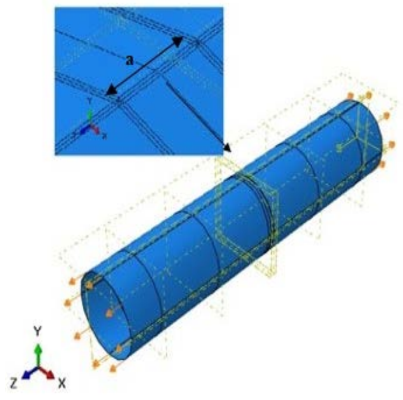


Figure 12 - Boundary conditions for a pipeline with a longitudinal crack subjected to tensile forces (U > 0)

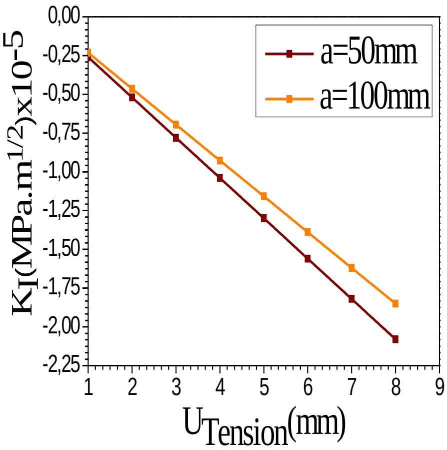


Figure 13 - Effect of Imposed Displacement U on Mode I Propagation of a Crack (U > 0, Tension)

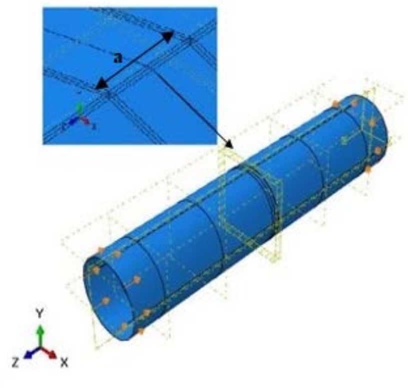


Figure 14 - Boundary conditions for a pipeline with a longitudinal crack subjected to compressive forces

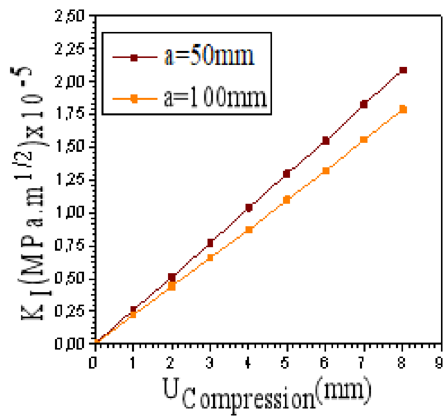


Figure 15 - Effect of Imposed Displacement U on Mode I Propagation of a Crack (U < 0, Compression*)*

Interaction between external forces and a crack oriented at 45°

The same simulation conditions as those used previously were retained for this part of the study. The model analysed in this case differs from the previous one only by the orientation of the crack (Figure 16). The same types of loadings - imposed tensile displacements (U > 0) (Figure 16) and compressive displacements (U < 0) (Figure 17) - were separately applied to the cracked pipeline. It should be recalled that these forces simulate external loadings acting on the cracked pipeline.

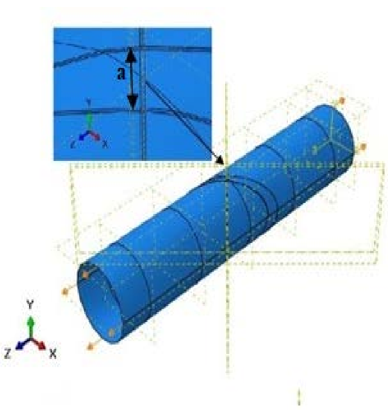


Figure 16 - Boundary conditions for a pipeline containing a crack oriented at 45° subjected to tensile forces (U > 0)

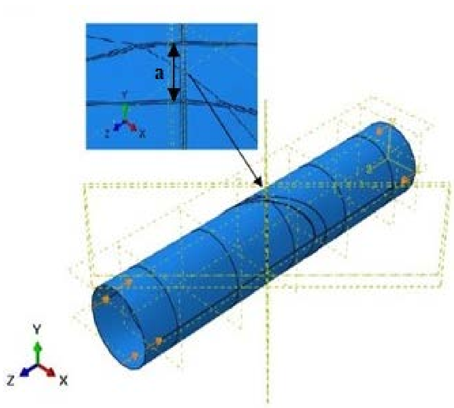


Figure 17 - Boundary conditions for a pipeline containing a crack oriented at 45° subjected to compressive forces (U < 0)

The results of this analysis, illustrated in Figure 18, confirm that a mixed crack, i.e., a crack oriented at 45° and subjected to tensile loading, propagates in a mixed mode, with both opening (Mode I) and shearing (Mode II) of the crack lips. The propagation kinetics in these two modes are comparable in terms of the values of the Stress Intensity Factors KI and KII. Regardless of the failure mode, longer cracks subjected to large displacement amplitudes exhibit significant instability. Combined with the operational loading of the pipeline (internal pressure) (Figure 6 and 7), these external forces may lead to sudden crack propagation. This risk becomes particularly likely for long cracks subjected to both high internal pressures and intense tensile displacements.

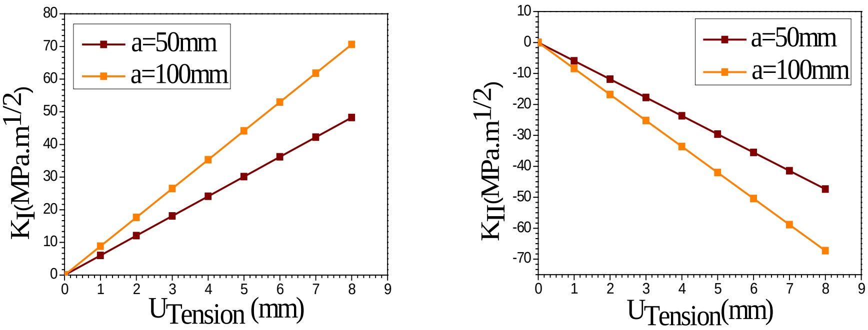


Figure 18 - Effect of Imposed Displacement U on the Propagation Kinetics in Modes I and II of a Crack Oriented at 45° (U > 0, Tension)

A different mode of crack propagation is observed when the pipeline is subjected to imposed compressive displacements (U < 0) (Figure 19). This figure clearly shows that a crack defect subjected to compression propagates through shearing of the crack lips (pure Mode II). The propagation kinetics, in terms of the value of the Stress Intensity Factor in Mode II, increase significantly with larger imposed displacements. This behaviour is even more pronounced for larger crack sizes. In opening mode (Mode I), this type of compressive loading (U < 0) leads to crack stabilisation through a closing phenomenon. Thus, this loading acts as a crack-closing force, which is reflected by negative values of the Stress Intensity Factor, as illustrated in Figure 19. The superposition of such external loading with the operational loading of the pipeline (Figure 6 and 7) leads to the propagation of the oriented crack in mixed Modes I and II. Under our simulation conditions, for large imposed displacements (U < 0), high internal pressures, and long cracks, the crack tends to propagate preferentially through shearing of the crack lips (pure Mode II).

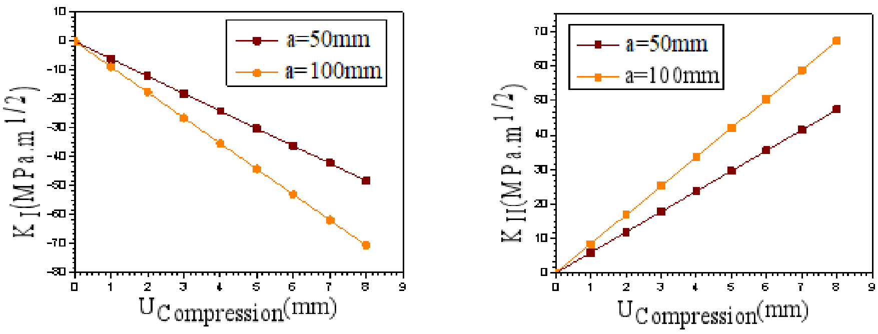


Figure 19 - Effect of Imposed Displacement U on the Propagation Kinetics in Modes I and II of a Crack Oriented at 45° (U > 0, compression)

Conclusion

The results obtained in this study have shown the following:

Under identical simulation conditions, longitudinal cracks initiated in a pipeline under high internal pressure are significantly more unstable in opening mode (Mode I) compared to circumferential and 45°-oriented cracks. Oriented cracks preferentially propagate, under the effect of internal pressure, in mixed Modes I and II. The risk of rupture is much higher in the case of longitudinal cracks; that is, pipeline bursting occurs exclusively along its longitudinal axis. This zone of the pipeline is therefore particularly pre-exposed to sudden damage.

External loadings in the form of imposed tensile displacements (U > 0) promote opening-mode propagation of circumferential cracks, closure of longitudinal cracks, and mixed-mode (Modes I and II) growth of oriented cracks. Conversely, imposed compressive displacements (U < 0) produce opposite behaviour: closure of circumferential cracks, opening of longitudinal cracks, and shearing-mode (Mode II) growth of oriented cracks.

The superposition of operational loads with external loadings significantly increases the crack propagation kinetics, regardless of the crack type (longitudinal, circumferential, or mixed), particularly in the case of long cracks.

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Prilog analizi oštećenja cevovoda usled pucanja pod visokim pritiskom

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Sažetak:

Uvod/cilj: Ovaj rad ima za cilj da doprinese predviđanju oštećenja usled pucanja u cevovodima za transport ugljovodonika koji su izloženi visokim unutrašnjim pritiscima, a kao odgovor na rastuću potražnju u industrijalizovanim zemljama.

Metode: Da bi se postigao ovaj cilj i analiziralo širenje pukotina u smislu određivanja faktora intenziteta napona (eng. SIF), primenjena je metoda konačnih elemenata (eng. FEM). Studija razmatra uticaj unutrašnjeg pritiska transportovanog fluida, kao i spoljašnjih naprezanja izazvanih prirodnim pojavama kao što su zemljotresi, klizišta i druge pojave. Ova *spoljašnja naprezanja predstavljena su zateznim i pritisnim silama. Posebna pažnja posvećena je širenju tri tipa pukotina: obodne, uzdužne i pukotine u mešovitom režimu.*

Rezultati: Zahvaćena zona cevaste strukture veoma je podložna pucanju u režimu I. Za razliku od dva početna tipa defekta pucanja, orijentisana pukotina pod uglom π/4 u odnosu na uzdužnu osu cevovoda razvija se gotovo podjednako u režimima I i II. Kinetika njenog rasta usko je povezana sa njenom veličinom, unutrašnjim pritiskom i intenzitetom spoljašnjih sila. Zatezne sile podstiču otvaranje obodnih pukotina, zatvaranje uzdužnih pukotina i širenje orijentisanih pukotina u mešovitom režimu (I i II). Nasuprot tome, pritisne sile pogoduju zatvaranju obodnih i orijentisanih pukotina, dok istovremeno podstiču otvaranje uzdužnih pukotina.

Zaključak: Studija pokazuje da, pod identičnim uslovima opterećenja, uzdužno inicirane pukotine predstavljaju najveću opasnost u pogledu rasta pukotine u režimu I. Rizik od pucanja cevovoda naročito je izražen duž cevovoda i značajno se povećava sa porastom unutrašnjeg pritiska.

Ključne reči: cevovod, pritisak, spoljašnje sile, metoda konačnih elemenata (FEM), pukotina, faktor intenziteta napona.

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