Politecnico di Milano

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Master of Science in Civil Engineering for Risk Mitigation

Failure analysis of gas pipelines in China

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Content

Abstract

The production and use of natural gas in China is growing quickly, and the same applies to the natural gas industry. Nowadays, several regions are crossed by natural gas pipeline networks. This document introduces the main gas transportation systems in this Country. Furthermore, it analyses the causes of the main gas pipeline incidents occurred in recent years in China, United States and Europe, as well as the most popular monitoring and failure prevention methods. Finally, the detrimental effects on safety due to the stress concentration induced by the possible presence of defects on the pipe wall is analyzed by the finite element method.

Key words:

Natural gas pipelines, failure analysis, stress concentration, finite element analysis

Sommario

La produzione e l’uso di gas naturale in Cina stanno crescendo rapidamente, e contemporaneamente cresce il relativo comparto industriale. Attualmente, sono numerose le regioni cinesi attraversate da condotte per il trasporto di gas naturale. Questa tesina introduce le principali reti di trasmissione di questo Paese ed analizza le cause e i metodi di monitoraggio e prevenzione degli incidenti in Cina, ma anche negli Stati Uniti e in Europa. Infine, si utilizza il metodo degli elementi finiti per verificare l’incidenza sui limiti di sicurezza della concentrazione degli sforzi che si realizza in corrispondenza di possibili difetti presenti sulla superficie delle tubazioni.

Parole chiave:

Gasdotti, sicurezza strutturale, concentrazione degli sforzi, analisi agli elementi finiti

1. Introduction

1.1. Natural gas pipeline system in China

Natural gas is developed and produced from the formation, combustible, mixed hydrocarbon and non-hydrocarbon gas, compared with traditional fossil fuels such as coal or petroleum, natural gas burns more completely and it is a more environmental-friendly fuel. Natural gas is safer and easier to store. For the above reasons, in China, not only industrial production, but also people's daily situation, are increasingly favoring the use of natural gas, the natural gas industry is also growing quickly, and more and more regions have established natural gas pipeline networks.

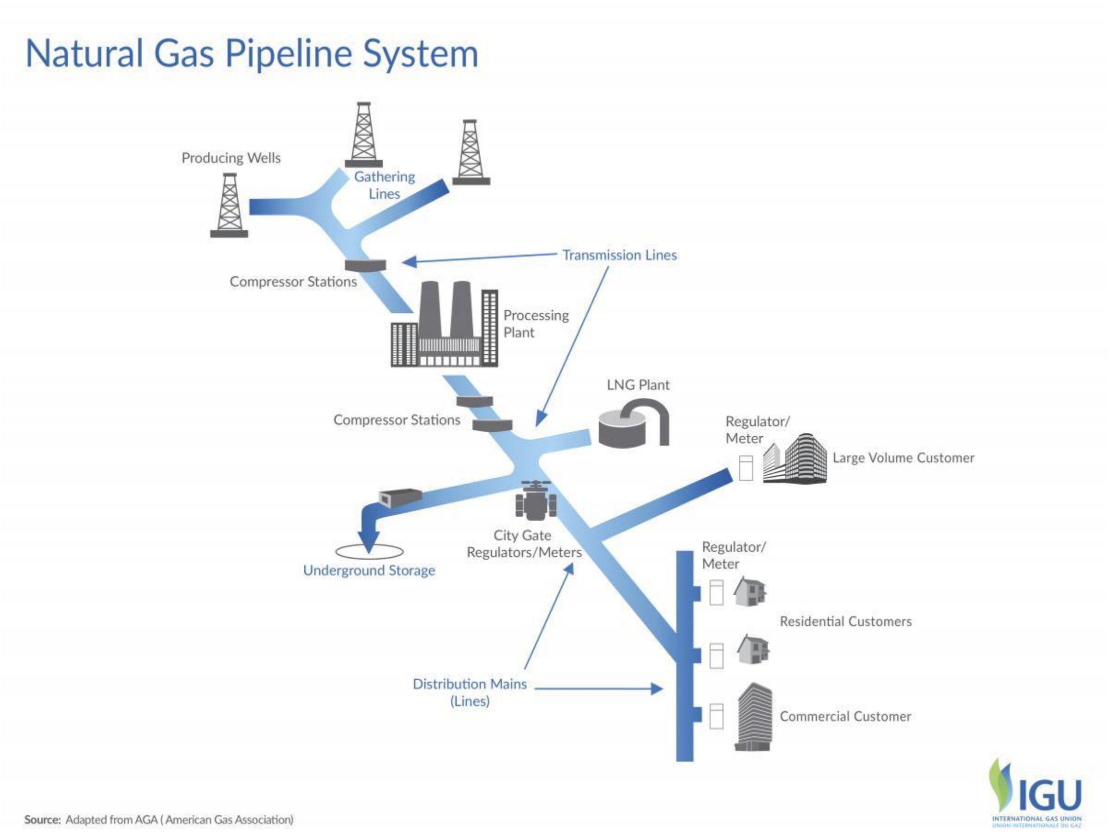
Natural gas pipelines refer to pipelines that transport natural gas from mining sites or processing plants to urban gas distribution centers or industrial enterprise users. The use of pipelines to transport natural gas is a way to transport natural gas in large quantities on land. Gas pipelines account for about half of the world ’s total pipelines.

Generally, there are three types of pipelines along the transportation route in China: gathering systems, transmission systems, and distribution systems.

Gathering pipeline systems: The pipelines from the gas field wellhead, through the gas gathering station, to the gas processing plant. They are used to collect and transit raw natural gas.

Transmission pipeline systems: The main part of the whole system to transport the processed natural gas that reached the pipeline transmission quality standards. In general, the diameter of the gas transmission pipelines is larger than that of the gathering pipelines and the gas distribution pipeline

Natural gas distribution pipeline systems: The pipeline from the urban pressure regulating station to the users, they have relatively low pressure, large number of branches, dense network and small diameter. In addition to steel pipes, low-pressure gas distribution pipes can also be made of plastic or other materials.



Source: Adapted from AGA (American Gas Association)

Figure 1: Natural gas pipeline system [1]

In gas transmission lines, the cut-off valves are usually set every 20-30km, the purpose is to cut off the accidental pipeline section and main line after the accident happening, to avoid the expansion of the accident along the whole pipeline web, reduce the loss of gas release, and shorten the maintenance time.

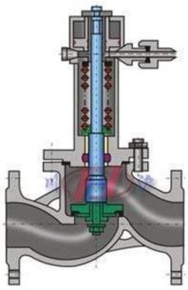


Figure 2: A commonly used cut-off valve in transmission pipelines [2]

The natural gas pipeline system is owned and operated by many different companies. The location, construction, and operation of these systems are usually governed by law.

1.2. China natural gas development

Natural gas in China is not only an energy source with a long history but also a new energy source with a short history of large-scale use nowadays.

There are natural gas resources and underground salt mines in the Sichuan Basin of China. It was recorded as early as 2000 years ago that natural gas was used to produce salt in the Zigong area of Sichuan. There is a book called "Tian Gong Kai Wu", which contains pictures of salt produced by natural gas.

Figure 3: people in Sichuan discovered natural gas in ancient books

But until 40 years ago, natural gas was only an energy source that few people in a few areas knew. At that time, natural gas was negligible in China's energy structure and could be ignored. In 1997, China built the first long-distance natural gas pipeline, the Shaanxi-Beijing pipeline, which was 918 kilometers long and transported natural gas to Beijing. After 2000, the Chinese government began to plan the construction of the West-East Gas Pipeline from Xinjiang to Shanghai, with a total length of about 4,000 kilometers and a design scale of 12 billion cubic meters per year. [3]

Since China 's discovered natural gas reserves cannot meet the rapidly growing market demand, government have begun negotiations with Russia, Central Asian and Myanmar countries to import their pipeline natural gas after 2005. In less than 20 years, China has grown from a country with an insignificant share of natural gas in energy to the world 's third largest natural gas consumer after the United States and Russia.

Figure 4: Four major natural gas import channels to China

2. Overview of natural gas transmission pipelines in China

In ancient times, Chinese people used wooden and bamboo pipes to transport natural gas in short distance, After the middle of the twentieth century, the modern natural gas industry began to develop in China, thanks to the usage of steel pipes, large quantity of pressurized natural gas can be transported for long distances, and government began to plan to build a huge national gas pipeline network.

2.1. China domestic natural gas pipelines

2.1.1. Shaanjing natural gas pipeline

Figure 5: the first long-distance gas pipeline in China: Shaanjing pipeline [4]

Shaanjing pipeline started construction in 1992 and was completed in October 1997, reaching the international advanced level in the 1990s. It is a landmark in the history of China 's long-distance oil and gas pipeline construction. At that time, the project was the longest natural gas pipeline on land in China and the first large-caliber, long-distance, fully automatic gas pipeline in China. The total length of the first-line project pipeline is 1098 kilometers, passing through three provinces and two cities (Shaanxi, Shanxi, Hebei and Beijing-Tianjin), from Jingbian County (Shaanxi province) to Beijing Shijingshan District, with a designed annual gas supply capacity of 3.3 billion cubic meters. [4] Today, 100% of the natural gas needed in Beijing is still transported by the Shaanjing pipeline system. [5]

2.1.2. Nationwide gas pipeline network: the West-East Gas Pipeline Project

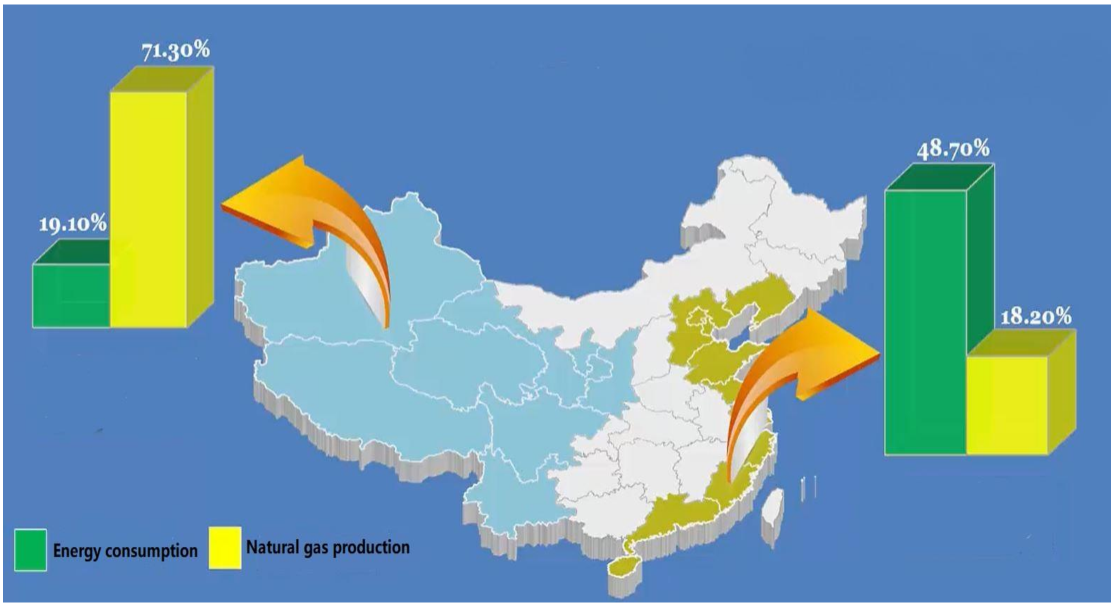


Figure 6: Distribution of natural gas production and consumption in China [6]

The distribution of natural gas in China: the resources of natural gas are mainly in the west part of China (over 70% of the total natural gas output in China), where less population and low demand of energy consumptions (less than 20%). However, the south-east part of China, is the concentration of population and industrial activities.[6]

In order to solve this problem, the West-East Gas Pipeline Project connects resource-rich western China with resource-poor eastern China. While transforming the resource advantages in the west into economic advantages, it provides strong energy support for development in eastern China.

2.1.2.1. First West-East Gas Pipeline

Figure 7: First West-East Gas Pipeline [7, page 7]

First West-East Gas Pipeline	
gas source	Tarim gas province, Xinjiang
start and end locations	Lunnan oil & gas field, Xinjiang to Baihe town, Shanghai
length	4380 km for main pipeline [8]
Natural gas transmission capacity	17 billion cubic meters per year [8]
provinces passed	Xingjiang, Gansu, Ningxia, Shaanxi, Shanxi, Henan, Anhui, Jiangsu, Shanghai, and Zhejiang (10 provinces)
date of initial operation	Dec, 2004 [8]

2.1.2.2. Second West-East Gas Pipeline

Figure 8: Second West-East Gas Pipeline [7, page 7]

Second West-East Gas Pipeline	
gas source	Central Asia
start and end locations	Horgos, Xinjiang (connected with the Central Asia-China Gas Pipeline), to Shanghai and HongKong
length	9102 km for main pipeline [9]
Natural gas transmission capacity	30 billion cubic meters per year [9]
provinces passed	Xinjiang, Gansu, Ningxia, Shaanxi, Henan, Hubei, Jiangxi, Guangdong, Guangxi, Zhejiang, Shanghai, Jiangsu, Hunan, and Shandong (14 provinces)
date of initial operation	Dec, 2012 [9]

2.1.2.3. Third West-East Gas Pipeline

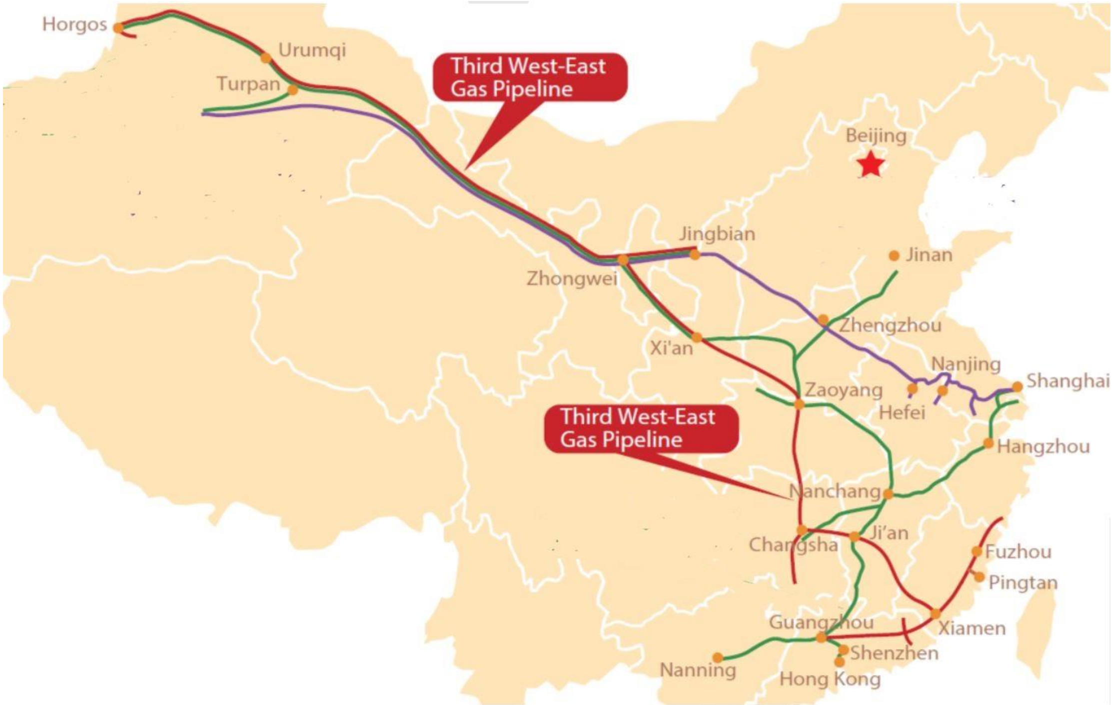


Figure 9: Third West-East Gas Pipeline [7, page 7]

Third West-East Gas Pipeline	
gas source	Central Asia
start and end locations	Horgos in Xinjiang (connected with the Central Asia-China Gas Pipeline), to Fuzhou in Fujian
length	6840 km for main pipeline [10]
Natural gas transmission capacity	30 billion cubic meters per year [10]
provinces passed	Xinjiang, Gansu, Ningxia, Shaanxi, Henan, Hubei, Hunan, Jiangxi, Fujian, and Guangdong (10 provinces)
date of initial operation	Aug, 2014 [10]

2.2. International pipelines

2.2.1. Central Asia-China Natural Gas Pipelines

Figure 10: Central Asia-China Natural Gas Pipelines [11]

The central Asia-China natural gas pipelines run from Uzbekistan to Kazakhstan, then to Horgos measuring station in China, then to all parts of China as far as Hongkong. The Central Asia-China natural gas pipeline is China's first overland cross-border energy channel. It is about 10,000 kilometers long, making it the world's longest natural gas pipeline. Since December 2009, it has facilitated the import of over 300 billion cubic meters of natural gas and has benefited more than 300 million people in China. It is an important project of energy infrastructure cooperation between China and central Asia countries. [12]

2.2.2. Gas pipeline 'Power of Siberia'

Figure 11: 'Power of Siberia' pipeline [13]

This giant cross-border natural gas pipeline project was put into operation in December 2019. The "Power of Siberia" gas pipelines run from the Chayandinskoye and Kovyktinskoye fields in Russia's east over more than 3,000 kilometers to Liaoning in northeastern China. It should export 38 billion cubic meters of gas annually when fully operational in 2025, according to a statement released by the Kremlin. [13]

2.2.3. The Myanmar-China Gas pipeline

Figure 12: The Myanmar-China Gas pipeline [14]

The total length of the China-Myanmar natural gas pipeline is 2520 kilometers, the Myanmar section is 793 kilometers, and the domestic section is 1727 kilometers. The starting point of the Myanmar-China natural gas pipeline is at Kyaukpyu Port, From Ruili, Yunnan into China via Myanmar's Rakhine State, Magwe Province, Mandalay Province and Shan State, 12 billion cubic meters of natural gas benefits Myanmar and southwestern China every year, it was completed and put into operation in July, 2013. [15]

3. Gas transmission incidents

The failure of natural gas pipelines may lead serious consequences, especially when the leaked gas is ignited, the following are three serious examples caused by the leakage of natural gas pipelines:

1) On August 19, 2000, an interstate natural gas pipeline exploded in southern New Mexico. The explosion killed twelve people that were camping near the Pecos River.[16]

Figure 13: Gas pipeline exploded in southern New Mexico, 19/08/2000 (cause: internal corrosion) [16]

The analysis of the cause of the accident shows that the accident was caused by severe internal corrosion that reduced the thickness of the pipe wall so thin that it could not withstand the pressure in the pipe, causing the pipe failure. The serious internal corrosion was caused by moisture, microorganisms, chloride, O2, CO2 and H2S in the pipeline.

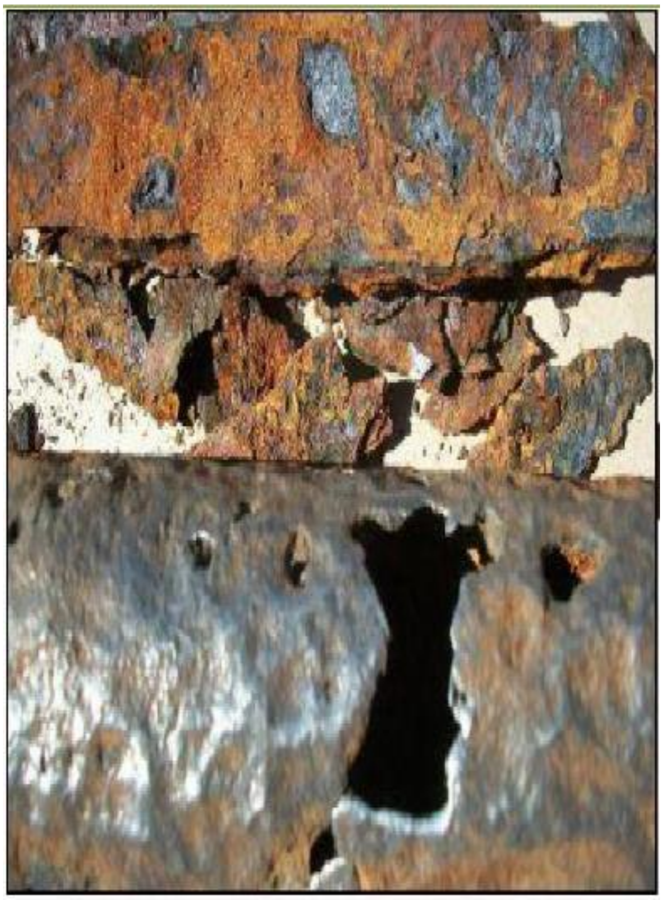


Figure 14: damaged pipeline caused by internal corrosion [16]

The corrosion defect is about 6.5m long, and the degree of corrosion damage at the bottom of the pipeline is the most serious. The thickness of the pipe wall is reduced to 72% of the original wall thickness where the corrosion is the most serious.[16]

2) At 10:44 am on July 2, 2017, the CNPC natural gas pipeline exploded in Qinglong, Guizhou province, 8 people have been killed and 35 injured, including 8 seriously injured and 4 critically ill. The survey showed that the continuous heavy rainfall caused the serious landslide, which squeezed the gas pipeline and lead rupture, caused the leak of gas and explode. [17]

Figure 15: Gas pipeline exploded in Qinglong, 02/07/2007 (cause: landslide) [17]

3) On October 2018, the 90-centimetre pipeline – part of the T-South gas system, in Enbridge, Canada, ruptured due to stress corrosion cracks on the outside surface of the pipe, led to natural gas shortages throughout British Columbia. [18]

Figure 16: Gas pipeline incident in Enbridge, Oct 2018 (cause: external corrosion) [18]

It said polyethylene tape coating applied to the pipe to protect it from corrosion deteriorated over time, allowing soil moisture to come into contact with the pipe surface and leading to corrosion and cracking.

3.1. Databases

Nowadays, in many countries and regions around the world, pipeline operators are required to report pipeline incidents to specific regulatory agencies, these reports provide valuable information about the detailed in-situ information, failure rate in terms of per year per unit length, failure causes for pipeline incidents, typical failure modes, severity of incidents' consequences, etc.

3.1.1. Pipeline and Hazardous Materials Safety Administration (PHMSA)

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration

Figure 17: Logo of the Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation [19]

Starting from 1970, the Pipeline and Hazardous Material Safety Administration (PHMSA) within the United States Department of Transportation (DOT) has collected information on incidents that occurred on gas pipelines regulated by PHMSA and met established specific reporting criteria. PHMSA's pipeline incident report includes information of the pipeline involved in the incident, such as the location, failure causes, operators' text discerptions, consequences of the incident and diameter, wall thickness, steel grade, operating pressure of the pipe.

The reports can be accessed from https://www.phmsa.dot.gov/incident-reporting.

3.1.2. European Gas Pipeline Incident Data Group (EGIG)

Figure 18: Logo of the European Gas Pipeline Incident Data Group [20]

In 1982, six European gas transmission system operators actively collected and shared data about accidents in their pipeline transmission systems. The formal establishment of European Natural Gas Pipeline Event Data Group (EGIG) was initiated by this cooperative relationship.

Today, EGIG is a partner between 17 major European gas transmission system operator groups and the owner of a large database of natural gas pipeline events. The creation of this huge pipeline event database has helped pipeline operators ensure the safety of European gas pipelines. This information has helped pipeline operators and managers and operators improve the safety of their natural gas pipeline transmission systems.

The incident data can be accessed by public from https://www.egig.eu/reports.

3.1.3. Chinagasmap

This is a commercial database website. China Oil & Gas Industry Maps, Project Databases and Reports introduce the nation's oil and gas blueprint by 10,000+ Key projects, including conventional oil and gas, coal to oil and gas, pipeline and storage map, refining and petrochemical information, and the information about China’s gas power, city gas. Access from www.chinagasmap.com.

So far, the database of China ’s natural gas pipeline incidents has not been established, and a large number of relevant information on oil and gas pipeline incidents has not been published in accordance with laws and regulations, resulting in a great waste of precious resources, affecting the further improvement and improvement of theoretical research, professional practice and public safety supervision. Nowadays many relevant scholars and organizations in China believe that it is imperative to establish an accident database for China ’s oil and gas pipelines, this action must be accelerated.

3.2. Failure causes

Type of leak:

Crack (safer case, most of this kind of leak is not ignited)

Hole

Rupture (most dangerous type, may lead explosion)

According to EGIG and PHMSA's report, the four main causes of pipeline incidents are explained as follow:

1) External interferences

   The third-party excavation activities (e.g. digging, piling, ground works) that directly damage pipelines.

2) Corrosion

   Corrosion is the deterioration of steel pipes due to electrochemical reactions with the surrounding environment. This reaction causes iron oxidation (rusting) in steel pipes or other piping accessories. Corrosion can cause metal loss in the pipeline. Over time, if corrosion is not slowed, the corrosion will cause the steel to lose strength and may prevent it from containing gas in the pipeline under working pressure.

3) Construction defect /material failure

   Including the defect that lead failure, introduced by the insufficiency in the process of material and components production, testing and construction, involves hard spot, lamination, material, field weld quality, mechanical damage, etc.

4) Natural force damage

   The ground movement introduced by natural forces also damage the pipeline, including dike break, erosion, flood, landslide, mining, river, etc. Landslides are by far the most common type causing a ground movement incident.

3.3. Failure causes distribution in different regions

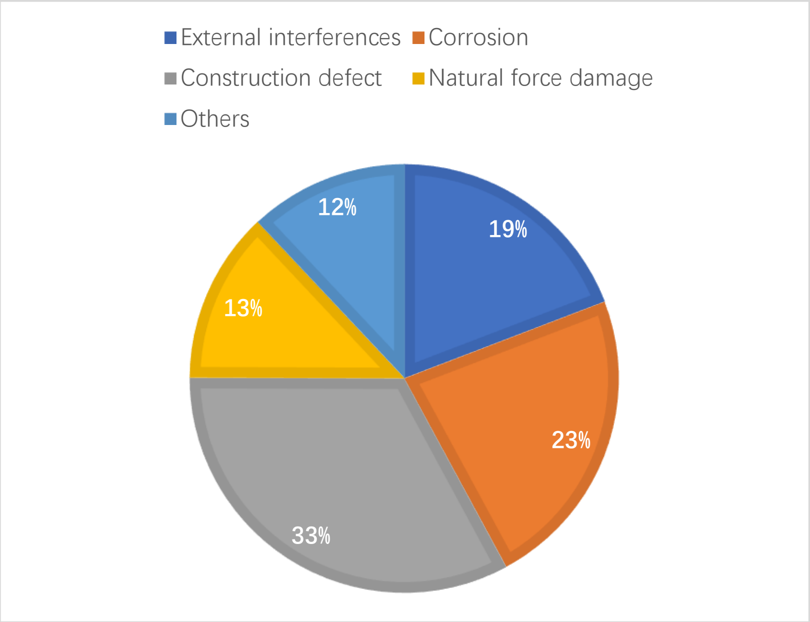


Figure 19: Failure causes of gas transmission pipelines failure in US 2005-2019 [21]

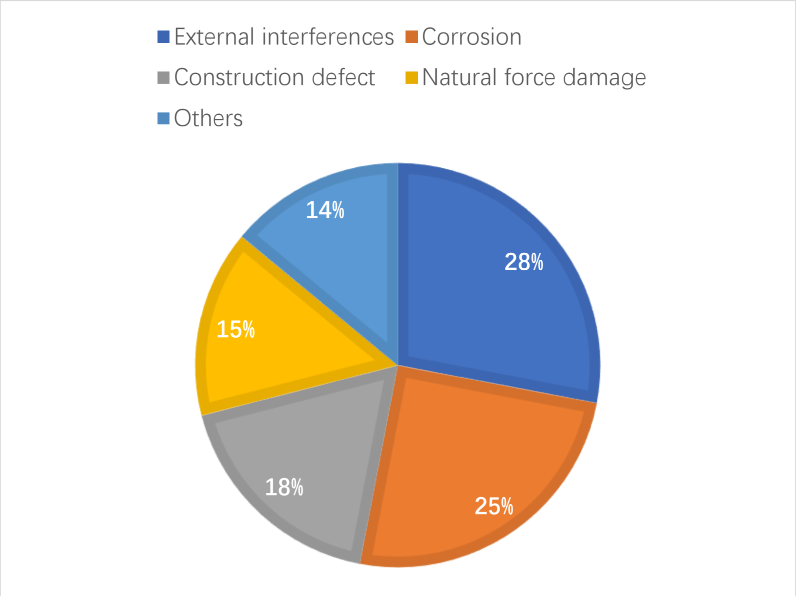


Figure 20: Failure causes of gas transmission pipelines failure in Europe 2007-2016 [22]

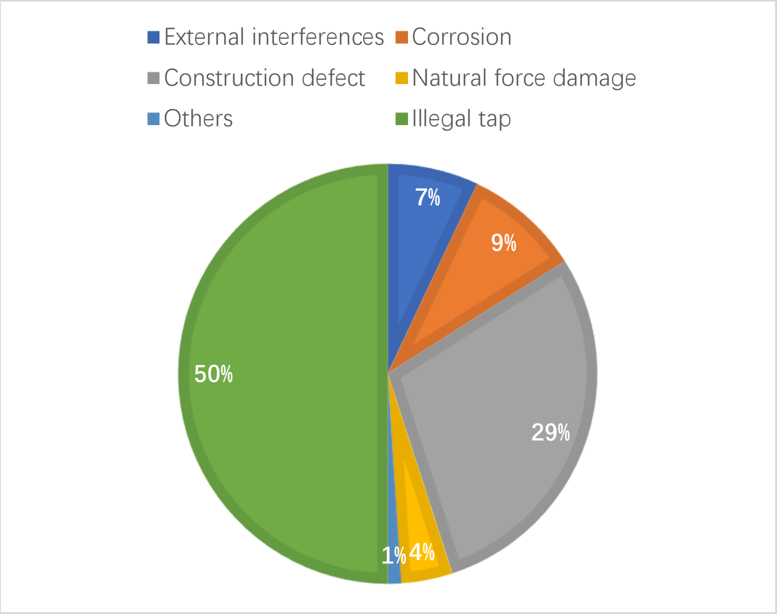


Figure 21: Failure causes of gas transmission pipelines failure in China 2006-2015 [23, page 6]

By analyzing the statics, we can point out that external interferences, corrosion and construction defect are the most common failure causes of natural gas pipelines.

Note that in China, the mainly cause of gas pipelines failure is illegal tap, which is rarely happened in US and EU, this situation is restricted by China's social and economic development level. However, with the promulgation and implementation of the "People's Republic of China Petroleum and Natural Gas Pipeline Protection Law", this failure cases had been significantly reduced nowadays.

3.4. Main failure causes analysis

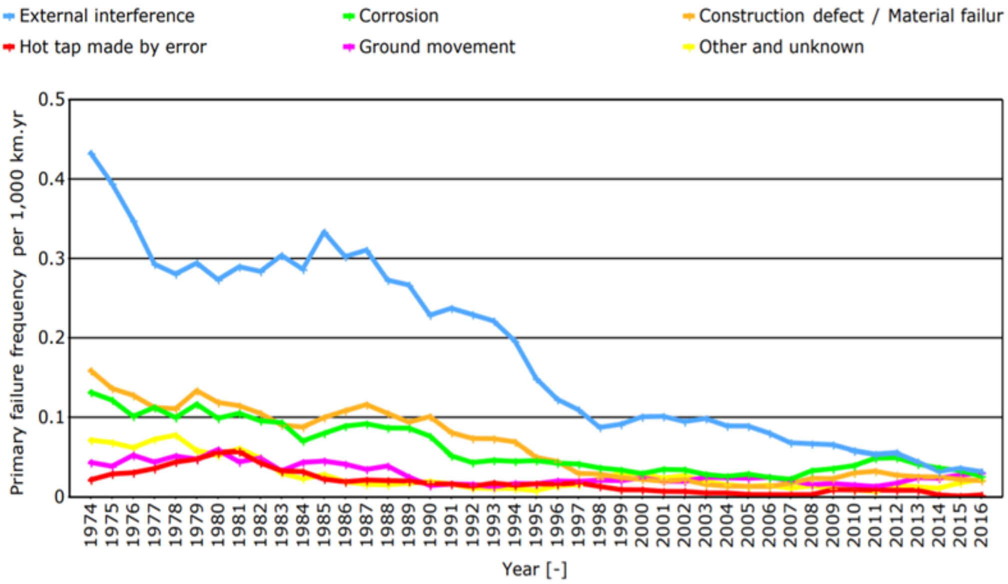


Figure 22: Primary failure frequencies per cause by EGIG [22, page 21]

3.4.1. External interference

In this type of failure cause, pipelines with (1) larger depth of cover and (2) larger wall thickness have a lower failure frequency, smaller diameter pipelines are more likely to be damaged by this failure cause, because of their small wall thickness and more chances to be found in urban areas.

We can notice that the failure frequency caused by external interference has been significantly reduced from 1976 to 2016, This factor can be improved through stricter implementation of regional land use plans and the use of one-call systems to alert all groups and individuals engaged in excavation activities. In some countries, there are legal requirements for reporting excavation activities, natural gas transmission companies have adopted appropriate actions, like monitoring or marking of the pipeline in the direct of the excavation activities.

3.4.2. Corrosion

In this type of failure cause, pipelines with (1) older pipelines, (2) predominantly tar coatings, have higher failure frequencies.

Thanks to the abandonment of old pipelines and the common usage of modern coatings like polyethylene coatings, corrosion failures are effectively reduced, but it is still one of the main causes of failures generally. This factor leads to almost a quarter proportion of failures.

According to EGIG's report, the corrosion of natural gas pipelines is divided into two categories based on the location where corrosion occurs:

3.4.2.1. Internal corrosion

The main factor causing the corrosion of the inner wall of the pipeline is water contained in the natural gas. It produces a hydrophilic film on the inner wall of the pipeline, leading the corrosion that is similar to original battery, causing electrochemical corrosion. Some contaminants in the gas, such as O2, H2S, CO2, or chlorides, are prone to introduce chemical reaction with steel, leading chemical corrosion.

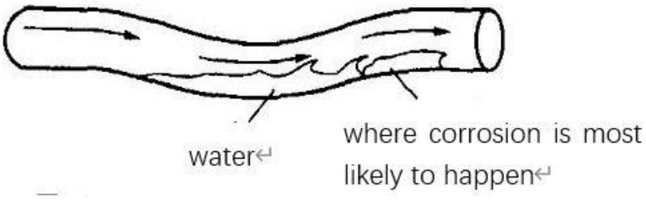


Figure 23: Internal corrosion in gas pipeline

3.4.2.2. External corrosion

Corrosion occurs at outer wall of the pipelines is always due to environmental conditions on the outer surface of the steel pipe that can cause an electrochemical interaction between the exterior of the pipeline and the water, soil and air surrounding it. Galvanic and atmospheric corrosion are the most common types of external corrosion.

3.4.2.3. Data and statistics

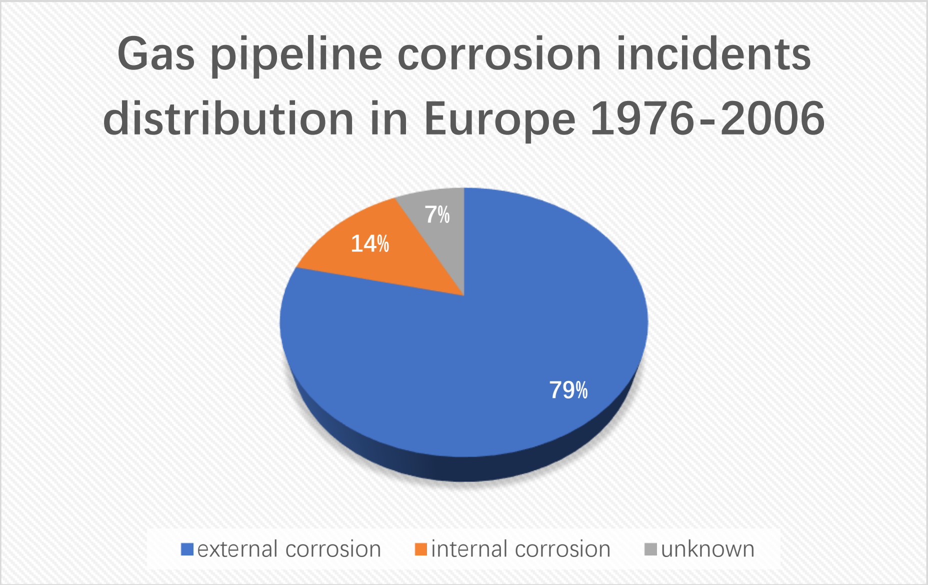


Figure 24: Corrosion incidents distribution [22, page 20]

The figure demonstrates that the external corrosion is obviously the most common type of corrosion incidents.

3.4.3. Construction defect

This cause is constrained by many factors, like: dents, girth weld defects, wrong operations on site, chisel marks and other defects. with the progress of today's technology and quality management, construction defects on pipelines can be significantly controlled.

3.4.4. Natural force damage

Although the design of the pipeline systems is as possible as we can to avoid the high earthquake occurrence areas, many natural factors such as soil displacement caused by small earthquakes, floods caused by continuous rainfall, landslides, debris flows, and lightning disasters can endanger the safety of natural gas pipelines. However, in recent years, weather forecast, slope reinforcement technology, environmental improvement, and the monitoring and maintenance regulations of natural gas pipelines, make the damage to natural gas pipelines caused by natural forces be effectively controlled.

4. Pipeline supervision and protection

4.1. Pipeline defect detection technology

Pipeline defect detection is an inner and outer wall defect detection method developed for pipeline safety. It is an innovation of pipeline non-destructive testing technology. So far, there have been many pipeline defect detection technologies, the four commonly used methodologies are introduced below:

(1) Magnetic flux detection technology

The principle is relatively simple. The magnetic field is applied to the pipeline through the magnetization device mounted on the corresponding robot. According to the magnetic field theory, if the pipeline does not have defects, it will produce uniform magnetic induction lines on the pipeline wall, but if the pipeline wall has defects, at the defect position of the pipe wall, the magnetic induction line will be severely deformed. The deformation information of the magnetic induction line can be obtained through the detection probe mounted on the corresponding robot, and the defect information of the pipeline can be obtained.

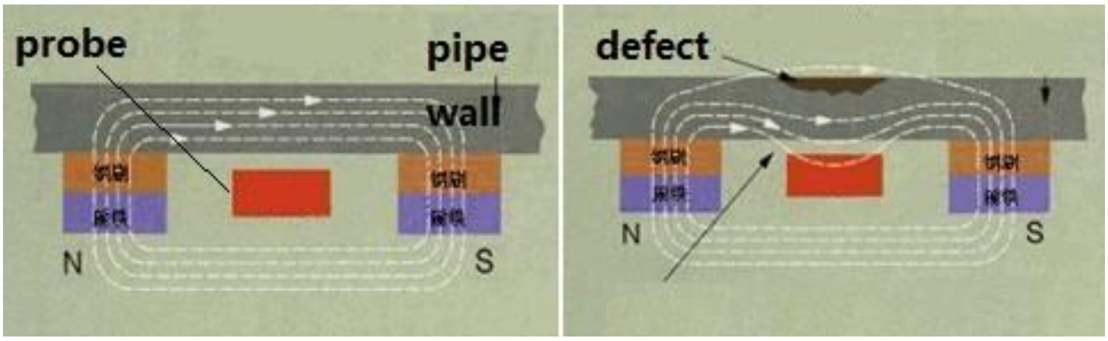


Figure 25: Magnetic flux detection technology [24]

This method has a relatively high level of automation, and during the entire inspection process, the pipeline does not need to be shut down, that is, it has no effect on the operation of the pipeline, but before use, the pipeline needs to be cleaned multiple times to prevent the detection robot from stuck.

(2) Ultrasonic detection technology

Figure 26: Ultrasonic pipeline flaw detector

For the propagation of sound waves, if the propagation medium is uniform and there are no marginal objects, the sound waves can theoretically propagate without attenuation. In reality, if the pipeline material does not have defects, the sound wave propagation should present a status of uniform attenuation If there is a defect in the pipeline, the sound wave will be reflected and refracted at the position of the pipeline defect, and the sound wave receiving device installed on the robot can determine the defect in the pipeline. The advantage is that it not only accurately determines the defects of the pipeline, but also has a very good sensitivity.

(3) Eddy current testing technology

Figure 27: Eddy current testing equipment [25]

The principle is also to apply a magnetic field on the surface of the pipe, and eddy current will be generated on the wall of the pipe. If there is a defect on the surface of the pipe, the eddy current on the pipe surface will change. Through the special eddy current detection device, operators can understand the defects distribution on the inner and outer walls of the pipe.

(4) Thermal image detection technology

The temperature distribution on the side wall of an intact pipe is regular, but if the inner and outer walls of the pipe have defects, this temperature distribution will be changed. For example, the position with reduced wall thickness caused by corrosion or abrasion has higher temperature compared with intact parts on the pipeline. So, the defects can be detected by thermal images.

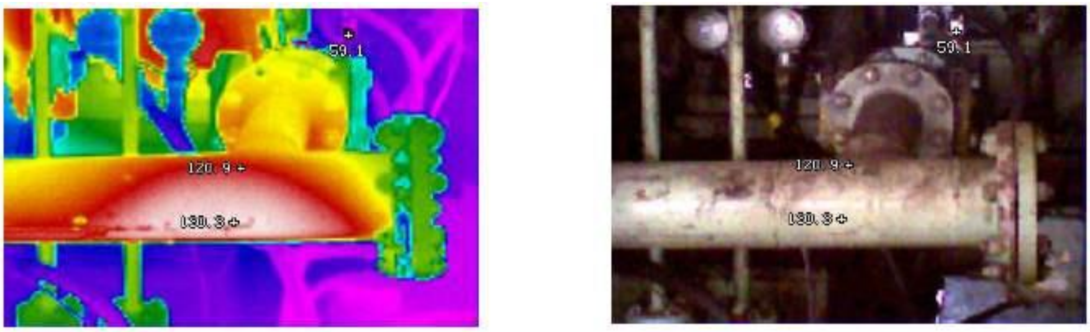


Figure 28: pipeline defects detected by thermal image [26]

This technology is different from the above three technologies. When identifying defects, the pipeline just needs to be scanned, and there is no need to directly contact the detection device with the pipeline. Therefore, the use of this method will not disturb the operation of the pipeline. But the accuracy of this method is extremely susceptible to the influence of external ambient temperature or sunlight, sometimes errors may be introduced by this reason.

4.2. Methods to prevent pipeline incidents

(1) Natural gas producers control the moisture and chemical content of the products transported through their pipelines, to prevent internal corrosion.

(2) Replacement of old pipelines and the common usage of modern coatings like polyethylene coatings.

Some of the pipeline coatings commonly used today are shown below:

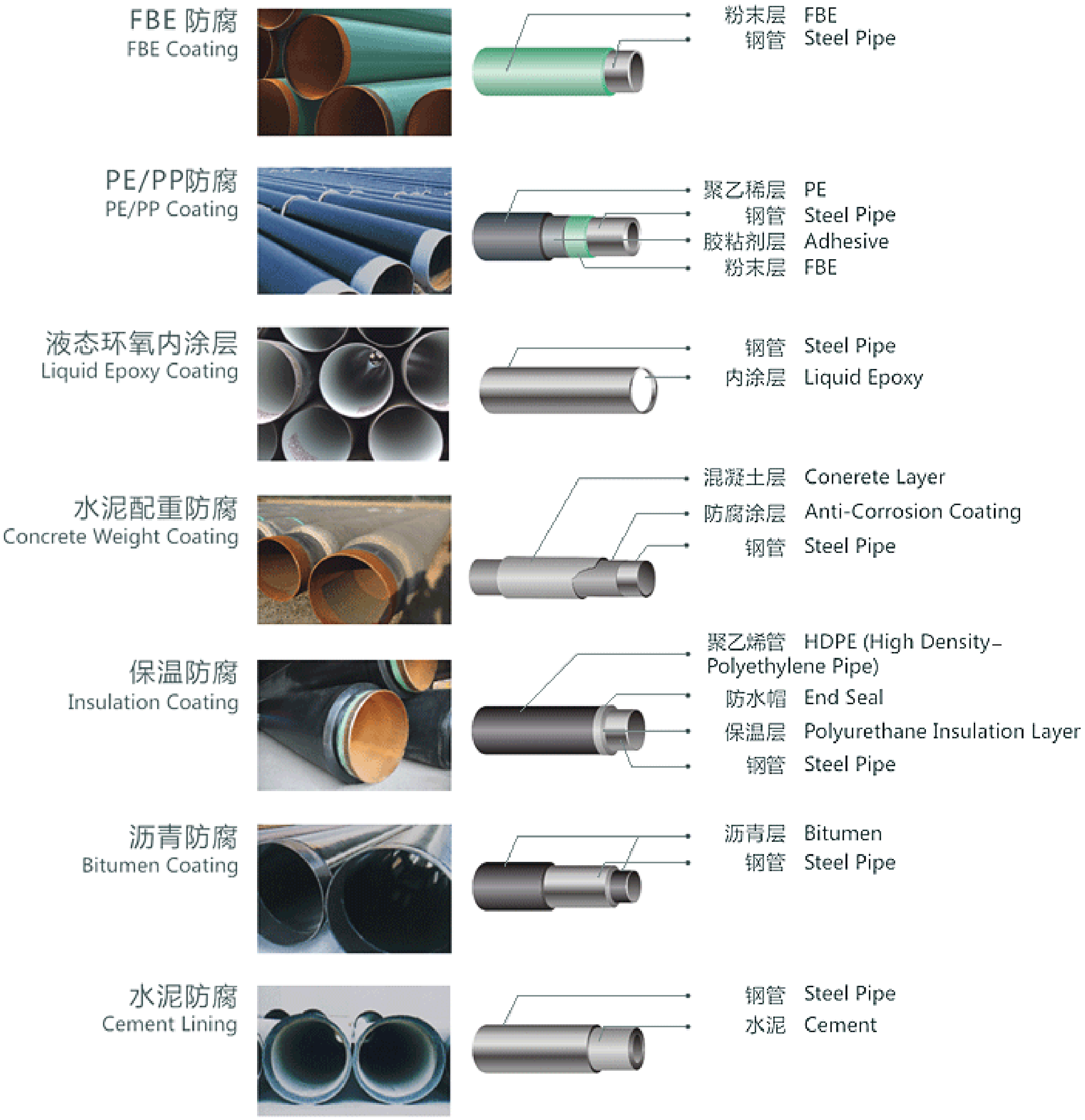


Figure 29: different types of coatings [27]

(3) Rigorous quality control standards should be followed to reduce the occurrence of defects that can lead failures.

(4) Operators are required to periodically inspect and assess their pipelines for cracks and other issues, and repair or replace affected pipe.

(5) After the defect is detected, in the field, pipeline operators always use cathodic protection systems (CPS) to prevent external corrosion. according to the information in PHMSA's website, two kinds of CPS that commonly used in the United States today are introduced below:

※ "Sacrificial" anode stops the electrochemical reaction between the pipe metal and the surrounding environment to prevent external corrosion.

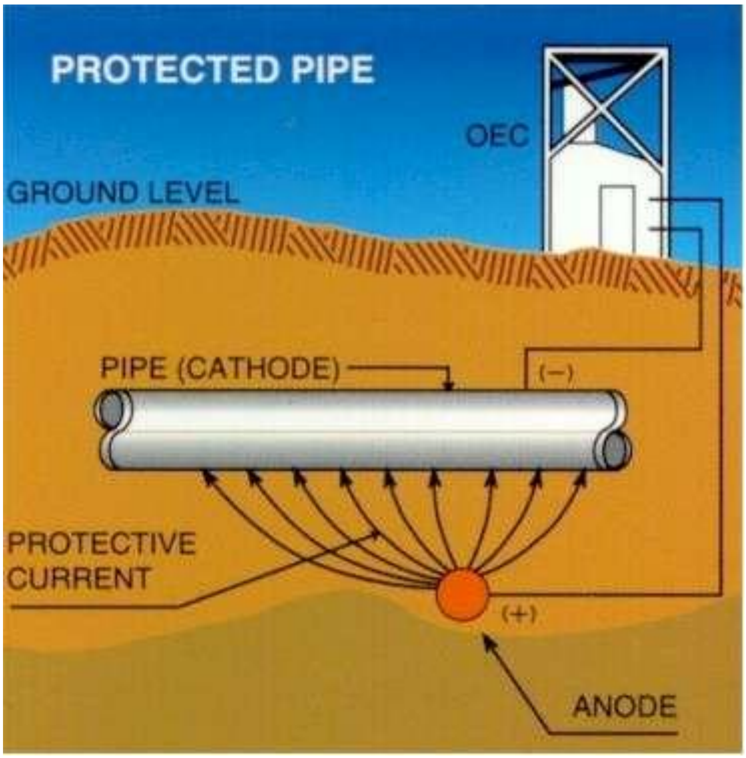


Figure 30: CPS 1 [28]

※ Another type of CPS imposes a very low-voltage direct electrical current on the pipeline to oppose the natural corrosion-inducing currents at locations where pipe coating flaws exist or where pipe coating is damaged.

(6) In areas where natural gas pipelines pass, warning signs should be set up, and security personnel should regularly patrol nearby areas to prevent pipeline damage caused by third-party organizations or individuals engaged in excavation and construction.

Figure 31: Natural gas pipeline warning sign [29]

(7) Last but not least, attention and cooperation of the whole society are powerful guarantees for the safety of natural gas pipelines, to do so, we should: establish relevant laws and regulations, improve pipeline monitoring and emergency response systems, popularize the common sense and basic knowledge of pipeline safety to the general public, and train relevant professional engineers.

5. Numerical analysis: the effect of crack

5.1. Application case

The application case is based on an under-pavement steel main gas pipe, the cross section shown in Figure31 [30]. Two parts of finite element analysis is included, first of which is the stress distribution when the cross section is intact; the second part considering the pipe wall with a longitudinal external crack (Figure 32), by changing the depth of crack, different stress distribution can be observed. The numerical analysis is carried out by using MATLAB code "Static elastic analysis for plane problems with 4-node finite elements", developed by Guiseppe Cocchetti.

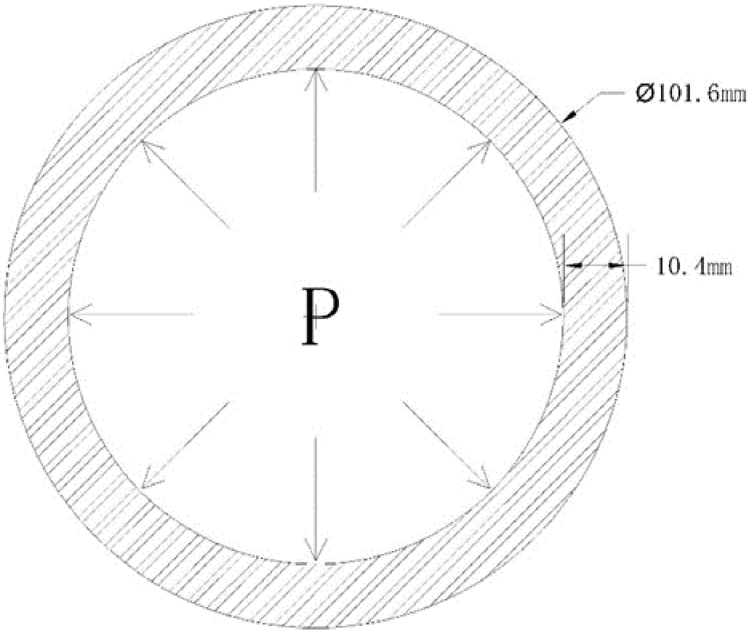


Figure 32: Cross section profile

Parameters of the steel pipeline:

diameter: 101.6 mm, wall thickness: 10.4mm, operating pressure: 34.47 MPa, modulus of elasticity: 2.06 GPa, Poisson's ratio: ν=0.3, Tensile strength, yield: σ_s=320MPa.

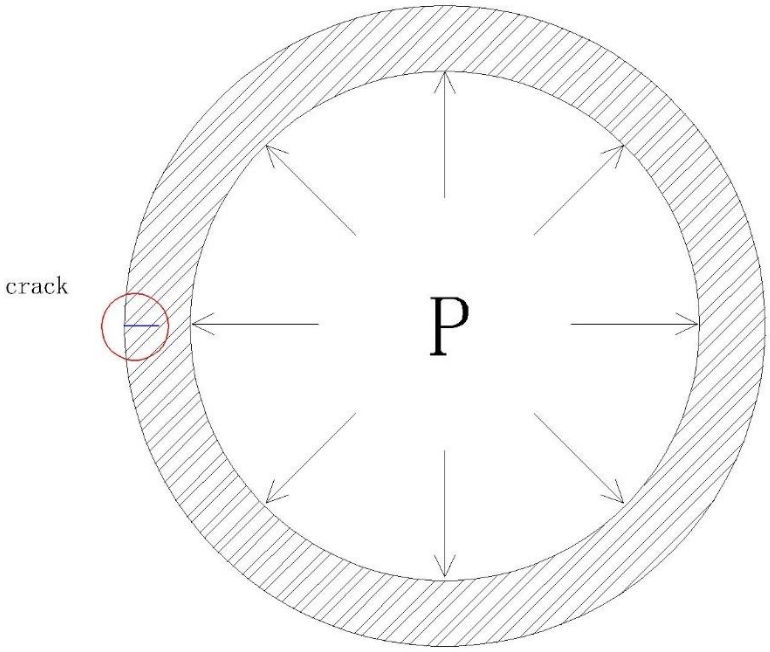


Figure 33: Cross section with crack

5.2. Intact cross section

5.2.1. Finite element model

The length of the pipeline is much larger than the dimensions of the cross section, the case can be analyzed as a plane strain problem. Self-weight and soil pressure are ignored because they are relatively very small compared to the internal gas pressure. Due to the symmetry of the structure, the simplified model is 1/4 of cross section (Figure 32). The internal pressure is calculated and converted into equivalent nodal forces acting on each node on the inner wall

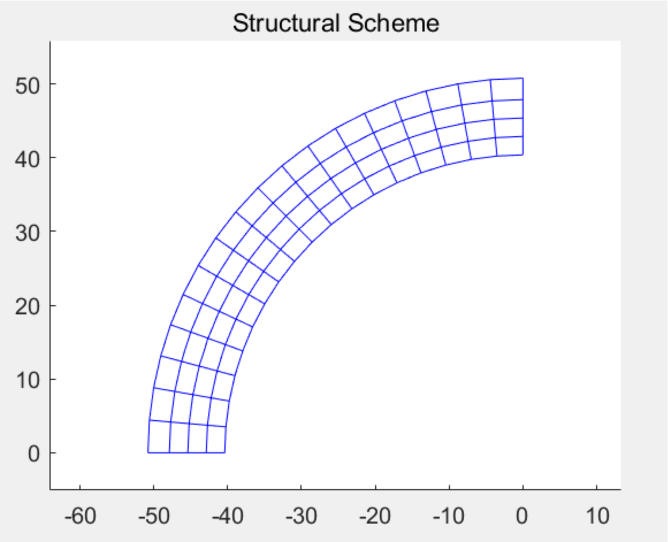


Figure 34: Structure scheme of intact cross section (unit: mm)

5.2.2. Numerical results

The stress distributions have been obtained by finite element analysis, and I compared them with theoretical values.

For the uncapped cylinder structure subject to internal pressure, there are two stress components, they are: circumferential stress (σ_c) and radial stress (σ_r) (Figure 33). σ_c acts around the circumference of the circle, σ_r is the stress away from the central axis of the cylinder.

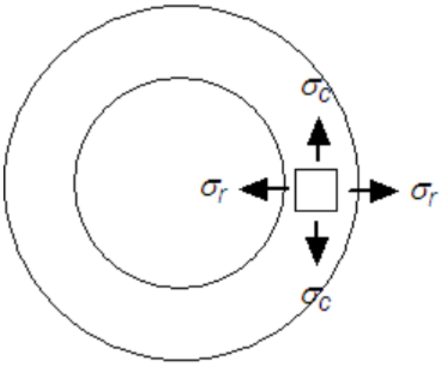


Figure 35: circumferential stress and radial stress [31]

Their value can be calculated by:

$$\sigma_c = \frac{p_i r_i^2}{r_o^2 - r_i^2}(1 + \frac{r_o^2}{r^2})$$

$$\sigma_r = \frac{p_i r_i^2}{r_o^2 - r_i^2}(1 - \frac{r_o^2}{r^2})$$

Where:

r_o: outside radius of cylinder

r_i: inside radius of cylinder

r: radius of interest point at sidewall

p_i: internal pressure

The comparison between numerical results and theoretical values shown below:

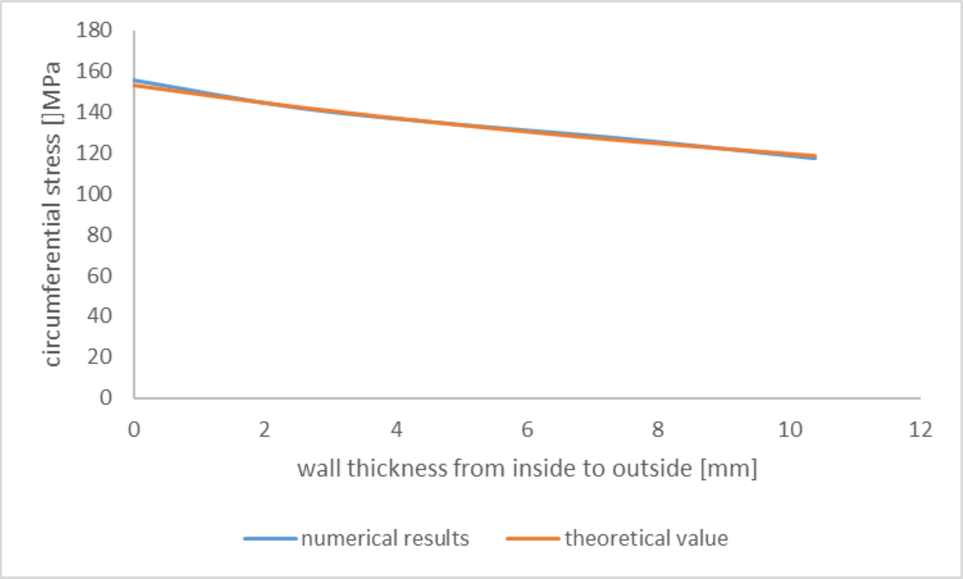


Figure 36: circumferential stress

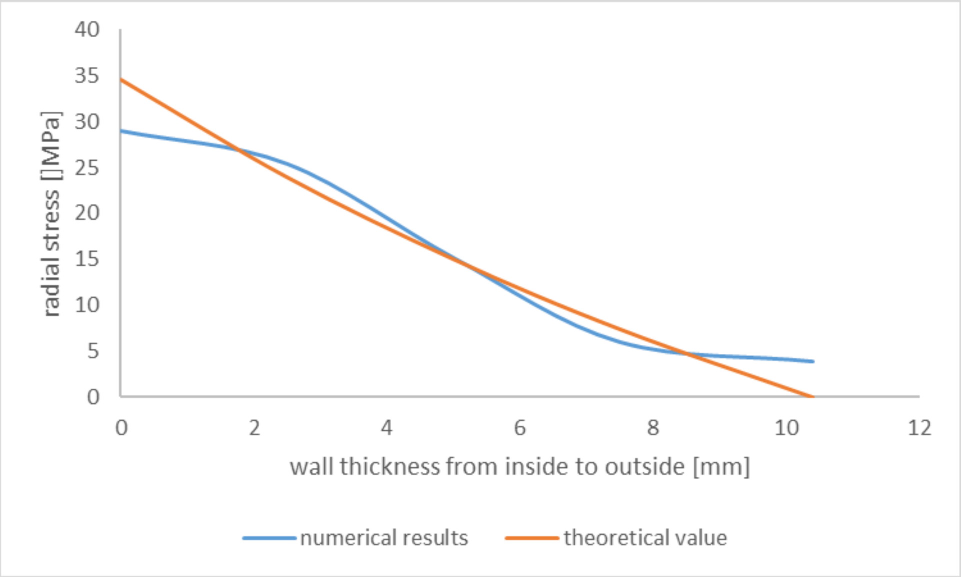


Figure 37: radial stress

According to above comparisons, numerical results are acceptable despite the rough mesh. The von Mises stress, is often used in determining whether an isotropic and ductile metal will yield when subjected to a complex loading condition.

Von Mises stress is expressed as:

$$\sigma_v = \sqrt{\frac{\left(\sigma_{xx} - \sigma_{yy}\right)^2 + \left(\sigma_{yy} - \sigma_{zz}\right)^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)}{2}}$$

For plane strain problem ($\sigma_{yz} = \sigma_{zx} = 0$):

$$\sigma_v = \sqrt{\frac{\left(\sigma_{xx} - \sigma_{yy}\right)^2 + \left(\sigma_{yy} - \sigma_{zz}\right)^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6\sigma_{xy}^2}{2}}$$

Result:

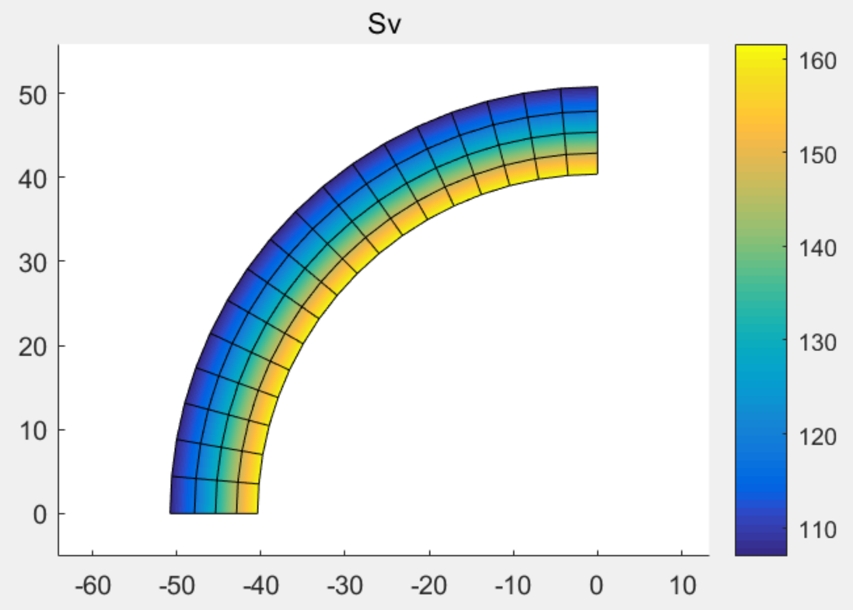


Figure 38: von Mises stress distribution (units: stress [MPa], length[mm])

The maximum von Mises stress at the pipeline wall is 161.5 MPa, which is smaller than the yield limit of material (320 MPa), the operating condition of the pipeline is safe.

5.3. Cross section with crack

5.3.1. Finite element models

In this part, the simplified model is half of the cross section, symmetric about the plane crossing the central axis of the crack, of depth varying from 1mm to 3mm. Two discretizations are introduced (Figure37 and 38), made of 4-node elements. A finer mesh is adopted near the crack to appreciate the stress distribution. The nodes in correspondence of the crack are not constrained.

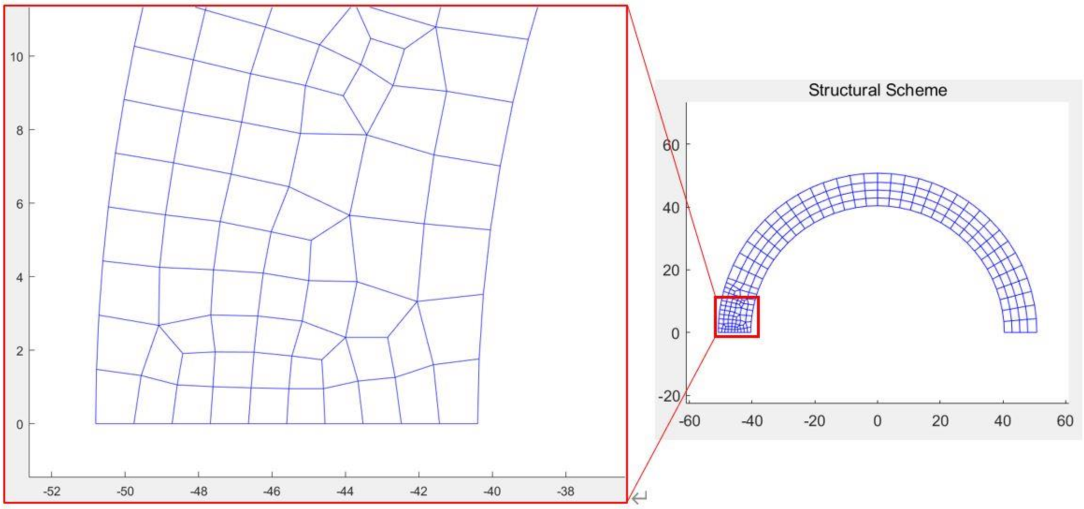


Figure 39: Rough mesh (unit: mm)

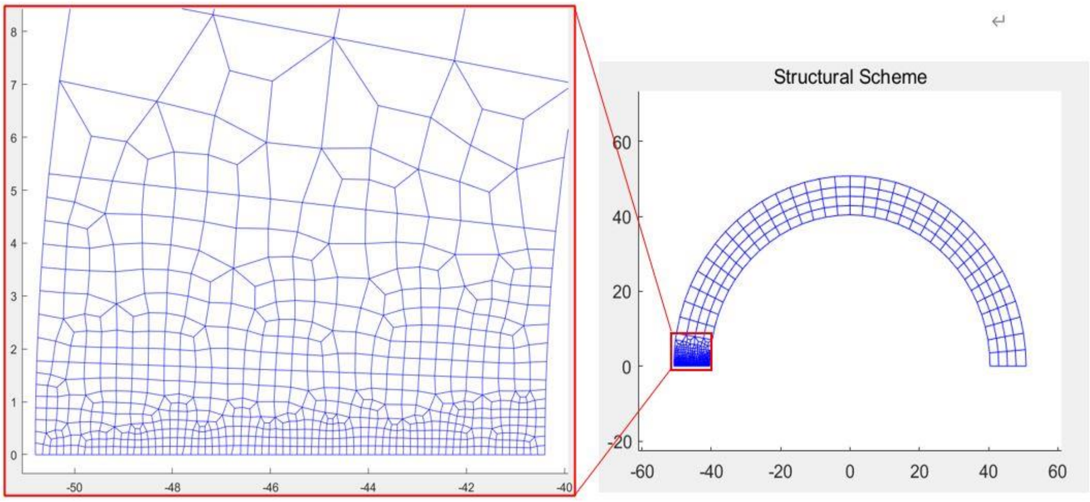


Figure 40: Fine mesh (unit: mm)

5.3.2. Numerical results

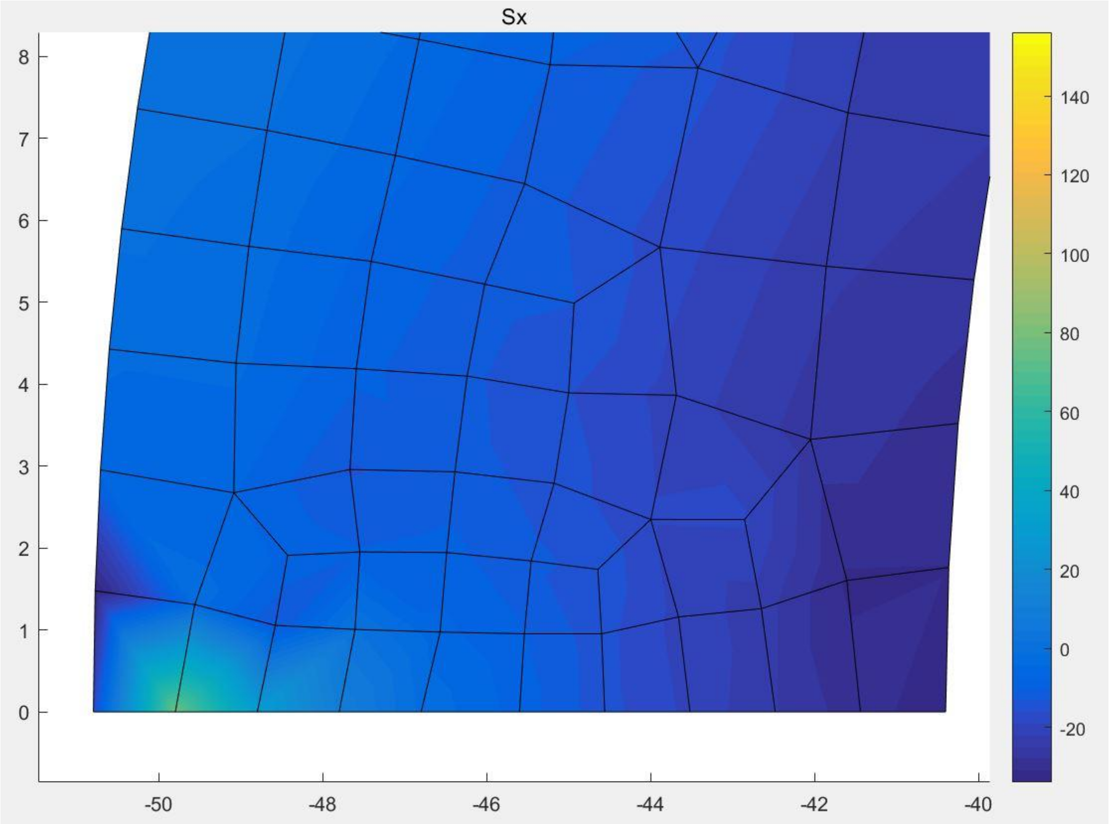


Figure 41: horizontal stress - rough mesh -1 mm crack depth (units: stress [MPa] lengh [mm])

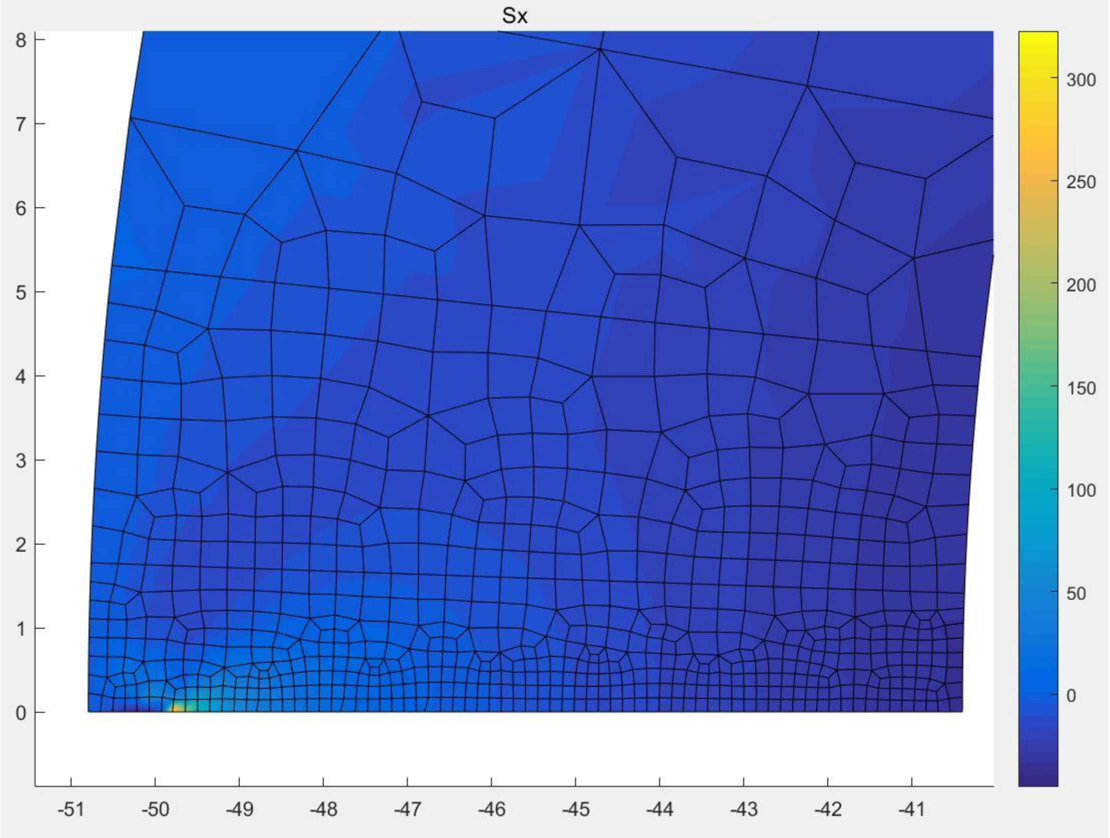


Figure 42: horizontal stress - fine mesh – 1 mm crack depth (units: stress [MPa] lengh [mm])

In order to make a comparison between different discretizations, the stress distribution is represented as a function of the distance from the crack tip are made:

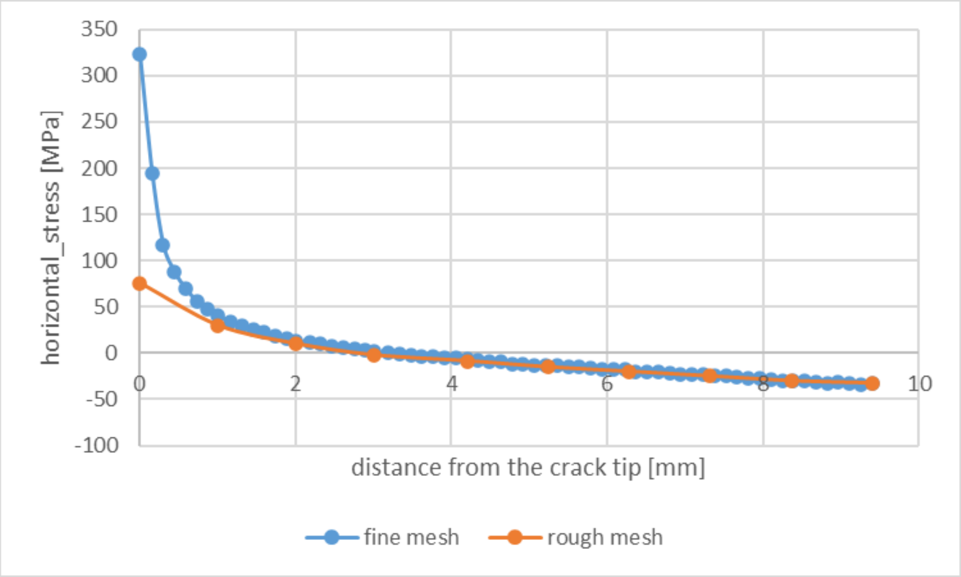


Figure 43: horizontal stress distribution (1mm crack depth)

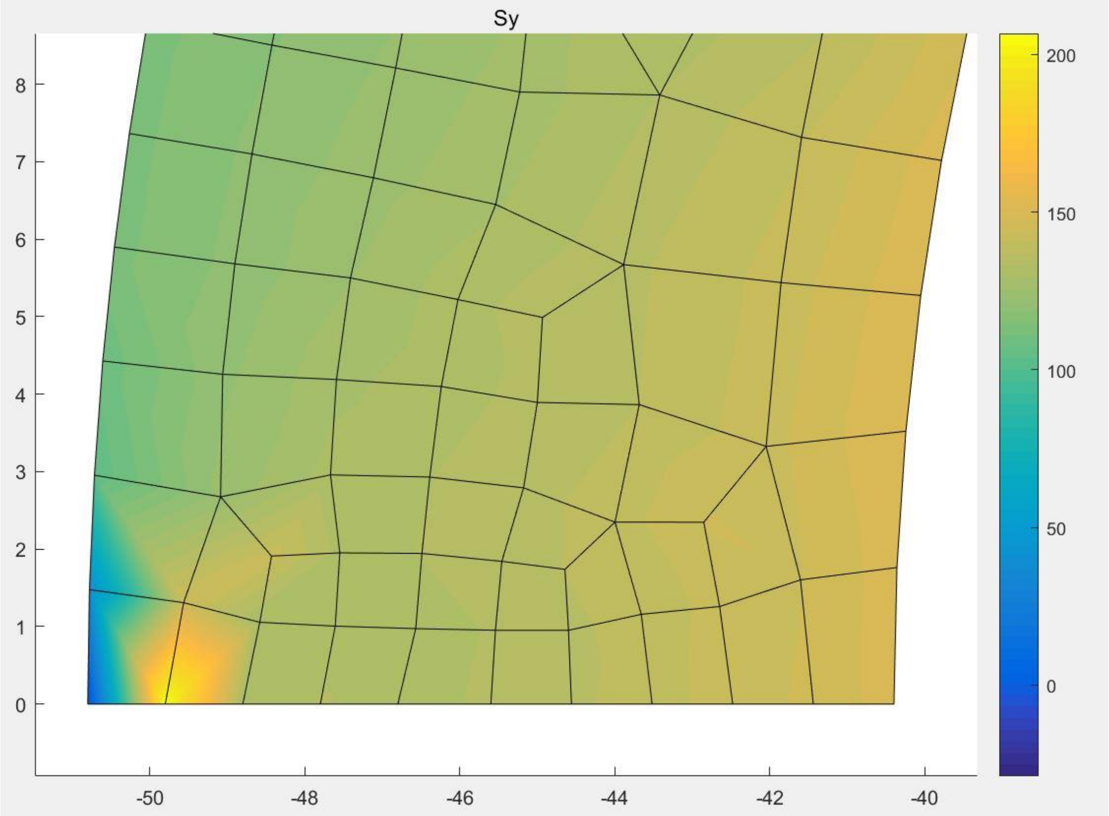


Figure 44: vertical stress-rough mesh-1 mm crack depth (units: stress [MPa] lengh [mm])

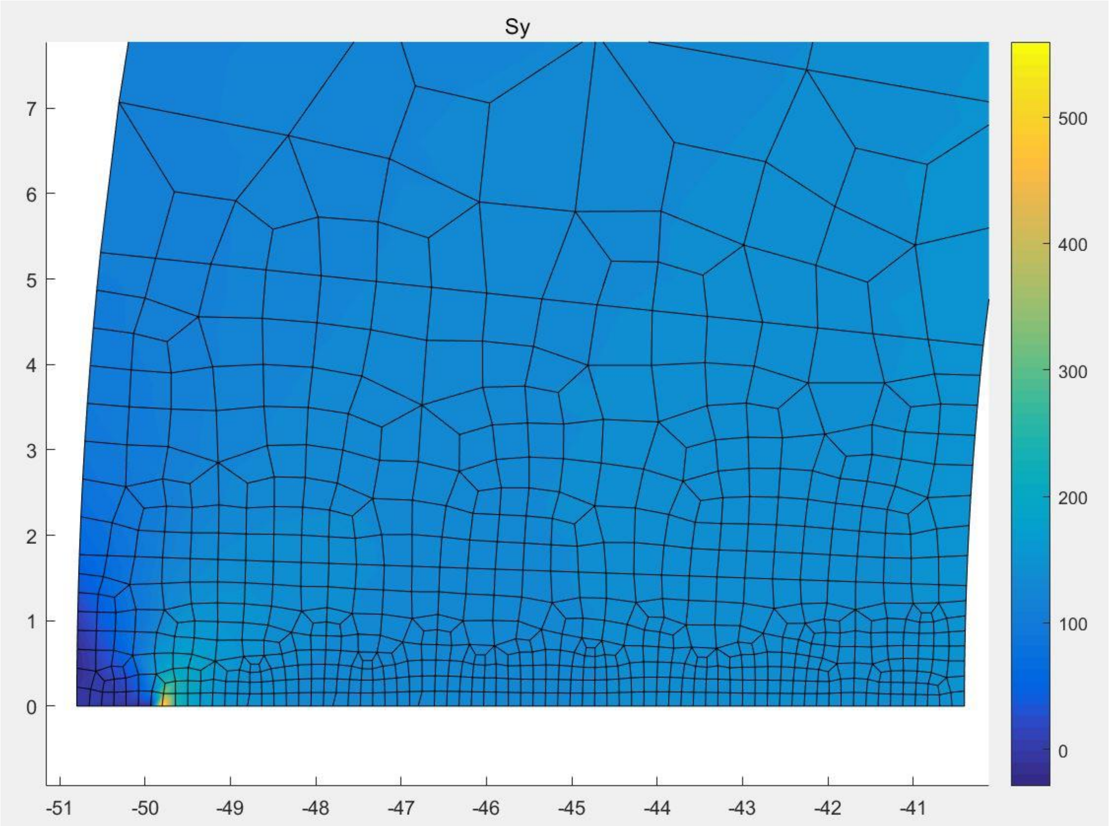


Figure 45: vertical stress-fine mesh-1 mm crack depth (units: stress [MPa] lengh [mm])

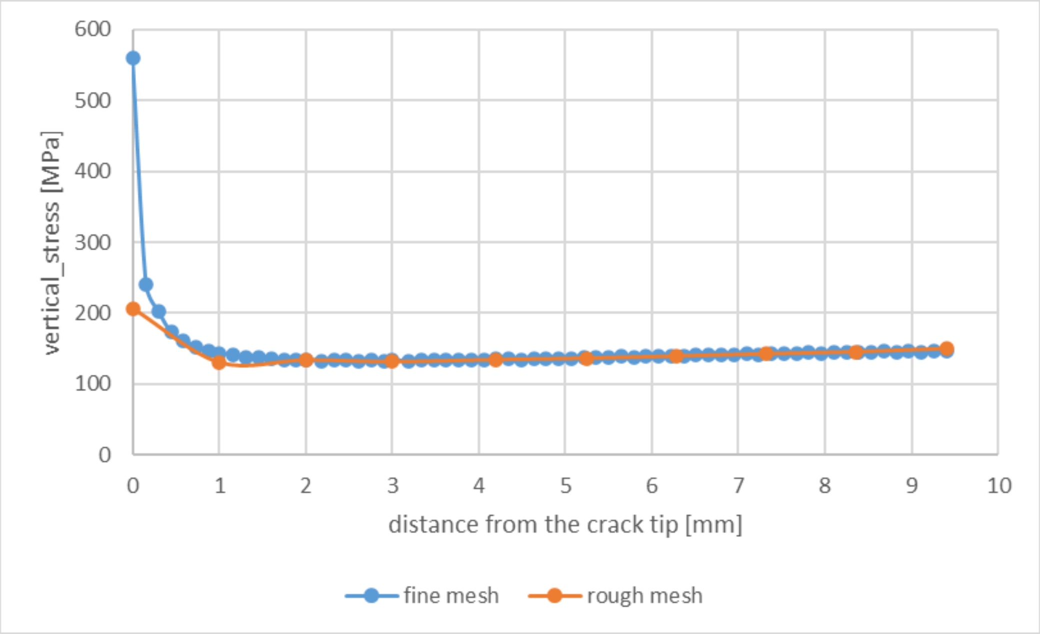


Figure 46: vertical stress distribution (1mm crack depth)

Numerical results of 2 mm and 3 mm depth of the crack are following:

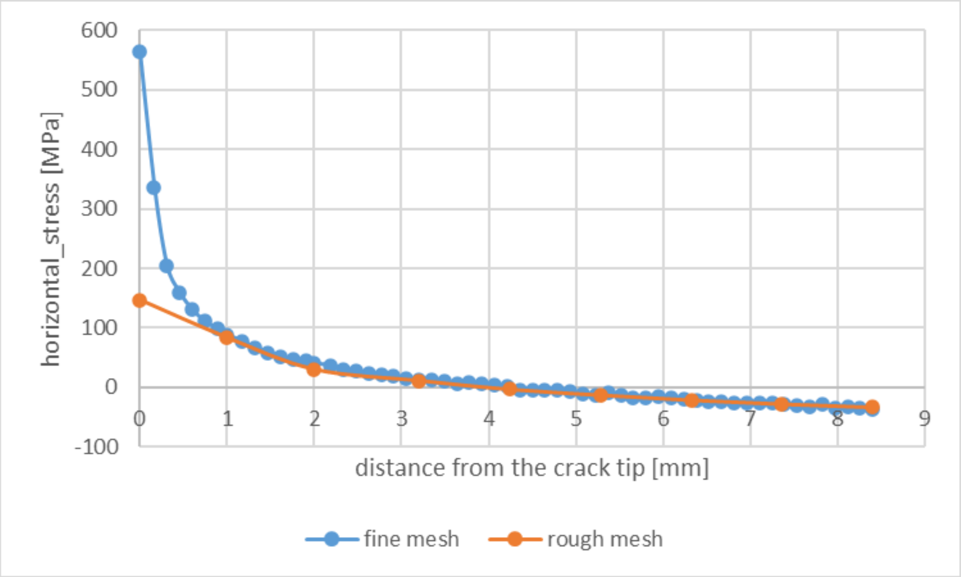


Figure 47: horizontal stress distribution (2mm crack depth)

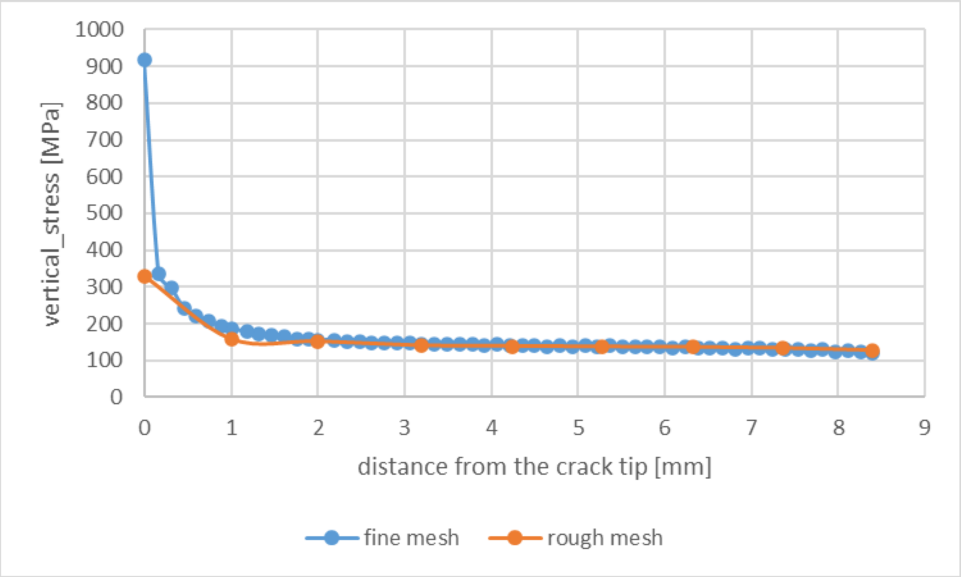


Figure 48: vertical stress distribution (2mm crack depth)

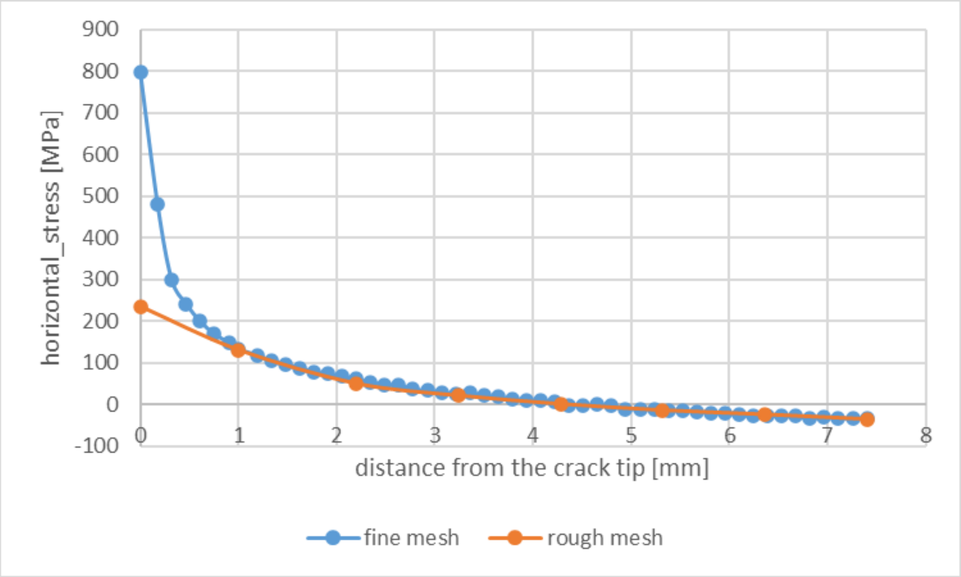


Figure 49: horizontal stress distribution (3mm crack depth)

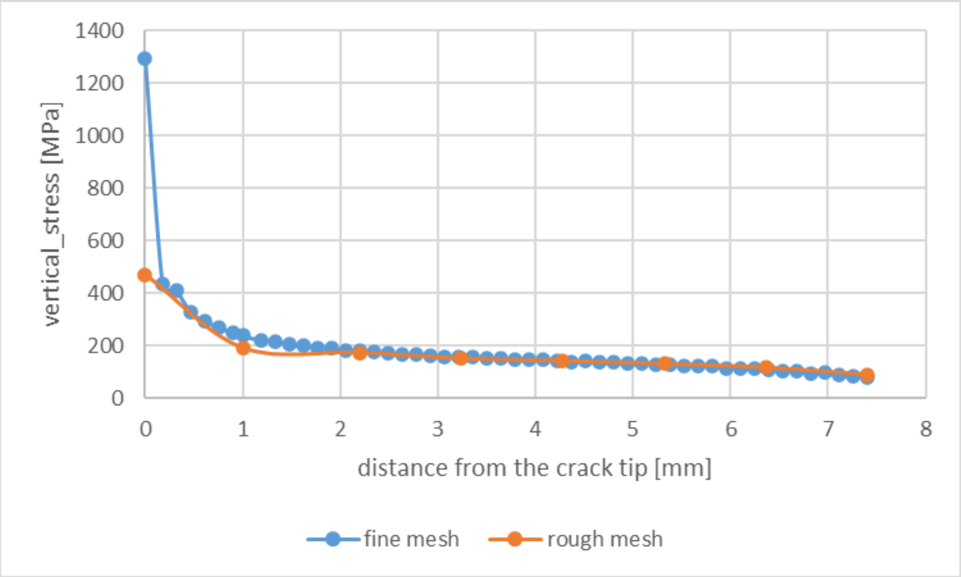


Figure 50: vertical stress distribution (3mm crack depth)

Comparison of the stress distribution of the results obtained at increasing of the crack depth, referring to the fine mesh results:

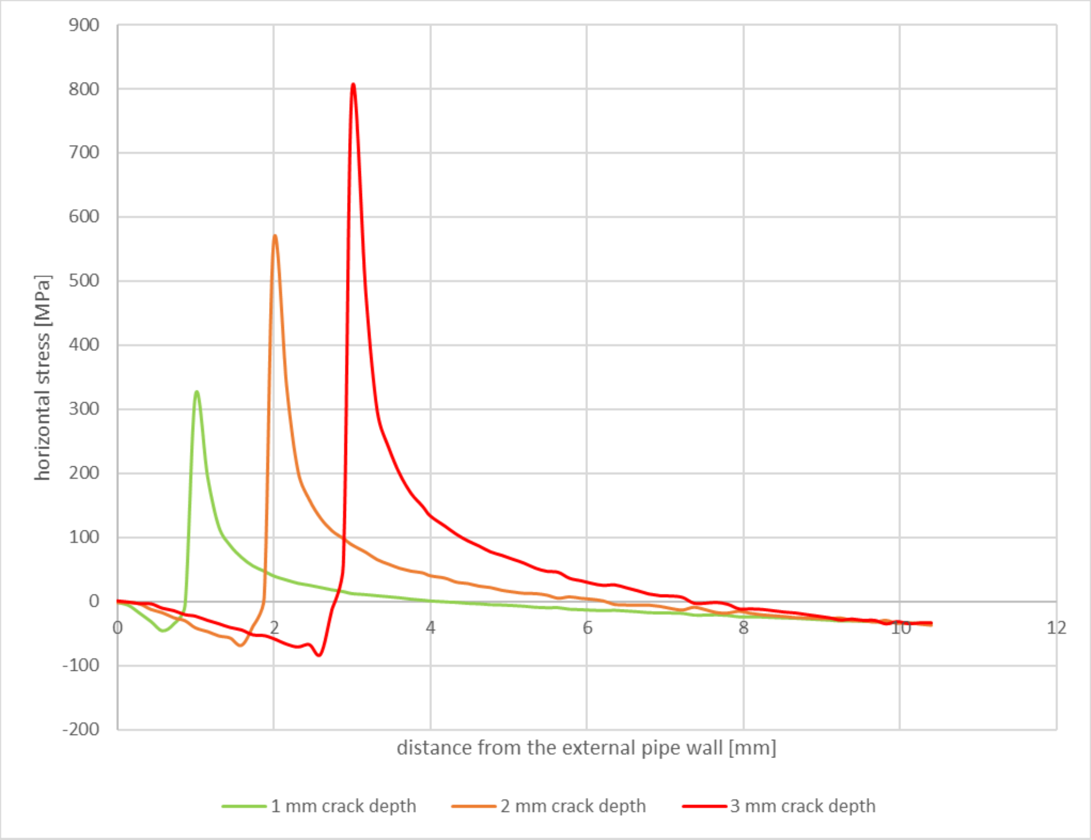


Figure 51: comparison of horizontal stress distribution

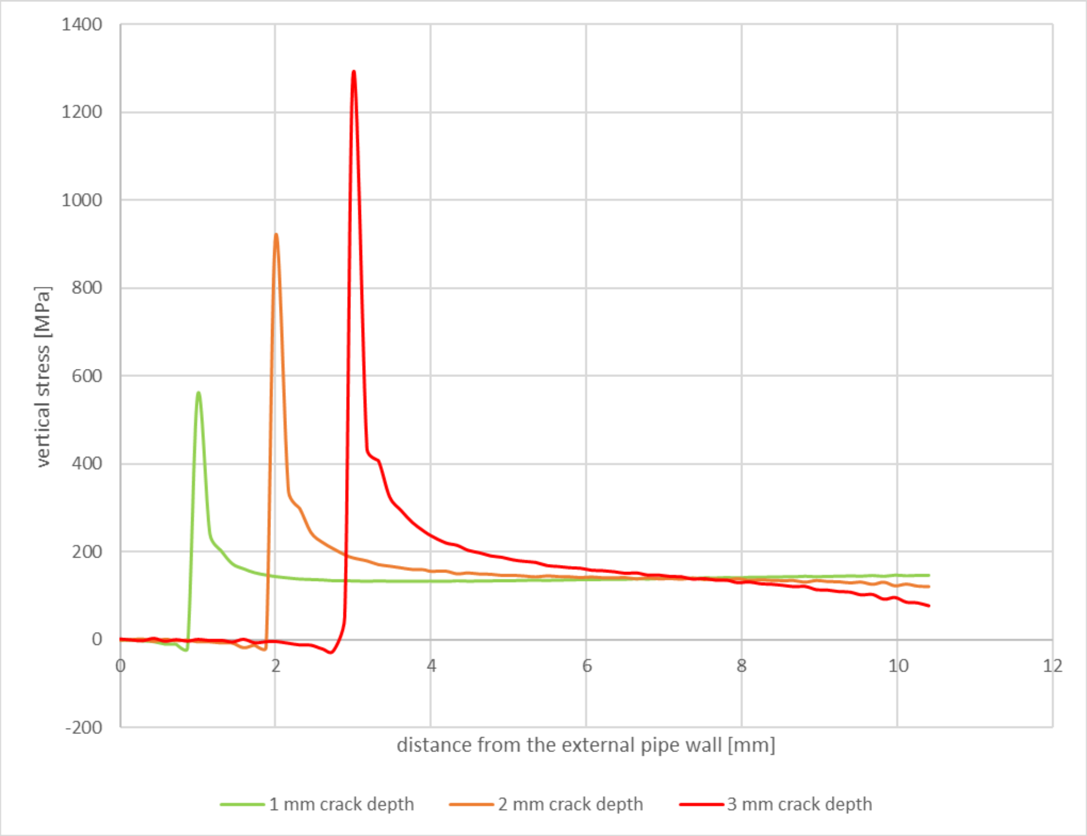


Figure 52: comparison of vertical stress distribution

5.3.3. Result analysis

By observing above results from linear elastic analysis with finite element models, we find:

(1) The presence of external crack, leads to significant stress concentration of all stress components. As the depth of crack increases, the values of each stress components increase, especially near the crack tip (Figure 49 and Figure 50).

(2) The difference between the results obtained from the two different discretizations is significant near the crack tip, where stress gradients occurs.

(3) In intact cross section, both circumferential stress and radial stress reach their maximum values at the inner wall of the pipe. Radial stress, parallel to the crack depth direction, is almost not affected by the present of external crack. Circumferential stress, is

significantly reduced at the inner wall to guarantee overall equilibrium in the direction perpendicular to the crack depth.

In other points of the pipe wall far from the crack, the stress distribution is almost unaffected by the presence of the defect.

5.4. Linear elastic theoretical solution

A theoretical solution has been given to the problem that consider the presence of a small discontinuity or slit in a large linear elastic solid. According to this theoretical approach, the presence of the crack induces stress concentration, when the distance of a point from the crack tip tends to zero, the stress that develops at this point tends to infinity.

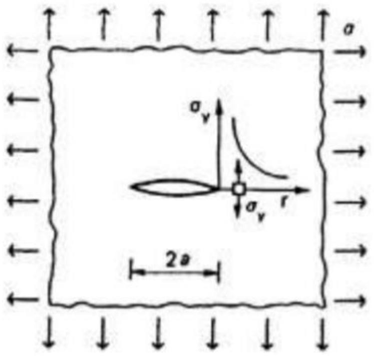


Figure 53: linear elastic theoretical solution of stress concentration caused by crack [32, page 658]

Comparing the numerical results reported above with the theoretical limit, it is possible to state that the stress components tends to infinity at points whose distance from crack tip tends to zero, and due to this reason, the finite element analysis based on linear elastic theory cannot give the exact solution at points that in the vicinity of to crack tip, but finer mesh gives much higher value of stress than that evaluated by rougher mesh.

In real materials, infinite stresses cannot exist. In ductile metals, a plastic zone shall develop around the crack tip, local plastic yielding occurred in this zone which means that the stress is in fact smaller than those expected by linear elastic theoretical solution. The plastic zone shall be more extensive if the material is more ductile. Beyond the plastic zone, stress components present a variation that follows linear elastic theoretical solution. In the following figure, the practical stress distribution is presented, where r_p is the size of plastic zone.

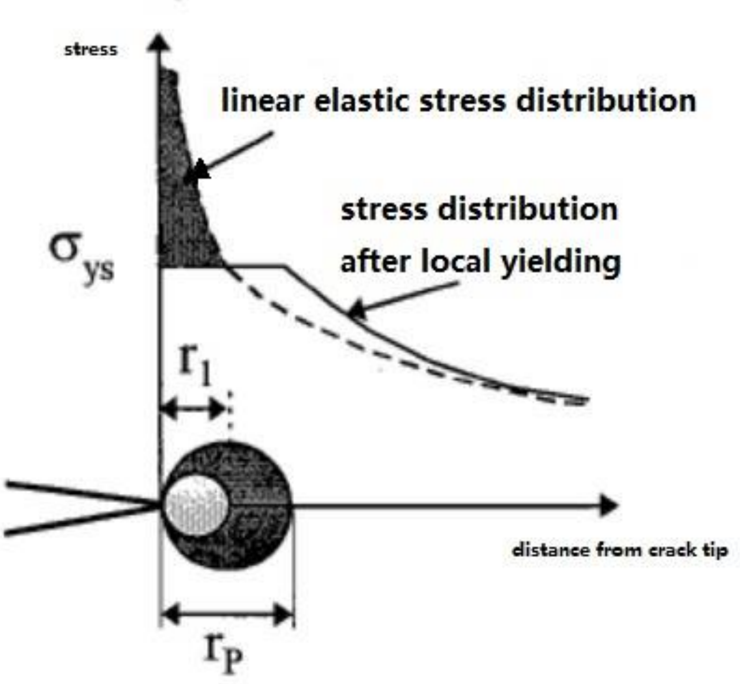


Figure 54: plastic zone and stress redistribution [33]

In the present application, it can be seen that for the natural gas pipelines, are mainly subjected to internal pressure, tensile stresses that acts around the circumference of the circled pipe wall, known as circumferential stresses, play a critical role at pipe wall. Under this stress distribution condition, the appearance of cracks is very dangerous for pipeline safety, because of severe stress concentration occurs near the crack tip and may lead the crack becoming unstable and propagate. Therefore, pipeline monitoring and periodical defect detection are efficient methods for precaution of cracks.

6. Conclusion

Natural gas, as an environmental-friendly fuel, is becoming more and more popular not only in industrial production, but also in people's daily life in recently years. As a powerful guarantee for energy supply in the economically developed areas of the eastern coast, a nationwide gas pipeline network “the West-East Gas Pipeline Project”, has been constructed and is operating well. After 2005, China begun to import natural gas from Russia, Central Asian and Myanmar, multinational long-distance natural gas pipelines have also been established, and connected with the West-East Gas Pipeline network.

Failure of natural gas pipelines may lead serious consequences. Many databases provide reports of natural gas pipeline incidents and failure causes analysis. In the past few decades, these huge databases have helped pipeline operators and managers to improve the safety of their natural gas pipeline transmission systems.

By analyzing the statistical results, top four causes of natural gas pipelines failure are external interferences, corrosion, construction defect and natural force damage. In recent years, with the application of modern technology, standardized management methods, and establishment of emergency response systems, the failure factors are effectively controlled.

In numerical analysis part, by using finite element method, a cross section of a steel pipe is analyzed. The results show, the stress concentration induced by the presence of a crack. The numerical results presented in this work are compared with the predictions of linear elastic theory, where stress components tend to infinity in the vicinity of to crack tip. However, in real materials, a plastic zone is formed near the crack tip. However, the presence of crack - like defects in the side wall of natural gas pipelines can lead severe stress concentration. This problem should be known to prevent failure.

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