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Abstract

Un-bonded flexible pipelines and risers are an alternative to conventional rigid steel pipes. The use of flexible pipes has enabled development of several offshore fields that seemed unfeasible with the use of rigid pipes due to extensive seabed preparation and large dynamic motions. The lack of knowledge and integrity management tools for flexible pipes is a limiting factor and cause pipelines and risers to be replaced before their service life has been reached. This thesis aims to discover the critical failure modes for flexible pipes and explore conventional and novel techniques for performing inspection and monitoring. By understanding the failures and having access to the necessary technology the remaining lifetime and lifetime extension calculation will be more accurate than to date. Degradations and failure mechanisms will be detected at an early stage giving the operators better time to initiate mitigating and repair measures.

By contacting industry experts and performing a study of the latest literature this thesis presents the possible failure modes for flexible pipes, as well as a screening of conventional and novel inspection and monitoring techniques. Reported incidents for Norway, UK and the rest of the world are presented to reveal the greatest risks for flexible risers. An integrity management strategy is based on the reported incidents, including recommendations and purpose of inspection and monitoring techniques.

Based on incident reports and inputs from stakeholders the most frequent and critical failures to flexible pipes caused by to damage to and degradation of the internal and external polymer sheath. Breach of the outer sheath creates a hazardous environment in the annulus leading to an increased risk for several failure mechanisms. Degradation of the internal pressure sheath threatens the fluid containment integrity, and is difficult to inspect for. It is recommended to have a well-functioning annulus vent system attached to a monitoring system to control the annulus environment. Integrated fiber optics is considered as the most promising technique currently under development. This would provide continuous temperature monitoring throughout the riser and pipeline which can be used for outer sheath breach detection and temperature degradation calculations. For existing pipelines a number of solutions are under development for integrity management, such as radiography, ultrasonic testing, and magnetic stress measurement among others. Individually they are useful, but if combined they might act as powerful multipurpose tools.

Acknowledgments

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I would like to give my sincere gratitude to my supervisors, Eiliv Janssen (UiS) and Charles Paton (Shell), for their guidance and mentoring throughout the entire process. They have given me the motivation and encouragement to finish this thesis.

I would also like to thank my fellow students that have made my days at the office to a positive experience.

Anders Simonsen.

June 2014.

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Abbreviations

API	American Petroleum Institute
AUV	Autonomous Underwater Vehicles
CO_2	Carbon dioxide
CODAM	COrrosion and DAMage database
CRA	Corrosion Resistant Alloy
CT	Computed Tomography
DP	Dynamic Positioning
DR	Digital Radiography
FAT	Fabrication Acceptance Test
FBG	Fiber Bragg Grating
FPSO	Floating Production, Storage and Offloading unit
GoM	Gulf of Mexico
H_2S	Hydrogen sulphide
HDPE	High-Density Polyethylene
HIC	Hydrogen Induced Cracking
IMS	Integrity Management Strategy
JIP	Joint industry project
MBR	Maximum Bend Radius
MEC-FIT	Magnetic Eddy Current Flexible Riser Inspection Tool
NCS	Norwegian Continental Shelf
NDT	Non-destructive Testing
PA	Polyamide
PSA	Petroleum Safety Authorities
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene fluoride
QA	Quality Assurance
QC	Quality control
R&D	Research and Development
ROV	Remotely Operated underwater Vehicle
RP	Recommended Practice
SLOFEC	Saturated Low Frequency Eddy Current
SSC	Sulphide Stress Cracking
TDP	Touch-down Point
TWI	The Welding Institute
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
UT	Ultrasonic Testing
UTS	Ultimate Tensile Strength

1 Introduction

1.1 Background

Flexible pipelines and risers have been in use worldwide for over 30 years and serve as an alternative for the conventional rigid steel pipe. Flexible un-bonded pipes consist of different layers of different materials that act together and allow for unique flexibility compared to rigid steel pipes. This complexity has facilitated the development of several fields and subsea tiebacks that would have been economically unfeasible with rigid pipes due to the need for extensive seabed preparations. Flexible risers ease the use of floating production facilities since they have a better dynamic response than conventional steel risers.

However, the complexity of flexible pipes makes them more vulnerable to degradations and the number of failure modes is considerably higher. The use of different materials enclosed within several layers makes the task of integrity management difficult. Still after so many years of development, manufacturing and operation of flexible pipes there exists large knowledge and technology gaps that need to be filled to meet integrity requirements. The lack of knowledge and appropriate technology has been the direct cause for a number of flexible pipes to be taken out of operation before their service life has ended. This is partially caused of undetected defects or too conservative remaining life predictions.

To mitigate the risk of failure and extend the service life of flexible pipe the industry has to cooperate. In recent years some initiatives have started and are leading the way for the industry to follow.

In 2009 Oil and Gas UK started a Joint Industry Project (JIP) funded by international oil and gas operators. The JIP was led by SureFlex and included international oil and gas operators, a flexible pipe manufacturer and a regulatory authority (ref. [19]). A key objective for this project was to collect data from international oil and gas companies regarding flexible pipe use, degradation, and incidents.

In recent years the Norwegian Petroleum Safety Authority (PSA) has motivated for focus on flexible pipeline integrity. They manage the database COrrosion and DAMage (CODAM) for reporting injuries and incidents of offshore structures and pipeline systems on the Norwegian Continental Shelf (NCS). In addition to this, PSA publishes an annual report regarding trends in risk level in the petroleum activity (RNNP) for the NCS. In 2012 the report stressed the concern of integrity management for flexible pipes, and presented a list of improvement areas for the industry (ref. [9, 33]):

"The industry needs to address the following improvement areas:

1. Updating standards with the most recent experience.
2. Integrity management of flexible risers with continuous monitoring and systems for documenting operations history, which are actively used in follow-up.
3. Ensure good training and expertise throughout the organization responsible for following up integrity.
4. Clear and unambiguous responsibilities for safe operation and integrity management.
5. The industry must do a better job at sharing information between companies in order to ensure continuous improvement throughout the sector.

6. The industry must actively commit to research and development in order to increase knowledge about flexible risers.
7. Quick and precise incident reporting associated with pipelines, risers and subsea facilities."

The two initiatives mentioned above are critical for the industry to progress in solving the integrity issues for flexible pipelines and risers. Information sharing is key to get an overview and to update standards and guidelines for safe fabrication and operation of flexible pipeline systems.

1.2 Purpose of this thesis

This thesis will have three main objectives:

1. Present and describe the most probable failure modes for flexible pipes including occurrences and statistics.
2. Present and describe conventional and new techniques for inspection and monitoring of flexible pipes.
3. Propose an integrity management strategy for flexible pipes considering the information provided in the two previous objectives.

By describing the failure modes with occurrence and statistics, the need for inspection and monitoring techniques will be established. The presentation of these techniques will serve as a screening of available integrity management tools within the industry. Conventional techniques are not sufficient to fulfil the integrity requirements, hence new technologies will be explored. Based on objective one and two an integrity management strategy will be proposed. The inspection and monitoring techniques will be allocated into categories, and the necessity of these techniques will be discussed. These objectives will serve as guidance for point one, two and six from PSA's list for improvements regarding the flexible pipe area.

1.3 Limitations

This thesis will be limited to un-bonded flexible pipelines and risers. Hence bonded flexible pipes will not be discussed. Ancillary equipment, including spools and jumpers, will be mentioned but, not described in detail. The main focus will be directed on risers as these are the subject of the largest concern. Information on new technologies and failures on existing developments are limited due to competitive reasons.

1.4 Methodology

To establish an overview of the failure modes and mechanisms a literature study will be performed. Contact with PSA and the utilisation of their reports on this subject, in combination with industry standards, will give a basis for understanding the criticality of the different failure modes and mechanisms. Conference papers and contact with authors and experts will provide information regarding inspection and monitoring techniques. Through this process a list of stakeholders will be established and act as personal channels for information sharing and input on important issues. These inputs will provide different perspectives on the integrity management issue to broaden the understanding of the wider context.

2 Flexible pipelines and risers

2.1 Introduction

A flexible pipe is a complex configuration of different flexible layers (described in section 2.2) which act together as one unit for containment of produced oil and gas or injection of gas and water. The flexible pipeline and riser have the same pipe configuration. The flexible pipeline is installed on the seabed and is not subjected to large and frequent movements, hence it can be referred to as a static application. Flexible risers are the connection between seabed and production unit. The riser follow the motions of the production unit, hence it can be referred to as a dynamic application.

The use of flexible pipelines has the potential to severely reduce the total installation cost compared to rigid pipeline installation. For rough seabed routes a rigid pipeline would require a large amount of seabed preparation, meaning renting and deployment of costly vessels and labour. An alternative is to find another route resulting in a longer pipeline, more material and fabrication cost and longer installation time. Another advantage of flexible pipeline is the change that may happen on the seabed over time. Currents can move the sand from beneath the pipeline creating free spans. This can cause problems for rigid pipelines and more seabed preparation may be needed.

Flexible risers have been a revelation for floating production units. The dynamic motions of ships and semisubmersibles can be relatively large, and in harsh environments rigid pipelines can be unfeasible. Figure 1 shows an illustration of a semisubmersible, to the left, and a Floating Production, Storage and Offloading unit (FPSO), to the right, both connected to flexible risers.

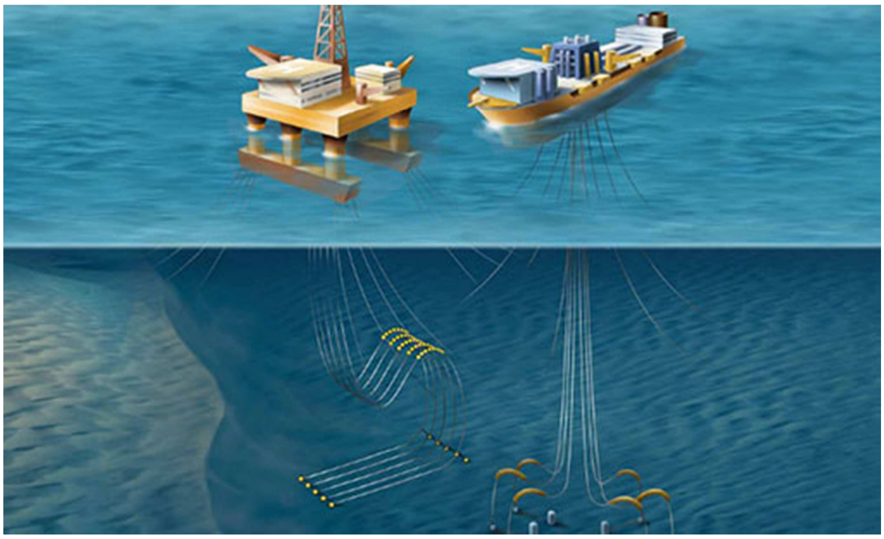

Figure 1 - Floating production units with flexible risers attached [sintef.no].

2.2 Layer description

Flexible pipelines are complicated compounds made from different layers and materials, each with its specific function. The main components of a flexible pipeline are shown in Figure 2 and comprise:

- internal carcass
- internal pressure sheath
- pressure armour wires
- tensile armour wires
- external pressure sheath

Operators can alter the configurations of their flexible pipes to achieve the properties they desire for each unique development. Examples include: adding layers to reinforce, adjusting the angle of armour wires to control the force distribution, vary materials for the operational environment and more. The different layers are described in the subsequent sections.

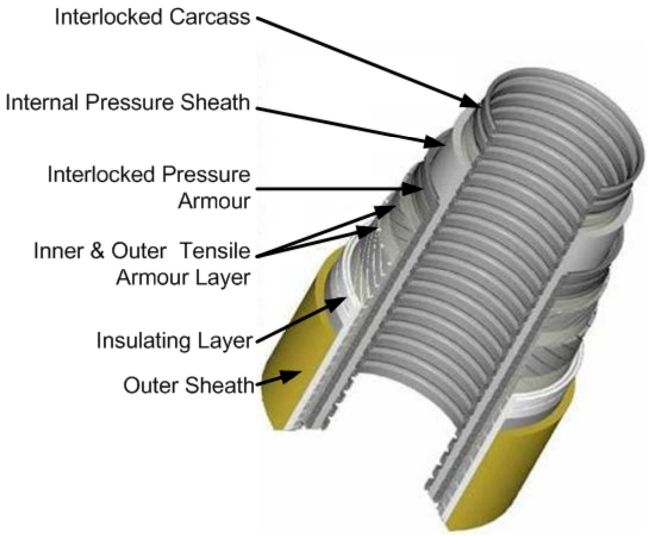

Figure 2 – Example of a basic configuration of flexible pipes [28].

A section of the flexible pipe cross section that will be frequently discussed in this thesis is the annulus. The annulus is the free space between the internal pressure sheath and the outer sheath, e.g. the spacing between the steel wires. It is common practice to install a vent system for the annulus at the end fitting of the riser. This system includes tubes leading from the annulus to vent valves and is designed to release pressure and perform monitoring and testing of the annulus environment.

2.2.1 Carcass

The innermost layer of the flexible pipeline is called carcass. The carcass is composed of stainless steel strips in an interlocked profile (see Figure 3). The carcass has two main functions; prevent collapse due to hydrostatic pressure, and protect the other layers from contact with the produced fluids. The interlocked profile gives the carcass the ability to flex in addition to preventing the pipeline from collapsing.

Figure 3 - Example of an interlocked carcass profile [2].

The dimensioning factor for the carcass is the expected hydrostatic. As the innermost layer the carcass acts as an abrasion cover for the rest of the layers so they don’t come in contact with the bore fluids. The produced fluids may contain solids with high erosion threat. This have to be considered and the steel type of the carcass must resist this force so that the pipe does not fail due to corrosion.

2.2.2 Internal pressure sheath

The internal pressure sheath is an extruded polymer (plastic material) layer that is designed to keep the bore fluid integrity intact. The carcass is not leak proof, so the internal pressure sheath is required to prevent fluids from flowing freely into the pipe annulus. There are different materials with different benefits used for the internal pressure sheath. Table 1 lists the different polymer materials used in flexible pipes. For temperature limits, fluid compatibility and blistering characteristics see Appendix A.

Layer	Material type
Internal pressure sheath	HDPE, XLPE, PA, PVDF
Intermediate (anti-collapse) sheaths	HDPE, XLPE. PA. PVDF, TPE
Anti-wear layers	PA, PVDF, HDPE
Outer sheath	HDPE, PA, TPE
Insulation	PP, PVC, PU

Table 1 - Different polymer materials used in flexible pipes [2].

The most commonly used polymers are HDPE and PA-11, as they have a greater strain resistance, lower cost, and there is a better understanding of how they react over time compared to the currently available other options.

However, the materials used for the pressure sheath is permeable to low-molecular-weight hydrocarbons, meaning there is a continuous diffusion of gasses from the bore into the steel armour layers. This was not a known phenomenon in the early years of flexible pipe manufacturing, and has caused problems later on (this will be discussed in chapter three and four).

2.2.3 Pressure armour

The pressure armour (also known as the hoop stress armour) serves to withstand the internal radial pressure caused by the bore fluids and gases. This is an interlocked metallic layer wound by profiled wires (see Figure 4) with an angle close to 90°, installed around the internal pressure sheath. The profile of the wires and angle of winding allows for flexibility of the layer along with the mechanical strength. If the pipe is to be subjected to a very high internal pressure, a second armour layer may be installed.

High strength carbon steel is commonly used in the pressure armour. The strength of the material used is based on design pressure and the “sourness” of the bore content. The sourness of the bore content is determined by the percentage of carbon dioxide (CO_2) and hydrogen sulphide (H_2S). Sweet and sour service is characterised by a low and high percentage of CO_2 and H_2S, respectively. For sweet service, high strength steel with Ultimate Tensile Strength (UTS) of 1400MPa can be used. High strength steel is prone to Hydrogen Induced Cracking (HIC) and Sulphide Stress Cracking (SSC) which is embrittlement of the steel caused by high values of H_2S and CO_2, respectively (further explained in section 3.7). Therefore sour service flexible pipes use steel wires with UTS as low as 750MPa.

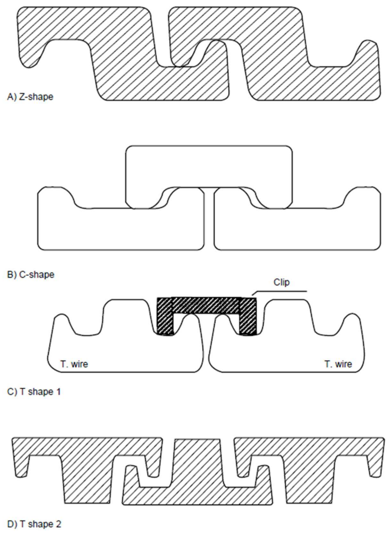

Figure 4 - Examples of pressure armour profiles [2].

2.2.4 Tensile armour

The tensile armour layer is designed to withstand the axial tension force in the pipe. Large tension forces are experienced by the pipeline during installation. The riser is under constant tension as it is suspended from the production facility down to the seabed. The tensile armour layer consists of several steel wires wound in a helical pattern around the pressure armour. The tensile armour is always installed in pair layers with opposing helical pattern to create torsional equilibrium in the pipe. Carbon steel is commonly used, and the UTS is governed by the same principals as for the pressure armour, i.e. HIC and SSC along with design forces.

If large axial forces are expected additional layers of tensile armour can be installed. The steel wires are wound with an angle of 20-60 degrees from the longitudinal axis. Lower angles are used when the flexible pipe includes a pressure armour layer. If the internal pressure is estimated to be low there is no need for pressure armour. Then the angle is typically 55 degrees to balance the radial and longitudinal forces in the pipe.

2.2.5 Outer sheath

The external sheath can be made from the same extruded polymer material as the internal sheath (see Table 1), HDPE is often used. The outer sheath serves as an abrasion layer and keeps the seawater out of the annulus. This is a critical layer as outer sheath damage is the most common recorded failure mode (ref. [19]).

2.2.6 Other layers

The five layers discussed above are the main layers in a flexible pipe configuration. As mentioned there can be differences in these layers with regards to material selection, angle of winding, number of layers etc. To specify each individual flexible pipe for its own development conditions and purpose, there are also some other layers that can be added to the cross section.

Anti-friction tape is a high strength tape that is wrapped around the steel layers to prevent wear when they are rubbing against each other in dynamic conditions (installation, vessel motion, environmental loads, etc.). High strength kevlar tape can be added to make sure that the wires keep their intended position and prevent wire buckling throughout the installation and operational stages.

For sour service developments with a high concentration of H_2S a double annulus solution has been developed. In this concept the inner annulus contains the pressure armour which does not require high tensile strength steel, this allows for a relatively high H_2S concentration. A second polymer sheath is wrapped around the pressure armour to make another "section" of the annulus where the tensile armour is located. Some H_2S gas will be able to diffuse through this layer as well, but not as much as if there only was one polymer layer. This allows for higher tensile strength in the tensile armour without increasing the risk of SSC and HIC failures.

For developments with cold water it is possible to install an insulation layer before the outer sheath. This layer will preserve the heat of the produced fluids for long distance pipelines. If the produced fluids are cooled down to a certain temperature the risk of hydrate and wax formation is increased. These formations can accumulate and block the pipeline, resulting in shut-down and potentially in costly repairs.

3 Failure mode review

Because of the complex configuration of the flexible pipeline with many layers and different materials there are a great number of events that can cause failure of the pipeline. This chapter will discuss:

- The failure modes that are listed in API RP 17B (ref. [2])
- Some of the mechanisms that may lead to these failure modes
- Occurrence of the failure modes in terms of examples and statistics
- Design solutions that can prevent the failure modes from happening

A failure mode is typically caused by a succession of defects or degradation that leads to loss of integrity. Integrity loss is characterised by loss of containment, reduced production capability or increased risk for human lives, environment or other assets. A failure mechanism is a single defect or degradation that individually does not cause the pipe to fail. The complete list of potential failure mechanisms for static and dynamic applications listed in [2] is presented in Table 8 and 9 in Appendix B.

The failure modes that will be discussed in this chapter are:

1. Collapse
2. Burst
3. Tensile failure
4. Compressive failure
5. Overbending
6. Torsional failure
7. Fatigue failure
8. Erosion
9. Corrosion

3.1 Collapse

Collapse of a flexible pipeline is when the pressure sheath and/or carcass fail by collapsing inwards to cause severe problems for flow assurance and integrity. The failure mechanisms that may lead to collapse are different, but the common denominators are excessive force or pressure, fabrication anomalies, erosion, corrosion of carcass and transport and installation damage.

Failure mechanisms

Collapse can be caused by excessive tension of the tensile armour wires. The weight of a flexible riser is relatively large; hence the tensile load near the hag-off point on the riser is large, especially for deep water developments. The tension causes the tensile wires to tighten, due to the helical pattern, and transforms the tension into compression on the layers within and can cause collapse of the carcass. Dynamic vessels and environmental forces will add to total tension force.

Collapse due to excessive external pressure may have different causes. Deepwater installations experience large hydrostatic pressure, and if not constructed correctly this may contribute to the collapse. Example of manufacturing defects is high initial ovality and high radial gap between pressure armour and internal pressure sheath. Under operation gasses will diffuse through the carcass and internal pressure sheath into the annulus. If the venting system is not working as designed, due to flattened or blocked vent tubes, a residual pressure will build inside the annulus and may cause the collapse. The most common reason for collapse in the cases of trapped gas in the annulus is when the pipe is subjected to rapid pressure release. The speed of the depressurization causes the pipe to be unable to stabilise the pressure so the residual stress in the annulus cause the carcass and/or internal pressure sheath to collapse.

Recent carcass collapse failures have shown that high pressure pipes with extra pressure polymer sheaths may cause diffused gas to be permanently or temporarily trapped between the layers and cause large radial inwards pressure high enough to cause collapse (ref. [24]). Shrinking of the polymer layers combined with self-weight is also known to cause carcass collapse.

Transportation and installation is a critical phase for every flexible pipe. With regards to collapse the greatest dangers are dropped objects, collisions and other unexpected forces that might cause ovalisation, overbending and excessive tension of the pipe.

For production pipes there is a risk of sand in the produced fluids. Especially for gas production pipes this may cause erosion on the inside of the carcass. This will in some places reduce the wall thickness and also lead to local corrosion. Thinning of the carcass wall reduces the collapse resistance.

Occurrence

The collected CODAM data presented in Table 3 shows that collapse is the most common reported incident for the NCS. In later years it has been discovered that collapse is especially threatening for double annulus risers. Statoil has had several incidents with flexible risers designed with this configuration. Problems with carcass collapse in flexible risers at Njord A, Visund and Snorre B is described in [21]. This investigation report reveals leakages during shut down activity in three different risers at three different location, all of the with the same double annulus configuration. Figure 5 presents an incident where the carcass has collapsed.

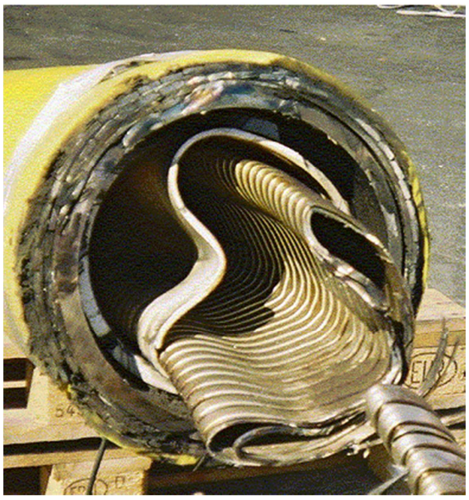

Figure 5 - Carcass collapse [21].

A failure in a flexible water injection riser with a smooth bore was experienced on the Draugen field in January 2000 (ref. [25]). The flexible riser was installed in a nitrogen pressurised J-tube. Nitrogen diffused through the outer sheath and into the pipe annulus. At some occasions the pressure in the top of the riser became so low that it acted as a vacuum and the pressure difference in the bore and annulus exceeded the collapse pressure. This caused the inner sheath to collapse. When reapplying pressure to the bore the inner sheath was "blown up" again and the injected water could flow freely.

This happened several times until the inner pressure sheath cracked and pressurised water filled the annulus. Tension wires were then subjected to the full hoop stress and started failing. When the outer layers failed they slide down inside the J-tube causing the internal pressure sheath to fail immediately and in the end also the pressure armour after substantial uncoiling.

Design solution

Increasing the thickness of the pressure armour will improve the resistance against the external hydrostatic pressure. Increasing the thickness and strength of the internal pressure sheath and/or carcass will improve the resistance against residual pressure in the annulus.

Increasing the thickness of the different layers may have limited effect if the transportation and installation loads are large enough to damage the pipe. Modification of transportation routines or installation procedures could reduce the number of failures, not only collapse, but also damage of the outer sheath.

3.2 Burst

Opposite of collapse, burst is caused by internal pressure or excessive forces and the materials will rupture outwards.

Failure mechanisms

Two potential failure mechanisms leading to burst is rupture of tensile or pressure armour due to excessive internal pressure. These failures may be caused by fault in engineering or fabrication of the pipe, fault in pressure integrity modules upstream in the system and operating above design limits.

Rupture of the external sheath is also failure mechanism that may lead to loss of pipe integrity. Diffused gasses in the annulus can cause pressure build up large enough to rupture the external sheath if the venting system is not working properly.

The probability of burst is largely increased by anomalies in the flexible pipe layers. Fabrication errors, internal corrosion and erosion or external abrasion will decrease the burst resistance and create weak spots.

Occurrence

The CODAM database includes several reported burst incidents of flexible risers. Figure 6 shows an example of burst of the external sheath near the end fitting. In this case there was a leak across the main seal inside the end fitting. This leak caused the pressure to build up inside the annulus leading to a rupture of the external sheath (ref. [11]).

Figure 6 - Rupture of external sheath due to leak in end fitting [11].

Figure 7 shows the rupture of the external sheath in a flexible riser where the annulus vent system is blocked or not functioning correctly. The diffused gas from the bore fluid will over time increase the pressure until it is larger than the burst resistance of the external sheath. This is however a well-known problem and large focus has in the later years been directed to a well-functioning vent system and vent gas monitoring.

Figure 7 - Rupture of external sheath due to blocked vent tubes [1].

Design solutions

Also for burst failure mechanisms a design solution is to increase the thickness of the pressure armour or external sheath. Another solution is to increase the material strength if feasible.

Design modification can dictate the distribution of force in the different layers. Angle of the tensile and pressure armour, shape of the wires and also installation angle of the pipeline are things that can prevent burst from occurring.

Adding more armour layers will obviously increase the burst resistance, but will also increase the size and weight of the pipe. If this is a deepwater riser the tension loads may be too large to make this solution feasible.

3.3 Tensile failure

Tension forces are mainly a riser problem as it hangs from the platform and all of the weight is distributed to the top of the riser. But also static flowlines can be subjected to excessive tensile forces due to snagging by fishing trawl or ship anchors.

Failure mechanisms

Excessive tensile forces may cause rupture in the tensile armour. The tensile armour wires are designed to withstand loads well above the normal service loads, but in case of corrosion, fabrication anomalies or other factors the resistance may be reduced.

As the tensile wires are configured in a helical pattern tensile force will tighten the wires and act as compression on the layers within. This may lead to collapse of the carcass and/or internal pressure sheath.

Snagging of the pipe can also cause overbending in the pipe. This may lead to rupture of tension armour or buckling of the pipeline.

Occurrence

Tensile failure is not one of the most threatening failure modes due to the high fatigue safety factor and focus from the start of the flexible pipe era. In the presented incident reports from CODAM (Table 3) and SureFlex (Table 4) tensile failure represents a low percentage of occurrences. However tensile failure has occurred in flexible risers in Brazil due to high tensile loads combined with corrosion or fatigue (ref. [1]). In other words, failure due to tension may happen if other factors like corrosion, abrasion, collision, anomalies etc. alter the tensile resistance of the flexible pipeline. The deep water developments in the Gulf of Mexico (GoM), Brazil and West Africa make these fields more applicable to tensile failure due to the high axial loads of the riser itself.

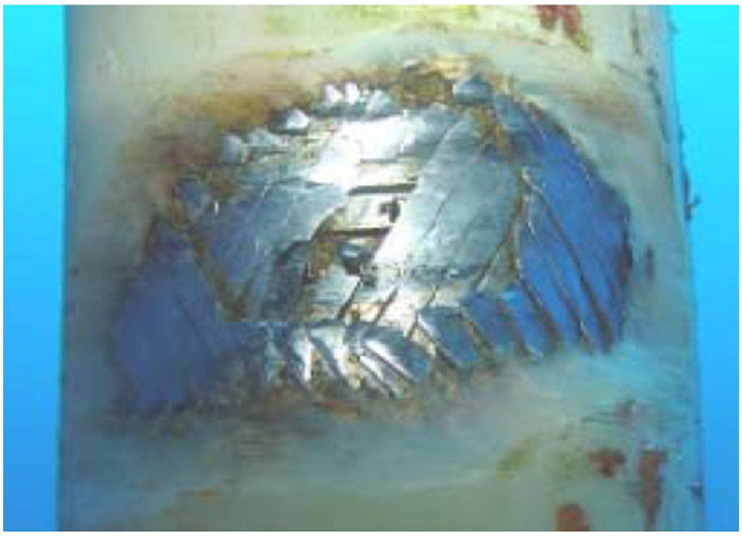

Figure 8 - Tensile armour wire rupture due to abrasion [14].

Figure 8 shows how abrasion can wear down the external sheath and some of the tensile wires risking the entire pipeline to rupture. Figure 9 is an example of how tensile wires can rupture due to fatigue, this time near the end fitting.

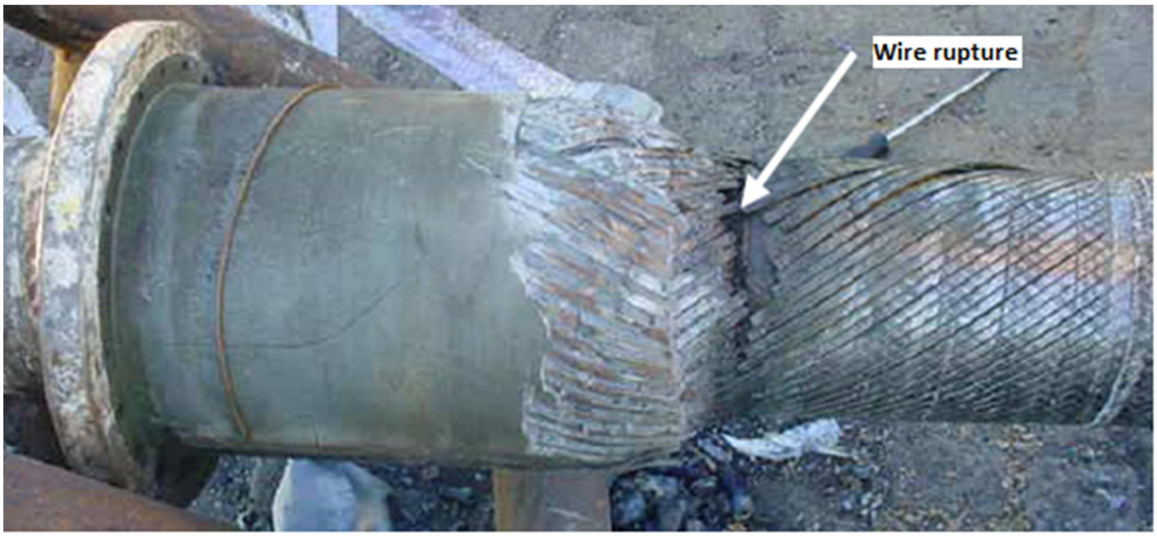

Figure 9 - Tensile armour wire rupture due to fatigue [14].

Design solutions
To prevent tensile failure it is advised to increase the thickness of the tensile armour wires or select a higher strength material if feasible. Modifying the wire angle alters the force distribution and can contribute to better tension resistance. Modifying the installation angle and pipeline route can decrease the tension force. Ultimately adding more tension armour layers should be considered. Another solution is to bury the pipeline. This will protect the pipe from snagging by fishing trawls and ship anchors.

For risers the riser configuration (see Figure 10) can reduce the tensile load experienced in the hang off point. By installing floaters at a point on the riser to create a lazy wave configuration some of the tension is relieved for the hang-off point and distributed to the arch over the floating buoy. This is more common for deep water installations than for shallow water as the tensile loads here are significantly larger.

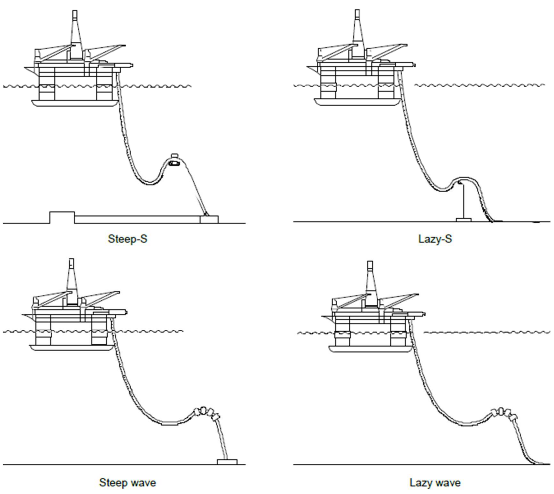

Figure 10 - Example of flexible riser configurations [2].

3.4 Compressive failure

When a pipeline is installed the temperature of the pipeline materials are equalised with the temperature of the ambient water. After starting production, warm gas and fluids conveyed in the pipeline raises the temperature. This causes the materials in the pipeline to expand and if it is restricted by friction or constrained ends compression forces will build and may cause buckling and overbending.

Failure mechanisms

An experienced failure mechanism in static flowlines is radial buckling, also known as bird-caging. This phenomenon occurs when the compressive loads are large enough to cause wire disordering. Usually the external pressure acting on the outer sheath is enough to prevent radial buckling to occur, but when the outer sheath is damaged the buckling resistance is severely reduced. This is however not a common failure in newer because of the use of high strength kevlar tapes used around the armour wire layers to prevent failures like birdcaging from happening.

Excessive compression force may also lead to upheaval buckling. Upheaval buckling is when compression forces press the pipeline towards a restricted end. When it is not allowed to move the pipeline arches upwards creating bending stress.

Occurrence

From SureFlex' incident report we see that birdcaging is a failure to be aware of, with 5% of the reported incidents worldwide (2010) being categorised as bird caging. Also overbending and upheaval buckling are represented on the incident chart, both being a result of compressive forces (among other reasons). Figure 11 shows a small example of birdcaging.

Figure 11 - Example of birdcaging [23].

Design solutions

To avoid bird-caging there are strengthening tapes developed for giving the tensile armour layer support and restricting them from buckling outwards. Also thicker outer sheath will serve somewhat of the same purpose.

However the best solution is to avoid these large forces if it is possible. Selecting a riser configuration that does not cause restrictions, adding spools or pipeline bends to safely guide the pipeline expansion and burying the pipeline are ways to avoid large compressive forces.

3.5 Overbending

Overbending is a threat especially for risers in at the touch-down point (TDP) and for flowlines as a result of buckling. Bending of a pipe cause compression on one side and tension at the other that may lead to collapse or rupture. Overbending can also be a result of trawler or anchor snagging.

Failure mechanisms

For the carcass and internal pressure sheath overbending can cause collapse due to the compression force and also ovalisation that reduces the collapse resistance. It can also be the reason for rupture of the internal or external pressure sheath as result of the tension forces.

Large bending forces may lead to unlocking of the interlocked layers (carcass and pressure armour) of the flexible pipe. This will reduce the collapse resistance of the carcass and also the pressure and tension resistance of both the carcass and the pressure armour.

The outer sheath can suffer cracking if the bending stress is large enough.

Occurrence

There has only been one reported incident regarding overbending in the Norwegian sector. This happened during installation over an arch in shallow water. Other incidents may have happened, but if the production has not started when the incident happens it has probably not been reported. It is known that the UK sector had several incidents during installation in the 90's, of which both overbending and birdcaging occurred. This was mostly due to poor equipment and procedures, reasons that are easy to correct.

Design solutions

Modifying the design of the flexible pipe, adding armour layers and alternating the pipeline route can prevent overbending. Rock dumping and burial of the pipeline can prevent buckling that could have led to overbending.

3.6 Torsional failure

As flexible risers are used for floating production systems they are in constant motion due to wind, waves and currents. This will sometimes cause torsion loads in the riser that may lead to a failure mode.

Failure mechanisms

As the tensile armour wires are configured in a helical pattern they are subjected to tension or compression as the riser is twisted. Excessive tension loads due to twisting may lead to rupture of one or several wires.

Torsional force in either direction on the flexible pipe may cause problems. If the force is in the same direction as the helical pattern of the wires, they will tighten and collapse of the carcass and/or internal pressure sheath may occur. If the torsional force acts in the other direction the wires may be subjected to excessive compression force causing radial buckling or unlocking of the armour wires.

Torsional force can also be caused by rupture of tensile armour wires. If a number of wires were to rupture the entire riser will twist to restore equilibrium (see Figure 12). The torsional force created to restore equilibrium may cause rupture of internal or external pressure sheath, or increase compressive force risking collapse of carcass and/or internal pressure sheath.

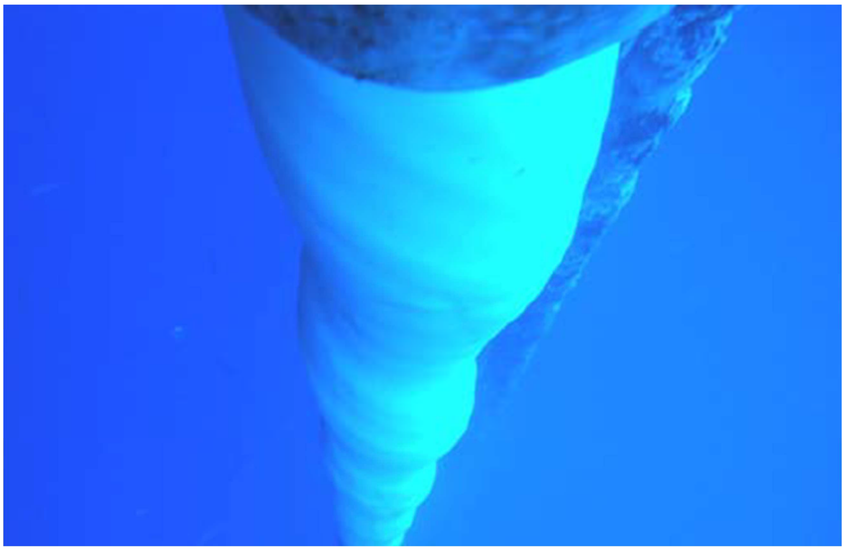

Figure 12 - Torsion at the top of a riser due to ruptured armour wires [14].

Occurrence
Torsional failure is not regarded as a large threat, and it is not an incident that is often reported. However it may contribute to other failures and one must be aware of the possibility for torsional failure.

Design solutions
Torsional loads can be reduced by modifying the system design. By modifying the cross sectional design the torsional capacity can be improved. Altering the wire lay angle, adding armour layers or strengthening tape around the armour layers are recommended solutions to improve torsional capacity.

3.7 Fatigue failure

In service the different layers of the flexible pipe will be subjected to several different stresses. This can be tension, compression, torsion, erosion, corrosion and temperature variations. A single load cycle of the mentioned stresses may not be large enough to damage the pipe, but the accumulated cycles can wear down the different layers.

Failure mechanisms
A known difficulty (especially in deep water developments) is the fatigue failure of tension wires near the end connection. Tension wires are designed to endure much higher loads than they are subjected to, but over time the tensile stress due to environmental forces will accumulate and fatigue wire rupture may occur.

Damage to the outer sheath is a well-known problem and is one of the most occurring defects that may lead to pipe failure. Abrasion against bell mouth, I-tube or bend restrictor, interfacing structures, other pipelines and the seabed at the TDP may lead to damage and seawater ingress. The flooded annulus creates an environment that can rapidly decrease the service life of the flexible pipe due to corrosion of the tensile and pressure armour wires and degradation of the polymer layers, thus increasing fatigue damage.

The polymer layers of the pipe can also experience failure due to time dependant stresses. Temperature cycles and flooded annulus may cause the polymeric layers to crack due to embrittlement (described in section 4.1).

Friction forces between the different layers add to the “wear and tear” and can increase the total fatigue loading.

Two chemical reactions within the flexible pipeline that may severely reduce the service life are SSC and HIC. SSC is when the pipeline operates with a sour service environment, e.g. there is a relatively large amount of H_2S in the produced fluids. The H_2S reacts with the steel layers if they are not rated for sour service operation. The reaction will cause embrittlement of the steel which reduces the cracking resistance of the material. HIC is a phenomenon that occurs when atomic hydrogen is discharged and diffuses into the metal to cause embrittlement. The discharging of atomic hydrogen happens in the vicinity of the sacrificial anodes in the cathodic protection system. Corrosion Resistant Alloy (CRA) materials is the most susceptible to the atomic hydrogen and therefor also in greater risk of HIC.

Occurrence

Fatigue failure is a complicated subject, and numerous tests and calculation models have been developed to estimate the fatigue life of the armour wires, aging of the polymeric sheaths, corrosion and erosion rate of the carcass or tensile wires etc. With this intense focus on fatigue and a recommended safety factor of 10 on fatigue life the failures are decreasing. In Norway there has not been a fatigue failure of tensile wires (ref. [1]). In Brazil and West Africa however there have been some incidents due to fatigue failure in tensile armour, but this is generally caused after corrosion or sour service has severely decreased the fatigue life of the wires (ref. [1]).

Fatigue failure may as discussed be rare without any other influencing factors. Another of these factors is fabrication faults. One example is explained in [1] where the carcass is fabricated so that the interlocked steel strips are unable to slide when they are fully expanded or compressed causing an unintended force distribution and fatigue damage to the carcass. This kind of fatigue failure may be one of a kind, but it can categorise as fabrication faults which is a critical category for most failures.

Design solutions

To mitigate the risk of fatigue failure it is recommended that the system is designed to minimise the fatigue loads. Optimizing the floater movement in the water (mooring or Dynamic Positioning (DP) system), install bend stiffeners to reduce the bending loads near the riser hang off; optimise the riser configuration (lazy wave, catenary, etc.) to minimise loads and movement of the riser.

Reassess the materials used and the thickness and configurations of these materials to ensure they can cope with the loads, fluids and temperatures they will be subjected to. Many new failure mechanisms and operating conditions have been learned since the first flexible risers were installed. This has to be incorporated into the new design of flexible pipes.

Material selection is important to prevent SSC and HIC from happening. Use steel that is rated for the expected sourness of the produced fluids, and be aware that the sourness can change over time.

3.8 Erosion

Erosion in flexible pipelines is when particles in the produced fluids collide with the internal wall of the carcass and over time causes thinning of the steel layer.

Failure mechanisms

When solids (sand) are produced and conveyed through a production pipeline erosion can be a problem. Especially for gas production the solid fragments have high velocity and collide with the inner wall off the carcass. Some areas will be more endangered by this problem as the lay route of the pipe cause certain areas to experience more erosion than others (bends and curves).

Development of hydrates in the flexible pipeline may also cause erosion problems as this may develop into solid material (ice) that can cause erosion if it is broken loose and transported along the pipe.

Erosion alone does not usually cause failure of the pipe, but the erosion process wears down the corrosion protecting layer of the internal carcass wall. If erosion and corrosion act together the thinning of the carcass may be sufficient enough to cause collapse or rupture. Figure 13 shows an example of internal erosion of a carcass.

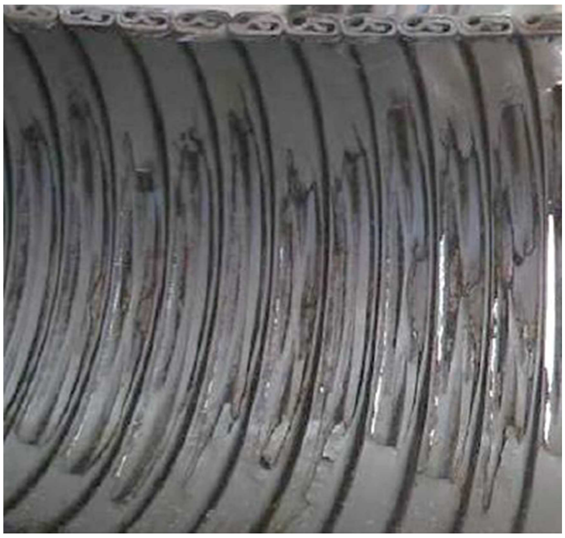

Figure 13 - Internal erosion of carcass [1].

Occurrence

There has not been reported any flexible pipeline failures due to erosion alone. The highest risk for serious erosion is for gas production lines when sand is produced with the high velocity gas.

Design solution

A good estimation of the sand content of the production volume is essential to the design of the carcass layer. Increased wall thickness or optimised material selection can increase the erosion resistance.

To reduce the sand content of the produced fluids would be the best solution to this problem. This is often ensured by a filter in the well near the reservoir.

Optimising the lay route of the pipeline will ensure better flow of the production fluid and decrease the critical areas for erosion.

3.9 Corrosion

Corrosion of the steel layers is caused by a chemical reaction in the material. This gradually destroys the material and reduces resistance and fatigue life. A typical reason for corrosion in pipelines is when seawater saturated with oxygen comes in contact with the steel layers to induce oxidation.

Corrosion is not by itself a normal cause to pipe failure, but together with high loadings or fatigue loads this is a serious threat of integrity. Figure 14 shows two different cases of corrosion of the tensile armour wires. Figure 14 a) and b) presents a fully corroded single tensile armour wire, while c) presents local corrosion on multiple tensile armour wires.

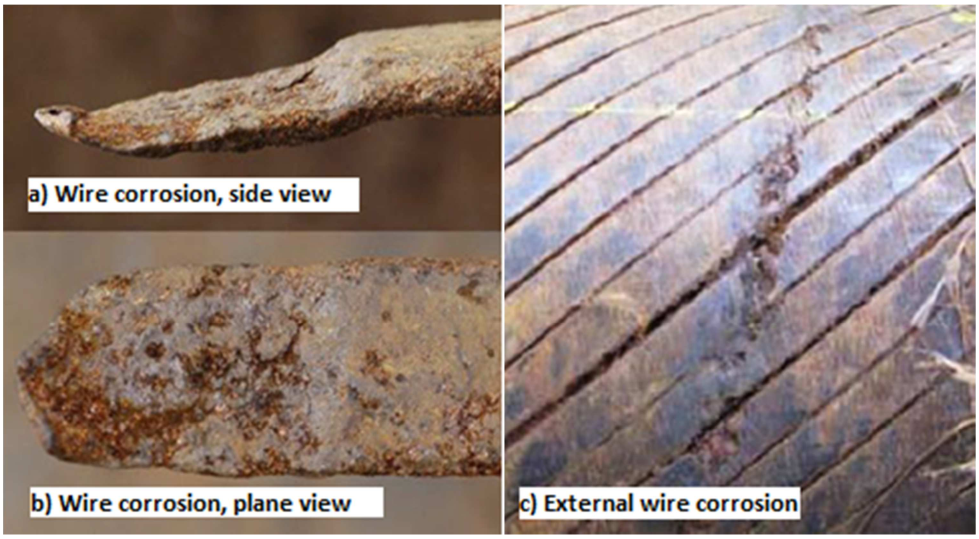

Figure 14 - Corroded tensile armour wires due to breach of outer sheath [1].

Failure mechanisms

If the corrosion protection on the internal wall of the carcass has eroded away, there might be internal corrosion of the carcass.

Tensile or pressure armour wires are threatened by corrosion both from produced fluids diffusing through the internal pressure sheath, and seawater ingress due to a damaged outer pressure sheath. The greatest integrity risk has been experienced to be near the splash zone near the top end of the riser. If the outer sheath is damaged here causing seawater to flood the annulus oxygen will be continuously supplied and the corrosion process will be rapid compared to if the same happened some distance under water. The top section of the riser is not protected by the cathodic protection system (corrosion protection). Corrosion in the tensile and armour wires will reduce their material capacities and hence reduce the fatigue life and system integrity.

Occurrence

The most frequent cause of corrosion is when there is a breach of the outer sheath and seawater and oxygen is allowed to flow into the annulus. A great deal of the incidents leading to breach of the outer layer is related to transportation or installation of the flexible pipeline where undiscovered damages are not repaired, and abrasion due to contact with ancillary equipment. All the latest statistics reveals this problem hence it is reason to believe that this is of high concern and that the occurrence of this type of failure will decrease in the coming years. Especially the transportation and installation process can be improved, and should not cause a threat to the integrity.

Design solutions

To improve corrosion resistance increased layer thickness and critical material selection is advised. By adding coatings and/or lubricants the surface of the steel layers will have larger "scratch" resistance hindering local corrosion attacks. Coating on the outer sheath will protect against abrasion. Lubrication in the annulus protects the armour wires from frictional damage.

Cathodic protection is a normal technique used for preventing corrosion in pipelines. This is achieved by installing sacrificial anodes of a metal that corrodes instead of the pipeline. These anodes need to be periodically replaced.

3.10 Summary of failure modes

Table 4 gives a summary of the failure modes listed and described in this chapter. The table includes a brief description of failure mechanisms, occurrence and design solution for each failure mode.

#	Failure mode	Failure mechanisms	Occurrence	Design solutions
1	Collapse	Excessive tension	Large problem, multiple reports both in CODAM and SureFlex JIP. Problem worldwide	Increased thickness of pressure armour/carcass
		External pressure		Increased thickness and strength of internal pressure sheath
		Residual pressure in annulus		
		Fabrication, transportation, installation error		QA/QC in fabrication, transportation and installation
		Aging of polymer (shrinking)		
		Ovalisation		
2	Burst	Rupture of tensile armour wires	Burst of the outer sheath is a common problem. Rupture of tensile wires may be a problem for deepwater developments.	Increase thickness of tensile armour wires
		Rupture of pressure armour wires		Increase thickness of pressure armour wires
		Residual pressure in annulus		Alter design configuration
3	Tensile failure	Excessive tensile force	Not a frequent failure mode. High risk for corroded wires in deep water developments	Increase thickness of tensile armour wires
		Large dynamic movement		Material selection
		Corrosion combined with high tensile loads		Alter design configuration
				Riser configuration
				Bury pipeline
4	Compressive failure	Radial buckling	Radial buckling (birdcaging) has been reported several times worldwide	Add strengthening tapes
		Upheaval buckling		Increase thickness of outer sheath
				Riser and pipeline configuration
				Bury pipeline
5	Overbending	Excessive bending force	Problem at end of pipelines and TDP for risers. Several occurrences due to sloppiness in the 90's	Riser and pipeline configuration
		Installation error		Bury pipeline
		Ancillary equipment		Alter design configuration
6	Torsional failure	Large dynamic movement	Not a frequent failure mode. Risers in harsh weather conditions are most vulnerable	Riser configuration
		Large environmental forces		Alter design configuration

#	Failure mode	Failure mechanisms	Occurrence	Design solutions
		Rupture of tensile armour wires		Adding strengthening tape or armour layers
7	Fatigue failure	Rupture of tensile armour wires	Fatigue alone is not the most occurring failure mode due to a very high safety factor. In combination with erosion, corrosion and other factors the fatigue life is severely reduced.	Riser and pipeline configuration
		Rupture of pressure armour wires		Material selection
		Aging of polymer layers		QA/QC in fabrication, transportation and installation
		Cracking of carcass or armour wires		
8	Erosion	Internal erosion of carcass	No reported failures. Risk when sand bore fluids contain sand, especially in high velocity gas pipelines	Limit sand production
				Increase carcass thickness
				Pipeline route configuration
9	Corrosion	Rupture of tensile armour wires	Large problem linked to the frequent damage of outer sheath.	Increase steel layer thickness
		Rupture of pressure armour wires		Add coatings or lubricants
		Corrosion of internal carcass		Material selection
				Cathodic protection

Table 2 - Failure mode summary

4 Failure mechanisms

In addition to the failure modes described in chapter three, there are some common failure mechanisms that should be explained further to get a clear overview of the risks involved with operation of flexible pipelines. This chapter includes typical failure mechanisms for the polymer sheaths, how the annulus environment can cause degradation to different layers and failures that can happen in the end fittings.

4.1 Polymer related failures

The use of polymer sheaths in flexible pipelines is one of the elements that make this technology possible. Without these materials the pipeline would not be able to contain the produced hydrocarbons or keep the seawater out of the pipe annulus. However the materials used have very different properties compared to steel. One of the consequences of the different properties is the increase or decrease in volume. For example the expansion coefficient for some polymer materials are more than 10 times higher than steel. For rapid cool down of pipelines, i.e. installation and shut-down scenarios, this causes the polymer sheaths to reduce in volume much faster than steel. This can result in large stresses in the pressure sheath that can cause cracks or transfer the loads to the carcass, and in worst case cause carcass collapse or end fitting pull-out.

Figure 15 – Example of internal pressure sheath cracking [1].

To give the polymer layers its flexibility they contain an additive called plasticiser. When in contact with production fluids this additive will migrate out of the polymeric sheath causing it to reduce in volume and become more brittle. Figure 15 shows the cracking of the internal pressure sheath. Figure 16 shows cracking of the outer sheath.

Figure 16 – Example of outer sheath cracking [1].

Time dependant degradation is a frequent problem for the polymer layers. Exposure to water and high temperature can cause hydrolysis which alters the molecular build-up of the polymer inducing embrittlement and cracking. Temperature variations can threaten the polymer layers. Especially in constrained areas like bend stiffeners, buoyancy elements and buried sections of the pipeline where the temperature can reach above design limits. Anti-friction tapes and high strength pressure tapes are made from polyamides that degrade at high temperatures. These layers can suffer from embrittlement and disintegrate causing blocked annulus vent tubes, but also soften and increase the friction between steel layers and accelerate fatigue.

Design solutions

Temperature management is of paramount importance regarding polymer layers. Gradually shut-downs and start up with focus on slow thermal changes is advised. Beware of chemical processes and choose the polymer material that is best suited for the operational environment for each development.

4.2 Annulus environment

As the reported failures from CODAM and SureFlex shows annulus environment represents a large portion of failures of flexible risers. When flexible pipes first was fabricated and installed it was a common belief that the annulus would stay dry as long as the outer sheath was intact. With this assumption the fatigue life was calculated for dry environment. After years of operation it was realised that water and gas could diffuse through the internal pressure sheath and condense inside the annulus. The condensed water fills up the annulus and degradation mechanisms act on both steel and plastic layers. It was also discovered that the outer sheath was relatively often damaged causing the annulus to fill up with water and/or air, also increasing the degradation of materials. The fatigue life of the different layers is reduced and pipelines and risers must be replaced before their expected service life is over. Polymer failures due to exposure to water, gas and air has been discussed in section 4.1 with the most critical failures of cracking, end fitting pull-out and collapsed carcass.

Corrosion of the armour wires is a severe consequence of flooded annulus. Seawater ingress, diffused H_2S and CO_2 are causes for corrosion of the armour wires, however there is a large knowledge gap regarding how corrosion acts and how severe the individual cases of corrosion is. The corrosion rate of steel wires, the location of outer sheath breach, composition of diffused gases, and the combination of this are factors that need more research to be fully understood. Pipelines and risers have been in operation for several years with damaged outer sheath and flooded annulus without any serious degradation of the flexible pipe layers.

Design solutions

The best way to limit the failures caused by annulus environment is QA/QC of fabrication and installation and early detection of external breach. Also monitoring vent gases from the annulus and examining gas samples. Early detection will give the operators time to repair or plan mitigating measures.

Procedures have been developed for re-establishing blocked vent systems, by drilling new vent ports through end fitting, epoxy filling port or the external sheath (ref. [24]).

4.3 End fittings

The end fitting is a complicated part of the flexible pipeline system. This is the connection point between the pipeline to a subsea module or riser to a production facility. The end fittings comprise the termination of all the layers in a flexible pipe, and needs to seal off each layer to prevent leakage into the annulus or out to the environment. Example of an end fitting configuration is presented in Figure 17.

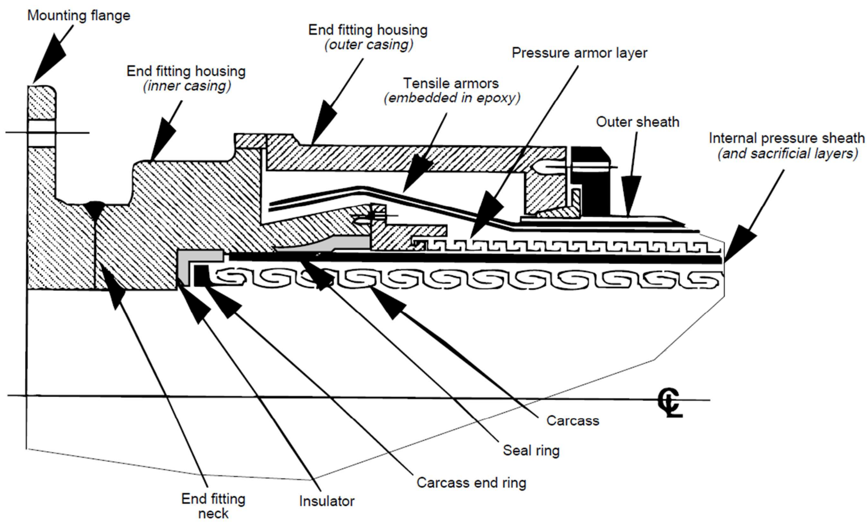

Figure 17 - Example of end fitting configuration [2].

There are a number of failure mechanisms that can happen in the end fitting. Carcass and pressure sheath pull-out are discussed in the section of polymer related failures. In addition there is an arising problem with the termination of the tensile armour wires for deep water risers where high tension loads create challenges. Also the vent tubes for the annulus vent system are normally installed through the end fittings. These tubes may be blocked in fabrication due to overbending, and also from particles from dissolved polymer layers. Leakage through the sealing inside the end fitting is a reported problem that can cause annulus flooding or leakage to the environment.

Design solutions

QA/QC in design and fabrication is important to assure the integrity of the end fittings.

5 Reported failures

Reporting of failures is an important process for further learning and information sharing between manufacturers and operating companies. By sharing failure experiences future failures can be avoided and technology improvement can advance faster. This chapter will present reported failures from two sources; the CODAM database for failure reporting on the NCS and the results from a JIP lead by SureFlex including a number of international operating companies.

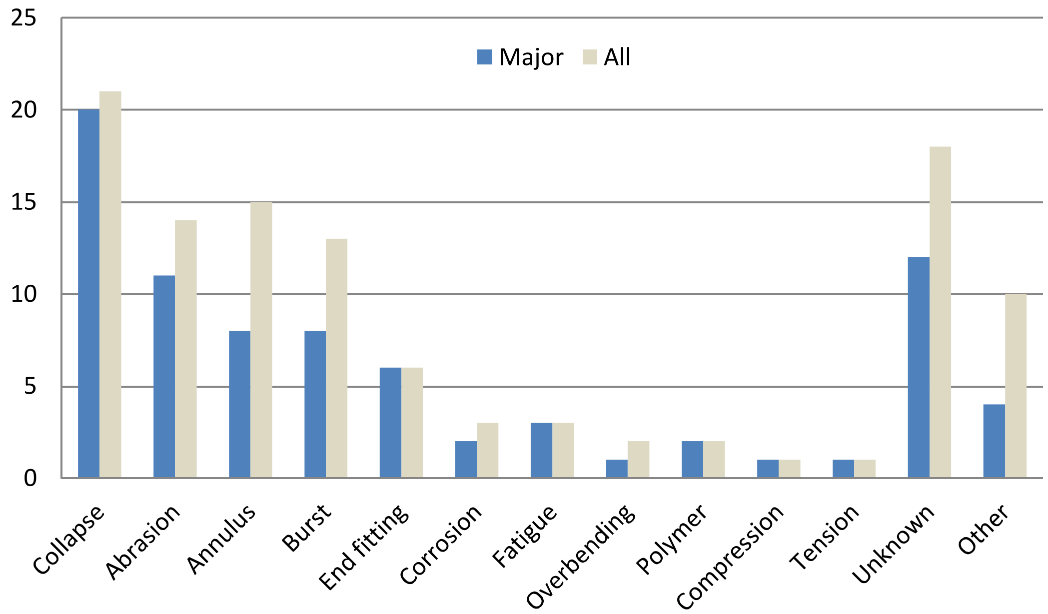

Table 3 - Reported failure of flexible risers in the Norwegian Continental Shelf (1995 – 2014). Source: CODAM, Ref. Appendix C.

Table 3 presents the reported failures of flexible risers in the NCS from 1995 to 2014. The data is provided by the CODAM database which is managed by PSA - Norway. The data used is listed in Appendix C. There may be some discussion about how the failures are categorised. In this table collapse and burst are treated as different categories although blocked or malfunctioning annulus vent system may lead to both these failures. Also abrasion and water filled annulus could be in the same category, but some of the reported failures do not coincide. It should be noted that the data in CODAM is not always conclusive and some assumptions has been made. The category "other" includes: micro leakage, hydrate plug, lacking end termination plug, dropped object, pigging and disconnected anchor wire for mid water arch. A large part of this chart is named unknown. This may partly be because the reporting is insufficient from the operators, but also the fact that flexible pipeline integrity still is not 100% understood.

An obvious observation from table one is that collapse, abrasion, water filled annulus and burst is the most common failure modes. A significant number of these failures happened due to blockage, failure or faulty operation of the annulus vent system. As discussed in the failure modes, overpressure in the annulus can cause both burst and collapse. Abrasion refers mainly to breach of the external sheath, and it is known that poor procedures and management of the fabrication and installation process in the early years of flexible pipelines are to blame. The positive note is that these failure modes are well known, and relatively easy to do something about. QA and QC throughout fabrication, storage, transportation, installation and operation should be of paramount interest for the operators when we see the outcome of “sloppiness”.

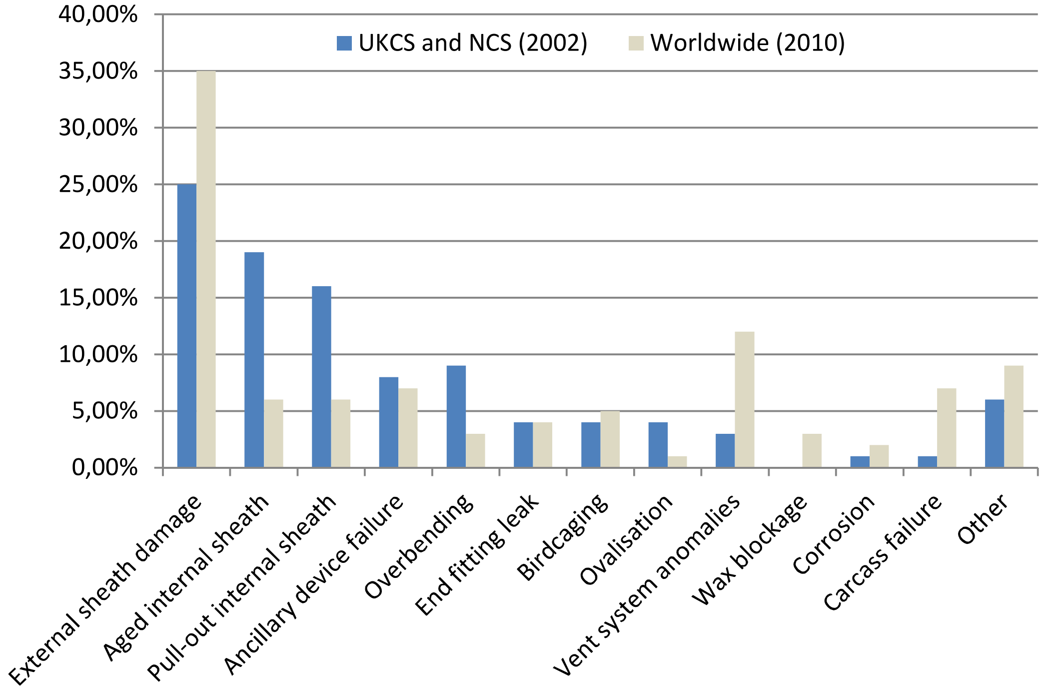

Table 4 - Reported failure of flexible risers in Norway, UK and worldwide [19].

Table 4 gives an overview of reported failures of flexible risers worldwide and is a result of a JIP lead by SureFlex (ref. [19]). This table is based on reports from different institutes as well as information provided from several operators worldwide through surveys. The table is included in this thesis to give an overview of failures not only in Norway, but also worldwide. From this table we see that external sheath damage and annulus vent system anomalies are common failures also worldwide. We also see that for the combined reporting from Norway and UK polymer aging and pull-out represent a large percentage of the total failures. This may be caused by different reporting processes, and more available data than for table 3, but indicates that these failures are common. However the percentage of the failures is allocated, all of them should be of concern and preventive measures should be taken. The category “other” includes: smooth bore collapse, pigging damage, upheaval buckling, excess torsion, excess tension, sheath cracking and armour wire failure.

6 Inspection techniques

In order to inspect the flexible pipes there are developed several inspection techniques for detecting failures and degradations. An inspection is a time constrained event that is planned with a beginning and an end. Some inspection techniques require deployment of vessels and equipment with experts analysing the results. This chapter will explain both conventional techniques that are used today as well as new techniques that are under development. The techniques will be presented with theoretical background, offshore application and development status.

The inspection techniques that will be described in this chapter are:

1. Conventional inspection techniques
    a. Visual inspection
    b. Annulus pressure testing
    c. Laser leak detection
    d. Coupon testing
2. New inspection techniques
    a. Radiography
    b. Ultrasonic testing
    c. Eddy current
    d. Magnetic stress measurement

6.1 Conventional inspection techniques

6.1.1 Visual inspection

An inevitable method for inspecting pipelines and risers is visual inspection. The most general inspection method is the manual deck visual inspection to check for obvious anomalies. Using divers for shallow water inspection, Remotely Operated underwater Vehicle (ROV) mounted cameras for shallow and deep water and climbers for the above water part of the riser will give a good opportunity for close or general visual inspection.

Visual inspection should seek to identify the following potential problems (ref. [2]):

1. Extent and type of marine growth
2. Pipe general integrity and condition, including leaks
3. Pipe outer sheath or external carcass integrity and condition
4. Debris and dropped objects
5. Evidence of scour and estimated length of free spans
6. Condition of end fittings
7. Condition of cathodic protection system
8. Any identifiable damage, distortion, or degradation
9. Any identifiable disarrangement of pipe and disarrangement or loss of pipe ancillary components
10. Interference with other subsea hardware
11. Loops and kinks
12. Movement or displacement from “as installed” conditions
13. Corrosion of and accumulation of marine growth in vent valves

External general visual inspection

The external visual inspection is performed mainly to investigate the integrity of the outer sheath. It is well known that from the hang off point of the riser and down to about 30m below sea level is the most critical area for damaging of the outer sheath. Where the riser is open (not inside bend restrictor or I-tube) regular intervals of visual inspection using ROV or divers subsea or climbers above sea level is common practice. For inspection and survey of static flexible flowlines it is common to deploy ROV's. There is however other solutions like Autonomous Underwater Vehicles (AUV) that can sit on the seabed for months and automatically inspect the pipeline. [30] Explains the operating principle and possible applications for their IMR AUV. The AUV has a "base" subsea that is connected to the host facility where it recharges between the surveys. Here it can be manually programmed to do a survey. When deploying the AUV automatically performs the inspection or light intervention tasks, returns to base and uploads the video and data to a computer on the host facility. This technology could potentially be a good alternative to ROV's. AUV's has not been used for pipeline inspection, but has the potential of carrying out this type of work in the future.

External close visual inspection
If monitoring or inspection results raises the question of pipe integrity, closer visual inspections of the threatened area is performed in addition to the planned inspection interval.

Internal visual inspection
For inspecting the outer sheath in the closed area of an I-tube it is necessary to insert a camera inside the I-tube. The camera that has to be approved for operating in an explosive environment is lowered down through an inspection window from deck level to examine the flexible riser. This technique also checks the bend stiffener fixation and the presence of debris inside the I-tube that may damage the riser (ref. [14]). Internal visual inspection of the carcass is also possible with the use of camera through an inspection window. This method searches the carcass for collapse, ovality, cracks, erosion and corrosion. Both these methods require that there are installed inspection windows.

By performing a thorough visual inspection several defects of the pipe may be identified, or reasons for further inspections can be found. Damage to the outer sheath is the most obvious defect as cuts, gouges, abrasion etc. can be located. It should be noted that this can be difficult if excessive marine growth covers the pipeline and riser. Other defects observed can be wrinkling of the external sheath (caused by torsional force and potential ruptured tension wires), or any form of separation from the end fittings. Internal inspection of the carcass can detect cracks or unlocking of the carcass and also ovalisation, collapse, or blockage of the bore.

6.1.2 Annulus pressure testing

Due to the lack of access to the annulus environment a technique involving gas injection into the annulus has been developed. This technology is dependent on functioning gas vent valves at the top of the riser. Nitrogen gas is injected at the top of the riser with a pressure below the pre-set vent valve opening pressure so that the external sheath is not endangered and the valve set up is not changed.

When injecting the gas the following data should be registered (ref. [14]):

- Nitrogen injection pressure
- Stabilization pressure
- Injection time
- Stabilization time
- Injected volume

When measuring these values it becomes clear if there is a sudden pressure drop, or if the pressure is not stabilised. If that is the case it is an indication of rupture of the external sheath or malfunction in the vent valves. The volume injected along with the time used indicates how far down the gas reaches in the annulus and can give an approximation to where along the riser there is a breach in the outer sheath. This test alone cannot substitute the need for visual inspection, but will give a basis for where the close visual inspection should be concentrated. Nitrogen injection can with benefit be performed simultaneously with internal and external inspection of the pipeline. In this way there is a chance of observing a potential leak through the outer sheath, giving a double confirmation.

6.1.3 Laser leak detection

Laser leak detection is an optical leak detection tool that emits a high intensity light or laser to detect emission of fluids from pipelines, risers or other subsea modules. The wavelength of the light is tuned so that it is reflected of a certain substance of interest, for example hydrocarbons, hydraulic fluids or specially developed injection dyes. The reflected light is detected by an intelligent camera, and the system is connected in real time to a computer located on the intervention vessel/host facility. Software is developed to analyse the data and sound an alarm when a leak is detected. The injection dye may be injected into the object that is being inspected (e.g. a water injection pipe) to give a clear result.

Figure 18 - Laser leak detection device - Smart Light Devices [26].

The system can be fitted to an ROV (see Figure 18), AUV or divers can use handheld devices emitting a specific wavelength to detect a single injected substance (ref. [20]). There has also been launched a system with multiple wavelength options to detect different substances (ref. [26]).

The laser leak detection technology is field proven and used over several years.

6.1.4 Coupon testing

One of the most difficult elements to measure integrity for in a flexible pipe is the internal polymeric layers. The degradation of the pressure sheath is known to cause problems for flexible pipes and large uncertainties are experienced with the existing degradation models presented in international standards. Currently the only way to inspect this is by installing and test coupons. A coupon is basically a pipe segment with the same layers and materials as the rest of the pipe. The coupon is installed in parallel or series with the pipe (see Figure 19) and can be removed for laboratory inspection. In operation the coupon will experience the same parameters as the rest of the pipe, i.e. pressure, temperature and fluid composition. The coupon should ideally be installed as near the wellhead as possible to ensure the worst case parameters. Coupons can also be installed near the riser or topside where the sample can be analysed and the results put into an aging model to extrapolate the conditions near the wellhead.

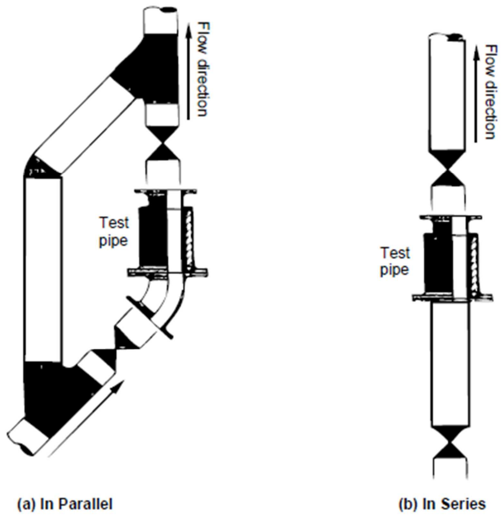

Figure 19 - Coupon testing setup [2].

6.2 New inspection techniques

6.2.1 Radiography

Radiography is the use of electromagnetic radiation (X- or gamma rays). The radiation consists of a spectre of wavelengths that is projected towards an object. As the radiation penetrates the object a part of the spectre is absorbed by the medium. The radiation spectre that has fully penetrated the object is captured by a digital detector, located on the opposite side. Different materials cause different intensity loss of the projected x-rays. The digital detector sends the result to a computer where an image is created, and the materials are differentiated based on the penetrated radiation.

Computed tomography (CT)

CT scans are basically a set of radiographic images of the same object taken from different angles around it. The CT scanner rotates around the object while sending rays through the object and onto the detector on the opposite side. The object is divided into millions of pieces called voxels (can be compared to pixels on a digital image). On a 2 dimensional image a voxel is considered a square, hence on a three dimensional image a voxel is considered a cube. Each radiographic image measures the intensity value of every voxel in 2D. Algorithms in a computer software calculate the intensity value of each voxel in 3D as the CT scanner rotates, giving a 3D image of the object.

Offshore application

A consortium known as FlexiRiserTest consisting of several R&D, Contracting and Operating companies has developed the world’s first underwater NDT DR Inspection System. This system uses the basics of DR together with specially developed algorithms for digital recognition. The system uses an external gamma ray source and an opposite positioned digital flat panel used for detection. Images that are detected on the flat panel are sent to a computer topside via an umbilical. The software developed for this system will filter out the most valuable images to be inspected and highlight anomalies such as unlocking of pressure armour, wire cracking, breaking and buckling and reduction of wall thickness (due to corrosion or erosion). The condition of the internal pressure sheath can to an extent also be inspected through radiographic images. The inspection system is mounted onto a robot crawler (see Figure 20), which can be attached to the riser either above or below the splash zone.

Figure 20 - Robot crawler with DR inspection tool [28].

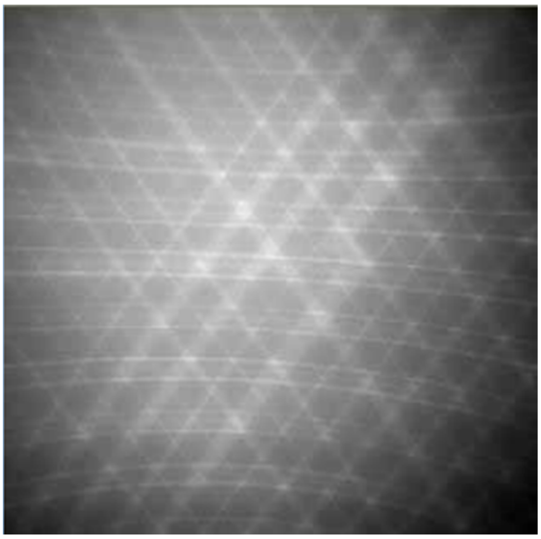

Figure 21 - Radiographic image of a flexible riser [28].

When attached, the robot crawler is manuvered up or down the riser taking images along the way. Example of a radiographic image taken of a flexible riser is shown in Figure 21. Through trial testing (2006) the system was submerged to 20 meters water depth, and was able to inspect flexible risers with wall thicknesses of 12 – 100 mm.

The Welding Institute (TWI Ltd.), member of the consortium, reports on their web page (www.twi-global.com) that the system is deployable and can be used by the other members of the consortium. They also state that future work includes more underwater trials (seawater) and development for deploying the system into deeper waters.

6.2.2 Ultrasonic testing

Ultrasonic testing (UT) consists of a power source that sends electrical current to a probe (transducer). The probe transforms the electrical current into mechanical energy or sound waves. The probe must be in contact with the object that is being observed to allow the sound waves to travel though the material(s). To eliminate the air gap between the probe and object a couplant is used which usually means lubricating the surface with oil or grease, water can also act as a couplant making UT possible under water. Sound waves, or the ultrasonic pulses are transmitted thought the material and is reflected when it hits an area of different density. The reflected pulses is either detected at the probe that transmits the pulses (pulse-echo mode), or a separate detector is placed on the other side of the object to detect the pulses that reaches through the object (through-transmission mode). Figure 22 shows the basics of defect detection using ultrasonic pulse-echo mode testing. A probe is positioned on top of a test object sending the ultrasonic pulse and receiving the echo. The computer monitor presents the result in intensity (can also be calibrated to show distance) and time. When there are no defects, the monitor shows two single peaks in intensity, transmission pulse and back wall echo. When the pulse hits the defect it is reflected in a shorter time and with higher intensity than the back wall echo.

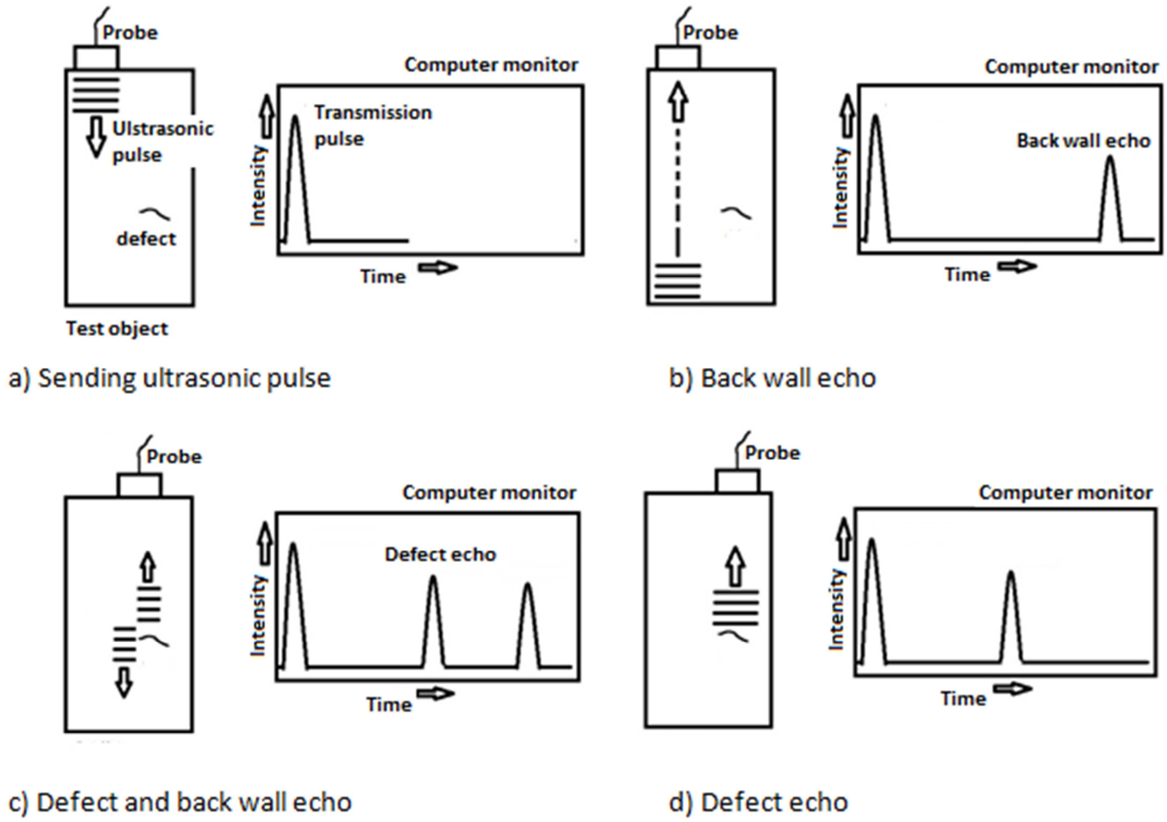

Figure 22 - Ultrasonic defect detection.

When measuring time and intensity of the return echo one can also measure the thickness of the material or layers of materials in testing. This can be used to detect corrosion and erosion of the layers as well as cracks and other anomalies.

Offshore application

ROV mounted UT tools have been developed for inspection of flexible pipelines. The purpose of UT with regards to flexible pipelines is to reveal annulus flooding. The sound waves projected into the pipeline needs a couplant between the external sheath and tensile armour wires to travel into the steel. Hence if the annulus is flooded with seawater or condensed gases from the bore, this will act as a couplant and measurements can be made. Figure 23 below shows the results of an inspected pipe with and without water in the annulus.

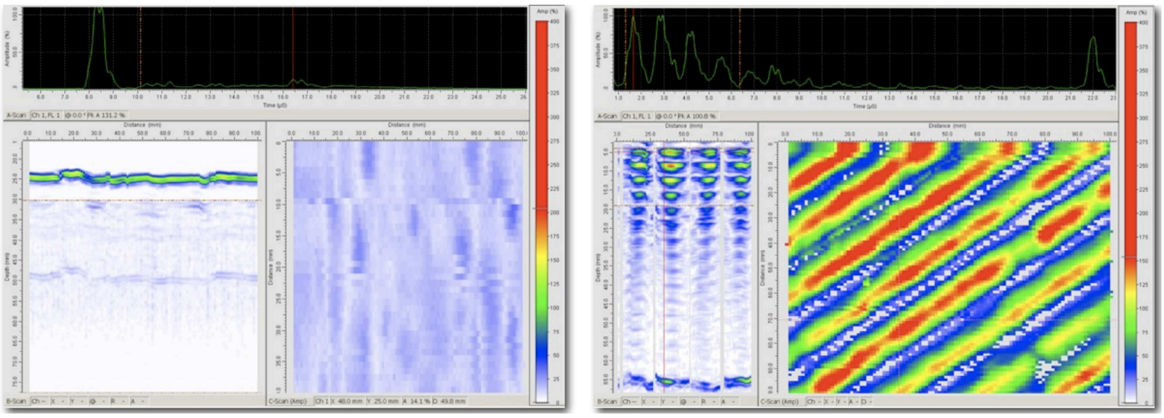

Figure 23 - Result of ultrasonic inspection of an unflooded and a flooded riser respectively [8].

If the annulus is flooded the UT tool can measure wire thickness of the most external tensile wires, hence detect corrosion (field proven accuracy of 0.2mm variation; ref. [8]), and also misalignment of tensile wires. This system is in use today and Flexlife in cooperation reports on their website that their system has scanned over 100 risers.

6.2.3 Eddy current

Eddy current testing is a method utilizing a process called electromagnetic induction. An eddy current probe includes a wire coil of a conductive material (i.e. copper), which is connected to a power source. When electrical current is allowed to flow though the coil it generates a magnetic field around the probe (Figure 24 a)). If the probe is positioned close to an object consisting of conductive material the probe's magnetic field will induce eddy currents (electrical current flowing in a circular motion) in the object (shown as red circles in Figure 24 b) and c)). The eddy currents will create its own magnetic field opposing the field of the probe. If there is a flaw (crack, hole etc.) in the conductive material the eddy currents are disrupted. The alternating magnetic field can be measured and analysed to confirm anomalies and measure layer thickness.

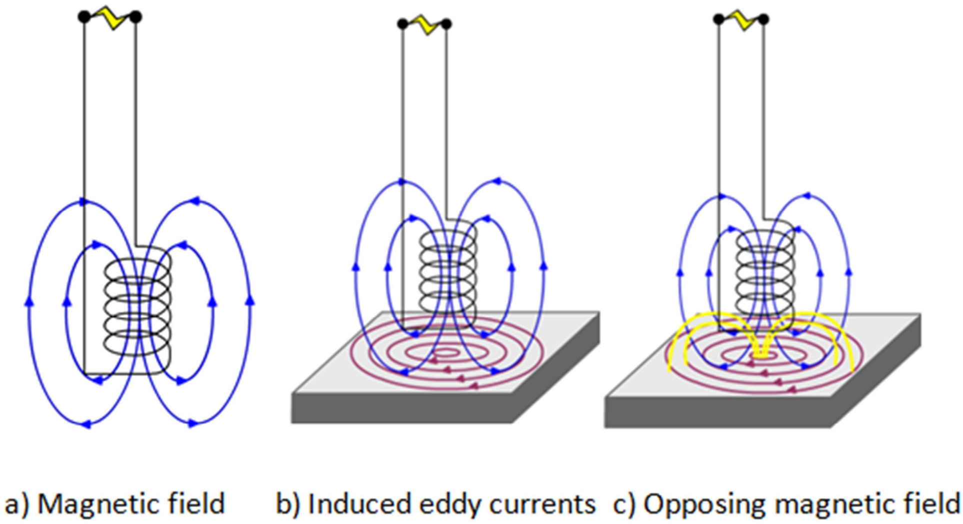

Figure 24 - Basic eddy current theory [18].

Offshore application
Innospection has developed a Magnetic Eddy Current Flexible Riser Inspection Tool (MEC-FIT). This tool utilises a further development of a technique called SLOFEC (Saturated Low Frequency Eddy Current). The SLOFEC inspection technique uses the principal of eddy currents, as described above, in combination with a magnetic field (see Figure 25). When using this system to inspect a flexible pipe it has to be calibrated against a similar pipe configuration to have a reference value to be able to detect anomalies. As this is an electromagnetic technique couplants are not necessary, and the probe do not have to be in contact with the steel layer, hence it can scan through the outer sheath. The Pipeline has to be cleaned for marine growth though, due to the limitation of scanner depth.

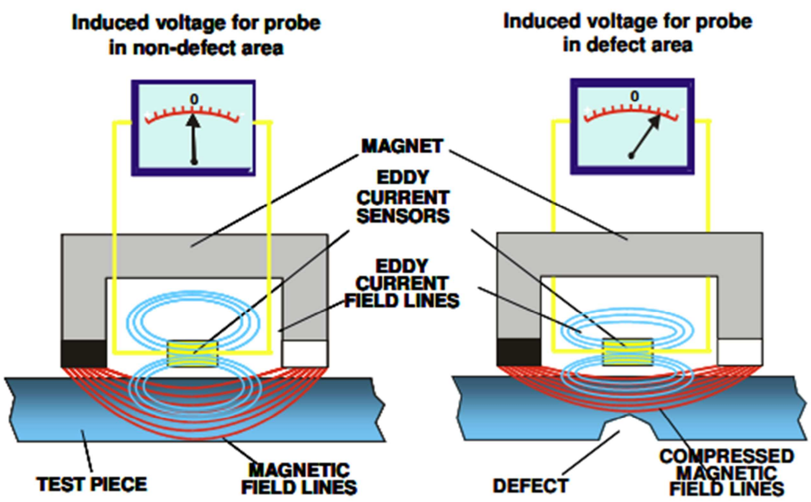

Figure 25 - Eddy current defect detecting [10].

With this technique transversal anomalies and ruptured tensile wires can be detected, but only in the most external tensile wires. With the further developed technique used in the MEC-FIT system stronger magnetic fields are created and the scanning penetrates further into the flexible pipe cross section. In [4] Innospection confirms that laboratory tests with an eddy current scanner has detected flaws in the pressure armour layer (through 10mm polyethylene, 2.3mm PVC fabric tape and 2x 3mm carbon steel tensile armour wires). Also a test confirms detection of cracks in the most external tensile wires through 200 mm of polyethylene. The configuration of the flexible pipe will influence how far the inspection tool can penetrate, but stronger tools are under development.

6.2.4 Magnetic stress measurement

The armour wires of flexible pipelines are made of ferromagnetic materials. As these wires are subjected to stress, the magnetic properties are altered and can be measured. This is known as magnetic stress measurement. For flexible risers this can be used to detect the event of an armour wire rupture, or inspect if a rupture has happened in the past. As a riser is in service, the armour wires experience tension due to the hang off load and the internal pressure. If a wire ruptures the stress level at the rupture point will be zero and also reduced some distance from the rupture point. The distance of the reduced stress level depends on the friction force between the layers in the riser.

Offshore application

MAPS is a magnetic method where a magnet probe induces eddy currents in the ferromagnetic armour wires, in this way the stress in each wire can be monitored. Figure 26 shows the eddy current vectors in the armour wires.

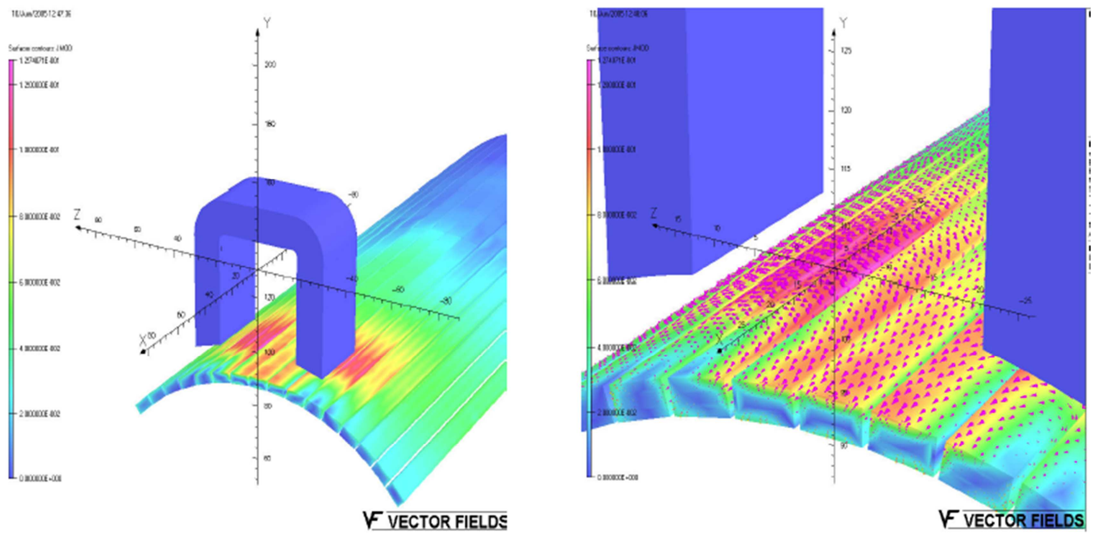

Figure 26 - Electromagnetic modelling of MAPS probe and the induced eddy current vectors [15].

Prototypes of the system have been designed with emphasis on standard components used in the offshore sector and tested in laboratory and on a full scale riser (ref. [12, 15]). Though these tests verify that armour wire breakage can be determined with this system there are several difficulties that still has to be looked into. Mechanical hardness, grain size, texture and other material properties affects the magnetic parameters, along with movement of the armour wires this causes distortions in the measurements done. To cope with problems like this testing with different frequencies are done to recognise and determine the results. A software is designed to manage the frequencies and to give an interface where the results can be displayed.

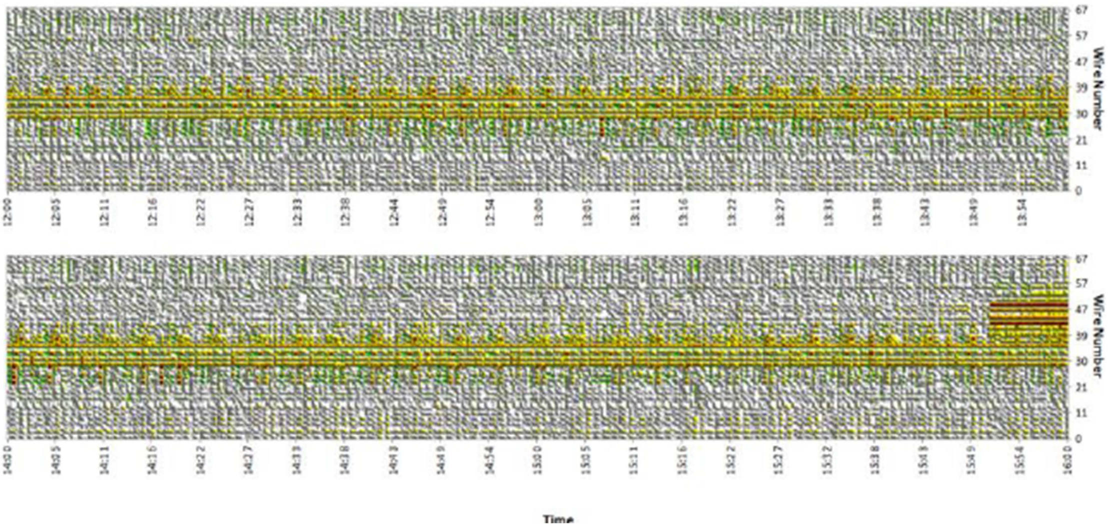

Figure 27 - Results of the stress test done by MAPS prototype in 2011 [15].

Figure 27 shows the results of a full scale test of a 12” nominal bore with a test rig in Newcastle 2011 (ref. [15]). The software is tune so that the “normal” stress level in the armour wires are displayed as grey. The yellow lines are wires that have ruptured and the red lines occurring at the bottom right is a new wire rupture.

The total stress level that is measured consists of residual stresses as well as the externally applied stresses due to weight and dynamic conditions. Since the history of residual stresses is not available when performing an inspection the two different stress sources have to be differentiated. This is done by measuring the stress in each wire two times with varying internal pressure. In this way the residual stress will not vary in the two separate measurements and can be differentiated.

An offshore inspection using the described stress measurement system was performed on a Shell operated Floating Production, Storage and Offloading unit (FPSO) in the UKCS early 2013 [12]. The inspected riser was a 3” gas lift riser comprising an outer sheath, two layers of tensile wires, one layer of pressure armour, one internal pressure sheath and an internal carcass. In this particular inspection there was not detected any wire breaks. It was characterised as a successful deployment. Lessons learned will contribute to further development.

6.3 Summary of inspection techniques

Table 5 gives a summary of the inspection techniques listed and described in this chapter. The table includes a brief description of function, failure detection, positive and negative aspects, development status and state of the art applications.

#	Inspection technique	Function	Failure detection	Positive	Negative	Development status	State of the art
1	Visual inspection	General inspection of the pipe integrity. Includes manual deck inspection, subsea diver and ROV inspection, internal camera inspection of I-tube or carcass	Outer sheath integrity (including inside I-tube), marine growth, pipeline movement. Internal carcass integrity, cracks, erosion, corrosion.	External general inspection is easy and gives an overview of the pipeline integrity. Close visual inspection can elaborate possible failure detected with other means	Subjective assessment of damage. Internal inspection requires planning and may force production to stop.	Proven technology	AUV's available for frequent inspections with pre-programmed surveys [30]
2	Annulus pressure testing	Injecting nitrogen gas through vent ports into the riser annulus. Failure detection by monitoring pressure, volume, and time.	Integrity of internal and external pressure sheath	Can detect the location of a hole in the external sheath.		Proven technology	
3	Laser leak detection	Uses laser to detect leaks from the outer sheath.	Integrity of outer sheath.	Can detect different substances. Specially developed dyes can be injected to give clear results	Time consuming, can be difficult to detect small leaks.	Proven technology	Devices can be mounted on AUV, ROV and can be handheld by divers [20]. Wavelength of the laser can be adjusted to detect different substances [26].
4	Coupon testing	Removable test pipe installed in parallel or series with flexible pipeline. Consists of the same materials and are tested after a while to inspect the different layers.	Aging of polymer layers and general fluid/material compatibility	Gives an indication of polymer degradation.	Once a test coupon is taken out and tested it cannot be replaced with the same history.	Proven technology	
5	Radiography	X- or gamma rays are projected through the flexible riser and onto a digital detection plate on the other side. A radiographic image is created and can be analysed.	Rupture and misalignment of armour wires and unlocking of carcass strip.	Can be submerged and gives a radiographic image of the flexible riser.	Radiation danger	Under development	Prototype fabricated and tested to a water depth of 20 meters

#	Inspection technique	Function	Failure detection	Positive	Negative	Development status	State of the art
6	**Ultrasonic testing**	Sends an ultrasonic pulse through the outer sheath and analyses the reflection.	Can detect annulus flooding. Can measure tensile armour wire thickness and misalignment if the annulus is flooded.	100% accuracy of annulus flooding. Corrosion detection of tensile armour wires.	Needs a clean surface.	Proven technology	ROV mounted tool in operation. Over 100 risers inspected to date.
7	**Eddy current testing**	Uses a probe to cause electromagnetic induction in the ferromagnetic materials in the flexible riser.	Ruptures and anomalies in the most external tensile armour wires.	No couplant needed. Does not require direct contact with the outer sheath	Limited penetration. Excessive marine growth must be removed. A test piece of the same pipe has to be available for calibrating the tool.	Under development	Laboratory tests have confirmed detection of flaws in the pressure armour.
8	**Magnetic stress measurement**	Electromagnetic induction is induced in the tensile armour wires so that the stress level of the ferromagnetic materials can be measured.	Stress level in-, and rupture of tensile armour wires.	No couplant needed. Does not require direct contact with the outer sheath	Limited penetration. Excessive marine growth must be removed. Complicated inspection method, specially trained personnel is need	Under development	System has been fabricated and tested offshore on a 3" gas riser [12].

Table 5 - Inspection techniques summary

7 Monitoring techniques

Monitoring techniques are continuously processes for monitoring specific parameters to detect time based degradations or sudden failures. By installing monitoring equipment deployment expenses can be reduced compared to inspection techniques and real time data can be acquired to minimise response time. If monitoring techniques can discover a failure in progress or degradations in an early stage the operating companies will have more time to plan mitigation and repair strategies. This chapter will explain both conventional techniques that exist and is used today as well as new techniques that are under development. The techniques will be presented with theoretical background, flexible pipeline application and development status.

The monitoring techniques that will be described in this chapter are:

1. Conventional monitoring techniques
    a. Annulus vent monitoring
    b. Annulus vacuum testing
2. New monitoring techniques
    a. Ultrasonic testing
    b. Torsion monitoring
    c. Fiber optics
    d. Magnetic stress measurement
    e. Acoustic emission
    f. Vibration monitoring

7.1 Conventional monitoring techniques

7.1.1 Annulus vent monitoring

Annulus vent flow pressure and flow monitoring is the monitoring of gas that has migrated through the internal pressure sheath and into the annulus (percolation). This gas will rise to the top of the riser where it accumulates. To prevent the pressure to build to a dangerously high level it is normal to have an integrated gas vent system. This system is a set of automated valves that opens when the pressure reaches a certain level. Logging of the amount of gas and the frequency of valve openings may help the operator to anticipate certain initiations of failure modes like:

- beginning of rupture process of tensile armour wires
- external sheath damages
- internal sheath sealing failures
- growth of discontinuities previously introduced in the pipe during termination handling and assembly.

Annulus gas monitoring is a well proven technology, and is widely used among operators. The system requires functioning annulus vent tubes, and is a good way to detect if these tubes are blocked. Inspecting the gas composition will also give valuable information of the annulus environment, and can detect initiating threats.

7.1.2 Annulus vacuum testing

Annulus vacuum testing is the opposite of annulus pressure testing. Vacuum is pulled through the annulus vent ports at the top end fitting of the riser. The extracted gas is measured and can also be analysed to inspect the gas composition in the annulus. This will give indications of corrosion or the presence of gases that can cause degradation in the different layers. After the vacuum is pulled it is hold for some time to monitor for leaks in the outer or internal pressure sheath. After the monitoring is complete the annulus is refilled with nitrogen.

Annulus vacuum testing can detect leaks in the internal and external pressure sheath, but cannot alone determine where the leak is located. A number of companies offer vacuum testing and it is a well-known and proven technique.

7.2 New monitoring techniques

7.2.1 Ultrasonic testing

UT can also be used as a monitoring tool where a stationary clamp on tool is mounted on the flexible riser below the still water line. This system can operate on batteries for 3 – 3.5 years (changeable batteries). The UT tool tests the annulus integrity every week and sends the results wirelessly to a computer every month. Flexlife have developed a system called FlexGuard which is field tested for 3 months. The system needs some adjustments, but a finished product will in short time be available on the market (some operators are already waiting to purchase and use the system).

7.2.2 Torsion monitoring

Three simple and smart solutions have been developed to monitor torsion and deformation of the emerged part of flexible risers (ref. [14])

Deformation monitoring is based on planned interval visual inspections of the riser. A 4000mm x 20mm longitudinal and two 20mm circumferential bands are painted on each riser. During the visual inspection a picture is taken from the same location every time, (can be done from deck level) so that the pictures can be compared to reveal unusual movement or deformation. This method will not necessarily detect failures, but can give indications and start further integrity investigations.

Another a bit more advanced method is the torsion monitoring method using a fixed camera directed to a fixed plate with a clear straight line painted on it. The camera is installed over the end fitting and the target plate is installed on the riser a distance below the bend restrictor. The video signal is digitalised and sent to a computer where the angle deformation can be measured with a precision of 0.3 degrees. The supporting software gives a continuous digital feed and the video is recorded to monitor historical movement for a defined period.

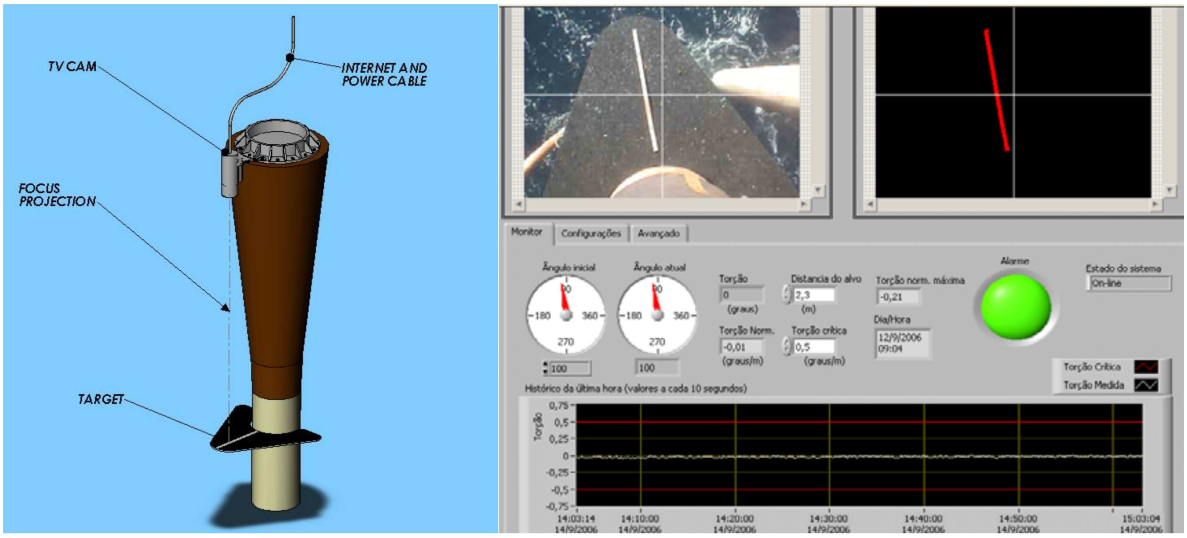

Figure 28 - Torsion monitoring configuration and monitoring software interface [14].

A third technology presented in [14] for torsion monitoring is similar to the camera and target configuration is a method based on magnetic sensors and a steel "rig". The magnetic sensors are installed on a rack on the riser top section, and a steel rig is installed further down on the riser with steel beams that rises from the rig and reaches the sensors above. In this way the movement of the riser is monitored by the magnetic sensors through the displacement of the beams (see Figure 29)

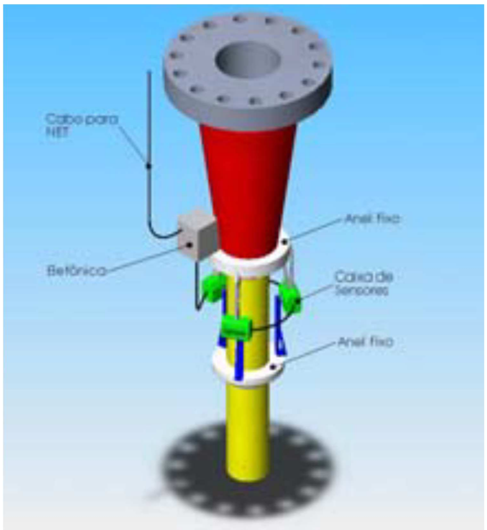

Figure 29 - Torsion monitoring using magnetic sensors [14].

The monitoring of torsion can detect wire ruptures at the top end of the riser, and provide input for fatigue calculations

7.2.3 Fiber optics

Fiber optical monitoring uses a fiber cable that conveys light pulses. The light is reflected back to a sensor positioned at the start of the cable that measures the change in wavelength of the reflected light. This change is analysed and transformed into property changes along the cable.

Two different fiber optic technologies can be used for monitoring different values along a pipeline, Fiber Bragg Grating (FBG) and Brillouin scattering.

FBG

An optical fiber is used by sending pulses of light through the cable. The light is reflected on the "walls" of the cable so the signal can travel for a long distance and also through bends and curves. FBG is a technology where predetermined areas (gratings) of the fiber cable where the refractive index is altered so some of the light is reflected back to the light source. When the cable is stretched or compressed over the altered grating due to strain, temperature or other parameters, a different wavelength of the light signal is reflected (see Figure 30). It is the variation in the reflected light that can be monitored and translated into change in strain or temperature. Several FBG's can be "written" into the cable along its length reflecting different wavelengths allowing for monitoring of multiple points along the cable.

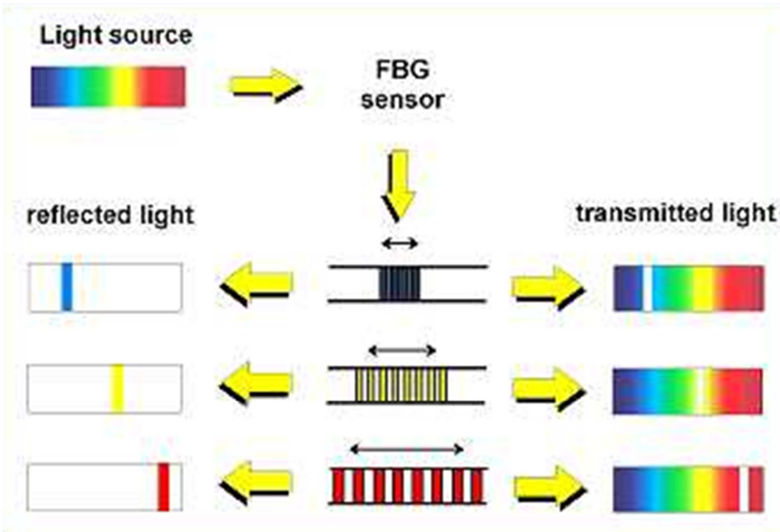

Figure 30 - Fiber bragg grating [http://www.fos-ta.com/FBG-sensors.html].

The weakness of this technology is that the monitoring points have to be predefined and there is a limit to how many points that can be monitored through the length of the cable.

Brillouin scattering

Brillouin scattering is a technology where the entire cable is used as a sensing medium. Light pulses are sent through the cable and the light is reflected so it can be analysed. If the cable is subjected to strain or temperature differences the refractive index of the affected area of the cable changes, and spikes in the reflected wavelengths can be monitored. Measuring the time and wavelength of the reflected light can be translated into differences in temperature or strain. The weakness of this technology is the spatial resolution (accuracy) which is limited to 1m. For strain sensing in risers the accepted limit of spatial resolution is 25 cm, but temperature monitoring has acceptance criteria above 1m (ref. [14]).

Direct optical strain monitoring

A direct optical strain monitoring system called MODA has been developed for Petrobras. This system uses fiber optical cables with integrated FBGs attached directly on each of the most external tensile wires. This requires the removal of a strip of the outer sheath to get access to the tensile wires. After installing the fiber optics the bare strip of the riser is covered with a polyvinyl-chloride based tape to protect the strain sensors for mechanical damage and the wires from the corrosive environment. The optical cables are connected to an interrogation unit that relays the results to the

Petrobras network. The system setup is illustrated in Figure 31. Petrobras installed this system in a first field trial on a semisubmersible platform in Campos Basin in 2009. The laboratory test and field trial is described in [17]. Results from the field test concluded in successful strain monitoring of all the sensors. There was however some damaged cables after the installation that had to be replaced the following year that limited the measurement to 54 of a total of 69 tensile wires until the problem was fixed. The MODA system was also able to monitor the wave loads on the pipe where the observations clearly detected the wave periods. Also bending of the pipe can be detected as the sensors cover the full circumferential length of a pipe segment.

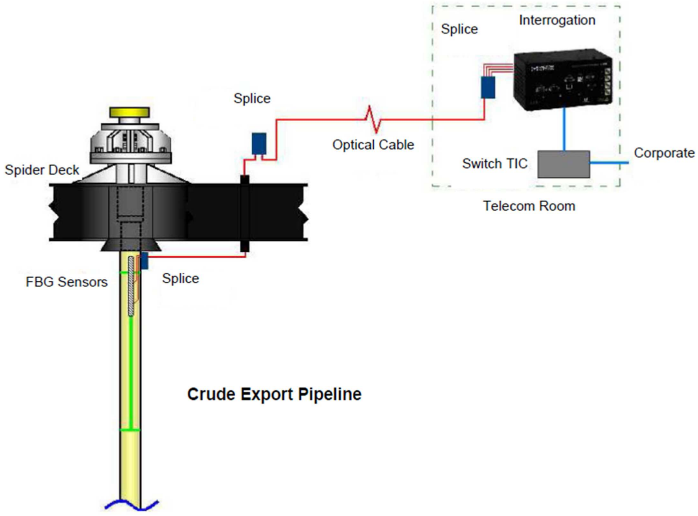

Figure 31 - MODA system configuration [17].

External sheath wrinkling monitor

External sheath wrinkling monitoring is a simple and smart system utilizing fiber optic strain sensing with FBG (ref. [14]). The theory behind the system is that when a tensile wire ruptures near the end fitting connection it is usual to detect wrinkling of the outer sheath some distance below. This phenomenon is due to the rupture in one or several wires causes the riser to elongate slightly as well as rotate to regain torsional equilibrium due to the spiral configuration of the wires. To monitor this event a fiber optic cable is attached to a metallic belt that is installed at the critical distance below the end fitting as seen on Figure 32. The fiber optic cable with will detect any change in stress levels and will detect the rupture of one or several wires. To improve the range of monitoring, several monitoring belts can be installed along the pipe, including inside the I-tube or bend stiffener.

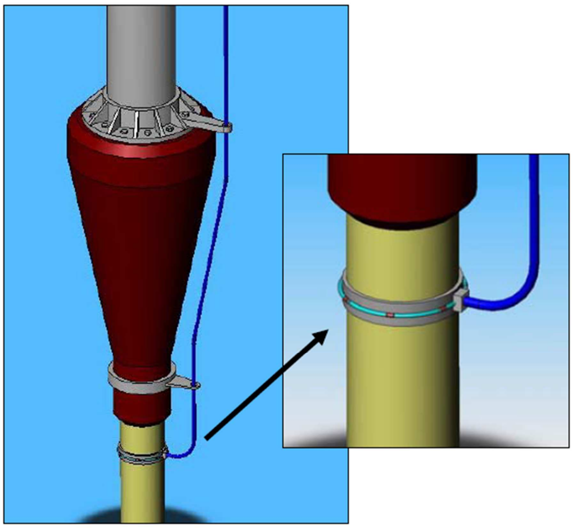

Figure 32 - External sheath wrinkling monitoring system [14].

Integrated fiber optics

One method that is being developed is the integration of fiber inside the flexible pipeline/riser. A challenge is to insert a slender and fragile fiber optic cable into the pipeline where dynamic forces easily can break an unprotected cable. One solution is to install the fiber optic inside a steel tube inside the pipeline. This would protect the cable, but would not give the opportunity of strain sensing as the steel tube would not experience the same tension forces as the armour wires. For temperature sensing though, this would be a sound option, however it is not an optimal scenario because a new element would have to be installed in an already "crowded" environment. Another method is to integrate the optical cables in prefabricated grooves in the tensile armour wires and sealing the cable with epoxy (see Figure 33). In this way the cable would be protected and also experience the same strain levels as the tensile wires, giving the opportunity of measuring both strain and temperature (ref. [31]).

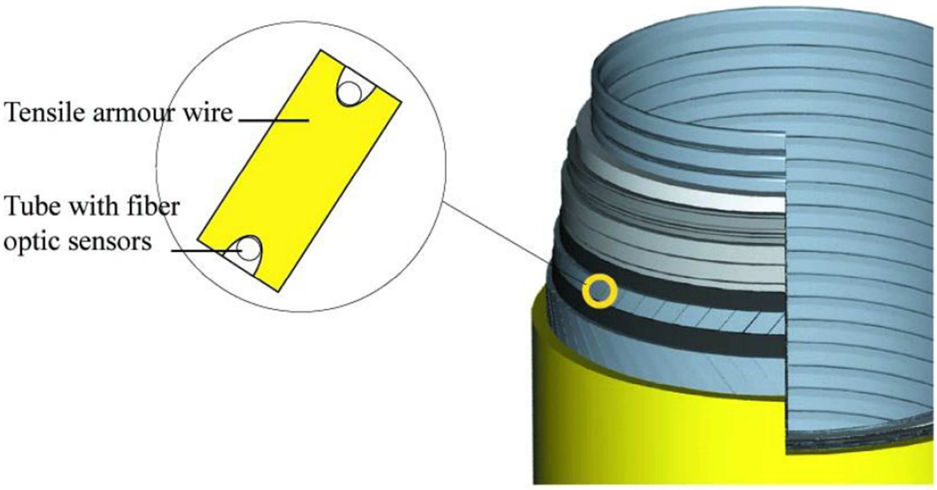

Figure 33 - Fiber optics integrated directly into the tensile armour wires [31].

By using this integrated method, the temperature can be monitored along the entire riser/pipeline, and critical segments like inside the bend stiffener/I-tube would be included. Temperature monitoring along the riser would allow the detection of external sheath breaching as the seawater ingress causes the local temperature to drop. Measuring the internal temperature or restricted areas like bend stiffener/I-tube, buoyancy elements and buried segments would give valuable information regarding the aging of polymers.

The downside of this method is obviously that it cannot be retrofitted, but has to be integrated into new flexible pipelines. Another challenge is the spatial resolution for strain sensing over long distances. There exist a technology that through fiber optics can monitor both strain and temperature along the entire cable with very high spatial resolution. This is done by using light sources in both ends of the optic cable, which raises a new challenge regarding flexible pipelines. It is however possible to develop this system with a special coating in the end of the cable that reflects the light signal up another cable that meets in the far end. This will eliminate the need for two light sources.

7.2.4 Magnetic stress measurement

The theory for magnetic stress measurement is explained in section 6.2.4 and also applies for this section. Different from the inspection method the monitoring method comprises of a static clamp that is mounted on the riser. This system gives a continuous monitoring of the stress level of the armour wires in the riser. When monitoring over a long period the residual stress history will be available and different pressure scanning will not be necessary. This monitoring system has not yet been deployed offshore.

7.2.5 Acoustic emission

Acoustic emission is the phenomenon of released sound waves from within a material that undergoes stress as a result of external forces. Tensile or compressive forces in a material cause elongation or contraction of the material which cause acoustic emission. These waves are registered via sensors that turn them into electrical signals and convey them to computers which can translate them into material behaviour.

Offshore application

Petrobras has performed laboratory and offshore testing (ref. [27]) to develop a system for detecting tensile wire breakage through acoustic emission technology. A test rig onshore was used to produce 19 tensile wire failures while recording the acoustic emission. From these tests a spectre of acoustic signals where made with the highest and lowest values (energy intensity, amplitude, rise time etc.) to anticipate a wire rupture. In addition to this, acoustic emission sensors was installed offshore on a production riser to create a filter for ignoring disturbances like environmental forces, riser collisions etc. With the filter applied, the sensors where still recording and picked up signals that passed through the filter. These were analysed together with the 19 referenced wire break signals to create an equation for calculating the probability of a wire break. The system is still under development and testing is ongoing.

7.2.6 Vibration monitoring

Vibration monitoring is similar to acoustic emission with regards to a specific signal that is released from the event of a ruptured wire. When a wire ruptures, the burst of energy that is released cause vibration in the riser. This technique uses accelerometers to monitor the vibrations caused by a wire breakage.

Petrobras has performed a laboratory test (ref. [5]) comprising a flexible riser segment with 6" internal diameter. Four separate accelerometers was mounted onto the riser, two on the external sheath and two on the end fittings, the test setup is shown in Figure 34. The system has not yet been field proven, and there are some questions around the distortion of the signals in an operational environment.

Figure 34 - Vibration monitoring laboratory test and field configuration [5].

7.3 Summary of monitoring techniques

Table 6 gives a summary of the monitoring techniques listed and described in this chapter. The table includes a brief description of function, failure detection, positive and negative aspects, development status and state of the art applications.

#	Monitoring technique	Function	Failure detection	Positive	Negative	Development status	State of the art
1	**Annulus vent monitoring**	Logging of the vent pressure and frequency of annulus valve openings. Analysing of gas composition.	Blocked annulus vent valves. Gas composition can give indications of annulus environment, hence anticipate material aging and corrosion	Detects blocked annulus vents that can cause failure modes if undetected	Possible contamination of fluids from one riser to another if this is not considered.	Proven technology	Automatic gas vent monitoring systems with data logging and gas sampling bottles. [Forcetechnology.com]
2	**Annulus vacuum testing**	Vacuum is pulled from the annulus vent valves, held and monitored. Measures the free volume of gas in the annulus.	Detects blocked annulus vent valves and flooding of annulus	Does not require production to stop	The location of leak cannot be identified from this test alone	Proven technology	
3	**Ultrasonic testing**	Stationary clamp on tool mounted below water line. Sends wireless data to topside. Same technology as for inspection technique	Same as for inspection technique	Same as for inspection technique	Same as for inspection technique	Under development	Prototype exists and is field tested for three months

#	Monitoring technique	Function	Failure detection	Positive	Negative	Development status	State of the art
4	Torsion monitoring	Monitors torsion of the upper part of the flexible riser compared to I-tube or bend restrictor.	Tensile wire ruptures causing torsion of the riser.	Simple systems, relatively easy to install and operate.	Cannot monitor torsion far from the top of the riser	Under development	Three different methods developed for Petrobras. General visual inspection of painted guidelines, camera inspection of mounted plate and magnetic sensing [14]
5	Fiber optics	Uses fiber optical cables to measure strain and/or temperature along the riser/pipeline	Tensile wire rupture, breach of outer sheath	High accuracy stress measurement for predetermined locations. Temperature measurement of the entire riser	Integrated cables must be installed when fabricated. FBG locations must be predetermine d and cannot be moved.	Under development	External sheath wrinkling monitor under development for Petrobras [14]. Full scale integrated fiber optical temperature monitoring system developed and performed by NKT Flexibles [32]
6	Magnetic stress measurement	Stationary clamp tool mounted on riser. Same technology as for inspection technique	Same as for inspection technique	Same as for inspection technique. Residual strain history available after continuous monitoring	Same as for inspection technique	Under development	Inspection tool has been deployed and tested offshore
7	Acoustic emission	Sensors detect acoustic emission in form of sound waves due to stresses in the riser.	Tensile wire rupture		Signals difficult to analyse. Multiple sources for acoustic emission that need filtering	Under development	Laboratory testing and offshore signal sampling performed by Petrobras. Signal filtering algorithm developed
8	Vibration monitoring	Accelerometers mounted on riser to detect vibration	Tensile wire rupture		Signals difficult to analyse. Multiple sources for vibration that need filtering	Under development	Laboratory testing performed by Petrobras, confirming detection of wire breaks

Table 6 - Monitoring techniques summary.

8 Discussion

Based on the understanding of both failure modes and inspection principles/techniques developed in chapter three through seven, an integrity management strategy will be proposed. The different inspection and monitoring techniques will be categorised into three IMS areas:

- Continuous monitoring
- Interval inspection
- Explorative inspection

Both conventional and new techniques will be recommended. Combination of techniques will be explored to establish new and more powerful techniques to cover detection of multiple failure modes.

8.1 Reflections

Based on the failure modes and reported incidents presented in this thesis, two layers of the flexible pipe stands out as more critical to integrity than the rest; namely the internal pressure sheath and the outer sheath.

The internal sheath is the most difficult layer to inspect as it is not a ferromagnetic material that can be inspected by magnetic techniques. In addition it is impossible to perform visual inspections of this layer. Several degradation modes threaten this layer including temperature variations, fluid compatibility, pressure and environmental stresses. Despite existing degradation models provide recommendation for calculating the state of this layer, they are proven to be insufficient as decommissioned pipelines and risers reveal varying results (ref. [1]). Conventional technology offers one technique for inspecting the internal pressure sheath; coupon testing. This technique is recommended but gives restricted results as the coupon is installed in a location that is not representative for the entire pipeline system. As the coupon is removed for testing the history is removed with it.

The most promising new technique for monitoring the condition of the internal pressure sheath is the integration of fiber optics. With this solution a complete temperature history of the entire pipeline can be provided and used for temperature regulation in start-up and shut-down scenarios. By monitoring the temperature in addition to annulus gas composition through vent monitoring, a combined dataset will provide valuable information. Reviewing this when testing the coupon samples can be beneficial for understanding the degradation mechanisms and updating the models provided in international standards.

The outer sheath is the main barrier for annulus integrity as it prevents seawater from entering. However, this is the layer that is most often damaged. Throughout the entire life cycle, from fabrication to operation, the outer sheath is threatened. A breach has the potential to cause a number of degradations to the internal layers.

Breach of the outer sheath has been in focus for several years. Conventional inspection and monitoring techniques for detecting outer sheath breach exist, while others are under development. However, some of these techniques are not instantly conclusive and others may not identify the location of the breach, which is necessary for repair. Integration of fiber optics will provide immediate detection and location of a breach as the local temperature will drop as seawater flows into the annulus. The problem is that this technique cannot be retrofitted. For existing pipes conventional techniques like nitrogen injection and annulus vent monitoring combined with visual inspection and laser leak testing is the best solution.

8.2 Integrity Management Strategy

Every offshore development, including flexible risers and pipelines, should have their own IMS specific for their riser and pipeline system. A proposed IMS is presented below. This plan is divided into three categories; continuous monitoring, interval inspection and explorative inspection.

The IMS should include an inspection and monitoring programme, based on potential failures and operating envelope, for each unique development. This plan includes specifics for each inspection and monitoring category and also a plan for action when anomalies are detected. The programme should start with including the Fabrication Acceptance Tests (FAT) and initial inspection and monitoring surveys for use as reference and baseline values for further integrity assessment. This information will be critical for defect-detection and life extension assessment.

8.2.1 Continuous monitoring

The continuous monitoring covers the methods that provide on-line or frequent data from a stationary mounted tool. These data usually consist of a defined parameter such as temperature, strain, vent rates etc. The purpose of continuous monitoring is to detect failures or degradations, when they happen or when they are emerging, to give the operator time to plan for mitigating repairs or further inspections. To get the most out of the monitoring, several parameters should be monitored, logged and analysed together, to complement each other. In this way if one parameter is abnormal it can be compared with the others to confirm or disprove possible threats. Each monitoring technique should be tested shortly after installation to determine a baseline value for the parameter of interest to set an acceptance limit. This is done together with the FAT result assessment.

Continuous monitoring is mainly used for confirming that the pipelines and risers operate within the design limits. Monitoring can also detect the rupture of the external sheath which is a critical factor for the remaining service life of the riser.

8.2.1.1 Conventional practice

Annulus vent monitoring

Annulus vent monitoring is a simple and automatic system for controlling the percolated gases from the annulus. This system offers automatic data logging providing information regarding gas percolation rate and pressure used for anticipating polymer sheath ruptures. Functioning annulus gas vents are critical for riser integrity, the malfunction of these vents will quickly be detected with this system. Easy access to gas samples is provided in this system for analysing the annulus environment. Gases like H_2S and CO_2 are dangerous for the different layers in the annulus and can be detected from the gas sample tests.

Annulus pressure monitoring during installation should be considered to detect damage of the outer sheath. This monitoring system is well known with extensive field experience. Annulus vent monitoring cannot determine where a potential outer sheath breach is located.

8.2.1.2 Recommended new practice

Integrated fiber optics

By integrating optical fiber cables into the tensile armour wires, temperature monitoring of the entire riser, and potentially pipeline, is possible. This can arguably revolutionise the pipeline and riser industry, especially for flexible pipes. Full temperature distribution would give immediate detection and location of breach of the outer sheath. Outer sheath damages can be fixed quickly, and the integrity of the repairs will automatically be monitored. Accurate temperature distribution is also valuable for the polymer degradation models. In combination with annulus vent monitoring and coupon testing new reliable models can be developed.

Accurate strain monitoring for the tensile armour wires will provide exact stress measurement in each wire and will immediately detect wire ruptures. This can also be useful for fatigue calculation as logged data is available when risers are retrieved and inspected.

The greatest limitation for this system is that it cannot be retrofitted but must be integrated in the fabrication process, hence other monitoring and inspection techniques are required for existing pipeline systems.

Combination of ultrasonic testing, vibration monitoring and acoustic emission

An UT tool has been developed and tested offshore, but both vibration monitoring and acoustic emission is under development. The combination of these three techniques would act as a powerful monitoring tool with the capability of detecting both annulus flooding and armour wire rupture. Separate signal filtering algorithms are required for vibration and emission monitoring, but the combination of these could complement each other and possibly anticipate the location of the wire rupture. The ultrasonic tool that is developed today runs on changeable batteries, but would require an umbilical for power and data transmission if these technologies were to be combined. This would be a retrofit system to mount on existing risers. Each system is developed with its own software that could be integrated into one for better overview and control.

8.2.2 Interval inspection

Interval inspections are inspections that ought to be performed regularly, for example every year, two years etc. The purpose of these inspections is to pick up any anomalies that cannot be detected from the monitoring techniques. Typical annular inspection is visual inspection of riser and pipeline to check the external integrity, or if the pipelines have moved considerably.

The first set of interval inspections is critical to set anomaly limits, i.e. determine the baseline for later inspections. This baseline limit will be used for later inspections to compare the results and determine the integrity level. The baseline should start the data logging for each inspection (and also monitoring) technique for easy assessment of anomalies. The first inspections after installation will also detect if there has been any unforeseen damages during transport and installation.

8.2.2.1 Recommended practice

Visual inspection

Annular visual inspection is recommended for ensuring the integrity of pipelines and risers. Manual inspection from deck level and inspection through video camera are simple operations for general pipe integrity. Images and videos from the baseline inspection are used for reference. Close inspection for critical elements like bend stiffener, riser TDP, end connections and pipeline curvature is recommended. For visual inspection subsea pre-programmed AUV's can simplify the operation and save costs by eliminating the need for ROV deployment. AUV's can be programmed to follow a defined route and inspect critical locations.

Internal inspection of I-tube or bend stiffener should also be performed in planned intervals. This is critical as this is a restricted location that is known to carry risks.

Annulus vacuum or pressure testing
Vacuum or pressure testing of the riser annulus will identify if there is a leak in the outer sheath. These tests can be done while the system is in operation. The location of the potential leak cannot be accurately determined, so exploratory inspection is needed if a breach is detected.

8.2.3 Explorative inspection

The last category is named exploratory inspection. If some anomalies or defects are detected during continuous monitoring or interval inspection further inspection is needed to explore the threat.

8.2.3.1 Recommended practice

Visual inspection combined with laser leak detection
After anomalies are detected from continuous monitoring or interval inspections, visual inspection is a good way to identify and acquire an overview of the failure. Visual inspection should also be carried out shortly after large storms, offshore operations or when other threatening activities have taken place in the vicinity of the pipeline system.

If there is suspicion or detection of breach of the outer sheath the visual inspection can be combined with laser leak detection to determine the location and severity of the leak. The laser leak detection system will improve the survey as small leaks can be difficult to detect only by visual inspection.

Ultrasonic testing
When there is a leak in the outer sheath there is an immediate threat of increased corrosion and reduced fatigue resistance. This should be detected as soon as possible, but experience shows that this problem can go undetected for a long time. To ensure the integrity of the tensile armour wires an UT tool can be deployed to scan the riser. UT can identify flooding of the annulus and, if flooded, measure the thickness of the tensile armour wires, hence detect corrosion. Corrosion detection provides a valuable input for the calculation of remaining service life of the riser, and also information for models used for corrosion anticipation in the future.

Coupon testing
Coupon testing is the best practice for analysing and inspecting the degradation of the different pipe layers, especially the polymer layers. There exists polymer degradation models for calculating the status of the polymer layers, but these are not always accurate, and coupon testing is advised to check the unique developments, and also improve the degradation models. If this could be implemented along with integrated fibre optics this could significantly improve the knowledge of polymer degradation due to temperature variations.

The disadvantage with this testing is that the coupons are normally installed near the wellhead or topside. The test piece will not experience the same temperature and fluid composition as the rest of the pipeline system. Once a coupon is pulled out and tested it cannot be re-installed with the same history of exposure as the rest of the pipeline system.

8.2.3.2 Recommended future practice

Radiography, eddy current testing and magnetic stress measurement

The future practice for exploratory inspections includes three different technologies that are under development. Radiography, eddy current testing and magnetic stress measurement are all designed for identifying tensile armour wire ruptures, with different positive and negative aspects for each technique.

Radiography is a promising new technology for inspection of flexible pipes. A prototype is tested and has produced radiographic images of a flexible pipe. Software to recognise defects and anomalies has been created and is still under development. Radiography can detect tensile wire rupture, wire misalignment and pitting from corrosion. The technique has however proven to have low sensitivity for detecting small cracks and non-volumetric defects. CT scanning is a very interesting technique that is under development. A CT scan of the pipeline can produce a 3D image of the full cross section. This will permit detection of transversal defects of the steel layers and polymer layers which cannot be done by other inspection techniques than coupon testing. The disadvantage with radiography is the radiation danger and safety restrictions. It also has a long inspection time.

Eddy current testing is a technique for detecting rupture and anomalies as well as thickness measurement of the outermost tensile armour wires. The system has low throughput that can cause challenges for thick coating layers, but stronger probes are under development. For eddy current testing to work a test piece of same configuration as the riser must be available for calibrating the inspection tool.

Magnetic stress measurement is an advanced technology that can measure the stress level in individual armour wires. This complex method requires experts to set-up and interprets the result. It is time consuming and expensive, but gives valuable information and can detect wire ruptures a few meters away from the inspection tool.

8.3 Futuristic view

Integrity management for flexible pipeline systems stands before a potential revolutionary change. If some of the new inspection and monitoring techniques that are under development today is applied to existing or future developments there is reason to believe that the failure count of flexible risers and pipelines will decrease. Retrofit inspection and monitoring tools will enable better control of existing developments.

Apart from the obvious gain of detecting failures and controlling the pipeline under operation, another benefit reveals itself by filling the knowledge and technological gaps. Monitoring results and better understanding will provide accurate calculations of remaining life and lifetime extension. Several pipelines have to date been replace before ended design life due to conservative calculations of remaining life.

New techniques and software for data logging will enable better availability of history and enhance the tracing of failure modes.

By better understanding the threats and failure mechanisms, new pipelines can to a greater extent be designed for inspection. This would be enhanced by better information sharing between companies and borders. Further development of international standards and recommended practices would also add to this aspect.

9 Conclusion

Integrity management for flexible pipelines will never be perfect; pipes will fail and have to be replaced also in the future. By implementing new inspection and monitoring systems the failure rate will decrease and the industry will establish a better understanding of the behaviour of flexible pipes. Following the initiatives of SureFlex and PSA the industry can increase their sharing and cooperation in order to provide information and update international standards.

The most common failure mechanism for flexible pipes today is linked to the internal and external polymer layer. Breach of the outer sheath and degradation of the internal pressure sheath have been the cause for replacing a large number of flexible risers worldwide. In addition the annulus environment with fault in the vent system continues to threaten flexible pipe integrity.

Based on the conventional and new inspection and monitoring techniques described in this thesis the most promising technology is the integration of optical fibres. This technology would enable detection and location of a breached outer sheath instantly. It can also be used for temperature monitoring for regulating start-ups and shut-downs to avoid rapid degradation and pull-out of the internal pressure sheath.

For retrofit systems a combination of techniques is the best solution for flexible pipe integrity. There are several suitable technologies available or in development, but they tend to focus on individual failure causes. A JIP involving several manufacturers and operating companies where critical and frequent failure modes are discussed, considering conventional and new inspection or monitoring techniques, can lead to good results.

10 Future work

This thesis provides a screening of failure modes, inspection- and monitoring techniques of flexible risers and pipeline. A logical continuation of this report would be to explore some of the inspection and monitoring techniques more in detail. This can be done by calculations combined with laboratory tests.

Due to limitations of this thesis, some tasks are left out that should be explored:

- Perform screening, describe and assess inspection and monitoring techniques for ancillary equipment;
    - Bend stiffener
    - End fittings
    - Spools and jumpers
    - Arch buoys
    - Mooring lines
    - Anchors
- Perform screening, describe and assess repair techniques for flexible pipelines and risers and for ancillary equipment

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Appendix A – Internal pressure sheath polymer characteristics [2]

Polymer material	Minimum exposure temperature (°C)	Maximum continuous operating temperature (°C)	General compatibility characteristics	Blistering characteristics
HDPE	-50	+60	Good ageing behaviour and resistance to water-based fluids. Some grades are susceptible to environmental stress cracking in alcohols, liquid hydrocarbons, and surfactants so resistance should be verified.	Good blistering resistance at low temperatures and pressures only.
XLPE	-50	+90	Good ageing behaviour and resistance to water-based fluids, weak acids and produced fluids with high water cuts. Less susceptible to environmental stress cracking than HDPE (environments include alcohols and liquid hydrocarbons).	Better blistering resistance than HDPE, but traditionally limited to relatively low temperature and pressure e.g. 20,68 MPa (3 000 psi) and 60 °C. Recent developments have produced grades of XLPE that can withstand temperatures/pressures of up to 90 °C / 1500 psi and 70 °C / 3000 psi for gas, oil and water
PA-11	-20	+65	Good ageing behaviour and resistance to hydrocarbons. Good resistance to environmental stress cracking. Limited resistance to acids, including heavy bromide brines, at high temperatures, methanol, high TAN crudes and traces of oxygen – see 6.5.3 for further details. Limited resistance to bromides. Weak resistance to high temperatures when any liquid water is present.	Good blistering resistance up to 68,95 MPa (10 000 psi) and 100 °C (212 °F).
PVDF	-20	+130	High resistance to ageing and environmental stress cracking. Compatible with most produced or injected well fluids at high temperatures including alcohols, acids, chloride solvents, aliphatic and aromatic hydrocarbons and crude oil. Weak resistance to strong amines, concentrated sulphuric and nitric acids and alkaline fluids (recommend pH < 8,5).	Good blistering resistance up to 68,95 MPa (10 000 psi) and 130 °C (266 °F).

Table 7 - Internal pressure sheath polymer characteristics.

Appendix B – Complete list of failure mechanisms

Potential pipe defects/failure mechanisms for static applications

Pipe layer	Defect ref.	Defect	Consequence	Possible cause
CARCASS	1.1	Hole, crevice, pitting, or thinning	Reduced collapse resistance and reduced tension capacity	a. sand erosion; b. crevice, pitting or uniform corrosion (and SSC/HIC); c. excessively sour service; d. pigging damage; e. hydrate formation (caused by excessive pressure drop and wet gas) causing pipe blockage and excessive pressure build-up in pipe bore.
	1.2	Unlocking deformation	Locally reduced collapse resistance and tension capacity.	a. overbending; b. excess tension with bending; c. pigging damage d. hydrate formation (caused by excessive pressure drop and wet gas) causing pipe blockage and excessive pressure build-up in pipe bore.
	1.3	Collapse or ovalisation	Blocked or reduced bore	a. excess tension; b. overpressure built between the different layers in a multi-layer pressure sheath design, when the pipe bore is unpressurised c. rapid gas decompression (RGD); d. high initial ovality (manufacturing defect); e. excess loading or deformation during installation; f. high radial gap between pressure armour and internal Pressure sheath (manufacturing defect); g. side impact or point contact.
INTERNAL PRESSURE SHEATH	2.1	Crack or hole	Leak of medium into annulus and/or rupture of outer sheath and/or pipe rupture/leakage	a. hole, bubble or inclusion during fabrication; b. pressure armour rupture; c. pressure armour unlocking; d. ageing (embrittlement); e. temperature above design levels; f. carcass defect; g. pressure above design levels; h. pigging damage; i. environment assisted cracking ; j. erosion (smooth bore pipes); k. product composition outside design limits; l. inadequate material finishing; m. fatigue related failure due to thermal and pressure load cycling.
	2.2	Rupture	Failure of pipe	a. pipe bending (tension side); b. collapse (outer sheath leak, low internal pressure, collapsed carcass); c. ageing and embrittlement; d. failure of pressure armour; e. fatigue failure due to multiple shutdowns associated with vacuum conditions (smooth bore pipe only).
	2.3	Collapse	Recoverable, but plastic straining	Excessive reduction in product pressure or excessive external relative to internal pressure (no carcass or collapsing carcass).
	2.4	Ageing embrittlement/Chemical degradation	Reduced elasticity and greater susceptibility to cracking; material properties degradation.	exposure to production fluids (temperature, pH, water/methanol content), chemical injection, drilling fluid etc.
	2.5	Excess creep (extrusion) of polymer into metallic layer	Possible hole or crack rupture	a. operation at pressures and/or temperatures outside limits; b. inadequate material selection; c. inadequate wall thickness.
	2.6	Blistering	Possible hole or crack rupture	a. rapid decomposition due to operation at pressures and/or temperatures outside limits; b. rapid decomposition under inadequate material selection.

Pipe layer	Defect ref.	Defect	Consequence	Possible cause
PRESSURE ARMOUR LAYER	3.1	Individual or multiple wire rupture	Reduced structural capacity or pipe rupture (burst) or extrusion/leakage of internal pressure sheath	a. corrosion; b. SSC; c. HIC; d. excess internal pressure; e. failure of tensile/backup pressure armour (excess tension/pressure); f. unlocking; g. manufacturing (welding) defect.
	3.2	Unlocking	Reduced structural capacity or pipe rupture (burst) or extrusion/leakage of internal pressure sheath	a. overbending; b. excess tension; c. impact; d. failure of tensile or backup pressure armour; e. radial compression at installation; f. excess torsion during installation; g. manufacturing defect (fishscaling, uncontrolled OD/pitch).
	3.3	Collapse or ovalisation	Reduced bore reduced structural capacity and collapse resistance	a. side impact; b. point contact; c. excess tension (in service); d. radial compression at installation.
	3.4	Corrosion	Pressure armour tensile failure	a. sour service/corrosive annulus; b. ingress of seawater into annulus.
BACKUP PRESSURE ARMOUR LAYER	4.1	Rupture (single or all wires)	Reduced structural capacity or pipe rupture (burst)	a. Corrosion; b. SSC; c. HIC; d. excess internal pressure; e. failure of tensile/pressure armours; f. manufacturing (welding) defect.
	4.2	Ovality	Reduced bore reduced structural capacity and collapse resistance	a. side impact; b. point contact; c. excess tension.
	4.3	Clustering	Uneven support of pressure armour layer, failure	a. Manufacturing defect. b. Overbending
	4.4	Corrosion	Pressure armour tensile failure	a. sour service/corrosive annulus; b. ingress of seawater into annulus.
TENSILE ARMOUR LAYERS	5.1	Multiple wire rupture	Reduced structural capacity or pipe rupture (burst)	a. corrosion; b. SSC; c. HIC; d. excess tension or internal pressure; e. manufacturing (welding) defect; f. accidental impact.
	5.2	Radial buckling or clustering	Reduced tension capacity	a. overtwist; b. compression; c. internal pressure below minimum design value; d. damaged, aged or inadequately designed holding bandages. e. overbending
	5.3	Kinking of pipe	Reduced tension capacity	a. side impact; b. point contact; c. loop in line due to design, manufacturing defect or installation error. d. overbending
	5.4	Corrosion	Tensile armour rupture	a. sour service/corrosive annulus; b. ingress of seawater into annulus.
	8.2	Ingress of seawater	Tensile or pressure armour wire corrosion (especially splash zone) vent valve blocked open or flooded insulation layer	a. Hole, tear, rupture, crack in outer sheath; b. Defective seal in the end- fitting.

Pipe layer	Defect ref.	Defect	Consequence	Possible cause
END FITTING	9.1	Internal pressure sheath pull-out	Leak of medium into annulus, failure	a. loss of friction (carcass deformation etc.); b. tear; c. sheath shrinkage due to temperature cycling or loss of plasticiser; d. creep.
	9.2	Tensile armour pull-out (all wires)	Failure, burst	a. wire break within end fitting; b. epoxy failure (sour service); c. epoxy failure (high temperature ageing); d. loss of friction; e. excess tension.
	9.3	Outer sheath pull-out	Ingress of seawater (hydrostatic pressure)	a. excess annulus pressure; b. creep.
	9.4	Vent valve blockage	Outer sheath burst (if it occurs to all vent valves)	a. debris; b. marine growth; c. mechanism failure (corrosion etc.); d. fabrication errors; e. installation/operation error
	9.5	Vent valve leakage	Possible seawater ingress into annulus	a. corrosion; b. failure of mechanism (seal failure etc.).
	9.6	Individual tensile armour pull-out	Reduced structural capacity	a. wire break within end fitting; b. epoxy failure (sour service); c. epoxy failure (high temperature ageing); d. loss of friction; e. excess tension.
	9.7	Failure of sealing system (sealing rings etc.)	Leak of medium into annulus, possible vent valve blockage, possible outer sheath burst and pipe leakage (failure), possible flooding of insulation layer and possible wax/hydrate formation in flexible pipe bore	a. fabrication errors – ineffective seal of internal pressure sheath; b. excess internal pressure; c. excess tension or torsion; d. inadequate installation; e. excessively low production temperature.
	9.8	Crack or rupture of pressure armour or backup pressure armour	Possible pipe burst or reduced pressure capacity	a. corrosion; b. SSC; c. HIC; d. excess internal pressure; e. failure of tensile armour layer (excess tension or internal pressure); f. inadequate material qualification.
	9.9	Crack or rupture of tensile armour	Possible progressive pull-out and pipe failure or reduced structural capacity	a. corrosion; b. SSC; c. HIC; d. excess internal pressure; e. failure of tensile armour layer (excess tension or internal pressure); f. Failure due to manufacturing defect.
	9.10	Structural failure of end fitting body or flange	Pipe burst/catastrophic failure	a. excess internal pressure; b. excess tension or torsion loads; c. hydrostatic collapse; d. corrosion/chemical degradation; e. brittle fracture; f. fatigue.
	9.11	Cracking of pressure sheath	Pipe burst/ catastrophic failure	Fatigue due to thermal stress cycling or pressure cycling
HOLDING BANDAGES	10.1	Rupture	Possible lateral buckling of tensile armours	a. pipe bending; b. flooded annulus; c. operation in annulus at pressures, temperatures and/or pH outside limits; d. damage during manufacture/installation; e. ageing. f. manufacturing defect (loose holding bandage)

Pipe layer	Defect ref.	Defect	Consequence	Possible cause
	10.2	Ageing	Reduced structural capacity of holding bandage	Material property changes (degradation) arising from ageing.
	10.3	Excess creep (extrusion) of polymer/composite	Loosening or failure of holding bandage, loss of or reduced support to tensile armours and possible lateral buckling of tensile armours	a. operation at pressures and/or temperatures outside limits; b. inadequate material selection; c. inadequate thickness.

Table 8 - Potential pipe defects/failure mechanisms for static applications.

Potential pipe defects/failure mechanisms for dynamic applications

Pipe layer	Defect ref.	Defect	Consequence	Possible cause
CARCASS	1.1–1.3	As Table 8 for static applications.	As Table 8 for static applications and reduced bending fatigue.	As Table 8 for static applications.
	1.4	Unsupported carcass / full extension of carcass under its own weight	Pipe collapse	Loss of carcass support from overlaying polymeric layer
	1.5	Cracking/wear	Reduced collapse resistance and reduced tension and bending fatigue capacity or pressure sheath rupture	a. fatigue + crevice, pitting or uniform corrosion; b. carcass-to-carcass wear or friction. c. inadequate manufacturing tolerances and controls d. excessive curvature of pipe
INTERNAL PRESSURE SHEATH	2.1	Crack or hole	Leak of medium into annulus and/or rupture of outer sheath and/or pipe rupture/leakage	a. to m. As for Table 8 static applications. n. fatigue related failure due to bending load cycling.
	2.2 to 2.6	As Table 8 for static applications.	As Table 8 for static applications.	As Table 8 for static applications
	2.7	Rupture	Failure of pipe	Fatigue cracking.
	2.8	Wear/nibbling	No adverse consequence if thickness is maintained above minimum value to prevent blow through or internal pressure sheath crack or hole	a. abrasion between internal pressure sheath and carcass; b. abrasion between internal pressure sheath and pressure armour.
PRESSURE ARMOUR LAYER	3.1 to 3.4	As Table 8 for static applications.	As Table 8 for static applications.	As Table 8 for static applications.
	3.5	Individual or multiple wire rupture	Reduced structural capacity or pipe rupture (burst) or extrusion/leakage of internal pressure sheath	a. wear at inter-wire contact; b. wear from contact with back-up pressure layer; c. cracking along wire; d. fatigue failure; e. welding defect.
	3.6	Longitudinal wire crack	Potential elongation to critical defect size	Inter-wire contact and local stress concentration.
BACKUP PRESSURE ARMOUR LAYER	4.1 to 4.4	As Table 8 for static applications.	As Table 8 for static applications.	As Table 8 for static applications.
	4.5	Individual or multiple wire rupture	Reduced structural capacity or pipe rupture (burst)	a. wear from contact with pressure armour layer; b. fatigue failure.

Pipe layer	Defect ref.	Defect	Consequence	Possible cause
TENSILE ARMOUR LAYERS	5.1 to 5.5	As Table 8 for static applications.	As Table 8 for static applications.	As Table 8 for static applications.
	5.6	Multiple wire rupture	Reduced structural capacity or pipe rupture (burst) Torsion imbalance	a. wear between armour layers (gap in anti-wear layer, loss of lubricating oil); b. fretting fatigue; c. notch or crack fatigue failure; d. fatigue failure. e. corrosion or corrosion combined with fatigue.
	5.7	Individual wire rupture	Reduced structural capacity or pipe rupture (burst)	a. wear between armour layers (gap in anti-wear layer, loss of lubricating oil); b. fretting fatigue; c. notch or crack fatigue failure; d. fatigue failure.
	5.8	Tensile armour lateral or radial buckling under compression	Disorganisation of armour wires and tensile armour rupture	a. axial compression and cyclic bending; b. Manufacturing defect; tension on holding bandages lost.
ANTI-WEAR LAYER	6.1	Wear, cracking	Radial contact of armour layers, wear	a. relative movement between layers; b. temperature; c. manufacturing defect.
	6.2	Clustering	Radial contact of armour layers, wear	Manufacturing defect.
INSULATION LAYER	7.1 to 7.3	As Table 8 for static applications.	As Table 8 for static applications.	As Table 8 for static applications.
OUTER SHEATH	8.1	As items 8.1 & 8.2 in Table 8 for static applications.	As items 8.1 & 8.2 in Table 8 for static applications.	As items 8.1 & 8.2 in Table 8 for static applications.
	8.2	Wear, tear	Possible rupture due to annulus pressure or possible hole due to wear or accelerated corrosion of metallic armour layers	Abrasive contact with seabed, other lines or other surfaces.
	8.3	Aging, fatigue	Accelerated corrosion of steel armour wires	Temperature exceeding allowable, (particularly when thermally insulated by ancillary components such as bend stiffener.
END FITTING	9.1 to 9.10	As Table 8 for static applications.	As Table 8 for static applications.	Pressure sheath pull-out and cracking due to layer dead weight and inertia
	9.11	Cracking of pressure sheath	Pipe burst/ catastrophic failure	a. As 9.11 of Table 8 for static applications. b. Fatigue due to bending load cycling.
	9.12	Crack or rupture of tensile armour	Possible progressive pull-out and pipe failure or reduced structural capacity	a. Fatigue failure due to non-uniform stress distribution in end fitting; b. Fatigue failure due to manufacturing defect (inadequate surface roughness, surface cracking in wire bending process, weakening of wire mechanical properties due to bending/heating processes).
	9.13	Rupture	Possible lateral buckling of tensile armours	a. fatigue failure

Table 9 - Potential pipe defects/failure mechanisms for dynamic applications.

Appendix C – Failure modes on NCS (1995 – 2014), CODAM database.

Anomaly	Severity	Dimension	Pipe content	Cause	Failure mode
Leak	Major	8	Oil/gas	Coflon layer shrinkage	Polymer
Broken	Major	10	Water	Micro leakage	Other
Leak	Major	8	Oil/gas	Coflon layer shrinkage	Polymer
Bulge	Minor	16	Oil	Unknown	Unknown
Leak	Major	9	Water	Bending	Overbending
Corrotion	Insignificant	16	Oil	Not reported	Corrosion
Leak	Major	9	Gas injection		Compression
Scratch	Minor	6	Gas injection		Other
Crack	Minor	8	Water	Unlocked Zeta wires	Overbending
breach of outer sheath	Major	6	Gas		Burst
Rupture	Minor	10	Water		Collapse
breach of outer sheath	Minor	6			Burst
Waterfilled annulus	Minor	6	Oil	Unknown	Annulus
Hole	Minor	6	Oil	Blockage of gas release valve	Burst
Waterfilled annulus	Major	6	Oil	Unknown	Annulus
Waterfilled annulus	Major	6	Injection	Unknown	Annulus
Waterfilled annulus	Major	6	Injection	Unknown	Annulus
Waterfilled annulus	Major	6	Injection	Unknown	Annulus
Waterfilled annulus	Minor	6	Oil	Unknown	Annulus
Waterfilled annulus	Major	6	Oil	Unknown	Annulus
Waterfilled annulus	Minor	6	Oil	Unknown	Annulus
Waterfilled annulus	Minor	6	Oil	Unknown	Annulus
Waterfilled annulus	Major	6	Injection	Unknown	Annulus
Waterfilled annulus	Minor	6	Oil	Unknown	Annulus
Waterfilled annulus	Major	6	Oil	Unknown	Annulus

Anomaly	Severity	Dimension	Pipe content	Cause	Failure mode
Waterfilled annulus	Minor	6	Injection	Not reported	Annulus
Leak	Minor	9	Oil/gas	Unknown	Unknown
Leak	Major	6	Injection	Collapse of coflon layer	Collapse
Leak	Major	6	Gas injection		Burst
End termination	Major	8	Oil		End fitting
Leak	Minor	11	Water	Hole in outer coating	Other
Leak	Major	6	Injection	Bursted outer coating	Burst
Deformation	Major	6	Injection	Collapse of carcass	Collapse
Deformation	Major	6	Injection	Collapse of carcass	Collapse
Deformation	Major	6	Oil	Collapse of carcass	Collapse
Other	Minor	8	Oil	Fallen off MWA	Other
Other	Minor	6	Water	Fallen off MWA	Other
Broken	Major	6	Injection	HIC	Fatigue
Scratch	Minor	11	Water	Unknown	Unknown
Broken	Major	6	Injection	HIC	Fatigue
Broken	Major	6	Injection	HIC	Fatigue
Waterfilled annulus	Minor	8	Oil	Not reported	Annulus
Leak	Major	10	Oil/gas	Fabrication/design	Burst
Hole	Minor	2,875	Gas	Lack of vent and pressure build-up in the annulus	Burst
End termination	Major	8	Gas		Corrosion
Leak	Major	8	Injection	Unknown	Unknown
Deformation	Major	6	Oil	Unknown	Collapse
Deformation	Major	6	Injection	Unknown	Collapse
Leak	Minor	4	Gas		Unknown
Scratch	Minor	6	Oil	Unknown	Abrasion
Scratch	Major	6	Oil		Abrasion
Scratch	Major	6	Oil	Not reported	Abrasion
Hole	Major	2	Gas lift	Unknown	Burst
Hole	Major	10	Oil/gas	N/A	Abrasion
Hole	Major	10	Oil/gas	N/A	Abrasion
Hole	Major	10	Oil/gas	N/A	Abrasion
Hole	Major	11,6	Condensate	N/A	Abrasion
End termination	Major	8	Oil		End fitting
Hole	Major	10	Oil/gas	N/A	Abrasion
End termination	Major	8	Oil		End fitting
Leak	Major	8	Oil	Hydrate plug	Other
Leak	Major	8	Oil		Unknown
Waterfilled	Major	16	Gas	N/A	Annulus

Anomaly	Severity	Dimension	Pipe content	Cause	Failure mode
annulus					
Breach outer sheath	Major	8	Oil		Unknown
Breach outer sheath	Major	8	Oil		Unknown
Deformation	Major	5	Service	Collapse of carcass	Collapse
Deformation	Major	5	Service	Collapse of carcass	Collapse
Deformation	Major	8	Oil/gas	Collapse of carcass	Collapse
Hole	Minor	2	Gas lift	Believed to be damaged during installation	Abrasion
Wear	Major	12	Oil/gas	Abrasive wear	Abrasion
Wear	Minor	12	Water	Abrasive wear	Abrasion
Hole	Major	16	Gas	Wear	Abrasion
Hole	Major	6	Injection	Lacking end termination plug	Other
Hole	Major	6	Oil	Unknown	Unknown
Hole	Major	6	Oil	Unknown	Unknown
Other	Minor	6	Oil		Unknown
Hole	Major	6	Oil/gas	Lacking end termination plug	Other
Other	Minor	6	Oil	Unknown	Unknown
Breach outer sheath	Major	2	Gas		Abrasion
Deformation	Major	6	Oil	Collaps of carcass	Collapse
Outer sheath	Major	8	Oil		Unknown
Outer sheath	Major	8	Condensate		Unknown
Crack	Major	6	Oil	Collapse of carcass	Collapse
Deformation	Major	6	Oil	Collapse of carcass	Collapse
Deformation	Major	6	Oil	Collapse of carcass	Collapse
Hole	Major	2	Gas	Unknown	Unknown
Hole	Major	4	Gas		Burst
Crack	Major	6	Oil	Carcass tear	End fitting
Crack	Major	6	Oil	Carcass tear	End fitting
Deformation	Major	6	Oil	Collaps of carcass	Collapse
Hole	Major	6	Oil	Carcass collapse	Collapse
Crack	Major	6	Oil	Carcass tear	End fitting
Leak	Major	6	Oil	Carcass tear off	Collapse
Deformation	Major	6	Injection	Collapse of carcass	Collapse
Broken	Major	6	Oil	Overload or fatigue	Tension
Outer sheath	Major	8	Oil		Unknown
Outer sheath	Major	8	Gas		Unknown
Crack	Major	2	Gas	Corrosion fatigue	Corrosion
Deformation	Major	9	Gas	Carcass collapse	Collapse
Leak	Minor	7,5	Gas	1	Burst
Leak	Minor	5	Gas	Wear of the outer sheeting	Burst
Deformation	Insignificant	11	Water	Foreign object	Other

Anomaly	Severity	Dimension	Pipe content	Cause	Failure mode
Outer sheath	Major	8	Oil		Unknown
Deformation	Major	9	Oil	Unknown	Collapse
Hole	Minor	8	Oil	Anchor replacement	Other
Deformation	Major	9	Oil	Carcass collapse	Collapse
Hole	Major	6	Gas	Overpressurised annulus	Burst
Outer sheath	Major	7,5	Gas		Abrasion
Outer sheath	Major	8	Oil		Burst

Table 10 - Reported incidents on NCS (1995 - 2014), CODAM database.