SUSTAINABLE PIPELINE SYSTEMS

SPS-0033-REP-0002

BEIS FINAL REPORT

Helical Optical Fibre Integrity monitoring for Hydrogen Pipelines

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Contents

Abbreviations

BEIS	Department of Business, Energy and Industrial Strategy
BOTDR	Brillouin Optical Time Domain Reflectometry System
DAS	Distributed Acoustic Sensing
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
DVS	Distributed Vibration Sensing
FEA	Finite Element Analysis
GIS	Geographic Information System
GUI	Graphical User Interface
HAPP	Hydrogen Transport Advisory Pipeline Panel
MASIP	Mobile Automated Spiral Intelligent Pipe
SPS	Sustainable Pipeline Systems
TPI	Third Party Interference

1 Executive Summary and Conclusions

This report addresses the feasibility of a helical optical fibre system to use fibre strain measurements all along a pipeline to provide quantitative fatigue life calculations in real time. A Hydrogen Advisory Pipeline Panel of leading energy companies was formed and gave industry feedback of significant interest in commercial roll out but a need to see a full-scale demonstrator to unlock potential. This technology addresses a gap in safety and security of existing technology for hydrogen systems and reduces their overall risk factor.

The helically wound optical fibre system is a part of MASiP – the mobile automated pipeline system developed by SPS. This is especially suited to hydrogen pipelines because the pipe structure includes a polymer liner to protect the steel reinforcement from direct contact with high pressure hydrogen. An associated report of SPS other BEIS feasibility project provides more information on the pipeline handling, layout and end connections context within which the fibre optic system embeds. The Stage 2 project which will bring the results of the two feasibility studies together.

A review of functional requirements and risk factors for hydrogen pipelines concluded that fatigue crack growth was the most important failure mechanism that designers of hydrogen pipelines need to address, and that hydrogen is a serious risk factor for girth welds in conventional pipelines. The evidence behind this conclusion comes from three sources, published collaborative work with National Grid, extensive published literature referenced in section 3 and discussions with members of our HAPP panel. In developing our Phase 2 proposal we have also been having discussions with the is engineering team at WOOD who are actively engaged in FEED work for hydrogen pipelines. Their technical experts are also in agreement that this is a critical risk factor.

A member of our team (AS) was involved in the lifetime assessments of deepwater structures in the past and for critical structure crack growth analysis and fatigue lifer analysis are key aspects of determining structure safety. In the past there were some well documented catastrophes (eg Alexander Kjelland) that occurred due to poorly understood and unmonitored crack growth from welds.

Hydrogen pipelines will have raised sensitivity to hydrogen embrittlement – which is a form of stress corrosion cracking and we therefore concluded that a pipe integrity algorithm should be based on a fatigue crack growth algorithm.

A review of the different types of fibre system available concluded that the optimum solution for commercial deployment would be to use Rayleigh based systems for the best response to dynamic events with real time monitoring but complemented with calibrations with independent static baseline measurements using a Brillouin system or otherwise. A fibre optic dashboard was developed to satisfy the minimum functional requirements for SPS software to be a standalone platform for MASiP Pipe for integration with other pipeline integrity management software platforms like PIMS, GIS and Risk Modules. The core of the dashboard is a geographic representation of the pipeline "caterpillar" – a colour coded line representing pipe health with dropdown menus updated in real time with key data from the channels along the line.

The design basis for a fatigue life algorithm was developed using 3D FEA to model the fibre route and materials data to design a statistical bin counting system for significant events. The status of the pipeline fatigue life is displayed using a 3D fatigue chart. This was all put to the test with a physical full scale pipe section test where pressure fatigue cycling was applied to a pipe section containing a defect so that this could be run to failure quickly. The result was that the strain based optical fibre system did detect abnormalities that the fatigue algorithm found. All project objectives were met on time and within budget.

It is concluded overall that a helical optical fibre system with a fatigue life algorithm can offer a significant advantage to the security and maintenance of hydrogen pipelines.

It is recommended that helical optical fibre be implemented on hydrogen pipelines to reduce the risk of fatigue crack growth and that this be demonstrated at kilometre scale to ready for roll out deployment.

2 Introduction

2.1 Aims and Objectives

The primary objective of the BEIS IFS Programme is to support the development of fuel switching and fuel switch enabling technologies for UK industry with a focus on low carbon fuels. Further to this, the aim of this project is to provide evidence and commercial viability of pipelines fuel-switching technologies and validation of industrial decarbonisation policy to reach the UK's Net Zero targets.

Hydrogen fuel switching requires a pipeline transportation network that supports a fuel switching initiative that fully addresses the integrity challenges posed by hydrogen service. Conventional pipeline integrity monitoring tools and threat assessment models are largely inadequate to support fuel switching in pipelines. Hydrogen pipeline systems introduce new risk factors, such as hydrogen embrittlement increasing the risk of fatigue failure. This is reduced by a pipeline system with an inner polymer liner to seal the fluid and protect reinforcing steel from hydrogen embrittlement. There are advantages of having helically wound optical fibre in the pipe wall from pipe manufacture to improve connectivity and data resolution along the pipe. SPS was granted a patent for helically wound sensing in September 2022.

This project was designed to assess the feasibility of using helically wound optical fibre as a distributed sensor for fatigue lifetime monitoring and threat alerting system. Current fibre optic pipeline threat monitoring systems are qualitative, and a key aim was to assess the feasibility of a quantitative threat alert system. The current feasibility report is based on a 12" MASiP Pipe system, and the full-scale demonstrator planned for Phase 2 will include a range of pipe diameters between 8inches and 36inches.

The key uncertainties which this project was designed to address are as follows.

1. Can quantitative measurements from fibre strain be used to develop a quantitative system?
2. Can data interpretation of strain events be counted using helically wound optical fibre?
3. What type of fibre and data interrogation system is best suited for dynamic fatigue life?
4. What is the feasibility of a fatigue life algorithm based on fibre strain cycle counting?
5. Test data from full 12inch diameter short length pipe sections with internal pressure
6. Design of a threat alert system for a full-scale pipeline above 1km in length
7. Industry interest in joining a hydrogen advisory pipeline panel

2.2 MASiP pipeline system

The MASiP pipeline system comprises polymer liner pipe reinforced by steel strip in a patented configuration. Optical fibre cable is wound in between the steel reinforcement and the outer environmental coating. SPS was granted a patent in September 2022 for the helical winding of distributed sensors.

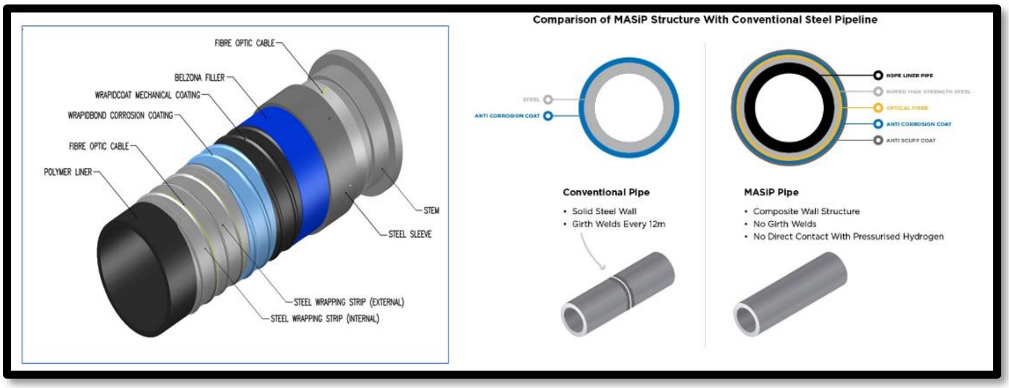


Figure 2-1: MASiP pipe structure

MASiP uses a mobile pipe manufacturing machine for producing pipe on the wayleave and directly laying it into the trench. The MASiP mobile pipe machine prototype is set up on SPS trial site in N Yorkshire and configured to wind optical fibre directly on to the steel reinforcement.

Figure 2-3: MASiP In Field Pipe manufacturing system

2-3 Project Logic Plan

This feasibility project started by reviewing the functional requirements for an effective digital pipeline integrity management system. This found that the risk factor for the introduction of hydrogen into pipelines is the risk of fatigue fractures due to hydrogen embrittlement in girth welds in conventional pipe structures. This highlighted a need for fatigue crack based quantitative measurements. The design of the optical fibre dashboard focussed on incorporating a fatigue life module to measure cycle counts of strain events. The optical fibre interrogation and cable options were reviewed to determine the optimum systems for full-scale commercial system. Software development was based on the result being commercially viable for pipelines of 100km length or more. This reduces the need for any further software develop to deploy the system for longer pipelines. Our appointed software contractor has worldwide experience in commercially deploying fibre optic interrogation hardware and software having installed 25000km of fibre worldwide. The time and budget of the feasibility project only allowed system to be tested on short lengths of pipe. A short pipe pressure cycling test was conducted so that a failure could be achieved within the time available. This leaves uncertainties in terms of full-scale implementation that need to be resolved in a larger scale pipeline demonstrator. Any feasibility study is inevitably qualitative in the sense that it is too small scale to generate quantitative statistical validation. Long pipe tests as conducted with a full-scale demonstrator as proposed for Phase 2 is required to provide the data for statistically quantitative validation before commercial deployment of the technology can occur.

3 Formation of Hydrogen Advisory Pipeline Panel

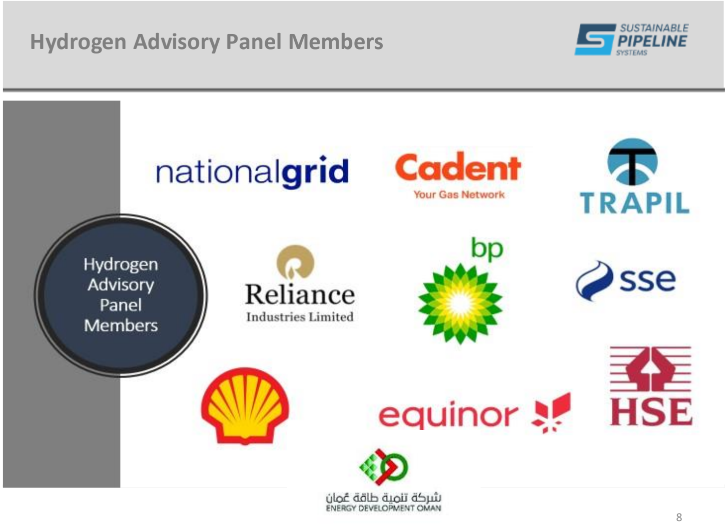


Figure 3-1: Hydrogen Advisory Pipeline Panel Members

At the start of the project a Hydrogen Advisory Pipeline Panel was formed to advise SPS on industry requirements and on early commercial project opportunities for MASiP pipeline system technology. The members of HAPP are National Grid (UK), Cadent (UK), SSE (UK), Equinor (UK), BP, Shell Health and safety Executive (HSE) the UK national regulator, and internationally Trapil (France), Reliance industries (India) and HDO (Hydrogen development Oman).

Swedish Steel (SSAB) gave considerable help and advice on how best to engage the leading energy companies meaningfully in the plan to invest in new pipeline infrastructure for hydrogen. and they presented to HAPP on their introduction of hydrogen-based steel production with 2 new steel mills in N Sweden. They have also connected SPS to preliminary plans to build a 1500km hydrogen pipeline from North to South Sweden.

The initial meeting started with a round table workshop to investigate all the issues that the energy companies see as problems in introducing hydrogen grid infrastructure.

The Technical director of Optasense gave a presentation on the current state of the art in Optical Fibre integrity management of pipelines.

A key conclusion of the panel workshop on factors that would delay the introduction of hydrogen infrastructure was the lack of availability of skilled manual labour (such as welders) needed for conventional pipeline technology. MASiP technology key attraction to them is the avoidance of girth welding and the introduction of automation with less need for skilled labour.

A questionnaire has been launched to refine HAPP advise on Demonstrator design for Phase 2.

4 Helical Optical Fibre System Options Review

4.1 Review of Functional Requirements

The Helical Optical Fibre system, (HOF), which has been patented by SPS, consists of optical fibre wound in a helical configuration directly on to the outer layer of steel reinforcement of the pipe. This completely automates monitoring of key parameters like pressure, temperature, strain, fatigue cycling and pipe movement. The fibre delivers high-resolution distributed sensing, all along the pipleine with an enhanced level of real-time information about stress-strain patterns in the pipe. This can prevent asset damage and pipeline leaks by detecting early warning signs. This can significantly reduce safety and environmental risks for hydrogen pipelines at a fraction of the pipeline construction costs.

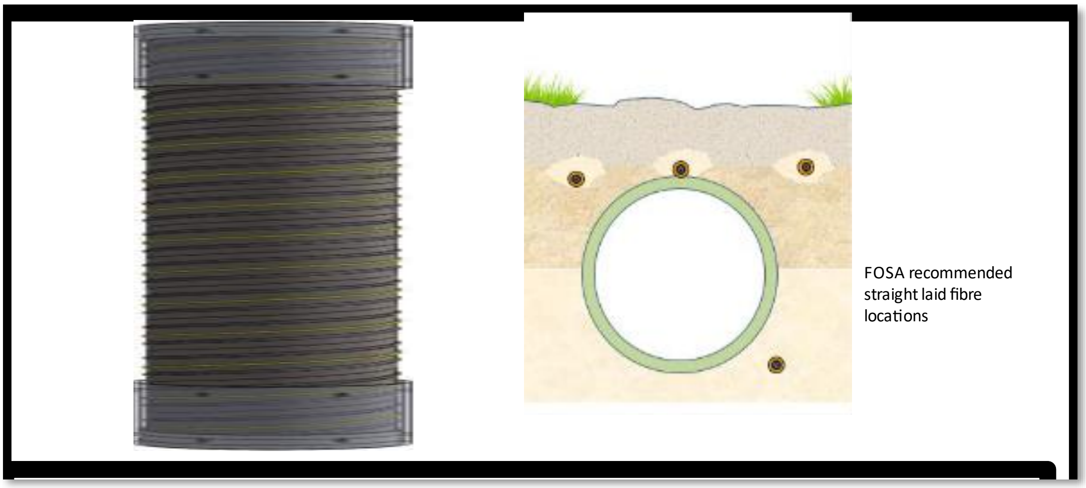


Figure 4-1: Helical Optical Fibre wound on the MASiP Pipe for distributed sensing.

A review was conducted of the industry reports, recommended practices and standards, to better understand the key integrity challenges to be addressed for long-term safe operations of hydrogen pipelines and risks associated with using legacy pipeline networks for blended or pure hydrogen service as well as new pipelines.

The review results were used to understand the material, manufacturing and process quality requirements to progress tests for hydrogen product compatibility and type approval qualification plans for MASiP Pipe System.

Hydrogen induces cracking with high concentrations, moisture, sour service conditions or cathodic over-protection. Hydrogen exposure affects the steel properties, SMYS / UTS, ductility, fracture toughness, and resistance to fatigue cracking

The most common damage mechanisms in conventional pipelines due to hydrogen exposure are:

- Hydrogen embrittlement
- Hydrogen-induced blistering
- Hydrogen attack
- Cracking from hydride formation
- Cracking from precipitation of internal hydrogen

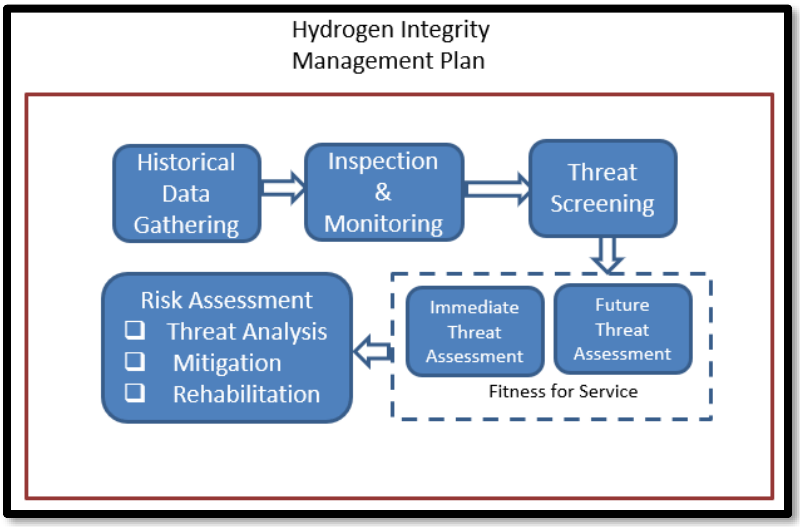


Figure 4-2: Typical Hydrogen Pipeline Integrity Management Plan

Pipeline operators perform pressure cycle fatigue analysis on crack anomalies, dents, welds or when out of roundness is detected. The advanced API 579 and BS 7910 Fracture Mechanics methods used by the industry rely on actual pressure transducer data for real-time monitoring and hydraulic modelling to determine the true pressure loading at anomaly locations for accurate growth predictions. This does not account for parameter variations throughout the length of the pipeline. A distributed sensing approach using a helically wound optical fibre integrated in the pipe structure would allow accurate counting of pressure cycles and thereby calculating fatigue life all long the pipeline. This allows pinpointing localised pipe sections exceeding fatigue life thresholds that may be set by the operator.

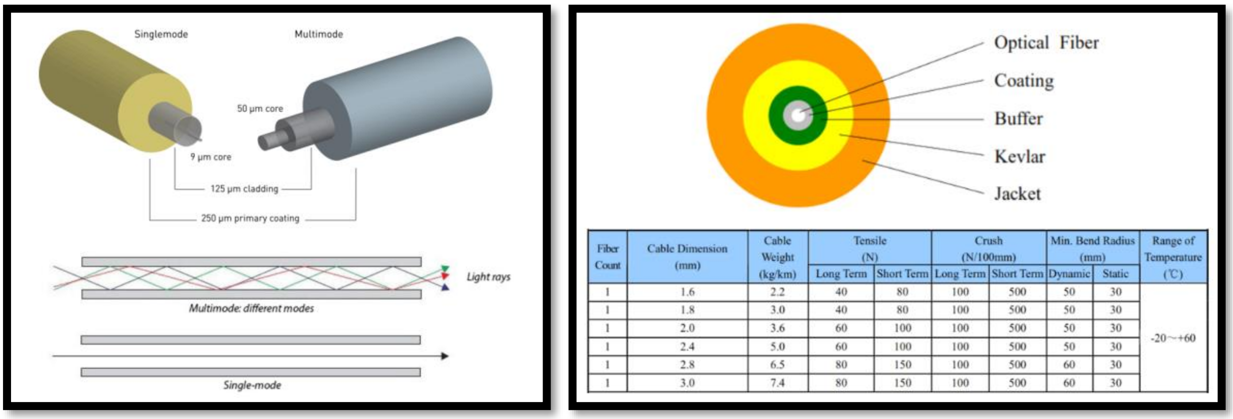
From this review it was concluded that fatigue crack growth was the most important failure mechanism that designers of hydrogen pipelines need to focus on. It was also concluded that hydrogen is a serious risk factor for girth welds in conventional steel pipelines.

A thorough literature review carried out by SPS as part of the HAPP meeting discussions follow up highlighted, hydrogen pipelines significantly raise sensitivity to hydrogen embrittlement – which is a form of stress corrosion cracking and therefore it was concluded that the SPS Dashboard for key pipe integrity threat monitoring should be based on a fatigue crack growth algorithm. The references reviewed are listed below:

1. Introducing Hydrogen into the UK Gas Transmission Network: A Review of the Potential Impacts on Materials NIA report - Bannister & Brown HSE – October 2019
2. Using the Natural Gas Network to Transport Hydrogen:10-year experience International Gas -Iskov & Konnek - Union Research Conference Rio 2017
3. Sandia National Laboratories, “Technical Reference on the Hydrogen Compatibility of Materials,” 2005.
4. Digital Automated Mobile Pipeline Construction – SPE 202988 – Society of Petroleum Engineers – Stevenson, Everard & Bobat – November 2020
5. H. Cialone and J. Holbrook, “Sensitivity of steels to degradation in gaseous hydrogen,” in Hydrogen Embrittlement, Prevention and Control, ASTM STP 962, Philadelphia, ASTM, 1988, pp. 134-152.
6. M. Dadfarnia and P. Sofronis, “Assessment of resistance of linepipe steels to hydrogen embrittlement,” University of Illinois at Urbana-Champaign, Illinois, 2016.
7. A review of Fatigue crack Growth for Pipeline steels exposed to Hydrogen- Nannings, White et al J Res NIST 437 2010.

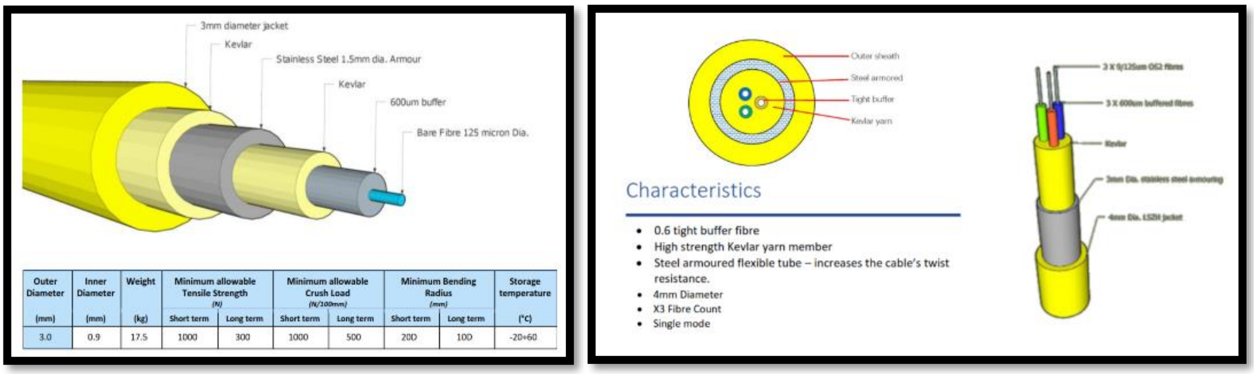
4.2 Review of Optical Fibre Options

Optical fibre cables are available in a variety of off-the-shelf or custom types. However, selection of fibre optic cables for distributed pipeline sensing applications have to be made based on the key parameters that are monitored, interrogation techniques and desired performance characteristics.



Fiber Count	Cable Dimension (mm)	Cable Weight (kg/km)	Tensile (N)		Crush (N/100mm)		Min. Bend Radius (mm)		Range of Temperature (℃)
			Long Term	Short Term	Long Term	Short Term	Dynamic	Static	
1	1.6	2.2	40	80	100	500	50	30	-20~+60
1	1.8	3.0	40	80	100	500	50	30	
1	2.0	3.6	60	100	100	500	50	30	
1	2.4	5.0	60	100	100	500	50	30	
1	2.8	6.5	80	150	100	500	60	30	
1	3.0	7.4	80	150	100	500	60	30	

Figure 4-3: (i) Single Mode Vs Multimode Fibre, (ii) Yellow jacketed, 3mm, SMF G 652



Outer Diameter (mm)	Inner Diameter (mm)	Weight (kg)	Minimum allowable Tensile Strength *(N)*		Minimum allowable Crush Load *(N/100mm)*		Minimum Bending Radius *(mm)*		Storage temperature (°C)
			Short term	Long term	Short term	Long term	Short term	Long term	
3.0	0.9	17.5	1000	300	1000	500	200	100	-20+60

Characteristics

- 0.6 tight buffer fibre
- High strength Kevlar yarn member
- Steel armoured flexible tube – increases the cable's twist resistance.
- 4mm Diameter
- X3 Fibre Count
- Single mode

Figure 4-4: Jacketed Micro Armoured Stainless Steel SMF G 652 Fibre (i) 3mm, single core, (ii) 4mm 3 core

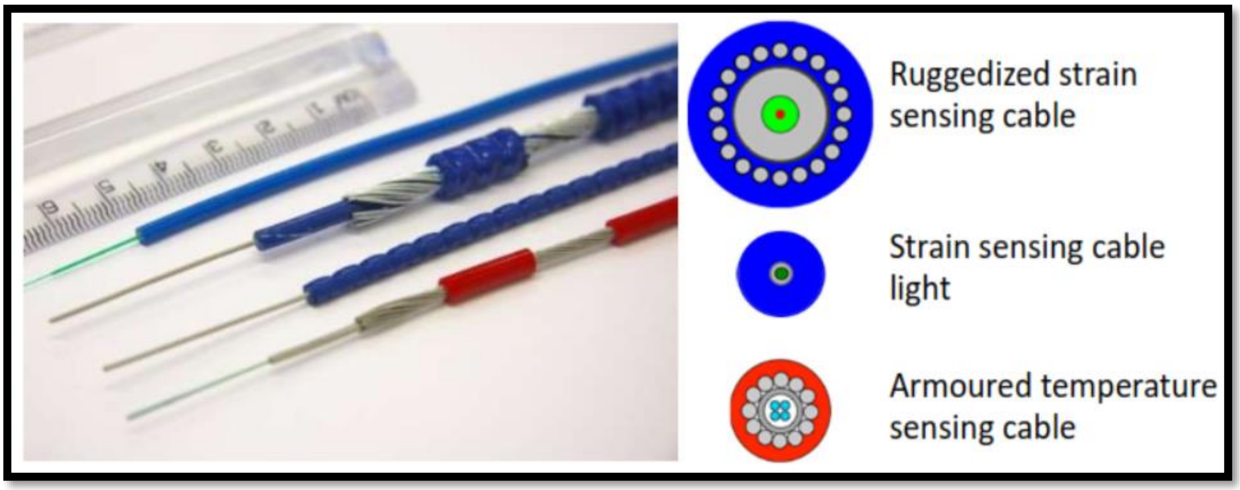
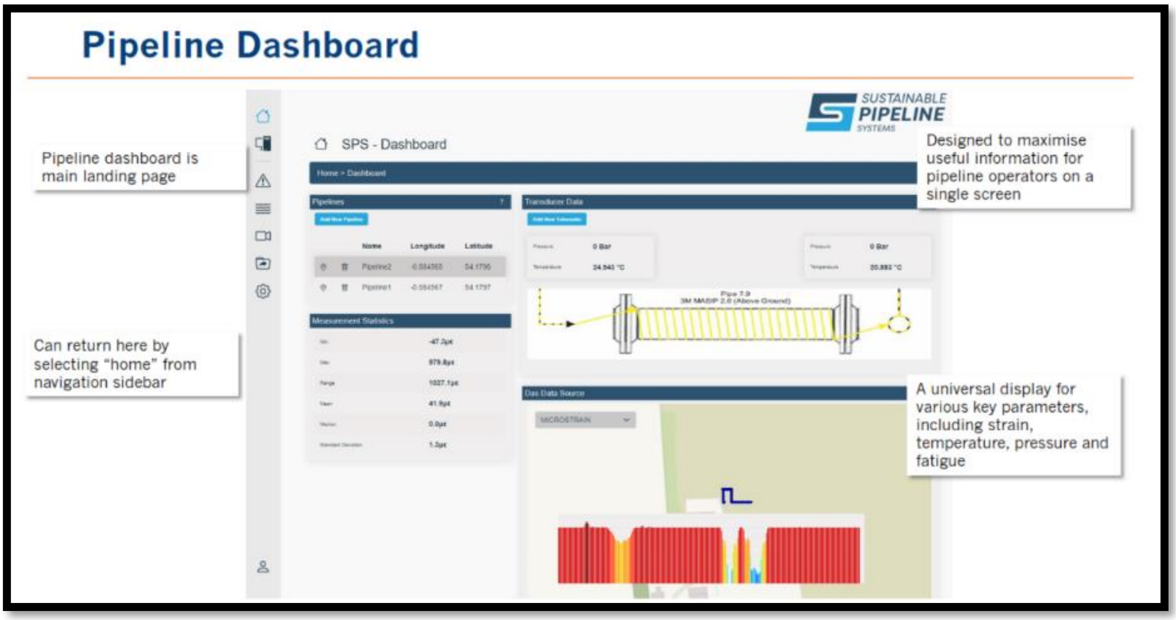


Figure 4-5: Ruggedised fibre cable designs with flexibility, for harsh environments.

There is a balance to be struck between armouring for ruggedness under field conditions and sensitivity for response to pipe wall changes. For strain sensitivity the fibre is best configured as tightly buffered cable while loose tube is better for temperature sensitivity. Mechanical stress produces a cross-influence on the measurement signal superposed on the temperature signal, so the fibre inside the cable must be kept free from mechanical influences (elongation, friction).

The basic concept of all distributed fibre-optic sensing technologies is to measure the response of an optical fibre to the excitation by an injected optical pulse. The optical pulse travels along the fibre and is subject to number of backscattering effects along the way. From every location the signal passes by, portions of light are being thrown back and travel to the injection end, where they are recorded over time and interpreted with an interrogation system. From the time of flight, the origin of the received backscattering at every instance in time can be reallocated. Thus, a distributed profile of optical backscattering can be recorded for the entire length of the fibre under test.

5 Digital Pipeline Integrity Monitoring Dashboard



Pipeline Dashboard

Pipeline dashboard is main landing page

Can return here by selecting "home" from navigation sidebar

Designed to maximise useful information for pipeline operators on a single screen

A universal display for various key parameters, including strain, temperature, pressure and fatigue

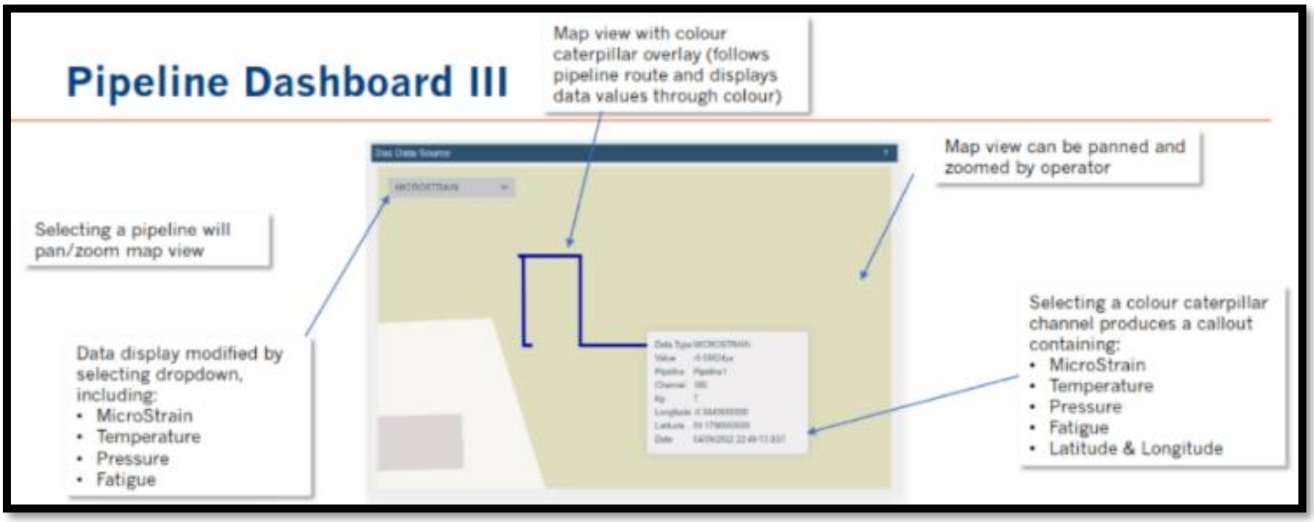
Figure 5-1: Dashboard Front Page for real time monitoring of pipeline health.

Central to any functioning threat alerting integrity monitoring system is a functioning dashboard. The dashboard developed for MASiP has been developed by combining SPS in house expertise on pipeline integrity monitoring with Optasense expertise in developing front end software for fibre optic systems. The dashboard home page allows new pipelines, pipe schematics and maps to be uploaded or removed. This delivers a universal display for various key parameters strain, temperature, pressure and fatigue life.

The Dashboard developed for fibre optic data visualisation enables real time monitoring of key operational parameters, external threat monitoring and long-term fatigue life monitoring. It is web-based and is hosted on SPS Administrator managed Amazon Web Services platform on SPS Domain. The Dashboard permits user authentication, access control and remote data management.

The final design after a number of iterations included a geographic map where the pipeline is represented by a coloured line. The dash board front page features the map view and shows the various parameters (as drop down) , fatigue threat alerts and fatigue bin count bar chart graph all on the same screen. The functionality includes the pipe line being colour coded – live in real time- whereby green indicates a low normal level and red is a level that alerts the pipeline engineer to conduct further investigation.

The alerts from the SPS Fatigue Threat Module are displayed on the coloured pipe caterpillar on the Fatigue Dashboard. Additional bar fatigue graphs for analysis bin counting results is also featured.



Pipeline Dashboard III

Map view with colour caterpillar overlay (follows pipeline route and displays data values through colour)

Map view can be panned and zoomed by operator

Selecting a pipeline will pan/zoom map view

Data display modified by selecting dropdown, including:
- MicroStrain
- Temperature
- Pressure
- Fatigue

Selecting a colour caterpillar channel produces a callout containing:
- MicroStrain
- Temperature
- Pressure
- Fatigue
- Latitude & Longitude

Figure 5-2: Dashboard geographic map view showing parameters monitored.

MASiP Fatigue Dashboard

Fatigue analysis by using dropdown on main dashboard

Fatigue analysis dashboard is a filter on the main dashboard which configures the displays to analyse pipeline fatigue

Functionality is similar to pipeline dashboard (filtering, map display and colour caterpillar) however focus is on fatigue

Additional fatigue graph

%life by distance

Figure 5-3: Fatigue analysis and alerting dashboard and pressure and temperature transducer link

Other real time alerts like third party interference (TPI), digging, leaks and strain are displayed on the coloured pipe caterpillar on the Live Pipeline Dashboard. The severity of various alerts can be classified as low, medium or high. The real time data files (H5 files), csv files, fatigue csv files, raw data files are archived on the SPS Citrix cloud. The dashboard also has readouts of the pipeline system pressure and temperature from transducers and dropdown boxes to show the relevant data at any section of pipeline by clicking on the coloured line.

The dashboard satisfies the minimum functional requirements for the SPS software as a standalone platform for MASiP Pipe for future integration with other pipeline integrity management software platforms like PIMS, GIS and Risk Modules.

6 Fatigue Algorithm Design Basis – Finite Element Analysis of Fibre Path

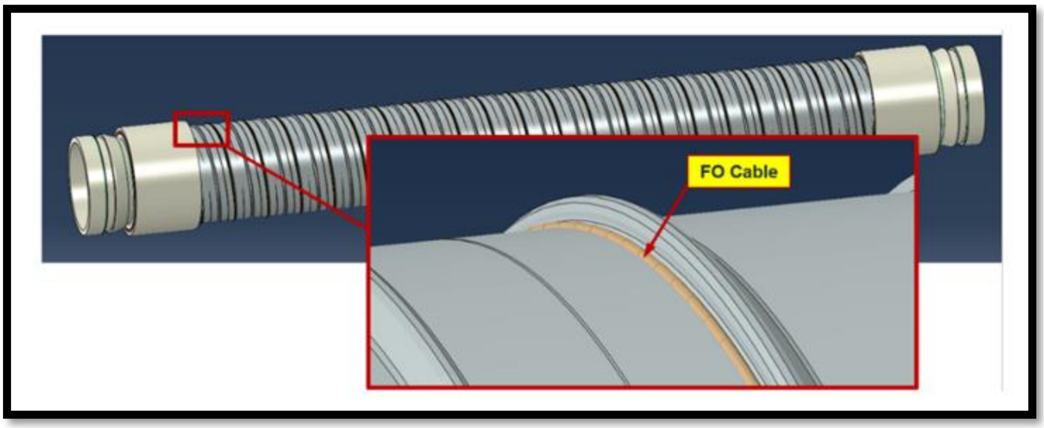


Figure 6-1: 3D finite element model was MASiP pipe with the optical fibre next to the steel reinforcement ribs.

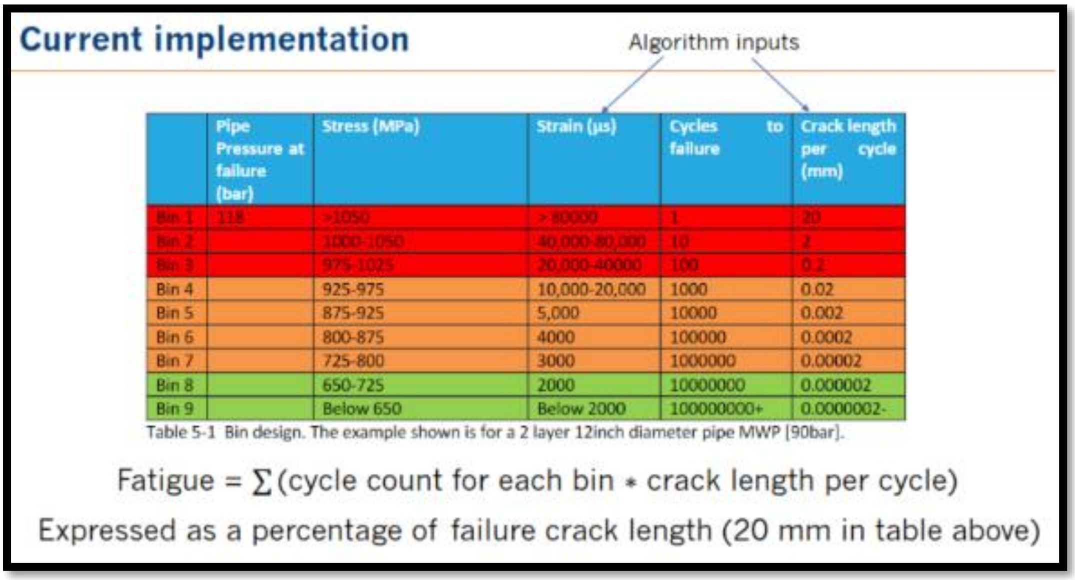
To be able to interpret the strain outputs from the fibre quantitatively in terms of the stress in the wall of the pipe a 3D finite element model was built of the pipe wall structure including the shape of the reinforcement and the location of the optical fibre next to the reinforcement ribs.

This enabled the relationship to be determined between fibre path length and therefore length along the pipeline and stress in the wall of the pipe. The materials fatigue data for the steel reinforcement was then used to develop a fatigue algorithm to convert the stress into a crack growth rate for the location at this strain amplitude has been measured.

This provided the design basis for the Fatigue Life Algorithm

7 Fatigue Life Threat Module

The fatigue algorithm counts each amplitude of each cycle. A series of statistical bins were designed so that the fatigue algorithm could count each cycle in to the right bin depending on the strain amplitude of each cycle. These strain bin levels are correlated to stress in the steel reinforcement, from the fatigue data. The stress amplitude is then related to the amount of crack growth nominally assigned to each cycle. Finally, the results are converted into a cumulative effective crack length and the expected remaining fatigue life for that section of pipe.



Current implementation

Algorithm inputs

	Pipe Pressure at failure (bar)	Stress (MPa)	Strain (µs)	Cycles to failure	Crack length per cycle (mm)
Bin 1	118	>1050	> 80000	1	20
Bin 2		1000-1050	40,000-80,000	10	2
Bin 3		975-1025	20,000-40000	100	0.2
Bin 4		925-975	10,000-20,000	1000	0.02
Bin 5		875-925	5,000	10000	0.002
Bin 6		800-875	4000	100000	0.0002
Bin 7		725-800	3000	1000000	0.00002
Bin 8		650-725	2000	10000000	0.000002
Bin 9		Below 650	Below 2000	100000000+	0.0000002-

Table 5-1 Bin design. The example shown is for a 2 layer 12inch diameter pipe MWP [90bar].

Fatigue = $\sum$(cycle count for each bin * crack length per cycle)

Expressed as a percentage of failure crack length (20 mm in table above)

Figure 7-1: Bin design for Fatigue algorithm based on a 2-layer 12inch diameter pipe.

The Fatigue Threat Module is a GUI developed based on the SPS Fatigue Algorithm to facilitate real time fatigue cycle counting into strain bins by a Rainflow-counting algorithm and convert that into a cumulative effective crack length and remaining fatigue life.

The results are converted into a cumulative effective crack length and presented in a 3D chart where the vertical axis is fatigue life used (expressed as cumulative crack length) , the x axis is length along the pipeline and the y axis is the fibre strain level- representing the bin or event severity.

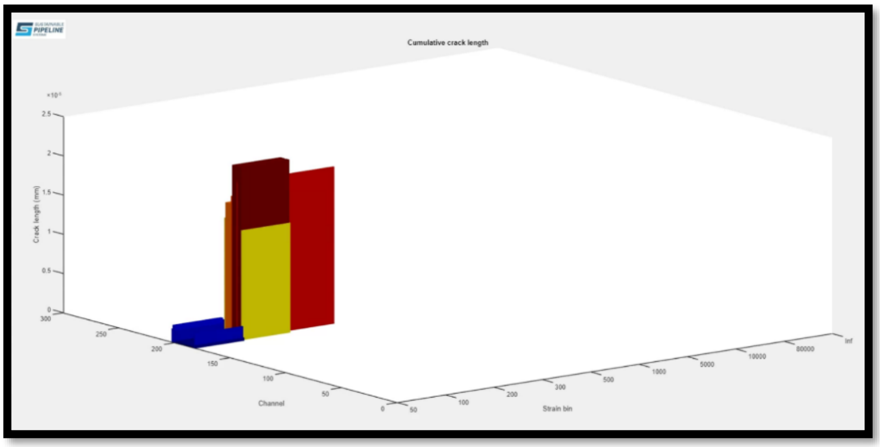


Figure 7-2: 3D Visualisation of fatigue life from the counted strain events vs pipe length position (channel number)

Fatigue life is expressed as the percentage of cumulative crack length calculated from the cycling to the failure crack length 20 mm. The Y-axis shows the fatigue life as a percentage from the counted strain events and X-axis shows the pipe length position (channel number).

Fatigue life threshold alerts can be set to alert the SPS dashboard operator and alert alarms triggered on the interrogator monitoring screens. The software algorithm was tested with simulated threats.

The fatigue life threat module software writing was successfully able to implement the design basis and described by the Technical Director of Optasense as unique and game changing technology

8 Physical testing and interpretation of strain cycling data

8.1 Tests within the elastic limit

The software development of the dashboard and the fatigue life algorithm was accompanied by a pipe testing programme so that the software could be tested on short full scale pipe segments. For bending tests a 9.5 m MASiP Pipe section was used to simulate practical field bend installations as shown in Figure 8-1 with the fibre optic system connected. The pressure / fatigue cycling trials were carried out on a shorter 2.2 m MASiP section that is mounted on a frame with end constraints as shown in Figure 8-3.

Initial tests characterised the nature of the fibre optic strain signals that represented pressure cycling and pipe bending. For the latter, a long pipe was bent through 30D and 40D bends and a model pig was developed and run through the pipe. Pigging is a common pipeline operation used for cleaning and data gathering. The fibre strain outputs successfully characterised pressure cycling, the different character of strain signals with different types of events such as a pig run, bending and pressure cycling.

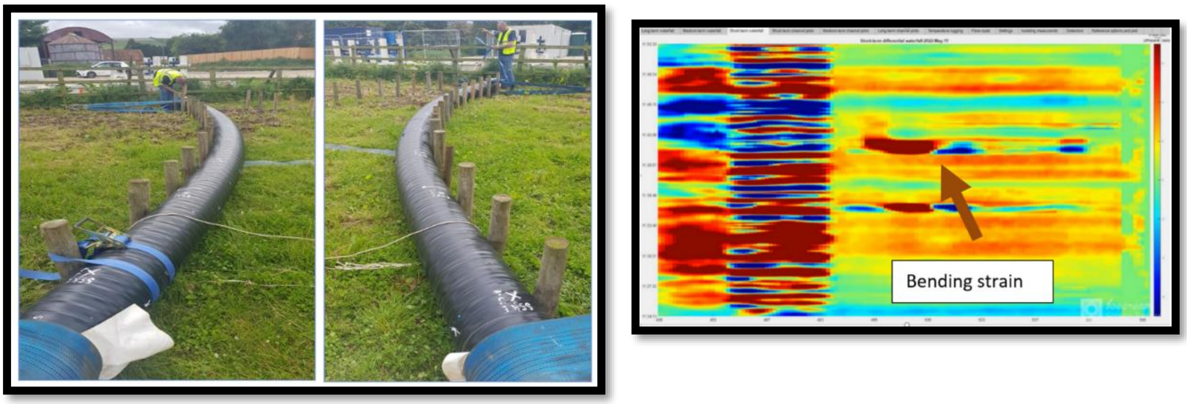


Figure 8-1: Pipe bending using wooden stakes ,measured bend angles and detection of bending strain.

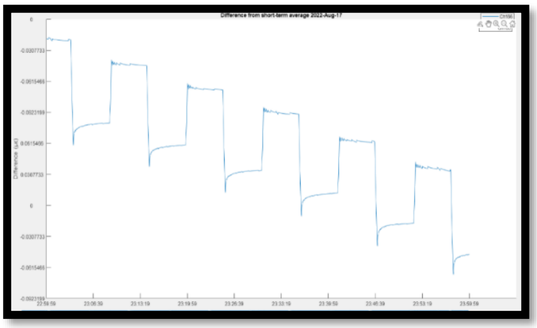


Figure 8-2 Fibre optic channel response to short pipe pressure cycling

It was concluded from these initial tests that the system does show excellent sensitivity to both internal pressure and bending.

8.2 Pressure Cycle fatigue test of fatigue life algorithm

The key test of the helical optical fibre fatigue cycle counting algorithm consisted pf running a dedicated pipe pressure cycling fatigue trial. The aim was to run a pipe section through to failure to see if there were any early warning signals that if heeded could prevent failure. The test pipe selected was an old pipe section with internal corrosion and so with a chance of failing within the limited timeframe of the tests.

Figure 8-2: MASiP Pipe 11 setup for the fatigue cycling tests.

A pressure control programme was written to apply a sequence of pressure fatigue cycles with increasing amplitude to test that the fatigue algorithm counted cycles into the right bins and also that the strain results correlated to the pressure amplitudes from the system pressure transducer.

As the test progressed, the pipe developed abnormal strain signals initially towards the centre of the pipe and physical inspection of the pipe showed that the pipe had indeed developed a severe bend.

The physical inspection showed that the pipe had lifted from the supports and twisted so that there was asymmetry in the support reactions and that there was a severe bend in both the horizontal and vertical planes of the pipe. This may normally have been enough to limit the pressure that the pipe should see but to provide a test through to failure the decision was then taken to continue cycling on to a more severe strain amplitude to see the outcome. This led to pipe failure and leakage. The strain signal character changed as the pipe got closer to the fatigue failure event. Bending was investigated after 100 cycles. The fibre strain data was corroborated by the system pressure transducer data.

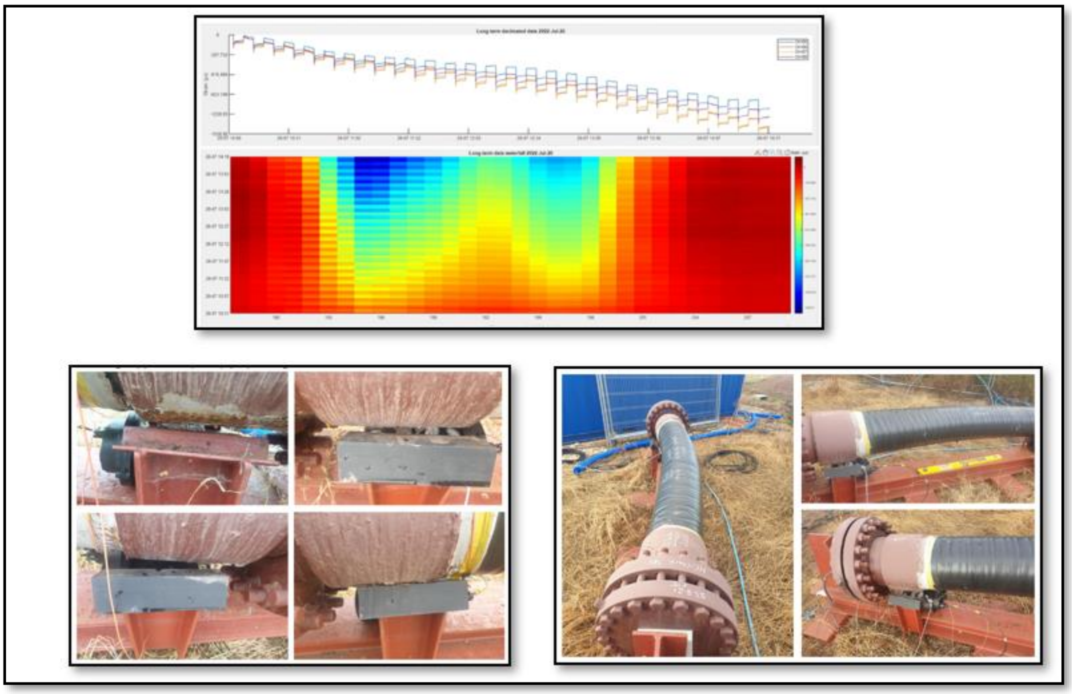


Figure 8-3: Pipe bending causing abnormal strain signals and lift off from supports.

It is concluded that the fatigue life algorithm based on helical fibre strain measurements can be used as a reliable threat alert system with good sensitivity to events affecting the condition of the pipe wall.

9 Technical Requirements for commercial deployment

9.1 Functionality requirements

This report addresses the requirements for a fibre optic based alerting system for hydrogen pipelines. An associated SPS BEIS project report addresses the end connection and pipeline handling and layout requirements for stage 2.

The lack of clear standards and regulator guidance on Hydrogen Pipeline Integrity Management is partly due to the limited experience the industry has in handling hydrogen as a fuel and gaps in validated data in steel pipelines to fully address hydrogen embrittlement issues and mitigate for fatigue cycle threats.

This section of the report addresses the requirements of a hydrogen pipeline demonstrator to become ready for commercial roll out deployment by 2025. The Helical Optical Fibre development has attracted strong interest from members of the Hydrogen Advisory Pipeline Panel who recognised the need for enhanced integrity monitoring. To quote National Grid feedback with the current technology “we are simply guessing about what is going on along the pipeline”.

The interrogator system used for this feasibility study is capable of analysing signals from up to 50km of fibre and so is suitable for use in a larger scale demonstrator although upgrades would allow a more complete system to be demonstrated for confidence in deployment for pipelines up to 100km length

The MASiP optical fibre monitoring system integrated with a Pipeline Integrity Management System enables real time assessment of associated risks and implements measures to predict, prevent and swiftly mitigate consequential failure. This proactively gathers the relevant data to enhance the reliability and operational safety of your pipelines, damage diagnosis, failure analysis, safety verifications to support regulatory compliance. Thus, specifying a suitable optical fibre distributed sensing system is an important aspect to consider in the design of a hydrogen pipeline demonstrator.

Operational Monitoring for hydrogen service: Pipeline parameters like Pressure, Temperature, Strain, Vibrations, Fatigue cycling etc. can be monitored using a combination of distributed fibre sensing interrogation systems to gather real time data along the entire length of the pipeline. However, transducers, point sensors or physical gauges may be used where applicable to provide redundancy or reference to the real time measurements to compensate for drift.

The key threat parameters measured by the optic fibre will be monitored via the SPS Dashboard for real time monitoring, integrity threat alerting and alarms for appropriate intervention. Specific integrity threat analysis tools can be further developed to utilise the archived raw fibre data, recorded based on user configurable settings to address the longer-term integrity management requirements of the hydrogen pipeline demonstrator.

The selection of the fibre optic system and adopting an efficient system design architecture is dictated by the key monitoring parameters and integrated pipeline integrity threat alert systems. A significantly large portion of data must be monitored real time for immediate / time independent threats or archived for analysis to decide on early intervention, and cost-effective implementation. This can be done by interfacing the SPS Dashboard with Advanced

Fibre Interrogation systems (OS6, QuantX), PIMS and GIS systems to enable real time monitoring real time health of pipeline and that can provide intuitive analytical tools for deep analysis to manage integrity of the pipeline.

S. No.	Parameter	Units	Interrogation method	Transducer / Sensor
Operational Monitoring				
1	Pressure	psi or bar	BOTDR	Pressure sensor
2	Temperature	Celcius or Kelvin	DTS	Temp. sensor
3	Flowrate	m3 / hr or SCFM	-	Flowmeter
4	Strain (Dynamic)	με	DAS	-
5	Strain (Static)	με	BOTDR	Strain gauges
6	Fatigue Cycling	Cycles / day	DAS	-
7	Acoustics or Vibrations	Hz	DAS or DVS	-
8	Hydrogen flux	pL/cm2/s	-	Hydrogen Flux Monitor

Table 9-1: Summary of parameters to be addressed

9.2 Optical Fibre System Features required for the stage 2 Hydrogen Pipeline Demonstrator

The Stage 2 Demonstrator needs to have the features needed to test the integrity management system Developed here on longer pipe sections and to turn the qualitative results into quantitative results required for commercial deployment.

Distributed Sensor: Distributed sensing for the full length of the pipeline is achieved by using single mode fibre optic, Multicore cable (> 3 cores) of an appropriate fibre length considering a pipe length to spiral winding ratio of 1:9.1 m (for 12” MASiP Pipe).

Interrogator Unit: The selection of interrogators shall be on the basis of the primary fibre parameters that are to be monitored. A combination rack mountable, DAS, BOTDR and DTS interrogator units shall provide a comprehensive threat monitoring solution to pipelines.

Data Processing: High reliability performance computing and predictive data analytics by combining Big Data Analytics, Machine Learning and AI.

Cloud Storage: Multi-cloud or hybrid cloud strategy, with potential to grow the network and provide various services, from large data transfers to integrated machine learning and AI.

SPS Threat Dashboard and Control Unit: User interface for real time threat monitoring, deep dive data analysis, alarm display, audio output, interfaces to external systems, etc.

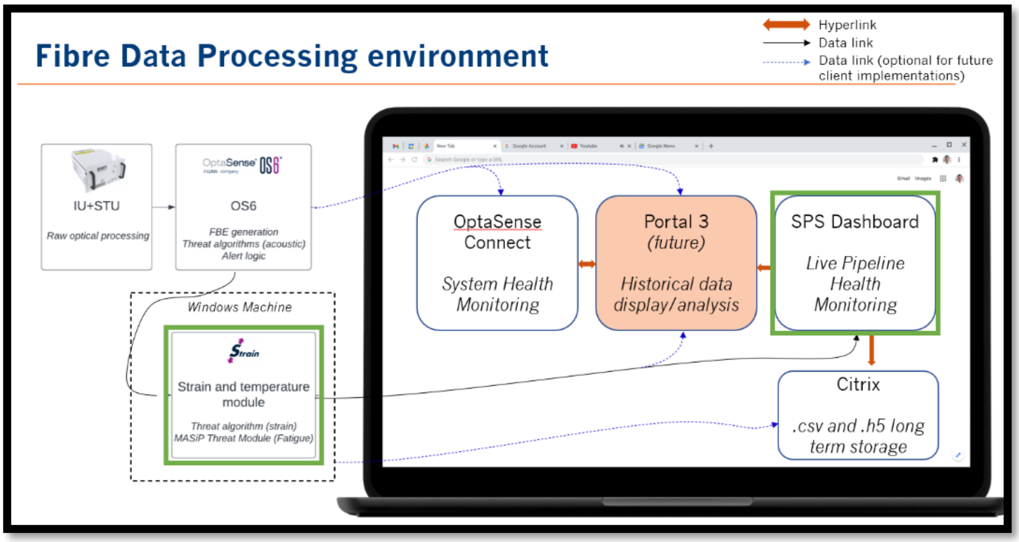


Figure 9-1: Fibre data processing environment diagram showing main external devices and cloud storage integration required for hydrogen demonstrator.

Scaling up the current fibre data processing environment for SPS dashboard integration.

- Citrix server implemented to allow long-term storage of automatically uploaded data
- Dashboard will have a hyperlink to the citrix online interface
- Citrix account secure and is managed by SPS
- Alternatively, future client installations could provide hyperlink to a client-preferred data storage instance.
- Flexible series of online modules which can be enabled on a client-by-client basis
- Control of data hosting
- SAAS based service upsell possibilities

Hydrogen Flux Monitoring

Inner surfaces of all hydrogen pipelines are exposed to high-pressure hydrogen and therefore hydrogen will permeate through the pipe walls to the atmosphere. The flux of hydrogen through the pipe wall is related to concentration gradient and diffusivity and this phenomenon cannot be avoided in hydrogen pipelines.

MASiP Pipe structure with the inner polymer liner completely eliminates direct exposure of the steel reinforcement with hydrogen inside the pipe. However low-pressure permeation through the polymer is anticipated and understood to cause negligible embrittlement risks to the steel reinforcement. By monitoring hydrogen flux rates, the concentration gradients can be maintained below threshold levels to avoid any embrittlement risks during hydrogen service.

Hydrosteel® 6500 is a hydrogen flux monitor sensor that works by the attachment of a flexible metal plate onto a pipe or vessel. Air is drawn between the plate underside and adjoining steel surface, capturing hydrogen flux exiting the steel. The sample stream is passed over a hydrogen sensor. From the sample gas flow, capture surface area, and increased hydrogen gas concentration in the air, the hydrogen flux is calculated and displayed.

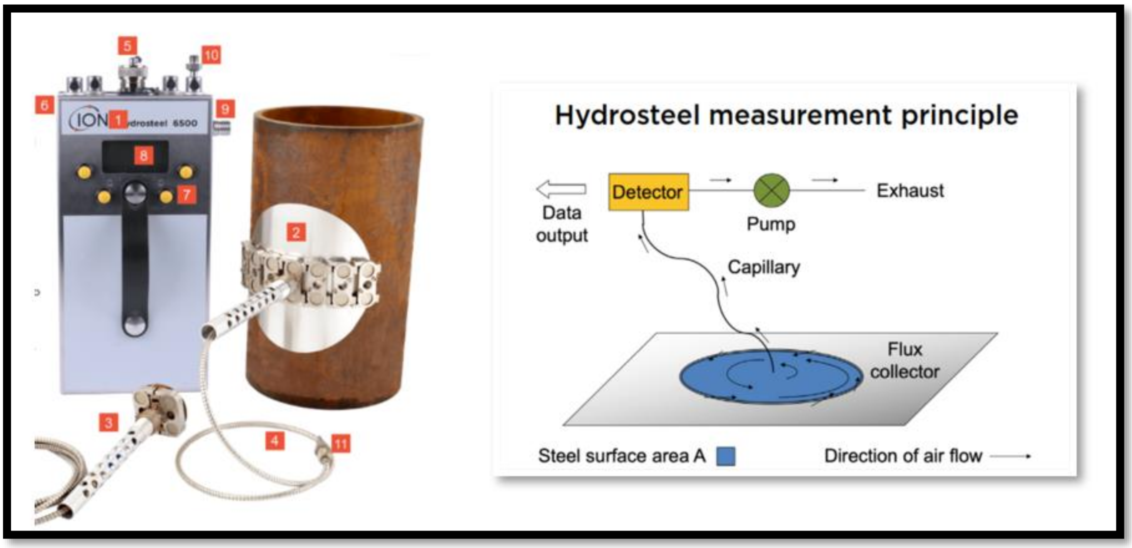


Figure 9-2: Hydrogen Flux measurement system

This is the same measurement system as being deployed by National Grid Gas in their hydrogen pipeline trials with conventional girth welded steel pipe sections. In the Stage 2 demonstrator there is provision for 5 hydrogen sensors all along the demonstrator pipeline and the data can be brought into the dashboard.

10 Project Management

The project had a short timeframe for the amount of work needed especially when supplier delivery timeframes for hardware are taken into account.

To keep project, focus a draft final milestone report was started at the outset of the project and this was added to on a monthly basis as the project work was undertaken.

The key subcontractor for writing the Dashboard software and fatigue algorithm software was Optasense and the subcontract was managed on time and within budget

There were also weekly meetings of the project team and the risk register was regularly updated.

This approach provided a flexible but focussed means for both the project manager and the project monitor to manage the project progress.

A supply chain team has been built which is ready for stage 2 and then commercial deployment

The project advanced the TRL status of the technology from TRL 4 to TRL6

The project achieved 100% completion of all milestones on time

11 Stage 2 Demonstrator – Outline

A clear commercial need for a km scale pipeline demonstrator has been established by feedback from the energy company members of The Hydrogen Advisory Pipeline Panel (HAPP). National Grid, for example, has emphasised the need for stage 2 demonstrator programme before they could roll out the technology commercially. There is considerable interest in the Helical Optical Fibre System by members of HAPP questionnaire response as a way of providing digital real time data currently unavailable to reduce the risk factor for hydrogen pipelines, improve safety and energy security.

We are developing the detailed design of the demonstrator through a series of workshops with WOOD and Peritus.

The Stage 2 demonstrator layout will bring together all elements of a realistic pipeline including end connections, valve stations, connections to different pipe diameter sizes. It will also demonstrate hydrogen storage at scale using pipeline bundles. Hydrogen flow rates and pressure capacities will also be addressed. Durability trials will use accelerated ageing techniques to determine lifetimes in a real system. Although this feasibility study has developed and tested a live digital integrity dashboard it needs to be validated on a longer pipelines system with realistic features and so the demonstrator is an essential requirement. The automated mobile nature of the system and the fact that the optical fibre is built in as part of the pipe structure also offers clear benefits in terms of reduced schedule for roll out and reduced costs of a hydrogen grid- both construction costs and lifetime costs.

A key choice for pipeline operators when developing hydrogen pipelines is the pressure at which they can be operated. Due to the different calorific characteristics of hydrogen compared to methane it is much more economic to run these pipelines at a higher pressure. Feedback from our HAPP members indicates a range of responses with operating pressure ranging from a cautious 40bar (and with only a hydrogen methane mix) to 150bar and 100% hydrogen. The higher the pressure the better the economics

Because of the power law relationship between pressure and wall thickness for increasing diameter we think that there is considerable merit in demonstrating the advantages of bundles of smaller (eg 12inch) diameter pipe rather than one large (eg 48 inch) diameter pipe which if it failed in crack growth would be catastrophic.

Conventional pipeline technology makes the use of pipe bundles somewhat difficult to deploy due to the amount of welding required. However, MASIP technology eliminates girth welding so pipe sections can much more readily built into bundles and so we think this is a system option that needs to eb demonstrated.

The features that will be included as well as bundles will also be straight and curved pipe lengths, connections including pipe connections between different diameter pipe and storage and flow characteristics.

The demonstrator will demonstrate the technology to Energy Companies operating the UK and for export opportunities overseas – especially India, France and Oman. The hydrogen advisory panel would be used as a steering committee to ensure that the detailed demonstrator design would meet industry requirements for roll out.

CO2 savings by using the MASiP Pipe technology have been characterised in an independent report by AVIECO which can be referenced. This showed about 55% reduction on CO2 from the operational benefits of using the automated in-field manufacturing that MASiP brings. We are also working with Swedish steel to offer a 73% carbon reduction by using green steel from their new steel plant in N Sweden.

Automation will increase the number of more skilled jobs and reduce the number of unskilled jobs. We expect to create 50 or so new highly skilled jobs as MASiP goes into full commercialisation but there will be a reduced demand for less skilled jobs.

The overall pipeline demonstrator layout will include both a flow loop consisting of a single pipeline with connections to various diameters and pipe bundling to demonstrate storage. This will also implement bends, tees, valves, bypass connection, swaged end connections and pipe supports.

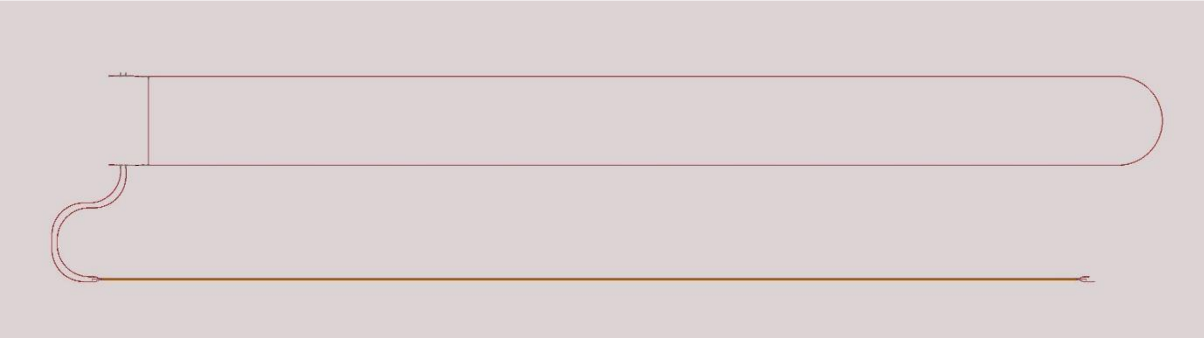
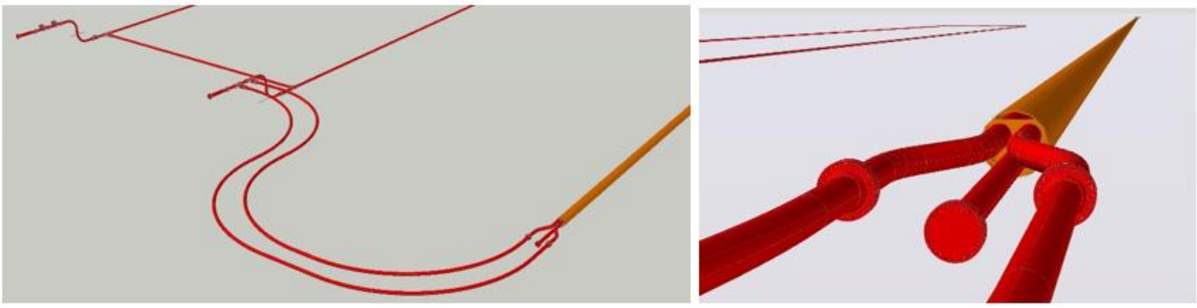


Figure 11-1 Overall layout of c 1km Hydrogen Pipeline demonstrator



After winding the steel reinforcement, the pipe can work to 40D as the minimum bend radius without degrading the pressure capability under normal conditions. This offers substantial advantages pipe laying during construction. It means that cold bend stations are not needed at all as the pipe has natural flexibility. Pipe handling trials are in progress to develop the procedures for this.

12 Conclusions and Recommendations

1. It is concluded that hydrogen pipeline systems will need an advance digital integrity management system. This project has shown that helical optical fibre monitoring is feasible as the basis of such a pipeline integrity management system.
2. The integrity monitoring dashboard system developed has been tested and this accommodates features like cycle counting and fatigue life estimation.
3. It has been found that the helical optical fibre system can provide early warning of emerging threats all along the pipeline not currently available from existing pipeline technology as acknowledged by National Grid
4. A full-scale demonstrator is planned in Phase 2 to address uncertainties, providing the data for statistically quantitative validation before commercial deployment of the technology can occur.
5. The key risks of emerging crack growth (e.g., due to the presence of hydrogen) can be detected by the optical fibre system and this has been shown by physical testing of a full-scale pipe section
6. Optimal sensor selection has been identified for application in a large-scale demonstrator. Armoured and multicore cable systems are desirable for large scale deployment in a km scale hydrogen demonstrator
7. The proposed threat alert system design based on fatigue cycle counting algorithm for cumulative crack length calculation, can be used effectively for remaining life estimation, and set as pipeline health warnings.
8. The fibre strain levels corresponding to pressure level changes can be used to classify the severity of fatigue cycle counts into different bins using a rain flow counting approach. The pipe test has shown the system to work and correctly count the number of cycles into the right strain bins and convert into cumulative life.
9. The feasibility of a fibre system for a hydrogen pipeline demonstrator including an alerting system for the key threat events was demonstrated
10. It is concluded that helical fibre strain measurements can be used as a reliable threat alert system with good sensitivity to events affecting the condition of the pipe wall. This makes it a fit-for-purpose solution as a effective real time integrity monitoring system for pipeline transportation networks supporting hydrogen fuel switching initiatives.
11. Helically winding the optical fibre within the pipe wall has enormous information gathering advantages for sensitive and high impact areas and even when the pipe is laid within steel or concrete sleeves at crossings.

It is recommended that helical optical fibre be implemented on hydrogen pipelines to reduce the risk of fatigue crack growth and that this be demonstrated at kilometre scale to ready for roll out deployment in a full MASiP pipeline operating system.