Cost Effective Pipeline Construction Design with Internal Coatings and Mechanical Interference Connections

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Various pipe-joining technologies have been developed over the years to increase pipeline lay speed and reduce installation cost. Particularly, the industry is interested to improve, or even eliminate, the welding process which is the bottleneck for pipeline installation cost reduction. Zap-Lok is a fast mechanical connection that doesn't require welding and thus can improve the lay speed significantly. In addition, it I s a repeatable process, requiring less skilled personnel and equipment. With over 40 years track record, with some 100+ km installed it is now being adopted as a relatively standard technology for marginal shallow water offshore concessions around the world. By utilizing the Zap-Lok connection, pipelay rates can be improved by a factor of 4 over conventional welding. Moreover, owing to reduction in the amount of equipment required, it enables smaller pipelay vessels, or vessels of opportunity to be used where the day rates are substantially cheaper than the conventional pipelay barge. Furthermore, by embracing internal plastic coating technology (IPC) in concert with Zap-Lok it is possible to utilize the pipe wall body for on-bottom stability and dispense with expensive concrete weight coating (CWC) thus reducing raw material costs and offshore rates further due to the increase in pipe that can be stocked on the pipelay vessel. This paper will seek to demonstrate the performance of the connection in an offshore environment, drawing upon numerical modelling and empirical data to prove it is more than fit for purpose.

Introduction

Pipeline installation cost is a major portion in overall oil and gas project development cost. Focusing on reduction of pipeline cost could potentially improve project economic return and increase end user revenue. One of the factors contributing to the installation cost is the pipe lay rate that varies depending on the lay barge capacity, the performance of the pipe joining technique used, and the weather condition.

Typically, pipe-joining process on pipelay barge consists of time consuming activities such as series of welding process at several stations, non-destructive examination, welding repair and field joint coating; with increasing time, the total project cost increases. A large installation vessel is also required to provide areas for stations in the firing line resulting in the expensive vessel day rate. Although there are several techniques developed to yield cost saving e. g. double-jointing systems, there has not been any break-

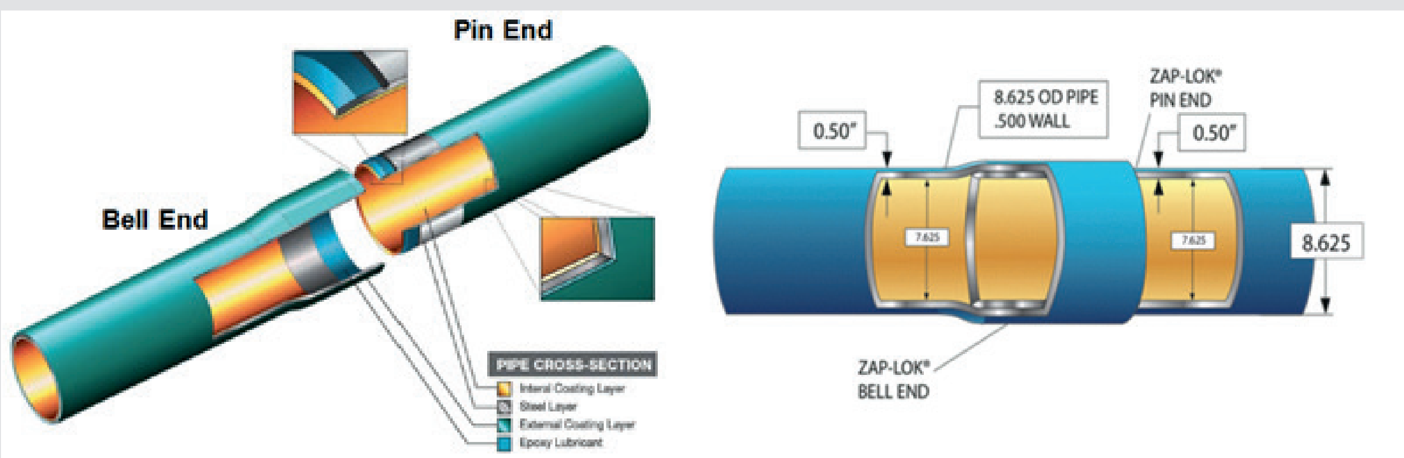


Figure 1

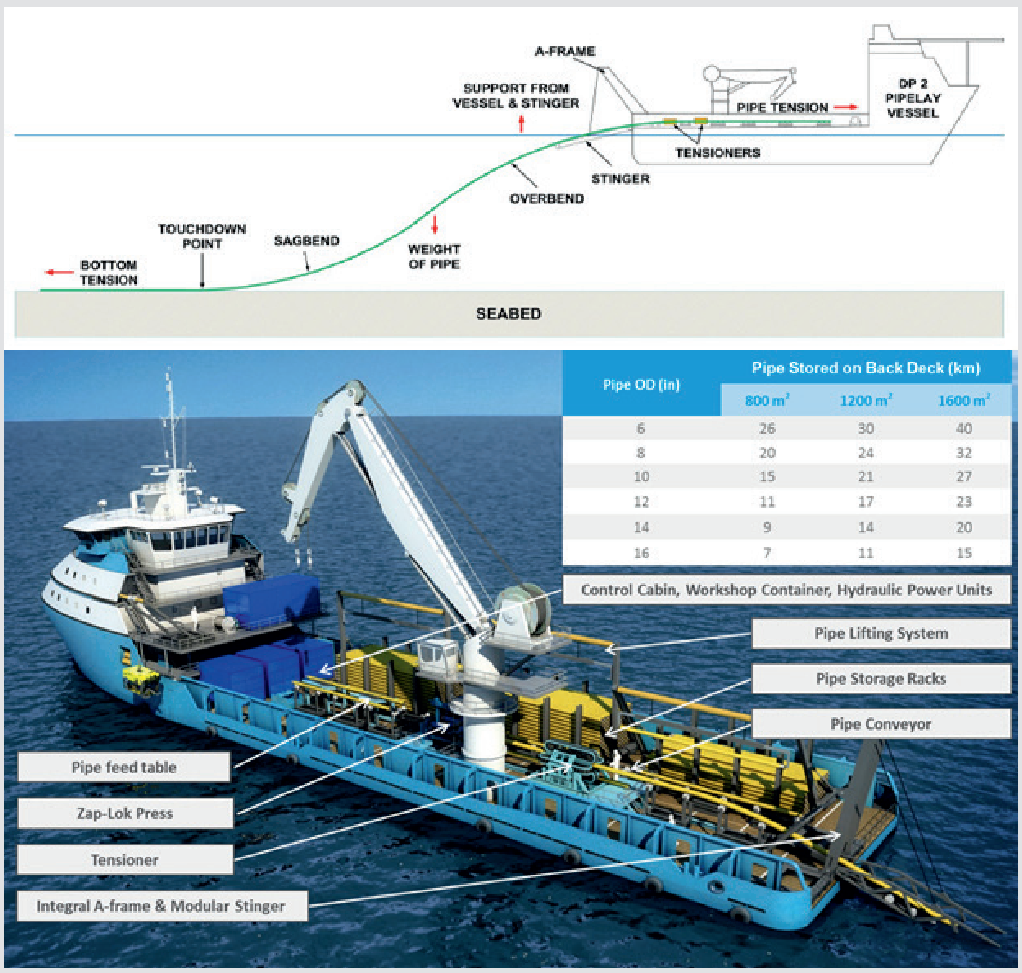
through that result in significant cost reduction – with the exception of notable operators who embrace mechanical -interference connections such as Zap-Lok.

The Zap-Lok mechanical connection was developed specifically to improve the pipeline installation time by eliminating the cumbersome pipe joining activities. The installation using Zap-Lok technology can be achieved using smaller vessels at 2-3 times the lay rate than that required by conventional girth welding.

In essence, the Zap-Lok mechanical connection is an interference connection system relying on radial compressive elastic and plastic residual stress and surface friction properties of steel caused by inserting an oversized male component (the "pin") into an undersized female component (the "bell") – see ***Figure 1***. The pipe joints are connected by inserting the pin end into the expanded bell (see Figure 1) to provide an interference fit using a mechanical press (***Figure 2***). The assembled pipe then passes through the tensioner and leaves into the sea in the same manner as the S-lay process (***Figure 3***). As previously mentioned, because the Zap-Lok mechanical connection requires less space, comparing to conventional pipe welding, for pipe feed table, press machine and tension it enables, a smaller vessel of opportunity to be used to install pipeline. In addition, non-destructive testing i. e. X-Ray, ultrasonic testing is not required after connection as it is a repeatable process.

The technique has been successfully used to install over 100,000 km of onshore pipeline and 6,500 km of offshore pipeline for several well-known oil and gas operators. Thus, this is considered as field proven technique. However, efforts to ameliorate and develop the system continue. One important point to note is that, since the Zap-Lok joint is a cold jointing process there is no Heat Affected Zone (HAZ) which is ideal for internal coating application. Enabling the feasibility of internal coating application is very useful for several reasons in pipeline design; (a) There is a reduction in all types of corrosion and erosion of the pipe bore, (b) the hydraulic efficiency of the pipe is increased significantly (20-30 %), (c) corrosion inhibitors can be eliminated and (d) the pipe wall thickness can be assured meaning that the pipe body can be used for on-bottom stability thus eliminating the requirement of concrete weight coating – in turn reducing raw material costs and permitting more pipe to be stocked on the lay vessel at sea reducing resupply costs.

Figure 2: *10-16 inch - Zap-lok Press for up to 1.000" wt and grade X65 pipe*



Pipe OD (in)	Pipe Stored on Back Deck (km)		
	800 m²	1200 m²	1600 m²
6	26	30	40
8	20	24	32
10	15	21	27
12	11	17	23
14	9	14	20
16	7	11	15

Figure 3: *Offshore Zap-Lok Pipeline Installation Schematics*

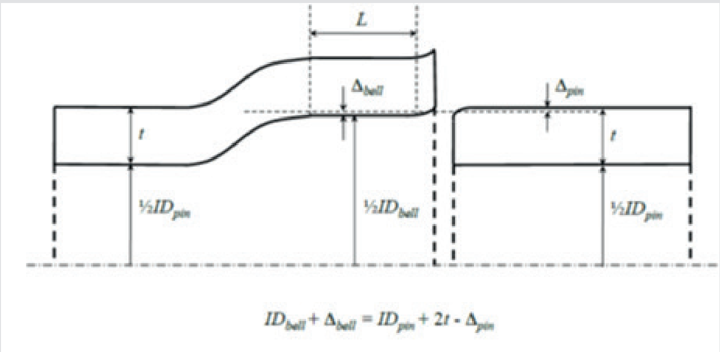


***Figure 4**: Schematic Showing Relationship between Bell and Pin Radial Growth/Shrinkage*

***Figure 5**: Stinger on Pipelay Vessel*

The Mechanical Interference Connection

The process of manufacturing the Zap-Lok connection is twofold; (i) fabrication of the ends, "belling and pinning", which can be performed at any pipe mills, pipe coating plants or construction sites since the plant is mobile and (ii) connection, that is affected in the field with presses similar to that shown in Figure 2. A specialized epoxy, called Zapoxy, is applied on the pin and bell end prior to connection process to lubricate the joint during the pressing process and to avoid galling of the steel. In consideration of ***Figure 4*** one can see the geometry of the connection whereby, and as previously mentioned, the bell inside diameter is marginally smaller than that of the pin outside diameter thus the pin will experience a residual and radial external stress. This creates a positive seal once internal pressure is applied to the connection, therefore enabling the connection to maintain the same pressure rating as the parent pipe when in service.

Thousands of mechanical tests have been performed to evaluate the capacities of Zap-Lok connection under types of loads e.g. axial tension, pressure, bending, compression, fatigue and at different temperatures and timings. Tests were carried out for several well-known oil & gas operators in order to reassure the performance of Zap-Lok connection. The results from the previous tests are summarized as below;

- » Axial Tension Capacity – The axial tension capacity of the Zap-Lok connection increases with pressure and insertion depth. The axial tension capacity is around 70-80 % of the ultimate tensile strength of the parent pipe, however this can be increased by larger pin insertion depth and being operated under pressure. It can be observed that the tension capacity is generally far greater than that of the required installation tension.
- » Pressure Rating – The pressure capacity of the Zap-Lok connection is the same as the parent pipe since it is effectively a positive seal.
- » Bending Capacity – In bending the Zap-Lok joint induces a 50 % stress concentration factor on the parent pipe so this needs to be considered in offshore laying design however within these limits it remains as strong as the parent pipe.
- » Compression Capacity – The compressive capacity of the Zap-Lok connection is the same as the parent pipe since it is effectively a positive seal.
- » Temperature Limits – The results indicated that the Zap-Lok connection is able to retain its pressure bearing integrity up to 93 °C. It is observed that there is a loss of tensile strength (without positive internal pressure).
- » Fatigue Capacity – The connection can be consistently considered as a C2 class weld.

In summary, the results from the previous tests found that the performance of the Zap-Lok connection is equal or better than that of the base material i.e. pipe body. Test results indicated that the Zap-Lok joint failure is at stresses in excess of the specified minimum yield strength of the pipe material.

Offshore Pipelay Analysis

A pipeline is generally subjected to combined loading due to bending moment and axial tension during pipeline deployment into the sea. The overbend occurs on the stinger (***Figure 5***) at the vessel stern whereas the sagbend occurs at the section before the pipeline touchdown point as shown in Figure 3. At these two regions, the pipeline will be subjected to high stresses which shall be controlled to be within the allowable limit by adjusting the stinger to control the curvature of pipeline.

As a result, the installation analysis was performed based on the conventional S-lay method to assess the impact on the Zap-Lok connection due to the combined stresses during pipelaying based on a number of installation vessels, sizes, stinger lengths, firing line set up, tensioner capacities and environmental conditions (tide, wave and curret). The different pipelay scenarios were modelled using an orcaflex software in order to outline any requirements or adjustments to allow safe installation of the pipeline using Zap-Lok mechanical connection.

The major effect of the Zap-Lok connection is that a slightly larger stinger radius is required for installation to maintain the strains and bending moments to be within the allowable limits in accordance with the relevant pipeline codes. The increasing of the strain due to Zap-Lok connection results in the increasing of the stinger radius at approximately 50 %. The pipelay tensions are relatively unaffected by the Zap-Lok connection. The typical pipelay tension for 12.75″ pipeline is approximately 25 tonnes in shallow water. For 16″ pipeline, it is approximately 40 tonnes and 20 tonnes for pipe with concrete coating and without concrete coating, respectively. It can be observed that these tensions represent only 5 % of the specified minimum yield strength of the pipeline. Thus, it can be concluded that the capacity of the Zap-Lok connection is technically satisfactory after the joint make-up is completed. The positioning of the Zap-Lok pressing machine further up the firing line of the pipelay vessel could help to maximize the joint integrity as it allows a greater length of time between the joint make-up and the commencement of the bending.

Numerical Analysis – FEA

Finite element analysis (FEA) was performed to determine the limit state behavior of the Zap-Lok connection under various load conditions. The Zap-Lok connection was modelled using ABAQUS finite element software. The analysis involves the connection make-up and installation processes in which the loads occurred could have the significant impact on the Zap-Lok connection. The detailed FEA and results are summarized in the following sections.

Connection Preparation and Make-Up

The connection make-up process consists of belling activities and pin insertion. The FEA model was used to simulate the belling process involving mandrel insertion and mandrel removal and then pin insertion. During mandrel insertion, the pipe end is plastically strained as presented in ***Figure 6***. Following the mandrel removal, there is some stress / strain relaxation which results in the marginal reduction of the bell diameter in this region, however a residual stress exists to provide connection integrity.

During pin insertion, a considerable amount of force is applied in order to drive the pin, which is slightly greater outside diameter than the bell inside diameter, into the bell. This produces a radial pressure between the pin and bell which would provide positive impact to the axial tension capacity of the Zap-Lok connection. It can be seen that the pin is under radial compression similar to external pressure and the bell is under internal pressure. As presented in ***Figure 7***, the stresses in the pin decrease

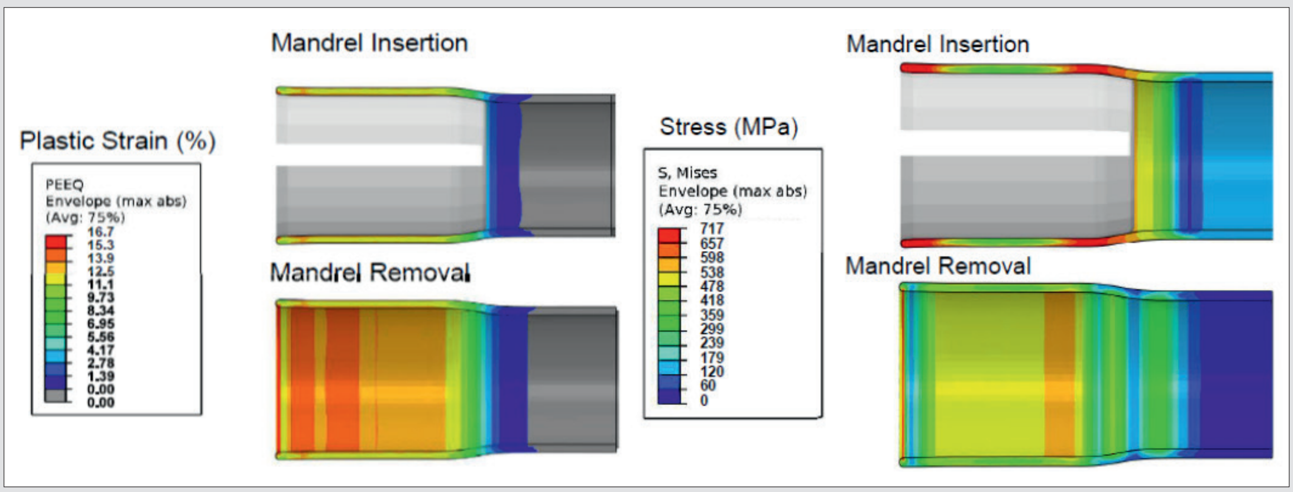


***Figure 6**: Plastic Strains and Stresses during Belling*

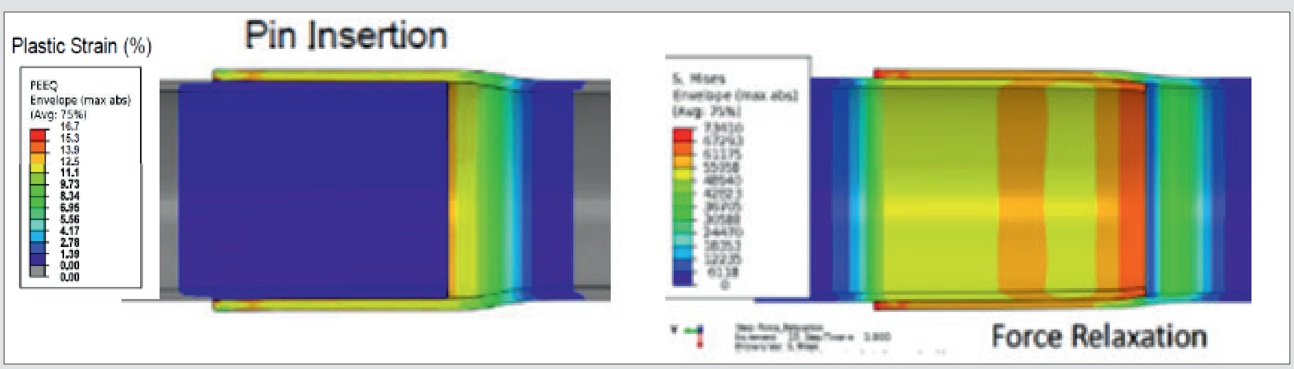
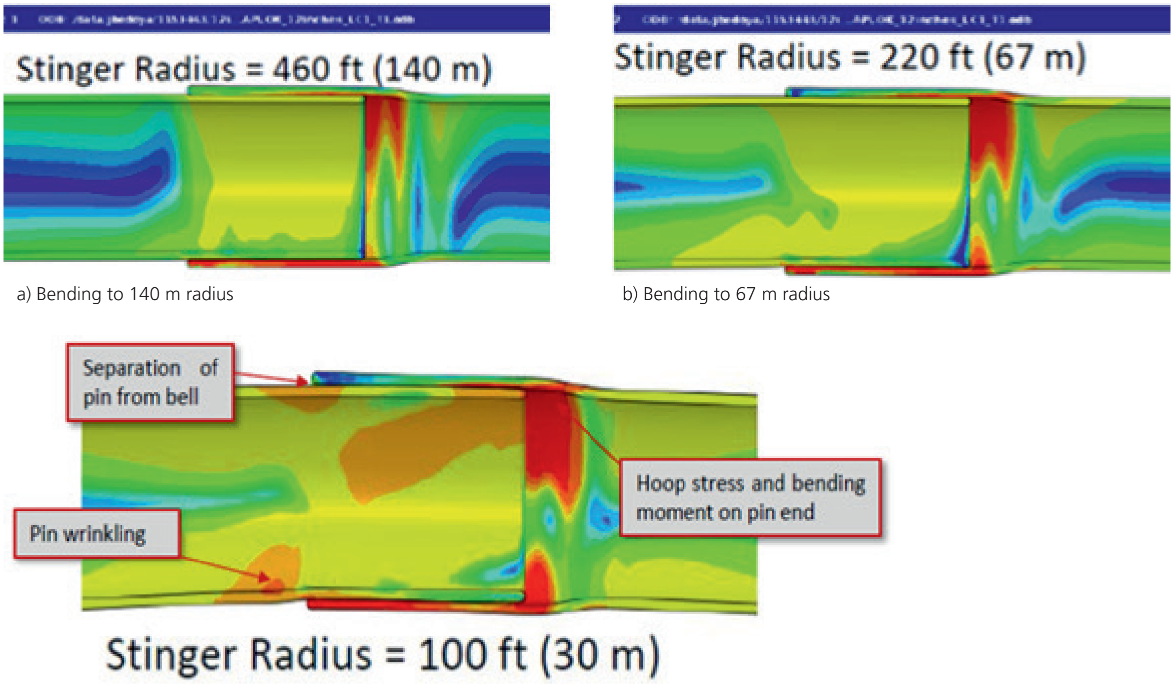


***Figure 7**: Plastic Strains and Stresses during Pin Insertion*



a) Bending to 140 m radius

b) Bending to 67 m radius

c) Bending to 30 m radius

***Figure 8** gesamt: Behavior of Connection under Buckling*

toward the end of the bell. When the internal pressure is applied to the connection, the pin is expanded resulting in the compressive strain relieving and hence increasing the radial contact force.

Installation

During the installation, the completed Zap-Lok connection make-up process then passes through the tensioner and is deployed into the sea via the stinger. At this stage, the Zap-Lok connection is subjected to constant tension loads from the tensioner and bending moments when the pipe conforms to the stinger radius. After the joint leaves the stinger, it will be suspended in the sea until it reaches the seabed. At the touchdown point, the Zap-Lok connection is also subjected to tension loads and bending moments without the support from stinger.

The purpose of these analyses was to estimate the combined bending and tension loads at which the Zap-Lok and adjacent pipe would be compromised as a result of plastic load. The bending loads in the analysis were increased by adjusting the stinger which would affect to the pipe radius of curvature. The failure mode from these loading was expected to be local buckling of the pipe or Zap-Lok.

After the make-up process was completed, a constant tension was applied on to the Zap-Lok joint model ends. The bending moment was then applied until the pipe body or Zap-Lok connection failure occurred. These simulations are in the same manner as the actual installation activities. The results indicated that a stress concentration occurs at the Zap-Lok connection referred to ***Figure 8***. It can be observed that the failure modes under the combined bending and tension are typically in the form of kinking, wrinking, ovalization and local buckling phenomenon.

It can be observed that at the limit state of curvature, deformation of the pipe at the inside surface of the pin would need to be considered in pipelay analysis. As presented in Figure 8, some wrinkling is noticed just to the left of the bell. This wrinkle causes a plastic hinge and buckle formation which is in the same manner as that of the girth weld in a welded pipeline. The load occurred on the pin end. At the outer face of the Zap-Lok joint, the separation of the bell from pin can be observed at a smaller (50 %) bending radius.

In addition to the above analysis, the different Zap-Lok geometric configurations and material properties under the various combined bending and tension loads were assessed using FEA to estimate the effect on the Zap-Lok joint integrity in the absolute worse conditions. The variation in tolerances between each joint includes pipe yield strength, wall thickness on the bell and pin ends and initial pipe ovality. The maximum and minimum of yield strengths, wall thicknesses and ovalities as allowed by the relevant pipeline codes were considered in the analysis for conservatism. The three sets of pipe tensions were applied to assess the effect of tension on the joint.

Summary of FEA

» The stress/strain concentration on the Zap-Lok connection with the nominal wall thickness, yield strength and no ovality is commonly higher than that of the welded

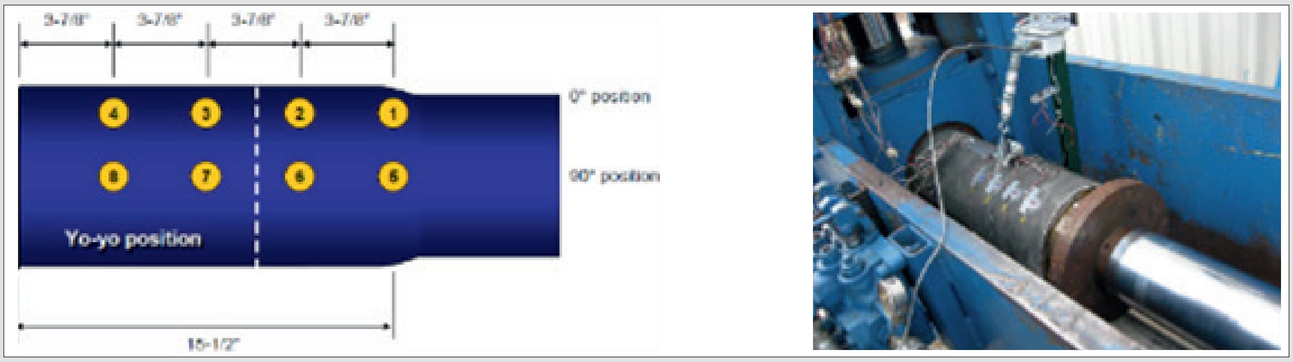


Figure 9: Belling Operation

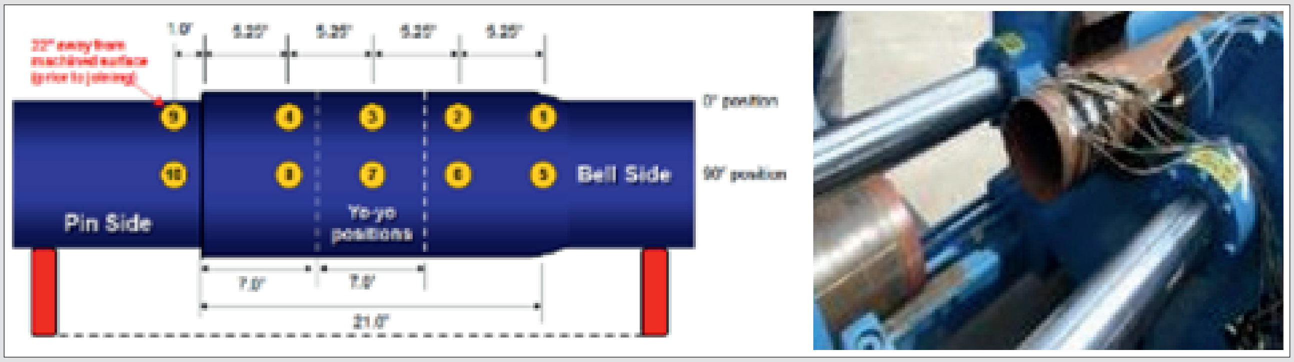


Figure 10: *Pin Insertion Process*

joint of pipeline. However, the pipe outside the connection region is subjected to the same limiting criteria as a welded pipe in terms of bending moment and strain.

- » The effect of tension on the Zap-Lok joint is minimal for the range of typical stinger radius considered in the analysis. In fact, the increasing in tension tends to increase the bending moment capacity of the pipe by reducing compressive stress which could cause wrinkling or buckling of the pipe.
- » The difference in pipe yield strength between joints can have the significant effect, however this is similar to the effect expected to occur on a welded pipeline.
- » The variations in wall thicknesses on the Zap-Lok joint does not create the significant impact on the Zap-Lok joint integrity as the strain increases in the similar magnitude as that of a welded pipeline.
- » The effect of initial ovality variations is not significant comparing with the girth weld. The mismatching of pipe ends due to the ovality variation could result in a geometric strain concentration at the girth weld. However, this is eliminated by the Zap-Lok process as the bell end is plastically deformed by the mandrel insertion to modify the initial ovality of the pipe end.
- » It can be observed that the effect of these variables is minimal. The most extreme tolerances of these variables applied on the Zap-Lok joint provide the comparable results to that of a welded pipeline.

Mechanical Testing

The FEA modelling is able to analyse a very precise and idealized conditions, however there are some physical aspects which cannot be determined by FEA. As a result, physical tests were performed in accordance with ISO 21329 to provide qualification as to the performance of the mechanical connection for application subsea for pipeline for hydrocarbon or water injection service.

The properties of pipe used in the tests are 16" x 0.656" (16.7 mm) WT, API 5L X42 with the actual yield strength of 55.4 ksi (382 MPa). The test samples include 8 bell ends and 8 pin ends. In total, there are 8 Zap-Lok connection prepared for the physical tests. The detailed procedure for testing and results are concluded in the following sections.

Make-up Tests

The make-up tests include the belling operation and pin insertion process (see ***Figure 9*** and ***10***). The strain gauges were attached on the test samples and the strains and temperatures were logged and monitored.

Robustness Tests

After completed make-up tests, the robustness tests were conducted for four (4-off) test specimens. Two specimens were subjected to cyclic tensions whereas the other two specimens were subjected to combined cyclic tensions and bending. The specimens were loaded into the test rig. The heat was

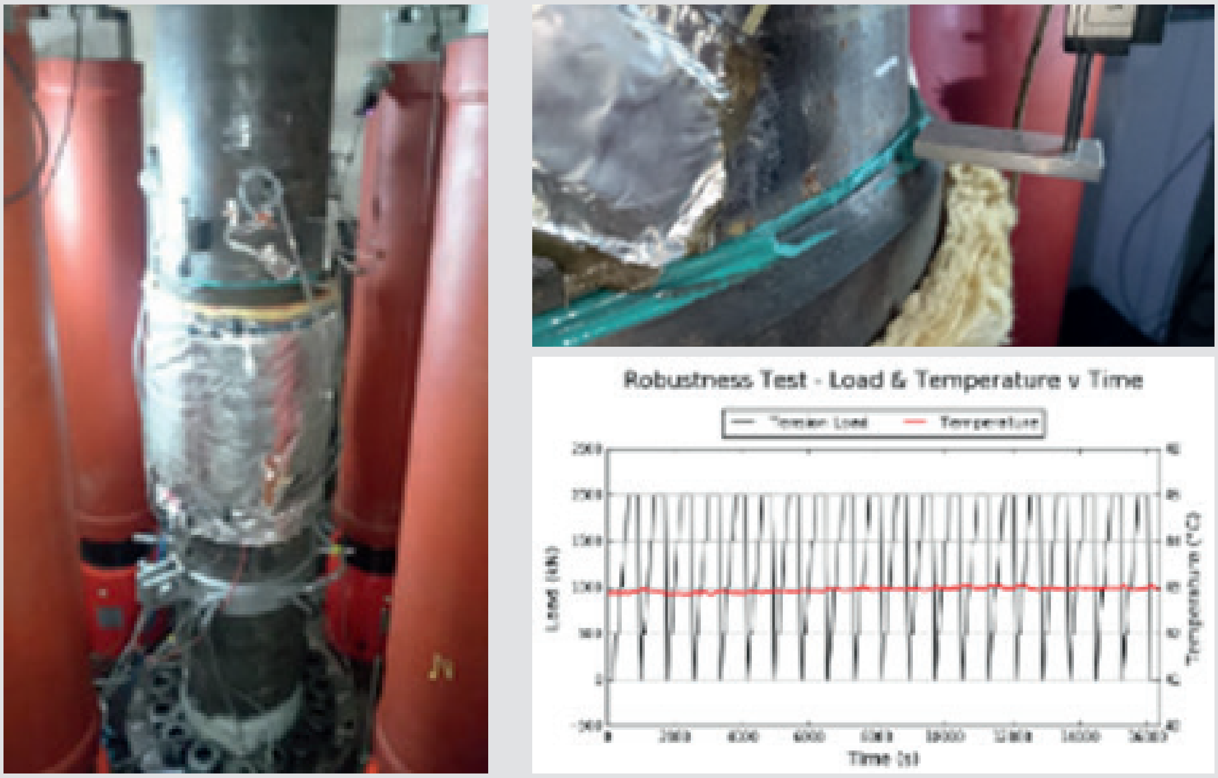


Figure 11: Robustness Tests

applied on the specimens to the temperature of 110 °F. Then, the tension was applied on two specimens and the combined tension and bending were applied on the rest. These loads were maintained for 5 minutes and then rest for 5 minutes. The step of load application was repeated for 20 times in total. Then, the heating system was turned off and the specimens were allowed to cool. This can be seen in ***Figure 11***.

Hydrotest

After the robustness tests, the specimens were removed from the test rig and placed in a pressure testing enclosure as shown in ***Figure 12***. The specimens were then subject to hydrostatic pressure at 281 bar for 24 hours at ambient temperature. During testing the pressure, temperature, strains and joint displacement were recorded. The specimens were connected to an automated system which controlled the pressure throughout the test.

Service Pressure Tests

Subsequent to the hydrotests, the specimens were subjected to either cyclic pressure testing at a constant elevated temperature or combined cyclic pressure and temperature. For a constant elevated temperature case, a suitable hydraulic fluid was filled into the specimens until the

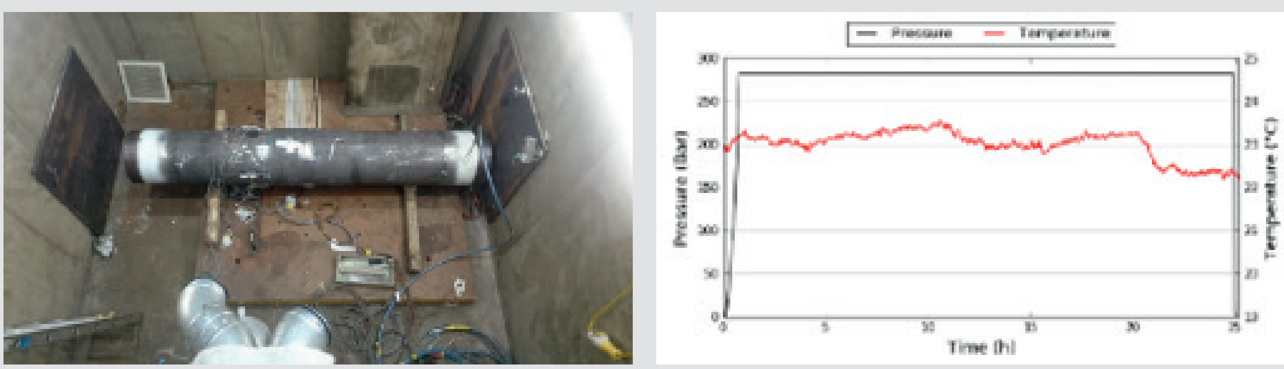


Figure 12: Hydrotest Setup

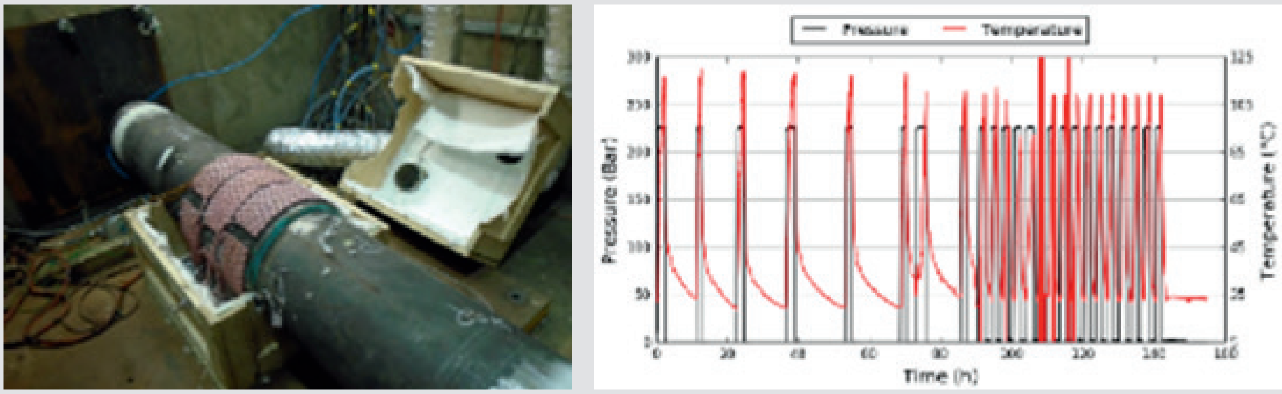


***Figure 13**: Service Pressure Tests*

pressure reached the required level. The pressure was maintained for 5 minutes and then released. The specimens were rested for 5 minutes. Then, the step of pressure application was repeated for 20 times in total.

For the cyclic temperature case, the hydro pump circuit was connected to fill the specimens with fluid until the pressure reached the required level. The pressure was maintained for 5 minutes and then released as can be seen in ***Figure 13***. The specimens were cooled by blowing cold air around the specimen and flushing the internal bore with cold water and then were rested for 5 minutes. The step of pressure application was repeated for 20 times in total. No failures occurred at this stage.

Limit Load Tests ((Subline Stufe 3 bitte))

After undergoing previous tests, each specimen was subject to a limit load test as detailed in the following sections. In addition, further limit load tests were carried out on specimens which had not undergone the previous tests.

Tension to Failure

The specimens were then subjected to gradually increasing tension load until the failure occurred. The failure can be on the pipe material, excessive movement of the joint or loss of bore pressure, whichever ensued first. The tests were carried out for both elevated and ambient temperature including with and without pressure as summarized in ***Figure 14***.

The results indicated that the Zap-Lok joint failure occurs at approximately 3,650 – 6,500 kN (372 – 663 tonnes) subject to the various load conditions. This is between 70-80 % of the parent pipe strength which is not surprising due to the fact that as you apply tension (without internal pressure) the wall thickness will thin and the interference will be lost. Nevertheless, for shallow water application the results are good and far exceed any safety factors that may be applied. To reiterate, these results are considered very high comparing with the typical tension found during pipeline installation. Again, the internal pressure could increase the axial tension capacity of the Zap-Lok joint. However, the high temperature could reduce the axial tension capacity of the Zap-Lok joint.

Specimen	Temperature	Pressure	Failure load
1	225 °F	N/A	4000 kN
9	Ambient	226 Bar	5860 kN
10	Ambient	N/A	6500 kN
11	225 °F	226 Bar	5000 kN
12	225 °F	N/A	3650 kN

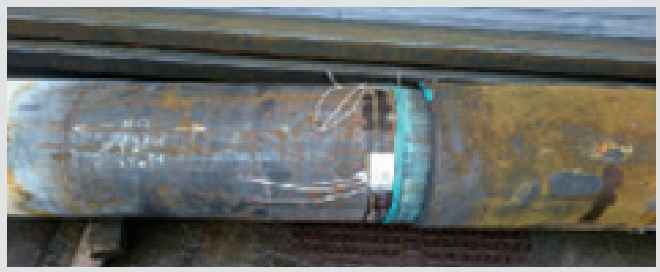


***Figure 14**: Tension to Failure*

Specimen	Temperature	Pressure	Failure load
2 13	225 °F Ambient	N/A 225 Bar	7000 kN 8000 kN
14	Ambient	N/A	8000 kN
15	225 °F	225 Bar	8000 kN
16	225 °F	N/A	6000 kN

***Figure 15**: Compression to Failure*

Specimen	Temperature	Failure Pressure
3	225°F	350 Bar
4	225 °F	370 Bar

Figure 16: *Compression to Failure*

Compression to Failure
The specimens were subjected to gradually increasing compression load until failure occurred. The failure can be in the form of buckling of the pipe material, excessive movement of the joint or loss of bore pressure, whichever happened first. The tests were carried out for both elevated and ambient temperature including with and without pressure as summarized in ***Figure 15***.
The results indicated that the failure on the Zap-Lok joint occurs at approximately 6,000 – 7,000 kN (612 – 714 tonnes).

Pressure to Failure
The internal pressure in the specimen was increased until failure occurred either by the pipe material or excessive movement of the joint – failure occurred due to joint separation, but this is due to the "end cap effect" or excessive axial loading on short samples. The tests were performed at elevated temperature as presented in ***Figure 16***.
The results indicated that the failure pressure is very high comparing the design pressure and indeed compares with the failure pressure with the parent pipe. This is unsurprising since the connection is a positive seal.

Resonant Fatigue Tests
The 2-off specimens were loaded into the test rig and then pressurized to allow for failure detection. The

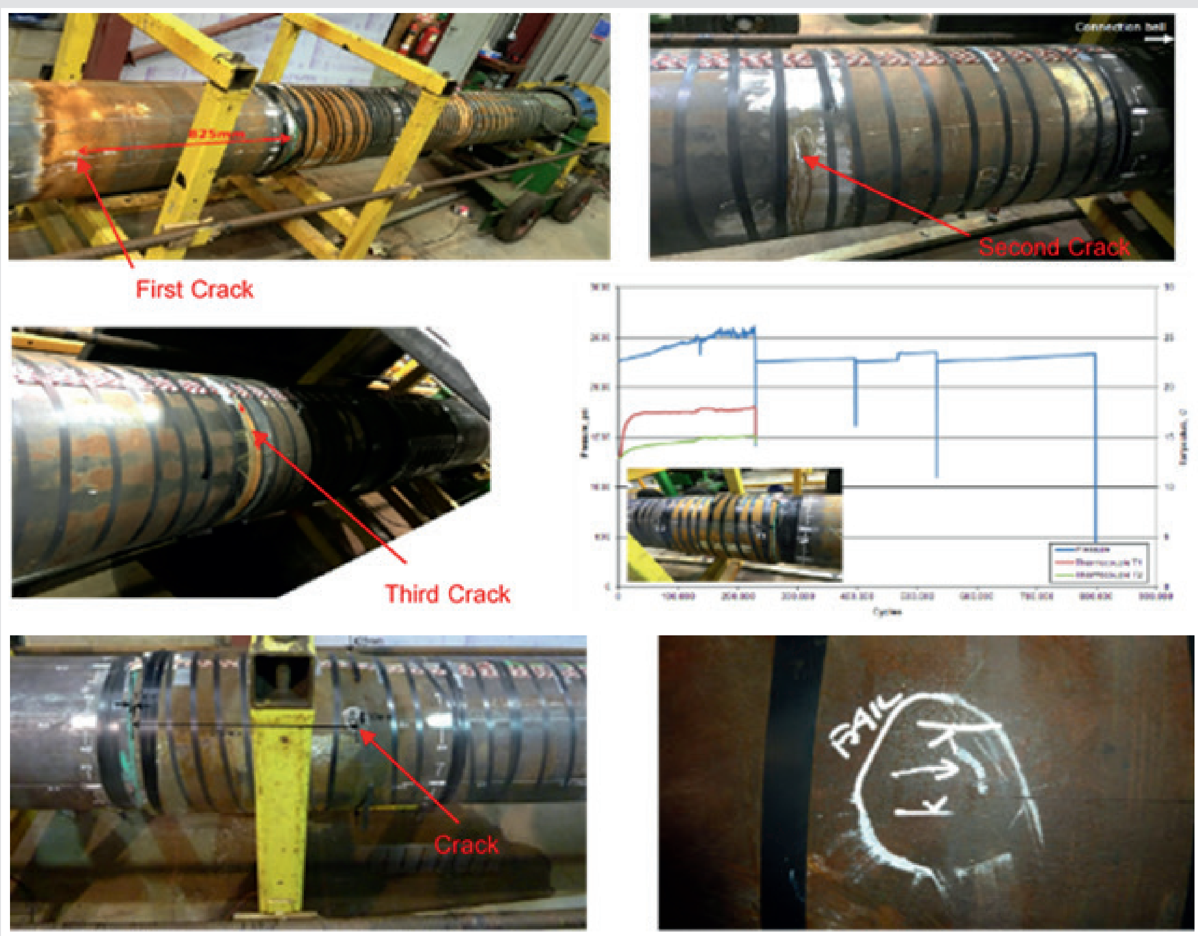


Figure 17: *Resonant Fatigue Tests*

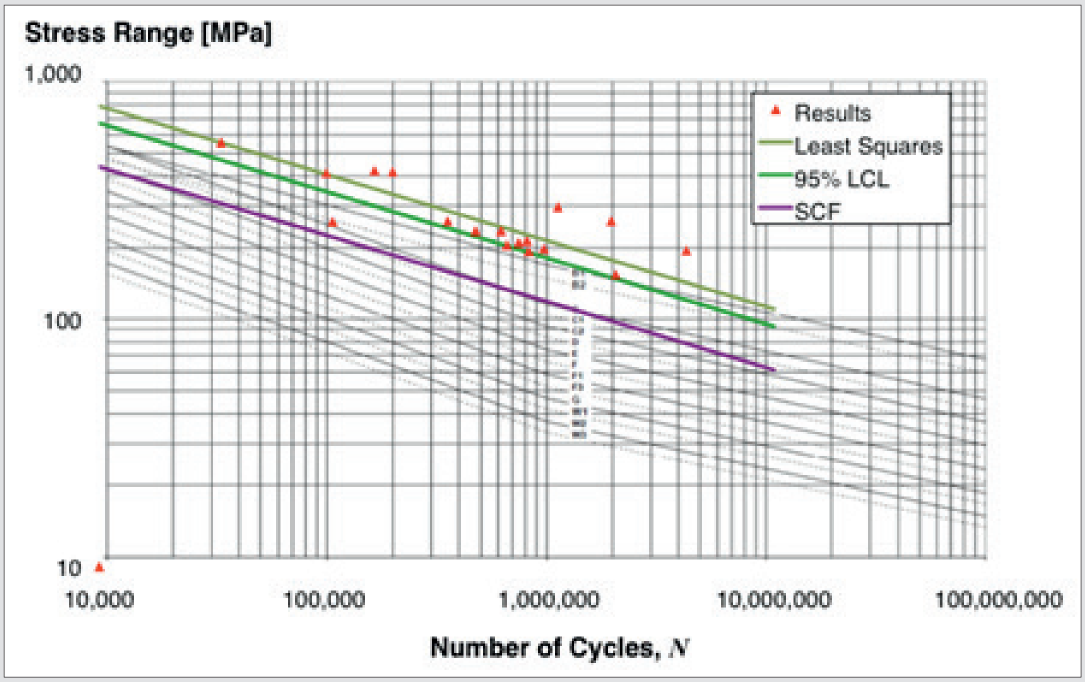


Figure 18: *S/N curve for Zap-Lok in water – derated at the 95 % LCL and then by stress concentration factor (SCF)*

motor was started, and the speed was increased until the desired stress was measured using the strain gauges. The rig set-up can be seen in ***Figure 17***. The test was monitored periodically to ensure the stress levels were being maintained. The test continued until pressure is lost in the specimen indicating that a failure had occurred. The results indicated that the girth welds are significantly less fatigue resistance than the Zap-Lok connection as the failure occurred on the girth weld/pipe body following ~ 800,000 cycles at 208 MPa. This is consistent with other fatigue tests conducted on the Zap-Lok connection as summarized in ***Figure 18***.

Cure Tests

The epoxy lubricant takes several minutes to cure and affects the coefficient of friction and thus the tensile strenght of the joint which is important during the installation of the pipe. The cure tests were carried out to test the strength of the joint 20 minutes after assembly – which is the time it takes to offload the pipe from a vessel during construction. The joint was assembled and then left for 20 minutes before being tested to failure in tension at the worst temperature that could be observed in the tropics. The results of which are presented in ***Figure 19***.

Sulphide Stress Cracking (SSC) Tests

Because the bell is cold formed and maintains some residual stress, it may be susceptible to stress corrosion cracking or in the case of sour service applications, Sulphide stress cracking, and as such it was decided to

Specimen	Temperature	Failure Load
5	Ambient	5600 kN
6	Ambient	6500 kN
7	110 °F	6450 kN
8	110 °F	7000 kN

Figure 19: *Cure Tests*

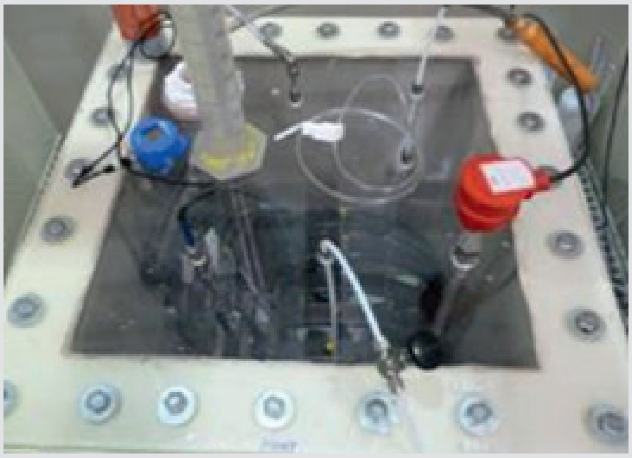


Figure 20: *SSC Tests*

test this phenomenon. The SSC tests were carried out using C-ring method in accordance with NACE TM0177 as shown in ***Figure 20***.
Further to testing, no evidence of SSC after visual, MPI and, where required, metallographic examination. All indications observed in visual and/or MPI could be traced to HIC and blister type cracking.

Third Party Inspection

Lloyds Register were engaged to review, witness and approve all the results from the Zap-Lok assessment and test program. This includes review of all the existing data from previous analysis and tests and the new data from this program. Moreover, detailing the relevant codes and standards the connection should be defined along with specific design parameters. The approval certificates have been issued in general order to permit Zap-Lok connection worldwide in accordance with accepted pipeline codes such as ASME B31.4, ASME B31.8 and DNV-OS-F101. Lloyds Register has approved the use of the Zap-Lok connection for the following conditions.

- Pipe size 2" to 16"
- Schedule 40 to 80 (wall thickness of 12.7mm to 21.4mm for a 16" pipe)
- Fatigue resistance is at least equal to that of a "D" class weld.
- Axial tension capacity limited to 70 % of code allowable stress.

Table 1: *Zap-Lok performance envelope*

Test	Average Result	Compliance
Axial Tension	> 70 % UTS	ASME B 31.4/B31.8, PD8010, DNV-OS-F101
Axial Compression	> 95 % UTS	ASME B 31.4/B31.8, PD8010, DNV-OS-F101
Internal Pressure	> 95 % UTS	ASME B 31.4/B31.8, PD8010, DNV-OS-F101
Bending	> 95 % UTS	ASME B 31.4/B31.8, PD8010, DNV-OS-F101
Fatigue–in air	D Class weld curve	BS 7608/DNV-RP-C203
Fatigue–in water	C2 Class weld curve	BS 7608/DNV-RP-C203
Stress Corossion Cracking	No reduction in strength	NACE MR0175/NACE TM0177–Method A
Crevice Corrosion	No reduction in strength	1 month exposure at 130 °F and 500 psi in brine with 1,000 ppm acetic acid, 30 % CO_2, 70 % N_2
Electrical Resistivity	±1µΩ/connection	N.B. 10 A, 25 mV FSD

Conclusion

Zap-Lok assessment and test program has been completed with positive results solidifying the notion that Zap-Lok pipe connection system is technically feasible and can be safely used offshore. Extensive Zap-Lok connection qualification programs have been carried out based on either ISO 21329 or ISO13679. Either of these codes provides the guidelines for tests to be carried out to qualify the Zap-Lok connection for use in subsea pipeline for hydrocarbon or water injection service. The tests were based on a variety of API 5L line pipe specification ranging from 2 ½" to 16" OD, schedule 40-80 wall thickness, carbon steel grade B to X65 and pipe type of ERW (Electric Resistance Welded), HFI (High-Frequency Induction) and SMLS (Seamless). The results are summarized in the table in **Table 1**.

The empirical and numerically modelled data are reassurance that the Zap-Lok mechanical connection system is technically acceptable to be applied for hydrocarbon or water injection pipelines in compliance with the industrial codes and standards.

Commercially speaking and to optimize installed costs, it is preferable to apply internal plastic eliminate the need for a corrosion allowance thus permitting the pipeline design engineer to use parent steel material as weight and then in turn negating the need for concrete weight coating. In keeping with lowering cost, it is preferable to use longitudinally welded pipe (HFI) where possible. Indeed, of the 6,000+ km installed, virtually all raw material has been either welded and not seamless.

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