FATIGUE OF GIRTH WELDS IN REELED CLAD STEEL CATENARY RISERS

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Abstract Steel catenary risers (SCRs) in deepwater developments can be subject to demanding environmental loading during service and their fatigue performance is normally limited by the girth welds. The need for transporting produced fluids containing corrosive constituents demands the use of carbon steel linepipe internally clad with a corrosion resistant alloy. Installation of SCRs by the reel-lay method has been shown to be cost effective. To date, however, reel-lay installation of clad risers has been impeded by the lack of available fatigue data specific to girth welds in clad pipe. Therefore the overall aim of the project was to develop and qualify a suitable welding procedure for internally clad pipe for SCR service and to demonstrate that the required fatigue life could be achieved after installation by the reel-lay method. A welding solution was developed based on the Auto Hot Wire PGTAW process using Alloy 625 filler wire. A clad pipe weld procedure was qualified in accordance with the requirements of DNV OS-F101:2007 and typical industry SCR specifications. Automated ultrasonic testing (AUT) was selected as the primary NDE method. A validation of the AUT inspection procedure was performed to ensure that the planar flaws of concern could be reliably detected and sized. Clad pipe strings comprising representative butt welds were then manufactured and inspected. These were subjected to a full-scale simulated reeling and installation cyclic strain procedure which was representative of pipeline installation by the Seven Oceans reel-lay vessel. These butt welds were subsequently subject to full-scale fatigue testing using high frequency resonance testing. The fatigue performance exceeded expectations, with most test samples failing in the parent material with endurances close to the Class B mean curve. This paper provides a description of the work performed and the results obtained.

1 INTRODUCTION

Steel catenary risers have been an attractive choice for deep water field development. One of the major design and fabrication challenges for SCRs is the achievement of the required fatigue performance at highly stressed regions. Additionally, the need for the transmission of corrosive constituents has demanded the use of corrosion resistant alloy linepipe materials. To date the most attractive pipe material option is the use of metallurgically bonded clad pipe. Installation of such SCRs by the reel-lay method is a cost effective approach. Up to the present time, reel-lay installation has been limited to carbon steel SCRs. The lack of fatigue test data to demonstrate the suitability of installation of clad SCRs by the reel-lay method has impeded the utilisation of this technique.

Therefore the overall aim of the project was to develop and qualify a suitable welding procedure for internally clad pipe for SCR service and to demonstrate that the required fatigue life could be achieved after installation by the reel-lay method. The three primary criteria that would verify the suitability of reeling included:

- Confirm by mechanical and corrosion testing that the girth welds made in Alloy 825 clad pipe meet the relevant industry standards.
- Confirm by physical testing that such girth welds are reelable.
- Confirm that the fatigue performance of welds made in clad pipe that have been reeled will meet or exceed the target levels of fatigue Class C/2.

The qualification programme was performed in general accordance with the requirements of DNV OS F101-2007 and typical industry SCR specifications. This programme was carried out as a collaborative project between Subsea 7 and Exxon Mobil Development Co. This paper provides a summary of the work carried out and the results obtained.

2 PROGRAMME APPROACH

The key steps in the qualification programme are listed below:

- Specification and procurement of clad line pipe material suitable for SCR service
- Development and selection of the preferred welding solution
- Perform weld procedure qualification testing in accordance with DNV OS F101 – 2007, including cyclic strain aged testing.
- Perform corrosion testing to assess resistance to both sulphide stress corrosion cracking and pitting corrosion.
- Perform fracture toughness testing to access resistance to failure during both pipe line installation and subsequent service.
- Select primary inspection method and establish an appropriate NDE acceptance criteria. Conduct a limited validation trial to show that the NDE procedure is appropriate for application.
- Fabricate and inspect pipe strings including representative butt welds in clad pipe.
- Perform simulated reeling of the pipe strings using procedure representative of pipeline installation using the Seven Oceans reel-lay vessel.
- Subject reeled butt welds to fatigue testing. Conduct post test investigations of test failures.

3 SPECIFICATION OF CLAD LINE PIPE MATERIAL

The first major step in the qualification programme was to specify the SCR clad line pipe and to procure it. The most commonly available grades of clad line pipes include:

- Stainless steel 316L clad pipe (UNS S31603)
- Alloy 825 clad pipe (UNS N08825)
- Alloy 625 clad pipe (UNS N06625)

For most SCR applications in the touch down and high stress regions, Alloy 825 or Alloy 625 clad line pipe is being specified. For the water depths under consideration for SCRs, the carbon steel element of the clad line pipe would be specified in a 450MPa grade yield strength (X65), with higher grades being considered for extreme depths.

For this specific qualification programme, material Grade 415 (which also met Grade X65 specification requirements) was identified, with an Alloy 825 metallurgically bonded liner. The nominal pipe dimensions were 263.5mm ID x 21.5mm WT and 3mm clad layer. This material was manufactured by Butting in Germany. On receipt by Subsea 7, the line pipe coating material was removed by water jet cutting which was performed by Bredero Shaw, Ellon, Scotland. Subsequently, the pipes were despatched to Butting for cutting to specific test pipe lengths. Pipe ends were then formed and counter bored in order to meet typical SCR requirements for hi/lo tolerance.

4 SELECTION OF PREFERRED WELDING SOLUTION

At the project outset, Subsea 7 proposed a welding procedure based on the use of the mechanised Hot Wire PGTAW process for the girth welding of clad pipe. Such procedures have been previously qualified and successfully applied for the Skarv Flowline project in Norway. This latter project involved the manufacture and reel-lay installation of 10” OD Grade X60 pipe with 316L internal cladding. In this case, an Alloy 625 welding filler wire was used. Subsea 7 also had previous successful experience in the use of the Hot Wire PGTAW process for the welding carbon steel SCRs, namely the BC10 and Blind Faith projects.

Installation of clad Grade X65 pipe by the reel-lay process places stringent requirements on the weld metal strength and toughness properties in order to ensure the integrity of the pipeline after installation and during subsequent service. In particular, overmatching weld metal yield strength about (0.2% PS) is normally required, which is the case of X65 pipe, is generally not less than 550MPa, depending on the actual pipe yield strength. At the present time, conventional welding of clad pipe involves making a dissimilar material weld joint, typically using Alloy 625 welding filler material. This is because Alloy 625 weld metal is tolerant to dilution by the carbon steel parent material without undue susceptibility to weld cracking. However with the use of higher strength substrate pipe material, i.e. X65 and higher, the weld metal yield strength (0.2% PS) of Alloy 625 in the as-welded condition undermatches that of the parent pipe material. However during the course of the reel-lay process, work hardening of the Alloy 625 weld metal results in overmatching weld strength (typically at a cumulative plastic strain exceeding 1.5%).

Whilst alternative welding filler wires, including 22% and 25% Cr duplex stainless steel, offered potential advantages in terms of higher strength in the as-welded conditions, these were considered to be relatively untried and unproven in production for welding clad pipe. Thus the use of an Alloy 625 filler wire was selected on the basis of the following technical justification:

- It is an established and proven solution for reeled clad pipe.
- Satisfactory weld metal mechanical properties are achievable. It was recognised that the weld metal yield strength is under matching in the as welded condition but that this strength increases as a result of plastic straining which occurs during initial reeling of the pipe. The DNV `Guideline for Design and Construction of Clad and Lined Pipe' classifies such girth welds as `partially overmatch' and recommends an assessment procedure taking this into account. Alternatively, an assessment procedure based on the use of 3D FE analysis is also permitted by the DNV Guideline.
- There is some test data to suggest that the use of Alloy 625 weld metal gives improved fatigue performance compared to C-Mn steel welds in similar pipe (Atkins et al.)

5 WELDING PROCEDURE QUALIFICATION TEST PROGRAMME

5.1 Scope of Qualification Testing

The test welds were manufactured using the Auto Hot Wire PGTAW process using the Alloy 625 filler wire throughout. A 6° J bevel closed butt joint configuration was used. Welding was performed using the Vermatt pipe welding system and in the 5G position which is representative of Subsea 7's spoolbase practices. Typical pipe welding equipment in operation is shown in Figure 1.

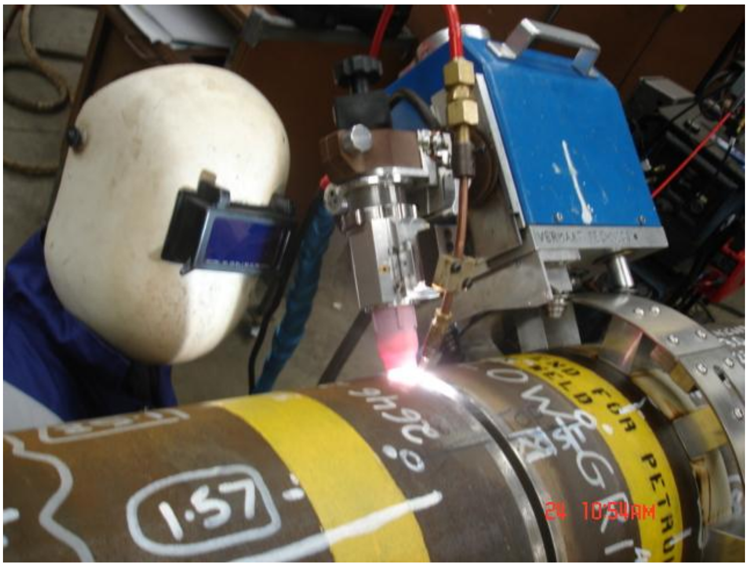

Figure 1. Typical pipe welding equipment in operation: Auto Hot wire PGTAW using Vermatt welding system

Mechanical and corrosion testing was carried out in general accordance with DNV OS F101-2007. Fracture toughness testing was performed in general accordance with DNV RP F108 and BS7910.

The scope of qualification testing and acceptance criteria are detailed in Table I.

Those test specimens tested in the strain aged condition were subject to plastic straining which was representative of the reel-lay installation by the Seven Oceans vessel. Cyclic straining of the test samples comprised three off of the following cycles ending in tension:

- Compression to 1.8% strain
- Elongation to original length (+0.2% strain in tension for final cycle)

Subsequently the test samples were thermally aged for 1hr at 250°C prior to testing.

Table I. Scope of Mechanical, Fracture Toughness and Corrosion Testing for Qualification Welding Procedure.

Tests proposed	Test standard	Requirement	Acceptance Criteria
Transverse weld tensile	DNV-OS-F101	2 specimens in as-welded condition 2 specimens in strain and aged condition	Min TS : 535 MPa Failure in PM
All weld metal tensile	DNV-OS-F101	2 specimens in as-welded condition 4 specimens in strain and aged condition	For information only
Base metal tensile	DNV-OS-F101	2 specimens in strain and aged condition	Min 0.2% PS : 450MPa
Side bend	DNV-OS-F101	4 specimens in as-welded condition	No defects on fracture face exceeding 3mm
Charpy-V notch impact	DNV-OS-F101	For both as-welded and strain and aged conditions, one set of 3 specimens to be tested in each of the following locations: weld metal CL, FL +2mm, FL +5mm. Test temperature to be -20°C	Min av : 45J Min single value : 38J
Macroexamination and hardness	DNV-OS-F101	3 traverse lines across the weld. Test to be carried out 1-2mm below the od surface, 1-2mm above the id surface and the mid-thickness position	Max value 250HV10 in weld root and 275HV10 weld fill and cap.
Fracture toughness SENT	DNV-OS-F101 / RP – F108	3 SENT specimens in the as-welded condition and notched in the weld metal and FL. Test temperature to be 0^{o}C.	
Fracture toughness SENB	DNV-OS-F101 / BS7910	3 SENB specimens in the strain and aged condition and notched in the weld metal and mid-thickness position. Test temperature to be -20°C	Min CTOD of 0.4mm No brittle failure
Corrosion testing – SSC	ISO 15156 / NACE TM 0177	Strain and aged conditions, specimen taken from across the girth weld area with steel substrate removed. Four point bend specimen. Ehra process conditions.	No cracking evident by PT and metallographic examination.
Corrosion testing – pitting	ASTM G48 – A	2 specimens in the strain aged condition. Test temperature 24°C	No pitting. Max weight loss 3.0 x 10^{-4} g/cm^2

5.2 Qualification Test Results

All mechanical test results met the required acceptance values detailed in Table I. The main results can be summarised as follows:

- All weld metal tensile (as-welded)
  0.2% PS: 481 and 505 MPa
- Transverse weld metal tensile (as-welded)
  TS: 604, 612, 631, 632 MPa
  All parent metal failure locations.
- Hardness : 275HV10 Max
  In cap weld metal

The stress strain curves were determined for the all weld metal samples. It was noted that the SMYS of the parent material was achieved following a strain level of 0.5% and the AYS of the parent material was exceeded beyond a strain level of 2.5%.

All the CVN test results met the acceptance criteria in both the as-welded and strain-aged condition, although the latter showed slightly lower values, Table II.

Table II. Charpy impact results

CVN at -20°C	As welded, J, average	Strain aged, J, average
Weld cap	138	131
FL cap	170	86
FL + 2mm cap	240	195
FL + 5mm cap	236	200
Weld root	139	143
FL root	201	198
FL + 2mm root	220	182
FL + 5mm root	254	210

A typical weld macrosection is shown in Figure 2. A detailed metallographic examination showed an absence of deleterious micro structural phases.

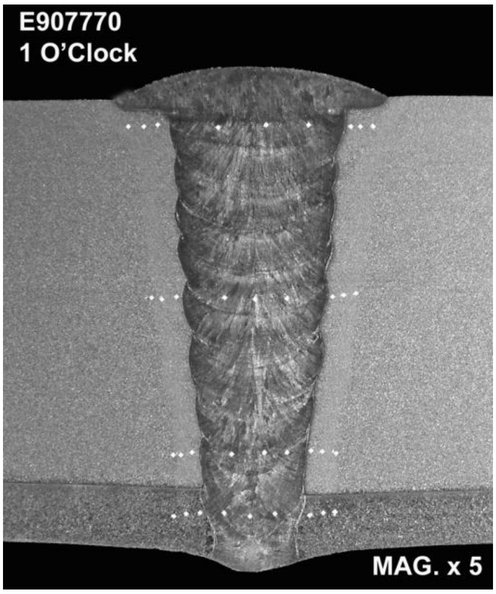

Figure 2. Typical weld metal macrosection x 5.

Fracture toughness testing was performed to demonstrate the achievement of adequate fracture resistance in the girth welds during pipeline installation and in subsequent service, whilst maintaining realistic weld defect acceptance criterion.

The SENT test provides an experimental estimate of resistance to ductile tearing under conditions of matched constraint (to weld flaws in the pipeline) for predominantly uniaxial loading. This is the postulated failure mechanism for pipeline reeling and installation. Testing was carried out with surface notches located in both the weld metal and fusion line locations, six off specimens in each case at a test temperature of 0°C. In accordance with DNV-RP-108, testing was carried out over a range of loads up to the maximum achievable in order to generate a full J-R curve, which is given in Figure 3.

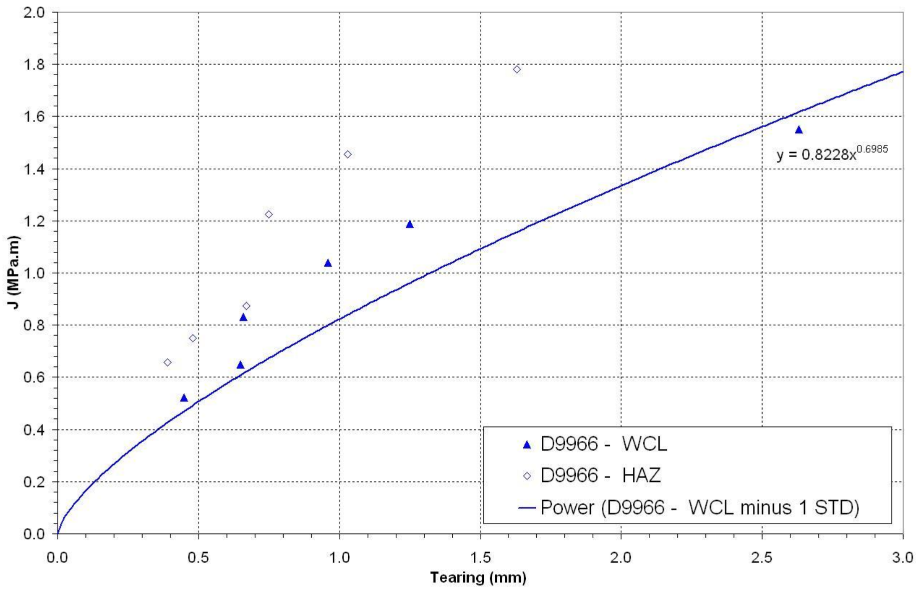

Figure 3. J-R curve for girth weld (SENT results), weld centre line (WCL) and heat affected zone (HAZ) notch locations.

All test results showed ductile behaviour. The lower bound tearing resistance of the weldment was in weld metal. The J-R curve shows a tearing extent of 1.0mm for a load in excess of 0.8MPam. This value is consistent with tearing resistance for similar Alloy 625 welds determined elsewhere.

The deeply notched SENB test provides experimental estimates of fracture toughness under high constraint conditions suited to the biaxial loading that occurs during pipeline operation at pressure. Six SENB specimens in the strain and aged condition were tested at a temperature of -20°C. Testing was carried out with notches located in the weld metal and fusion line locations, three off specimens in each case. Test specimens were surface notched for FL testing and through thickness notched for weld metal testing. Testing was carried out to a maximum load condition and in accordance with the requirements of BS7910. All the test results exceeded the target CTOD requirement of 0.4mm by a significant margin. No brittle failures were recorded.

Corrosion testing was performed to assess both resistance to pitting corrosion and to SSC. Testing was carried out on specimens in the strain and aged condition. For SSC testing purposes, the steel substrate material was removed completely by machining so that testing of the clad lining/root weld could be performed in isolation. Constant load four-point bending of specimens was performed in triplicate in accordance with ISO 15156 / NACE TM 0177. Testing was carried out at a stress level of 100% AYS. The test solution and temperature was selected to be representative of typical riser produced fluid constituent conditions:

- 1.73% H_2S/N_2 gas mix
- Target pH of 5.0 – 6.0
- Target temperature 10°C

The SSC test satisfied the acceptance criteria, i.e. no evidence of cracking detectable by PT or metallographic examination.

Pitting corrosion testing was performed on specimens in the strain and aged condition accordance with ASTM G48-A 2003. Testing was performed in duplicate at a test temperature of 22°C for a 24 hour period. Similarly, the pitting corrosion test met the acceptance criteria, i.e. corrosion weight loss below acceptance limit and an absence of pitting.

6 VALIDATION OF AUT PROCEDURE

The primary NDT method for the girth welds in clad pipe was AUT as developed and implemented by Shaw Pipeline Services. The AUT procedure comprised a multiprobe digital pulse echo technique. The weld acceptance criteria were based on a typical riser specification.

Shaw was selected as the preferred AUT contractor because of their previous experience and prior qualification for the AUT inspection of clad pipe welds for SCR applications. For this reason, the execution of only a limited AUT validation procedure was considered necessary.

This comprised the following steps:

- Manufacture of two off representative girth welds in clad pipe containing 12 off deliberate defects.
- Blind AUT inspection of the defective girth welds by Shaw personnel using the qualified procedure.
- Verification of defect type, dimension and location by a combination of IUT inspection and physical measurement by macroexamination. This was performed by SWRI, San Antonio
- Comparison of the AUT and IUT/macroexamination results.

The following conclusions were drawn from a comparison of the AUT results with those defect dimensions determined independently:

- The test samples included a total of 10 lack of side wall fusion and two lack of root fusion/penetration defects.
- All the defects were detected and sized by the AUT inspection.
- The AUT inspection overestimated the defect height in the majority of cases (~75% of defects). Compared to the IUT inspection, the difference in defect height reported by AUT was in the range of -0.6 to 1.4mm with the exception of a single lack of root fusion/penetration which was underestimated by 1.6mm.

The overall conclusion was that the results of the validation procedure gave confidence that the proposed AUT procedure could detect and size, within reasonable accuracy, planar flaws of concern.

7 MANUFACTURE OF FULL SCALE TEST SAMPLES

A total of 4 off fatigue test pipe strings were manufactured in accordance with the test specimen design shown in Figure 4. The specified dimensions were designed to suit the bending rig operated by Exova, Edinburgh, together with the fatigue test specimen requirements. The test welds are located within the pipe string such that they were in full contact with the bending former and were remote from any influence of the end fixtures.

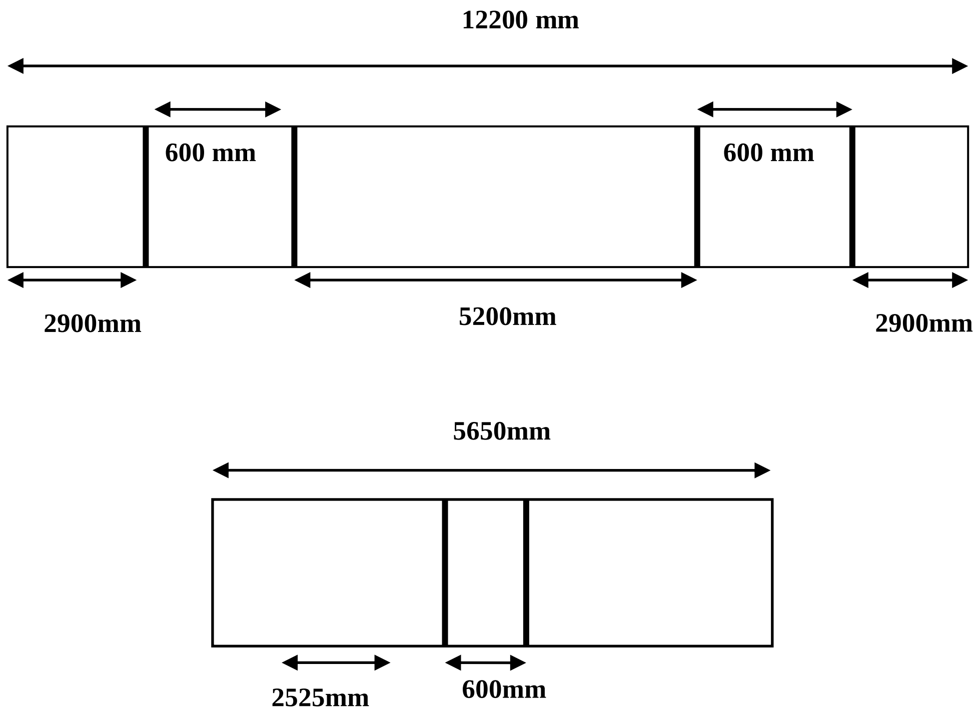

Figure 4. Pipe string and fatigue test specimen design

Each fatigue test pipe string specimen intended for reeling comprised two off fatigue specimens to give an overall nominal pipe string length of 12.2m. Each fatigue test specimen included two test welds made with the qualified procedure and subject to inspection by both MUT and AUT. The fatigue test specimen length was

5.65m. The test welds were equispaced about mid-length with a separation of about 600 - 650mm. Three off pipe strings of nominal length 12.2m were manufactured for simulated reeling. A further single string of nominal length 5.65m was manufactured for fatigue testing in the non-reeled condition.

The sequence of operations to manufacture the fatigue test pipes strings involved the following steps (see also Figures 5 - 7):

- Cutting of pipes to required test specimen length and counterboring pipe ends to be butt welded within the hi/lo tolerance required of typical SCRs.
- Dimensional checks of pipe ends.
- NDT of pipe ends including MUT and PT.
- Assembly and fit up of test pipes to butt joint configuration.
- Visual inspection and hi/lo measurements.
- Back purging of internal side in accordance with the WPS. Back purge maintained until completion of hot pass as a minimum.
- Perform butt weld in accordance with approved WPS, using the Vermatt pipe welding system.
- Perform post weld sanding procedure to remove weld cap reinforcement and any undercut associated with weld toes.
- Perform post weld NDE comprising AUT and MUT.

Figure 5. Manufacture of fatigue test pipe strings at Subsea 7, Glasgow.

Figure 6. Manufacture of test pipe Strings – girth welding in operation

Figure 7. AUT inspection of the test welds using Shaw equipment

In general, the dimensional measurements performed at the fit up stage confirmed that typical SCR hi/lo tolerance was achieved i.e. 0.5mm max.

8 SIMULATED REELING OF FULL SCALE TEST SAMPLES

The completed fatigue test pipe strings, 3 off 12.2m lengths, were transported to a purpose built simulation reeling rig at Exova, Edinburgh. This facility comprised a stiffened V-frame which can accommodate full length pipe sections. By means of winching systems, pipes can be pulled around various formers representative of the drum sizes used for reel-lay vessels. Following initial bending, the pipe is then bent around a straightening former which simulates the straightening rollers when the pipe is unloaded leaving the pipe substantially straight.

The specific reeling procedure used simulated the strains experienced with the Seven Oceans reel diameter. Forward bending was performed around a former with a radius of 9m which had been fabricated to match the hub diameter of the installation vessel reel. Reverse bending was performed against a straightening with a larger radius calculated to leave the test string substantially straight, i.e. with a radius of 50m. The 12 o'clock circumferential welding location on the pipe circumference was aligned with the extrados location on the bending former, i.e. the most likely location for weld defects was located at the position of peak plastic strain during reeling and installation only. To achieve this condition the pipe strings were subject to three cycles of bending and straightening. For the specific project pipe, a peak strain of ~1.8% was estimated, giving a total cumulative plastic strain level of 5.4%.

Photographs showing the typical pipe bending and straightening sequences are shown in Figures 8-11. Following completion of the reeling procedure, the entire test string will be visually examined for any signs of distress or damage. The reeled test samples were returned to Subsea 7 and the welds re-inspected by AUT, MUT and PT to check the integrity of the test welds. The AUT inspections showed no ultrasonic differences relative to the post weld inspections. The pipe strings were then cut to the required length for fatigue testing, i.e. nominally 5.65m.

Figure 8. Reeling string in position at start of simulated reeling cycle.

Figure 9. Reeling string fully conformed to the bending former.

Figure 10. Reeling string conformed to the straightening former.

Figure 11. Reeling string at the end of the simulated reeling cycle.

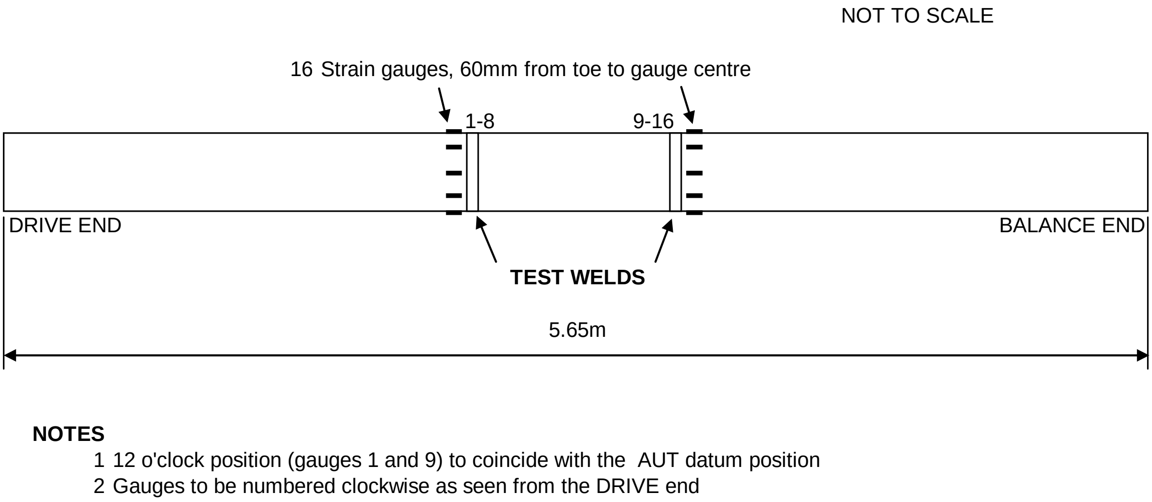

Figure 12. Instrumented fatigue specimens showing strain gauge locations.

9 FATIGUE TESTING OF FULL SCALE TEST SAMPLES

The fatigue testing procedures were performed by TWI Ltd, Cambridge. Subsea 7 supplied 7 off fatigue test strings, 6 off in the reeled condition and 1 off in the as-welded condition. Each test string included two test welds which had flush ground caps.

In order to maintain the internal pressure to generate mean axial stress, TWI manufactured and fitted end caps onto the pipe ends. These were set-on flat steel discs, secured by an external fillet weld. Each specimen was instrumented with eight single element strain gauges, adjacent to each weld, equispaced around the circumference of the pipe shown in Figure 12. The strain experienced by each gauge was logged for the whole duration of each test.

In order to create a positive axial mean stress, the specimens were filled with water and pressurised. The test pressure was 4960psi, giving a maximum axial mean stress of 86N/mm^2 based on nominal pipe dimensions. A mass tuning device was applied to correct for the effects of pipe ovality (due to the reeling procedure) and to restore the strain distribution to a pattern similar to that normally seen in non-reeled specimens.

The specimens were tested in air, at room temperature, in TWI designed resonance fatigue machines. A rotating alternating bending moment is applied at the resonant frequency of the pipe, typically 25 – 30Hz which enables high cycle testing of girth welds to be carried out rapidly. The test speed was finely controlled to achieve a constant stress range throughout the test, and set so that the average of the strain gauge readings corresponded to the required stress range. Two specimens (four welds) were tested at each of the three stress ranges in Table III.

Table III. Fatigue test stress ranges.

Category	Stress range, N/mm^2
High	240
Medium	170
Low	120

Additionally the non-reeled sample, comprising two test welds, was tested at the medium stress range.

During testing, in the event of a through-wall failure, the fatigue test was stopped automatically by the detection of the drop in internal pressure. Post test the specimens were drained of water and rings of pipe containing the welds and cracks were cut from each sample. For welds, at each of the strain gauge positions plus the crack initiation position (if different), measurements of pipe wall thickness either side of the weld and the axial misalignment in the root were taken.

The fatigue cracked sections were then cut out and broken open to expose the fracture surfaces. These were photographed and inspected visually to determine (where possible) the precise point(s) of crack initiation and the presence of any significant initiating defects.
After first failure, in order to continue testing of unbroken welds, the failures were cut out and the strings repaired by Subsea 7 using the same procedure as that employed for the test welds.

At the project outset the qualification target was BS7608 Class C design divided by two on life, i.e. Class C/2. In order to qualify the test results, 12 off test welds had to achieve a mean curve of 3.20 x design life, as given by Maddox and Schneider (2003).

The test welds performed well during the test programme and the majority of failures were in the parent material. It was therefore decided that the Class B curve was a more appropriate comparator than Class C. The run-out target was chosen to be a factor of 3.20 times the Class B design life. The target and run-out endurances are given in Table IV below. Note that the targets used in the test program were calculated for the actual stress ranges experienced during the tests.

Table IV. Fatigue test target endurances.

Stress Range	Class C/2 design life, cycles	C/2 target life, cycles	3.20 x Class B design (run out target), cycles
High	98,750	316,000	974,150
Medium	330,150	1,056,480	3,869,690
Low	1,117,300	3,575,360	15,586,420

The S-N curves derived from analysis of the fatigue test results are presented in Figures 13-16, where the results for unfailed welds, weld failures and parent material failures are plotted separately. Of the 24 welds tested, there was only one weld failure (which failed from the weld root), 13 unfailed welds and ten parent material failures.

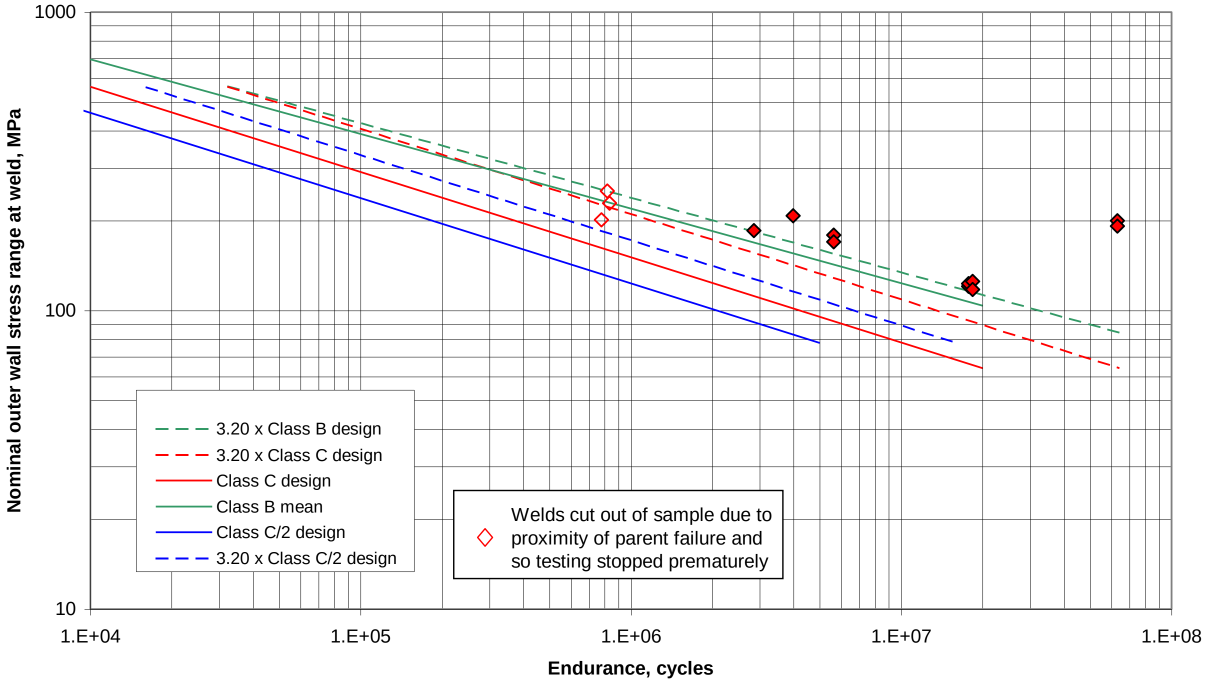

Figure 13. All unfailed test welds plotted using average nominal outer wall stress range.

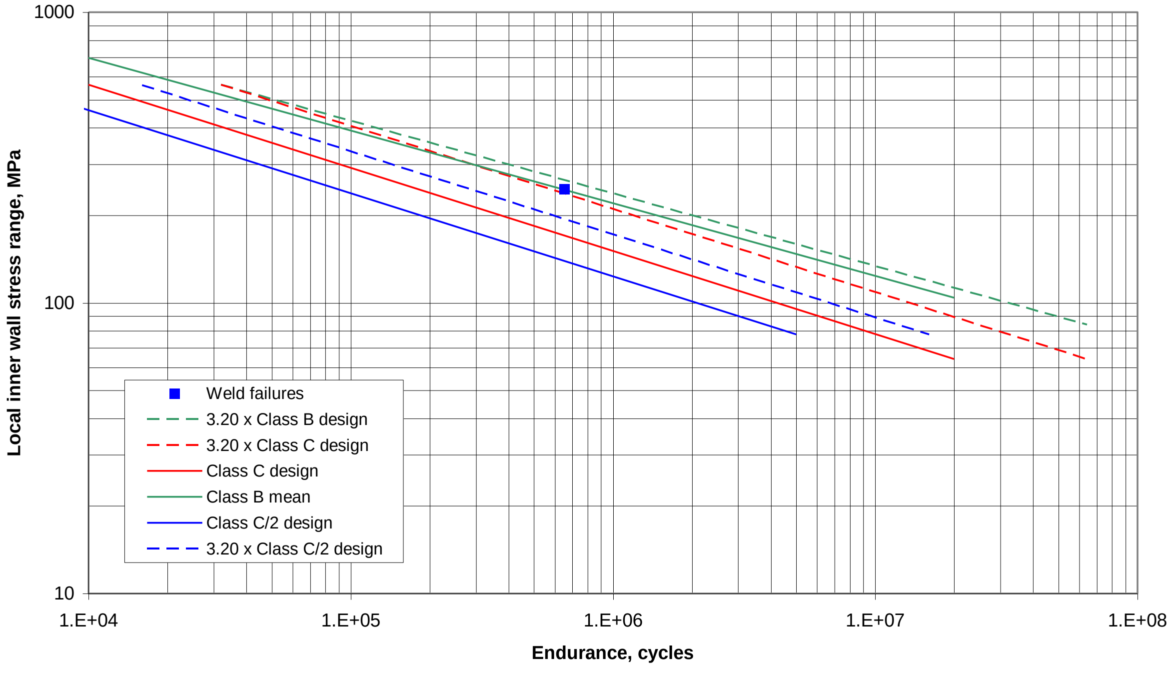

Figure 14. The single weld failure, plotted using the local inner wall stress range.

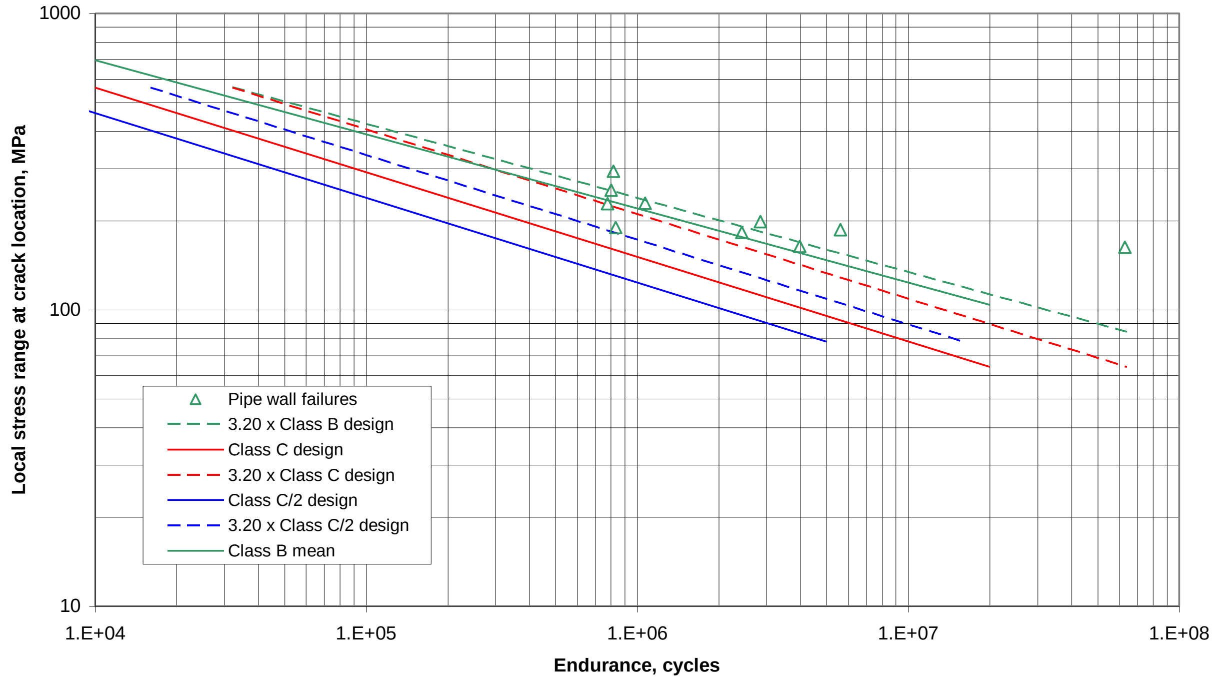

Figure 15. Parent material failures, plotted using local stress range.

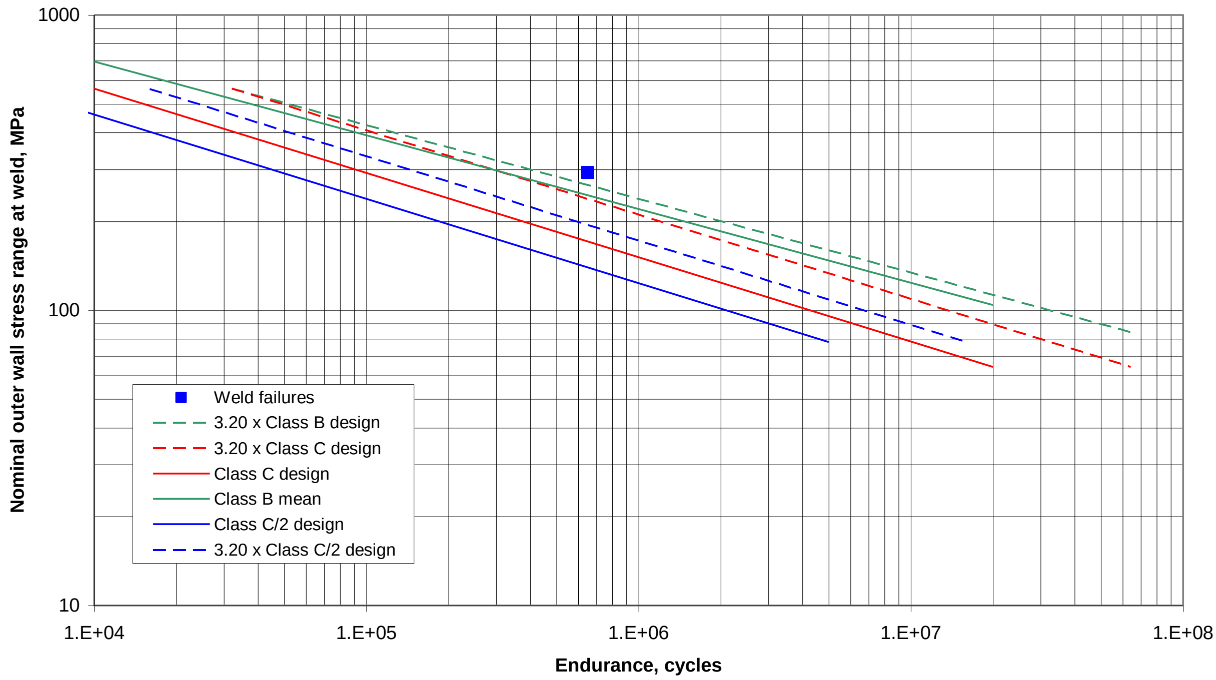

Figure 16. Weld failure plotted using average nominal outer wall stress range.

All welds passed the Class C/2 target and almost all welds passed the Class B mean curve. The only welds that did not pass the Class B curve were which could not be tested fully because they were in close proximity to adjacent parent material failures.

Six of the parent material failures occurred at 12 or 6 o'clock. This is also the reeling axis (the extrados was located at 12 o'clock and the intrados at 6 o'clock). This suggests that the reeling process influenced these parent material failures, and this suggestion is supported by the long endurance exhibited by the un-reeled sample.

Typical fracture faces for parent metal failures are shown in Figures 17 and 18.

Figure 17. Fracture face and associated surface indentation at the crack initiation position in a parent material failure.

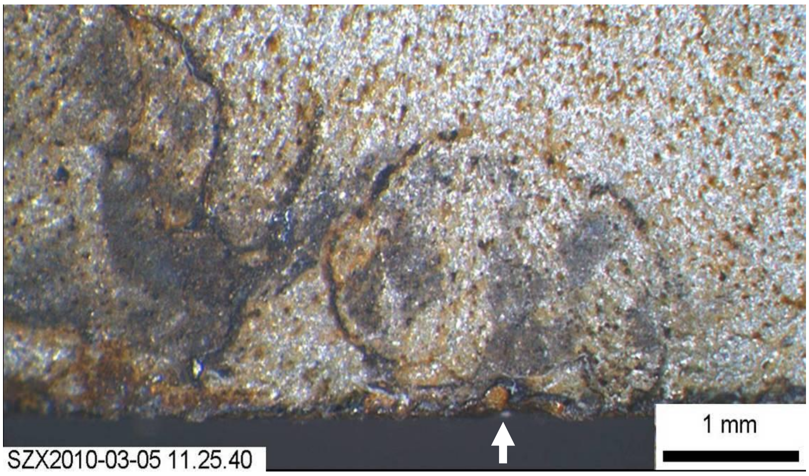

Figure 18. Sub-surface flaw at the crack initiation position in the first parent material failure in S1A.

The results demonstrate that the fatigue strength of the test welds was generally equal or superior to the parent material. The conclusions drawn from the test programme were as follows:

- All of the welds tested passed the target life of Class C/2 design by a large margin.
- All welds (with the exception of those which could not be tested fully due to adjacent parent material failures also passed the Class B mean.
- The unreeled sample achieved a very high endurance of over 63 million cycles.
- There were 10 parent material failures and only one weld failure (from the weld root).
- The parent material failures tended to be at either 12 or 6 o'clock and are likely to have been influenced by the reeling process.

10 DISCUSSION

At the outset, the project aimed to dispel industry concerns regarding the suitability of reeled clad pipe for SCR applications. Whilst successful production experienced has been demonstrated for carbon steel SCRs, there was a lack of fatigue performance data for reeled clad pipe. The results showed that the effect of reeling impacted on fatigue performance which was evident when comparing the fatigue performance in the as-welded and reeled conditions. However what is important to note is that the fatigue performance of the reeled samples with girth welds in the ground condition far exceeded typical SCR requirements, ie Class C/2. Indeed the majority of the test welds gave fatigue lives around the Class B mean curve and were often limited by the parent material performance. This qualification programme gives confidence that the fatigue performance of reeled clad pipe satisfies the requirements of SCR applications with a significant safety factor. Furthermore all other SCR requirements in terms of weld integrity and mechanical and corrosion performance were also comfortably achieved.

11 CONCLUSIONS

The overall aim of the project was to develop and qualify a suitable welding procedure for internally clad pipe for SCR service and to demonstrate that the required fatigue life could be achieved after installation by the reel-lay method.

The following conclusions can be drawn:

- The preferred welding solution is based on the Auto Hot Wire PGTAW process and Alloy 625 filler wire for applications where the maximum fatigue performance is needed.
- The welding procedure qualification programme performed in general accordance with DNV OS F101, satisfied the acceptance requirements for mechanical testing.
- SCC and pitting corrosion testing performed as part of the qualification programme satisfied typical SCR requirements.
- Fracture toughness testing, both SENT and SENB showed ductile behaviour which, satisfied typical SCR requirements.
- Validation of the AUT procedure gave confidence that planar flaws of concern can be reliably detected and sized. Inspection of the test welds showed that they met the defect acceptance criteria for typical riser specifications
- All the test welds in the reeled condition passed the Class C/2 target fatigue life and almost all welds passed the Class B mean curve.

It is considered that the qualification programme performed and results obtained satisfy typical industry specifications which are required to demonstrate the suitability of welded and reeled clad pipe for SCR applications.

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13 NOMENCLATURE

AUT	Automated Ultrasonic Testing
AYS	Actual Yield Strength
CRA	Corrosion Resistant Alloy
CTOD	Crack Tip Opening Displacement
CVN	Charpy V-Notch
DNV	Det Norske Veritas
FEA	Finite Element Analysis
FL	Fusion Line
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
IUT	Immersion Ultrasonic Testing
MUT	Manual Ultrasonic Testing
NDE	Non Destructive Examination
PGTAW	Pulsed Gas Tungsten Arc Welding

PS	Proof Stress
PT	Penetrant Testing
RT	Radiographic Testing
SCR	Steel Catenary Riser
SENB	Single Edge Notch Bend
SENT	Single Edge Notch Tensile
SSC	Sulphide Stress Corrosion
SWRI	Southwest Research Institute
TS	Tensile Strength
WM	Weld Metal
WPS	Welding Procedure Specification

14 REFERENCES

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