

The Suitability of CRA Lined Pipes for Flowlines Susceptible to Lateral Buckling

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Duncan Wilmot, Technical Manager, Cladtek International, Australia
Paul Montague, Managing Director, Cladtek International, Australia

Abstract

CRA lined pipes are a proven and economical solution, widely used for pipelines operating at moderate temperatures. However, increasingly, CRA lined pipes are being considered for HPHT fields where the flowlines operate at high temperatures and are susceptible to lateral buckling.

This paper presents results of testing performed on 24" CRA lined pipe under typical HPHT conditions including high temperature, high axial compressive strain and low internal pressure.

Testing confirmed that strains exceeding DNV design guidelines could be applied without incurring localised wrinkling of the CRA liner.

The results validate the use of CRA lined pipe for HPHT pipeline systems

1. Introduction

Corrosion Resistant Alloy (CRA) lined steel pipes are an established and economical solution to the problem of transporting corrosive multiphase fluids between well heads and processing facilities for onshore and offshore oil and gas fields.

For offshore fields, the use of CRA lined pipe has largely been limited to pipelines that operate at moderate temperatures or to pipelines that operate at elevated temperatures and that are highly constrained in order to prevent lateral pipeline buckling. However, with the increasing development of High Pressure High Temperature (HPHT) fields, there is a growing demand to utilise CRA lined pipes for flowlines that are designed to operate at high temperatures and in conditions where the pipeline will be subjected to lateral buckling.

The demand to use CRA lined pipe for these flowlines is driven by the significant commercial benefits that can be realised: CAPEX is substantially reduced as CRA lined pipe can cost 30-60% less than comparable CRA clad pipe and project schedule is improved as the market for CRA linepipe is opened up to more manufacturers.

However, in the case of CRA lined pipe, as the bonding of the CRA liner to the backing steel is mechanical, the pipeline design needs to consider limit states for the onset of liner wrinkling, particularly for flowlines where there will be high levels of axial compressive strain. In order to address this, Cladtek initiated a programme of testing on NPS 24 diameter CRA lined pipe.

The aim of the test programme was to validate the proposal that NPS 24 CRA lined pipe was suitable for use in high temperature flowlines susceptible to lateral buckling.

This paper outlines the test methodology and presents results derived from the testing.

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2. Test Programme

A detailed test programme with representative test parameters was developed after consultation with engineering and operator companies. The test programme takes account of offshore HPHT flowline design conditions and has some key features:

- NPS 24 (609.6mm OD) SAWL CS Outer Pipe
- Test Pipe with 2 Girth Welds
- Simulation of Pipeline Coating
- Installation Condition Testing
- Pipeline System Pressure Test
- Operating Condition Testing
- Start-Up/Shut-Down Condition Testing

The test pipes were manufactured by Cladtek using 24" x 24.3mm SAWL carbon API 5L-X65 steel pipe that was lined with 4mm thick 316L UNS S31603 liner pipe (Table 1). The materials used (CS SAWL pipe and 12m 316L sheet) were not manufactured with properties and finish optimised for CRA lined pipe but were standard materials sourced from stockists. The test pipes were manufactured in line with DNV OS-F101 [1] using controlled hydraulic expansion.

Test Pipe	Requirement
CS pipe OD (nominal)	NPS 24 (609.6mm)
CS pipe WT (nominal)	24.3mm
CS material grade	API 5L X65 SAWL
CRA thickness (nominal)	4.0mm
CRA material grade	316L (UNS S31603)

Table 1: Test Pipe Materials

The mechanical properties of the materials are shown in Table 2.

Material Property	Sample Test Result
Carbon Steel Pipe (Base Metal Transverse)	
Yield Strength $R_{t0.5}$	520 MPa
Tensile Strength R_m	620 MPa
Elongation	45%
Carbon Steel Pipe (Cross Weld - Seam)	
Tensile Strength R_m	668 MPa
CRA Liner (Base Metal Transverse)	
Yield Strength $R_{t0.5}$	319 MPa
Tensile Strength R_m	640 MPa
Elongation	55%
CRA Liner (Cross Weld - Seam)	
Tensile Strength R_m	629 MPa

Table 2: Test Pipe Mechanical Properties

The pipe ends were sealed using 75mm of 309LMO weld overlay cladding with the inside diameter machined (tolerance ± 0.5 mm) after cladding. Hot wire GTAW (TIG) was specified for the weld overlay cladding as this process produces an overlay weld with a narrow fusion line, minimal penetration of the CS base, reduced iron dilution, fewer lack of fusion defects and the reduced heat input results in lower residual stress and reduced thermal distortion.

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The test pipe assembly (Figure 1) included two pipeline girth welds, 2m apart, in the middle 3.5m pipe section that was subject to constant bending moment. The girth welds were made with Inconel 625 using a qualified GTAW (TIG) butt weld procedure. The CS seam weld in the 2m pipe section between the girth welds was located at the 180° position (bottom), while the CS welds in the adjacent lined pipe sections were offset from this (at 135° and 225°). Alloy steel load pins were welded to the outside of the test pipe along the bend neutral axis.

Testing was performed at Cladtek’s dedicated test facility in Batam using a 4-point bend test rig, equipped with 4 x 100 tonne two-way vertical hydraulic actuators, able to bend full scale 11-12m long test pipes using programmable controlled displacement loading (Figure 2). The rig was configured to have the central 3.5m pipe section under constant bending moment. Although the rig was fitted with horizontal actuators able to exert up to 250 tonnes load at each end, to apply axial tension or compression loading during bending, the application of end loading during installation and service bend testing was excluded by the specification.

Heating was achieved using electric ceramic pad heaters strapped to the external diameter and compressed air was used as the pressurising medium (with appropriate safeguards).

Instrumentation used to monitor the bend testing included: 12 strain gauges mounted on the external surfaces at 0° and at 180° positions to measure local axial strain; 5 displacement transducers to measure the deflection of the pipe and calculate global bending strain, 1 dial type pressure gauge, 1 electronic pressure transducer, 4 thermocouples and 2 networked HD digital video cameras with light sources. The cameras were fixed inside the pipe, one either end, to view the central 3.5m section during bending. On account of the low angle ‘back’ lighting effect, the cameras were able to detect very small liner deformations. The output from the instrumentation was captured by a data acquisition system and recorded digitally.

3. Test Parameters and Results

Representative test parameters were developed taking due account of design conditions and limits appropriate for a subsea flowline of size NPS 24 operating at high temperatures and therefore being susceptible to lateral buckling. The reference standard used as the basis of the pipeline design was DNV OS-F101 “Submarine Pipeline Systems” [1].

Test Parameter	Test Requirement
Pipeline Coating	240-250°C
Installation Simulation (S-lay):	
Temperature	Ambient
Pressure	Ambient
Axial Strain	±0.25%, ±0.30%, ±0.35%, ±0.40%
Pipeline System Test Pressure	320 barg
HPHT Flowline Simulation:	
Temperature	110°C
Pressure	20, 15, 10, 5, 0 barg
Axial Strain	-0.40%, -0.50%, -0.60%
Start-Up/Shut Down Simulation:	
Temperature	110°C
Pressure	10 barg
Strain	500 cycles -0.2% to -0.5%

Table 3: Summary of Test Parameters

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3.1 Coating Simulation

The application of anti-corrosion pipeline coating is known to cause the gripping force to decrease substantially from the original gripping force measured in the pipe mill.

The extent of the reduction is illustrated by Figure 4, which compares the ex-mill average gripping force for two different expansion pressures (lower bound and mid range) with the average gripping force measured after coating simulation. The average liner gripping force has dropped from 260kN to 7kN after coating simulation. This is a known effect due to the CRA liner having a larger coefficient of thermal expansion than the backing steel. The thermal expansion coefficient for 316L and CS are 16.5×10^{-6} mm/mm/°C and 13.0×10^{-6} mm/mm/°C respectively. Increasing the temperature increases the grip force until the point is reached when the CRA liner undergoes compressive yielding, at which point the grip force is reduced.

The temperature used during pipeline coating (240-250°C) is sufficient to cause compressive yielding of the liner with the result that the grip force is substantially reduced after coating.

Cladtek performed the coating simulation by feeding the NPS 24 lined pipe through an 800kW induction furnace with water quench. There was no data available from coaters for the internal temperature during coating so the induction furnace was conservatively configured to heat the inner CRA liner surface to 240-250°C. Figure 5 shows the time-temperature profile achieved, measured using thermocouples attached to internal CRA and external CS surfaces.

3.2 Post-Coating Hydrostatic Pressure Test

Liner gripping force can be restored (at least partially) by performing a pressure test after pipeline coating. The pressure test has to cause the liner to yield and increase the liner contact pressure. However if the test pressure is lower than the original expansion lining pressure, the 'restored' level of grip will be lower than the original level of grip (Figure 4).

There is a case for performing hydrostatic pressure test after pipeline coating, particularly for large diameter CRA lined pipes, to ensure the gripping force is optimised prior to installation. For the test programme, a post-coating hydrotest at 320 barg was performed on one pipe.

3.3 Installation Bend Testing

The test pipe was subjected to the following bending cycles in order to replicate the strain experienced by the pipe during S-lay pipeline installation. The testing is conservative as the strains specified are in excess of the maximum allowable installation strain, which would be limited to 0.250% per DNV OS-F101 guidelines for grade X65 steel pipe without concrete weight coating (this figure is based on DNV OS-F101 Simplified Criteria, Overbend, Criterion I, static loading and includes the effects of bending, axial force and local roller loads).

Bend testing was performed at ambient conditions (i.e. no heating, no internal overpressure).

- 3 cycles between +0.25% and -0.25% strain
- 3 cycles between +0.30% and -0.30% strain
- 3 cycles between +0.35% and -0.35% strain
- 3 cycles between +0.40% and -0.40% strain

A few minor ripple-like features with height less than 1mm did appear at -0.4% strain in the area above the CS seam weld at the 180° position but they subsequently flattened and then disappeared when the axial bend loading was changed from compression to tension.

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The test pipe was inspected on completion of the installation bend testing. No liner wrinkles or buckles were apparent in the pipe after completion of installation bend testing at +/-0.4%.

3.4 Pipeline System Pressure Test

For the reasons outlined earlier in the discussion on post-coating hydrostatic pressure testing, if the liner gripping force has been reduced by coating, or if pipeline installation has caused some minor separation between the CRA liner and backing steel, the pipeline system pressure test will increase the liner contact pressure and restore gripping force in the CRA lined pipe.

Post-installation field hydrotest has not been included in previous bend test programmes, even though it is necessary to perform before the pipeline can be put into service. Accordingly the pipeline system pressure test was replicated in this test programme.

For the test programme, a test pressure of 320 barg was specified. This is marginally below the calculated system test pressure based on DNV OS-F101 (350 barg).

3.5 Operating Condition: Bend Testing

After completing the installation bending and the pipeline system pressure test, the test pipes were subjected to bending that replicated the pipeline design maximum strain. The test pipe was heated to 110°C and internal pressure was introduced. The initial pressure was 20 barg but this was progressively reduced in 5 bar increments down to 0 barg (ambient pressure) to test the sensitivity of the lined pipe to internal pressure.

For each different internal pressure, the test pipe was subjected to:

- 1 cycle between 0% (straight) and -0.40% strain at 110°C and [0-20] barg
- 1 cycle between 0% (straight) and -0.50% strain at 110°C and [0-20] barg
- 1 cycle between 0% (straight) and -0.60% strain at 110°C and [0-20] barg

Figure 7 illustrates the cycles of strain and internal pressure in the order they were applied.

The liner did not collapse and did not form any ripples or wrinkles during the decompression stages when the pressure was suddenly dropped with the pipe held at maximum strain.

The service condition strain bend tests were satisfactorily performed and completed with no liner wrinkles or buckles, even at -0.60% strain with zero overpressure (ambient pressure).

3.6 Operating Condition: Limit State A (20 barg Pressure)

The in-service bend testing was extended to include higher strains in order to explore the limit state strain for liner wrinkling at the operating condition service.

One test pipe was re-pressurised to 20 barg and while still at 110°C, was strained to -0.73% and then -0.80%. Figure 8 is a still that shows this pipe without wrinkling when the axial compressive strain was -0.80%, temperature was 110°C and internal pressure was 20 barg.

As Figure 8 shows, there were no signs of any ripples or wrinkles in the liner at an axial compressive strain of -0.80% at 110°C with 20barg overpressure.

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As this test pipe was showing no signs of wrinkle initiation with 20 barg internal pressure, the bend testing was stopped to preserve the test pipe for other tests.

This result was not unexpected. Previous bend test programmes, performed using NPS 12 and NPS 20 lined pipes, have demonstrated that the presence of a relatively low internal pressure (6 bar) can be sufficient to prevent liner wrinkling. In the case of the pipes mentioned, there was no liner wrinkling at strains in the order of -1.9%, the physical limit of the test equipment.

This particular test programme with NPS 24 lined pipe specified that the internal pressure should be 20 barg as this pressure was the minimum design pressure. The results confirm that no wrinkling occurs under high axial compressive strain at the minimum design pressure.

The results verified that 20 barg internal pressure was sufficient to delay the onset of any liner wrinkling. The testing was stopped at -0.8% strain but, in light of previous test results, the expected limit state with 20 barg internal pressure would be far greater than this.

Nevertheless the test result exceeds the specified design requirements

3.7 Operating Condition: Limit State B (ZERO barg Pressure)

Using the same test pipe as above, the internal pressure was reduced to ambient (0 barg) and the bending strain progressively increased until liner wrinkling was observed. This testing was not required by, but was performed in addition to, the specified test programme.

The test pipe was strained to -0.75%, -0.80%, -0.90% and finally -1.0% with 0 barg pressure

Liner wrinkling was clearly visible at -1.0% strain although the onset of wrinkling was judged to occur at about -0.83% strain with 0 barg pressure. Figure 9 is a still frame that shows wrinkling in the liner at an axial compressive strain of -1.0% at 110°C and 0 barg pressure.

After straining to -1.0%, the test pipe was removed and the wrinkles examined further. The wrinkle height was found to vary between 0.5mm and 1.0mm, with a separation or spacing of about 100mm between adjacent wrinkles. There were no indications of surface defects.

The liner wrinkling had initiated in the liner above the CS seam weld, which is consistent with expectations given that the CS seam weld presents a geometrical imperfection.

These wrinkles were smooth in profile, relatively small and low in height. As they were, it is not clear there would have been any impact on flow assurance or pigging performance in service. There also remains the possibility that if the pipe was re-pressurised, to the pressure expected in normal flowline service, then these wrinkles would flatten and disappear. However for the purpose of testing, the onset of wrinkling was determined to be -0.83% at 0 barg pressure.

3.8 Operating Condition: Start-Up/Shut-Down

Over the life of an HPHT pipeline system, the installed flowline will experience periodic cycles of start-up and shut down and these will impose cyclic stresses (high strain, low cycle fatigue) on the pipeline as it is subjected to changes in pressure and temperature.

In order to simulate start-up and shut down cyclic conditions, one test pipe was subjected to an additional 500 strain cycles as noted below (after completing the bend testing outlined above) over a period of about 24 hours, during which the test pipe was continuously monitored.

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- 500 cycles between -0.2% and -0.5% strain at 110°C and 10 barg

On completion of the 500 cycles between -0.2% and -0.5% strain, the test pipe was examined (visually and with surface NDE) for fatigue defects. Particular attention was given to the liner-to-overlay interface but no defects were found in the liner or at the interface. Also there were no liner wrinkles or buckles visible after the 500 cycles of start-up/shut-down strain.

4. Discussion

Liner wrinkling or buckling can occur under conditions of high axial compressive strain because the liner is only mechanically bonded to the carbon steel outer pipe.

The accepted mechanism for the formation of a liner wrinkle or buckle is:

- 1) The contact pressure between the liner and pipe in the bending compression region reduces towards zero as the bending strain is increased. This is caused by the ovalising effects of the bending on the liner and the yielding of the liner material. When the contact pressure reaches zero, a thin gap is opened between the liner and the pipe
- 2) Small scale rippling can then be initiated, which leads to a localised variation in the longitudinal stress and strain.
- 3) The small scale ripples grow in size as the bending strain increases.
- 4) As the strains increase further, one or more ripples will grow and become larger than the rest. Several smaller wrinkles may coalesce and plastically localise to form fewer but larger permanent wrinkles or buckles.

Wrinkle formation is therefore sensitive to internal pressure as the internal pressure inhibits liner rippling and wrinkle initiation by maintaining a contact or interface pressure between the liner and the backing steel. These test results confirm this: the presence of 20 barg internal pressure was enough to suppress liner wrinkling.

Wrinkle initiation is sensitive to the presence of material and geometric imperfections. In the case of SAWL outer pipe, the internal weld reinforcement resulting from the longitudinal carbon steel seam weld is a potentially significant geometric imperfection. This was confirmed by the testing as, where liner wrinkling did occur, the wrinkling initiated in areas where the liner was fitted over the carbon steel longitudinal seam weld.

DNV has established a set of design guidelines that include a strain criterion for CRA lined pipe based on the onset of liner wrinkling. This work is part of the DNV Joint Industry Project "Lined and Clad Pipeline Materials" [2], The criterion for the onset of liner wrinkling is in the form of an equation, which is based on a set of test results.

For the pipes used in this test programme, NPS 24 x 24.3+4mm lined pipe, the calculated limit state for the onset of wrinkling using the DNV formula would be -0.61% strain.

Under the service conditions used for this test programme, liner wrinkling was observed at levels of strain that were much higher than predicted by the DNV formula. For NPS 24 lined pipe at 110°C with ZERO overpressure, liner wrinkling appeared to initiate at about -0.83% strain compared to the DNV predicted -0.61% strain (Table 4).

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ONSET OF LINER WRINKLING NPS 24 x 24.3+4mm X65 / 316L LINED PIPE Service Condition: Temperature 110°C and Pressure 0-20 Barg		
Strain limit (DNV Design Guidelines)	Wrinkling Strain (ZERO barg pressure)	Wrinkling strain (20 barg pressure)
-0.61%	-0.83%	(No Wrinkling)

Table 4: Bend Test Results

The DNV limit state strain criterion for the onset of liner wrinkling appears to be relatively conservative when compared to the test result achieved with 0 barg internal pressure.

Pipeline system pressure testing (which ensures adequate gripping force is restored after coating and installation) and elevated service temperature (which increases the gripping force) are not considered by the DNV formula and these may have contributed to the result achieved.

Nevertheless the test result for NPS 24 lined pipe exceeds the DNV design criterion.

5. Conclusions

- Gripping force trials verified that the heating process used during pipeline coating can cause a significant and substantial reduction in the liner gripping force.
- Gripping force trials demonstrated that performing hydrostatic pressure testing after pipeline coating is an effective way to restore some liner gripping force.
- The installation bend testing verified that NPS 24 lined pipe is suitable for installation by offshore lay barge. There were no permanent wrinkles or buckles in the liner after testing at strains of up to +/-0.40%. The strain used for the testing exceeds the DNV OS-F101 guidelines, which limit the maximum strain to 0.25%.
- The operating condition bend testing verified that NPS 24 lined pipe meets the specified pipeline design parameters. There were no wrinkles or buckles in the liner after testing at greater than -0.60% strain at 110°C with or without pressure.
- There were no liner wrinkles, or liner-to-overlay interface defects, after 500 cycles of strain between -0.2% and -0.5% at 110°C with 10 barg pressure. This meets the pipeline design criteria for start-up and shut-down conditions.
- The results obtained during the secondary operating condition testing exceed the DNV strain criterion. Wrinkle initiation was judged to occur at -0.83% strain, which exceeds the DNV predicted onset criterion of -0.61% strain. The DNV design criterion can be considered conservative compared to the test result.
- NPS 24 x 24.3+4mm X65/316L lined pipe meets (or exceeds) the pipeline design criteria and, on that basis, NPS 24 CRA lined pipe is considered suitable for use in high temperature flowlines that will be prone to lateral buckling during service.

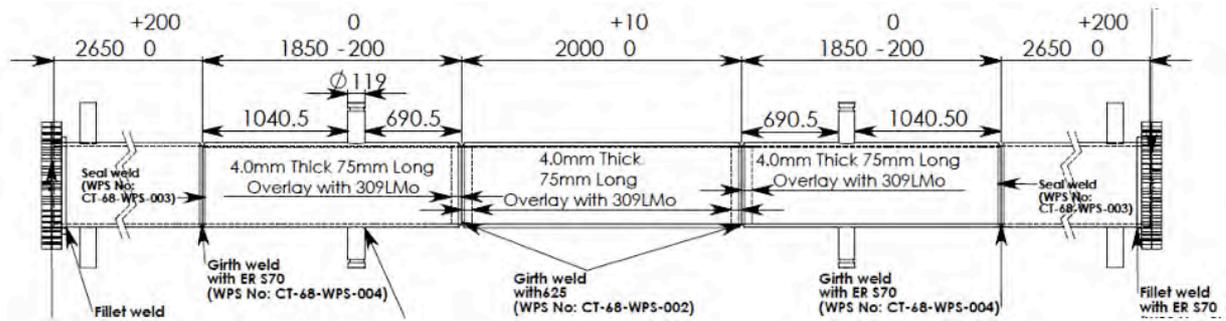
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6. References

[1] DNV OS-F101 October 2010 "Submarine Pipeline Systems"

[2] DNV Technical Report 2007-0220 rev 2 "JIP Lined and Clad Pipeline Materials: Guidelines for Design and Construction of Clad and Lined Pipelines"

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24" LINED PIPE 4 POINT BEND TEST

Project No: CT-97

Base Material: Gr X65 WT 24.3mm
Liner Material: 316L WT 4.0mm

Test Pipe: 01 (With Coating Simulation)

FIGURE 1: Drawing of NPS 24 CRA Lined Test Pipe Configuration

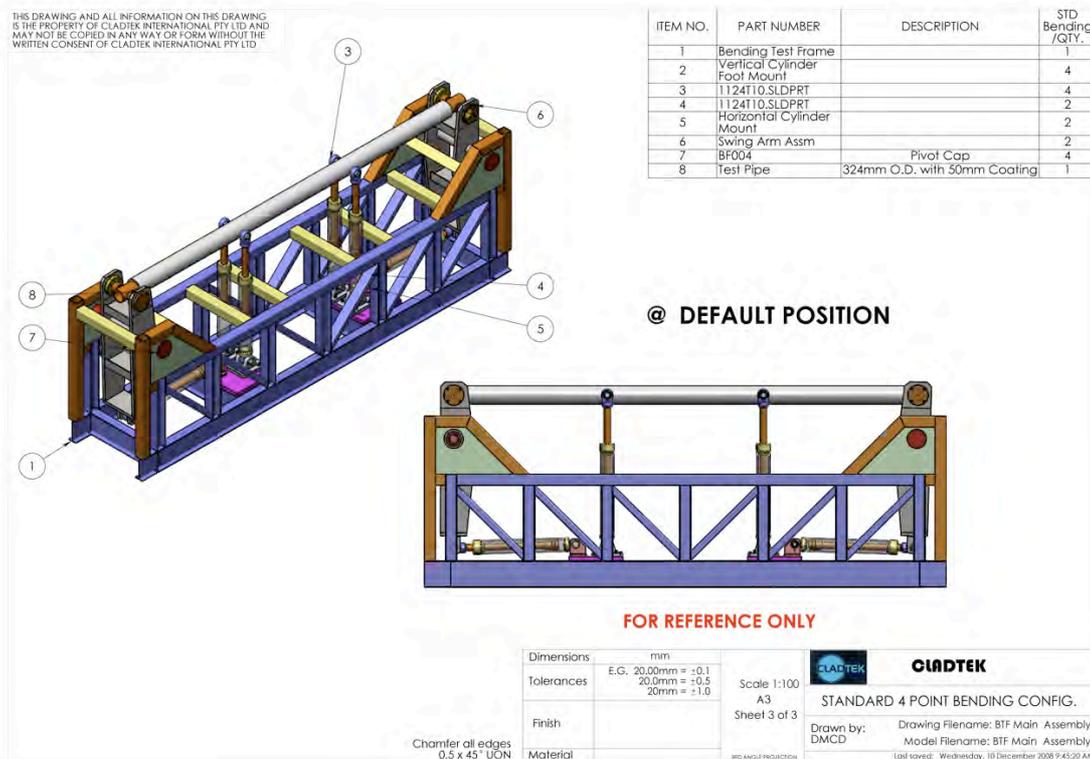


FIGURE 2: Diagram Illustrating Test Rig in 4-Point Bend Test Configuration

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FIGURE 3: Photograph of Test Pipe on Test Rig with Heating and Instrumentation

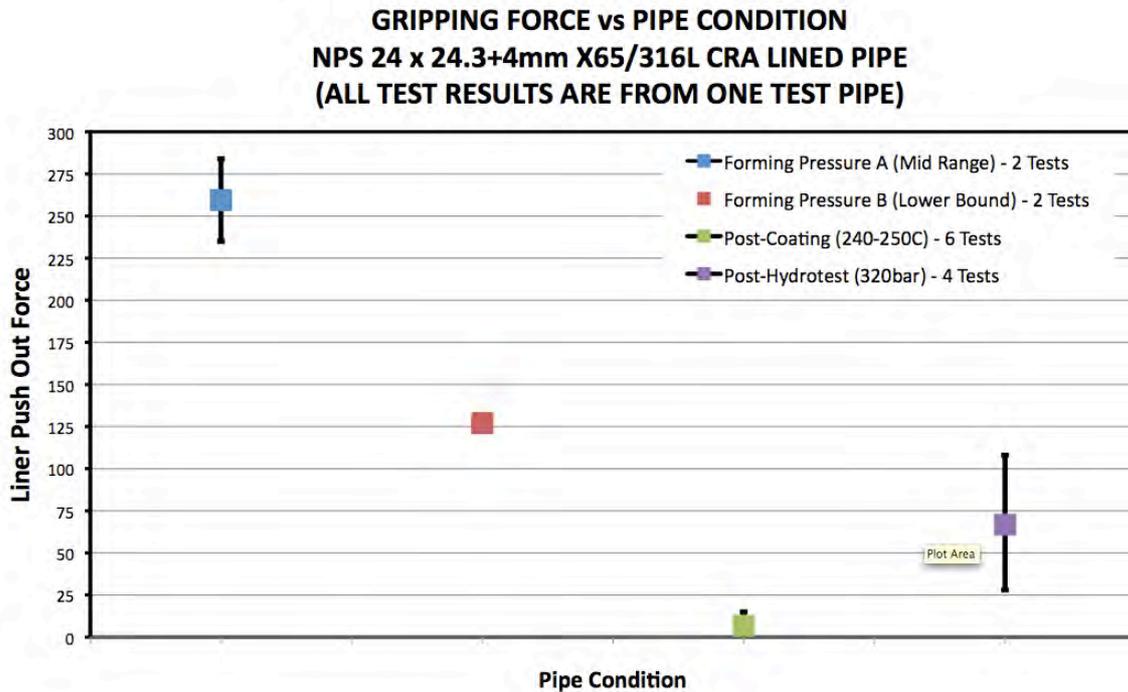


FIGURE 4 - Chart showing Variation of Gripping Force with Pipe Condition

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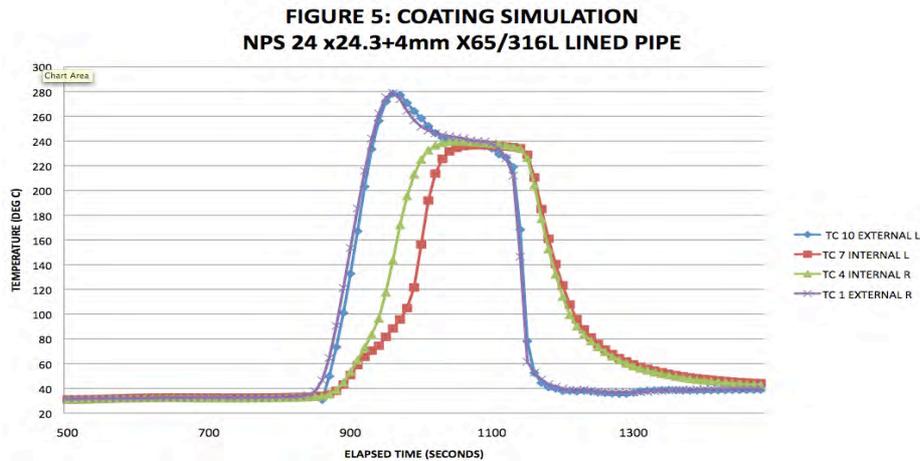


FIGURE 5 - Simulation of Coating Thermal Cycle (Temperature v Time)



FIGURE 6 - NPS 24 Lined Pipe - No Wrinkles after +/-0.4% Strain (Ambient)

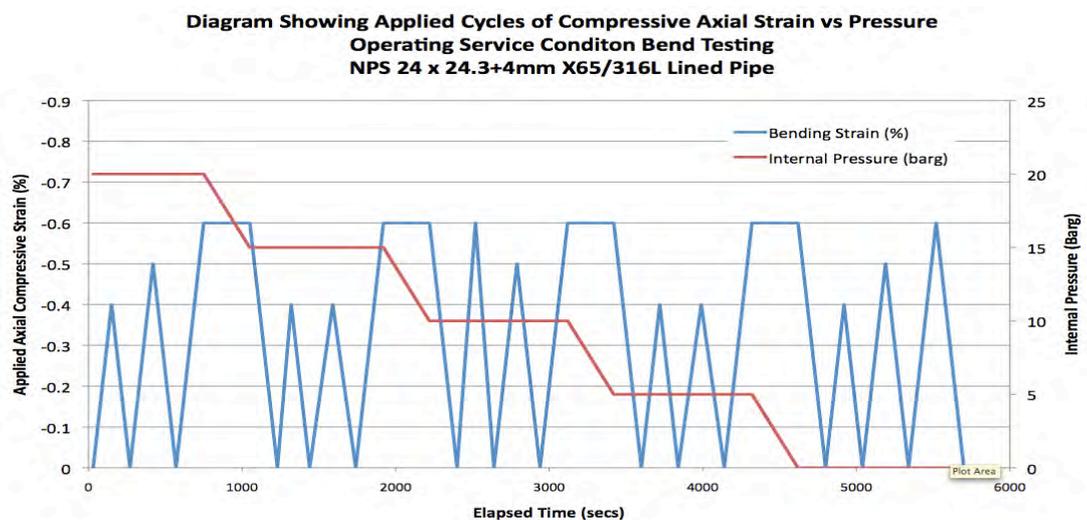


FIGURE 7: Operating Condition Bend Testing - Applied Strain vs Internal Pressure

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FIGURE 8: NPS 24 Lined Pipe - No wrinkles at -0.80% strain, 110°C and 20barg



FIGURE 9: NPS 24 Lined Pipe - Wrinkles at -1.0% strain 110°C with ZERO overpressure