HEAVY WALL LINE PIPE FOR SEVERE APPLICATIONS

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ABSTRACT

The new and near future oil field are expected to be characterised by increasing technical challenges. The increasing severity of the scenarios of application (large plastic cyclic deformations, high pressure, high temperature, sour environment, etc.) calls for an improvement of all the technology involved in the field development. Certainly, pipe material is one of the technological areas directly involved in this challenge. Line pipe materials have hence specifically developed to guarantee their suitability for severe scenarios. Various testing activities have then been performed, both in laboratory and full scale, to study the material behaviour in presence of large, even cycling, strains and to verify their suitability for application in the most challenging scenarios.

In laboratory activities, pipe material has been cycled to severe strains in longitudinal direction (1% and 2% maximum strain for various numbers of cycles, up to 200 cycles). This has been done on-on purpose designed full thickness specimens. Material exhibited an important reserve of strength even after application of severe strain cycling. In fact, after a limited softening in initial shakedown stage, the stress resistance stabilized both during tensile and compressive straining.

Furthermore, even after the severe straining sequences and after artificial ageing, mechanical properties, although varied from the unstrained condition, confirmed their suitability for severe applications.

Full scale testing of pressurized X65, 10 3/4” OD X 46 mm WT line pipe has been performed in cyclic plastic axial straining. A huge measurement campaign allowed to establish the relevant parameters that characterize the actual material behavior, in particular with respect to ratcheting exhibited by the heavy wall pipe axially cycled in presence of internal pressure.

Full scale testing performed on strings of pipeline, consisting of different pieces of pipe, allowed also to study the behaviour of distribution of deformations. In fact, the loading sequence was applied in global strain control, averaged on the whole string length, but necessarily the local distributions of strain differs in the three pieces of pipe. The high strain hardening capability of the X65 steel pipes, guaranteed a good recovery of any non-homogeneity in straining, both during cycling and in larger axial deformation of the string. Furthermore, due to the material capability to redistribute the cycling strains along the whole sample length, any section experienced limited ratcheting with un-reversed circumferential expansion during cycling well within limits of tolerability.

It is worth nothing that, even in presence of severe cycling conditions, both on-shore type girth welds (double joint) and off-shore type (GMAW in Narrow Groove Bevel Preparation) preserved their integrity with no cracking or other damage.
1. INTRODUCTION

The always increasing demand of oil resources brought to the commercial feasibility for the exploitation of those fields which, in the past, were considered excessively complex to be faced. As a consequence, the demand for high performance pipes increased, pointing out always more severe scenarios of applications (large plastic cyclic deformations, high pressure, high temperature, sour environment, etc.).

Heavy wall seamless pipes are required for deep and ultra-deep water fields [1] as well as for ultra-high pressure applications. LPs currently considered for such applications are seamless pipes with wall thicknesses up to 40-50mm, diameter in the range 8"÷16" and YS up to about 490 MPa. The envisaged service conditions are really demanding, involving the following main critical points:

- sour environment;
- very high pressure;
- high strains in operating condition (up to about 2 %);
- severe load cycles;
- wide temperature range (-30 °C to 200 °C).

Oil & Gas industry (manufacturers as well as operators) are interested in exploring the working window of heavy wall LPs when subjected to such severe conditions. Various technical points connected with extreme loading conditions are worth of studying. Among them it can be mentioned: sour resistance after severe straining, cyclic softening, ratcheting and uniformity of strain distribution along the line.

Within this context, Tenaris and RINA – Centro Sviluppo Materiali promoted a multi years research effort that faced such issues for the heavy wall line pipe produced by Tenaris. A joint industrial project was set up in order to facilitate the participation of oil and gas companies and laying contractors to receive their in-kind contribution for the steering of project towards the technical challenges of major interest regarding the material.

2. LABORATORY TESTING

A special laboratory testing programme was set-up in order to investigate material response when subjected to severe stain cycling. A Dalmine mill produced X65, OD 219.1 mm X WT 44 mm was considered for laboratory testing.

A full thickness tensile sample was designed to withstand also important compressive strains without undergoing to buckling instability. Such testing configuration, for cyclic testing in full thickness, are denominated as Multi Plastic Straining Cyclic (MPSC) tests.

MPSC samples are shown in Figure 1, together with the extraction position sketched in Figure 2. To be noted that to facilitate the sampling of the full wall thickness, without impairing the test execution for excessive required loads, the sample width has been limited to a value lower than the wall thickness.

Specimen dimension in the testing portion are: width in the gauge length: 23 mm, gauge length: 60 mm, width in the clamping heads: 30 mm. In Figure 3 an example of MPSC specimen mounted on the servo-hydraulic machine is reported.
To face the problem of studying the material behaviour, when subjected to multi plastic strain cyclic loading, in absence of a project-specific scope, the general material behaviour during cycling has been experimentally studied in different conditions.

It was decided to start with the condition of 10 straining cycles at 1% maximum strain. First laboratory tests showed, in such condition, cyclic softening occurrence. As a consequence interest arose in exploring higher number of cycles (10, 100, 200) and strain levels (1%, 2%) to explore possible occurrence of saturation of the phenomenon.

In Figure 4 a stress – strain diagram of a MPSC sample cyclically strained at 1% maximum strain for 100 cycles is reported. On this graph it is observable the presence of Lüders elongation on the first cycle, which disappears in the other cycles, where, as expected, a continuous stress – strain curve is present. Due to the fact that it is difficult to evidence the fine material behaviour in the various cycles in plot type of Figure 4, another kind of plot is proposed in Figure 5. Here the stress experienced by the material when passing, during different cycles, at certain fixed values of strain (absolute values, referred to the original un-deformed material) is plotted versus cycle number. These fixed levels of strains are shown in Figure 4, which are 0.5 % and 1.0% absolute strain.
The graph of Figure 5 clearly shows that at any cycle, at the same level of strain, a slightly lower level of stress corresponds. This is the previously mentioned cyclic softening experienced by the material. Nevertheless, material response seems to tend towards a steady stress with saturation of cyclic softening and no further reduction of resistance at high numbers of cycles. As a consequence other samples have been tested at even higher number of cycles, since, after 100 cycles, the material still results to be in shakedown stage.

![Figure 4](image1.png)

**Figure 4.** Stress – strain diagram of a MPSC sample cyclically strained at 1% max strain for 100 cycles.

![Figure 5](image2.png)

**Figure 5.** Stress at fixed strain versus cycle number, for a sample cyclically strained at max 1% strain.

In Figure 6 another sample tested at 1% maximum strain is reported. In this case the cycling was extended up to 200 cycles. In this case, the attainment of a stable condition with no further decrease of material strength is observable approximately starting from cycle number 180.

Various other samples confirm attainment of saturation before 200 cycles approximately. Such behaviour could be observed even plotting the stresses at any other value of fixed strain, instead of 0.5% and 1.0%, showing that stabilization of cyclic resistance is attained.

![Figure 6](image3.png)

**Figure 6.** Stress at fixed strain versus cycle number, for a sample cyclically strained at max 1% strain.

In Figure 7 the curves of stresses at fixed strain *versus* cycle number are plotted for two distinct samples subjected to different maximum cyclic strains, which are 1% and 2%.

![Figure 7](image4.png)
In the graph it can be observed that a stronger softening, with bigger rates of strength decrease, is present in the first cycles for the 2% case. Furthermore it has to be noted that the most important difference in behaviour between the two cases is due to the drop in yield strength experienced in the first cycle, which is then ascribable to the Bauschinger effect. About 50 MPa of strength is lost between first and second cycle for the 1% max strain case and about 80 MPa for the 2% max strain case.

On the other hand, cyclic softening has similar slope after first 40 cycles. Finally, attainment of saturation at approximately 200 cycles, even if at different levels of cumulative softening, is similar for the two cases. Total cumulated softening is about 100 MPa for the 1% max strain case and about 130 MPa for the 2% max strain case, being this difference mainly due to the difference in Bauschinger effect, already experienced in the first reversed straining.

![Graph](image)

**Figure 7.** Stress at fixed strain versus cycle number, comparison of samples subjected to different maximum cyclic strains.

As a consequence of the above described material behaviour, and considering that attainment of saturation in cyclic softening could correspond to a possible attainment of stable conditions even for material properties, the investigation of straining and straining – ageing effect on mechanical and stress-corrosion performance of the material, has been performed on materials deformed as follows.

- Cycling extent: 1% total strain,
- Number of cycles: 200.
- Last cycle to be ended after tensile straining stage.

This last point implies that the cycle ends open, i.e. after last tensile straining of the material, no compression is applied to close the last cycle at zero strain and zero stress. Such condition was selected since widely recognized to be the most critical condition in terms of resistance properties after straining (Y/T ratio, toughness and sour resistance). At this regard, previous experience showed that the material can exhibit less favourable mechanical properties if it presents a tensile plastic deformation from previous loading history [3].

In Figure 8, the stress – strain plots of as-received, strained and strained – aged materials full thickness tensile tests are superposed. Thermal ageing is performed exposing materials to a temperature of 250°C during 1 hour. In the figure, it can be observed that no dramatic downfall of tensile properties due to cyclic straining is present in strained and strained – aged materials. Anyway, the softening experienced by strained material is present along the whole curve, with a similar decrease of strength, for the strained material compared to as-received material, at any value of strain. In this graph, tensile curves of strained and strained – aged materials are translated to take into account previous straining, since last straining cycle was ended open in tension, as explained in the previous paragraph. By this kind of plotting we can observe that, after 3.5% strain, strained-aged material curve superimposes with as-received material, showing that, at such levels of strains, effects of cyclic softening on material strength are undone by ageing.
In Figure 9, stress-strain curves obtained by round bar samples extracted from MPSC specimens, of As-Received and Strained + Aged material conditions are reported for room and high (100°C) test temperatures. Since the cyclic straining is ended in tension, a sensible increase of yield strength is experienced after straining and ageing. Furthermore, S+A ultimate strength practically equals the As-Rec. condition, highlighting that ageing allowed to recover the softening experienced after cycling. Such behaviour is observed at both test temperatures. Even after strain-cycling the material preserved its reserve of strength also at high temperature, with de-rate in tensile properties not larger than those anticipated in standard DNVGL-ST-F101.

Charpy-V tests have been performed in As-Received, Strained and Strained+Aged conditions, in different positions along the wall thickness, at -30°C and -50°C test temperatures, as shown in Figure 10. Pure straining did not cause any observable reduction in CNV toughness. On the other hand, even if, as expected,
staining and ageing caused a reduction in toughness, this reduction is little and As-Received material has as high toughness levels that the eventual subsequent decreases do not produce any practical effect on the material resistance against fracture.

3. FULL SCALE TESTING OF LINE PIPE IN RATCHETING REGIME

Two full scale testing have been performed at CSM on pipe pieces, to study the actual full pipe behavior when subjected to severe strain cycling conditions applied in presence of internal pressure. The strain cycles were defined to exceed the pipe resistance to ratcheting, first full scale test, definitely getting the worst condition for the steel material. The second full scale test was defined at the start-up of ratcheting, limiting the phenomenon even under hundreds cycles, which should be the worst case experienced by a well designed pipeline project.

The First full scale testing imposes to the pressurized pipe, the constant strain range cycles with:

\[ \varepsilon_{L,\text{peak}} = \Delta \varepsilon_L = 1.0\%. \]

The Second full scale testing imposes to the pressurized pipe, a sequence of variable strain cycles, with:

\[ \varepsilon_{L,\text{peak}} = 1.0\%; \]
\[ \Delta \varepsilon_L = 0.5\% \] (approximately corresponding to a pastic strain cycling: \( \Delta \varepsilon_L^{\text{plastic}} = 0.1\%; [5] \)).

Figure 11 shows the testing rig adopted for full scale testing. This machine is able to apply tensile (2’500 tons) and compressive (3’000 tons) loading. Also bending loading (300 ton x m) can be applied but this is not the case for the present testing. Internal water pressure is also applied to the pipe during pipe straining.

Pipe piece subjected to testing is 3,000 mm long. This length is adopted to guarantee an important length of pipe (the central portion) which can be considered unaffected by constraint of clamping heads.

To prevent buckling of the pipe during compressive straining, an anti-buckling frame has been applied close to the pipe body across the entire pipe length (see Figure 12) and anti-rotation system has been applied to each rig head, to prevent the rotation of the hinge and make it a fixed clamping point.

During the testing a continuous monitoring of the pipe behavior has been carried out employing four digital cameras, in Figure 13 two images of the cameras are reported.

Figure 11. Full scale testing rig.

Figure 12. Full scale testing rig, sketch of the anti buckling system.
3.1 First Full Scale Testing

A constant strain cycle equal to 1.0 % was imposed in the first full scale test.

The internal pressure was defined to achieve an Usage Factor of 60%, i.e. producing the hoop stress in pipe wall equal to 60% SMYS of pipe material. Due to the important value of wall thickness over pipe diameter ratio of present heavy wall pipes, this usage factor results in a high inner pipe pressure, corresponding to 85 MPa.

Since important ratcheting extent is expected under these testing conditions, the cycling sequence was expected to be heard in safety for few tens of cycles before the pipe undergoes excessive circumferential deformation due to ratcheting.

The tests have been carried out at room temperature of about +30°C.

In Figure 14, the load versus strain curve is reported. The total remote strain applied is measured by the LVDT survey of displacement between remote sections of pipe segment. It is worth noting the similarity in shape of the cycles with those performed in laboratory scale reported in a previous paragraph.

In Figure 16, the circumferential strain gauges values are reported for the cycles from 21 to 27. The strain gauges, applied to the pipe body on section C1, C2, C3 and on circumferential positions C and D (as defined in Figure 15), exhibits an increasing mean value. Actual occurrence of ratcheting is evidenced by the fact that, on each cycle, the total strain increases, therefore the circumferential section is expanding during the test. To further highlight the occurred ratcheting, in Figure 17, the diagram of the load versus circumferential strain is reported. For each cycle the circumferential strain value, at any position in the cycle, increases with respect to previous cycles.
3.2 Second Full Scale Testing

Figure 18 shows the sample of 2\textsuperscript{nd} full scale test, mounted on the CSM testing rig during application of cyclic straining.

Cycling sequence correspond to the following testing sequence:

- First Tensile Straining till +1\% Total Strain.
- Subsequent sub-cycling in tension / compression ranging 0.5\% Total Strain. 200 sub-cycles are performed.

Also this test has been performed with the internal pressure corresponding to 60\% Usage Factor (\textit{i.e.} 85 MPa). Test is performed at room temperature.
In Figure 19, Stress – Strain reading during the test execution is reported, including 200 cycles at 0.5% total strain. It can be noted, even in this plotting, that also in full scale testing, pipe material underwent some softening, similarly to what is observed in laboratory scale MPSC testing.

In Figure 20, strain readings in circumferential orientation during the pipe cycling are reported as surveyed in correspondence of the pipe sections as previously shown in Figure 15. It can be noted that a small permanent deformation is continuously added to the cyclic variation of circumferential strain, showing occurrence of slight bi-axial ratcheting.
4. FULL SCALE TESTING OF WELDED PIECES OF PIPES

Two further full scale tests have been carried out on sting of pipe containing girth welds, with the twofold aim of verifying the capability of girth welds to resist the extremely severe straining sequence defined above, and studying the straining behaviour of the different pieces of pipes, when the string is subjected to elastic-plastic straining.

A first tensile straining till 1% total strain and 200 subsequent cycles in 0.5% total strain range have been applied, never exceeding the maximum strain of 1%. Internal pipe pressure, corresponding to 60% usage factor (850 bar water pressure), is imposed also in these tests. Tests are conducted at room temperature.

The second GW full scale test adds, to the above described straining sequence, a second tensile straining in the middle of the cycling. This allows to verify the capability to reabsorb the differences in strain distribution experienced when 1% global strain was applied.

Further difference between full scale tests on girth welded pipe strings consists in the technique adopted for the production of girth welds. 1st GW test presents two girth weld for on-shore double jointing adopting Lincoln’s Surface Tension Transfer ® (STT-GMAW) process for the root pass and traditional Submerged Arc Welding (SAW) for the fill and cap passes (further details in [6]). 2nd GW test, on the other hand, presents two girth weld for off-shore welding. Also in this case, root pass is produced by STT-GMAW process, while fill and cap passes are produced by GMAW on a narrow groove bevel preparation for high productivity.

4.1 First GW Full Scale Test.

In Figure 21, the pipeline sample configuration for testing is reported. It can be noted that the two girth welds are symmetrically located in the central zone of the sample with an inter-distance of 820 mm, which is considered suitable to prevent influence of each weld on the deformation behavior of the other one.

The figure shows the strain gauged sections for local measurements of strains. The globally applied strain is measured by means of four long LVDTs, mounted as sketched of Figure 22. Such configuration is defined to guarantee the measure of the actual global strain applied, irrespective of any localization of strain, and to exclude any bending effect from the measured axial strain.
In Figure 23, the test readings of load versus global strain are reported. It can be noted that, as already shown in previous full scale testing (second test on pipe material, reported in previous paragraph) the sub cycling of 0.5% total strain corresponds to 0.1% plastic strain.

![Figure 23. Load vs. Global Strain of the whole strain sequence of the 1st Full Scale Test.](image)

Figure 24 shows the strain gauges reading in three positions representative of the behavior of the three distinct sections A, B and C of Figure 21. It can be noted that Section A presents a straining behavior quite different from sections B and C. In fact, it can be noted, first of all, that the Sec. A strain readings are upward shifted with respect to Sec. B and Sec. C readings, and they cycles around a mean value of approximately 1.5% strain. On the other hand, sections B and C cycle around a mean value very slightly above the zero. This corresponds to the fact that, the first monotonic tensile straining is cumulated in the weakest pipe, that, in the present case, corresponds to the pipe of Section A. Meanwhile, the other two pieces of pipe are almost not plastically strained.

Besides, it has to be noted that even the strain range during cycling is different between Sec. A (Strain range 0.6%) on one hand, and Sec. B and Sec. C (Strain range 0.46%) on the other hand. Also in this case, the strains are cumulated in the piece of pipe supposed to be the weakest. Nevertheless, here the differences are sensibly less marked than in first tensile straining. This is possibly due to a smoothing in strength difference facilitated by different extents of strain hardening and Bauschinger effect.

![Figure 24. Longitudinal Strain gauges reading in the three different sections.](image)

Consequence of this unequal repartition of strain on the three distinct pieces of line pipe is a different ratcheting evolution. As showed in previous paragraphs, 0.5% total strain in longitudinal direction (corresponding to 0.1% plastic strain in sub-cycling), is an important threshold between none and appreciable ratcheting occurrence [4; 5]. This anticipated behavior is confirmed in present case. In Figure 25, the circumferential local strain readings in the three different sections are reported. Here it can be noted that Sec. A, experiencing sub-cycling at the local strain range of 0.6%, is exhibiting noticeable ratcheting, with a continuous, cycle by cycle, increase of circumferential elongation. Sections B and C, are also experiencing...
some un-reversed circumferential elongation, but these elongations are one order of magnitude smaller than in Sec. A.

- Section A: 1.1% permanent circumferential distortion cumulated between cycle no. 50 and cycle no. 100.
- Sections B and C: 0.08% permanent circumferential distortion cumulated between cycle no. 50 and cycle no. 100.

![Circumferential Strain Gauge](image1)

**Figure 25.** Longitudinal Strain gauges reading in the three different sections.

Finally, the other relevant result regards the girth welds that, even in presence of some ratcheting of the pipes, did not show any visible crack or other damage after the cycling sequence very severe for the welding resistance (also known as ratcheting fatigue regime, [7]). Post-test appearance of the welds can be observed in Figure 26.

![Girth Welds](image2)

**Figure 26.** Girth Welds in the 1st Full Scale Sample.

### 4.2 Second GW Full Scale Test.

This test, as anticipated above, was intended to test the girth welds for on-shore welding in high productivity technique (fill and cap by GMAW in narrow groove bevel preparation).

This testing reproduces the same testing conditions of the previous full scale test on double joint girth welds.

In Figure 27, the pipeline sample configuration for testing is reported. It can be noted that the two girth welds, as in previous test, are symmetrically located in the central zone of the sample, with an inter-distance of 760 mm.
The figure shows the strain gauged sections for local measurements of strains. The globally applied strain is measured by means of four long LVDTs, mounted as already shown in the sketch of Figure 22, in order to measure the average strain applied along the whole string.

In Figure 23, the test readings of load versus global strain are reported. It can be noted that, also in the present case, the sub cycling of 0.5% total strain corresponds to 0.1% plastic strain. Nevertheless, the most evident peculiarity of this 2nd Full Scale Test is the occurrence of a second tensile severe straining that, after Cycle 80, brought the pipe to a 1.68% total absolute strain. This second tensile straining offers the possibility to further demonstrate the resistance, against large strains, of the pipes and its girth welds. It provides, furthermore, valuable experimental evidences about the strain distribution behaviour of a string of different pipe sections.

Figure 29 shows the strain gauges reading in three positions representative of the behaviour of the distinct sections C, F and I of Figure 27. The cycles in the plot have been opportunely selected before and after the second straining. It can be noted that, before the second straining, similarly to what occurred in the 1st Full Scale Test, Sec. C presents a straining behaviour quite different from sections F and I. In fact, Sec. C strain readings are upward shifted with respect to sections F and I readings, and they cycle around a mean value of approximately 1.2% strain. On the other hand, sections F and I cycle around a mean value very slightly above the zero. This corresponds to the fact that the first monotonic tensile straining is cumulated in the piece of pipe corresponding to Sec. C while the other two pieces of pipe are almost not plastically strained. This behaviour can be explained with even small differences in strength among the pieces of pipes. After the second severe straining, thanks to the strain hardening capability of the pipe material, all the sections reach a similarly high value of mean strain of cycling. The further stain has been distrusted in the different sections in a way that compensated the initial inhomogeneity.
Figure 29. Longitudinal Strain gauges reading in the three different instrumented sections of the 2nd GW Full Scale Test.

In Figure 30, the local strain readings in correspondence of the three instrumented sections are plotted against the Global applied Strain (from LVDTs readings).

As shown in Figure 30, during the 1st tensile loading, only Sec. C reaches yielding, cumulating a local strain of approximately 1.6% total strain, similarly to what happened in previous GW full scale testing.

In the 2nd tensile loading (after Cycle 80), the further straining of Sec. C is minimal, thanks to local strain hardening subsequent to Lüders elongation. In such conditions, Sec. F and Sec. I are allowed to yield, entering the Lüders plateau.

At about 1.4% global total strain, also Sec. F reaches the end of Lüders plateau and enters into the strain hardening part of the stress – strain curve.

Finally, a much more homogeneous distribution of strains is observed when the global strain is sufficiently big to allow all the sections to reach yielding.

Regarding the strain distribution during cycling, it can be noted that even the cycling strain range, before second severe straining, is different between Section C (Strain range 0.46% approx.) on one hand, and sections F and I (Strain range 0.35% approx.) on the other hand. Nevertheless, as observed in 1st Full Scale Test, the differences among strain ranges are sensibly less marked than absolute straining differences in first tensile loading. Here, we can mention the same possible causes of the 1st GW FST, i.e. smoothing in strength difference, facilitated by different extents of strain hardening and Bauschinger effect. A specific work on cycling strength evolution of line pipe materials is hoped to clarify this point.

After the second severe straining, when all the sections reach a similarly high value of mean strain of cycling, also the strain ranges are closer in extent (0.44% to 0.47% tot. strain range).

Also in the present case, a different ratcheting evolution in the three instrumented sections is consequence of the, even small, unequal repartition of strain ranges on the three distinct pieces of line pipe before second
severe straining. The already mentioned threshold of 0.5% total strain range in longitudinal direction (corresponding to 0.1% plastic strain), before Cycle no. 80, is substantially reached only in Sec. C. Consequently, as observable in Figure 31, where the circumferential local strain reading in the three different sections are reported, Sec. C is exhibiting some ratcheting before Cycle no. 80, with a continuous, but small, cycle by cycle, increase of circumferential elongation. Sections F and I, on the other hand, are experiencing no un-reversed circumferential elongation.

After the second severe straining, as said, the stress range is very similar for all the sections and, consequently, the progressive expansion of the pipe, even if very small, has the same magnitude in any section.

Finally, to be noted that the off-shore type girth welds, adopted in the present full scale test, did not present any visible crack or other damage, as shown in Figure 32, even after the severe straining sequence above described and in presence of some ratcheting of the pipes.

5. CONCLUSIONS

The heavy wall line pipe material produced in Tenaris showed to resist the very severe condition of elastic-plastic cycling with limited and stabilizing softening. This has been demonstrated by on-purpose designed full thickness samples. After the severe cyclic straining, material showed to preserve satisfactory mechanical performances, with very limited loss of resistance with respect unstrained material.

Full scale testing in severe straining conditions showed that the full pipe is able to withstand operative internal pressures even in presence of the extreme envisaged straining. Due to the simultaneous presence of significant internal pressure and severe axial cyclic straining, biaxial ratcheting occurred in the various full scale test performed. The variety of test conditions experiences, allowed to confirm the validity of the practical rule about biaxial ratcheting that claims biaxial ratcheting became observable in extent (and hence worth of designer attention) when the axial cycling exceed the span of 0.1% plastic strain, approximately corresponding to 0.5% total strain span. This has been shown on the full scale tests of pure line pipe on the full scale tests including different sections of girth welded pipes.

Girth welds have been performed following WPS typical for on-shore prefabrication of double joint and in-line welding procedures. In both cases, the girth welds demonstrated to preserve their integrity even in the very severe cycling conditions.
Finally, the strain hardening capability of the material allowed to recover any inhomogeneity of strain distribution in the different segments of pipes consequent to the presence of Lüders elongation in the tensile curve of the heavy wall pipe material.

6. REFERENCES


