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MEASUREMENT OF RESIDUAL STRESS SHAKEDOWN IN PRESSURE/TENSILE ARMOUR WIRES OF FLEXIBLE PIPES BY NEUTRON DIFFRACTION

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ABSTRACT

The manufacture of unbonded flexible pipes (flowlines and risers) involves wrapping steel wires to create pressure and tensile armour layers. The forming of armour wires from vendor supply conditions to a helix shape on the pipe involves significant plastic straining and the wires that are wrapped onto the pipe are not unloaded. Therefore the armour wires in flexible pipes are expected to contain significant residual stress (RS) as a result of the plastic straining and loading during manufacture and placement. This may lead to detrimental effects on the strength, durability and the service integrity of the pipe. It is postulated that the unfavorable RS introduced during pipe manufacture reduces due to stress shakedown during the factory acceptance test (FAT) where the pipe is subjected to a high internal pressure.

This paper describes the first attempts to measure RS in the armour wires in unbonded flexible pipes. The key development is the use of a neutron diffraction method which allows the measurement of RS in-situ on the manufactured pipe through the whole wire sections. Pipe samples were prepared exposing the relevant metal layer and the measurements were performed on pipe samples taken before and after performing the pressurized FAT. The effect of the FAT on the shakedown of residual stress in pressure armour wires is discussed. As shown by the measurements, the elastic strains and stresses in the pressure armour wires are much larger in the hoop direction of the pipe (i.e. along the length of the wire) than radial or axial to the pipe. In pre-FAT pipe the hoop stresses are essentially tensile on the extrados and compressive on the intrados. The results have shown that the FAT reduces the hoop strains and stresses to approximately 1/3 of their as manufactured level.

INTRODUCTION

Flexible pipes are widely used in the offshore oil & gas industry to transfer crude petroleum products and service fluids to and from the seabed and floating vessels and between floating facilities. These are long tubular structures designed to withstand relatively high internal pressure and axial load with sufficient flexibility to move under rigorous multi-directional dynamic loading exerted by random sea conditions. The pipes are expected to provide over 20 years of reliable leak-free service in harsh seawater environments with minimum maintenance.

As shown in Figure 1, the flexible riser is of unbonded multi-layer construction comprising several metallic and polymer layers. Whilst the internal polymer layer provides a leak-free boundary (fluid barrier) for the transporting medium the metallic layers, the Flexlok™ pressure armour, Flextensile™ tensile armour and the carcass, provide hoop, axial and collapse strength for the barrier respectively. The polymer anti-wear layers are used to prevent direct contact between the metallic layers and the polymer outer sheath gives protection from external damage. Accurate design and proven durability of metallic layers are crucial in order to maintain the integrity of the pipe for dynamic service and to assure the leak free functioning and safety of offshore riser systems.

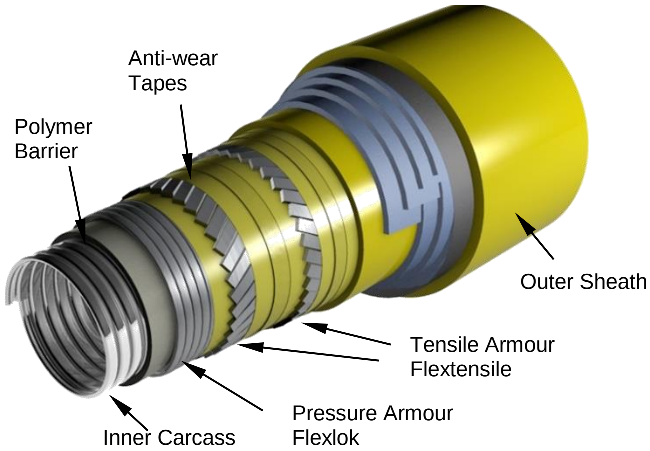


Figure 1: Unbonded Flexible Pipe Structure

Pressure armour (Flexlok), which gives hoop strength, is constructed by wrapping two profiled section wires with a low helix angle (close to 90°). The interlocking arrangement of the wire section allows the necessary axial movement of the layer to provide bending and twisting flexibility of the pipe. The tensile armour layers are constructed using several rectangular shaped wires (Flextensile) which are wrapped parallel to the pipe axis at a larger helix angle (between 40^o and 50^o) to give axial strength. These layers are repeated several times with different helix shapes to provide the necessary axial and torsional stiffness, internal pressure and water depth capacity of the pipe.

The design of pressure and tensile armour in flexible pipes is performed to comply with the guidelines provided in the American Petroleum Institute design specification for flexible pipes API 17J [1]. This code gives a recommended practice for selecting relevant loading cases, evaluating the maximum stress and dynamic stress ranges for each layer, material requirements and material utilization factors that need to be considered for various service applications of the pipe. It is anticipated that during service the stresses in pressure and tensile armour wires are within acceptable limits and the evaluation of stresses in the wires is sufficiently accurate to predict the fatigue durability of the wires and overall integrity of the pipe with high confidence. The presence of unknown levels of residual stress in the wires makes this a difficult task [2]. Consequently the aim of this paper is to quantify the residual stresses in the wires and to assess the extent of their relaxation by the FAT.

RESIDUAL STRESS IN ARMOUR WIRES

The Flexlok and Flextensile wires are manufactured from forged carbon steel ingots by hot rolling followed by cold rolling to final shape. Finally the wires in coils are batch annealed at the vendors before being supplied for pipe manufacture. During manufacture of the pipe these wires are taken through a torturous deformation path, bent several times in different planes, causing the wires to undergo significant cyclic plastic straining. Final wrapping of the wires to the pipe involves bending of the wires beyond their yield limit without allowing any recoil or unloading. Consequently, the armour wires wound in the final product contain unknown levels of RS and stored elastic energy.

The knowledge of RS distribution in the wires of the final product is essential in order to estimate the actual dynamic stress behavior in the structure and the maximum safe pressure and acceptable dynamic bending cycles that can be applied to the pipe during service. Therefore proper assessment of RS in armour wires is a key requirement to improve the current design procedure for pressure and tensile armour. Proper control of RS in the final product would enable improved safety and increase dynamic durability. The presence of compressive RS is considered to be beneficial in general although the tensile RS at highly stressed regions can be detrimental as it exacerbates the cyclic plastic strain accumulation under dynamic loading. On this basis, the beneficial or detrimental effects of RS in the pipe cannot be properly evaluated without knowing the actual RS distributions in the armour wires.

Currently there is no established method to evaluate RS in the armour wires of manufactured pipe although several attempts have been made to predict the straining behavior of the wires during pipe manufacture [3, 4]. The work based mainly on finite element analyses has indicated that the RS induced in the wires during the manufacture of the pipe can be significant and it is hypothesized that this can adversely affect the durability of the pipe under dynamic service. These analyses have also indicated that stress above the nominal yield stress of the wire material could be trapped in the wires in the manufactured pipe and additional stresses superimposed due to service loading would increase the stress beyond what would be acceptable limits of material utilization stipulated in API 17J.

API 17J requires all flexible pipes to be subjected to a FAT following manufacture. During FAT the pipe is over pressurized, approximately 1.5 times the design pressure for dynamic risers and approximately 1.25 times the design pressure for static flowlines. API 17J also allows the average stress in the wire section to increase up to 90% of the UTS of the wire material during the FAT. It has been postulated that the RS introduced in the wires during pipe manufacture is favorably redistributed (shakedown) during FAT [3]. It is expected that the RS in the wires after FAT is significantly lower and, properly handled and operated, the wire material is not subjected to any additional plastic straining during subsequent installation and service loading [3].

According to current design procedures the stresses in the wires and the deformation of the pipe during FAT and service conditions are evaluated without considering the RS in the wires introduced during pipe manufacture. Moreover, any fatigue or durability analyses of the pipe structure under dynamic service conditions do not consider the RS in the wires. Acceptability of this design procedure relies on the previously mentioned premise that no additional plastic straining of the wires would occur during service loading. However, no experimental evidence has been generated to confirm this important principal or to understand the behavior of RS shakedown in the wires due to FAT. Within the work presented in this paper an attempt has been made to measure RS in the armour wires of a flexible pipe and evaluate the actual RS shakedown caused by FAT.

RESIDUAL STRESS MEASURING PROGRAM

Due to the importance of understanding the RS in armour wires of flexible pipes, we have undertaken a comprehensive research program to measure the RS in wires in the vendor supplied condition, evaluating the re-distribution of RS at each stage of wire deformation during pipe manufacture and measuring the RS shakedown by measuring the RS distributions in the wires before and after the FAT.

As previously mentioned the wires from vendor coils are deformed through a torturous path during the manufacture of the pipe. Firstly the wires from the vendor coils are re-wound to bobbins that fit in to the manufacturing machines. Secondly the wires from the bobbins are formed within the manufacturing machines to give the required pre-determined helical shape of the layer. Both processes involve sequentially twisting and bending the wires in different planes with significant plastic deformation. The measurement of RS in the wires before applying onto the pipe was performed by taking wire samples at different stages of wire deformation. At each stage of deformation the wires were strain gauged and approximately 200 mm length of wire sample separated by cutting the wire either side of the stain gauge. The release of elastic strain of the wire was measured from the change of strain gauge readings. We have investigated several different techniques for measuring the RS in the cut wire samples after elastic unloading. However, this paper is primarily concerned with the measurement by neutron diffraction of the RS shakedown of Flexlok pressure armour due to FAT.

MEASUREMENT OF RS IN FLEXLOK

Measurement of RS shakedown in Flexlok wires is extremely difficult and complex for a number of reasons. Firstly the Flexlok wires are embedded in the pipe inside the Flextensile layers which are applied to the pipe after wrapping the Flexlok. Therefore access to the Flexlok wires in-situ of the pipe is difficult. Even when the all outer layers are removed exposing the Flexlok layer it will only give access to the outer surface (extrados) of the wire. Secondly, the conventional RS measuring techniques cannot give sufficient information to study RS in these wires. Conventional destructive methods such as hole-drilling cannot measure the distribution of stress across the wire dimensions, while X-ray Diffraction can only measure RS near to the outer (extrados) surface of the wire. Therefore we have used the Neutron Diffraction method to measure RS in the Flexlok wires of pipe before and after FAT. It should be noted that a magnetic method which uses stress induced magnetic flux changes in ferromagnetic materials [5], has also been used however, the results of this work will not be presented or discussed within this paper.

RESIDUAL STRESS USING NEUTRON DIFFRACTION

Neutron scattering has played an important role in studying the structure and understanding the dynamics of condensed matter. The large penetration depth and selective absorption of neutrons make them a powerful tool for the NDT of engineering materials [6]. As such it was considered to be ideal for the measurement of RS in the Flexlok wires of the flexible pipe. The work was carried out at the European Neutron Facility [7] - Institute Laue-Langevin (ILL), Grenoble, France using the engineering beamline SALSA [8] shown in Figure 2.

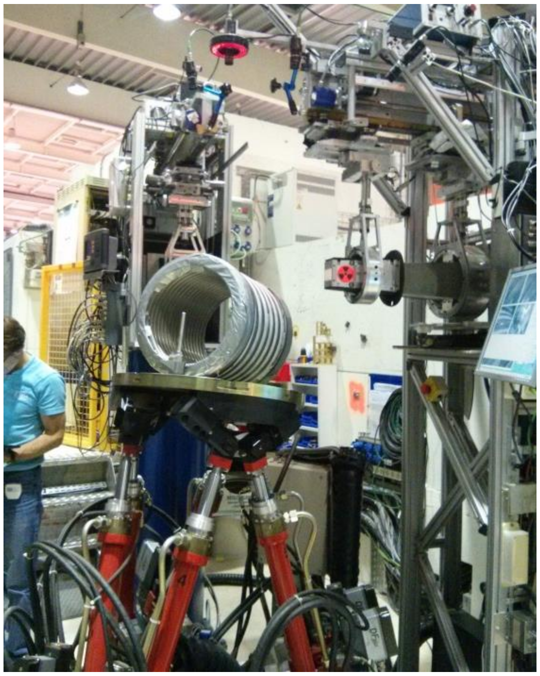


Figure 2: SALSA at ILL showing the pipe sample setup

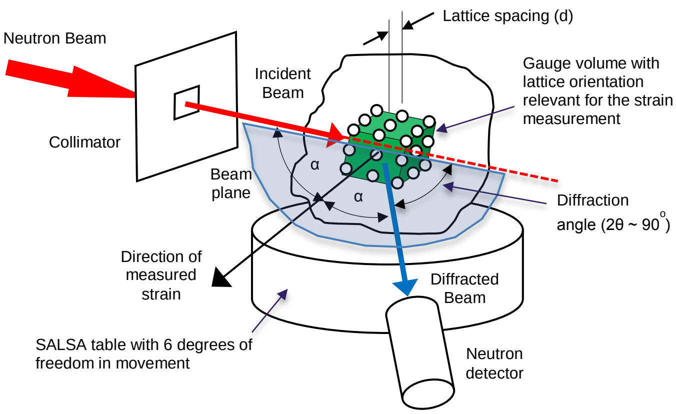
On SALSA a fine monochromatic beam of neutrons illuminates a gauge volume within the sample as depicted in Figure 3a.

When a polycrystalline metal such as carbon steel is illuminated by a monochromatic collimated beam of neutrons with wavelength of λ neutrons are scattered according to Bragg's law creating a diffraction peak at a specific scattering angle (2θ) as shown in Figure 3b. The lattice spacing (*d*) of the material can be inferred from the scattering angle: [9].

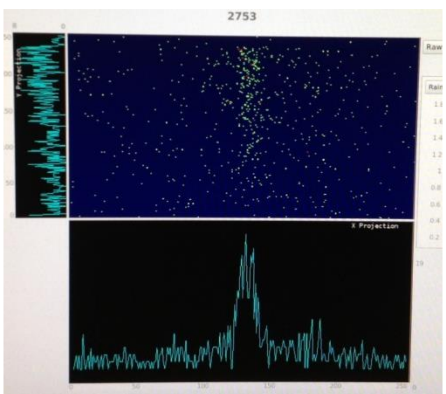
$$d = \frac{\lambda}{2\sin\theta}$$

The elastic strain (ε) is then derived from the change in the lattice spacing from the unstressed case (d_0):

$$\varepsilon = \frac{d-d_0}{d_0} = \frac{\sin\theta_0}{\sin\theta} - 1 \sim -\Delta\theta\cot\theta_0$$



(a) The strain measurement using neutron diffraction



(b) Typical neutron scattering image from SALSA

Figure 3: Principal of Strain Measuring

The direction of strain measured bisects the angle between the incident and diffracted beams. The procedure can be used to measure three orthogonal strains at any given location of the sample from which the three corresponding stresses can be calculated from Young's modulus, E, and Poisson's ratio, ν [10].

$$\sigma_1 = A\left[(1-\nu)\varepsilon_1 + \nu(\varepsilon_2+\varepsilon_3)\right]$$
$$\sigma_2 = A\left[(1-\nu)\varepsilon_2 + \nu(\varepsilon_3+\varepsilon_1)\right] \qquad A = \frac{E}{(1+\nu)(1-2\nu)}$$
$$\sigma_3 = A\left[(1-\nu)\varepsilon_3 + \nu(\varepsilon_1+\varepsilon_2)\right]$$

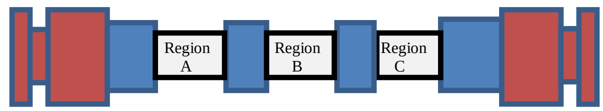
By translating the sample through the 2 x 2 x 2 mm gauge volume the strain could be mapped.

PREPARATION OF RS PIPE SAMPLES

The pipe samples on which the RS measurements were from a 12-inch internal diameter production riser designed for 40 MPa design pressure. Two pipe segments of approximately 20 m were cut (see Figure 4) from the pipe. One was end fitted and a FAT performed at 62 MPa internal pressure in the straight pipe position. Three RS samples were prepared from each pipe segment. The samples taken from the completed FAT pipe were referred to as post-FAT and the samples taken from the other pipe were referred to as pre-FAT.

(a) Flexible pipe segment before FAT (pre-FAT)

(b) Flexible pipe segment after FAT (post-FAT)



(c) Arrangement of test samples from the original pipe section

Figure 4: Sample Preparations for RS Measurements

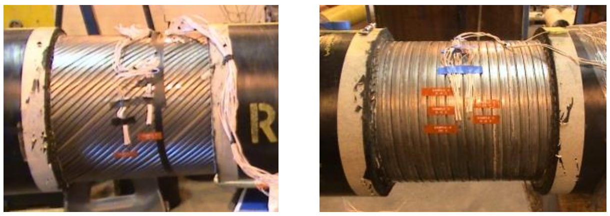
As mentioned above, three pipe samples approximately 0.5 m in lengths were prepared from each pipe for RS measurements. The sample preparation procedure is outlined here. As depicted in Figure 4c three samples were cut approximately 300 mm apart so that cutting of one sample did not affect the second sample. The outer layers of sample A were removed to expose the outer most Flextensile layer. Selected wires of this layer were strain gauged and two solid steel rings were welded at the ends of region A to secure the tensile wires in place. The outer layers of sample B were removed to expose the inner Flextensile layer. Similar to sample A, selected wires of this region were also strain gauged and two solid rings were welded at the ends of region B. The same procedure was performed for sample C where all layers outside of the Flexlok were removed. After welding of the steel rings to the sample region C, the three samples were cut outside the welded rings. The readings of the strain gauges were continuously monitored to check any unloading or distortion of the wires due to the welding and cutting processes. The different stages of sample preparation are shown in Figure 5. It should be noted although three samples were prepared from each pipe only two (one with the Flexlok exposed and the other with the inner Flextensile exposed) were used for the RS measurement by neutron diffraction.

As mentioned previously during this investigation, the deformation and RS state of two wires (one Flexlok and one Flextensile) was continuously monitored from the vendor supply condition to manufacture of the pipe. These specific wires were identified and marked (white for Flexlok and blue for Flextensile) and RS measurements of both the pre-FAT and post-FAT pipe samples performed using these wires.

MEASUREMENT OF STRAIN

Although the RS measurements were performed for both the Flexlok and Flextensile during this investigation, only the study of the Flexlok wires are presented and discussed in this paper.

(a) Exposing outer Flextensile and welding solid rings



(b) Exposing inner Flextensile and Flexlok

(c) Pre and post-FAT Flexlok RS samples after preparation

Figure 5: Residual Stress Sample Preparation Procedure

For the measurements of strain three orthogonal directions were identified as shown in Figure 6. These were defined as hoop, axial and radial based on pipe coordinates. The relationship of the defined strain directions relative to the wire profile is shown in Figure 6.

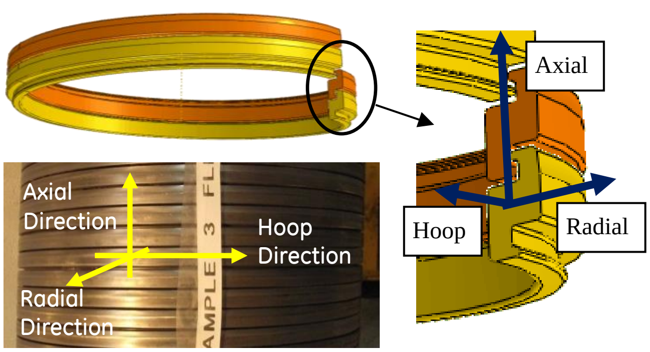
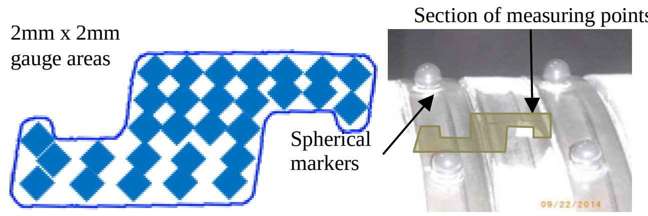


Figure 6: Definitions of Orthogonal Strain Directions

For the measurement of strain 29 co-planar gauge locations were identified on the Flexlok wire section. As depicted in Figure 7a, these were chosen to span the section without significant overlap with all the gauge volumes completely within the wire profile. Since the measurement of points near the extrados takes less time, more points were chosen in the extrados compared to the intrados.



(a) Strain measuring points (b) Markers for locating points

Figure 7: Definition of Strain Measuring Points

The calculation of stress requires the measurement of three orthogonal elastic strains at each gauge point. This required meticulous setting up of the pipe sample in specific orientations. This was achieved by an ingenious method. The focusing of the neutron beam on a specific gauge point was achieved by using four fixed spherical markers attached on the outside of the pipe (see Figure 7b). The plane of the measuring points and the exact location of each gauge point with respect to these spherical markers were established using a coordinate measurement machine (CMM) prior to setting up the sample on the SALSA stage. These four markers were used to orientate the pipe sample on the SALSA equipment and the CMM measurements were used to move the sample from one gauge point to another in a sequential manner. The scanning time for an individual gauge point varied from a few minutes to several hours depending on the distance the neutron has to travel through the Flexlok material before entering the detector. The number (29) of measuring points was determined so that the majority of the measurements could be completed within the limited neutron beam time allocated for this study. The strain measurements of the Flexlok wire in three orthogonal directions are explained in the following sections.

Measurement of Hoop Strain

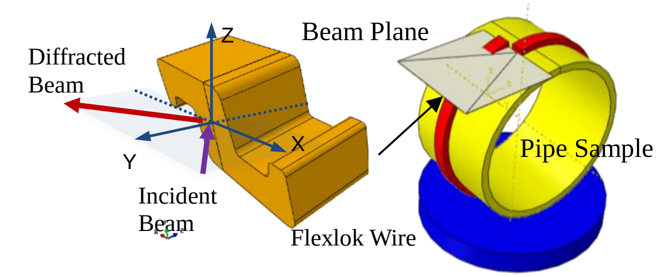
The measurement of hoop strain required that the wire section was positioned perpendicular to the plane of the beam. This significantly increased the path length of neutrons through the metal making the hoop strain measurement difficult and time consuming. To reduce the scan time the plane of the measuring section was orientated 10° to the beam plane, as shown in Figure 8a. This significantly reduced the scanning time and improved the signal to noise ratio of the diffraction peak. The actual pipe arrangement is shown in Figure 8b.

Measurement of Axial Strain

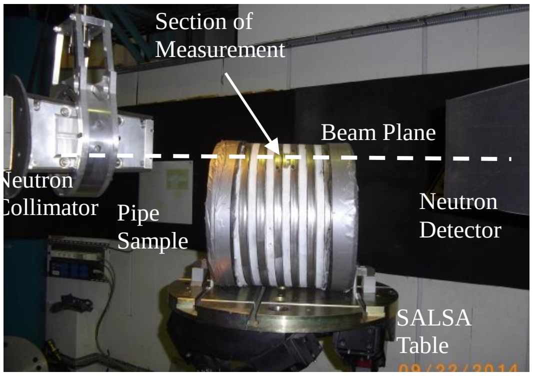
The measurement of axial strain also required the beam plane to be oriented parallel to the axial direction of the pipe. To reduce the neutron path length and thus shorten the scan time the pipe sample was tilted so that the axial direction of the pipe was inclined 10° to the plane of the beam, as shown in Figure 9.

Measurement of Radial Strain

The measurement of radial strain was the easiest and quickest as it required the axis of the pipe to be perpendicular to the beam plane, as shown in Figure 10.



(a) Beam Plane Relative to Flexlok Wire and Pipe Sample

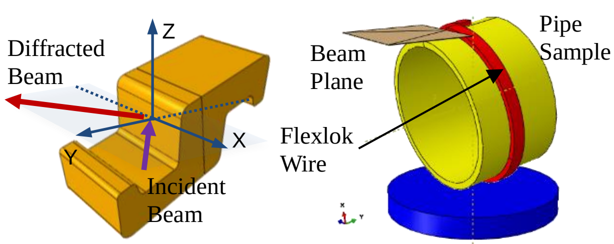


(b) Pipe Setup on SALSA Equipment

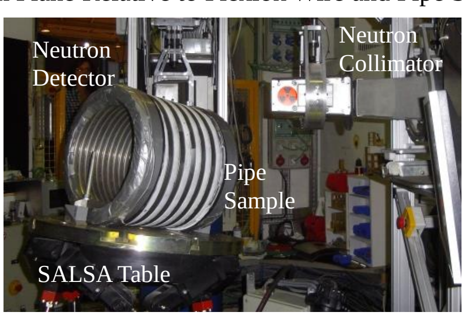
Figure 8: Setup on SALSA for measuring the hoop strain

Estimation of the stress free diffraction angle θ_o

The measurement of diffraction angle θ_o for all three strain directions of the wire was performed using a 2 mm thick slice cut from the Flexlok wire. Several slices were stacked and the measurements were performed for each slice and at each gauge point for all three strain directions.



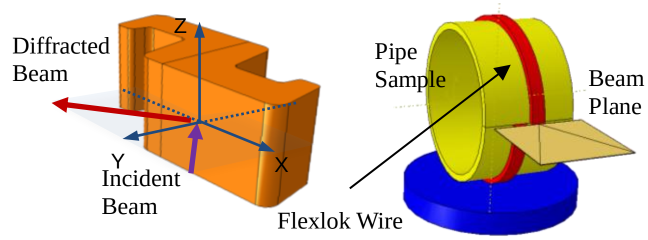
(a) Beam Plane Relative to Flexlok Wire and Pipe Sample



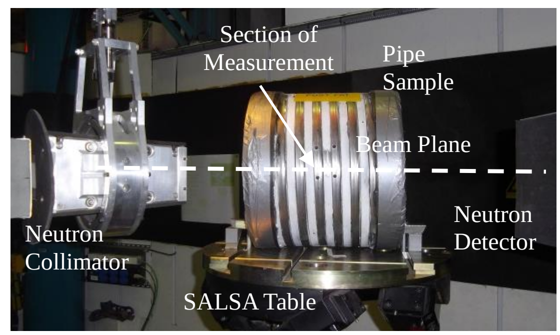
(b) Pipe Setup on SALSA Equipment

Figure 9: SALSA Setup for Measuring Axial Strain

The measurements of θ_o showed a small variation in the value d_0 between different points on the wire section. Due to this a global value of the stress-free lattice parameter, d_0, was assumed in the analysis presented in this paper. The stress free lattice parameter d_0 can vary for a variety of reasons and methods for obtaining d_0 when using diffraction to measure residual stresses have been detailed in [10]. Further studies are currently being undertaken to quantify whether any variation in d_0 exists over the cross-section of the wire. For this reason, the results in this paper should be regarded as a preliminary analysis.



(a) Beam Plane Relative to Flexlok Wire and Pipe Sample



(b) Pipe Setup on SALSA Equipment

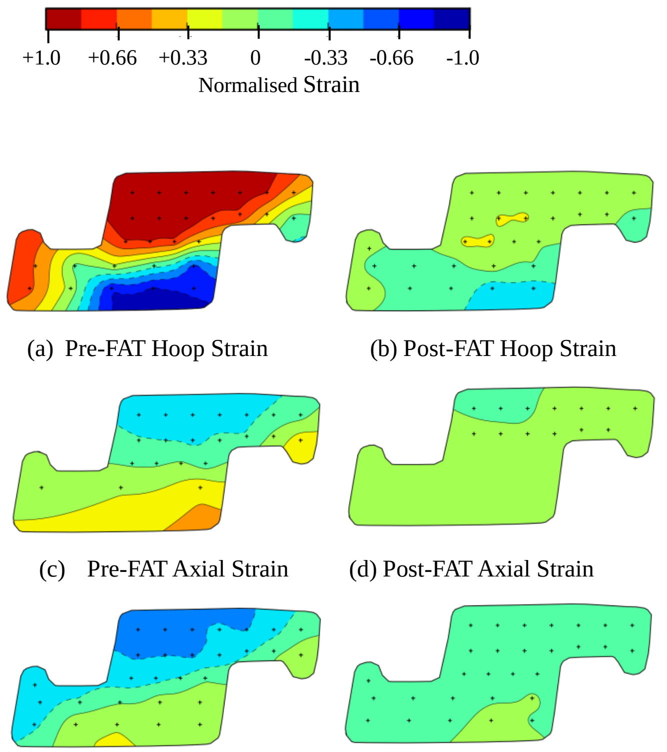
Figure 10: Setup on SALSA for measuring radial strain

PRE-FAT AND POST-FAT STRAIN RESULTS

The pre-FAT and post-FAT strain results for the Flexlok obtained from the neutron diffraction measurements [12] are graphically presented in Figure 11. For both cases three strains, hoop, axial and radial, are presented as contour plots drawn to the same strain scale. The results show that the hoop strain in the pre-FAT Flexlok is significantly higher compared to other strain directions as one might expect. The plots are normalized to the pre-FAT hoop strains so that all the plots can be easily compared.

The presented results are normalized using the maximum tensile strain (red colour) and maximum compressive strain (blue colour) of the hoop strain distribution in the pre-FAT sample. The dots indicate the gauge points that actual neutron data were collected.

It should be noted that the strain measurements were made only at gauge points (dots in Fig 11) and these results are extrapolated and interpolated to create the maps in Figure 11. This procedure assumed that the strain distribution in Flexlok before and after FAT is gradual and without localized high or low hot spots.



(a) Pre-FAT Hoop Strain (b) Post-FAT Hoop Strain

(c) Pre-FAT Axial Strain (d) Post-FAT Axial Strain

(e) Pre-FAT Radial Strain (f) Post-FAT Radial Strain

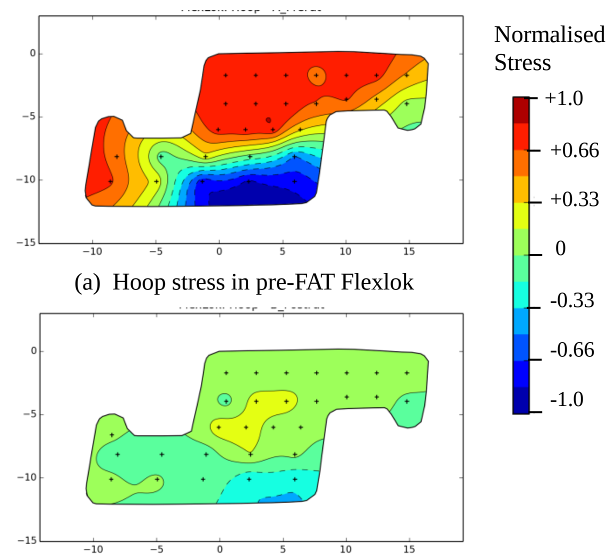
Figure 11: Pre and post-FAT Strain Distributions in Flexlok.

The results clearly show that significantly high hoop tensile and high hoop compressive strains exist in the extrados and intrados regions of the pre-FAT Flexlok wire. This is compatible with the severe bending of the wire to form the Flexlok layer. As shown by the results, these high strains are significantly reduced after FAT confirming the model prediction of strain shakedown during FAT. In fact the maximum tensile and maximum compressive hoop strains post-FAT are approximately one third (1/3) of the pre-FAT values. Moreover, it can be noticed that the maximum hoop strain in the post-FAT Flexlok occurred at mid thickness, away from both the extrados and intrados surfaces.

CALCULATION OF RESIDUAL STRESS

The strain results in Figure 11 have been used to calculate hoop stress in Flexlok. The calculated hoop stress values of pre-FAT and post-FAT Flexlok are shown in Figure 12. As in the case of strain plots, the results in Figure 12 are also normalized using the maximum tensile and maximum compressive hoop stresses of the pre-FAT Flexlok.

The hoop stress results also show that the high tensile stress in extrados and high compressive stresses in intrados of the wire are reduced to approximately one third of their pre-FAT values after the FAT. The stress distributions after shakedown also show that the highest hoop stress in the wire after FAT occurred at mid-section, away from both the extrados and intrados.



(a) Hoop stress in pre-FAT Flexlok

(b) Hoop stress in post-FAT Flexlok

Figure 12: Pre and post-FAT Hoop Strain in Flexlok

It should be noted that the actual strain measurements for axial and hoop directions were made on approximately 10^{o} inclined planes. The stress calculations were done neglecting this difference in strain orientation. This could change the stress predictions however, the error is stress calculation considered to be small.

CONCLUSION

The presence of RS in the armour wires of flexible pipe can significantly affect the fatigue performance of the wires and the service durability of the pipe. The RS in the wires are created during the pipe manufacturing process and there is currently no established procedure to evaluate RS in the wires. As such the effects of RS are not properly accounted for in the design of the armour wires in flexible pipes.

Within this study an attempt has been made to measure RS in armour wires using a neutron diffraction method. As presented in this paper, this highly advanced non-destructive technique was used successfully to measure three orthogonal strains in Flexlok wires while held in place on the flexible pipe. The procedure allowed measurement of strain in a whole wire section and gave a good picture of the RS distributions in the pre-FAT and post-FAT Flexlok for the first time. The data obtained for Flextensile wires will be presented in a later paper.

The elastic strains and stresses are much larger in the hoop direction of the pipe (i.e., along the wire) than radial or axial to the pipe. The strains are consistent with bending across the diagonal of the wire (i.e., the neutral section lies inclined in Fig 12). The stresses are essentially tensile on the extrados and compressive on the intrados. We have shown that the FAT reduces the hoop strains and stresses to approximately 1/3 of their as manufactured level.

Several studies have been performed to predict the RS in the pressure and tensile armour of wires in Flexible pipes. Almost all of these studies are based on finite element analyses and very few are involved in the actual measuring of RS in the wires of the pipe. Due to the lack of reliable experimental data there was no way to establish the validity and accuracy of the RS FE model predictions. As far as we know this study is the first attempt to measure RS in the armour wires, especially measuring the RS in the whole wire section and evaluate the effect of FAT on the shakedown of RS.

The knowledge developed through this study allows validation of FE models developed for the prediction of RS. Moreover the results show the effect of RS shakedown during FAT, allowing the assessment of the validity of fatigue analysis procedures used in pressure and tensile armour designs. It is believed that a proper understanding of the distribution of RS and of the way that this is developed in the wires during manufacture will enable the development of new design guidelines to increase confidence in durability analyses and improve the manufacturing route to obtain beneficial effects of the known RS. The knowledge gained through this investigation would be extremely useful in the assessment of safety and development of larger diameter high pressure pipes for deep water oil exploration where the safety margins of current design procedures are not well understood.

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