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NEW METHODOLOGY FOR FLEXIBLE RISER END-FITTINGS FATIGUE ASSESSMENT BASED ON REMOTE S-N CURVES

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ABSTRACT

Production of oil and gas in the Brazilian pre-salt will face several technical challenges. One of them that is a major concern is the fatigue life of top risers end-fittings. The new ultra-deep water fields will require a complete new fatigue assessment methodology with higher accuracy. Besides that, the historical data of failure for this sort of equipment shows that the current methodology is not quite optimized for floating units operating in deep water fields. With this, even worst results are expected in ultra-deep water fields.

During its assembly inside the end-fitting, the tensile armor wires need to be folded, unfolded and set in position using epoxy resin. This assembly process involves localized plastic deformation and as consequence of this produces a complex residual stress field and also introduces an elastic stress to maintain the wires in position. Both stresses are not actually taken into account in the current fatigue assessment methodology.

Therefore, the aim of this work is to develop and evaluate a new fatigue assessment methodology for top risers end-fittings based on remote S-N curves. The proposed methodology takes into account both residual and assembly elastic stresses. The effect of stress concentration on the tensile armor wire at the region with localized plastic deformation is also evaluated. Basically, the objectives of this investigation will be achieved through the construction of remote S-N curves using a test box that contains the deformed wire embedded in resin representing a single wire physical 2D model of an end-fitting, the so called mid-scale testing. For this investigation, a six inches API end-fitting was selected because it is widely used and most available in the market.

The results produced here indicated that the localized plastic deformation imposed during the folding and unfolding process has a very important detrimental effect on the flexible risers end-fittings tensile armor wires fatigue life, which makes mandatory a revision of the current four-point bending fatigue assessment methodology.

INTRODUCTION

Flexible risers are subsea equipment used to transport oil and gas from the wells to the production units. End-fittings are employed to connect them to both extremities and also to join them to form a long pipeline when that is the case. Flexible risers net weight combined with strong sea currents impose to the end-fittings high cyclic loads, which can lead to catastrophic fatigue failure of the tensile armor wires.

Some studies have been carried out to understand the end-fitting components mechanical behavior under specific stress states [1, 2]. Full scale cyclic tests have also been used to evaluate the fatigue performance of flexible risers including the end-fittings [3, 4]. Previous studies have shown that the stress state within a loaded end-fitting is complex, composed not only by the service loads but also by residual and assembly elastic stresses [5].

During the assembly process of the flexible pipe end-fitting, within the objective of provide good access to internal layers of the structure for the mounting of the seals, the two armor wire layers are folded and unfolded as showed on Figure 1. This manufacturing procedure imposes a high degree of localized plastic deformation, which creates a complex stress state with residual stresses, mounting stresses and an important effect of stress concentration.

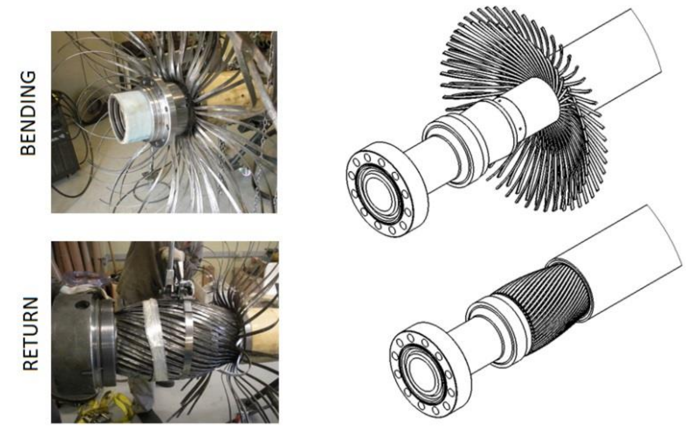

Figure 1- Tensile armor wire forming process during a typical end-fitting assembly.

Therefore, in order to better understand the stress distribution within the end-fitting, static mid-scale testing was developed [6]. These tests employ in fact a simplification of an end-fitting, i.e. only the region comprising one wire from the tensile armor is used as a 2D structure. Indeed, the concept employs a metallic box that contains a "slice" of a real end-fitting as shown on Figure 2. This strategy provides more reliability for the tests as the number of variables is reduced. The main objective of the mid-scale testing is to compare different assembly configurations of the tensile armor within the end-fitting and its behavior as it is loaded statically [6, 7].

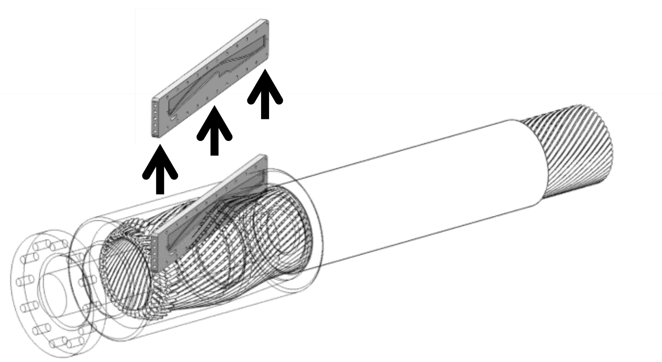

Figure 2 – Mid-scale 2D box sample concept.

The testing box comprises the external structure of the end-fitting and a cavity that simulates the wire 2D positioning all covered with resin for anchoring. There are two critical regions of stress concentration in the box, i.e. on the wire's tip (there is a geometric feature which depends of the manufacturer used to anchor the wire) and on the plastically deformed region which was as explained before folded and unfolded to access the internal layers and provide sealing (end-fitting entrance).

Most of the failures in operation of flexible risers have occurred in the tensile armor within the end-fitting, more precisely at the plastically deformed region [3]. Controversially, mid-scale static tests have produced fracture on the geometric feature at the wire's tip [6, 7]. The reason for that discrepancy might be related to the fact that fatigue is the cause of the failures in service while in laboratory the wires were subjected to static loads.

Therefore, in order to reproduce more accurately the service tensile armor failure in the end-fitting and consequently be able to optimize the fatigue assessment methodology, a 2D mid-scale testing is proposed here to evaluate the plastically deformed region fatigue performance through remote S-N curves.

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials

For this experimental study, the material used is a high strength low alloy steel close to a SAE 1070 cold drawn flat wires. To fill up the testing box made of SAE 1045 carbon steel and anchor the wire samples, a commercial high compression strength epoxy resin was used.

Monitoring

To monitor the dynamic tests, two electrical resistance strain gages were placed outside the box at its entrance on each side of the wire as suggested by Vargas [8]. The mean strain was used for the remote S-N curve construction. To measure the temperature during the resin application and curing, two thermocouples were employed, i.e. T1 at the plastically deformed region and T2 near the wire's tip. In addition, it was also monitored by the testing machine control system the sample displacement and axial load.

Test Procedure

The first part of the procedure is the sample assembly, which approximately reproduces the procedure used for real end-fittings (see Figure 1) with the difference that the work is carried out for a 2D condition as shown on Figure 3.

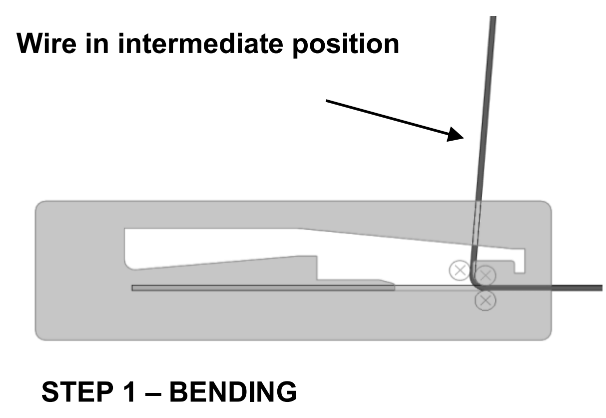

Figure 3 – Armor wire forming process, step 1 – bending.

To accurately measure the bending angle, a digital goniometer and a laser level were employed.

A hydraulic bending machine was used to bend the wires samples with precision and repeatability. The same machine was again used to return them to their final resting position (see Figure 4).

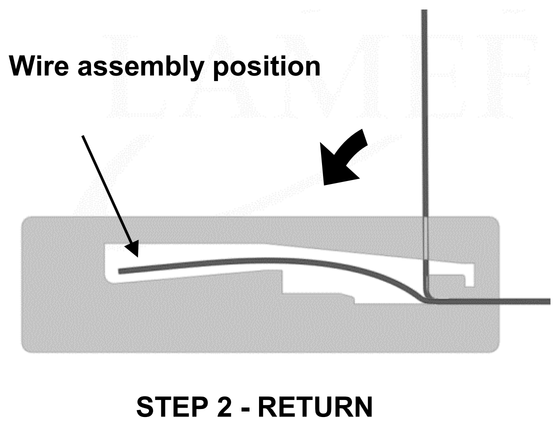

Figure 4 – Armor wire forming, step 2 – return.

Following bending, the testing 2D boxes were closed using fasteners and then filled with epoxy resin.

After resin curing, each testing box was attached to a servo-hydraulic MTS 100KN capacity test machine (see Figure 5), carefully aligned to the hydraulic cylinder and the wire clamp system, being only then the strain gages reset with no loads applied.

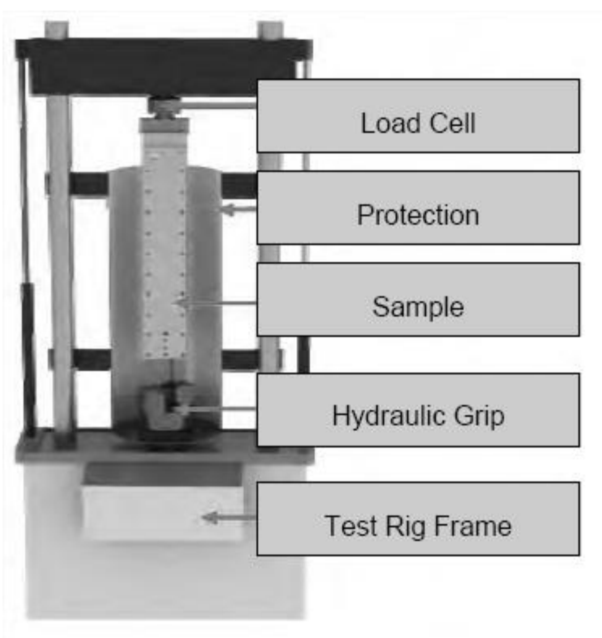

Figure 5 – MTS servo-hydraulic test machine and test setup.

The external strain gages correlation is used to ensure a correct sample alignment with the test equipment and therefore avoid bending loads on the wire outside the testing box. This strategy is crucial in the test setup, since bending loads could interfere in the results and generate a remote S-N curve with a high degree of dispersion.

Before the application of the fatigue loads, a factory acceptance test (FAT) is carried out in static mode at a rate of 2 mm per minute up to a stress of 77% of the steel wire yield strength (Sy). It is believed that this procedure is used for residual stress relieving and redistribution (homogenization). As soon as FAT is finished, the dynamic loads are applied following a sinusoidal wave with a test frequency of 10 Hz.

For strain gages and thermocouples data acquisition (DAQ), an HBM QUANTUM X was used with acquisition frequency of 100 Hz for the stain gauges and 1 Hz for the thermocouples. Also the MTS control sensor (LVDT and load cell) are replicated and acquired on the same HBM DAQ for perfect time sync of all sensors used on the tests.

The stop criteria of the fatigue tests are the complete wire rupture. After the end of each test, samples are disassembled and dissected in order to determine the exact region of failure. Scanning electron microscopy is used to confirm that the cause of failure is actually fatigue. The test result is only considered valid for S-N curve construction if failure occurred in the plastically deformed region.

Remote S-N curve

The remote S-N curve method consists of building fatigue S-N curves based on 2D box mid-scale tests using the indirect relation of the remote stress on the flat wire point outside the box (depicted as 1 on Figure 6) with the fatigue life (number of cycles) of the fractured region which is supposed to be the point where the wire is folded and unfolded (depicted as 2 on Figure 6). This approach allows the assessment of the real fatigue stress concentration factor caused by the folding operation and also by the stress (residual and elastic assembling) not considered in the calculations. Figure 6 shows the two regions of interest for remote S-N curves construction.

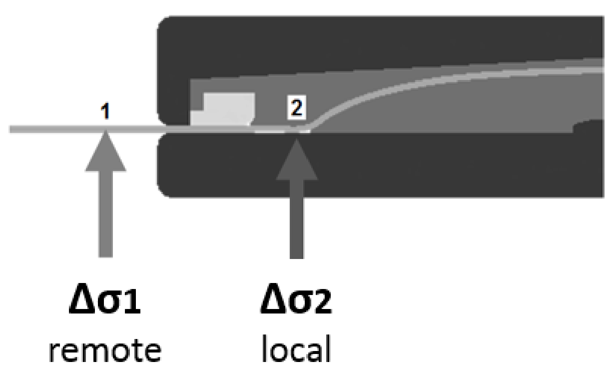

Figure 6 – Scheme of the remote region (where stress are measured) and the deformed region (where the number of cycles is measured).

Figure 7 shows a comparison between material four-point bending SN curve (wire FPBT) and the remote SN curve. The stress amplitude from the wire characterization four-point bending SN curve is matched to the remote SN curve at the number of complete cycles to determine the SCF. Figure 7 represent this approach.

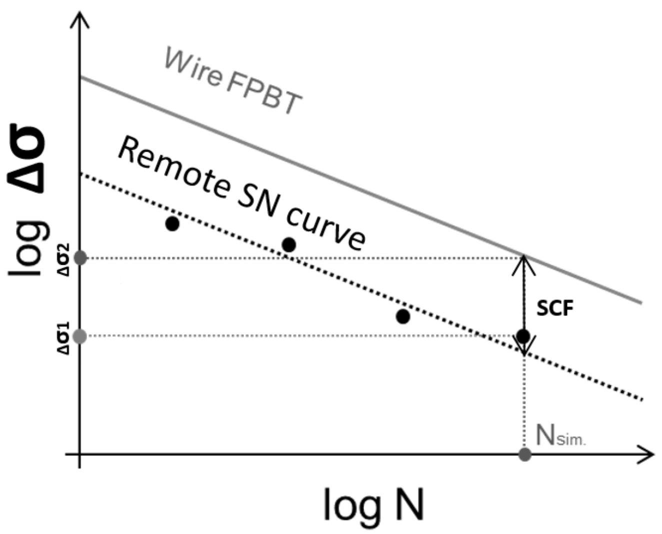

Figure 7 – Comparison between remote S-N 2D box mid-scale fatigue curve with the material four point bending (wire FPBT) S-N curve.

For the fatigue tests, different load amplitudes were applied in order to build a remote S-N curve for a specific set of bending parameters, which were bending radius of 30 mm and bending angle of 135º. Four samples for five stress levels were tested given a total of 20 boxes as shown on Table 1.

RESULTS AND DISCUSSION

The current fatigue assessment methodology is based on four-point bending fatigue tests. This methodology does not actually take into account the complex stress state found on flexible risers end-fittings. Otherwise, the remote SN curve methodology comes to fill this gap with more accurate fatigue material properties, for folded region, based on sixteen 2D mid-scale fatigue tests.

As commented before, most of the service flexible risers fatigue failures have occurred inside the end-fitting, more precisely on the point where the wires are bended for the end-fitting assembly. For all samples tested here, fatigue fracture has always initiated at this same position, which totally converge with field results.

Table 1 presents fatigue data in terms of stress amplitude (Δσ) and the number of cycles for total wire fracture.

Table 1 – Test results for the 2D box mid-scale fatigue tests.

Sample	Bending Radius	Failure region	FAT [kN]	Δσ	Cycles
BX-30-01	R30	Bending region	77% Sy	72% Sy	33500
BX-30-02	R30	Bending region	77% Sy	64% Sy	49594
BX-30-03	R30	Bending region	77% Sy	55% Sy	54260
BX-30-04	R30	Bending region	77% Sy	55% Sy	87625
BX-30-05	R30	Bending region	77% Sy	55% Sy	70502
BX-30-06	R30	Bending region	77% Sy	55% Sy	78138
BX-30-07	R30	Bending region	77% Sy	69% Sy	41000
BX-30-08	R30	Bending region	77% Sy	69% Sy	29100
BX-30-09	R30	Bending region	77% Sy	69% Sy	30475
BX-30-10	R30	Bending region	77% Sy	64% Sy	44027
BX-30-11	R30	Bending region	77% Sy	64% Sy	58088
BX-30-12	R30	Bending region	77% Sy	64% Sy	34183
BX-30-13	R30	Bending region	77% Sy	46% Sy	166419
BX-30-14	R30	Bending region	77% Sy	46% Sy	123915
BX-30-15	R30	Bending region	77% Sy	46% Sy	76840
BX-30-16	R30	Bending region	77% Sy	46% Sy	134791
BX-30-17	R30	Bending region	77% Sy	38% Sy	1077415*
BX-30-18	R30	Bending region	77% Sy	38% Sy	1047954*
BX-30-19	R30	Bending region	77% Sy	38% Sy	198708
BX-30-20	R30	Bending region	77% Sy	38% Sy	472375

**run out (1E6)*

Based on results presented on Table 1, the remote S-N curve for the 2D mid-scale samples is given on Figure 8. For comparison, the material (wire) four point bending S-N curve in air was also plotted on the same figure, in which points represent test data, dash lines are the mean curve and full lines are the project curves that consider two standard errors.

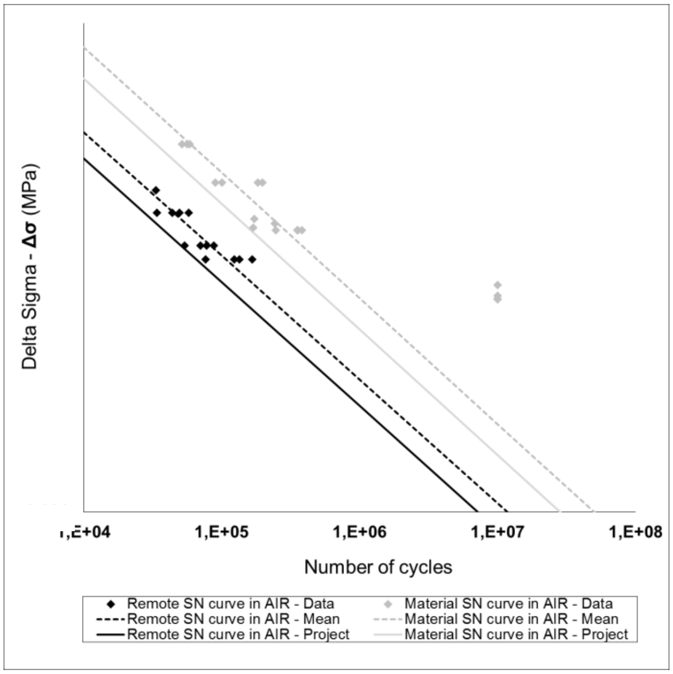

Figure 8 – Comparison between 2D box mid-scale test remote S-N curve and the material (wire) four point bending S-N curve.

The S-N curves calculated coefficients are given on Table 2. The coefficient *m* refers to the slope of the curves while r^2 is the fitting coefficient.

Since the slope coefficients are quite similar, it is reasonable to assume that the observed difference in fatigue behavior can only be attributed to the bending operation which creates a quite localized plastically deformed region and consequently imposes a stress concentration factor (SCF) which has reduced the fatigue life by a factor of seven (7). This is a very important result since it makes clear how distant the current fatigue assessment methodology is from real service conditions.

Table 2 – S-N curve coefficients.

Curve	m	r^2
Material S-N Curve	3,899	0,99
Remote S-N Curve	3,951	0,98

It is relevant tough at this point to stress out that the 2D mid-scale box strategy does not take into consideration the 3D capstan effect that is present in a real end-fitting. This effect is important to increase the normal force between the wires and the epoxy resin inside the end-fitting.

An alternative approach to avoid excessive and time consuming mechanical testing and still ensure good repeatability is numerical modeling using the finite element method (FEM). In fact, one would find even more promising the combination of a small and optimized set of mechanical tests with numerical simulation. In this way a complex numerical model could be developed and calibrated, yielding the possibility of varying the test parameters and compare results in quite a shorter period of time.

Furthermore, combining the numerical modeling results with data obtained from the material's characterization it is possible to generate a numeric (simulated) S-N curve for each sample condition. The stress amplitude from the wire characterization is matched to the stress amplitude obtained from the folded region of the model to determine the virtual number of cycles. Then, this number of cycles can be used with the stress amplitude from the region outside the test box (straight wire) to create a point on the SN curve. This procedure is repeated for different stress levels to generate the entire virtual remote SN curve.

CONCLUSIONS

The experimental approach adopted here aimed to evaluate a proposed method for fatigue assessment of flexible risers end-fittings. The new remote S-N curve methodology proved that the SCF is due only to the process of forming during the assembly of the component and showed a severe reduction on the fatigue life.

The following results can be presented:

- Mid-scale box remote S-N curve methodology proved functional for end-fitting fatigue assessment with consistent results;
- The new methodology allows comparison between different end-fitting geometries and materials with costs and time saving;
- The slope of the mid-scale remote S-N curve is the same of the wire material four-point bending S-N curve in air;
- The fit of the SN curve was compatible with a linear SN curve region;
- Standard deviation obtained was better than expected and comparable with a normal SN curve result.

NOMENCLATURE

SCF – Stress concentration factor;
EF – End-fitting;
FEM – Finite Element Method.

ACKNOWLEDGMENTS

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REFERENCES

[1] Smith, R. et al.: "Fatigue Analysis of Unbonded Flexible Risers with Irregular Seas and Hysteresis", OTC 2007, paper no. 18905.

[2] API.: "Recommended Practice for Flexible pipe", Specification 17J, 2000.

[3] Campello G.C., 2014, "Flexible Pipe End Fitting Anchoring System Design Methodology and New Technology Proposal", Philosophy Doctor Thesis, UFRJ – COPPE, Rio de Janeiro, Brazil.

[4] API.: "Recommended Practice for Flexible pipe", Recommended Practice 17B, 2000.

[5] Lopes, D.G., 2013, "Avaliação das Tensões Residuais Provenientes do Processo de Montagem de Conectores em Armaduras de Tração de Dutos Flexíveis", Master Degree Dissertation, Rio de Janeiro, CEFET/RJ.

[6] Sheldrake,T., 2008, "Development of the End Fitting Tensile Wires Fatigue Analysis Model: Sample Tests and Validation in an Unbonded Flexible Pipe", OTC 1997.

[7] Xavier, F. G., 2009 "Avaliação da vida em fadiga de um novo modelo de terminal conector para dutos flexíveis", Philosophy Doctor Thesis, - Rio Grande do Sul, UFRGS, Porto Alegre, Brazil.

[8] Vargas F.A. at al., "Experimental Comparison of Tensile Armor Wires Using Strain Gages and Fiber Bragg Grating Techniques", ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, Volume 6A: Pipeline and Riser Technology, San Francisco, California, USA, June 8–13, 2014, ISBN: 978-0-7918-4546-2.