STRAIN HISTORY EFFECTS ON FRACTURE MECHANICS PARAMETERS

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ABSTRACT

It is now well accepted that all welded structures contain flaws, and that these do not necessarily affect structural integrity or service performance. This is implicitly recognized by most welding fabrication codes which specify weld flaw tolerance levels based on experience and workmanship practice. However, these flaw acceptance levels are somewhat arbitrary and cannot provide quantitative measures of structural integrity, for instance how "close" a particular structure containing weld flaw is to the failure condition.
That concept is applicable to pipes components, and it is of special interest in cases in which the pipe is subjected to loads that produce important deformations. In particular the reeling process, used for installation of offshore lines, produce large cyclic plastic deformation on pipes.
The reliability of linepipes subjected to the reeling process must be guaranteed during and after the installation process, since failures in the oil and gas industry can have severe consequences.
It is therefore of primary importance to understand the effects of plastic straining cycles, produced during reeling process, on the material of the linepipes.

In this work, the effect of the strain history on the fracture mechanics parameters was studied. A theoretical model to determine the fracture mechanics parameters ($CTOD_{applied}$, $J_{applied}$) evolution through the strain cycles was proposed. The model is based on cyclic plasticity and fracture mechanics concepts.

A testing program was carried out using single edge notch tension (SENT) specimens to determine the material resistance curve and to study the effects of the strain history on the different fracture mechanic parameters and material properties.

1 INTRODUCTION

To install pipelines in offshore applications, the process of reeling is often used. The reeling is a method that provides a fast and efficient means of laying offshore pipelines. This process has an installation rate of 2 Km/h. Another feature of the reeling process is that it imposes high plastic deformation, due to extensive bending, in the pipe.
During the process the pipeline is subjected to cyclic loading. The welded pipes are reeled onto a drum, reeled off, aligned and straighten.

1.1 Plastic deformation cycles

1.1.1 Reeeling On

In the installation the first step involves winding the pipe, previously welded on shore, onto a drum or reel. The pipe is plastically deformed until it conforms to the curvature of the reel hub. Strains are such that the pipe yields over most of its cross section. The amount of plasticity depends on the outer radius of the pipe, the radius of the drum and the material properties of the pipe.

1.1.2 Reeling Off

During the unreeling the pipes begins to straighten as it moves between the reel and ramp of the aligner and the bending moment unloads elastically. The pipe then undergoes plastic bending such that the pipe is almost fully straightened in the span between the reel and the aligner.

1.1.3 Straightening

If the loads imposed on the pipe during the reeling off phase were release, the pipe would recover elastically, developing a residual strain in the outer fibers and a corresponding curvature. It is its curvature which must be removed by the straightening process. Straightening involves applying a reverse bending, so that when the loads released the pipe recovers elastically to be perfectly straight. The stress-strain relationship obtained in the reeling process is showed schematically in the fig. 1.

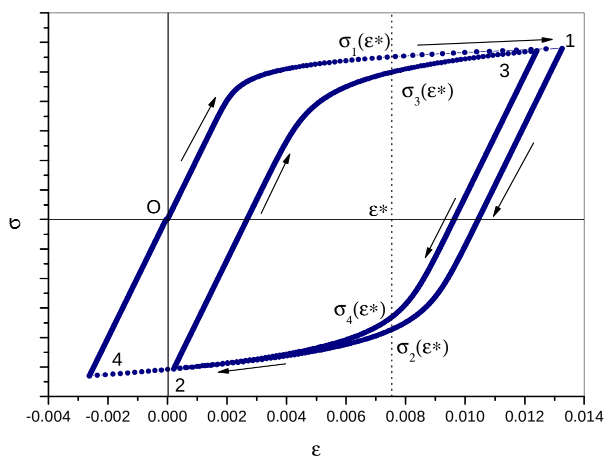

Figure 1: Schematic Strain History

It is of primary importance to understand the effects of strain history on the material properties and fracture mechanics parameters to assess the integrity of the component during the strain cycles.
The following points has to be addressed before applying a structural reliability analysis (SRA): i) after stress reversal(s) the history effect in material response is direct result of the history dependence of plastic deformation. If it is required to know the stress at a particular strain it is not sufficient merely to specify the strain, but also the deformation history that preceded this strain, i.e. the stress-strain relationship is not unique, ii) For monotonically increasing load case is know that J_{appl} (a, P) = J_{appl} (a, v), but when unloading and reloading are considered so the applied fracture mechanics parameters (J_{appl}, $CTOD_{appl}$) are not clearly defined, i.e. J_{appl} (a, P) ≠ J_{appl} (a, v).

In fig. 1 can be observed that for the deformation ε* four different values of σ can be obtained. It is unknown the stress that have to be considered to determine the J_{appl} for ε* and iii) the material fracture mechanics parameters (J_{mat}, $CTOD_{mat}$) evolution through the strain cycles is unknown, i.e. when the component in loaded, unloaded and reloaded or when deformation cycles are imposed is unknown if the value of the J_{IC} will be found at the same point or if is shifted to a new value.

2. CRACK DRIVING FORCE FOR COMPLEX STRAIN HISTORY

2.1 Proposed Model

A model was developed to describe the fracture mechanics parameters evolution through the strain cycles. An incremental method is proposed to calculate J (as a loading parameter) and CTOD (crack face displacement at a single point) evolution.

Beyond the point of stress reversal, for a generic point (P, v) the fracture mechanic parameter will be:

$$J = J_{rev} + \delta J \tag{1}$$

Where $|\delta J|$ is the value of J taking the reversal point as origin, and the axis (P′, v′), i.e. Load = $|P - P_{rev}|$ and displacement = $|v - v_{rev}|$.

$$|\delta J| = J(|P - P_{rev}|, a) \tag{2}$$

with $\delta J < 0$ for $d\sigma/dt < 0$ and $\delta J > 0$ for $d\sigma/dt > 0$

For a generic point B, beyond a reversal point A (loading +unloading):

$$J_B = J_A + \delta J_{AB} \qquad \delta J_{AB} < 0 \tag{3}$$

Where:

$-\delta J_{AB}$: is the value of J at load P_B or displacement V_B, referred to the new coordinate axes (P′, v′).

Defining:

$$P'_B = P_{rev} - P_B \quad \text{and} \quad v'_B = v_{rev} - v_B \tag{4}$$

So:

$$-\delta J_{AB} = J(P'_B, a)\delta J_{AB} = [K^2/E\,(P'_B) + (\eta/bB)Up(P'_B, v'_B)] \tag{5}$$

For a generic point C, beyond a second reversal point A′ (loading + unloading + reloading):

$$J_C = J_{A'} + \delta J_{A'C} \qquad \delta J_{A'C} > 0 \tag{6}$$

Defining:

$$P''_C = P_C - P_{rev} \quad \text{and} \quad v''_C = v_C - v_{rev} \tag{7}$$

So:

$$\delta J_{A'C} = J((P_C - P_{A'}), a) = K^2/E\,(P''_C) + (\eta/bB)Up(P''_C, v''_C) \tag{8}$$

Consequently:

$$CTOD = CTOD_{rev} + \delta CTOD \tag{9}$$

where:

$$\delta CTOD = dn(Y', n)\,\delta J / Y' \tag{10}$$

Y´ is the yield strength corresponding to that particular point. For the second stage, A-A´, (and consecutives) the effective yield stress will be –2Y, since the material must be stressed to –Y from an initial value of +Y.
This model is general for processes where the deformation evolves cyclically. The present work was made specific for the reeling process case, but the methodology may be applied in other examples with cyclic deformation.

2.2 Experimental model validation
An experimental program was carried out, tests were performed using single edge notch tension (SENT) specimens to study the effects of the strain history on the different fracture mechanic parameters.
The objective of the experimental work was to validate the proposed model that describes the fracture mechanics parameters evolution.

2.2.1.Material

X65 - Tube 355.4 x 22.2 mm

2.2.1.Mechanical Properties

Several tests were carried out to determine the mechanical properties, in table 1 are shown the results.

Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	α	n	Energy Impact (J)
475.8	564.6	32.6	6.09	7.09	330

Table 1: Material Properties

2.2.3.Specimen
A material´s fracture resistance is usually described by a single parameter, either K, CTOD or J-integral. It is however known that the stress and strain state at the crack tip is not fully characterized by such a single parameter alone but that the crack tip constrain, i.e. the degree of crack tip stress triaxiality, will also influence the fracture resistance.
Commonly used testing standards, e.g. BS 7448 [2] and ASTM E 1820 [3], describe methods for determining the fracture resistance from deeply notched SENB (Single Edge Notch Bend) or CT (Compact Tension) specimens. These specimens, both predominantly loaded in bending, have high crack tip constraint and will hence lower bound estimates for the fracture resistance that can be used for conservative fracture assessments for a large range of engineering structures.
During installation, pipelines are however predominantly loaded in tension even if the pipe is globally subjected to bending. It is therefore acceptable to determine the fracture resistance from a specimen with a crack tip constraint that is closer to the actual crack tip constraint in the pipe.
Single Edge Notch Tension (SENT) specimen has both a loading mode and crack tip constraint which is close to the loading mode and constraint for a crack in the pipe.
SENT specimens were used in two configurations: i) short crack (a/w=0.225) and ii) large crack (a/w=0.375).
Instrumentation (gauges) was attached on the specimen tested to determine: a) crack tip opening (2 sides), b) crack mouth opening (CMOD) and c) remote deformation (ε).

2.2.4 Results

The tests over the SENT specimens were carried out in a MTS test machine with a maximum load of 50 ton. Monotonic testing was performed to determine the resistance curves. Due the fact that the pipe is subjected to cyclic loading during the installation process, it was necessary to generate information about cyclic fracture mechanics parameters and material properties. In figs. 2-4 are shown results obtained in the tests and comparisons with the theoretical model of fracture mechanic parameters evolution were performed.

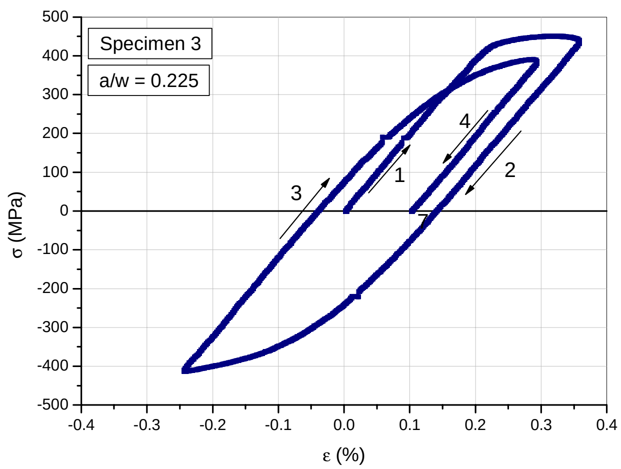

Figure 2: Stress vs. Strain diagram for SENT specimen. Short Crack.

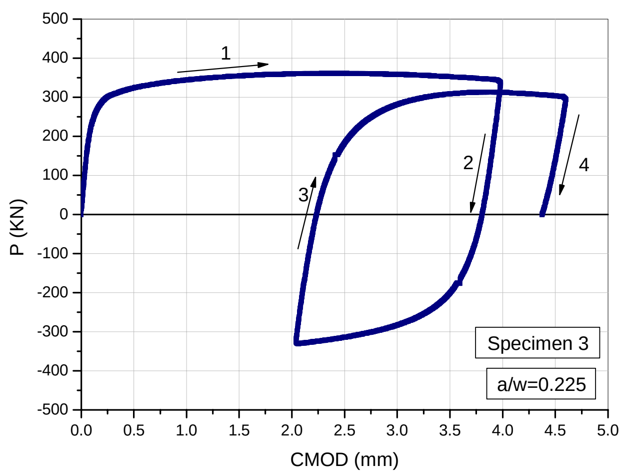

Figure 3: Load vs. Displacement diagram for SENT specimen. Short Crack.

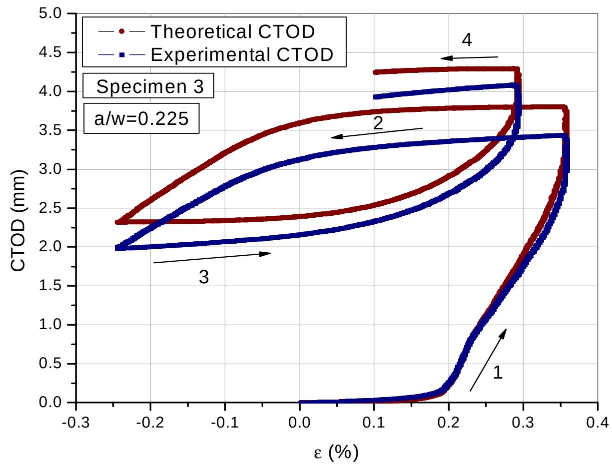

Figure 4: Comparison Experimental / Theoretical CTOD vs. Strain diagram. Short Crack.

3 REFERENCES

[1] H. A. Ernst, R. Bravo and J. Villasante, "Effect of the Yield to Tensile Ratio, Y/T, on Structural Reliability of Linepipes Subject to Bend Loading", CINI Report 2040/2003.

[2] BS 7448, *"Fracture Mechanics Toughness Testing, Parts 1-4"*, British Standard Istitution.

[3] ASTM E1820-99, *"Standard Test Method for Measurement of Fracture Toughness"*.