Analytical Verification of Requirements for Safe and Timely Lay-down of an Offshore S-Lay Pipeline Abandonment Head during Some Pipe-Lay Stops: A case study of Forcados Yokri Integrated Pipeline Project in Nigerian Shallow Offshore.

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Abstract

It is not often planned that an S-lay installation barge will stop operation for longer time than necessary. In some cases, one may think that stoppage will last for some minimal time. In some other time, it could be for an unpredicted number of days, especially when it is an industrial dispute or security crisis. This happens frequently in developing countries. This paper demonstrates the importance to always abandon pipelines on seabed when there are interruption in continuing pipeline construction, especially when such interruption are beyond the control of the engineering team. The result of this paper indicates that consequence of not doing so is very cruel to the structural integrity of the pipeline structure after the first twenty four (24) hours of exposure in West African Nigerian mild offshore weather condition. Environmental pollution and therefore safety of lives and properties may be jeopardized should the pipeline structure be used for oil or gas transport when such limits are ignored. Fracture mechanics approach is used on API 5L X52 of wall thickness of 0.5 inches pipeline structure. The pipeline was failed in a fatigue event due to wave loads in Forcados offshore in the Nigerian Niger Delta area. A 30-days wave data is employed in the analysis and result computations.

1.0 Background

A lay-barge was installing pipeline in the Nigeria shallow Forcados offshore. The project was part of the effort of Shell Nigeria to reduce gas flaring in the region. The project of pipe-laying was mobilized in 1999. In March 2004, an industrial problem took place. The pipeline was not abandoned as supposed due to the crisis. The barge was left with the pipeline hanging for six (6) months. On the 180th day, as unfair sea weather hit the area, the pipeline parted from the welded joint just after the Stinger [1].

Ordinarily, one would expect that due to the ductility of the pipe, the pipeline would at its worst undergo excessive twisting, bending and buckling. These were not obvious prior to the parting of the pipeline. The likely reason for the parting is believed to be the cyclic swell/wave loading on the pipeline joint over time, causing yielding of then the eventual failure.

Forcados offshore, similar to the rest of the West African Ocean is mild in nature. Environment of Offshore West Africa lacks locally generated storms, therefore storm surge is minimal and tidal current and swell dominate water level variations [2]

In pipeline installation design practice, static analysis is performed for various configurations of pipe-laying and the worst case is selected to perform the dynamic analysis which will include the Response Amplitude Operators (RAO) for the barge and the hydrodynamic loading on the pipeline itself. The Response Amplitude Operator is simply a measure of the Heave, Surge and Pitch of the barge relative to wave period.

In the authors' experience, the static and dynamic computations and analysis do not cover adequately the effect of number of cyclic wave loading on the girth welds on long exposure period, especially as certain degree of weld surface and buried imperfections are often allowed during pipeline fabrication.

In a normal practice, stoppage of offshore pipe-lay work mid-way is done by installing an Abandonment-head and then lowering this head to the sea bottom with an attached buoy for easy identification and retrieval. However, in Nigeria and other part of world where military/militant and industrial crisis could emerge at any time during pipe-laying, time is often insufficient to lay-down the pipeline as supposed. It becomes therefore reasonable to determine the limit of cyclic loading on pipeline that could endanger the integrity of pipeline structure.

The purpose of this presentation is to demonstrate the danger inherent in pipelines when exposed to cyclic loadings over a period of time. The paper reinforces a requirement that pipelines on S-Lay must be abandoned as soon as delay on site is beyond a reasonable period of time

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2.0 Literature review

The crack tip opening displacement (CTOD) of a pipeline segment with an external circumferential surface crack has been investigated by [3] under pure bend loading as well as bending with internal pressure. Though the loading considered in the investigation is not fatigue loading, the result indicated variation of CTOD with strain as approximately a simple linear relationship. The implication of the observation is therefore that CTOD will increase with increasing strain, be it strains from bending, internal pressure or fatigue.

Reference [4] agrees that the installation of pipelines under bending may alter the material properties and increase the weld defects, thus, reducing the fatigue life of the joints under operational loads. The work of [4] was based on cyclic bending processes as it occurs during reeling installationmethod. Lack of fusion and lack of penetration with varied dimensions in girth weld were considered. The work paid attention to localized deformation that occurs in the vicinity of the defect during reeling

Although, more bending stresses are found on pipeline in the reeling method but more cyclic loadings are encountered on S-lay installations between the over-bend and sag-bend especially at fairly higher depth of water (Figure 1). This is because the rate of pipe-laying is slower with manual welding and the wave action is always active. And when there are technical or industrial relation problems, the line with the girth welds containing defects could be exposed to the loading for longer period. This complicates the problem

3.0 Methodology

A related investigation as was performed by [4] for reel method is now carried out for S-lay installations. In attempting to present cyclic loading effect on the girth weld of S-lay pipeline installation, the following analytical approach is proposed:

Heave, H = H (t).

The Heave acceleration is of great interest as this is responsible for the rate of change of momentum of the S-part of the pipeline structure in the near-vertical direction, giving rise to the cyclic stresses.

Heave acceleration of the barge, 1) (

(1)

Examining the vessel at pipe laying condition, the submerged S-part of the pipeline between the Stinger and the sag-bend of the pipeline is tossed up and down in a cyclic manner with respect to the heave. The stress on this S-part is worked out:

Force on S-part as it tosses up and down due to heave = Submerged weight of S-pipeline in water + Net Mass x acceleration of the S-pipeline due to Heave.

$$= (m - \rho v)g + (m - \rho v)\, a_{barge} \qquad (2)$$

Where:

mg = weight of the S-pipeline in air

ρgv= upthrust on the S-pipeline

$(m - \rho v)\, a_{barge}$ =acceleration force on the S-pipeline due to heave m=mass of the S-part of the pipeline of the pipeline under consideration

v=outer volume of the s-part of the pipeline under consideration

ρ=density of water

a_{barge}= acceleration of barge stinger carrying the S-pipeline under consideration.

Then:

Stress on the S-pipeline under consideration, in water exposed to heave,

$$\delta = [(m - \rho v)g + (m - \rho v)\, a_{barge}]/A \qquad .(3)$$

Where A is the cross-sectional area of this pipeline under consideration

Equation (3) is related to the work of [5] as further described in the analysis section. The effect of the cyclic loading on girth weld in water exposed to wave action is then analyzed using typical API 1104 guideline.

4.0 Data

Sea State reports for the project in 2004 was unavailable. Wilkens Weather Technologies Weather Report 04 UTC May/June-2008, for a pipeline project in a close location is therefore used in the computation of the results [6].

5.0 Aanalysis

The following assumptions are considered in this work:

1. Pitching is minimal
2. Barge heave acceleration, a_{barge}= acceleration of the S-pipeline. (This is a good assumption, since the s-pipeline is assumed fixed by the lay-barge's tensioner).
3. The girth weld is assumed to contain minimum defect similar to the work of [4].
4. The position of the girth weld is mid way prior to the touch-down-point.
5. The cross-sectional area of the cresting or troughing parts of the sea wave is approximately half-ellipsoidal. This is fair assumption since the West African wave can be considered using a 1st order Stoke wave theory [7].
6. Vessel is positioned aft or bowed to the wave front.
7. The West African Swell characteristic applies such that wavelength is longer than the length and breadth characteristic of the lay barge and can be considered to follow the first order linear theory.
8. The pipeline between the over-bend and sag-bend is held by the vessel's tensioner such that forces are transmitted through the axis of the pipeline. See Figure 1.
9. Note that when the vessel undergoes high pitching, depending on subsea bottom condition, reasonable variation exists between barge heave acceleration and pipeline, the pipeline begins to 'bang' on the Stinger rollers causing high stresses on the pipeline. In this work however, it is assumed that this condition does not exist and the interest is on the girth weld lying between the Stinger (over-bend) and the sag-bend as shown in Figure 1.

Generally speaking, pipelines are built with materials of good ductility, but at the welded joints and Heat Affected Zone (HAZ), ductility is lower and can be characterized by J-fracture toughness measure or Crack Tip Opening Displacement (CTOD).

CTOD is related to J and following the work of [5]:

$$\frac{da}{dN} = c\,(\Delta J)^m$$

Where

$$\Delta J = \frac{\Delta K^2}{E^1} = \frac{(Y\Delta\delta\sqrt{\pi a})^2}{E^1}$$

And

$$E^1 = \frac{E}{1-v^2}$$

E=Modulus of elasticity of the pipeline

v= Poisson ratio

m is the coefficient of model influence and vary between 2 and 4 depending on the magnitude of the stress cycles

C is an empirical crack growth constant that depends on material elasticity, yield stress and fracture strength.

a=imperfection or crack length. (Note that in this paper we are assuming this length to be growing along the thickness).

Y is the imperfection characteristics

;

N is the cyclic loading

δ is the cyclic stress (4)

K=Fracture toughness.

$$\frac{da}{dN} = c\left[\frac{(Y\Delta\delta\sqrt{\pi a})^2}{E^1}\right]^m$$

Observe distinctively that if the initial size of our imperfection, $a_{initial}$ is known, the only critical variable required to identify the number of cycles to failure is $\Delta\delta$.

Consider that the cross-sectional area of the Cresting part of the sea wave is approximately half-ellipsoidal (Figure 2) such that Lay barge moored bow to or Aft of the wave front will have wave crest $r_1/2$ as it heaves the vessel, and simplifying the problem using a simple 1st order Stoke's wave theory, the following derivation is further made

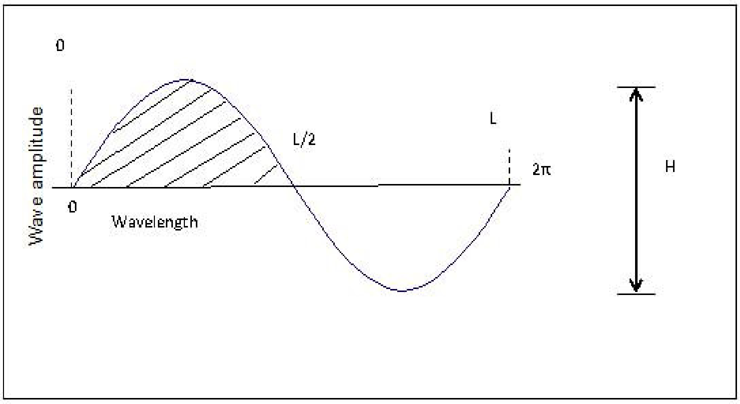

Figure 2. Crest volume of the wave. Crest – Trough Semi elliptical shape assumption.

Volume of the Cresting wave, $V_w = (0.5)(b_L/0.5L)(\pi\,(0.5r_1)r_2\,b_b)$.(6)

r_1 = wave height

r_2 = quarter wavelength (i.e. 0.25L)

b_b= barge characteristic breath along the water line and

b_L = barge characteristic length along the water line

L= wavelength

The factors (b_L/0.5L) is the relative dimension factor as the crest volumes are formed by a particular wave traveling crest to trough from the bow to the aft of the barge or vice versa through the length of the barge bottom, so that the shorter the wavelength relative to the barge length characteristic, the more the wave crest is peaked, the more the effect. The rest part of the equation is half the area of the ellipsoidal wave form. The equation then is the total volume of water crested as it heaves through.

Equation (6) can be re-written:

$V_w = 0.125\;\pi\; b_L\, b_b H$ (7)

Mass of this wave volume acting underneath the lay-barge, $M_w = \rho\, V_w$ (8)

Wave vertical acceleration for a linearized wave formulation, as given by [8] is:

$a_w = -\epsilon_0 g \kappa$ Sinh κ (z+d) Sin (ωt-κx)/Cosh (κd) (9)

ϵ_0=1/2 maximum wave height.

κ =wave number

z =depth variation (z = 0 at mean level, z = -d at sea bottom)

d= depth at sea bottom.

Therefore, wave-upward force under the barge due to the wave cresting volume= $M_w a_w$

From Newton's second law:

$$M_b' a_{barge} - M_w a_w = 0 \quad (10)$$

Where

M_b'= mass of the lay barge plus added mass in water

a_{barge}= barge acceleration

Giving:

$$M_b' a_{barge} = M_w a_w$$

$$a_{barge} = M_w a_w / M_b' \quad (11)$$

.

Observe that barge acceleration increases with reduction in mass of barge.

The time of the barge acceleration from trough to crest = 0.5 wave period =T/2.

Then, from Newton's first law;

$$\text{Heave max} = H_{max} = 1/2\ a_{barge} (T_c/2)^2 \quad (12)$$

T_c = Time within a period to reach crest from trough.

Equation 11 shows that a_{barge} can be used to determine the magnitude of the Heave as the barge tosses from trough to crest.

Equation 11, can be re-written as

a_{barge}= - (0.125 ρ $\pi B_B B_L$ H)($\epsilon_0 g \kappa$ Sinhκ (z+d) Sin(ωt-κx)/Cosh (κd))/ M_b']…………………(13)

Utilizing equation (13) into known variables of equation (3) and equation (7), it is possible to estimate the stresses induced by various sea state for given size of pipeline and barge characteristic in a girth joint

Date of Record		Period T/sec	Sig.H Hs/m	Hmax Hmax/m	Mean T/day Tmean	Avg.Hs/day Hs(mean)	Avg Hmax/day Hmax(mean)	Max Stress KN/m^2	Min Stress KN/m^2
31/05/2008	00hr	13	1.8	3	13.5	1.85	3.025	512	464
	0600hrs	13	1.8	2.9					
	12hrs	14	1.9	3.1					
	1800hr	14	1.9	3.1					
1/6/2008	00hr	13	1.9	3.1	13	1.8	2.95	510	465
	0600hrs	13	1.8	3					
	12hrs	13	1.8	2.9					
	1800hr	13	1.7	2.8					
2/6/2008	00hr	13	1.7	2.7	12.25	1.7	2.825	511	464
	0600hrs	12	1.7	2.8					
	12hrs	12	1.7	2.9					
	1800hr	12	1.7	2.9					
3/6/2008	00hr	12	1.6	2.7	11.25	1.6	2.625	512	463
	0600hrs	11	1.6	2.6					
	12hrs	11	1.6	2.6					
	1800hr	11	1.6	2.6					
4/6/2008	00hr	11	1.5	2.5	10.5	1.5	2.5	513	463
	0600hrs	11	1.5	2.5					
	12hrs	10	1.5	2.5					
	1800hr	10	1.5	2.5					
5/6/2008	00hr	10	1.3	2.2	9.75	1.3	2.15	509	467
	0600hrs	10	1.3	2.2					
	12hrs	10	1.3	2.1					
	1800hr	9	1.3	2.1					
6/6/2008	00hr	9	1.3	2.1	8.75	1.3	2.1	513	463
	0600hrs	9	1.3	2.1					
	12hrs	9	1.3	2.1					
	1800hr	8	1.3	2.1					
7/6/2008	00hr	8	13	2.1	12.75	4.375	2.4	503	472
	0600hrs	13	1.5	2.5					
	12hrs	15	1.5	2.5					
	1800hr	15	1.5	2.5					
8/6/2008	00hr	15	1.6	2.7	14.25	1.625	2.7	504	471
	0600hrs	14	1.7	2.7					
	12hrs	14	1.6	2.7					
	1800hr	14	1.6	2.7					
9/6/2008	00hr	14	1.6	2.7	13.25	1.525	2.65	507	470
	0600hrs	13	1.5	2.7					
	12hrs	13	1.5	2.6					
	1800hr	13	1.5	2.6					
10/6/2008	00hr	13	1.4	2.3	13	1.525	2.5	504	470
	0600hrs	13	1.6	2.6					
	12hrs	13	1.6	2.6					
	1800hr	13	1.5	2.5					

Date of Record		Period T/sec	Sig.H Hs/m	Hmax Hmax/m	Mean T/day Tmean	Avg.Hs/day Hs(mean)	Avg Hmax/day Hmax(mean)	Max Stress KN/m^2	Min Stress KN/m^2
11/6/2008	00hr	13	1.5	2.5	13	1.5	2.5	504	470
	0600hrs	13	1.5	2.5					
	12hrs	13	1.5	2.5					
	1800hr	13	1.5	2.5					
12/6/2008	00hr	12	1.4	2.4	11.5	1.35	2.25	504	471
	0600hrs	12	1.4	2.4					
	12hrs	11	1.3	2.1					
	1800hr	11	1.3	2.1					
13/6/2008	00hr	10	1.3	2.1	10	1.3	2.1	507	469
	0600hrs	10	1.3	2.2					
	12hrs	10	1.3	2.1					
	1800hr	10	1.3	2					
14/6/2008	00hr	9	1.3	2.1	11	1.3	2.125	504	471
	0600hrs	9	1.3	2.1					
	12hrs	13	1.3	2.1					
	1800hr	13	1.3	2.2					
15-06-08	00hr	12	1.3	2.2	12	1.35	2.25	503	473
	0600hrs	12	1.3	2.1					
	12hrs	12	1.4	2.3					
	1800hr	12	1.4	2.4					
16-06-08	00hr	11	1.4	2.4	8.6	1.55	2.55	525	450
	0600hrs	11	1.6	2.6					
	12hrs	11	1.6	2.6					
	1800hr	1.4	1.6	2.6					
17-06-08	00hr	14	1.6	2.6	13.75	1.65	2.7	505	470
	0600hrs	14	1.7	2.7					
	12hrs	14	1.7	2.8					
	1800hr	13	1.6	2.7					
18-06-08	00hr	13	1.6	2.7	12.25	1.45	2.45	505	470
	0600hrs	12	1.5	2.5					
	12hrs	12	1.4	2.4					
	1800hr	12	1.3	2.2					
19-06-08	00hr	11	1.3	2.2	11	1.3	2.2	505	471
	0600hrs	11	1.3	2.2					
	12hrs	11	1.3	2.2					
	1800hr	11	1.3	2.2					
		Mean Period over 30days-			12.2				
		Average Maximum & Minimum Stress Over the 30days						508.8387	466.6452

Planar Surface imperfection
Acceptable height
0-0.153in (0-3.9mm)
0.154-0.31in (3.9-7.9mm)

7.0 Discussion of the results

About 5 stress cycles are made within a minute for the pipeline lay stop. Lay-stop means that pipeline fabrication and pipe-laying activities have come to a halt and have been left on the Stinger. On a quick look, it could be found that the stresses caused by the exposed wave conditions are quite low compared to the yield strength of the pipeline in question. The long time effect however is dangerous.

The relevance of this result can be found when one considers a related case as illustrated in [9], API 1104 (2005) section A7.3 Table A6.

For the purpose of this paper, it is assumed that during the welding of the joint, an initial acceptable defect, a_i = 3mm was introduced, due to lack of weld fusion. Let the growth be depth-wise. Acceptable limits for both surface and buried imperfections are shown in Table 1.

Table 1: Limit for Deep Imperfections in Heavy-Wall Pipe (Source: API 1104, 2005 Revision).

Planar buried imperfection
Acceptable height
0-0.153in (0-3.9mm)
0.154-0.354in (3.9-9mm)

Taking the work of [10], and noting that the stress variations within cycles relative to the yield strength of the pipeline is small,C and M are taken as 5 and 2 respectively.

Also considering the work of [11];

Y can be taken as 1.1.

a= $a_{initial}$= 3mm (acceptable depth of imperfection according to Table 1).

$$E^1 = \frac{E}{1-v^2}$$

Given:

$E=207X10^9$ pa

v=0.3

$E^1=2.27x\ 10^{11}$pa

Equation 5 becomes

$$da = cY^{2m}\left[7.32X10^{-5}\right]^m dN$$

Further computation gives the results shown in Table 2.

Table 2. Showing the imperfection depth growth as days of pipeline exposure is increased at five (5) stress cycles per minute.

Days exposed	Stress cycles	Difference, da (mm)	Final height (mm)
1	7200	0.282419971	3.282419971
30	216000	8.472599119	11.47259912
60	432000	16.94519824	19.94519824
90	648000	25.41779736	28.41779736
120	864000	33.89039647	36.89039647
150	1080000	42.36299559	45.36299559
180	1296000	50.83559471	53.83559471

Table 2 shows that the structure has lost its fatigue life just during installation almost after the first day of exposure. The wall thickness of the pipeline is 12.7 mm and nearly used up within the first 30 days.

Checking vessel natural period T_0,

Stiffness K = $\rho g A_{wl}$=1025x9.81x22x75=16.6x10^6 N/m

Total mass of vessel M_T=2541600kg

$$T_0 = \frac{2\pi}{\sqrt{\frac{K}{M_T}}} = 2.5\text{sec}$$

Mean wave period. T = 12.2sec

The vessel is unlikely to pick on resonance.

The relative frequency relation $\beta = \frac{\omega}{\omega_0} = \frac{T_0}{T} = 0.2 << 1$

If λ=damping ratio is assumed to be 1%

Checking on the phase angle between the wave condition and the vessel response,

$$\theta = \text{arctg}\ {2\lambda\beta}/{(1-\beta^2)} = 240^0$$

The vessel is Stiffness controlled and responds nearly in opposite behavior to the wave conditions.

Dynamic amplification $D = \frac{1}{\sqrt{[(1-\beta^2)^2 + (2\lambda\beta)^2]}}$

D=1.04

The vessel is stiff enough to resist motion amplification due to the wave loadings.

Therefore resonance or wave loading amplification did not happen within this period under consideration and the result of the damage is purely due to fatigue caused by the wave loadings.

8.0 Conclusion

The work demonstrates that the effect of the cyclic loading imposed by sea condition in the circumstance under consideration cannot be ignored. Though, simple assumptions were made to ease the calculations, it is a pointer that girth welds at positions considered in this project stand structurally jeopardized if exposed beyond 24 hours.

An interesting parameter identified and used in this work is the vessel heave acceleration. This parameter has been observed to be dependent on the wave condition, weight of the barge and the vessel dimensional characteristics.

It is suggested that further work be carried out to define the effective wave-crest volume value which is the function of actual weight of crest water above the mean water-line that acts on the vessel bottom against the vessel's weight at a given time. It is also necessary to test the validity of this model using direct measurements and nite Element Methods

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