1. Introduction

Indonesia has a lot of jacket offshore structure to support operation and exploration of oil and gas. Indonesia has approximately 449 oil and gas platform spread all around the area (Indiyono, 2006). And the problem is, most of the jacket structure have pass their design life. Conceptually, jacket offshore structures, which have passed their life design, have an uncertain safety and uncertain reliability. This research, analyze the reliability of the offshore structure that has pass its operational design life and check the . The subject for this research is ETB Wellhead Jacket Offshore Platform. This structure operated by Pertamina Hulu Energy Offshore North West Java Ltd. It's located at Java Sea and being installed at 1993. Pertamina as the operator and owner for this structure want to check the residual fatigue life, probability of failure, risk matrix and effective mitigation advice to make sure the performance and safety level of ETB Jacket Offshore Platform.

This research focus on three main steps, the first step is modeling the global structure by using SAC verse 5.2. This step calculate the fatigue life of the global structure and find critical joint of the structure. The method of fatigue life calculation using deterministic approach. The outputs of this step are global fatigue life of the stress value of each member. The second step is modeling the structure by using local structural modeling software (ANSYS verse 12.0) and also modeling the crack at the hot spot area. The output of this step is stress value at the crack. The third step is calculating the fatigue life. And the last step calculates the probability of failure, consequence, matrix and mitigation advice (RBI concept).

2. Principal Theory

2.1 Fracture Mechanic Concept

Fracture Mechanics is a science technique to study and analyze a material failure that caused by formed defect. The usage of fracture method can be applied to high quality material in which the material is considered to have early defects (crack initiation) (Rahmanjaya, 2010). Fracture mechanics concepts are used in the occurrence of damage to the existing crack tip. So that these cracks will spread, causing damage or final fracture.

2.2 Linear Elastic Fracture Mechanics

LEFM methods based on elastic stress distribution around the crack tip, beside of that it also based on energy balance for the crack propagation. This concept can be used for the assumption, the plastic area at the tip smaller than crack length.

Based on the explanation above, fracture theory can be chosen by the material condition to receive the load. That cause the material has the plastic and elastic area at the model/structure. And for this final project the writer state to use LEFM (Linear Elastic Fracture Mechanics) methods.

Linear Elastic Fracture Mechanics Method is a method that shows relation between stress field and its distribution around the crack tip with the size, shape, orientation of cracks and material properties due to external loads imposed on the material. Imposition of this material produces a linear stress-strain curve, so that material will undergo the crack if passed the elastic limit. LEFM can be used for plastics area, crack tip smaller than the crack length, where the stress is lower than the stress a permit ($\sigma = 0.8\sigma_{ys}$). (Broek, 1984).

2.3 Fracture Mode

![Figure 1 – Fracture Mode (Broek, 1984)](image)

**Mode I (opening mode)**

Cracks caused by the tensile stress perpendicular to the direction or area of crack propagation. So it can be concluded that the surface displacement field perpendicular to the crack.

**Mode II (sliding mode)**

Cracks caused by shear stress in the direction of crack propagation. Crack surface displacement is in the field of crack and perpendicular to the leasing edge of crack.

**Mode III (Tearing Mode)**

Cracks caused by shear stress work on the transverse direction and an angle to the direction of crack propagation. Crack at the structure could be caused by one of the load or the combination of the load.

By reference to the linear elastic theory on the method that developed by Westergaard and Irwin, the analysis of stress and displacement at the crack tip can be distinguished according to three modes of deformation (Rolfe and Barsom, 1987), but the MODE I is the mode that is generally used. In this final project mode of type I are used with the related equation as follows:
2.4 Stress Intensity Factor

Stress intensity factor is a parameter that contains an understanding principle of energy balance and distribution around the crack tip. Range of the SIF given by (Bai, 2003) by this equation:

\[
\Delta K = F \sigma \sqrt{\pi a}
\]

By \( F \) is geometric function of the crack and the structure and \( \sigma \) is the stress range due to the cyclic load.

2.5 Crack Propagation

Crack propagation is influenced by the parameters stress intensity factor (K). This parameter indicates the crack propagation due to stress and strain field around the crack tip. The total number of cycles that cause failure of fracture is the sum of the number of cycles that causes the initial cracks and phase propagation (Bai, 2003). In general, the process of crack propagation described the picture below. In the curves shown the division three areas namely:

Region I:

Crack propagation in region I shows the characteristics of "fatigue-threshold" which is a fluctuation in the value of stress intensity factor increases with \( \Delta K_{th} \) parameters. Value \( \Delta K \) (stress intensity factor range) should have a value greater than the value \( \Delta K_{th} \) to allow for crack propagation. \( \Delta K_{th} \) martensitic steel materials for steel, bainitic, pearlitic and ferrite-austenitic can be calculated with the equation:

\[
\Delta K_{th} = 6.4 (1 - 0.85 R) \text{ksi} \sqrt{\text{in}} \text{ untuk } R > 0.1
\]

\( R \) is the ratio between the minimum and maximum voltage.

Region II

An area where there is stable crack propagation can be described by a linear relationship between \( \log da / dN \) and \( \log \Delta K \). In this area propagation began.

Region III

Crack propagation is described by the rapid increase in the rate of crack propagation towards infinity as the maximum value of stress intensity factor reaches the material fracture toughness \( K_{IC} \).
2.5 Paris Law (Crack Propagation Calculation)

Paris’ law (also known as the Paris-Erdogan law) relates the stress intensity factor range to subcritical crack growth under a fatigue stress regime. As such, it is the most popular fatigue crack growth model used in materials science and fracture mechanics. The basic formula reads:

$$\frac{da}{dN} = C (\Delta K)^m$$

(2.16)

To get the cyclic number (cyclic amount) at the failure, so the Paris equation need to be integrated (Bai, 2003):

$$N_f = \int_{a_0}^{a_{cr}} \frac{da}{c(\Delta K)^m}$$

(2.17)

The value of $\Delta K$ define as:

$$\Delta K = F \sigma \sqrt{\pi a}$$

(2.17)

By substitute both of the equation, founded:

$$N_f = \frac{acr^{1-m/2} - a_0^{1-m/2}}{C(F\sigma \sqrt{\pi})^m(1-R^{1-m/2})}$$

(2.18)

By $acr$ is the critical crack and $N_f$ is the load cycle up to the critical crack happen.

The most important parameter at the fatigue are stress range and mean stress. Stress range is the difference mean of the maximum stress and minimum and man stress is mean stress. The affect of mean stress at the fracture fatigue represent by load parameter ratio ($R$) that is same with $P_{min}/P_{max}$. Mean stress cause correction factor to the equation, so it change into:

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1-R)^m}$$

(2.20)

So,

$$N_f = \frac{(acr^{1-m/2} - a_0^{1-m/2})(1-R)^n}{C(F\sigma \sqrt{\pi})^m(1 - (1 - R)^{1-m/2})}$$

(2.21)

$$a_{cr} = \left(\frac{N_f C(F\sigma \sqrt{\pi})^m(1-m/2)}{(1-R)^n} + a_0^{1-m/2})^{2/m}\right)$$

(2.21)

The difference between the stress intensity factor at maximum and minimum loading:

$$\Delta K = K_{max} - K_{min}$$

(2.22)

Paris’ law can be used to quantify the residual life (in terms of load cycles) of a specimen given a particular crack size. Defining the crack intensity factor as

$$K = \sigma Y \sqrt{\pi a}.$$  

(2.23)

where $\sigma$ is a uniform tensile stress perpendicular to the crack plane and $Y$ is a dimensionless parameter that depends on the geometry, the range of the stress intensity factor follows as:

$$\Delta K = \Delta \sigma Y \sqrt{\pi a}.$$  

(2.24)

2.6 Risk Analysis

After the estimated probability of failure and the consequences have been calculated, risk evaluation is then performed using a risk matrix. Risk matrix itself is a reflection of the combined probability of failure and the consequences, so that can know the level of risk in the plots where on the risk matrix. Acceptance criteria for deciding the equation of the design goals should be held. Acceptance criteria should be applied to the evaluation matrix that has been selected. If the size used for the evaluation matrix, at this stage, the matrix of risk with acceptance criteria to be used. With the option, for comparison valuation, the acceptance criteria can be based on consequences or only on the frequency alone. Below is a picture of the risk matrix used to determine acceptance criteria.
3. Result and Analysis

3.1 Global Model

Output that came from global structural modeling is Fatigue Life of member and joint at the structure and also the Force and Moment value that will be use for local modeling. In this analysis, to clarify and verify the result of the fatigue life by using manual calculation for some joints use Ms.Excell. That use to minimize the mistake at the modeling process. And this is the local model view by using Structural Analysis Software (SAC ver 5.2).

After set the load and run the global model, then analyze by using deterministic approach, the fatigue life of each joint founded and these is the stress value at the most critical joint of the structure;

Table 1 – Fatigue Life at The Critical Joints by SAC

<table>
<thead>
<tr>
<th>Joint Number</th>
<th>Fatigue Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>401</td>
<td>452</td>
</tr>
<tr>
<td>301</td>
<td>735</td>
</tr>
<tr>
<td>102</td>
<td>739</td>
</tr>
</tbody>
</table>

Table 2 – Fatigue Life at The Critical Joints by Manual calculation

<table>
<thead>
<tr>
<th>Joint Number</th>
<th>Fatigue Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>401</td>
<td>469</td>
</tr>
<tr>
<td>301</td>
<td>758</td>
</tr>
<tr>
<td>102</td>
<td>729</td>
</tr>
</tbody>
</table>

The result of the modeling between Software SAC and Manual calculation are different, but the difference value are not quite far. The difference may occur by the calculation and assumption that used for the modeling and also by the simplify process of value of calculation. This fatigue life shown the critical joints at the structure. To model the crack it’s very important to define which joint has very critical joint. And

Figure 4 – 3D View of Global Model

Figure 4 – Isometric View of Global Model

The Most Critical Joint
for the next step the crack modeling (local modeling) will be applied at the most critical join (Joint number 401).

Table 3 – Fatigue Life at The Member at The Most Critical Joint

<table>
<thead>
<tr>
<th>Joint</th>
<th>Member</th>
<th>Type</th>
<th>Size</th>
<th>SAC</th>
<th>Manual</th>
<th>Ms.Excel</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>401</td>
<td>305-401</td>
<td>BRC</td>
<td>16</td>
<td>0.5</td>
<td>456.9</td>
<td>462</td>
<td></td>
</tr>
<tr>
<td>401</td>
<td>301-401</td>
<td>CHD</td>
<td>34</td>
<td>1</td>
<td>460.4</td>
<td>489</td>
<td></td>
</tr>
</tbody>
</table>

The values of fatigue life at the member are also different between two methods, that because the same reason as defined above. After completing the global modeling, the next step focus on the local modeling for the most critical joint.

3.2 Local Model

Local modeling for the critical joint was used to define the hot spot stress and also the value of the stress at the hot spot. That would be used as data for crack (fracture) modeling. Local modeling done by using local analysis software ANSYS version 12.0. The modeling applied for the most critical joint, and these are the local models for the critical joint.

And below is the model view that has been meshed and adjusted for the material properties. Then the load mounted to the model. The loads of the model are force at each member by three kind of loads/force. The load are: axial force, in plane bending and also outplane bending. That load applied at each member and the load came from global modeling by using SAC at the step before.
After load process and run this is the result of the analysis, at this picture shown the hotspot area and possibility of the crack. This used to model the sublocal model (crack model) which also use ANSYS ver 12.0 either.

This picture indicates the stress distribution on the local model. The red color indicates the maximum point of stress and that are the position of hot spot. For the sublocal model (crack model) the crack initial will paced at the red color. The value of the stress only shown as x axis and y axis only, that’s because the crack model defined as 2 Dimensional model, as shown as below:

3.3 Sub Local Modeling (Crack Model)

The crack model refers to American Bureau Shipping (ABS) where the initial crack of the model is 0.5 mm. And the mode of crack is Mode I. The result of the crack model shown below:

3.4 Fatigue Life Analysis by using Fracture Mechanics

Crack propagation is the important factor to count the fatigue life of the structure. Crack propagation defined as the amount of cycle by the certain initial crack up to next another certain crack up to fracture occur. Smaller the ΔK, slower the crack propagation. ΔK value affected by stress ranges and cracks initial size.

Crack growth (propagation) relation with crack depth and Δ KI shown at the curve below. The crack depth start at 0.02 inch (based on ABS rules). Both of the curve are linear this is match with the theory Linear Elastic Fracture Mechanics, and at the linear crack Paris Erdogan (Paris Law) can be applied at this case.
From the chart above we can define that deeper the crack, the crack growth speed will be increase. And below is the calculation of fatigue life of the structure.

<table>
<thead>
<tr>
<th>N (cycles)</th>
<th>Fracture Fatigue Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>358980000</td>
<td>186</td>
</tr>
<tr>
<td>320380000</td>
<td>166</td>
</tr>
<tr>
<td>208440000</td>
<td>108</td>
</tr>
<tr>
<td>164050000</td>
<td>85</td>
</tr>
</tbody>
</table>

From the chart above we can define that deeper the crack, the crack growth speed will be increase. And below is the calculation of fatigue life of the structure.

<table>
<thead>
<tr>
<th>Figure 15</th>
<th>Fracture Fatigue Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>358980000</td>
<td>186</td>
</tr>
<tr>
<td>320380000</td>
<td>166</td>
</tr>
<tr>
<td>208440000</td>
<td>108</td>
</tr>
<tr>
<td>164050000</td>
<td>85</td>
</tr>
</tbody>
</table>

The crack initial 0.02 inch the load cycle 3.59E+08 cycles, and that produce fatigue life 186 years. And so for the initial crack 0.039 it produce fatigue life 85 years.

3.5 Probability of Failure

The model defined fail, if the crack depth same as the thickness of the brace.

The failure mode for the model shown below.

In the equation above, the random variable and the constant variable define below.

Table 5 – Load Cycle due to Initial Crack

<table>
<thead>
<tr>
<th>a0 (inch)</th>
<th>af (inch)</th>
<th>da/dN (inch/cycle)</th>
<th>N (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.5</td>
<td>1.33712E-09</td>
<td>358980000</td>
</tr>
<tr>
<td>0.025</td>
<td>0.5</td>
<td>1.48261E-09</td>
<td>320380000</td>
</tr>
<tr>
<td>0.035</td>
<td>0.5</td>
<td>2.23086E-09</td>
<td>208440000</td>
</tr>
<tr>
<td>0.004</td>
<td>0.5</td>
<td>2.81012E-09</td>
<td>164050000</td>
</tr>
</tbody>
</table>

Table 6 – Fatigue Life of the model

From the table above we can find the fatigue life (in years) of the model/structure, shown that at
To get the random number based on the distribution, used Minitab ver.15 to generate the number then, fill the value of all variable to the failure mode to get the probability of failure. The simulation process of Pof calculation done by using Microsoft Excell 2011 version. The simulation held 10,000 times by count failure mode above, but at the process the writer count the possibility of failure for 1,000, 3,000, 6,000, 8,000, 10,000 simulation to recheck the stability of the possibility of failure. The result shown below, and the probability of failure of the model is 0.354. The example of the simulation process shown at the Appendix A.

The annual probability of the system shown below,
Annual Pof= Pof / Fatigue Life 
= 0.3542 / 186 years 
= 0.001904 per year (1.904 x 10^{-3} per year)

Reliability of System= 1 – Pof 
= 1 - 0.354 = 0.646

Reliability Index = 0.36

<table>
<thead>
<tr>
<th>Personnel (PER)</th>
<th>Environment (ENV)</th>
<th>Asset (As)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>Significant</td>
<td>Critical</td>
</tr>
</tbody>
</table>

3.6 Consequence Analysis

The personnel factor categorized as minor consequence because ETB wellhead Platform is an unmanned platform, because of that the probability of death or serious accident is very minimum or at the minor condition.

Environment categorized as significant consequence because this structure is a wellhead offshore structure that operate to support oil production at the sea. The oil that was transport from the structure, has a very serious effect to the sea environment and sea creature. It harmful to all kind of sea creature. Because of that this factor categorized as Significant result.

For the asset itself, categorized as critical because this structure is very valuable to the oil system at the Offshore North West Java Area. The structure are connected one to each other, so when one structure have a problem/failure it will disturb the whole process, sometimes the production platform that receive the crude oil from ETB will loose or reduce the production capacity because of problem of ETB. That will be react to another factor, for example cost, company production target and public needed. Because of that ETB is very
important asset of Pertamina, and the problem of ETB will be a critical consequence for Pertamina.

3.7 Risk Matrix Analysis

After check the probability of failure and also define the consequence, the next step is finding the risk by multiply the probability of failure by the consequence. This is the classification of the probability of failure;

Table 9 – Classification of Consequence

So that, the **Annual Probability of Failure** at the system is $1.904 \times 10^{-3}$ it match with **Low** Characteristic. And the result of the risk shown below.

3.7 Mitigation Analysis

According to the risk matrix, ETB categorized in low annual probability of failure it need not to certain mitigation analysis. The inspection process held as usual.

4. Conclusion and Advice

4.1 Conclusion

Based on the whole process of the research these are the conclusions:

1. The fatigue life of the structure by using fracture mechanic approach (LEFM) defined as 186 years for 0.02 inch initial crack, and 85 years for the 0.04 inch initial crack. The residual of fracture-fatigue life of the structure defined as 168 years forward for the 0.02 initial crack and 67 years forward for the 0.04 initial crack.
2. The probability of failure of the structure based on fracture mechanics approach is 0.0354, the annual probability of failure is $1.904 \times 10^{-3}$ (assumed that the probability of failure distribution due to time in linear ways). The Reliability of System is 0.646, and the Reliability Index = 0.36.
3. According to the annual probability of failure the structure categorized in Low consequence and the consequence divide into three categories; personnel (PER), Environment (ENV), and Asset (As). The risk matrix for personnel (PER) factor located at the Low Risk – Minor consequence, The environment (ENV) factor located at the Low Risk-

Significant Risk Matrix, and Asset (As) categorized at Low Risk and Critical Consequence.

4. According to the low value of probability of failure the mitigation process are need not to do. The inspection process just held as usual.

4.2 Advice

For the next development of the research, writer advice to use 3 Dimensional model to check (verify) the result of the 2 dimensional model.

<table>
<thead>
<tr>
<th>Pof</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6000 - 1.0000</td>
<td>High</td>
</tr>
<tr>
<td>0.3000 - 0.5999</td>
<td>Medium High</td>
</tr>
<tr>
<td>0.1000 - 0.2999</td>
<td>Medium Low</td>
</tr>
<tr>
<td>0.0000 - 0.9999</td>
<td>Low</td>
</tr>
</tbody>
</table>

Reference


