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Crack Analysis Due to Fatigue Load During Subsea Pipeline Installation

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***Abstract* — Most of the subsea pipelines in Indonesia are installed using the S-Lay method with the pipelay barges equipped with mooring spreads, tensioners, and stinger. During the subsea pipeline installation, static loads occur due to the pipeline configuration from the firing line of the pipelay barge up to the seabed. The pipe will experience axial tension and bending moment in two critical areas: overbend and sagbend. In addition, fatigue loads occur during subsea pipeline installation due to environmental loads (i.e., currents and waves). Defects that are found after welding will grow due to these fatigue loads. Crack analysis with a fracture mechanic approach known as Engineering Critical Assessment (ECA) is carried out by considering the fatigue load due to significant wave height variations for 0.5m, 1.0m, and 1.8m. BS 7910 is used as a standard reference to determine the allowable defects criteria for external and internal flaws. The depth of the defect (a) is simulated from a depth of 1mm – 3mm. The analysis found that the allowable defect length is decreased by 12.7% - 25.0% from a significant wave height of 0.5m to 1.8m for the external surface flaw. While for an internal surface flaw, the allowable defect length is decreased by 5.9% - 13.6% from a significant wave height of 0.5m to 1.8m. These results can be used as a basis for subsea pipeline installation contractors to perform fatigue load sensitivity and optimize the allowable defects based on the actual wave load at the site.**

Keywords — crack growth, ECA , fatigue, fracture mechanic, S-Lay.

I. INTRODUCTION

Referring to the British Petroleum Statistical Review of World Energy 2016, the level of consumption/demand for oil in Indonesia continues to increase from 2010 to 2015. This is not accompanied by the production of petroleum in Indonesia, which continues to decline yearly. New well development efforts have been stepped up in Indonesia to increase oil production in Indonesia. However, developing new wells offshore is highly dependent on global oil prices where the price of oil is highly influenced by external/foreign factors, which in real-time can change/decrease at any time.

It is necessary to optimize efforts in developing or exploring offshore oil. The offshore pipeline is one of the main components in developing or exploring offshore oil and gas. In the offshore pipeline installation process, the work duration is an essential factor in optimizing the offshore pipeline installation. This optimization is closely related to the production laying rate, which is influenced by several factors.

1) Welding technique
2) NDT (Non-Destructive Test) technique
3) Field Joint Coating (FJC) and Infill application technique
4) Installation method
5) Pipeline properties
6) Water depth
7) Pipelay barge used for subsea pipeline installation.

In Indonesia, subsea pipeline installation is generally carried out at shallow water depths where the water depth is approximately less than 100m. So, the installation method and type of pipelay barge used are generally almost similar from one project to another. Welding and NDT techniques are closely related to welding defects that are likely to occur in the girth weld joints between pipe joints.

Generally, the criteria for weld defects have been regulated in standards, e.g., DNVGL-ST-F101 [9] It is known as workmanship criteria, which are conservative approaches that cause the rejection rate to be higher and has implications for the productivity of the subsea pipeline installation. To optimize the productivity of the subsea pipeline installation, Engineering Critical Assessment (ECA) is required to increase the criteria of weld defects. It is based on initial crack and cracks growth when experiencing loads that occur during installation.

In today's industry, Engineering Critical Assessment (ECA) is a defect acceptance criterion based on a fracture mechanic. Fracture mechanics-based assessment methods are usually used to present flaw acceptance criteria for girth weld in subsea pipelines. Utilizing alternative ECA acceptance criteria for pipe girth welds can significantly reduce subsea pipeline installation costs by minimizing the number of repairs.

S.M.H. Sharifi has conducted the previous research, S.R. Soheili, A.S. Moghaddam, and F. Azarsina [1]. They compared the fracture response results from 3-D finite element analysis modeling with methods based on BS 7910 standards by considering the load of pure tension. The BS 7910 standard has been used in previous studies by S.M.H. Sharifi, M. Kaveh, and H.S. Googarchin [2]. The purpose is to determine the effect of axial misalignment on girth welds and ductile tearing. In this research, the software used is CRACKWISE. From the results of this research, it is evident that axial misalignment will have a significant effect on axial internal flaws.

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The two researches above do not consider the presence of a concrete weight coating thickness. Whereas subsea pipelines in shallow water generally have a thicker concrete weight coating thickness, which is necessary for pipe stability. This concrete weight coating thickness will affect the bending moment value, where the concrete stiffening factor must be considered. It has been considered in a research by N. Nourpanah and F. Taheri [3]. This research aims to create an equation to calculate the Strain Concentration Factor (SCF) value of the concrete pipe with grade X65. The joint field coating is obtained from the nonlinear regression approach from finite element analysis modeling.

An Engineering Critical Assessment (ECA) for subsea pipeline installations using the reel lay method was previously carried out by I. Permana [4]. Research by I. Permana aims to conduct an Engineering Critical Assessment (ECA) when installing a subsea pipeline using the reeling method. During the reeling process, the pipe will experience a substantial plastic strain when it spools in the reel drum or straightened back when it passes through the aligner during the installation process. The simulation process obtained the maximum nominal value of the Strain at 1.772%. Based on the stress-strain curve of the base metal, the nominal Strain of 1.772% is equivalent to the nominal Stress of 791.4 MPa. Furthermore, actual stress is obtained using the Neuber rule. From the input data provided, I. Permana has conducted an Engineering Critical Assessment (ECA) using the CRACKWISE software. From the CRACKWISE results, several parameters will determine the critical crack size curve: residual stress and misalignment effects. I. Permana [4] also compared the critical crack size curve results using the LINKpipe software. From these results using the same parameters. CRACKWISE produces a more conservative crack size curve than LINKpipe. The maximum difference is 39% when the crack length reaches a crack length of 200mm.

Referring to the previous research, it is necessary to perform crack analysis due to maximum static stress during the subsea pipeline installation. It corresponds to maximum stress in the overbend and sagbend areas. Using the S-Lay method, the maximum fatigue loads caused by the pipelay barge motion and environmental load during the subsea pipeline installation are also used.

II. METHOD

A. Pipeline Properties

The pipeline properties used are based on a project that has been carried out by PT Meindo Elang Indah previously in the "*Pertamina Hulu Mahakam 10.75" Offshore Pipeline project from WPN4 to WPS2*". **Table 1.** shows the details of the pipeline properties data considered in the analysis.

B. Environmental Load

Environmental load data is considered in the installation analysis, especially for dynamic and fatigue analysis. **Table 2.** shows the detailed environmental load data considered in the analysis.

C. Pipelay Barge Data

The pipelay barge data used for subsea pipeline installations is typical of pipelay barge data used for shallow-water depth installations. It is widely used in Indonesia. In this case, the pipelay barge data is a ship owned by PT Meindo Elang Indah, namely "*DLB Armada KP1*".

D. Tensile Test

Tensile test data is taken from the results of the tensile test carried out by the line pipe manufacturer, which has been carried out previously. This tensile test was carried out on the base metal through 29 tests.

Referring to Chapter 7.11 of DNVGL-RP-F108 [11], the stress-strain curves are determined based on lower bound values. The values for YS (yield strength) and UTS (Ultimate Tensile Strength) are determined from the average value minus Z and multiplied by the standard deviation. Z value based on Table 7-6 of DNVGL-RP-F108 [11] corresponds to some tests. **Table 3.** shows the determination for the lower values of YS and UTS.

E. Fracture Toughness

Fracture toughness data from SENB (single-edged notched bending) test results for the mainline procedure HHI and LHI are taken from the fusion line and weld metal. A minimum value δ of 0.32mm is considered in the analysis.

The results of this SENB test will be converted into a critical stress intensity factor (K_{mat}) using the equation, which refers to BS7910 [10]. Considering YS, UTS, and δ, the critical stress intensity factor (K_{mat}) is 213.87 MPa$\sqrt{m}$.

F. Ramberg-Osgood Relationship

The Ramberg–Osgood equation describes the nonlinear relationship between Stress and Strain, namely the stress-strain curve. In its original form, the equation for Strain (deformation) is as follows;

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{n} \tag{1}$$

Where;

ε = Engineering Strain
σ = Engineering stress
E = Elastic Modulus
K & n = Constant

TABLE 1.
PIPELINE PROPERTIES DATA

Descriptions	Units	Values
Outside Pipe Diameter	mm (inch)	273.1 (10.75)
Steel Wall Thickness	mm	12.7
Grade	-	API 5L X52 PSL2
Elastic Modulues	MPa	207000
Poisson Ratio	-	0.3
Corrosion Coating Thickness	mm	3.2
Density of Corrosion Coating	kg/m^3	900
Concrete Coating Thickness	mm	40
Density of Concrete Weight Coating	kg/m^3	2300
Concrete Coating Cutback	mm	350

TABLE 2.
ENVIRONMENTAL DATA

Descriptions	Units	Values		
Water Depth	m	69.41 – 84.28		
Current Velocity at Surface	m/s	1.2		
Current Velocity at Mid-water Depth	m/s	1.1		
Current Velocity at 1m above Mudline	m/s	0.65		
Wave Height Significant	m	1.8	1.0	0.5
Peak Wave Period	s	6.50	4.84	3.43

TABLE 3.
LOWER BOUND VALUES OF YIELD STRENGTH (YS) AND ULTIMATE TENSILE STRENGTH (UTS)

Descriptions	Units	YS	TS
Average / Mean Value (a)	MPa	422.34	491.91
Standard Deviation (b)	MPa	13.00	10.44
Z (c)	-	2.37	2.37
Lower bound values (a – b x c)	MPa	391.54	467.16

For this analysis, the strain point on yield strength (YS) is determined by offsetting 0.2% of the elastic Strain. Because the pipe is manufactured using the ERW process, the pipe does not experience yield discontinuity.

G. Pipeline Installation Analysis

G.1. Static Analysis

The profile control data will be developed from pipeline installation stress analysis based on three-dimensional, static, large deflection, and slender rod mechanics. OFFPIPE, version 3.02 GO (Offshore Pipeline Installation Program), will be the primary software for pipeline installation analysis. It is a general-purpose finite element analysis system for modeling nonlinear beam and cable structures.

The water depth considered for pipeline installation analysis will be computed as the maximum water depth along the route concerning the chart datum (CD) + maximum astronomical tide and minimum water depth for CD. A finite element model of the pipeline up to the touchdown at the seabed will be generated with accurate modeling of the barge and stinger roller supports. Static analysis will be performed with functional loads by assuming a linear stress-strain relationship.

The static analysis determines the optimized position of rollers, stinger angle, and heights and recommended lay tension. The total combined pipe stress is calculated from the given tensile, hoop, and bending stress using the Von Misses criteria and compared against the allowable stresses for the sagbend section. While for overbend section, the total Strain shall be limited to less than allowable strain criteria. A local buckling check shall be performed for overbending and sagbend sections. Refer to DNVGL-ST-F101 [9]. The general procedure of static analysis used to establish the optimum position of rollers, stinger angle, stinger roller heights, and recommended lay tension and derived resultant pipe profiles and stresses is as follows;

- Pipe profiles on overbending and sagbend are based on pipe properties and water depth.
- Roller support will be modeled on the pipelay barge and stinger. This stinger will be connected to the pipelay barge by hinges that allow rotation about the main horizontal axis. A one-dimensional model parameter represents this.

- The tension in this model will be varied to find the most optimum profile, and the stress along the pipe is still below the allowable stress.
- For static analysis, the loads considered in the OFFPIPE model will include self-weight/buoyancy, the curvature of the pipe profile, tensile forces from tension loads, and external pressures based on water depth.
- Under static conditions, no current or wave loads will be applied.

G.2. Dynamic Analysis

The dynamic response and stresses of the pipeline are calculated in the frequency domain. The irregular sea state is considered by describing the wave spectrum. JONSWAP wave spectrum has been selected. Directional wave and current have been considered for every 45deg from 0deg to 315deg. The hydrodynamic forces exerted on the pipeline and stinger by steady currents and waves and by the dynamic motions of the pipeline and stinger are calculated using Morison's.

Response Amplitude Operators (RAOs) are considered in the dynamic analysis. These RAOs are used to model the barge's response during pipelay analysis. Dynamic analysis is performed using the pipe lay analysis computer program OFFPIPE.

The resulting loads from the dynamic lay analysis are checked against the requirements of DNVGL-ST-F101 [9] to determine the maximum workable wave conditions for safe pipelay operation. The total combined pipe stress is calculated from the given tensile, hoop, and bending stress using the Von Misses criteria and compared against the allowable stresses for the sagbend section. While for overbend section, the total Strain shall be limited to less than allowable strain criteria. Local buckling check shall be performed for overbending and sagbend sections; refer to DNVGL-ST-F101 [9].

The general procedure of dynamic analysis used to establish the maximum workable wave conditions for safe pipelay operation and derive resultant pipe profiles and stresses is as follows:

- The configuration of the roller support on the pipelay barge, the stinger, and the tension from the results of the static analysis must be used in the dynamic analysis
- Parameters for ship response to environmental loads will be modeled through Response Amplitude Operators (RAO)
- Tension in the model will be varied +/- 10% of the nominal static range.
- For dynamic analysis, the loads considered in the OFFPIPE model will include self-weight / buoyancy, the curvature of the pipe profile, tensile forces from tension loads, external pressures based on water depth, current loads, and wave loads.
- Current loading is considered based on one (1) year return period condition
- Wave loading is considered based on significant wave heights of 0.5m, 1.0m, and 1.8m corresponding to the peak period.

G.3. Fatigue Analysis

Fatigue analysis is carried out using Offpipe. Fatigue analysis should be carried out for the weld root and weld cap. Referring to DNVGL-RP-C203 [13], the SN curve for weld toe/root shall be referred to as SN F1 curve – in air, while the SN curve for weld cap shall be referred to as the SN D curve – seawater with CP. However, a conservative approach was chosen by considering SN F1 – in air curves.

Accumulated fatigue damage induced in the pipeline during installation is recorded from the software Offpipe uses a rain-flow counting algorithm. It determines the number and magnitude of the stress cycles experienced at each point. Based on the chosen S-N curve, maximum fatigue damage experienced by the pipeline at different nodes is reported. A segment length of 12.1m is considered in the analysis to capture the pipeline's weakest section, none other than the pipeline welds. The standby time of the barge during offshore execution is estimated based on the pipeline node, which experiences the maximum fatigue damage. The total fatigue damage that the pipeline experiences during installation is expressed as the accumulated damage from each load cycle at different stress levels, independent of the stress cycles' sequence.

The number of cycles to failure associated with the stress ranges is extracted from class F1 (weld root) S-N curves of DNV-RP-C203 [13]. The basic design S-N curve is given as follows;

$$LogN = Log\bar{a} - m.Log\Delta\sigma \tag{2}$$

Where;

$\Delta\sigma$ = stress range (hot spot stress)
N = predicted number of cycles to failure for stress range
$Log\bar{a}$ = intercept of Log N – axis by S-N Curve
$\Delta\sigma$ = negative inverse slope of S-N curve

According to mine "s rule, the cumulative fatigue damage is the sum of the partial damage given by the ratio of the number of expected cycles in a certain duration to the number of cycles to failure for the associated stress range:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{3}$$

Where;

D = accumulated fatigue damage
k = number of stress block
n_i = number of stress cycles in block (i)
N_i = number of cycles to failure at a constant stress range

Fatigue assessment is performed for various environmental conditions likely to be encountered during pipelay operations and within the limiting sea state condition. The design parameter considered in fatigue analysis is summarized in **Table 4.**

H. Engineering Critical Assessment (ECA) Analysis

British Standards Institution set up a logical acceptance standard that was safer and more economical than the traditional workmanship acceptance standards. In BS 7910 [10], three levels are available for a fracture assessment. Option 1, a simplified assessment procedure, is based on a conservative Failure Assessment Diagram (FAD) applicable when the data on the material's properties is limited. The Level 1 FAD has K_r, S_r coordinates, where K_r is the applied crack driving force ratio to fracture toughness. S_r the ratio of applied stress to flow strength where the flow strength is the mean of yield and tensile strength, hence including some plasticity. For the cases where the material properties (i.e., Stress-strain curve) and fracture toughness data are available, option 2 is used, which is named the normal assessment method. Option 3 is similar to option 2, except it is appropriate for ductile materials showing the tearing mode of failure. Option 3 depends on the type of stress-strain data available.

For the flow analysis of ECA is carried out by DNVGL-RP-F108 [11], the following **Table 5.** summarizes the sequence of ECA analysis at each stage. Each step below refers to a different analysis model.

TABLE 4.
DESIGN PARAMETER FOR FATIGUE ANALYSIS

Descriptions	Units	Values
SN Curve	-	SN Curve F1 in air
Expected laying time	minutes	20
Standby duration	hours	60
Allowable fatigue damage	-	0.01

Notes:
1) The expected laying time is required to complete the fabrication of one pipe joint. Normally this time is obtained from the maximum time required to complete one pipe joint from all stations (welding, NDT, FJC, and infill).
2) Standby time duration is the estimated time required if any damage to the equipment causes the installation process to be stopped. The pipeline will be exposed to dynamic loads during that time.
3) The safety class considered is high, so the design fatigue factor (DFF) is 1/10, and the common split during installation is 10%. Therefore, the allowable fatigue damage is 0.01 (1/10 * 10%).

TABLE 5.
ECA FLOW ANALYSIS

Step	Model	Assessment Level	Values
1	Installation Assessment	Option 2 fracture & plastic collapse assessment	Max. longitudinal stress during pipeline installation (static)
2	Installation Fatigue	Flaw fatigue growth	Stress range and cycle–fatigue (dynamic)
3	Post Installation Assessment / Operation	Option 2 fracture & plastic collapse assessment	Longitudinal stress after pipeline installation (i.e., hydro test and operation) assumed longitudinal stress at 80% SMYS

Following the assumptions are taking account for ECA analysis:

1) The type of crack is sharp planar, where located at girth weld.
2) The orientation of the cracks to be analyzed is a circumferential flaw. This orientation was chosen based on the orientation that is most frequently seen in the girth weld structure. In addition, these cracks are sensitive to longitudinal crack opening stress due to the installation process and fatigue. The analysis results can also be applied conservatively to other defects such as pores, inclusions, undercuts, and concave root profiles.
3) The crack depth is simulated from 1mm to 3mm, with an increment of 0.1mm.
4) Stress Concentration Factor (SCF) due to misalignment welding is calculated based on DNVGL-RP-F108 [11]

III. RESULTS AND DISCUSSIONS

A. Stress Concentration Factor (SCF)

Stress concentration factor (SCF) due to misalignment during welding has been calculated according to DNVGL-RP-F108 [11], section 4.3.5. **Table 6.** below shows the stress concentration factor (SCF) to be considered in engineering critical analysis (ECA).

The stress concentration factor (SCF) for the weld cap is assumed to be conservatively applicable to the weld toe/root. The SCF equation for the weld toe/root is calculated based on the ratio between the weld root width divided by the weld cap width so that the SCF for the weld root will be less than this value.

B. Stress-Strain Curve

The stress-strain curve is made using the Ramberg-Osgood relationship equation by considering the following points:

1) The yield strength (YS) and tensile strength (UTS) values are 391.54MPa and 467.16MPa, respectively, refer to **Table 3.**
2) The elastic limit of Stress (R_{el}) is 0.9 of the yield strength, which is 352.39MPa.
3) The minimum value of Strain at the tensile strength point from the tensile test results is considered in forming the stress-strain curve. It is 7%, which refers to the minimum value of tensile test data.

C. Static Analysis of Pipeline Installation

Static analysis using OFFPIPE software has been carried out to obtain the most optimum parameters where the maximum stress is still within the allowable stress in static conditions. This analysis is carried out for the pipeline route's minimum and maximum water depth. The parameters considered in the static analysis are as follows;

1) The required tension is 550kN (56MT).
2) The angle of the stinger (to the horizontal) required is 14^0.

Figure 2. shows the stress and pipe configuration from static analysis for the minimum water depth (69.44m) and maximum water depth (84.31m).

Figure 2. shows that the maximum stress occurs at the maximum water depth (84.31m). The total maximum stress (max. von misses's stress) in the overbend area is 273.8MPa (69.93% of YS), and at the stinger, the tip is 225.6MPa (57.61%). of YS) and the sagbend area is 95.2MPa (24.31% of YS). The maximum stress value is still within the allowable stress by the code/standard, where the total allowable stress for static conditions is 281.9MPa (72% of YS). Local buckling check (LCC) is also checked based on the DNVGL-ST-F101 [9] standard, where the maximum value of the LCC ratio is still below 1.0. So it can be concluded that the parameters used in the static analysis can be used further for dynamic analysis.

D. Dynamic Analysis of Pipeline Installation

Dynamic analysis using OFFPIPE software has been carried out by considering 8 directions of incoming waves & currents (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, $270^{0,}$ and 315^0).

This analysis is carried out for the minimum and maximum water depths along the pipeline route, considering the environmental load data in accordance with **Table 2.** The significant wave heights of 0.5m, 1.0m, and 1.8m are considered, where 8 directions of incoming waves & currents are performed for each significant wave height. **Figure 3.** shows the stress and pipe configuration from the dynamic analysis for the minimum water depth (69.44m) and maximum water depth (84.31m).

From **Figure 3.**, it can be concluded as per followings:

1) For a significant wave height of 0.5m, the maximum total stress (max. von misses stress) occurs at the maximum water depth (84.31m), and the incoming wave & current direction is 270^0. The maximum stress (max. von misses stress) is 361.4MPa (92.31% of YS).
2) For a significant wave height of 1.0m, the total maximum stress (max. von misses stress) occurs at the maximum water depth (84.31m), and the incoming wave & current direction is 90^0. The maximum stress (max. von misses stress) is 365.9MPa (93.45% of YS).
3) For a significant wave height of 1.8m, the maximum total stress (max. von misses stress) occurs at the maximum water depth (84.31m), and the incoming wave & current direction is 90^0. The maximum stress (max. von misses stress) is 380.6MPa (97.2% of YS).
4) The dynamic analysis results show that the weather limitation of the significant wave height is 1.8m during subsea pipeline installation, where the result of the maximum stress that occurs is still below the yield strength. The maximum value of the local buckling check (LCC) ratio is still below 1.0.
5) For fatigue analysis, significant wave height variations for 0.5m, 1.0m, and 1.8m are considered.

E. Fatigue Analysis of Pipeline Installation

Fatigue analysis using OFFPIPE software has been carried out for subsea pipeline installations, both minimum, and maximum water depths, by considering 8 directions of incoming waves & currents and through significant wave height variations for 0.5m, 1.0m, and 1.8m. **Figure 4.** shows the fatigue damage from the analysis for the minimum water depth (69.44m) and maximum water depth (84.31m).

TABLE 6.
STRESS CONCENTRATION FACTOR (SCF)

Descriptions	Units	Values
Max. Permissible Hi/Lo (e)	mm	1.5
Average cap width (L_{cap})	mm	23.5
Wall thickness (t)	mm	12.7
Manufacturing tolerances (t_{fab})	mm	0.7

Reference thickness (t_c) = t - t_{fab}	mm	12
Diameter steel pipe (D)	mm	273.1
Beta factor (β)	-	2.392
Alpha factor (α)	-	0.374
Stress concentration factor (SCF)	-	1.258

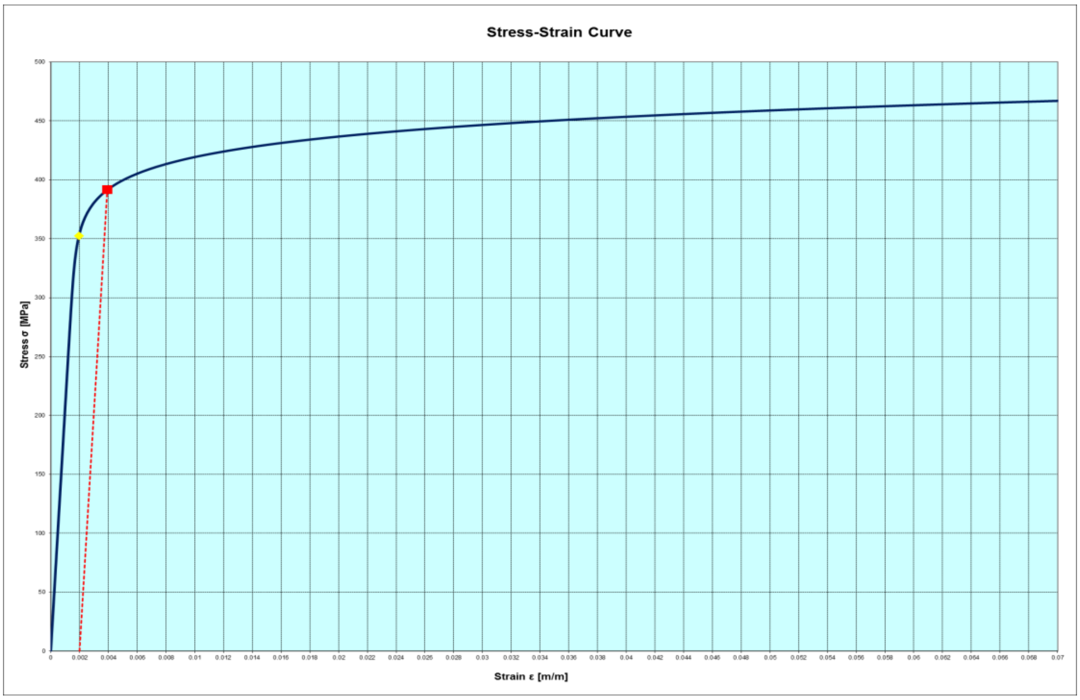

Figure. 1. Engineering Stress and Strain Curve.

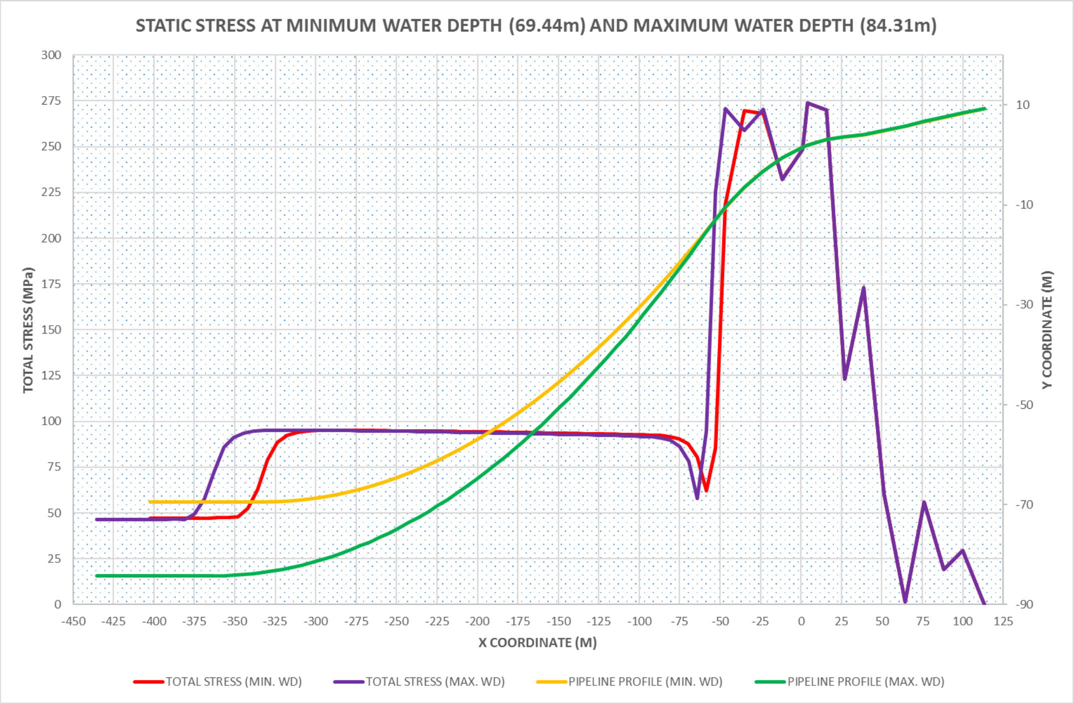

Figure. 2. Stress Result and Pipeline Configuration for Static Analysis.

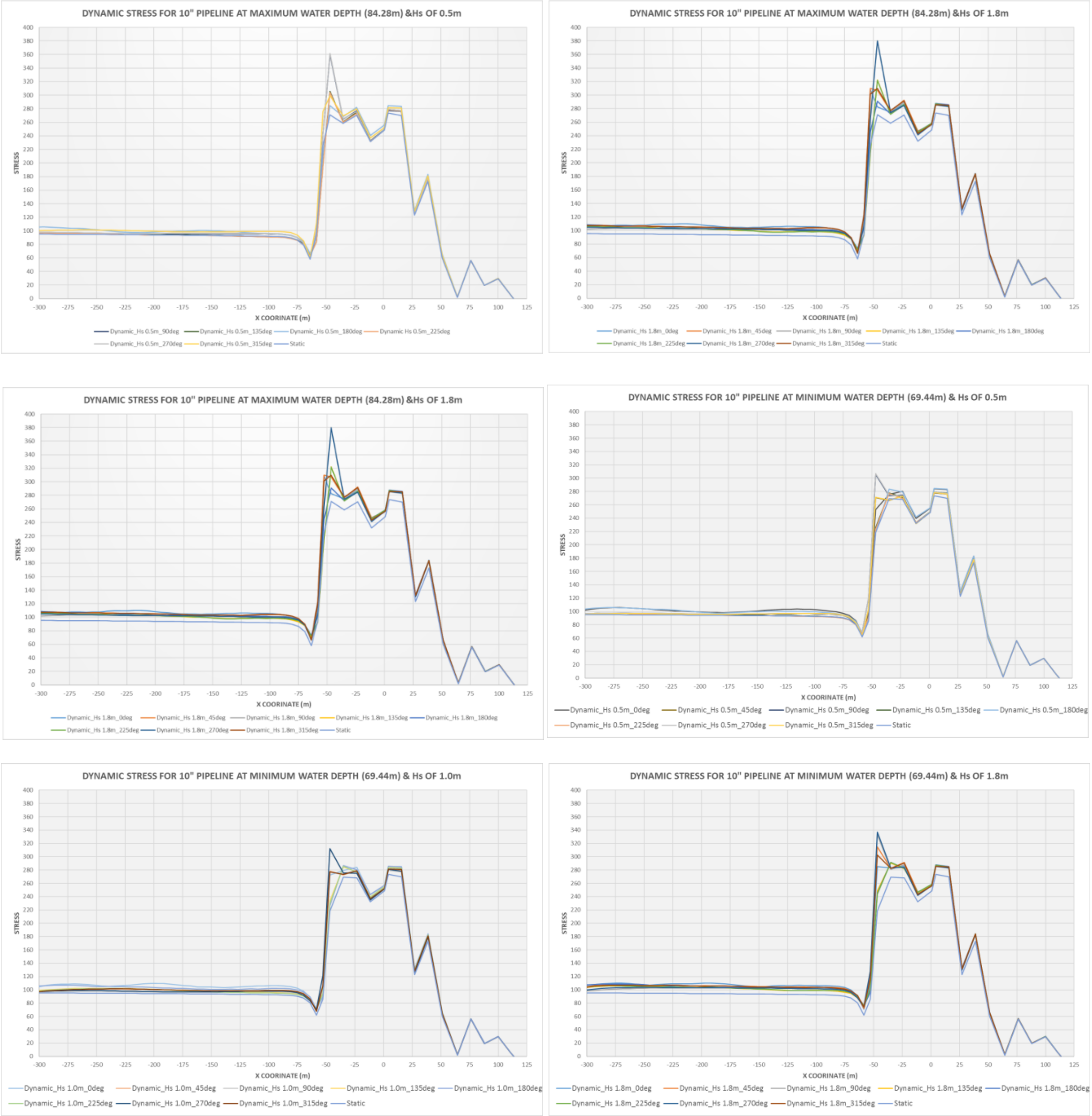

Figure. 3. Stress Result and Pipeline Configuration for Dynamic Analysis.

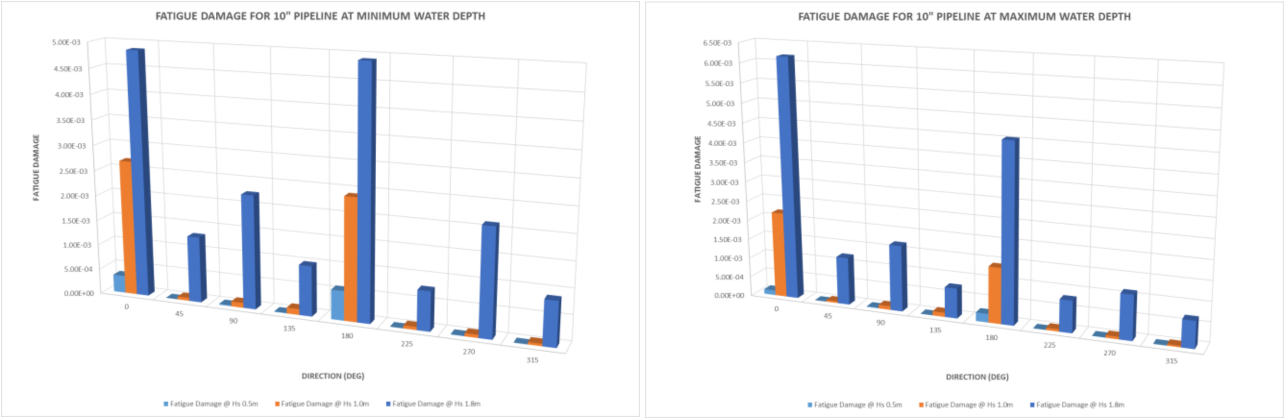

Figure. 4. Fatigue Damage Results for Fatigue Analysis.

From **Figure 4.**, it can be concluded as per followings:

1) The stress range increases when the significant wave height increases. The result is in line with the static and dynamic analysis, where the maximum stress difference between static and dynamic analysis occurs at the highest significant wave height of 1.8m. However, the value of the number of cycles decreases when the significant wave height increases. It is related to the mean wave period, where a higher significant wave height also gives a higher mean wave period. Therefore, with the same exposure time duration, with a larger mean wave period, a smaller number of cycles is obtained.
2) The fatigue analysis results show that the fatigue damage for significant wave height variations of 0.5m, 1.0m, and 1.5m is still below the allowable fatigue damage, which is 1 x 10^{-2}.
3) For critical engineering assessment (ECA) analysis, the fatigue load for each significant wave height variation is based on the maximum fatigue damage value from the maximum and minimum water depths. The following fatigue loads will be considered in the ECA analysis;
   - ✓ Significant wave height of 0.5m, stress range = 15.01 MPa, cycle = 67263
   - ✓ Significant wave height of 1.0m, stress range = 26.57 MPa, cycle = 57670
   - ✓ Significant wave height of 1.8m stress range = 38.22 MPa, cycle = 45605

F. ECA Analysis

Engineering critical assessment (ECA) is carried out in accordance with BS 7910 [10], using CRACKWISE v5 software. According to BS 7910 [10], the sharp planar type defect is considered the most destructive defect concerning fracture and fatigue. The orientation of the defects considered in the analysis is the circumferential flaw in the girth weld for both external and internal surface flaws. Defects in this orientation will be sensitive to longitudinal stresses (axial and bending moments) that occur during installation and fatigue. Analysis of option 2 (option 2) is carried out based on the stress and strain curves of the material according to **Figure 1**.

Defect stability was assessed using a failure assessment diagram (FAD) approach. In the FAD diagram, the x (L_r) axis shows proximity to plastic collapse, and the y (K_r) axis shows proximity to brittle fracture. Suppose the assessment point is located within the FAD line. In that case, it can be concluded that the defect is acceptable or "safe." If the assessment point is outside the FAD line, it can be concluded that the defect is unacceptable or "unsafe." This FAD is made based on the material's stress-strain curve; following **Figure 5.** is a generic FAD obtained from the stress-strain curve.

The results of the ECA analysis are shown in the table containing information on critical defects, where critical defects are acceptable defect sizes in terms of the height and length of the defect. The acceptable defect size will be calculated using CRACKWISE v5 software based on the input parameters. The simulation starts during installation by introducing the initial crack (height and length). Firstly, this initial crack is checked by considering the load during installation. Suppose the assessment point is still within the FAD line. In that case, the fatigue load during pipeline installation is considered the initial crack to determine the growth of defects. The final result of the growth of this crack or post crack is then assessed further in the operation phase by considering the load that occurs during operation. But other than the pipe wall thickness considered during the operation phase, is pipe wall thickness after being fully corroded (or wall thickness minus corrosion allowance). Suppose the assessment point is outside the FAD line. In that case, the analysis shall be repeated by reducing the length of the defect in the initial crack. It continues until the operating phase, where the assessment point is within the FAD line. So it can be concluded that the initial crack is the critical crack size that will be used as a reference for acceptance criteria during NDT / ultrasonic testing.

According to DNVGL-RP-F108 [11], it is stated that unstable fracture due to reduced ligaments should be considered. This situation is usually the result of crack growth from a significant fatigue load, so it can be said that the weld is very sensitive to fatigue. However, it can also occur when excessive corrosion occurs, resulting in a reduction in the ligaments and a risk of fracture or unstable fracture when subjected to a crack driving force failing. Therefore, it is determined that the final defect should not exceed 50% of the wall thickness after considering corrosion at the end of its service life, which is 3mm (0.5 x (12.7mm – 0.7mm – 6mm)). So that the initial crack will be carried out by considering the height of the defect from 1mm – 3mm.

Figure 6. and **Figure 7.** below show the critical crack sizes for external and internal surface flaws for significant wave height variations of 0.5m, 1.0m, and 1.8m. For comparison, workmanship criteria based on DNVGL-ST-F101 [9] are included in the graph to show how significantly an engineering critical assessment (ECA) impacts the determination of allowable defects.

Figure 6. shows a significant difference in the allowable defects for the external surface between the workmanship criteria DNVGL-ST-F101 [9] and the critical engineering analysis (ECA) results through a fracture mechanic approach. For defect height (a), the maximum allowable based on workmanship criteria is 2.54mm (0.2 x 12.7mm - pipe wall thickness), where the allowable defect length (2c) is 12.7mm (pipe wall thickness). However, by performing critical engineering analysis (ECA), with the same defect height (a) (2.54mm), the allowable defect length (2c) is 34mm for a significant wave height of 1.8m. This shows that the allowable defect length from engineering critical analysis (ECA) results is 2.67 x longer than the workmanship criteria.

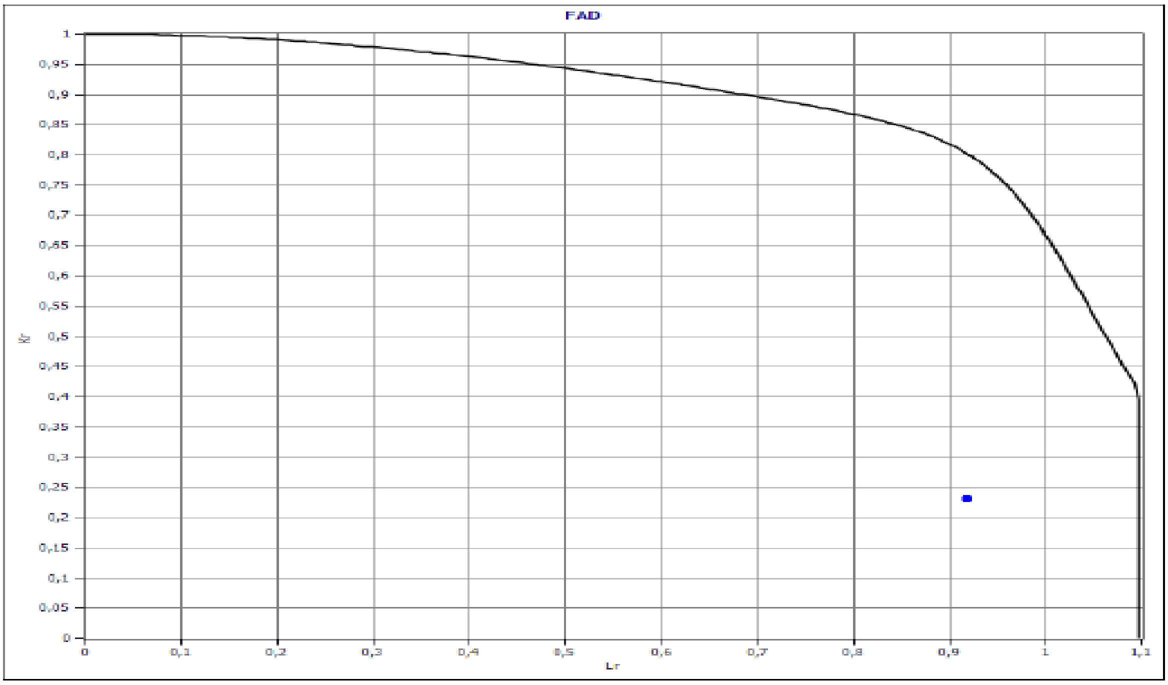

Figure. 5. Generic Failure Assessment Diagram (FAD).

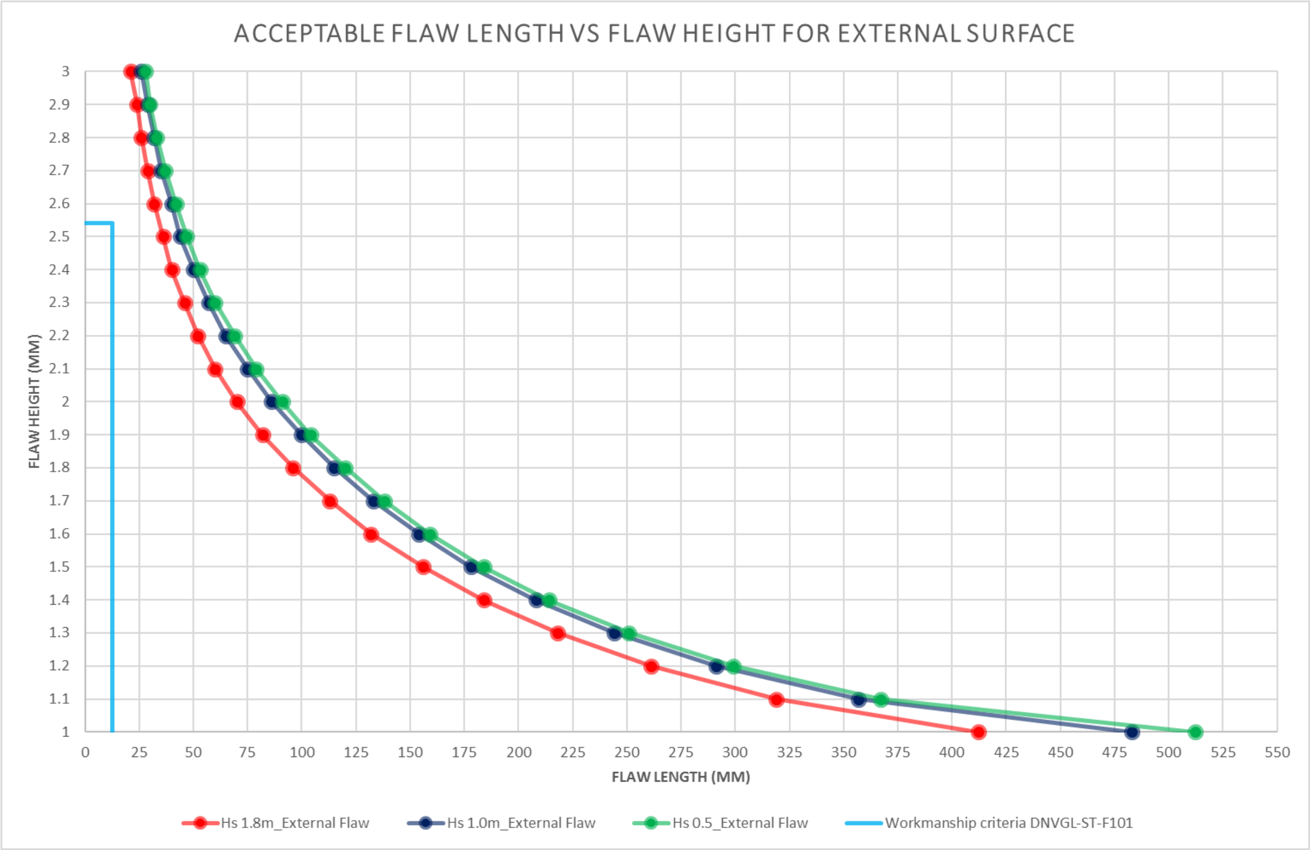

Figure. 6. Critical crack size for the external surface flaw.

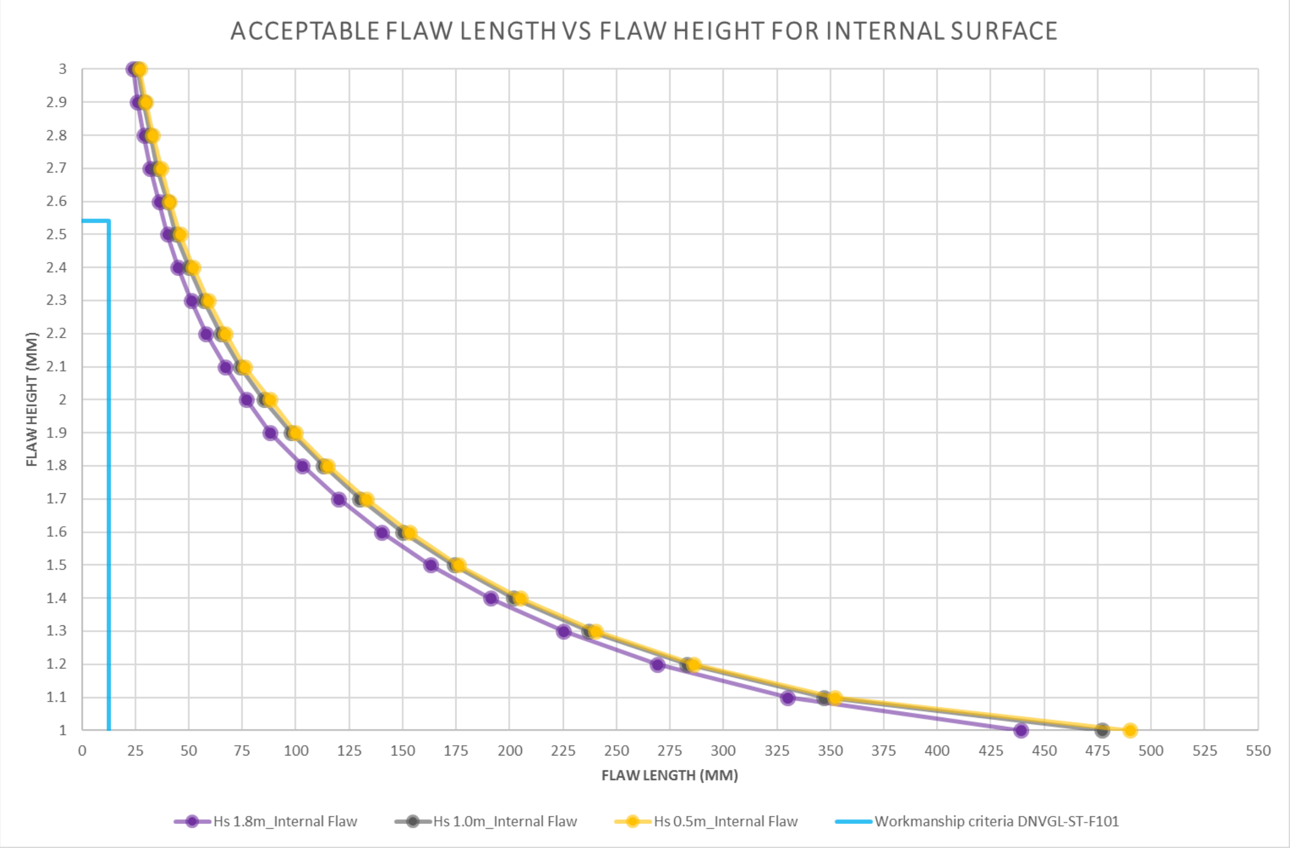

Figure. 7. Critical crack size for the internal surface flaw.

TABLE 7.
CRITICAL CRACK SIZE FOR EXTERNAL SURFACE FLAW

Critical Crack Size (mm)					
Wave significant of 0.5m		**Wave significant of 1.0m**		**Wave significant of 1.8m**	
Flaw height (a)	**Flaw length (2c)**	**Flaw height (a)**	**Flaw length (2c)**	**Flaw height (a)**	**Flaw length (2c)**
1.0	512	1.0	483	1.0	412
1.1	367	1.1	357	1.1	319
1.2	299	1.2	291	1.2	261
1.3	251	1.3	244	1.3	218
1.4	214	1.4	208	1.4	184
1.5	184	1.5	178	1.5	156
1.6	159	1.6	154	1.6	132
1.7	138	1.7	133	1.7	113
1.8	120	1.8	115	1.8	96
1.9	104	1.9	100	1.9	82
2.0	91	2.0	86	2.0	70
2.1	79	2.1	75	2.1	60
2.2	69	2.2	65	2.2	52
2.3	60	2.3	57	2.3	46
2.4	53	2.4	50	2.4	40
2.5	47	2.5	44	2.5	36
2.6	42	2.6	40	2.6	32
2.7	37	2.7	35	2.7	29
2.8	33	2.8	32	2.8	26
2.9	30	2.9	29	2.9	24
3.0	28	3.0	26	3.0	21

TABLE 8.
CRITICAL CRACK SIZE FOR INTERNAL SURFACE FLAW

Critical Crack Size (mm)					
Wave significant of 0.5m		**Wave significant of 1.0m**		**Wave significant of 1.8m**	
Flaw height (a)	**Flaw length (2c)**	**Flaw height (a)**	**Flaw length (2c)**	**Flaw height (a)**	**Flaw length (2c)**
1.0	490	1.0	477	1.0	439
1.1	352	1.1	347	1.1	330
1.2	286	1.2	283	1.2	269
1.3	240	1.3	237	1.3	225
1.4	205	1.4	202	1.4	191
1.5	176	1.5	174	1.5	163
1.6	153	1.6	150	1.6	140
1.7	133	1.7	130	1.7	120
1.8	115	1.8	113	1.8	103
1.9	100	1.9	98	1.9	88
2.0	88	2.0	85	2.0	77
2.1	76	2.1	74	2.1	67
2.2	67	2.2	65	2.2	58
2.3	59	2.3	57	2.3	51
2.4	52	2.4	50	2.4	45
2.5	46	2.5	44	2.5	40
2.6	41	2.6	40	2.6	36
2.7	37	2.7	35	2.7	32
2.8	33	2.8	32	2.8	29
2.9	30	2.9	29	2.9	26
3.0	27	3.0	26	3.0	24

It is also applied to internal surface flaws, as shown in **Figure 7.**, where performing a critical engineering assessment (ECA), with the same defect height (a) (2.54mm), the allowable defect length (2c) is 38mm for significant wave height of 1.8m. This also shows that the allowable defect length from the critical engineering assessment (ECA) results is 2.99 x longer than the workmanship criteria. In addition, **Figure 6.** and **Figure 7.** show that the permissible height of the defect (a) may be more than 2.54mm based on the ECA analysis, in which case the height of the defect is limited to 3mm. Furthermore, if the defect height (a) is less than 2.54mm, the allowable defect length (2c) will be even greater than the workmanship criteria. So it can be concluded that performing a critical engineering assessment (ECA) based on BS 7910 [10] can improve the criteria for welding defects, reducing the rejection rate and have implications for productivity rate during subsea pipeline installation. However, it should be noted that the increase in the criteria for welding defects does not reduce the welding quality. i.e., personnel, methods, tools, etc.

The actual wave height during the campaign of the subsea pipeline installation can't be predicted, and this wave height will certainly have an impact on fatigue loads which will affect the propagation of defects (crack growth). Generally, the fatigue load is based on the maximum wave height where the pipe is experienced higher stress. Still, during the installation of subsea pipelines, the wave height that occurs can be smaller than that considered at the design time. Therefore, the ECA analysis was carried out to determine the criteria for defects from fatigue loads due to significant wave height variations for 0.5m, 1.0m, and 1.8m for both external and internal surface flaws, as shown in **Table 7.** and **Table 8.** This analysis aims to determine how significant the defect criteria refer to significant wave heights that were introduced. From **Table 7.** and **Table 8.**, it can be concluded as follows;

1) For external surface flaws, the allowable defect length (2c) is decreased by 2.7% - 7.1% from significant wave heights of 0.5m to 1.0m, while a larger decrease is 12.7% - 25.0% from significant wave heights of 0.5m to 1.8m.
2) For internal surface flaws, the allowable defect length (2c) is decreased by 1.0% - 5.4% from significant wave heights of 0.5m to 1.0m, while a larger decrease is 5.9% - 13.6% from significant wave heights of 0.5m to 1.8m.
3) It can be concluded that the effect of wave height variation has more impact on the external surface flaw. In addition, it proves that the height of the wave has a significant influence in determining the criteria for welding defects. It can be a consideration for the pipe installation contractor to carry out a detailed ECA analysis based on variations in wave height in determining the criteria for welding defects. The results of this ECA can be used based on the actual condition of the wave height that occurs during the subsea pipeline installation.

IV. CONCLUSIONS

Based on the analysis that has been carried out and the discussion in the previous chapter, several conclusions can be drawn as described in the followings;

1) Static analysis has been carried out for the minimum water depth (69.44m) and maximum water depth (84.31m). The results show that the stress is still below the allowable limit, where the maximum stress is 273.8 MPa.
2) Dynamic analysis has been carried out for both the minimum water depth (69.44m) and the maximum water depth (84.31m). The results show that the significant wave height limitation at the time of the subsea pipeline installation is 1.8m, where the stress is still below the yield strength (yield). strength) is 380.6 MPa (97.2% of YS).
3) Fatigue analysis has been carried out with significant wave height variations of 0.5m, 1.0m, and 1.8m, with the following results;
    - Significant wave height 0.5m stress range: 15.01 MPa, cycle: 67263
    - Significant wave height 1.0m stress range: 26.57 MPa, cycle: 57670
    - Significant wave height 1.8m stress range: 38.22 MPa, cycle: 45605
4) The results of the ECA analysis prove that the fatigue load has a significant impact on determining the criteria for acceptable defects. The results of the analysis show that the allowable defect length (2c) has decreased by 12.7% - 25.0% from a wave height of 0.5m to 1.8m for defects outside the pipe wall (external surface) with crack height (a) from 1mm – 3mm, while for defects in the pipe (internal surface) with crack height (a) it was found that the allowable defect length (2c) decreased by 5.9% - 13.6% from the wave height of 0.5m to 1.8m. These results can be used as a basis for subsea pipeline installation contractors to perform fatigue load sensitivity in optimization to determine allowable defects based on the actual wave load.

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