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Engineering Critical Assessment of Offshore Pipelines under Operational Loading Phase According to BS 7910 Guideline

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ABSTRACT

Offshore pipelines are an efficient long-distance transportation method for oil and gas. These are usually constructed by the use of girth welds, while welds may naturally contain flaws. Hence, it is essential to inspect the fracture response of girth welds in order to check the structural integrity of the pipeline. One of the guidelines that is using wide spread for investigating the fracture response of steel structures is BS 7910 which is based on Engineering Critical Assessment (ECA) method. In this paper Engineering Critical Assessment (ECA) of offshore pipeline girth welds is done according to BS 7910 through Crackwise software and the influence of several parameters on ECA is presented. It is concluded that Influence of misalignment on axial internal surface flaws is more significant than on axial external flaws. Furthermore it is observed that internal surface flaws have always larger values for tolerable defect heights than external surface cracks. In addition, circumferential surface flaws have evermore larger amount of acceptance level in defect heights than axial flaws.

1. Introduction

In order to transport oil and gas e.g. from the platforms to land-based terminals, offshore pipelines are utilized which are usually composed of a number of short pipes joined by welding. The girth welds may contain weld imperfections of certain size (height and length) at specific location along the longitudinal direction of the weld. [1]. Therefore, it is important to find a suitable fracture assessment procedure for welded pipeline and know how these eventual cracks develop in order to assess the structural integrity of the pipelines [2]. For this means, two methods were introduced which are quality control and Fitness-For-Purpose (FFP) approaches. Quality control approach usually gives both arbitrary and conservative levels for acceptance; however FFP procedure make the acceptance levels very less conservative by providing the conditions to cause failures in structures are not reached[3]. Engineering Critical Assessment (ECA) is a FFP procedure which is based on fracture mechanics principles. It was introduced by Kumar et al [4] in 1981. They proposed an analytical methodology for computing crack driving force based on J-Integral which was published by Electric Power Research Institute (EPRI). The EPRI equations for fully plastic condition suppose a simple power law for the material's plastic stress-strain curve. Anisworth modified the EPRI relationships in order to make it more representative of the flow behavior of real materials. He defined reference stress approach and substituted it to the plastic component of EPRI procedure to characterize the possibility of plastic collapse alongside fracture failure [5]. With additional simplifications and modifications to the reference stress approach, BS7910:2005[6] express it in terms of a Failure Assessment Diagram (FAD). At the moment, this regulation is widely used in order to determine defect acceptance criterion in steel structures.

First attempts on ECA analysis in accordance with BS 7910 code have been made by Darcis et al [7]. They studied fracture assessment process in fillet-welded joints where cracks emanate from the weld toe. Pysarsky and his colleagues [8] investigated ECA analysis of high strength steel pipeline girth welds which are subjected to plastic axial loading. Several studies have been performed in order to compare different methods of ECA analysis. Permana [9]

performed a case study on ECA analysis of a pipeline girth weld during reeling installation and compare BS 7910 code with direct finite element. Although BS 7910 tends to be conservative for long crack lengths compared to finite element analysis, it shows less conservative critical crack sizes in the region of short cracks. Smith and Pisarski [10] compare API 1104-Appendix A and BS 7910 FAD procedure with and without residual stress. Larger flaws are allowed by the BS 7910 procedure compared with API 1104 procedure, irrespective of whether the safety factor on flaw length is included or not in the API 1104 assessment. Also, Larrosa and Anisworth [11] showed the differences in ECA results which are assessed by the API 579, the UK nuclear industry standard for fracture assessment (R6), and BS 7910 procedures. They revealed that BS 7910 has larger plastic collapse limitation compare to the other codes.
However, few literatures contribute to investigate the effect of various parameters on ECA of offshore pipelines in accordance with BS 7910. Holtman [12] focused on examining the fracture behavior of offshore pipeline steel in sour environment (containing water and hydrogen sulphide). Wei and Handley [13] presented the effects of bi-axial stressing (internal pressure plus external axial loading) on ECA analysis of plate and cylinder containing surface cracks. Recently, Bonara et al [14] investigated the ECA procedure to assess CRA welds for clad and lined pipe material in bi-metallic girth weld joints. As an extension, this study is aimed to investigate the influence of axial misalignment in girth welds and ductile tearing on engineering critical assessment of girth welded offshore pipelines under operational loading phase based on BS 7910 guideline for various flaw geometries.

In this paper, influence of various parameters on engineering critical assessment of offshore pipelines is performed. Accordingly, a brief overview of BS7910 and theoretical background of engineering critical assessment method is provided; afterward, geometrical configurations, mechanical properties of pipeline materials, and loading scenarios are described in details. Influence of axial misalignment in girth welds and ductile tearing on ECA analysis of offshore pipeline in various flawed geometries is presented based on BS 7910 code. Finally, summary of results and conclusions are given in the last section.

1. BS 7910

Because workmanship standards settle totally specific rules for allowable lengths of slag inclusion and density of porosity, a large amount of repair work is carried out for innocuous planar flaws such as cracks based on these codes. It has been estimated that such unnecessary repairs may add as much as 10% to construction costs [15]. In this order, British Standards Institution set up a logical acceptance standard which was both safer and more economical than the traditional workmanship acceptance standards.

In BS 7910: 2013[3], there are three levels, available for a fracture assessment. The Level 1 which is called simplified assessment procedure is based on a conservative Failure Assessment Diagram (FAD) applicable when the data on the materials properties is limited. The Level 1 FAD has Kr, Sr co-ordinates, where Kr is the ratio of applied crack driving force to fracture toughness and Sr the ratio of applied stress to flow strength where the flow strength is mean of yield and tensile strength hence including some plasticity. For the cases where single-value measurements of fracture toughness are available level 2 which is named normal assessment method is used. Further there are two assessment strategies: Level 2A and Level 2B. When material specific full stress–strain information is available, Level 2B is utilized based on reference stress solution. Level 3 is similar as level 2 with the exception that is appropriate for ductile materials showing tearing mode of failure with Level 3A and 3B dependent on the type of stress-strain data available. A typical figure of level 2 FAD is shown in figure 1.

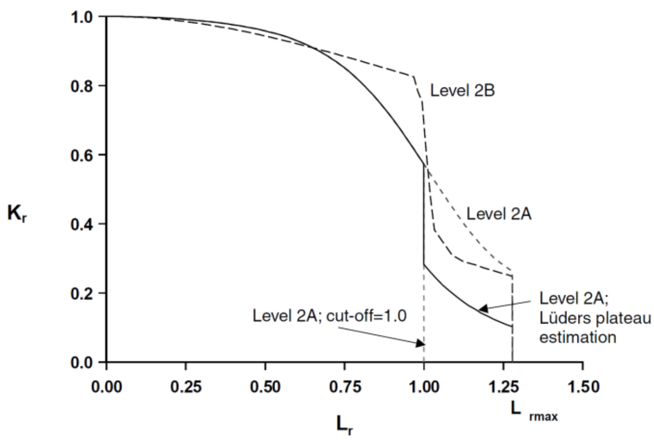

Figure 1- BS 7910 level 2 failure assessment diagram [3]

According to BS7910 level 2B, a flaw can be accepted when the following equation is satisfied:

$$K_r \le \left(\frac{E \times \varepsilon_{ref}}{YS \times L_r} + \frac{L_r^{\ 3} \times YS}{2 \times E \times \varepsilon_{ref}} \right)^{-1/2} \qquad (1)$$

In the above equations, $K_r = K_I \,/\, K_{mat}$ is fracture ratio, σ_{ref} is reference stress, ε_{ref} is the true strain obtained from the uni-axial tensile stress-strain curve at reference stress, $L_r = \sigma_{ref} \,/YS$ is load ratio and $L_{r(max)} = UTS + YS \,/2YS$ is cut-off value, E is the Young's modulus. The first term in equation 1 considers both the limiting elastic and fully plastic behaviors. The second term determines the response in between these two limits where the general behavior is elastic but fracture parameter exceeds its elastic value, and a minor plasticity correction is supply by this term.

2. Methodology

In order to perform engineering critical assessment of offshore pipeline in accordance with BS 7910 guideline, Crackwise software [16] is utilized. Crackwise is a software which is used to compute multiple parametric equations, propagating flaws in ductile tearing, calculation of limiting conditions (for example, the maximum tolerable flaw size in a structure under given conditions), reporting, editing and archiving such complex calculations. Input values of this software for current study are as fallows.

2.1. Geometrical Configuration

The outer radius of pipeline is 203.2 mm, and the average wall thickness is 20.4 mm. The length of the pipe is considered three times as long as the outer diameter**.** Two types of cracks are proposed which are including external surface and internal surface flaws. These defects are located in axial and circumferential direction along the pipeline length and girth weld, respectively. Figure 2 shows the pipeline cross section alongside with various crack types used in this paper. "r_O" represent outer radius of the pipeline, "B" shows average wall thickness, the crack height is symbolized as "a", and "2c" representing the crack length and "p" showing crack ligament height in embedded flaws.

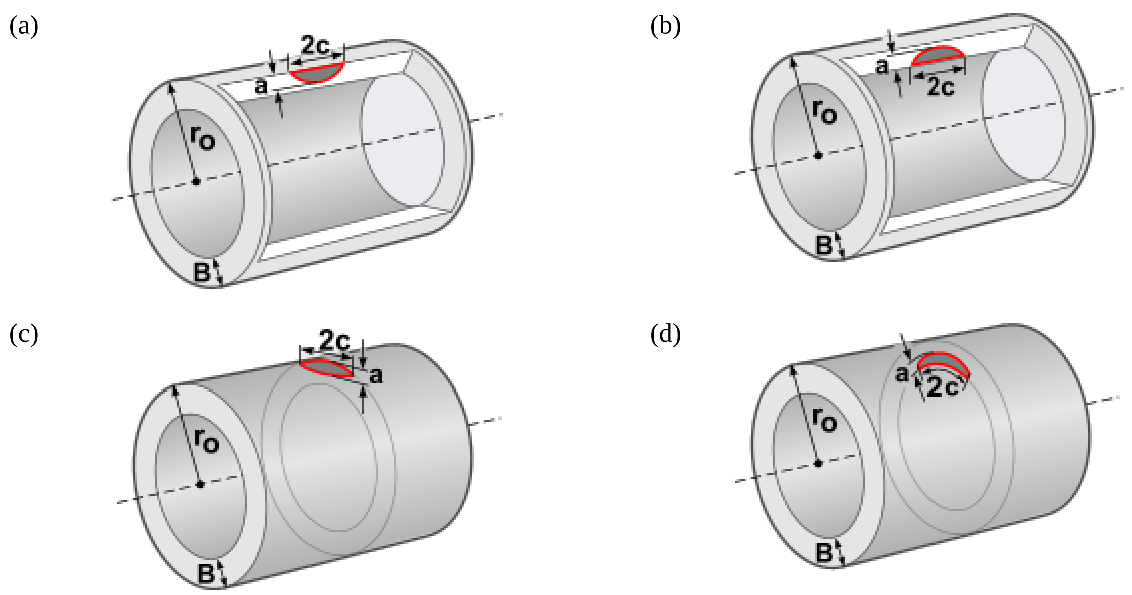

Figure 2- Crack geometries used in current study: (a) axial external surface, (b) axial internal surface, (c) circumferential external surface, (d) Circumferential internal surface flaws [16]

2.2. Material Properties

Two stress-strain curve equations which are widely used for modeling engineering materials are Ramberg-Osgood equation and the CSA Z662 [17] equation. CSA Z662 in contrast to Ramberg-Osgood equation provides the relationship between the stress and strain as mentioned in equation 2:

$$\varepsilon = \frac{\sigma}{E} + (0.005 - \frac{YS}{E})(\frac{\sigma}{YS})^{n} \qquad (2)$$

where *E* is young modules, *YS* is the yield stress at 0.5% strain and *n* is the strain hardening exponent of the CSA equation. Equation 3 determines a unique *n* for any given set of yield stress (YS), Ultimate Tensile Strength (UTS), and uniform Elongation (uEL). Hence, a full stress-strain curve can be determined uniquely by the CSA equation for the input YS, UTS, and uEL. Based on the aforementioned observations, in this paper the CSA Z662 equation is selected to produce the full stress-strain curves (option 2 in Crackwise FAD failure locus) in all models. Table 1 shows the input information for generating stress-strain curve which is mentioned in reference [18].

$$n = \ln(\frac{uEL - UTS/YS}{0.005 - YS/E}) \Big/ \ln(\frac{UTS}{YS}) \qquad (3)$$

Table 1-Mechanical properties used in pipeline [18]

Pipe	YS (MPa)	UTS (MPa)	E (GPa)	uEL (mm/mm)	n	Poisson's ratio
API-5L-X65	545	592	207	0.0816	39.25	0.3

2.3. Toughness

Fracture toughness is described by single-value measurements (K_I, J-Integral, CTOD) on level 2 assessment and expressed in terms of an resistance curve (J-Δa or CTOD-Δa) on level 3 assessment method. Hence, in this paper for level 2 assessment K_I is equal to 338 MPa.$\sqrt{m}$ [18]. Based on DNV-RP-108 [19], the resistance curves shall be established as a lower bound curve for the experimental results. Often a curve of the form J=x* Δa^m fits the data well. X=713.43 and m= 0.5 is considered here as in reference [18].

2.4. Loading Scenarios

A pipeline is laid on the seabed will be inclined to expand longitudinally because of temperature and pressure differential along the pipeline path. If the expansion is constrained by the frictional resistance force between pipeline and soil, then an axial compressive load which is called effective axial force will be exerted on the pipeline (High Pressure/ High Temperature condition) [20]. The effective axial force increases from pipeline end until it reaches its maximum at the point of full axial constraint. The effective axial force in fully constrained condition during operation can be calculated as a result of end-cap effect, Poisson's effect, thermal and residual lay tension [21]. For design purposes, according to Subsea7 documentations [22] the residual lay tension may be assumed to be negligible. Therefore, full constrained effective axial force is given as in equation 4:

$$N_{eff}(x) = H - \left(N_{end-cap(x)} + N_{poisson} + N_{thermal}\right) \quad (4)$$

Where H is residual lay tension, $N_{end-cap(x)} = \Delta P.A_i$ is end-cap effect, $N_{poisson(x)} = -\nu \dfrac{\Delta P.D_i.A_s}{2t}$ is Poisson's effect, and $N_{thermal(x)} = -E.A_s.\alpha.\Delta T$ is thermal effect.

Largest effective axial force at anchor point is occurred when the fully constrained effective driving force equals the soil frictional force. Friction force induced by pipeline-soil interaction is as in equation 5.

$$S_{f,max} = \mu_{max,axial} \times W_{submerged} \times \frac{L}{2} \quad (5)$$

In the above equation, $\mu_{max,axial}$ is maximum axial frictional factor, L is pipeline length, $W_{submerged}$ is the submerged weight which is calculated with respect to the pipeline data's. In this paper, $\mu_{max,axial}$=0.45, $W_{submerged}$=3.345 KN/m, and L=10 km are assumed according to reference [22]. Effective axial force along the pipeline and anchor point is shown in figure 3.

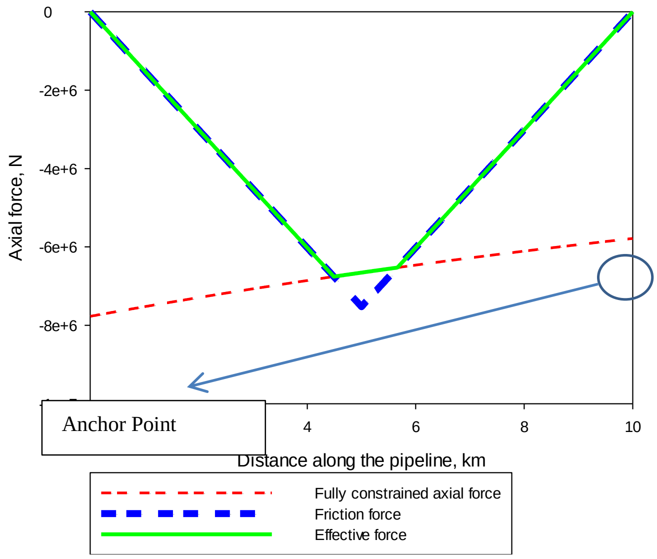

Figure 3- Effective axial force along the pipeline length

According to BS 7910, the stresses that will be considered in the analysis are primary and secondary stresses. The primary stress is stresses that could contribute to plastic collapse. They include all stresses appearing from internal pressure and external loads. Thermal and residual stresses are usually classified as secondary stresses. A significant characteristic of secondary stresses is that they do not, cause to plastic collapse. However, both primary and secondary stresses can contribute to failure by fracture. The stresses are separated into membrane and bending primary and secondary components. In this study, primary membrane stress due to High Pressure/ High Temperature condition is assumed as 288 MPa which is the largest stress occurred at anchor point along the pipeline length. Primary bending stress component that is induced by misalignment in the pipeline is calculated using Stress Concentration Factor (SCF) in association with Neuber's rule [23]. 3 different bending stresses are considered in order to investigate the influence of misalignment on fracture response of offshore pipeline. The base case is performed without misalignment. Afterward, it was compared with alternative eccentricities of 1 mm and 2 mm. Since offshore pipes had appropriate dimensional tolerances, 1 mm misalignment might be more realistic in many cases. However, 2mm misalignment is supposed to have maximum value along the girth weld direction [24]. According to annex Q of BS7910 with considering non-uniform residual stress distribution, secondary membrane and bending stress will be equal to 591.79 and 78.67 MPa.

2.5. Crackwise Modeling

The flowchart which is shown in figure 4 describes the crackwise analysis sequence. For ECA analysis in level 2B and 3B, full stress-strain data for the material are needed. Yield and tensile strength, and modulus of elasticity should be determined along with adequate co-ordinate stress/strain points to define the curve. The cut-off limit is to prevent localized plastic collapse and it is set at the point at which $L_r = L_{r,max}$ where [3]:

$$L_{r,max} = \frac{YS + UTS}{2 \times YS} \tag{6}$$

The load ratio L_r is calculated from the following equation [3]:

$$L_r = \frac{\sigma_{ref}}{YS} \tag{7}$$

Where, $\sigma_{ref}$is obtained from an appropriate reference stress solution as outlined in BS 7910. Fracture ratio is calculated from the following equation [3]:

$$K_r = \frac{K_I}{K_{mat}} + \rho \tag{8}$$

Where ρ is plasticity correction factor and is necessary to allow for interaction of the primary and secondary stress contributions, and the applied stress intensity factor, K_I, has the following general form [3]:

$$K_I = (Y\sigma)\sqrt{(\pi a)} \tag{9}$$

$$(Y\sigma) = (Y\sigma)_P + (Y\sigma)_Q \tag{10}$$

Where $(Y\sigma)_P$ and $(Y\sigma)_Q$ represent contributions from primary and secondary stresses, respectively.

$$(Y\sigma)_P = \mathrm{M}f_w(k_{tm}M_mP_m + k_{tb}M_b(P_b + (k_m - 1)P_m \tag{11}$$

$$(Y\sigma)_Q = M_mQ_m + M_bQ_b \tag{12}$$

Where,
F_W = Finite width correction factor,
$K_{tm/tb}$ = Membrane/bending stress SCF,
$M_{m/b}$ = Membrane/bending stress intensity magnification factors,
K_m = Misalignment,
In the above expressions, equations for M, f_w, M_m and M_b can be found in BS9710 Appendix M for different types of flawed geometry configurations. For k_{tm}, k_{tb} and k_m, BS9710 part 6.4 and Annex D should be referenced. Eventually, the main result of ECA is the curve of critical crack size or allowable defect size. The curve can be generated by crackwise by selecting flaw height as critical analysis parameter and flaw length as sensitivity analysis parameter.

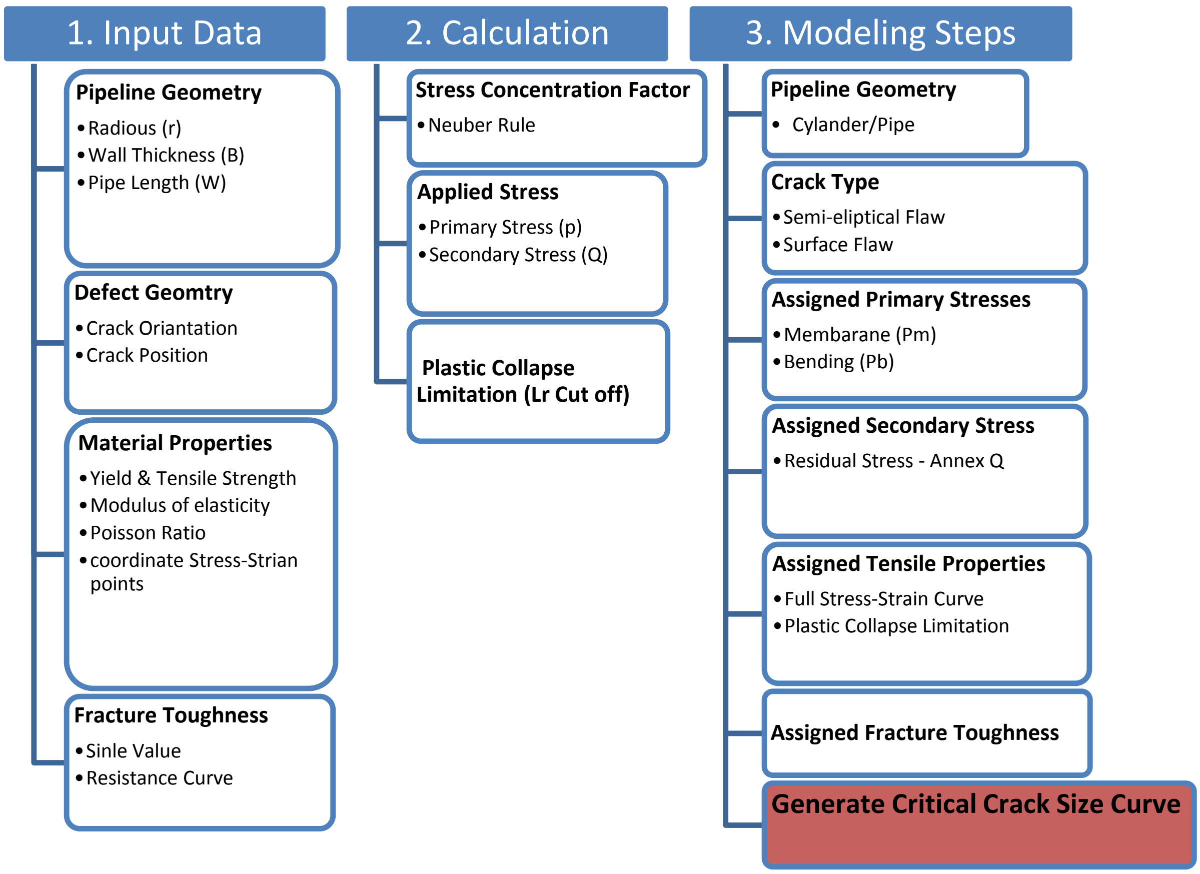

Figure 4 - Crackwise modeling and analysis sequences [16]

3. Results and Discussion

Tolerable defect size curves are presented through Crackwise software according to BS 7910 guideline level 2B and 3B. In level 3B crack ductile tearing is simulated via resistance curves, however in level 2B cracks are assumed to not propagate. According to figure 1, FADs are shown in the form of tolerable crack size curve for axial external and internal surface flaws in compliant with level 2B. Each curve represents specific misalignments that are including 0, 1, and 2 mm misalignment at girth welds. In figure 2, six FADs are presented as in figure 1 but pursuant to level 3B.

It is observed from figure 4 and 5 that by changing in misalignment, the variation in acceptance curve in level 2B for axial internal surface flaws are more than in external flaws. However, the variation between external and internal surface flaws curves are almost identical to each other in level 3B but external flaws still have more evolution. Hence, the influence of girth welds misalignment is more influential for axial internal surface flaws.

(a) (b)

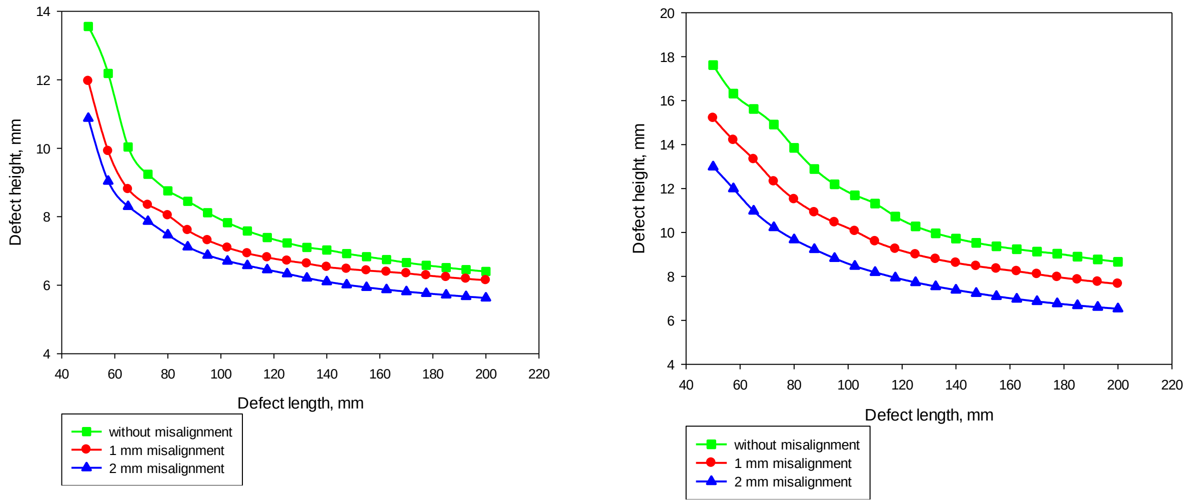

Figure 5- Tolerable defect size curve according to BS 7910- level 2B for axial: (a) Extrnal surface flaw, (b) Internal surface flaw

(a) (b)

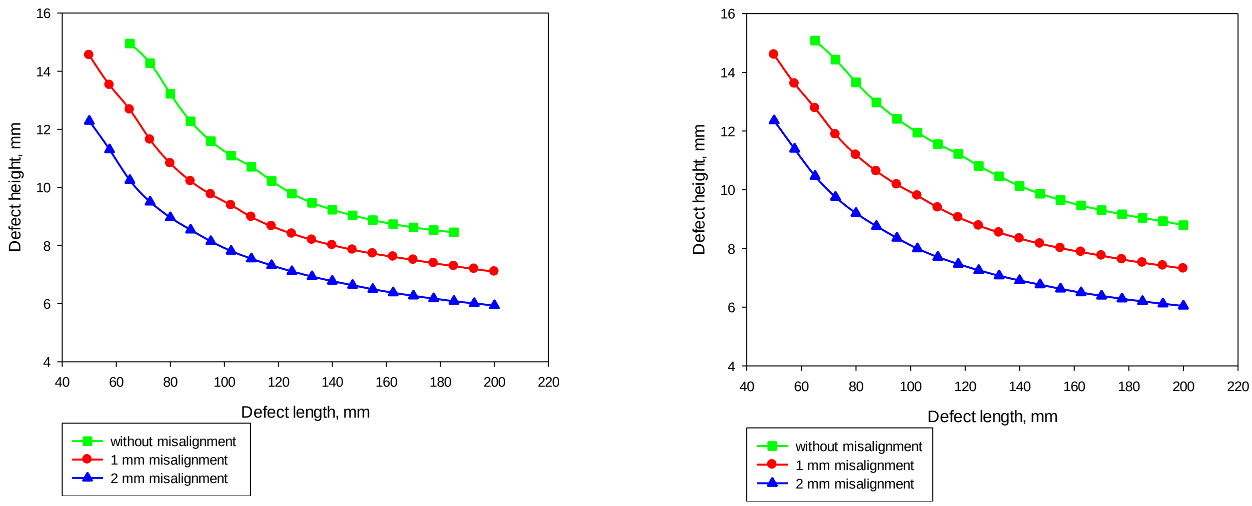

Figure 6-Tolerable defect size curve according to BS 7910- level 3B for axial: (a) External surface flaw, (b) Internal surface flaw

From the figure 6 and 7 the following results can be extracting. The values of defect heights in level 3B for external surface flaws are more than level 2B but whatever the misalignment increases, the amount of flaw heights in level 2B become closer to level 3B. However, for short external surface cracks the difference between flaw heights in level 2B and 3B is more significant than in large cracks. For short internal surface flaws (less than 70 mm), defect heights in level 2B and 3B are adjacent to each other but they are separate with increasing in misalignment amount. However, for large cracks situation is quite the opposite and defect heights get closer with increase in misalignment level.

Internal surface flaws have larger acceptance level for crack heights than external surface flaws especially for short cracks (less than 70 mm). With increasing in misalignment the difference between external and internal flaws heights get reduced. In level 3B external and internal surface flaws have closer results than in level 2B.

Acceptance level for defect heights in circumferential external surface flaws is always larger than axial external flaws. In large cracks, the difference between accepted flaw height between axial and circumferential flaws is greater than in short cracks (less than 70 mm). In the case of internal surface flaws although circumferential cracks still have larger acceptance criteria for defect heights but the difference between axial and circumferential crack heights become greater with increasing in crack length.

(a) (b)

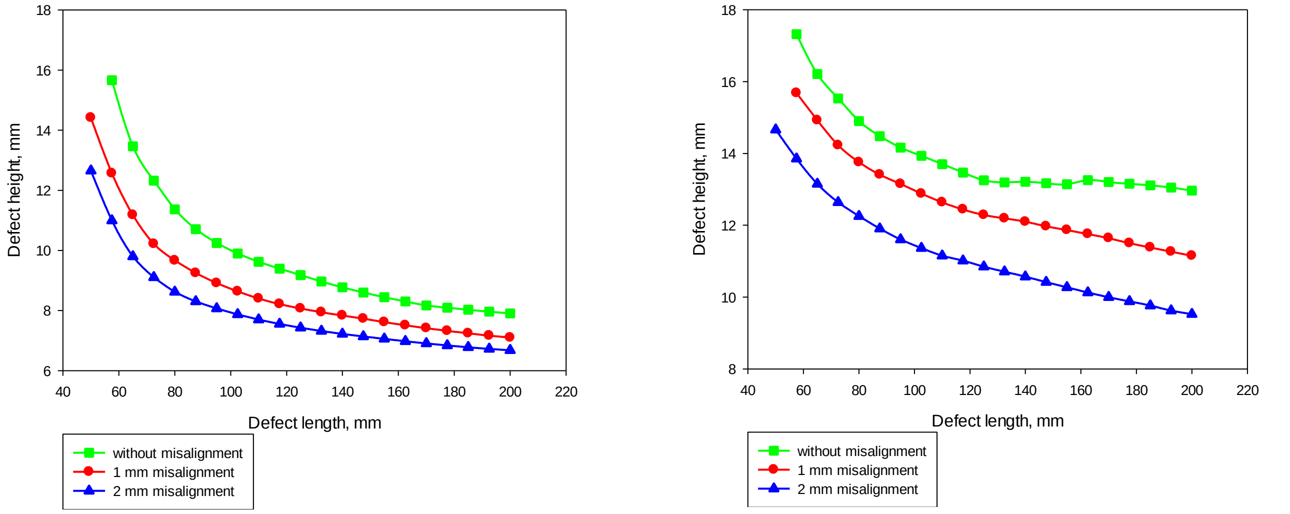

Figure 7-Tolerable defect size curve according to BS 7910- level 2B for circumferential: (a) Extrnal surface flaw, (b) Internal surface flaw

(a) (b)

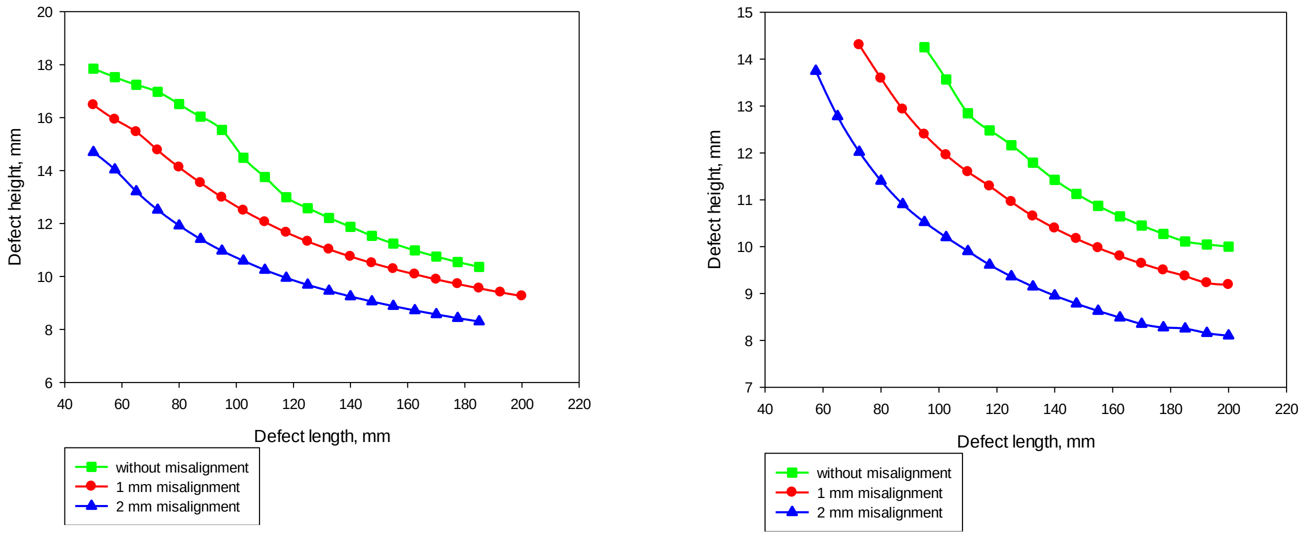

Figure 8- Tolerable defect size curve according to BS 7910- level 3B for circumferential: (a) External surface flaw, (b) Internal surface flaw

4. Summary and conclusions

In the current study, the Engineering Critical Assessment (ECA) of an offshore pipeline with elliptical surface external and internal cracks subjected to different misalignment level under operational loading phase has been analyzed according to BS 7910 level 2B and 3B.Crackwise software is employed to investigate the complex multiple parametric calculations and fracture behavior limit conditions. The influence of the misalignment values, the crack geometries including external, internal, axial, and circumferential flaws on the evolution of FAD in the form of defect acceptance size curves is investigated. The main conclusions and observations are made as follows:

- Influence of misalignment on axial internal flaws is more significant than on axial external flaws, however in level 3B misalignment influence is almost equal on internal and external axial flaws. In the case of circumferential cracks misalignment is more influential for short external cracks (less than 70 mm) but for long cracks it is more significant for internal defects.
- In short external flaws the difference between level 2B and 3B is significant but it becomes smaller for large cracks (larger than 70 mm). for internal cracks the condition is totally vice versa which means that level 2B and 3B for short cracks are almost equal to each other but their difference get larger with increasing in crack length. In both cases increasing in amount of misalignment cause to reduction in crack height acceptance level.
- Internal flaws have always larger values for tolerable defect heights than external surface cracks in both axial and circumferential directions. However the difference between tolerable sizes in level 3B becomes insignificant.
- Circumferential external surface flaws have evermore larger amount of acceptance level in defect heights than axial flaws but with increasing in crack length, acceptance levels for axial and circumferential flaws get closer. However, in the case of internal surface circumferential flaws acceptance levels for crack height is still more than axial flaws but the difference become larger with increasing in crack length.

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