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Engineering Critical Assessments of Marine Pipelines with 3D Surface Cracks Considering Weld Mismatch

S.M.H. Sharifi [1,*], M. Kaveh [1], H. Saeidi Googarchin [2]

[1] *Department of Offshore Structures Engineering, Faculty of Marine Science, Petroleum University of Technology, Abadan, Iran*
[2] *Automotive Fluids and Structures Analysis Research Laboratory, School of Automotive Engineering, University of Science and Technology, Tehran, Iran*

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ABSTRACT
Offshore pipelines are usually constructed by the use of girth welds, while welds may naturally contain flaws. Currently, fracture assessment procedures such as BS 7910 are based on the stress-based methods and their responses for situations with large plastic strain is suspicious. DNV-OS-F101 with limited modifications proposes a strain-based procedure for such plastic loads. In this paper 3D nonlinear elastic-plastic finite element analyses using the ABAQUS software are performed in order to compare existing stress- and strain-based procedures beside newly strain-based method which is called CRES approach in order to improve the criteria used in current guidelines particularly at large plastic strains. It is concluded that although BS 7910 values are closer to finite element results than other methods in elastic region, but it is still conservative. In the area of large plastic strain, CRES method is very less conservative in both case of with and without internal pressure in comparison to others. The comparison of numerical simulation results with those available experimental data reveals a good agreement.

Keywords: Engineering critical assessment (ECA); Marine pipelines, Girth welds; Surface cracks; Weld mismatching; CTOD.

1 INTRODUCTION

OIL and gas fields are today being developed at water depths characterized as deep waters. Marine pipelines which are considered as major components of these developments will experience large plastic strains both in installation and operation loading phases. A vast majority of research efforts has been done in order to fracture assessment of marine pipelines subjected to large plastic deformations. Thus, Engineering Critical Assessment (ECA) of pipeline girth welds under large plastic strains has received increasing attention. Current codes and guidelines for ECA analysis of marine pipelines at such large deformations may give suspicious results. These approaches which are suited to load controlled situations are called stress-based ECA. Consequently, strain-based methods are highly desirable for ECA analysis of offshore pipelines girth welds subjected to large plastic strains [1]. First attempts to improve the accuracy of stress-based fracture assessment accounting for strain-based situations have been made by Schwalbe [2]. He proposed a strain-based estimation on CTOD and J integral for small strain

*Corresponding author. Tel.: +98 09126086493.
E-mail address: Sharifi@put.ac.ir (S.M.H.Sharifi).

levels (small scale yielding). Compared to reference stress concept, Linkens et al. [3] firstly derived one alternative formulation which is known as the reference strain method for large plastic deformation by replacing reference stress and strain with their ‘‘un-cracked body” values beside some simplifying assumptions and applying a safety factor of 2.

Researches indicated that although reference strain method can qualitatively detect the fracture response of large plastic strain, the quantitative accuracy is not adequate. Recently, a new strain-based ECA approach has been published for the design of pipelines through Pipeline Research Council International and US Department of Transportation sponsored project which is completed by the Center for Reliable Energy Systems (CRES) and is referred as the CRES procedure [4-6]. This approach is intended to be applied to pipes with and without internal pressure when subjected to tensile strains up to one half of the parent pipe uniform elongation. While the strength mismatch between the base and weld materials of the pipeline plays a significant role in the process of the pipeline fracture response as signified in DNV-OS-F 101 [7], few studies could be found in literature contributed to investigation of the strength mismatch on ECA of girth welded offshore pipelines at various crack geometries particularly under large plastic strains in such a quantitative manner. Therefore, this study is dedicated to the investigation of the combined effect of these two factors on Crack Tip Opening Displacement (CTOD) as a failure criterion for the improvement of the current standards.

In this paper, first ECA analysis methods of marine pipelines are compared, and then the CTOD evolutions of the cracks in the pipeline girth welds are investigated in order to propose a new strain-based equation. In Section 2, geometrical configurations, material properties of pipeline, loading scenarios, and finite element meshing technique are illustrated in details. In section 3, BS 7910 stress-based ECA fracture assessments and strain-based DNV-OS-F 101 and CRES assessments are accomplished for pipelines girth welds. Comparisons of mentioned fracture assessment methods and current study in addition to investigation of internal pressure influence on fracture response of pipeline girth weld are presented in section 4. Finally, a summary of the results and conclusions are given in the last section.

2 PRINCIPLE OF MODELING

2.1 Geometrical configurations

Nonlinear 3-D finite element analyses are performed for circumferentially flaws in pipeline’s girth weld. The geometric features of a girth welded pipeline are shown in Fig. 1(a). The outer radius of pipeline is 203.2 *mm*, and the average wall thickness is 20.4 *mm*. The cross-section of the girth weld is shown in Fig. 1(b). As can be seen in Fig. 1(c), a canoe shape surface crack (with its fillet radius equal to the crack depth) is located at the weldment which is believed to be a typical weld-defect in offshore pipelines. However, it is worthy to note that the crack shape does not influence the fracture response at the crack center, where the maximum CTOD occurs [8]. The crack depth is symbolized as "a", while "$2c$" represents the crack length. The ratio "c/a" is denoted as the aspect ratio. In order to describe the effect of crack geometrical configurations on fracture response of pipeline’s girth welds, three crack depths of 6, 8, 10 *mm*, and aspect ratios of 1, 3, 5 are considered. In addition, it is noted that only a segment of the pipe with the length of two times the outer diameter was modeled. It is sufficiently long to capture the strain and stress discontinuity caused by the crack recommended by Jayadevan et al. [9] and Øtsby [10].

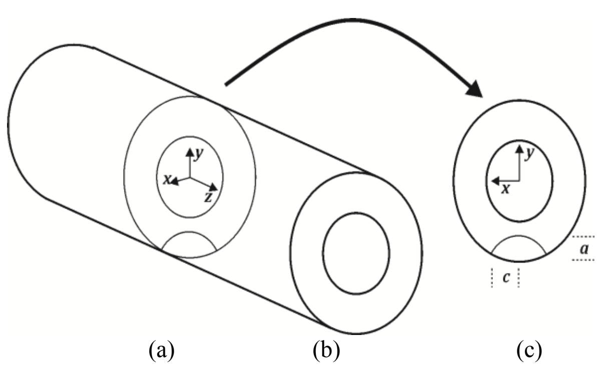


Fig.1
Schematic drawing of the cracked pipeline model: a) Synopsis view of the pipeline with a semi-elliptical surface crack. b) Detailed cracks geometry used in the simulations.

2.2 Material model

Materials of the pipeline could be divided into the base metal, carbon steel, and the weld metal. API 5L Grade X65 is considered as the base metal of the pipe and for the weld metal, an Inconel filler metal is used. The mechanical properties of the materials used in the pipeline are listed in Table 1.

The CSA Z662 [11] isotropic strain hardening model is selected to produce uniaxial true stress-strain curves for the carbon steel (i.e. base metal) in all finite element models since it can generate a unique hardening exponent for any given set of Yield Stress (YS), Ultimate Tensile Strength (UTS), and uniform E Longation (uEL). CSA Z662 design code defines the nonlinear plastic behavior of material as follows:

$$\varepsilon = \frac{\sigma}{E} + (0.005 - \frac{YS}{E})(\frac{\sigma}{YS})^n \tag{1}$$

where E is Young's modules, YS is the yield stress at 0.5% strain and n represents the strain hardening defined in equation 2 which is 39.25 in current study.

$$n = \ln(\frac{uEL - UTS/YS}{0.005 - YS/E}) \Big/ \ln(\frac{UTS}{YS}) \tag{2}$$

As for the weld metal, the uniaxial stress-strain relation would be divided into three parts. The first part stands for a straight line of slope E (the Young's modulus). The second part represents the Lüder's expansion, which have a constant stress equal to YS and the third one characterizes the strain hardening of the curve, represented as follows in Eq.(3):

$$\begin{aligned} &\varepsilon = \frac{\sigma}{E} && \text{if } \varepsilon \le \frac{YS}{E} \\ &\sigma = YS && \text{if } \frac{YS}{E} < \varepsilon \le 1\% \\ &\varepsilon = \frac{\sigma}{E} + (0.005 - \frac{YS}{E})(\frac{\sigma}{YS})^n + 0.005 && \text{if } 1\% < \varepsilon \le uEL \end{aligned} \tag{3}$$

The true stress–strain curves for the materials are plotted in Fig. 2. The UTS of current weld metal is 622 *MPa*, 5% higher than the UTS of base steel which is 592 *MPa*. That is, the weld has the median value of even-matched strengths according to experimental researches [4], obtaining the hardening exponent, n, as 24,45.

There are two other scenarios for weld mismatching conditions which are called under-matched and over-matched situations respectively. The corresponding uniaxial stress–strain curve follows Eq. (3), yet the hardening exponent n would for under-match and over-match situations. Meanwhile, mechanical properties of the base metal are remained constant. The stress–strain curves for the three different weld metal are plotted in Fig. 3. In this study even-match condition is assumed for weld metal modeling.

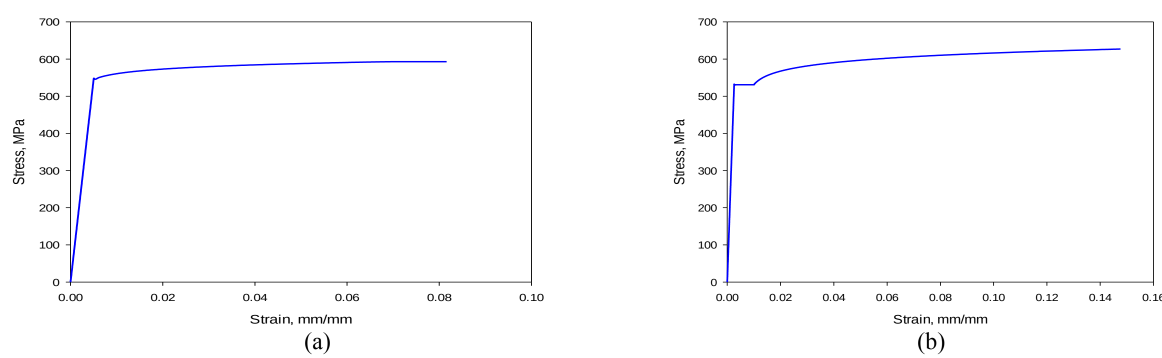


Fig.2
The uniaxial stress - strain curve for a) Carbon steel and b) Weld metal.

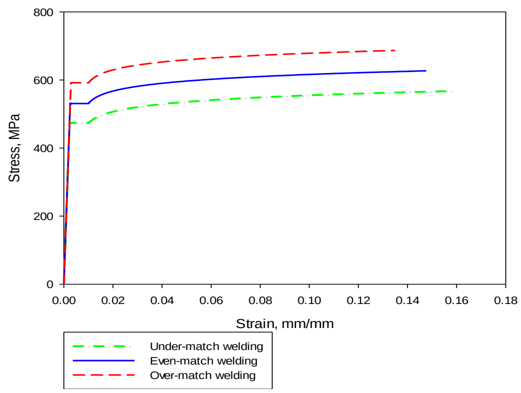


Fig.3
Stress-strain curve for different mismatching conditions.

Table 1
Mechanical properties of materials used in the pipeline (at $150^{\circ c}$)

Material	Young's Modulus E (*GPa*)	Poisson ratio υ	Yield stress YS (*MPa*)	Ultimate tensile strength UTS (*MPa*)
Base metal	207	0.3	545	593
Weld metal	178	0.3	531	622

2.3 FE modeling

Finite element simulations are carried out using ABAQUS 6.14 code [12]. Pre-processing, processing, and post-processing of finite element models were executed automatically using an internal script developed which significantly expedited the study. Due to the symmetry, only one-quarter of the pipe was modeled using eight node 3D elements (known as C3D8R).

For large plastic strain analysis, Anderson [13] had recommended the use of finite radius at the crack tip. The initial blunt crack tip should not affect finite element results as long as CTOD value after deformation is at least 5 times the initial value [13]. Therefore, a blunt crack front is modeled with a radius of 0.01 *mm* (the initial value of CTOD is 0.02 *mm*). So, finite element analyses with the CTOD larger than 0.1*mm* are considered to be accurate.

Spider web mesh technique is adopted to simulate blunt crack tip region. Fig. 4 shows a sample finite element model and a close-up view of the near-tip spider web mesh. The crack tip region was modeled with 10 rows of elements covering in the circumferential and radial directions as suggested in literature [14]. In addition, the size of the smallest element around the blunt crack tip is on the order of 0.001 of the crack length. Within the crack tip zone, the number of element rows along the crack line varies from 15 to 30. Hence, each finite element model consists of 21,000 to 32,000 elements depending on the crack size.

*J*2 flow theory of plasticity with isotropic hardening is taken to describe the material behaviors of the carbon steel and the weld metal. The Nlgeom option in ABAQUS software is activated to include the feature of the non-linear geometry in the analysis. Meanwhile, mesh convergence studies were carried out scrutinizing both the global behavior and the J-integral values, providing confidence in the established mesh.

The boundary condition and loading for the model in this study are as shown in Fig. 5, two surfaces of which the normal direction is the *X* axis are not allowed to move along this axis. One end of the pipeline segment except the cracked surface is constrained in *Z* direction and the other end is imposed by displacement in the same way.

In order to investigate the effect of internal pressure, bi-axial loading condition, uni-axial tensile displacement combined with internal pressure is also considered as in Fig. 5. In this case, the loading process includes two steps, first the internal pressure was exerted on the inner surface of the pipe; and then the tensile displacement was imposed in second step. Such a subsequent of loading is common in practice and corresponding for generating the worst case [15, 16]. The magnitude of the internal pressure is presumed as 13.68 and 27.36 *MPa*, which induces the hoop stress of $\sigma_H = 0.25\sigma_y$ and $\sigma_H = 0.5\sigma_y$ respectively.

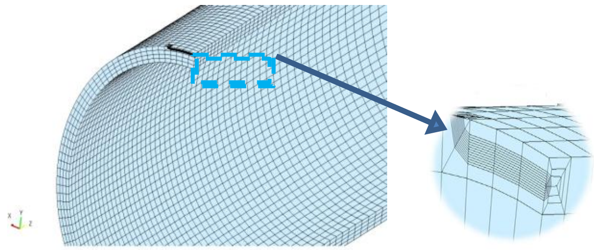


Fig.4
Finite element model and close-up of the near-tip mesh.

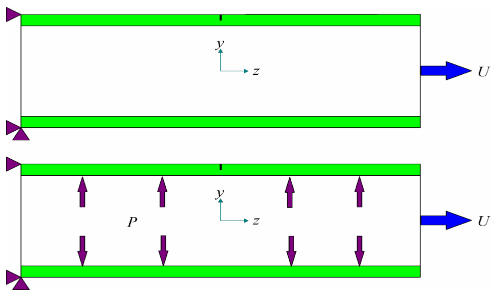


Fig.5
Boundary conditions and two loading scenario considered for investigating internal pressure effects.

3 INTERPRETATION OF GUIDELINES

3.1 Reference stress solution

BS 7910 [9] is one of the guidelines that is using wide spread for investigating the fracture response of steel structures which is based on reference stress approach. In this procedure, reference stress is estimated from the loads applied on the un-cracked pipeline based on elastic calculations. According to BS 7910, a flaw can be accepted when Eq. (4) is satisfied:

$$K_r \le \left(\frac{E\,\varepsilon_{ref}}{YS\,L_r} + \frac{L_r^{\,3}\,YS}{2E\,\varepsilon_{ref}}\right)^{-0.5} \tag{4}$$

where $K_1 = K_I / K_{mat}$ 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. The first term in Eq. (4) describes both the limiting elastic and fully plastic behaviors. The second term describes the behavior in between these two limits where the general behavior is elastic but *J* exceeds its elastic value, and a minor plasticity correction is provided by this term.

There are three levels of fracture assessment in BS7910. All levels are expressed as failure assessment diagram, in which level 1 is a simplified assessment method applicable when the information on the materials properties is limited. Level 2 is the normal assessment method for cases where single-value measurements of fracture toughness (apparent toughness) are available. Further, there are two assessment strategies: Level 2A and Level 2B. When material's specific full stress–strain data is available, Level 2B is used based on reference stress model. DNV guideline is one of the few codes published until now, which provide procedure to perform the fracture assessment of the pipeline subjected to large plastic strains. It mostly endorses the usage of BS7910 with limited modifications and is derived from the reference stress approach. The differences of these two rules are listed in the Table 2. Because of lower cut-off value of BS 7910, plastic strains (more than 0.5%) cannot be modeled with this rule. In this paper critical crack size curves are obtained using level 2B.

According to BS 7910 guideline, the stresses that will be considered in the fracture assessment 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. Because, in this study fracture response of marine pipelines at large deformations is considered, residual stress is not taking into account in both numerical and analytical (BS and DNV) calculations.

Table 2
Differences between BS 7910 and DNV-OS-F 101

	DNV-OS-F 101	BS 7910
Toughness	SENT Specimen	SENB Specimen
Residual Stress	Equal to YS of parent pipe, uniform through thickness	Non-uniform distribution through thickness
Stress-Strain Curve	True uniaxial curve	Engineering uniaxial curve
Biaxial Longitudinal Stress	$\begin{cases} \varepsilon_{nominal} \le 0.4\% & \sigma_{bi-axial} = \frac{\sigma_H}{2} + \sqrt{\sigma^2_{uni-axial} - 0.75\sigma^2_H} \\ \varepsilon_{nominal} > 0.4\% & 3D\ FE\ Analysis \end{cases}$	No Comments
Cut-off Value	(YS+UTS)/2YS	Max{1.5, UTS/YS}

3.2 CRES strain-based method

A lot of attempts have been made accounting for strain based situation. Pipeline Research Council International CRES procedure is one of the newest and most complete methods. In this section CRES method has been illustrated so as to predict girth welds critical cracks sizes made by GMAW and either SMAW (FCAW).

Fracture assessments are performed in a four-level format. The Level 1 procedure provides rough estimation in a tabular format for quick initial assessment. The Level 2 procedure is based on an initiation-control limit state. Fracture analysis can be computed using this level with the input of a pipe's dimensional and material property parameters. The apparent toughness is estimated from either upper shelf Charpy energy or upper shelf toughness of standard CTOD test specimens. The level 3 procedure uses the same procedure as in level 2 and the toughness values are obtained from low-constraint tests. In the Level 3 procedure, two limit states based on either initiation control or ductile instability are considered. In this paper critical crack size curves are obtained using level 2 and toughness values are obtained from low-constraint standard CTOD test specimens.

4 RESULTS AND DISCUSSION

4.1 Validation of finite element model

Finite element results are validated against the full scale experimental tests conducted by Wang et al [6]. They tested two different pipes, known as X65 "high" and "low" YS/UTS pipes. The pipes were of 323.85 *mm* outer diameter and 12.7 *mm* wall thickness. The high YS/UTS pipes had two types of girth welds which were referred to as the even-matched and over-matched welds. The low YS/UTS pipes had one type of weld which overmatched the pipe strength. The tests were performed under both pressurized and non-pressurized conditions. More details of pipe and weld materials may be found in Table 3. It is noteworthy that tests were conducted for median pipe properties. For the cases defined in Table 4., numerical calculations are compared with the full scale experimental data in Fig. 6 and it is revealed that for strain below 2%, simulating pipeline and weld metal homogenously and assuming crack at weld metal and even-match welding is accurate (with the maximum difference less than 10%). It is revealed that finite element results are in a good agreement. Differences between the measured Tensile Strength Capacities (TSCs) and the predicted TSCs via finite elements could be explained by the strength variation along the length of the pipe. Very smooth stress-strain curves which has happened in strain values beyond approximately 2% would cause a small variation in the strength, leading to a large variation of the measured remote strain even when the weld mismatching is considered in the models.

Table 3
Summary of pipe and weld properties used in full scale tests according to to the experimental tests reported in [6].

	X65 High YS/UTS Pipe			X65 Low YS/UTS Pipe		
	Pipe Property			Pipe Property		
	YS (*MPa*)	UTS (*MPa*)	YS/UTS	YS(*MPa*)	UTS(*MPa*)	YS/UTS
Minimum	514.4	577.8	0.87	385.4	466.1	0.83
Maximum	566.8	606.1	0.94	444.0	494.4	0.93
Median	544.7	592.3	0.93	426.1	478.5	0.88

Table 4
Full scale experimental tests were compared with numerical calculations.

No	Position	Mismatch	Crack Height (*mm*)	Crack Length (*mm*)	σ_H / YS	YS/UTS
1	BM	-	3	50	0	High
2	HAZ	Over	3	50	0	High
3	WM	Over	3	50	0	High
4	BM	-	3	50	0.8	High
5	HAZ	Even	3	50	0.8	High
6	HAZ	Over	3	50	0.8	High
7	WM	Over	3	50	0.8	High
8	WM	Even	3	50	0.8	High
9	HAZ	Even	3	35	0	High
10	WM	Even	3	35	0	High
11	HAZ	Even	3	35	0.8	High
12	HAZ	Over	3	35	0.8	High
13	WM	Even	3	35	0.8	High
14	WM	Over	3	35	0.8	High
15	WM	Over	2	70	0.8	High
16	BM	-	3	50	0	Low
17	HAZ	Over	3	50	0	Low
18	BM	-	3	50	0.8	Low
19	HAZ	Over	3	50	0.8	Low
20	WM	Over	3	50	0.8	Low

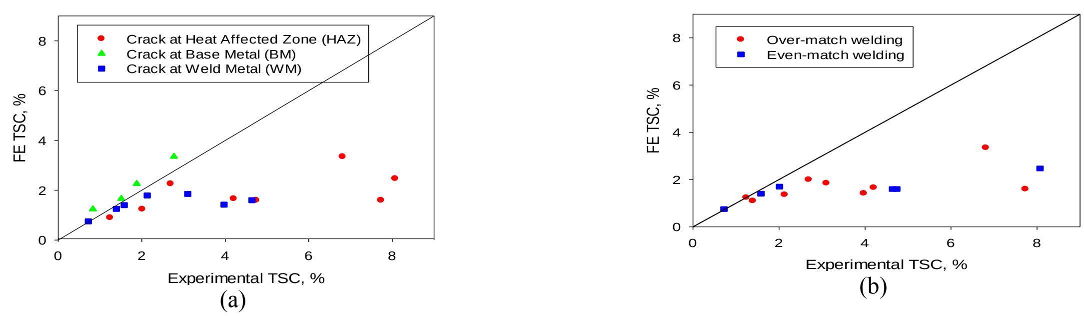


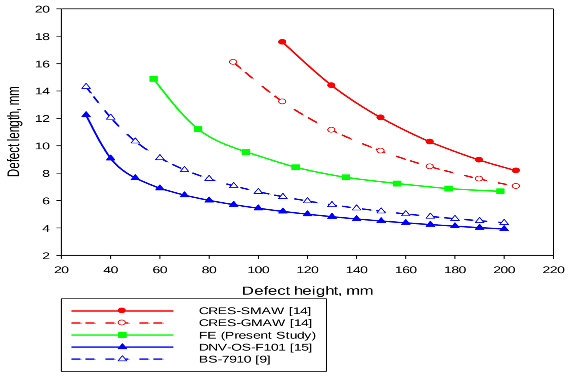
Fig.6
Comparison of finite element and full scale tensile strain capacity for a) Crack position and b) Strength mismathing according to the experimental tests reported in [6].

4.2 Comparison of fracture assessment methods

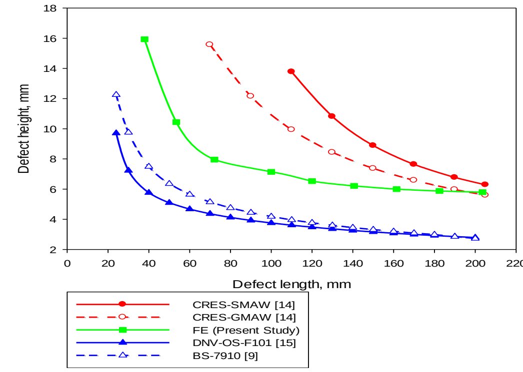
In this section, critical crack size curves obtained from stress- and strain-based methods and direct finite element are compared in several strains and the following results are acquired.

Fig. 7(a-h) shows that at low strains (less than 0.5%), responses derived from strain-based formula are un-conservative as expected and those derived from stress-based assessments are conservative. DNV-OS-F101 reveals more conservative results than BS 7910 method but in large cracks (defect length of almost 120 mm) they give same results. Although CRES represents results which are closer to finite element than DNV-OS-F101 strain-based method for large cracks in the region of plastic strains, it shows still a level of conservation for large cracks and has un-conservative results for short cracks. Furthermore, slightly larger allowable flaw heights are permitted in plastic strains when CRES-SMAW (FCAW) procedure is employed since it makes wider weldments than GMAW girth welds, however, the differences between procedures in plastic zone are significantly large.

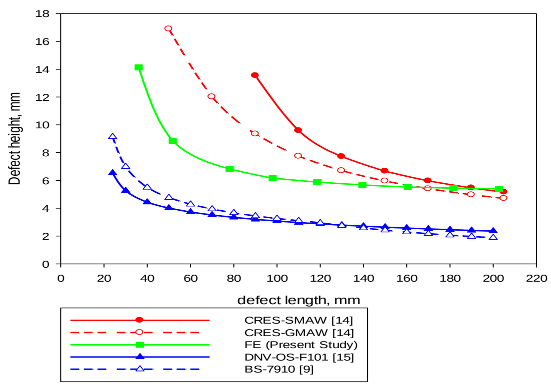
In Fig. 8, the critical crack sizes obtained from uniaxial tensile strain and biaxial loading are compared for different strains. Generally, the internal pressure applied in the biaxial loading causes the curves to accept a smaller zone than uniaxial condition and reduces the flaw tolerance capacity. Fig. 8(a-c) shows the effect of internal pressure on DNV-OS-F101 and CRES strain-based methods. It is observed that DNV formulation for calculating internal pressure is more effective in elastic region than in plastic zone where the results for $\sigma_H = 0.25\sigma_y$ and $\sigma_H = 0.5\sigma_y$ are almost identical. CRES method has better fracture response in plastic strains with internal pressure in contrast to DNV.



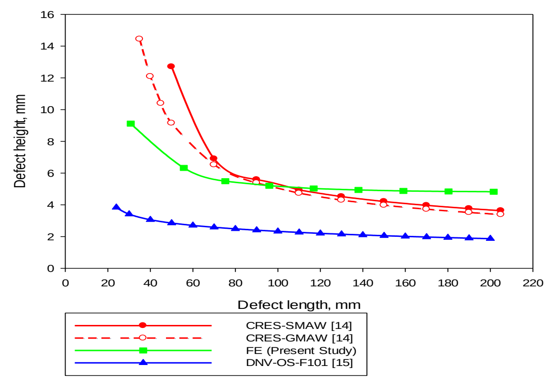
(a)



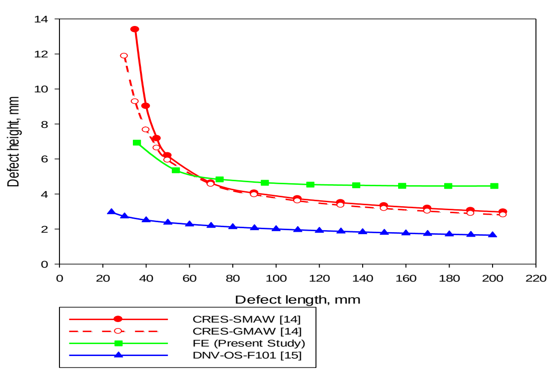
(b)



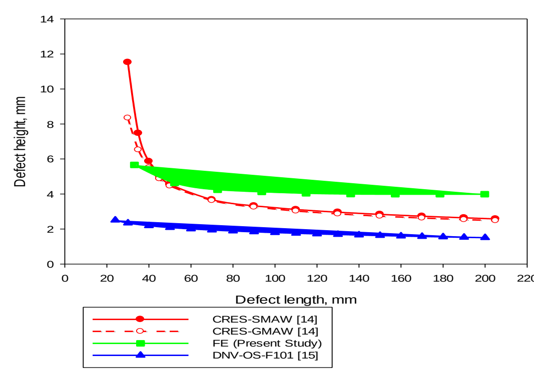
(c)



(d)



(e)



(f)

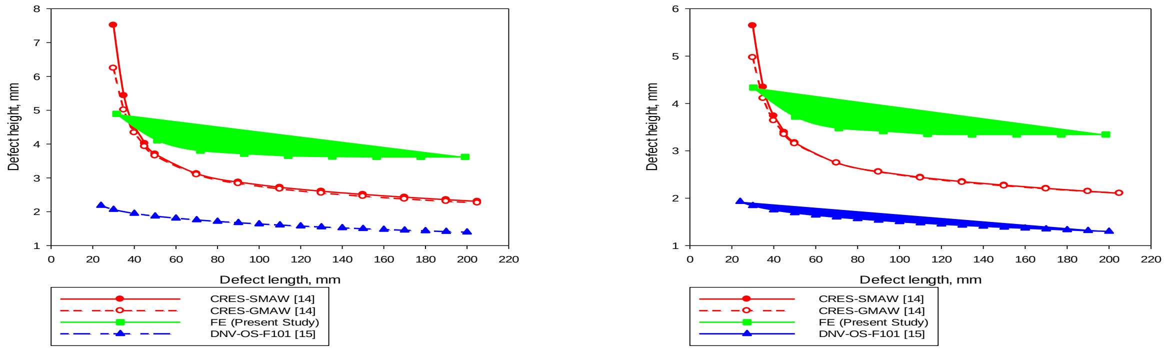
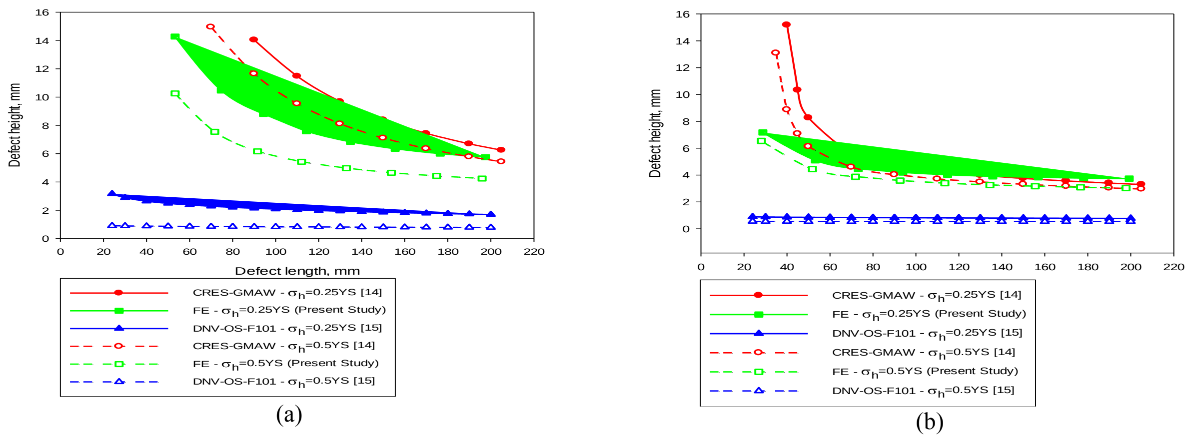


Fig.7
Comparison of BS 7910 stress-based [9], FE, and DNV [15] and CRES [14] strain-based fracture assessment methods for a) 0.3%, b) 0.4%, c) 0.5%, d) 0.8% e) 1.1%, f) 1.4%, g) 1.7%,h) 2.0% tensile strains.



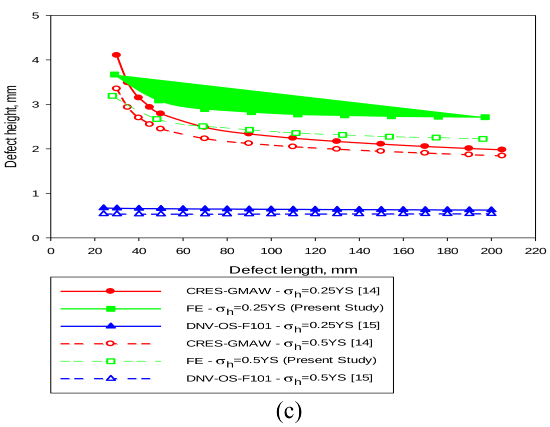


Fig.8
Comparison of CRES [14] and DNV strain-based [15], and FE fracture assessment methods with effect of internal pressure for a) 0.3%, b) 0.8%, c) 2.0% tensile strains.

5 CONCLUSIONS

In the present study, various fracture assessment methods for the girth welded pipeline with surface cracks are compared and presented through 3D elastic–plastic finite element models. The effect of the crack depth, the crack aspect ratio on crack assessment curves is investigated. It is believed that, the models were used would cover many of the practical combinations relevant to marine pipelines. The comparison of numerical simulation results with those available experimental data in literature reveals a good agreement. The most important conclusions of the current study are made as follows:

- BS 7910 formulas in elastic region have more contiguous values to finite element results than DNV-OS-F101 in this region; however, CRES strain-based procedure shows adequate results and very less conservative than DNV-OS-F101 for large plastic strains.
- CRES method reveals un-conservative results for short cracks.
- The internal pressure applied on the pipeline before uni-axial tensile strain, reduces the value of critical crack size curve significantly.
- For the case of tensile strains with internal pressure in elastic region, although DNV-OS-F101 strain-based approach is conservative, it has better fracture response than CRES method. In plastic zone CRES method has appropriate results. DNV-OS-F101 has no sensitivity to internal pressure in plastic zone and has very conservative results for all cases.
- Even though DNV-OS-F101 fixes the problem of low rate cut-off value at BS 7910 procedure, it still gives conservative results.
- For investigating direct finite element fracture response at large deformations, it is revealed that for strain below 2%, simulating pipeline and weld metal homogenously and assuming crack at weld metal and even-match welding is accurate (with the maximum difference less than 10%). But for strains more than 2%, it is necessary to model Base Metal (BM), Weld Metal (WM), and Heat Affected Zone (HAZ) separately because of flat stress-strain curve at plastic strains.

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