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An Experimental Determination of Fracture Toughness of API X46 Steel Pipeline Using Single Edge Bend and Crack Assessments by Failure Assessment Diagrams

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Article info

Abstract

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Keywords: Fracture toughness Single edge bend Single specimen method J-integral Failure assessment diagrams For the first time, the fracture toughness of pipeline with outer diameter of 168.3mm (thickness: 6.9mm; grade: API X46) was determined using the J-integral (according to ASTM standard E1820), Single Edge Bend [SE(B)], and single-specimen method. The pre-crack was created using fatigue and the crack propagation was measured using the unloading compliance method. In each stage of crack propagation, the J-integral parameter was calculated and J_Q was obtained using the J-R curve. The results indicated that satisfied the test's validity criteria, and was equated to J_Q . Subsequently, K_{IC} was gained from the relationship between J_{IC} and K_{IC} . For the given pipeline, J_{IC} and K_{IC} were equal to 51kJ/m² and 105.4MPa \sqrt{m} , respectively. In addition, assessment of longitudinal cracks with different depths and lengths on the pipes body was conducted using fracture toughness and Failure Assessment Diagrams (FADs) for levels one and two of BS7910 standard. Results showed that a longitudinal crack with a depth of 5mm and a length of 220mm lies in the safe zone.

Nomenclature

σ_Y	Effective yield strength (MPa)	σ_{YS}	0.2% offset yield strength (MPa)
σ_{TS}	Ultimate tensile strength (MPa)	E	Modulus of elasticity (MPa)
v	Poisson's ratio	B	Specimen thickness (mm)
a	Crack length (mm)	a_0	Initial crack length (mm)
Δa	Crack extension (mm)	w	Specimen width (mm)
J_{IC}	Resistance against crack initiation character-	A_{PL}	Area under force vs. displacement curve
	ized by J-integral (kJ/m^2)		(kN.mm)
S	Distance between specimen supports (mm)	J	J-integral (KJ/m^2)
J_e	Elastic component of J (kJ/m^2)	J_P	Plastic component of J-integral (kJ/m^2)
p	Load (kN)	K	Elastic stress intensity factor $(MPa\sqrt{m})$
C_i	Corrected compliance (mm/kN)	C	Surface crack half length (mm)
Q_b	Secondary bending stress (MPa)	Q_m	Secondary membrane stress (MPa)

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CTOD	Crack tip opening displacement (mm)	Kra	Plain strain fracture toughness (MPa (m)
	Clack-tip opening displacement (inin)	Λ_{IC}	i iam strain nacture toughness (Mi av m)
f(a/W)	Non-dimensional geometric coefficient	d	Crack depth
$(Y\sigma)_P$	Contribution of the main stresses	$\sigma_{\rm max}$	Maximum tensile stress (MPa)
$(Y\sigma)_S$	Contribution of the secondary stresses	P_b	Primary bending stress (MPa)
p_m	Primary membrane stress (MPa)	r_i	Internal shell radius (mm)
$\sigma_{ m ref}$	Reference stress (MPa)	K_{tm}	Membrane stress concentration factor
M_T, M_s	Stress magnification factors	M	Bulging correction factor
$M_m, M_b,$	Stress intensity magnification factors	K_{tb}	Bending Membrane stress concentration
M_{kb}, M_{km}			factor
f_w	Correction terms in stress intensity factor		

1. Introduction

Nowadays, oil and gas pipelines are of the most important and vital sectors of every country. As a result, their maintenance is undoubtedly a key issue. Defects, such as longitudinal and peripheral cracks on the pipeline body, as well as corrosion, are among the challenges facing these pipelines [1]. Pipes used in the gas pipelines should have adequate fracture toughness to resist the spread of cracks. The tolerable stress of pipeline can be obtained by using K_{IC} and measuring the crack length. As a result, the fracture toughness has become widely applicable in the design and evaluation of materials resistance to the fracture and spread of cracks [2]. However, structural defects in pressurized piping systems are very often surface cracks that form during fabrication or during in-service operation (e.g., blunt corrosion, slag and nonmetallic inclusions, weld cracks, dents at weld seams, etc.). In the current study, some longitudinal cracks were observed during the inspection of the 52-year-old API X46 steel pipelines, with outer diameter of 168.3mm and thickness of 6.9mm. The fracture toughness of this pipeline was determined using the J-integral (according to ASTM standard E1820), single edge bend [SE(B)], and single-specimen method.

The pipeline safety can be investigated using the fracture toughness and Failure Assessment Diagrams (FADs) [3]. FAD technology is used to do Ftness-For-Service (FFS) assessment for pipelines with cracks [4]. There were numerous assessment procedures of a clearly national nature, such as the BS PD6493/6539 [5] (now combined with BS7910), FITNET (European Fitness-for-service Network) [6], ASME Section XI [7], the French RCC-MR [8], and SINTAP (Structural Integrity Assessment Procedures for European Industry) [9]. At present, the two important standards, namely API579 [10] and BS7910, are applied to pipelines FFS, which are able to identify all modes of failure from linear elastic to plastic, and are accepted for the assessment of natural gas pipes with pseudo-crack defects [11].

Chatzidouros et al. [12] studied the effect of hydrogen on the fracture toughness properties of an API X65 pipeline steel under simulated H2S in-service conditions. The fracture toughness properties were measured in LT and SL directions (perpendicular and parallel to the pipeline wall thickness, respectively), following ASTM E1820. It was observed that the KQ moderately decreased with increase in hydrogen concentration in the bulk of the steel, while CTOD0 showed a significant reduction with increasing hydrogen concentration. Lamborn et al. [13], Converting Charpy V-Notch (CVN) value to fracture toughness via different empirical correlation models, derived throughout the years, while laudable, have inherent shortcomings. Suggestions for standard fracture mechanics sub-scale coupon testing, such as ASTM E1820, on pipeline steel samples were delineated with rationale for each test type. This data will support minimizing material assumptions and increase the accuracy of structural integrity predictions to improve the overall pipeline performance. Ibáñez-Gutiérrez and Cicero [14] combined the use of Failure Assessment Diagrams for the fracture assessment and the application of the Theory of Critical Distances for the estimation of the apparent fracture toughness. The methodology was applied to 125 fracture specimens, combining five different fiber contents and five different notch radii. The results obtained validated the proposed assessment methodology, with a clear reduction of the conservatism obtained when the notch effect is not considered. Baek et al. [15], calculated the fracture toughness by using quasi-experimental relationships obtained from applying the Sharp Impact Test to steel gas pipeline (grade: API X65). They performed this test for different pre-strain rates (0-10%) at the temperature of -40 to 20° C. The obtained result for K_{IC} at the room temperature without pre-strain was $316 MPa \sqrt{m}$. Angeles et al. [16] investigated the fracture toughness of submerged arc welding (SAW) in a 36" X52 steel pipe, and compared the Circumferential Longitudinal (CL) and Circumferential Radial (CR) directions of the weld metal. They showed the validity of experimental values according to the standard ASTME399. Their findings indicated lower fracture toughness by approximately 25.37% in CR direction than the CL direction. The K_{IC} at CL and CR directions was obtained as 75.4 and 56.3MPa \sqrt{m} , respectively. Asghari et al. [17] determined the fracture toughness of base steel and direct seam welded of gas pipeline (grade: API X65), using the unloading compliance method. In their study, the Compact Test (CT) in single-sample method was used to determine. After the conduction of required experiments and calculations, numerical values of K_{IC} for the pipe body and the seam weld were obtained as 302 and 262MPa \sqrt{m} , respectively. Moreover, they obtained the fracture toughness using the relationships between toughness and sharp impact. The majority of previous studies investigated the pipeline grades of X65 and X70, which are more common in the oil and gas pipelines [18-21].

In the current study, some longitudinal cracks were observed during the inspection of the 52-year-old API X46 steel pipeline, with outer diameter of 168.3mm and thickness of 6.9mm. Subsequently, the Young's modulus of the pipeline was obtained to increase the accuracy of calculation. For the first time, the fracture toughness of a pipeline with this size, material, and low thickness was determined using the Single Edge Bend [SE(B)] and single-specimen methods. This finding could be used as a source of information for evaluation and comparison of resistance to the crack propagation, and for determining critical crack length on this pipeline. Assessment of longitudinal cracks with different depths and lengths was conducted using fracture toughness and Failure Assessment Diagrams (FADs) for levels one and two of BS7910 standard. The manuscript contains valuable experimental data from the Iranian Gas Transmission Company.

2. Experimental Materials and Procedures

The test sample was prepared from a 52-year-old steel pipeline, with outer diameter of 168.3mm and 6.90mm thickness, which was fabricated in 1963 and was used for transmission of Iranian petroleum products, and was repurposed in 1984 for gas transmission at 7.2MPa. The type of coating, pipe fabrication date, operational conditions and the type of soil were the factors of investigation for determining the probability of SCC along the pipeline. Given the age of the coating and the date of fabrication, the pipeline was excavated at a number of locations. A Non-Destructive Testing method, Magnetic Particle Inspection (MPT), was performed on the pipeline and longitudinal cracks were found (Fig. 1). Observations suggest the presence of these cracks all across the pipeline route.

In the previous study, The present authors [22] found that this pipeline is a steel of X46 grade based on the API 5L standard [23]. In addition, experimental results attributed the cause of these cracks to the formed during fabrication [22]. Since the pipeline was operational, it was first emptied before cutting out a section of it.



Fig. 1. Cracks detected by Magnetic Particle Inspection.

The direct and indirect methods were used to determine the K_{IC} of the materials. The direct method was in compliance with the standard ASTM E399 [24]. In this method, the specimen thickness should be large enough to meet the standard's plane strain condition. Due to the low pipeline thickness (6.9mm), direct determination of K_{IC} was not possible [25]. As a result, indirect methods were used to determine the pipeline toughness. To this end, the toughness was determined based on another criterion, such as J_{IC} . Then, K_{IC} was calculated based on the relationships between J_{IC} and K_{IC} . The measurement of the critical value of J-integral, K_{IC} was performed according to the standards of ASTM E813 and ASTM E1820. To determine J_{IC} , ASTM E1820-15 recommends both the multisample and single-sample methods [26]. In the multisample method, some specimens are fabricated using the experimental materials, and then tested. This is a costly method, which needs a great amount of primary materials. To reduce costs and material consumption, the current study used the single-sample and Single Edge Bend [SE(B)] methods, in which J_{IC} of the material is determined with a single specimen. In this method, the extent of crack extension in length should be determined during the experiment [27, 28].

The hoop stress caused by the passage of a highpressure gas leads to first mode loading (the most dangerous loading mode) and opening of the longitudinal cracks. This stress can be calculated using Eq. (1).

$$\sigma_{\theta} = \frac{pr}{B} \tag{1}$$

where P is the gas pressure, r stands for mean radius of the pipe, and B presents thickness of the pipe. As a result, the specimens should be positioned in a way that the direction of applied experimental stress conforms to the direction of the actual hoop stress inside the pipeline. As a result, directions of the tensile and toughness tests were selected according to Fig. 2. Therefore, the application of transversal loading leads to longitudinal extension of the crack.



Fig. 2. Orientation of the tests specimens.

3. Results and Discussion

3.1. Transverse Tensile Test and Determination of Young's modulus

Table 1 presents the results from transversal tensile stress based on the standard ASTM A370 [29]. The transverse tensile test results were relatively similar to the longitudinal tensile test results obtained in the previous work of the authors [22], which was conducted to determine the pipeline grade and the nature of the cracks. Moreover, the Young's modulus was obtained as 198GPa, using the tensile extensioneter.

3.2. Specifications SE(B) Specimen and Test Device

To conduct the three-point bending test based on ASTM E1820-15, the ratio of width to thickness of the specimen should be 1 < W/B < 4. This study considered a specimen with the width (W) of 15mm, thickness (B) of 5mm, and length (L) of 80mm. The gouging process was applied to the specimen through wire-cut process. Fig. 3 presents the dimensions of specimen under the three-point bending test. The root

Table	1						
Result	from	simple	tensile	test	for	the	trans

radius should not exceed 0.08mm as possible. Fig. 4 presents the specimen after fabrication.

The three-point bending test was conducted using an INSTRON 1343 machine with capacity of 20tons (Fig. 5). To measure the opening of crack tip, an Instron A136 clip gage with the measurement range between 0-10mm was used.

3.3. Forming Fatigue Pre-crack

After specimen fabrication, a pre-crack was formed along the specimen's groove under fatigue loading. The formation of fatigue pre-crack is often one of the most complicated and time-consuming stages of fracture toughness test.

According to the standard ASTM E813-89, the loading used to form the pre-crack should not exceed, obtained from the following equation:

$$P_L = \left[\left(\frac{4}{3}\right) \left(\frac{Bb_0^2 \sigma_Y}{S}\right) \right]$$
(2)
$$\sigma_Y = \frac{(\sigma_{YS} + \sigma_{TS})}{2}; \quad S = 4W; \quad b_0 = W - a_0$$

where B is the specimen thickness, W is the specimen width, a_0 is the initial crack length (notch length + pre-crack length), σ_{YS} is the yield stress, and σ_{TS} is the ultimate stress. For the present specimen, P_L is equal to:

$$\sigma_Y = \frac{(506 + 361)}{2} = 433.5 \text{MPa}$$

$$S = 4 \times 15 = 60 \text{mm}$$

$$a_0 = 6.57 + 1.3 = 7.87 \text{mm}$$

$$b_0 = 15 - 7.87 = 7.13 \text{mm}$$

$$P_L = \left(\frac{4}{3}\right) \left[\frac{5 \times 7.13^2 \times 433.5}{60}\right] = 2487.6N$$



Fig. 3. Dimensions of SE(B) specimen in mm.



Fig. 4. Specimen under three-point bending test.



Fig. 5. Fracture toughness test equipment.

For loading, the specimen was precisely placed in the particular jig and fixture. Then, the fatigue cycles were applied. These cycles often have sinusoidal form with maximum possible frequency. The objective of applying fatigue loading is to form a sharp groove with a zero radius at the groove tip to model the crack as precisely as possible, which is essential for calculation of the stress intensity. Since the ordinary machining process cannot produce a completely sharp groove, fatigue loading was applied to create a natural groove on the specimen. To eliminate the effect of machined groove geometry in calculations, the fatigue pre-crack length should exceed 0.05B. Nevertheless, the crack size considering the fatigue crack extension should be in the range between 0.7W and 0.45W [26].

Certainly, the fatigue pre-crack formation requires suitable instruments for crack length measurement. Among the suitable instruments is the movable optical extension installed on the specimen in a way that the pre-crack extension could be observable under the stress cycles. The engraved lines on the specimen surface can be also used to measure the crack extension. In the current study, a line was first engraved 1.3mm below the machined groove tip. Then, the specimen was placed on the device and fatigue pre-crack extension was observed using a digital extension (Dino-Lite, 200x magnification). The loading frequency for this specimen was adjusted between 9-11Hz. In addition, the minimum and maximum values of the applied alternating loading were considered to be 0.21 and 2.19kN, respectively. It is worth noting that the ratio of the minimum to maximum fatigue force should not exceed 0.10. Based on the standard and regarding the specimen size, and groove type, the required stress cycles should be often between 10^4 and 10^6 cycles. In the current study, the operation was conducted during 71133 cycles. The fatigue pre-crack extension from the crack tip is presented in Fig. 6.



Fig. 6. Fatigue pre-crack formed on specimen.

3.4. Measurement of Initial Crack Length

To conduct computations required for determining toughness, the initial crack length (a_0) , which is equal to the machined groove length plus the pre-crack length, should be determined.

According to the standard, to obtain the fracture levels and to measure the initial crack length, the crack is marked with one of the following methods. For steels and titanium alloys, heat tinting at about 300°C (570°F) for 30 min works well. Another technique is the application of liquid penetrants, which is not recommended. Then, to expose the crack, the specimen was broken with care to minimize additional deformation. To ensure brittle behavior, cooling ferritic steel specimens may be helpful. Cooling nonferritic materials may help to minimize deformation during the final fracture [26]. In the current study, the specimen was placed in an oven at 300°C for 30 minutes. Then, it was remained in liquid nitrogen for 30 minutes. Immediately, it was brittlely broken by applying adequate force in the tensile machine. The aim was to specify the boundary of the brittle and ductile fractures. To compute the initial crack length, a high quality image of the fracture levels was taken (Fig. 7a). It was then analyzed in Digimizer software. According to the standard, the initial length of the stable crack extension was measured from the end of the flat surface formed under fatigue loading.

According to the standard ISO 12135-14, along the front of the fatigue crack and the front of the marked region of stable crack extension, the length of the original crack was measured at nine equally spaced points centered about the specimen centerline and extending to 0.005W from the side groove or surface of smooth-sided specimens (Fig. 7b) [30].





Fig. 7. a) Fracture surface of a tested SE(B) specimen, b) Measurement of initial crack length in the crack surface.

Table 2

Crack length at nine points (mm).

Points	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
Crack length	7.760	7.750	7.865	7.925	7.915	7.895	7.885	7.830	7.600

The original crack length (a_0) was then computed using Eq. (3). In this equation, the average of two cracks' lengths close to the surface is obtained, it is added to the other seven measured crack lengths, and the total average is taken [26].

$$a_0 = \frac{1}{8} \left[\left(\frac{a_1 + a_9}{2} \right) + \sum_{j=2}^{j=8} a_j \right]$$
(3)

Table 2 presents the crack length at nine points. According to Eq. (3), the crack length a_0 was obtained as 7.83mm.

3.5. Force Variations Based on Displacement Along the Force Direction

After the formation of fatigue pre-crack, the loadingunloading was applied to the specimens for 16 times. The loading rate was 0.017mm/s and unloading rate of each cycle was 12-21% of the maximum force at that cycle (Fig. 8). According to the standard, the unloading should not exceed 50% of the maximum force of each cycle. It is worth noting that from the beginning of loading to the end of each cycle is equal to a specimen in the multisample test [26].

3.6. Calculation of J

Based on the standard ASTM E1820-15, the J-integral is formed from the elastic and plastic terms [26].

$$J = J_{el} + J_{pl} \tag{4}$$



Fig. 8. Experimental data of load versus load-line displacement.

The elastic term is obtained from the following equations [26]:

$$J_{el} = \frac{K_i^2 (1 - \nu^2)}{E}$$
(5)

where E is the Young's modulus equal to 198GPa, ν is the Poisson's ratio equal to 0.3, K is the stress intensity factor, and i presents the i^{th} index. K_i is obtained from following equation [26]:

$$K_i = \left[\frac{p_i S}{BW^{1.5}}\right] f\left(\frac{a_i}{w}\right) \tag{6}$$

where p_i is the ultimate force and $f\left(\frac{a_i}{w}\right)$ is obtained from following equation [26].

$$f\left(\frac{a_i}{w}\right) = \frac{3\left(\frac{a_i}{w}\right)^{1/2} \left[1.99 - \left(\frac{a_i}{w}\right)\left(1 - \frac{a_i}{w}\right)\left(2.15 - 3.93\left(\frac{a_i}{w}\right) + 2.7\left(\frac{a_i}{w}\right)^2\right)\right]}{2\left(1 + 2\frac{a_i}{w}\right)\left(1 - \frac{a_i}{w}\right)^{3/2}}$$
(7)

The plastic component of the J-integral is obtained as follows [26]:

$$J_{pl0} = \frac{\eta_{pl} A_{pl0}}{Bb_0} \tag{8}$$

where A_{pl0} presents the plastic area under the force curve based on displacement, and η_{pl} is obtained from the following equation [26].

$$\eta_{pl} = 3.667 - 2.199 \left(\frac{a_i}{w}\right) + 0.437 \left(\frac{a_i}{w}\right)^2 \qquad (9)$$

The plastic component of the first cycle is obtained from Eq. (9). The corresponding calculations are presented in Table 3.

Eqs. (8) and (9) are based on the initial crack length and J variations caused by crack length increase are not considered. The calculation of the plastic part of the J-integral in next cycles is as follows:

There are different methods, such as potential drop, compliance, and visual measurement, for calculation of the crack length in Laboratory [11]. In this study, the compliance method was used for calculation of the crack length. The compliance for each of 16 loadingunloading cycles was obtained from Eq. (10). Based on Eq. (12), ΔV and ΔP were displacement and force variations. As a result, the corrected compliance in each unloading point $C_{(i)}$ is the inverse of unloading slope line [26].

$$C_{(i)} = \left(\frac{\partial V}{\partial P}\right)_{(i)} \tag{10}$$

Table 3

Main calculated initial parameters of fracture toughness test.

$$C_{(i)} = \frac{V_{i.reload} - V_{i.unload}}{P_{i.reload} - P_{i.unload}}$$
(11)

The crack length in each cycle was obtained from Eq. (12) [26].

$$\frac{a_i}{w} = \begin{bmatrix} 0.999748 - 3.9504u + 2.9821u^2 \\ -3.21408u^3 + 51.51564u^4 - 113.031u^5 \end{bmatrix}$$
(12)

where u was obtained from Eq. (13) [26].

$$u = \frac{1}{\left[\frac{\text{BWEC}_i}{S/4}\right]^{0.5} + 1} \tag{13}$$

The ratio of crack extension to the initial length in each cycle was obtained from Eq. (14) (Table 4) [26].

$$(\Delta a)_i = a_i - a_0 \tag{14}$$

Eq. (15) was used to calculate the $J_{pl(i)}$ integral in each cycle (Tables 4) [26].

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl(i-1)}}{b_{(i-1)}} \right) \left(\frac{A_{pl(i)} - A_{pl(i-1)}}{B} \right) \right] \times \left[1 - \gamma_{pl(i-1)} \left(\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}} \right) \right]$$
(15)

$a_0 \ (\mathrm{mm})$	P_0 (kN)	$\left(\frac{a_0}{w}\right)$	$f\left(\frac{a_0}{w}\right)$	$J_{el(0)}~(\rm kJ/m^2)$	$K_0 (\mathrm{MPa}\sqrt{\mathrm{m}})$	$J_{pl0}~({\rm kJ/m^2})$	$J(o) ~({\rm kJ/m^2})$
7.8431	1.60	0.5229	2.867	4.1397	29.94	4.126	8.2657

Main calculated parameters of fracture toughness test.

Cycle	C_i	$a_i \ (mm)$	$(\Delta a)_i$	P_i	K_i	$A_{pl(i-l,i)}$	$J_{pl(i)}$	J
	$(mm/kN) \times 10^{-2}$		(mm)	(kN)	$(MPa\sqrt{m})$	(kN.mm)	(kJ/m^2)	(kJ/m^2)
1	4.113924051	7.8569	0.0138	1.90	35.665	0.25025	22.530	28.360
2	4.250000000	7.9423	0.0992	1.91	36.537	0.02953	24.459	30.585
3	4.254838710	8.0059	0.1628	1.97	38.219	0.03370	26.735	33.438
4	4.379310345	8.0205	0.1774	2.01	39.127	0.02806	28.784	35.809
5	4.380952381	8.0214	0.1783	1.98	38.556	0.02933	30.980	37.800
6	4.393939394	8.0291	0.1860	2.00	39.010	0.02607	32.900	39.888
7	4.428571429	8.0495	0.2064	2.01	39.379	0.02947	35.023	42.139
8	4.451612903	8.0629	0.2198	2.02	39.695	0.02740	37.022	44.253
9	4.472727273	8.0752	0.2321	2.03	40.000	0.02957	39.030	46.641
10	4.482758621	8.0810	0.2379	2.04	40.250	0.02747	41.340	48.775
11	4.508474576	8.0958	0.2527	2.00	39.597	0.02586	43.210	50.410
12	4.517857143	8.1012	0.2581	2.05	40.640	0.02795	45.290	52.870
13	4.520000000	8.1024	0.2593	2.06	40.850	0.03144	45.659	55.318
14	4.555555556	8.1227	0.2796	2.10	41.830	0.02850	49.688	57.718
15	4.615384615	8.1563	0.3132	2.12	42.564	0.03671	52.249	60.563
16	4.831804281	8.2736	0.4305	2.12	43.726	0.02756	53.548	62.317

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In Eq. (15), $A_{pl(i)} - A_{pl(i-1)}$ is an increase in plastic area under the force-displacement curve between the i and ith stages, obtained from Eq. (16). In addition, $\eta_{pl(i-1)}$ and $\gamma_{pl(i-1)}$ are dimensionless geometric coefficients, obtained from Eqs. (17) and (18), respectively [26].

$$A_{pl(i)} = A_{pl(i-1)} + \frac{\left[P_{(i)} + P_{(i-1)}\right] \left[V_{pl(i)} - V_{pl(i-1)}\right]}{2}$$
(16)

$$\eta_{pl} = 3.667 - 2.199 \left(\frac{a_{(i-1)}}{W}\right) + 0.437 \left(\frac{a_{(i-1)}}{W}\right)^2 \quad (17)$$

$$\gamma_{pl} = 0.131 - 2.131 \left(\frac{a_{(i-1)}}{W}\right) - 1.465 \left(\frac{a_{(i-1)}}{W}\right)^2 \quad (18)$$

The J-integral for each cycle was obtained from Eq. (19) [26].

$$J_{(i)} = \frac{(K_{(I)})^2 (1 - \nu^2)}{E} + J_{pl(i)}$$
(19)

3.7. Drawing $J - \Delta a$ Diagram

To draw $J - \Delta a$ diagram (Fig. 9), a line $(J = 2\sigma_Y \Delta a)$, called construction line, passing the origin was first drawn. In this equation, σ_Y is the effective yield strength and is equal to the mean value of the yield and ultimate strengths. In the current study, σ_Y was considered 433.5MPa. Then, a line parallel to the construction line was drawn at 0.15mm on the x-axis. This line is called the exclusion line. In the next stage, the crack growth and J-integral points were computed and inserted into the coordinate system. According to the standard, only the points located after the exclusion lines are considered valid points. These points are presented as solid points in Fig. 9. An exponential curve can be fitted, using solid points. The fitted curve equation in this study was $J = 109.36 (\Delta a)^{0.5614}$. In the last stage, a horizontal line, called the offset 0.2mm, was drawn parallel to the construction line at 0.2mm on the x-axis. The value of J where this line intersects the fitted curve is equal to the conditional toughness J_Q , which was obtained as 51kJ/m².



Fig. 9. Definition of construction lines for data qualification using experimental data $J - \Delta a$.

3.8. Conditions Required for Verification of Results and Calculation of Fracture Toughness

The value of J_Q is assumed equal to J_{IC} if the inequality condition of Eq. (20) is met, and the exponential curve is concave down (or the exponent of the exponential curve is less than 1) [26].

$$10\frac{J_Q}{\sigma_{YS}} < B \tag{20}$$

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Regarding the investigated conditions, the left side of above equation is equal to 1.41 and the right side of it is equal to the thickness of the specimen B (5mm). As a result, inequality of Eq. (20) is met and J_Q can be considered to be J_{IC} .

Now, Eq. (21) can be used to determine K_{IC} [26].

$$K_{IC} = \sqrt{\frac{J_{IC}E}{(1-\nu^2)}} \tag{21}$$

Based on J_{IC} , E, and ν , K_{IC} , the fracture toughness would be equal to $K_{IC} = 105.4 \text{MPa} \sqrt{m}$.

4. Crack Assessments with Failure Assessment Diagrams

The K_{IC} value and crack size can be used to determine the safe zone and the location in the Failure Assessment Diagram (FADs). Based on the available material properties, the FADs are generally classified into three different types to assess the suitability and conservatism of the diagram. Higher levels in these diagrams require more complex data and are less conservative [31]. Level 1 shows the failure assessment diagram based on crack tip displacement diagram, which is the basis for assessment of elastic-plastic failure in BS7910 [5]. Level 2a is another case of failure assessment diagram that is based on the lower boundary of a large number of diagrams obtained from austenitic steel experimental data. Both levels 1 and 2a include general failure assessment diagrams that are independent of material properties, while the 2b level depends on material properties. Level 3 of the diagrams has three types and requires more complex data and, as mentioned before, is less conservative.

4.1. Assessment of Longitudinal Crack on Pipe Body Using the BS7910 Level 1 FADs

Level 1 of BS7910 standard is usually used when a conservative estimate is needed, and there is a limit. In the level 1 FADs, the required vertical component, K_r , and horizontal component, S_r , are obtained using the existing relationships in the BS7910 standard. The

indicated range is a rectangle, where the safe zone is stress, σ_{ref} , was calculated with the following equation considered within $K_r < 0.707$ and $S_r < 0.8$ [32].

$$K_r = \frac{K_I}{K_{IC}} \tag{22}$$

The stress intensity factor (K_I) is determined with the following relation [32]:

$$K_I = (Y\sigma)\sqrt{(\pi d)} \tag{23}$$

where d is the crack depth, and the factor $Y\sigma$ is defined as [32]

$$Y\sigma = (Y\sigma)_P + (Y\sigma)_S \tag{24}$$

in which [32]

$$(Y\sigma)_P = M f_w \left[K_{tm} M_{km} M_m P_m + K_{tb} M_{kb} M_b \{ P_b + (K_m - 1) P_m \} \right]$$
$$(Y\sigma)_S = M_m Q_m + M_b Q_b$$

 $K_{tm} = 1$ membrane stress concentration factor), $P_b =$ 0 (primary bending stress),

 $K_{tb} = 0$ (bending stress concentration factor), $Q_m = 0$ (secondary membrane stress),

 $Q_b = 0$ (secondary bending stress), $M_{km} = 1$ (stress intensity factor magnification factor, for membrane)

where M is the bulging correction factor (which is also known as the Folias factor for thin-walled cylinders), M_m is the stress magnification factor and f_w is the finite width correction. Annex M of BS7910 provides analytical expressions and Fig. 10 for M, M_m , and f_w as functions of d/t and c/d and P_m is the primary membrane stress.

The used stress is the maximum tension stress $(\sigma_{\rm max})$ which is equal with sum of the stress components [32].

$$\sigma_{\max} = k_{tm} P_m + K_{tb} [P_b + (k_m - 1)P_m] + Q \quad (25)$$

$$k_m = K_{tm} = 1, \quad P_b = K_{tb} = Q = 0$$

Eqs. (24) and (25) yield [32]:

$$Y\sigma = M f_w M_m \sigma_{\max} \tag{26}$$

The load ratio, S_r , is calculated from the following equation [32]:

$$S_r = \frac{\sigma_{ref}}{\sigma_Y} \tag{27}$$

where the flow strength, σ_Y , should be assumed to be the arithmetic mean of the yield strength and the tensile strength up to a maximum of $1.2\sigma_{YS}$. Reference [32]:

$$\sigma_{ref} = 1.2M_s P_m + \frac{2P_b}{3(1-a^{"})^2}$$
(28)

 P_m is the primary membrane stress, which is assumed as $\left(P_m = \frac{PR}{B}\right)$, where P is the internal uniform pressure, B the pipeline thickness, R the pipeline radius. P_b is the primary bending stress (no primary bending stresses were assumed: $P_b = 0$ · M_s is the stress magnification factor (Eq. (29)) and $a^{"}$ is a function used to calculate the collapse stress (Eq. (30)) [32].

$$M_s = \frac{1 - \{d/(BM_T)\}}{1 - (d/B)} \tag{29}$$

$$a^{"} = (d/B)/(1+B/c) \text{ for } W \ge 2(C+B)$$
 (30)

$$a" = 2(d/B)\left(\frac{c}{\pi r_i}\right)$$
 for $W < 2(C+B)$

where d is the crack depth of the surface flaw, B the thickness of the pipeline (Fig. 10), and M_T the stress magnification factor, equal to [32].

$$M_T = \sqrt{1 + \left(\frac{c^2}{r_i B}\right)} \tag{31}$$

where C is the half-length of the surface flaw and r_i is the internal pipeline radius (Fig. 10).



Fig. 10. Cross section of a pipe with an external longitudinal crack.

The values for longitudinal cracks at depths of 5 and 5.5mm with lengths of 220 and 110mm are obtained according to Table 5 for crack assessment of level 1 FADs. As seen in Fig. 11, cracks with a depth of 5.5mm and lengths of 220 and 110mm do not lie in the safe zone.

Table 5

Calculated values for different lengths and depths of longitudinal cracks for level 1 failure diagram.

Point	d (mm)	2c (mm)	σ_{ref} (MPa)	$K_I (MPa\sqrt{m})$	S_r	K_r
1	5.0	220	307.3	34.1	0.7	0.32
2	5.5	220	422.0	43.5	0.97	0.40
3	5.5	110	358.6	35.8	0.83	0.34

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4.2. Assessment of Longitudinal Crack on Pipe Body Using the BS7910 Level 2a Failure Assessment Diagram

In level 2a FADs, the vertical component, K_r , and horizontal component, L_r , are obtained from the BS7910 standard relations. The cut-of line is fixed in point where $L_r = L_{\text{max}}$ where [32]:

$$L_{\max} = \frac{\sigma_{YS} + \sigma_{TS}}{2\sigma_{YS}} \tag{32}$$

where σ_{YS} and σ_{TS} are the yield stress and ultimate tensile stress, respectively; and L_r and K_r , as defined in the following equations [32]:

$$L_r = \frac{\sigma_{ref}}{\sigma_{YS}} \tag{33}$$

$$K_r = (1 - 0.14L_r^2) \{ 0.3 + 0.7 \exp(-0.65L_r^6) \}$$

for $L_r \le L_{\max}$ (34)

$$K_r = 0 \qquad \text{for } L_r > L_{\max} \tag{35}$$

where σ_{ref} is obtained from reference stress (Eq. (28)).

The values for longitudinal cracks at depths of 5 and 5.5mm with lengths of 220 and 110mm are obtained according to Table 6 for crack assessment of level 2a FADs. As seen in Fig. 12, cracks with a depth of 5.5 mm and lengths of 220 and 110mm do not lie in the safe zone.



Fig. 11. Level 1 FADs for the steel pipe body: assessment of longitudinal cracks with different lengths and depths.

Table 6

Calculated values for different lengths and depths of longitudinal cracks for level 2a failure diagram.

Point	d (mm)	2c (mm)	σ_{ref} (MPa)	L_r	K_r
1	5.0	220	307.3	0.85	0.76
2	5.5	220	422.0	1.17	0.35
3	5.5	110	358.6	1.00	0.57



Fig. 12. Level 2a FADs for the steel pipe body: assessment of longitudinal cracks with different lengths and depths.

5. Conclusions

The experimental measurement of fracture toughness of the steel pipe (grade: API X46) was conducted using the Single Edge Bend [SE(B)] specimen method in a single specimen. The application of unloading compliance method to estimate the crack length during the conduction of experiment and application of the force to the sample was one of the innovations of the current study. Due to its advantages over other crack length estimation methods, ASTM E1820 introduced the unloading compliance method as the major crack length measurement techniques. Due to the low thickness of the steel pipe's wall, dimensions of the specimen did not meet the plain strain conditions. Therefore, indirect fracture toughness determination methods were used by means of J_{IC} , as a criterion for determination of fracture toughness on the crack extension threshold. The fracture toughness of the API X46 steel pipe was obtained as 105.4 MPa \sqrt{m} .

It is worth noting that the determination of fracture toughness is essential for obtaining the failure assessment diagrams (FAD). Failure assessment diagrams for level 1 and 2a BS7910 standard showed that a longitudinal crack with a depth of 5mm and a length of 220mm on the pipe body lied in the safe zone, but cracks with a depth of 5.5mm and lengths of 220 and 110mm did not lie in the safe zone.

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