CTOD fracture toughness assessment method of High-strength steel based on BS7910

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Abstract As one of the essential criteria of assessment to welding toughness, CTOD(Crack tip opening displacement) is widely applied in engineering. The research on allowable values of the CTOD of high strength and thickness steel has been a hot issue, therefore the theoretical research in China lags behind its overseas. The present paper takes the single edge fatigue precrack of CTOD specimen as a flaw with the technical route of the British Standard 7910-2005, that is "Guide to methods for assessing the acceptability of flaws in metallic structures". In the meanwhile, make the grading assessments of the welding seam center of the EQ70/56 joints, combining the results of the CTOD tests. The assessments on welded joints of EQ70/56 show that the CTOD values are in the acceptable range. This method provides some useful guidance in researches of allowable CTOD values.

Key Word Welded joint of High strength steel，CTOD，BS7910，FAD ,EQ70/56

1 Introduction

With the development of the ocean engineering, the high-strength steel and ultra-high-strength steel are widely applied in the Deep-water Semi-Submersible Drilling Platform. As the complicated welding joints, high-strength and big thickness, the welding procedure of the marine structure becomes the key to the construction of the platform. The specification and classification societies around the world, including the CCS (China Classification Societies), are beginning to take the CTOD tests as a means to assess the toughness of the welded joints and the high-strength and heavy steel plates. However, there is much difference on the allowance value of CTOD with different societies, especially for the new high-strength and heavy steel plates.

As the development of the methods for assessing the acceptability of flaws of the welded metallic structures, the British Standard 7910:1999, called "Guide to methods for assessing the acceptability of flaws in metallic structures", replaced the old standard PD 6493:1991[1] and was being widely applied in the engineering[2]. Basing on the fracture mechanics, the stand BS7910 fulfills the assessments with the FAD (failure assessment diagram) and takes the compare between the crack resistance of the structure and the actual ability to crack loading as its main idea.

When majority standards of flaw assessment of metal structure were applied on the issue of ‘Fitness for Purpose’, the BS7910:1999 was amended and extended to an update version BS7910:2005[3], which has three levels of fracture assessment for the flaws in metallic structures. The choice of level depends on the materials involved, the input data available and the conservatism required.

In the standard BS7910, flaws include Planar flaws, Non-planar flaws and Shape imperfections. In the assessment of high-strength and heavy steel plates, the specimen of the CTOD test was pre-carved with crack throughout the thickness. The welding seam center of the specimen was determined by the Level 2B. In the FAD of Level 2B, the axis is assessment index of fracture toughness, appears as Kr which is the ratio of the stress intensity factor, or $\sqrt{\delta_r}$, the square root of CTOD fracture ratio. In the CTOD tests, the single edge running through crack [4] could be taken as the flaws assessed by FAD with the fracture ratio as ordinates against load ratio (Sr) as abscissa. The applied Level 2 assessment has an assessment curve given by the equation of a curve and a cut-off. If the assessment point lies within the area bounded by the axes and the assessment curve, the flaw is acceptable; if it lies on or outside the curve, the flaw is unacceptable.

The CTOD toughness assessment of the heat affected zone and welding seam center of

high-strength and thickness steel with the FAD method are summarized as follow:
1) Measure the CTOD values of the welding joints of the high-strength steel at a specific temperature;
2) Plot the stress-strain curve of the welding joints of the high-strength steel through an uniaxial tensile test, and then transfer it to a true stress-strain curve with related equations;
3) Plot the Level 2B FAD with the true stress-strain curve, make the failure assessments of the joint and the welding seam center of the high-strength steel plates;
4) Calculate the load ratio and fracture ratio (coordinates of the assessment points) with the CTOD values and stress-strain curve, and then plot the FADs with the ratios. The toughness assessments of the welding joint would be completed with the FADs.

2 CTOD experiment and results

The present paper mainly research on the FADs of the welding seam center of butt-weld joint between EQ70 and EQ56 high-strength steel plates(Level-AB) with 38 mm thickness. The CTOD test is carried out according toBS7448[5] and Offshore Standard DNV-OS-C401[6]The chemical composition of the EQ70 and EQ56 steel plates are shown in the table 1 and table 2, while the different welding technologies are shown in table 3.
The EQ 56 and EQ 70 were butt welded with equiangular welding groove (45°K style groove), by multi-layer and multi-pass manual arc welding. While it should preheat temperature to70 ℃, kept the groove straight edge perpendicular to the specimen plane, with 210 to 230 ℃thermal insulation per hour after welding. To the specimen of EQ56/70, the K type groove straight edge should perpendicular to the side of EQ70[7].
Three-point bending specimens, with single side fatigue precrack, were applied in the CTOD test and processed into 26 mm thickness(B) and 52 mm width(W). The results and effectiveness of the CTOD test were list in the table 4.

Table 1 The chemical compositions of EQ 70 specimen with 38 mm thickness (%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo
0.14	0.08	0.86	0.011	0.002	0.26	0.49	0.76	0.32
V	ZR	Ti	Nb	Sol Al	N	B	Ceq	PCM
0.04	0.005	0.013	0.016	0.064	0.0023	0.0010	0.56	—

Table 2 The chemical compositions of EQ56 specimen with 38 mm thickness (%)

C	Si	Mn	P	S	Al	Ni
0.05	0.41	1.51	0.009	0.001	0.033	0,73
Cr	Cu	Nb	V	Ti	Mo	w(C)eq
0.33	0.71	0.04	0.04	0.009	0.22	0.51

Table 3 Welding technologies of the joints of EQ70/56

Technical parameter Type	No.of welding bead	Diameter (mm)	Electricity (A)	Voltage (V)	Welding speed (mm/min)	Maximum Energy Input (kJ/mm)	Average Energy Input (kJ/mm)
A	1	3.2	130~160	20~25	69	3.62	2.85
	others	4.0	170~195	22~27	77	4.10	3.51

B	1	3.2	120~145	23~30	104	2.88	2.02
	others	4.0	180~196	25~35	112	3.68	3.02

Table 4 The CTOD experimental results of EQ70/56 specimen with 38 mm thickness

Technical parameter	Crack Position	NO.of specimens	B / mm	W / mm	a_0 / mm	δ_u / mm	Available Test
A	Welding seam center	1	26.03	52.03	26.364	0.099	Available
		2	25.99	52.02	27.026	0.137	Available
		3	26.04	52.04	26.360	0.122	Available
B	Welding seam center	1	29.99	59.96	30.156	0.243	Available
		2	30.09	60.01	29.823	0.222	Available
		3	30.09	59.90	29.990	0.192	Available

3 Uniaxial tensile test and results

Take an uniaxial tensile test on the EQ7/56 specimen with the Electric Servo-hydraulic Material Test system, under the guidance of the Standard, "Metallic materials Tensile testing at ambient temperature"[8]. The present paper take a butt-welding joint of EQ70/56 as an specimen(d_0=4mm), and get its stress-strain curve, some basic outputs were list in the table 7.

Table 7 Basic data of the uniaxial tensile test

NO.of Specimens	EQ70/56	EQ70-HAZd6
Shape of Specimen	Circular cross section	Circular cross section
Diameter(mm)	4.01	3
S_o(mm^2)	12.63	7.069
L_o(mm)	19.9	15.4
Extensometer gauge length(mm)	50	50
F_m(kN)	10.46	5.65
Tensile Strength R_m(MPa)	830	800
F_{eH}(kN)	/	5.42
Upper Yield Strength R_{eH}(MPa)	/	765
F_{eL}(kN)	/	5.24
Lower Yield Strength R_{eL}(MPa)	/	740
F_p(kN)	9.25	5.36
Proof Strength Non-proportional Extension	730	760

R_p(MPa)		
F_t(kN)	1.2	0.67
Proof total Extension R_t(MPa)	95	95
The ratio of Yield strength	0.88	0.95
The ratio of tensile strength to Yield Strength	1.14	1.05

The yield strength σ_s and ultimate strength σ_b were calculated according the equation (1) as follow:

$$\sigma_s = \frac{F_s}{A_0}, \quad \sigma_b = \frac{F_b}{A_0} \quad (1)$$

in which, F_s means the yield load, F_b means the maximum load and the A_0 original cross section area of specimen.
As the yield stress of the EQ70/56 has no yield step, it is very difficult to accurately determine its yield stress(which means it is difficult to determine the stress at the beginning of its yield step). Generally, It takes the stress, when it generate a specific permanent strain (usually 0.2%), as the yield stress [9].
At the beginning of the stress-strain curve, the stress proportionally rises against the strain, while its ratio is the elastic modulus. While the strain increased to 0.2%, plotted a straight line with a slope equaling to elastic modulus. The corresponding value to the intersection between the plotted line and the stress-strain curve was the equivalent yield stress.
The outputs of the test were forces and deformations, which should be calculated to the inputs of the stress-strain curve. In the present test, the stress $\boldsymbol{\sigma}$ and strain $\boldsymbol{\varepsilon}$ were determined by the equation (2) as follow:

$$\sigma = P/S_0, \ \varepsilon = \delta/L_0 \quad (2)$$

According to the results of the test and calculated date, the stress-strain curve could be plotted as figure 1.

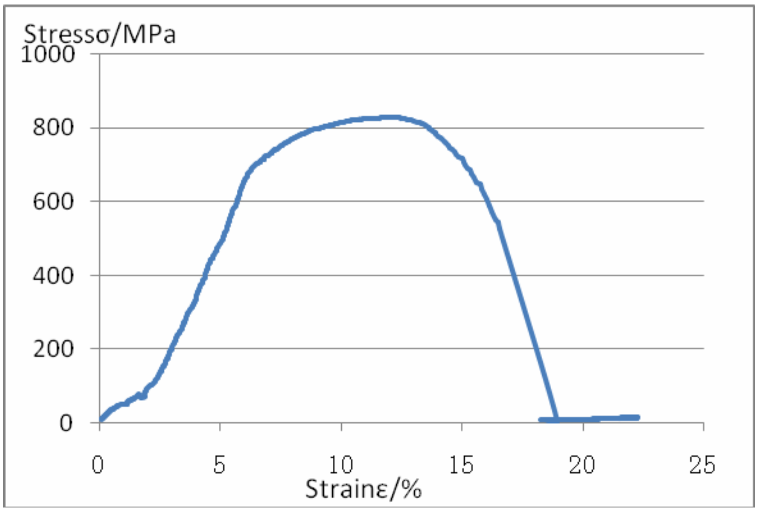

Figure 1 The stress-strain Curve of EQ70/56

The maximum load could be calculated from the displacements and forces of the test, the results were listed in the table 8.

Table 8 The uniaxial tensile experimental results of the Welding seam center

The type of the steel	The position of the specimen	Yield Stress (Mpa)	Tensile Stress (Mpa)
EQ70/56	Welding seam center	728.8	828.2

According to the uniaxial tensile stress-strain curve, the true stress expression was as follow:

$$\sigma_t = (1 + \varepsilon)\sigma \quad (3)$$

while the true strain expression was as follow:

$$\varepsilon_t = \ln(1+\varepsilon) \quad (4)$$

Plot the true stress-strain curve from the equations (3) and (4), and then the true stress-strain curve of the welding seam center could be plotted as figure 2.

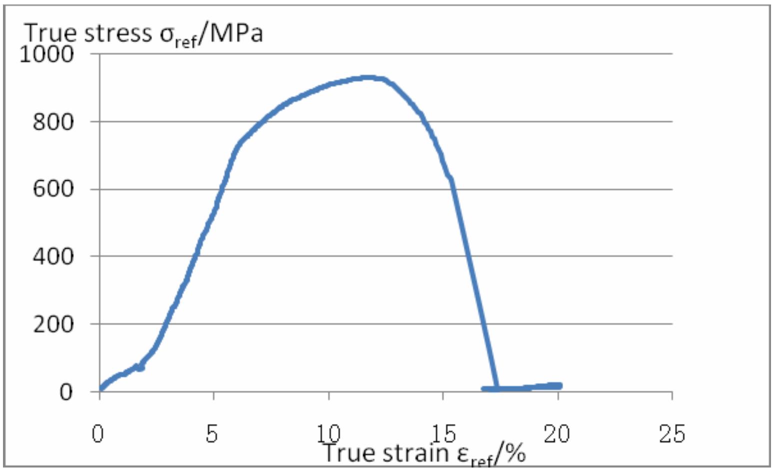

Figure 2 True stress-strain curve of EQ70/56

Under the guidance of the Standard <Metallic materials Tensile testing at ambient temperature>, it measured the elastic modulus with electrometric method. As the elastic modulus was independent of the thickness of the specimens, there was no elastic modulus distinction in the same position of the specimen. The elastic modulus E was determined by the equation (5) as follow:

$$E = \frac{F}{S_0 \varepsilon} \quad (5)$$

Here, F denotes the load increment, while the S_0 denotes the cross section area.

Table 9 The results of Elastic modulus test

Position	*E* （Gpa）
Welding seam center	215.5

4 The FADs of welding seam center of EQ70/56

With the Guidance of Level-2B assessment in Standard BS7910 and the true stress-strain curve from the uniaxial tensile test, it could comes to the FAD basing on the CTOD test. The boundary values of FAD(L_{rmax}) were determined by the equation (6):

$$L_{rmax}=\frac{\sigma_Y+\sigma_u}{2\sigma_Y} \quad (6)$$

The tensile strength of the EQ70/56, as well as the yield strength and the ultimate strength, could be got from the tests. Then the boundary value could be calculated by the strength as $L_{rmax} = 1.06$.
Stress-strain data are required at the appropriate temperature for parent material and/or weld metal. The lower yield or 0.2% proof strength, tensile strength, and modulus of elasticity should be determined together sufficient co-ordinate stress/strain points to define the curve. Particular attention should be paid to defining the shape of the stress/strain curve for strains below 1%. It is recommended that the engineering stress/strain curve should be accurately defined at the following ratios of applied stress, σ, to yield strength, $\sigma_{y:}$ σ / σ_y =0.7,0.9, 0.98,1.0,1.02,1.1, 1. 2 and intervals of 0.1 up to σ_u.
The equations describing the assessment line are the following:
a) for Lr ≤ Lrmax

$$\sqrt{\delta_r} \text{ or } K_r = \left(\frac{E\varepsilon_{ref}}{L_r\sigma_Y}+\frac{L_r^{\ 3}\sigma_Y}{2E\varepsilon_{ref}}\right)^{-0.5} \quad (6a)$$

b) for $L_r > L_{rmax}$

$$\sqrt{\delta_r} \text{ or } K_r = 0 \quad (6b)$$

Where
the εref is the true strain obtained from the uniaxial tensile stress-strain curve at a true stress,LrσY.

$$L_r=\frac{\sigma_{ref}}{\sigma_Y} \quad (7)$$

According to the equations (6) and (7), the horizontal axis Lr and the vertical axis √δr could be calculated to plot the FADs of EQ70/56 and EQ70, as shown in figure 3.

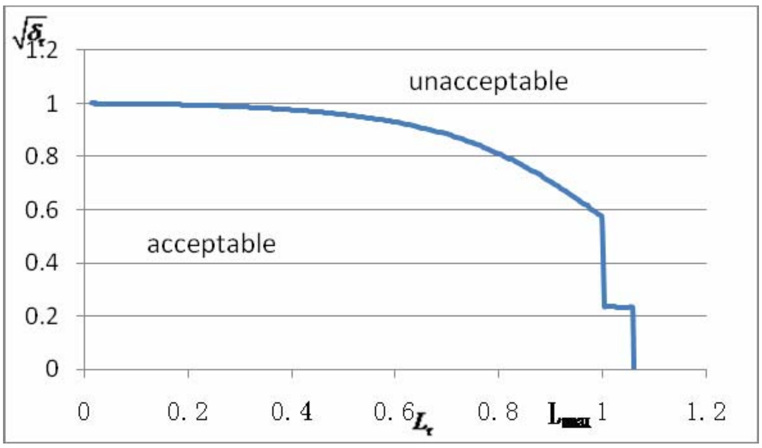

Figure 3 FAD of the welding seam center of EQ70/56

5Calculation of The CTOD test assessment point

5.1Abscissa of the assessment points

In the Level-2B assessment, the horizontal axis is $L_{r,}$ which could be calculated with the the equation (7) as mentioned above in section 4 with the Standard BS7910:

While the CTOD theory was put forward initially, it was recognized that, for the elastic-perfectly plastic material, there was a plasticity area in the crack tip. Which means that the stress of the ligament area in the crack tip would not increase, after the crack tip fracture stress under general yielding. The stress of the plastic yielding area was equal to the yield strength σ_Y. Therefore, while assessed the CTOD values with the Level-2B method, the value of Lr should be taken as 1.0 [10]and the abscissa of the assessment point should be 1.0 as well.

5.2 Ordinates of the assessment points

In the FAD, the vertical coordinate was fracture ratio δ_r, determined by the following equation:

$$\sqrt{\delta_r} = \sqrt{\delta_I / \delta_{mat}} \quad (8)$$

Where δ_{mat} is the fracture ratio of the material obtained by CTOD test, and the δ_I are calculated by K_I as the following equation:

$$\delta_I = \frac{K}{X\sigma} \delta_I = \frac{K_I^2}{X \sigma_Y E'} \quad (9)$$

X is the factor(generally of value between 1 and 2) influenced by crack tip and geometric constraint and the work hardening capability of the material. Appropriate values of X may be determined from elastic analyses which model structural constraint. If values of X are not quantified by structural analyses, use X =1.0. E' is the elastic modulus considering restrain. In the plane stress condition, $E' = E$, while $E' = 1 - \mu^2$, the in the plane strain condition. The applied stress intensity factor of the I-type crack, K_I, has the following general form in the three bending condition:

$$K_I = \frac{FS}{BW^{3/2}} \cdot f\left(\frac{a_0}{W}\right) \quad (10)$$

$$f\left(\frac{a_0}{W}\right) = \frac{3\left(\frac{a_0}{W}\right)^{1/2}\left[1.99 - \left(\frac{a_0}{W}\right)\left(1 - \frac{a_0}{W}\right)\left(2.15 - 3.93\frac{a_0}{W} + 2.7\left(\frac{a_0}{W}\right)^2\right)\right]}{2\left(1 + 2\frac{a_0}{W}\right)\left(1 - \frac{a_0}{W}\right)^{3/2}} \quad (11)$$

where, S denotes the distance between specimens, W denotes the width and S =4W, B denotes the thickness, F denotes the loads.

5.3 Toughness assessment of CTOD

According the method in section 5.1and 5.2, the toughness assessment of CTOD could be transferred to the assessment points in the FAD of EQ70/56, the results shown in the table 10.

Table 10 The assessment points in the FAD of EQ70/56

Technical parameters	Crack position	NO. of specimen	B/mm	δ_I /mm	δ_{mat} /mm	Lr	$\sqrt{\delta_I/\delta_{mat}}$
A	welding	1	26.03	0.012	0.099	1	0.353
	seam	2	25.99	0.014	0.137	1	0.315
	center	3	26.04	0.010	0.122	1	0.284
B	welding	1	29.99	0.017	0.243	1	0.265
	seam	2	30.09	0.016	0.222	1	0.278
	center	3	30.09	0.015	0.192	1	0.281

Note：In the present CTOD test, the elastic modulus applied in the calculation was measured in the uniaxial tensile test, instead of the parameters given by the manufacturer. The elastic modulus was $E' = \frac{E}{1-\mu^2} =$ 234.5 Gpa, which conduct the yield strength as 729 Mpa.

Then mark the coordinates of the assessment points into the PAD of the EQ70/56, as shown in figure 6.

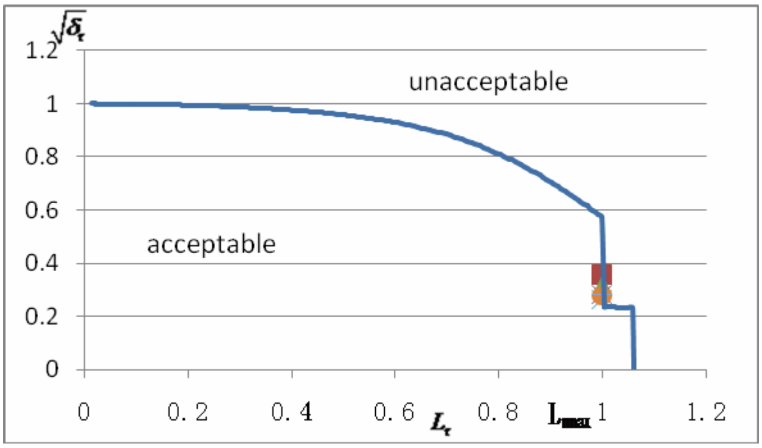

Figure 6 FAD of the EQ70/56 with the assessment points

5.4 Error analysis

It could get the stress-strain curve through the tensile test while making the toughness assessment of the CTOD of the welding joints. In the meanwhile, the Level-2B assessment required the true stress-strain curve, it should transferred the test data to the true stress-strain curve. The present

paper took the transformation as follow:
True stress

$$\text{True Stress} \qquad \sigma_t=(1+\varepsilon \qquad (12)$$

True strain

$$\text{True Strain} \qquad \varepsilon_t=\text{In}(1+ \qquad (13)$$

The above equations could directly measure the responses in the range of plastic-flow, the true stress and strain could be calculated by the equations before the strain developing to necking. However, after necking, the material exceeded the elastic limit, which caused the geometric size was great different from the initial condition. The plane of the specimen was in a complicated three dimensional stress states, and the strains were nonuniform in the gauge length of the specimen. In this situation , it would bring some errors to calculate the true stress-strain.
To get more accurate true stress-strain curve, it generally used the semi-empirical and semi-analytical Bridgman formula, which was deduced to average longitudinal stress correction formula as follows:

$$\sigma=\frac{\sigma_{\text{average}}}{\left(1+\frac{2R}{a}\right)\ \text{In}\left(1+\frac{a}{2R}\right)} \qquad (14)$$

where, R denotes the radius of the necking surface, a denotes the minimum radius after necking and σ_{average} denotes the average longitudinal stress of the minimum cross section.
The present paper provided the CTOD toughness assessment for the high strength steel plate, the more accurate results need more accurate true stress and strain while there are several method to get the true stress-strain curve after necking as Photographs method[11], FEM[[12], etc.

6 Conclusions

As the steel plates applied in the ocean engineering structure becomes more and more thicker, the acceptable CTOD value of different Standards are applied to prevent the structural safety and stability. Such as the minimum acceptable value is 0.15 mm in the DNV-OS-C401-2008, while it is 0.13 mm in the API RP2Z standard. This paper takes the single edge fatigue precrack of CTOD specimen as a flaw under the guidance of BS7910 Standard, plots the FADs of the the welding seam center. The failure boundary value is 0.576, which are applied in the acceptable value of CTOD. The average critical CTOD value is 0.06 mm, which is calculated by $\sqrt{\delta_r}=\sqrt{\delta_I}/\sqrt{\delta_{mat}}$ and far lower than the value specified by the Standards. As the true stress-strain curve is calculated within the elastic stage, which would cause the errors. If the true stress and strain are measure by photography with single specimen, the true stress and strain values would larger than the values obtained by the equations. It would caused the critical value of CTOD would larger than 0.06 mm, the results should be corrected.
In the meanwhile, the present CTOD test ensures the straightness of the front crack with the partial compression method, which would cause the results of test much more conservative[13]. According to the critical CTOD value calculated above, it suggests that the CTOD acceptable value of heavy plates could be modified lower appropriately based on value specified by Standards.

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