EXPERIMENTAL AND NUMERICAL ANALYSIS FOR SE(B) AND SE(T) J-INTEGRAL FRACTURE TOUGHNESS TESTING

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Abstract. *To obtain elastic-plastic fracture toughness the single edge notch tensile specimen SE(T) can offer an advantage when both standard single edge bend SE (B) and compact tension C(T) specimens are difficult to extract from the particular location of a thin structures or components, but one difficulty is the plastic factor that does not exist in the standards for the SE(T) specimen. Several recent works suggest that use of experimental load-crack mouth opening displacement (CMOD) records provide reliable J-integral estimation with SE(T) specimens. The present paper compares the experimental results of the elastic-plastic fracture toughness for API 5L X65 steel, with SE(B) and SE(T) specimens, in elastic-plastic regime, using CMOD concepts, and these experimental results have been compared with a Finite Element Model implemented for the test specimens. The J-integral versus crack growth resistance curves (J-R curves) has been determined for both specimens – SE(T) and SE(B). Fracture characteristics of the fracture toughness specimens were studied in a scanning electronic microscopy (SEM) for determining the crack extension and the fracture micromechanisms. The final results of this work show that it is possible the determination of the elastic-plastic fracture toughness with not standardized SE(T) specimens.*

Keywords*: J-integral, API 5L X65 steel, single edge notch tensile specimen SE(T), plastic eta factor.*

1. Introduction

A very important mechanical property of the materials is the fracture toughness. Through this property it is possible to select materials, to project structures or parts, and still to evaluate industrial systems that in operation accused presence of cracks. To obtain the fracture toughness of structures and industrial parts with thin thickness is not possible using the standards procedures that demand larger thickness to achieve a plane strain state (high triaxiality of stress in the tip of the crack), in these cases it is necessary to accomplish the tests with non standard specimens in elastic-plastic conditions. Recent literature (Kim et al., 2004) reports the advantages of the single edge notched specimens loaded in tension SE(T) for the estimation of elastic-plastic fracture toughness using crack mouth opening displacement CMOD records. This method has little sensibility to the variations of the relative length of crack (a/W), and additionally the stress and strain field in the front of the crack is very similar with crack in pipelines.

Little systematized information exists for the use of non standard specimens SE(T) in the determination of the elastic-plastic fracture toughness. One difficulty is the determination or calculation of the plastic eta factor, η_{pl}. Wu, Mai and Cotterell (1990) estimated the η_{pl} factor, by using the concept of "slip line field solutions". Lee and Parks (1993) studied these specimens submitted to combined stress of tension and bending, analytically and with finite elements. Donoso et al. (1995) studied the test specimens SE(T) numerically applied to welding materials and determined the plastic rotation factor r_p. Kim and Budden (2001) determined the plastic eta factor for SE(T), by using analytical concepts and 2D finite elements modeling, finding divergences with the previous publications. Kim et al. (2004) published a numeric study with 3D finite elements that it supplies solutions for the determination of the plastic eta factor for normalized and non normalized specimens among them SE(T). Aguirre, Ferreira and Hernandez (2005) determined the eta plastic factor for non standard specimens SE(T) by modeling with Finite Elements 2D and 3D.

The API 5L X65 steels belong to the family of the Ti-Nb micro-alloyed steels, with a minimum limit of yield stress of 65 ksi (450 MPa), the main industrial application of this steels is the production of piping for the petroleum and gas industry.

In this work elastic-plastic fracture toughness is determined of the API 5L X65 steel using both experimental and numeric procedures. For the numerical analysis was used the commercial program of finite elements Abaqus® and for the experimental procedure was used both standard single edge notched bend specimens, loaded in three-point bending SE(B), and non standard single edge notched specimens loaded in tension SE(T).

2. Background

For any specimen testing, it is convenient to estimate the J-Integral separating into elastic and plastic components (Kanninen and Popelar, 1985) according to Eq. (1).

$$J = J_{el} + J_{pl} \tag{1}$$

The elastic component J_{el} is defined by

$$J_{el} = \frac{K_I^2}{E'} \tag{2}$$

Where E' for plane stress is equal to E (Young modulus), and for plane strain is equal to $E/(1-\nu^2)$, ν is the Poisson ratio, and K_I is the stress intensity factor given by

$$K_I = \frac{f(\frac{a}{W})P}{B\sqrt{W}} \tag{3}$$

Where B is specimen thickness, W is the width, a is the crack length and P is the load. The function f(a/W) for SE(T) is given by Eq. (4), and for SE(B) is defined by Eq. (5) (Anderson, 1995).

$$f(\frac{a}{W}) = \frac{\sqrt{2\tan\frac{\pi a}{2W}}}{\cos\frac{\pi a}{2W}}\left[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37\left(1-\sin\frac{\pi a}{2W}\right)^3\right] \tag{4}$$

$$f(\frac{a}{W}) = \frac{3\frac{S}{W}\sqrt{\frac{a}{W}}}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{1.5}}\left[1.99 + \frac{a}{W}\left(1-\frac{a}{W}\right)\left\{2.15 + 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)^2\right\}\right] \tag{5}$$

In Eq. (5) S is the support span of the three-point bending specimen; the standard ASTM E 1820 specify S=4W.
The plastic component J_p can to be estimated with EPRI method by

$$J_{pl} = \alpha\varepsilon_0\sigma_0 b g_1(a/W) h_1(a/W,n)\left(\frac{P}{P_0}\right)^{n+1} \tag{6}$$

Where ε_0, σ_0, n, and α are respectively yield strain, yield stress, strain hardening exponent, and the fitting constant of material, the functions g_1, h1, and de reference load P_0 are tabulated in reference Kanninen and Popelar (1985).

Several works suggest that the use of crack mouth opening displacements (CMOD) records, for experimental determination of J_{pl}, provides more reliable results. This work adopted this methodology using

$$J_{pl} = \eta_{pl}\frac{A_{pl}}{(W-a)B} \tag{7}$$

Where A_{pl} is the plastic work, found from the experimental load versus CMOD curve, and η_{pl} is the plastic eta factor.

Other important elastic-plastic parameter in structural integrity assessments is the concept of crack tip opening displacement (CTOD) designed with δ symbol, similar to J-integral, CTOD can to be separating into elastic and plastic components given by

$$\delta_{el} = \frac{K_I^2}{m\sigma_{YS}E'} \tag{8}$$

$$\delta_{pl} = \frac{r_p(W\times a)V_{pl}}{r_p(W\times a)+a+z} \tag{9}$$

Where r_p is the plastic rotation factor, V_{pl} is the plastic component of CMOD, and z is the distance from knife edge measurement point to the notched edge.

3. Experimental Procedures

The material used for the manufacturing of the test specimens for the experimental procedures was a API 5L X65 steel sheet, ½" thick and in as-rolling condition. Fig 1 shows the dimensions of the specimens. The preparation of the specimens for metallographic analyzes was based in ASTM E 3-01, the determination of the grain size was based in ASTM E 112-96, and the mechanical properties in tension were obtained according to ASTM E 8M-01. Table 1 shows the basic mechanical properties.

Table 1. Basic mechanical properties of API 5L X65 steel.

Metallurgical condition	S_u [MPa]	S_y [MPa]	Reduction of area [%]	Elongation at fracture in 25 mm [%]	HV
Controlled rolling	605	504	58	30	205
Normalized	513	367	62	36	171

The determination of J-Integral and J-R curves for SE(B) specimens was made according to ASTM E 1820-01 and in the case of non normalized SE(T) specimens, the value of the plastic eta factor was obtained from Aguirre, Ferreira, and Hernandez (2005).

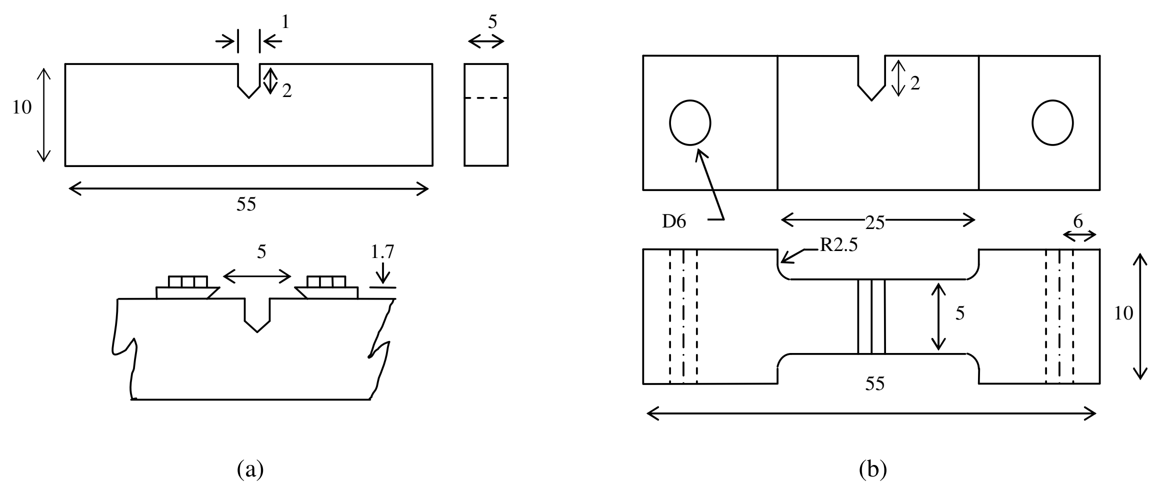

Figure 1. Dimensions of the SE(B) (a) and SE(T) (b) specimens in mm.

The specimen fracture surface analysis was conducted in a scanning electronic microscope (SEM) Jeol, JXA 840A model.

4. Computacional model

The FEM analysis was made in the commercial program Abaqus®, for 2D analysis. It was used 8-node solid element CPE8R for plane strain and CPS8R for plane stress. Fig. 2 shows the used mesh. Eight cases were analyzed with ν= 0.29, E= 211 GPa, n= 7.53, α= 0.926, and S_y= 504 MPa, using material definition "deformation plasticity" Abaqus option.

The applied load per unit thickness was 250 N/mm (P_{max}= 12,500 N), the crack length, a, was taken as half of the specimens width and a/W= 0.5. For the symmetry only the half part is modeled, the mesh has 584 elements, a focused mesh around the crack tip was generated using the "swept meshing" technique, and the size of elements at the crack tip was 0.8 μm.

For 3-D calculations the reduced 20-node brick elements are used, the front of crack as modeled using degenerate element, figure 3 shows the 3-D mesh. In this case, the load per unit thickness was 125 N/mm applied in the half of pin hole. The mesh has 2,972 elements and the size of elements at the crack tip was 35 μm.

a) b)

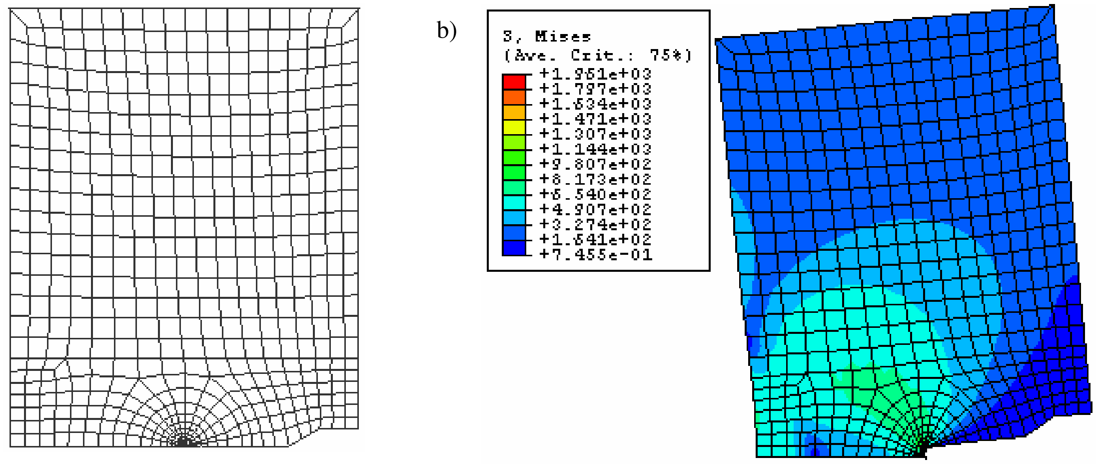

Figure 2. a) 2D mesh for half SE(T) specimen. b) Color-map analysis result for half SE(T) specimen in plane strain.

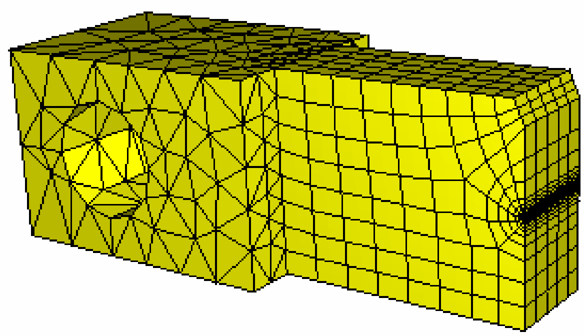

Figure 3. 3D mesh for half SE(T) specimen.

5. Results

The metallographic analyses shown that the specimens in controlled rolling condition have a ferritic-perlitic microstructure with grain size ASTM 11.

Table 2 shows the results for SE(B) standard specimens and Tab. 3 shows the results for non standard SE(T) specimens.

Table 2. Experimental results for SE(B) specimens for API 5L X65 steel and a/W ratio = 0.5.

Specimen number	Initial crack length a_0 [mm]	Crack extension $\Delta a^{(1)}$ [mm]	Load at the point of stopping test P_{stop} [kN]	Area under load displacement curve A_{pl} [Nm]	J integral [kJ/m^2]
1	5.1	0.03	2.42	0.556	73.57
2	5.1	0.20	2.72	1.73	206.15
3	5.2	0.30	2.75	3.1	365.65
4	5.3	0.50	2.92	4.235	506.97

(1) Measured in a SEM in according with the ASTM E 1820-01.

After the tests, the specimens were cooled with liquid nitrogen and broken by impact in order to have different fracture micromechanisms and to facilitate the identification and measurement of the crack extension region (Δa in Tab. 2 and 3). Figure 4 shows a typical fractography for both specimens, pointing out this region. Three regions are identified: the fatigue pre-crack extension region, the stable crack extension region, and finally the region of the brittle fracture induced by liquid nitrogen. As expected, the fractography analysis shows three different fracture micromechanisms: fatigue at the fatigue pre-crack region, dimples at the stable crack extension region, and cleavage at the brittle fracture region induced by liquid nitrogen.

Figure 5 shows the J-R curves for both SE(T) and SE(B) specimens and Fig. 6 shows the CTOD curves.

Table 3. Experimental results for SE(T) specimens of API 5L X65 steel and a/W ratio = 0.5.

Specimen number	Initial crack length a_0 [mm]	Crack extension $\Delta a^{(1)}$ [mm]	Maximum load P_{max} [kN]	Load at the point of stopping test P_{stop} [kN]	Area under load displacement curve A_{pl} [Nm]	J integral [kJ/m^2]
1	5.0	1.4	12.65	11.35	32.3	1292
2	5.3	0.6	11.16	11.16	11.9	506
3	5.1	1.0	12.65	12.65	19.45	794
4	5.1	1.2	12.09	11.72	25.85	1055
5	5.0	1.5	12.41	11.44	33.77	1351
6	5.2	0.7	11.64	11.64	12.56	523
7	5.0	1.2	12.41	12.41	19.42	777
8	5.4	1.4	12.22	12.22	23.7	1030

(1) measured in the SEM in accordance with ASTM E 1820-01.

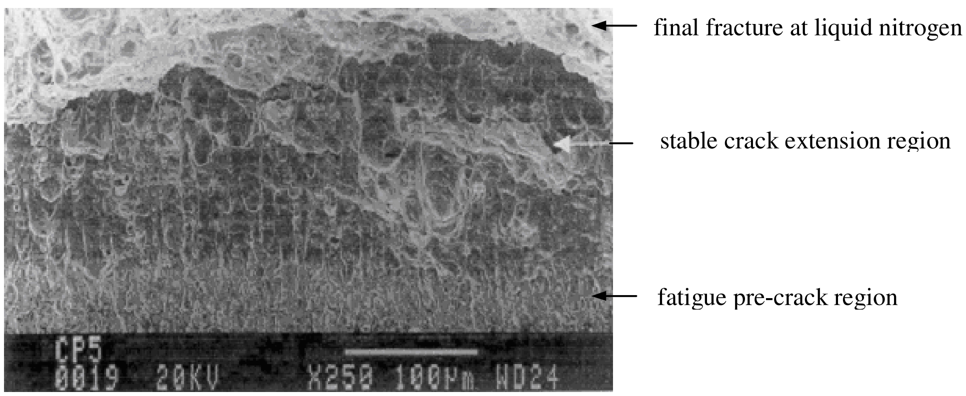

Figure 4. Typical fractography for SE(B) and SE(T) specimens.

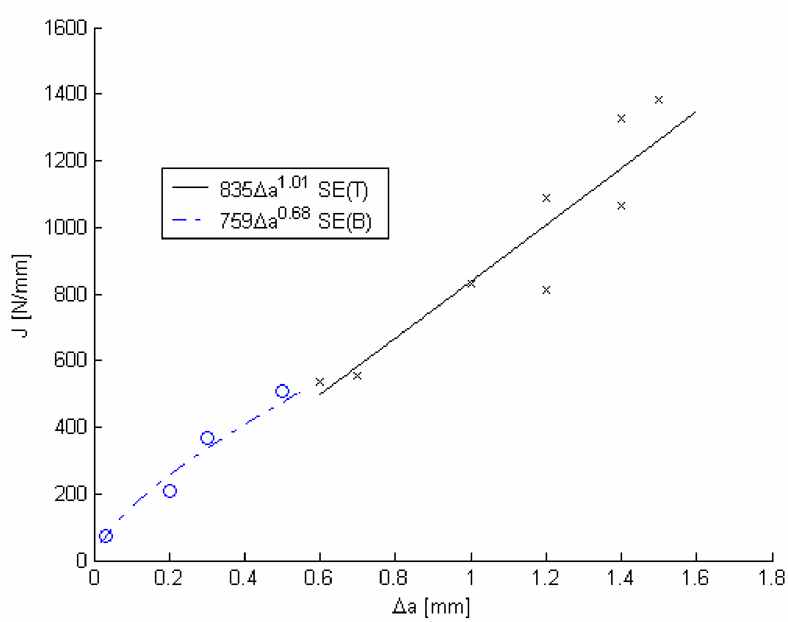

Figure 5. J-R Curves for SE(T) and SE(B) specimens.

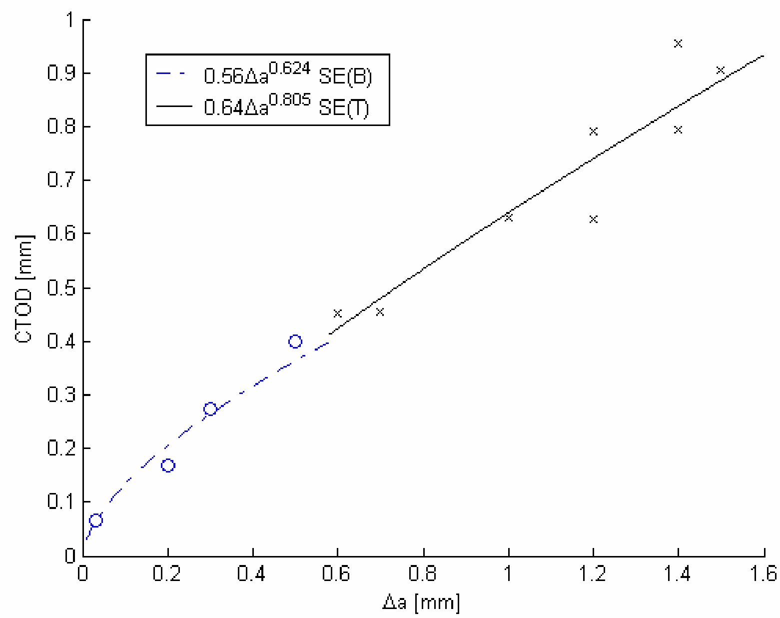

Figure 6. CTOD versus Δa curves for SE(T) and SE(B) specimens.

Figure 7 shows the J versus CTOD curves for both specimens.

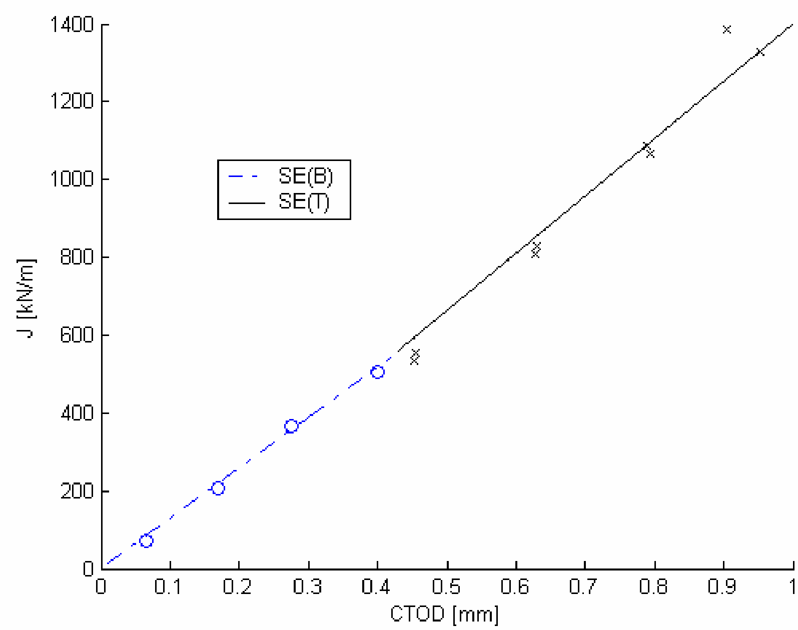

Figure 7. J-Integral versus CTOD for SE(T) and SE(B) specimens.

Table 4 shows the experimental results of the fracture toughness and the values obtained by the EPRI method. It is possible to observe that the experimental and 3D results are very closed.

It is not possible to use 2D finite element analysis or the EPRI method for obtaining the fracture toughness of thin not standard specimens, because the results are very far from the experimental values.

The results of the fracture toughness for both experimental and finite element analysis in 3D have a good correlation.

Table 4. Comparison results, experimental an numerical, for SE(T) specimens.

Specimen Type[(1)]		a_0 [mm]	P_{max} [kN]	J [kJ/m^2]	% Relative difference [(5)]
Experimental	SE(T) #3 [(2)]	5.1	12.65	794	9.4 %
	SE(T) #7 [(2)]	5.0	12.41	777	7,0 %
Numerical	2D FEM Plane stress	5.0	12.50	2188	201 %
	EPRI Plane stress	5.0	12.50	1345	85.3 %
	2D FEM Plane strain	5.0	12.50	183	-74.8 %
	EPRI Plane strain	5.0	12.50	144	-80.2 %
	3D FEM model	5.1	12.50	726[(4)]	0 %
	3D FEM model	5.1	12.50	996[(3)]	-

(1) All specimens with 5 mm thick;
(2) Extracted of the table 3;
(3) Maximum values at the middle of thickness;
(4) Average value;
(5) Compared with average 3D value.

6. Conclusions.

Using experimental analysis with SE(B) and SE(T) specimens, the J-Integral and both CTOD-R and J-R curves was computed for the API 5L X65 steel. Both analytical Epri method and 2D FEM analysis were applied. Finally, the 3D finite element analysis of SE(T) specimens was presented and it was possible to observe that the analytical Epri method and 2D FEM analysis provide a difference of 75 % and the 3D FEM analysis has a difference inferior to 10% with the experimental SE(T) specimens.

7. Acknowledgements

The authors are grateful to CAPES by the doctorate scholarship.

8. References

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9. Responsibility notice

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