Crack Growth Testing of an X80 Pipeline Girth Weld Using SE(T) and SE(B) Fracture Specimens

Conference Paper · July 2012

DOI: 10.1115/OMAE2012-83056

5 authors, including:

Diego F. B. Sarzosa
University of São Paulo
22 PUBLICATIONS **70** CITATIONS

Gustavo Donato
University Center of FEI
33 PUBLICATIONS **66** CITATIONS

Marcelo Paredes
Massachusetts Institute of Technology
18 PUBLICATIONS **48** CITATIONS

Claudio Ruggieri
University of São Paulo
136 PUBLICATIONS **1,512** CITATIONS

Proceedings of the ASME 31st International Conference on Offshore Mechanics and Arctic Engineering
OMAE2012
June 10-15, 2012, Rio de Janeiro, Brazil

OMAE2012-83056

CRACK GROWTH TESTING OF AN X80 PIPELINE GIRTH WELD USING SE(T) AND SE(B) FRACTURE SPECIMENS

Leonardo L. S. Mathias
Dept. of Naval Arch. and Ocean Eng.
University of São Paulo
São Paulo, SP 05508-900, Brazil
Email: leonardomathias@usp.br

Diego F. S. Burgos
Dept. of Naval Arch. and Ocean Eng.
University of São Paulo
São Paulo, SP 05508-900, Brazil
Email: dsarzosa@usp.br

Gustavo H. B. Donato
Dept. of Mech. Eng.,
FEI University Center
S. B. Campo, SP 09850-901, Brazil
Email: gdonato@fei.edu.br

Marcelo Paredes
Dept. of Naval Arch. and Ocean Eng.
University of São Paulo,
São Paulo, SP 05508-900, Brazil
Email: lmparedes@usp.br

Claudio Ruggieri
Dept. of Naval Arch. and Ocean Eng.
University of São Paulo,
São Paulo, SP 05508-900, Brazil
Email: claudio.ruggieri@usp.br

ABSTRACT

Accurate measurements of fracture resistance properties, including crack growth resistance curves for pipeline girth welds, become essential in defect assessment procedures of the weldment region and the heat affected zone, where undetected crack-like defects (such as lack of penetration, deep undercuts, root cracks, etc.) may further extend due to to high tension stresses and strains. This work presents an investigation of the ductile tearing properties for a girth weld made of an API 5L X80 pipeline steel using experimentally measured crack growth resistance curves ((J-Δa curves). Use of these materials is motivated by the increasing demand in the number of applications for manufacturing high strength pipes for the oil and gas industry including marine applications and steel catenary risers. Testing of the pipeline girth welds utilized side-grooved, clamped SE (T) specimens and 3P bend SE(B) specimens with a weld centerline notch to determine the crack growth resistance curves based upon the unloading compliance (UC) method using a single specimen technique. Recently developed compliance functions and η-factors applicable for SE (T) and SE(B) fracture specimens with homogeneous material and overmatch welds are introduced to determine crack growth resistance data from laboratory measurements of load-displacement records. This experimental characterization provides additional toughness data which serve to evaluate crack growth resistance properties of pipeline girth welds using SE (T) and SE(B) specimens with weld centerline cracks.

INTRODUCTION

Structural integrity assessments of pipe girth welds play a key role in design and safe operation of piping systems, including deep water steel catenary risers. More efficient and faster installation methods now employ the pipe reeling process which allows welding and inspection to be conducted at onshore facilities. The welded pipe is coiled around a large diameter reel on a vessel and then unreeled, straightened and finally deployed to the sea floor. However, the reeling process subjects the pipe to large bending loads and plastic deformation (2～3%) well beyond the material's elastic limits with a potentially strong impact on flaw acceptance criteria for the girth weld. Consequently, accurate measurements of fracture resistance properties, including crack growth resistance curves of the girth weld material, become essential in defect assessment procedures of the weldment regio and the heat affected zone, where undetected crack-like defects (such as lack of penetration, deep undercuts, root cracks, etc.) may further extend due to to the high tension stresses and strains.

Fracture mechanics based approaches to describe ductile fracture behavior in structural components, including welded structures, rely upon crack growth resistance (J-Δa) curves (also termed *R*-curves) to characterize crack extension followed by crack instability of the material [1,2]. These approaches allow the specification of critical crack sizes based on the predicted growth of crack-like defects under service conditions. Current standardization efforts now underway [3-5] advocate the use of single edge notch tension specimens (often termed SE(T) or SENT crack configurations) to measure experimental *R*-curves more applicable to high pressure piping systems, including girth welds of marine steel risers.

The primary motivation to use SE(T) fracture specimens in defect assessment procedures for this category of structural components is the strong similarity in crack-tip stress and strain fields which drive the fracture process for both crack configurations [6-9]. Recent applications of SE(T) fracture specimens to characterize crack growth resistance properties in pipeline steels [10] have been effective in providing larger flaw tolerances and, at the same time, reducing the otherwise excessive conservatism which arises when measuring the material's fracture toughness based on high constraint, deeply-cracked, single edge notch bend (SE(B)) or compact tension (C(T)) specimens. defect assessment procedures for steel structures and weldments. However, while now utilized effectively in fracture testing of pipeline girth welds, some difficulties associated with SE(T) testing procedures, including fixture and gripping conditions, raise concerns about the significance and qualification of measured crack growth resistance curves. Such uncertainties in measured fracture toughness may potentially affect tolerable defect sizes obtained from ECA procedures. While slightly more conservative, testing of shallow−crack bend specimens (which is a nonstandard SE(B) configuration) may become more attractive due to its simpler testing protocol, laboratory procedures and much smaller loads required to propagate the crack. Consequently, use of smaller specimens which yet guarantee adequate levels of crack-tip constraint to measure the material's fracture toughness becomes an attractive alternative.

This work presents an investigation of the ductile tearing properties for a girth weld made of an API 5L X80 pipeline steel using experimentally measured crack growth resistance curves ((J-Δa curves). Use of these materials is motivated by the increasing demand in the number of applications for manufacturing high strength pipes for the oil and gas industry including marine applications and steel catenary risers. Testing of the pipeline girth welds employed side-grooved, clamped SE (T) specimens and 3P bend SE(B) specimens with a weld centerline notch to determine the crack growth resistance curves based upon the unloading compliance (UC) method using a single specimen technique. Recently developed compliance functions and η-factors applicable for SE (T) and SE(B) fracture specimens with homogeneous material and overmatch welds are introduced to determine crack growth resistance data from laboratory measurements of load-displacement records. This experimental characterization provides additional toughness data which serve to evaluate crack growth resistance properties of pipeline girth welds using SE (T) and SE(B) specimens with weld centerline cracks.

EXPERIMENTAL DETAILS

Material Descrption

The material utilized in this study was a high strength, low allow (HSLA), API grade X80 pipeline steel produced by Usiminas, Brazil, as a base plate using a control-rolled processing route without accelerated cooling. The mechanical properties and strength/toughness combination for this material are mainly obtained both by grain size refinement and second-phase strengthening due to the small-size precipitates in the matrix. The 20-inch UOE pipe with longitudinal seam weld from which the girth weld SE(T) and SE(B) specimens were extracted was fabricated at Tenaris-Confab plant in Pindamonhangaba, Brazil. Table 1 provides the mechanical properties of the base plate material (measured values based on standard tensile testing) and the weld metal (estimated values based on measured hardness HV values [11]).

Table 1 *Material properties of the base plate and weldment for the tested pipeline girth weld.*

Base Plate			Weld		
σ_{ys} (MPa)	σ_{uts} (MPa)	n	σ_{ys} (MPa)	σ_{uts} (MPa)	n
558	722	11	613	793	11

Using Annex F of API 579 [12], the true stress-true strain response for the tested materials can be described by

$$\bar{\epsilon} = \frac{\bar{\sigma}}{E} + \left(\frac{\bar{\sigma}}{H}\right)^{1/N} \tag{1}$$

where $\bar{\sigma}$ and $\bar{\epsilon}$ are the (total) true stress and logarithmic strain, H is a material constant and $n = 1/N$ defines the Ramberg-Osgood exponent which is often required in J (and CTOD) estimation procedures using the η-method (to be addressed in the following sections). Now, using the estimation expressions provided in Annex F of API 579 [12], the Ramberg-Osgood exponent for the base plate and weld metal is given by $n \approx 11$ and $H \approx 984$ MPa.

Welding Procedure

The tested weld joint was made from the API X80 UOE pipe having thickness, $t_w = 19$ mm. Girth welding of the pipe was performed using the FCAW process in the 1G (flat) position with a single V-groove configuration in which the root pass was made by GMAW welding employing the Surface Tension Transfer (STT) process developed by Lincoln Electric. The main weld parameters used for preparation of the test weld using the FCAW process are: i) Number of passes 12 (including the root pass made by the STT process); ii) Welding current 165 A; iii) Welding voltage 23 V; iv) Average heat input 1.5 kJ/mm. Fernandes [11] provide additional details on the welding process and weld preparation using the STT procedure for the root pass followed by the FCAW process to produce the test weld employed in this work.

Specimen Geometry

Unloading compliance (UC) tests at room temperature were performed on center notch weld, clamped SE(T) specimens with a fixed overall geometry and crack length to width ratios, a/W, to measure tearing resistance curves in terms of J-Δa. The clamped SE(T) specimens have $a/W = 0.4$ and $H/W = 10$ with thickness $B = 14.8$ mm, width $W = 14.8$ mm and clamp distance $H = 148$ mm (refer to Fig. 1(a)). Here, a is the crack depth and W is the specimen width which is slightly smaller that the pipe thickness, t_w. UC tests at room temperature were also conducted on center notched welded SE(B) specimens with $a/W = 0.25$ with thickness $B = 14.8$ mm, width $W = 14.8$ mm and spam $S = 4W$ (refer to Fig. 1(b)). Conducted as part of a collaborative program between the University of São Paulo, Tenaris-Confab, Lincoln Electric Brasil and Petrobrás, testing of these specimens focused on the development of accurate procedures to evaluate crack growth resistance data for pipeline girth welds.

All specimens, including the SE(T) configuration, were precracked in bending using a three-point bend apparatus very similar to a conventional three-point bend test. After fatigue precracking, the specimens were side-grooved to a net thickness of $\sim 85\%$ the overall thickness (7.5% side-groove on each side) to promote uniform crack growth and tested following some general guidelines described in ASTM E1820 standard [13]. Records of load *vs.* crack mouth opening displacements (CMOD) were obtained for the specimens using a clip gauge mounted on knife edges attached to the specimen surface.

ESTIMATION PROCEDURE OF *J-R* CURVES

Laboratory measurements of fracture toughness resistance data focus primarily on the unloading compliance method based upon testing of a single specimen. The methodology essentially relies on determining the instantaneous value of J and specimen compliance at each partial unloading during the measurement of the load-displacement curve as illustrated in Fig. 2(a). This technique enables accurate estimations of J and Δa at several locations on the load-displacement records from which the J-R curve can be developed. Here, we provide an overview on the methodology which builds upon previous work of Cravero and Ruggieri [5,14], Ruggieri [15] and Paredes and Ruggieri [16].

The procedure to estimate crack growth resistance data considers the elastic and plastic contributions to the strain energy for a cracked body under Mode I deformation [2] so that J can be conveniently defined in terms of its elastic component, J_e, and plastic component, J_p, as

$$J = J_e + J_p = \frac{K_I^2}{E'} + \frac{\eta_J A_p}{B_N b_0} \tag{2}$$

where K_I is the elastic stress intensity factor for the cracked configuration, A_p is the plastic area under the load-displacement curve, B_N is the net specimen thickness at the side groove roots

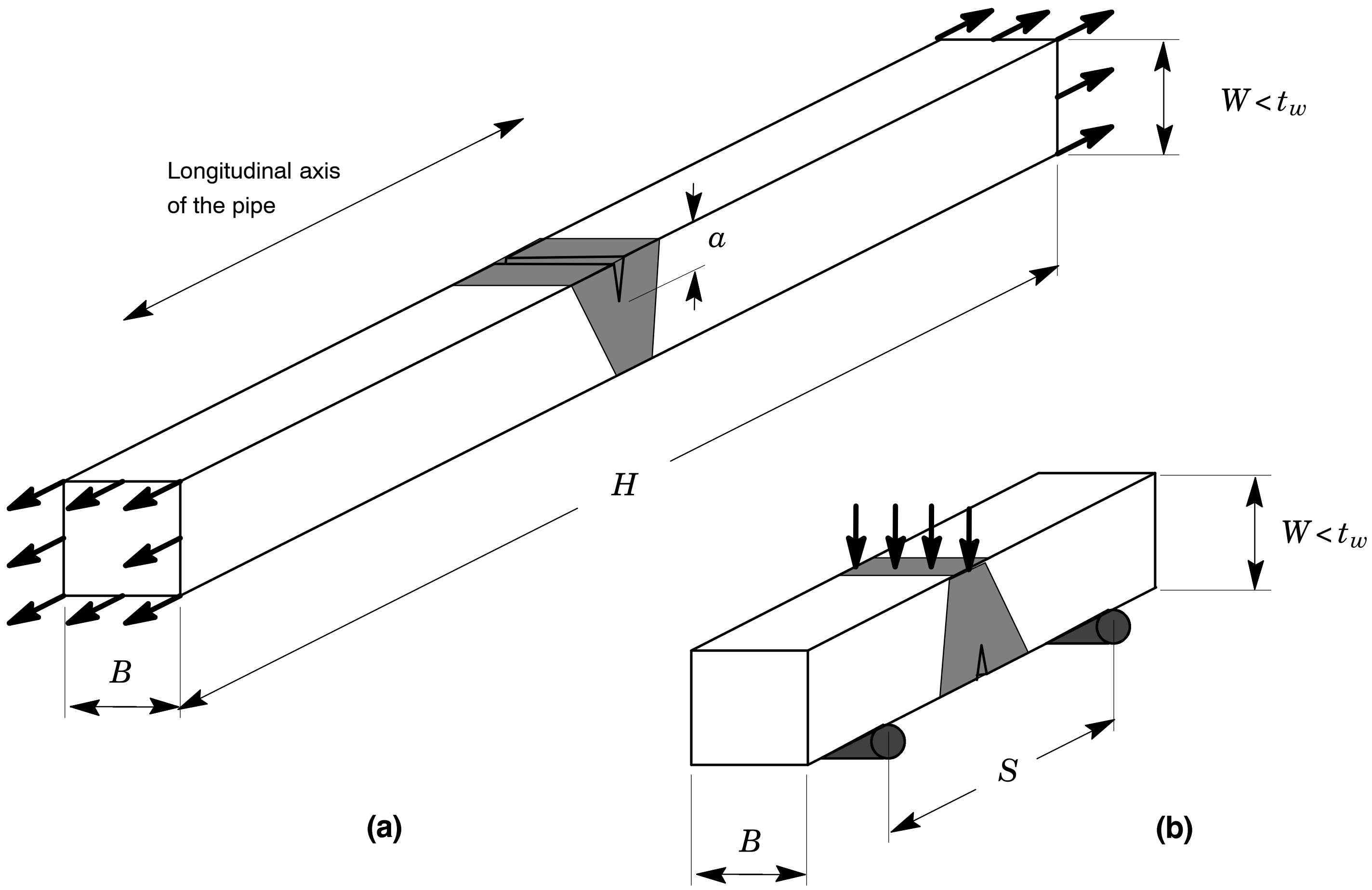

Figure 1 *Geometry of tsted fracture specimens with weld centerline notch. (a) Clamped SE(T) specimen with a/W = 0.4 and H/W = 10; (b) 3P SE(B) specimens with a/W = 0.25 and S/W = 4 (BxB configuration).*

($B_N = B$ if the specimen has no side grooves where B is the specimen gross thickness), b_0 is the initial uncracked ligament ($b_0 = W - a_0$ where W is the width of the cracked configuration and a_0 is the initial crack length). In writing the first term of Eq. (2), plane-strain conditions are adopted such that $E' = E/(1 - \nu^2)$ where E and ν are the (longitudinal) elastic modulus and Poisson's ratio, respectively. Factor η_J introduced by Sumpter and Turner [17] represents a nondimensional parameter which relates the plastic contribution to the strain energy for the cracked body and J. Fig. 2(b) illustrates the essential features of the estimation procedure for J_p. Here, we note that A_p (and consequently η_J) can be defined in terms of load-load line displacement (LLD or Δ) data or load-crack mouth opening displacement (CMOD or V) data. For definiteness, these quantities are denoted η_J^{CMOD} and η_J^{LLD}. While both definitions serve essentially as a means to quantify the effect of plastic work on the J-integral, η_J-values based on LLD have a different character than the corresponding η_J-values based on CMOD. Specifically, factor η_J^{LLD} enters into the expression to correct the J-value due to crack extension as discussed next.

The previous expression (2) defines the key quantities driving the evaluation procedure for J as a function of applied (remote) loading and crack size. However, the area under the actual load-displacement curve for a growing crack differs significantly from the corresponding area for a stationary crack (which the deformation definition of J is based on) [2]. Consequently, the measured load-displacement records must be corrected for crack extension to obtain an accurate estimate of J-values with increased crack growth. A widely used approach (which forms the basis of current standards such as ASTM E1820 [13]) to evaluate J with crack extension follows from an incremental procedure which updates J_e and J_p at each partial unloading point, denoted k, during the measurement of the load *vs.* displacement curve in the form

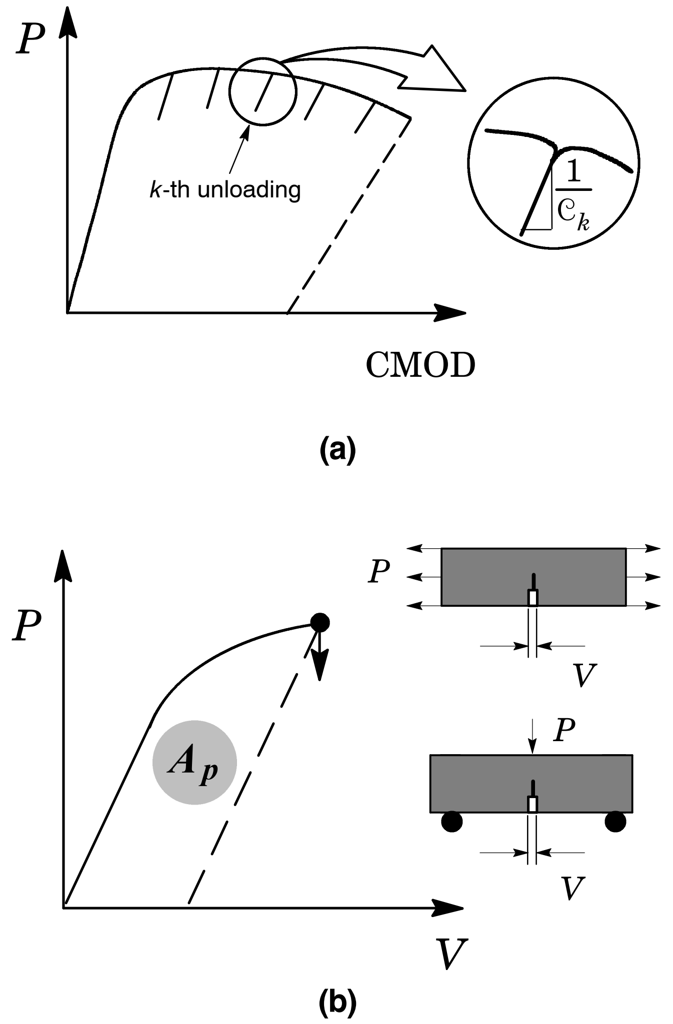

Figure 2 *(a) Partial unloading during the evolution of load with crack mouth opening displacement; (b) Definition of the plastic area under the load-displacement curve.*

$$J_k = J_e^k + J_p^k \quad . \tag{3}$$

Within this approach, the k-th elastic term of J is directly calculated from the corresponding k-th value of K_I using the first term of previous Eq. (2) which yields

$$J_e^K = \frac{\left(K_I^k\right)^2}{E'} \quad . \tag{4}$$

Similarly, the k-th plastic term of J follows from the second term of Eq. (2) using the current plastic area, A_p^k. Given an estimated value for J_p at $k-1$, the k-th value of J is given by

$$J_p^k = \left[J_p^{k-1} + \frac{\eta_{k-1}^{CMOD}}{b_{k-1}B_N}\left(A_p^k - A_p^{k-1}\right)\right] \times \Gamma \tag{5}$$

in which Γ is defined as

$$\Gamma = 1 - \frac{\gamma_{k-1}^{LLD}}{b_{k-1}}(a_k - a_{k-1}) \tag{6}$$

where factor γ^{LLD} is evaluated from

$$\gamma_{k-1}^{LLD} = \left[-1 + \eta_{k-1}^{LLD} - \left(\frac{b_{k-1}}{W}\frac{\hat{\eta}_{k-1}^{LLD}}{\eta_{k-1}^{LLD}}\right)\right] \tag{7}$$

with

$$\hat{\eta}_{k-1}^{LLD} = W\frac{d\eta_{k-1}^{LLD}}{da_{k-1}} \tag{8}$$

Another key step in the experimental evaluation of crack growth resistance response involves the accurate estimation of the instantaneous crack length as testing progresses. The unloading compliance technique provides a convenient and yet simple procedure to correlate crack extension to the specimen compliance with increased crack growth. Fig. 2(a) illustrates the essential features of the method. The slope of the load-displacement curve during the k-th unloading defines the instantaneous specimen compliance, denoted $\mathcal{C}_k$, which depends on specimen geometry and crack length. The following section provides improved expressions for factors η_J^{CMOD} and η_J^{LLD} as well as the nondimensional compliance, μ, for the tested clamped SE(T) specimen and the 3P bend SE(B) specimen which lead to accurate measurements of crack growth resistance data.

The previous development based upon the η-factor concept retains strong contact with current standards to determine experimental J-values using common fracture specimens for homogeneous materials. Computation of η-factors for fracture specimens made of heterogeneus materials, such as welded crack configurations, is relatively straightforward and depends upon the mismatch ratio, M_y, defined by

$$M_y = \frac{\sigma_{ys}^{WM}}{\sigma_{ys}^{BM}} \tag{9}$$

where σ_{ys}^{BM} and σ_{ys}^{WM} denote the yield stress for the base plate metal and weld metal.

J-R CURVE TESTING

Stress Intensity Factors

Following the procedure described before, parameter K_I is evaluated at the current load, P_k, using

$$K_I^k = \frac{P_k}{B_N\sqrt{W}}\mathcal{F}(a_k/W) \quad (10)$$

where $\mathcal{F}(a_k/W)$ defines a nondimensional stress intensity factor dependent upon specimen geometry, crack size and loading condition. For the tested SE(T) specimen with clamped conditions with $H/W = 10$ analyzed here, Cravero and Ruggieri [5] provide analytical expressions for the nondimensional stress intensity factors $\mathcal{F}(a_k/W)$ in the form

$$\mathcal{F}(a_k/W) = \sum_{r=0}^{5} \xi_r (a_k/W)^r \quad (11)$$

where it is understood that a 5-th order polynomial fitting is employed with the polynomial coefficients, ξ_r, given by $\xi_0 = 0.2832$, $\xi_1 = 3.8497$, $\xi_2 = -1.4885$, $\xi_3 = 4.1716$, $\xi_4 = 9.9094$ and $\xi_5 = -7.4188$. For the SE(B) specimen, analytical expressions for $\mathcal{F}(a_k/W)$ are given in Tada et al. [18].

Elastic Compliance

Standard elastic analyses under plane-strain conditions typically define the (linear) dependence of applied load on displacement for a given specimen geometry with different crack length. Such dependence provides the required data from which the specimen compliance for varying crack size is extracted. For a fixed displacement, *V* or CMOD, increasing the crack size decreases the specimen stiffness which, consequently, reduces the applied load, *P*. The slope of each curve on the *P*-CMOD relationship then defines the inverse of the specimen compliance, denoted as $\mathcal{C}$, which enables building the functional dependence of $\mathcal{C}$ and a/W. Figures 3-4 provide the variation of normalized compliance, $\mu_{CMOD}^{SE(T)}$, with crack length to specimen width ratio, a/W, for the clamped SE(T) specimens with varying H/W-ratios, and the variation of $\mu_{CMOD}^{SE(B)}$, with a/W for the SE(B) specimen. In this plot, the normalized compliance μ_{CMOD} is defined by [13,19]

$$\mu_{CMOD}^{SE(T)} = \frac{1}{1 + \sqrt{EB_e\mathcal{C}}} \quad (12)$$

and

$$\mu_{CMOD}^{SE(B)} = \left[\sqrt{\frac{(B_e W E \mathcal{C})}{S/4}} + 1\right]^{-1} \quad (13)$$

where

$$B_e = B - \frac{(B - B_N)^2}{B} \quad . \quad (14)$$

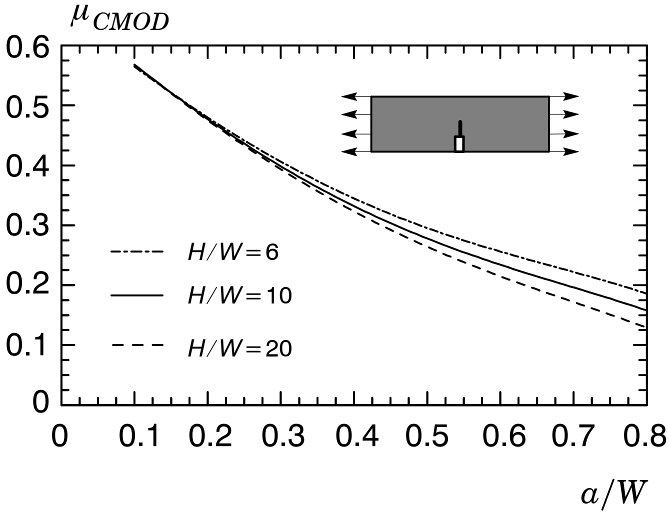

Figure 3 *Variation of normalized compliance in terms of CMOD with increased a/W-ratio for the clamped SE(T) fracture specimen.*

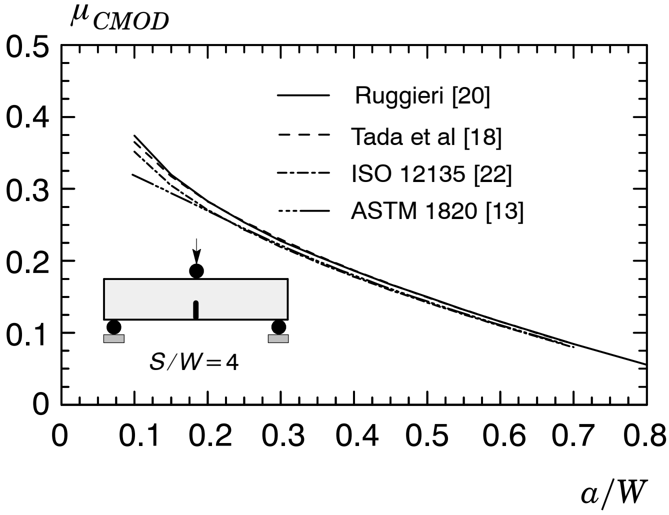

Figure 4 *Variation of normalized compliance in terms of CMOD with increased a/W-ratio for the 3P SE(B) fracture specimen.*

Using now the previous results for guidance, Cravero and Ruggieri [5] and Ruggieri [20] provide the functional dependence of crack length and specimen compliance in the form

$$a/W = \sum_{m=0}^{5} \beta_m \mu^m \quad (15)$$

where it is understood that a 5-th order polynomial fitting is employed. For the clamped SE(T) specimen with $H/W = 10$, the polynomial coefficients, β_m, are given by $\beta_0 = 1.6485$, $\beta_1 = -9.1005$ $\beta_2 = 33.0250$, $\beta_3 = -78.4670$, $\beta_4 = 97.3440$ and $\beta_5 = -47.2270$. For the 3P SE(B) specimen with $S/W = 4$, Cravero [23] gives the polynomial coefficients, β_m, given by $\beta_0 = 0.7590$, $\beta_1 = 1.2961$ $\beta_2 = -37.9076$, $\beta_3 = 154.9671$, $\beta_4 = -270.3815$ and $\beta_5 = 182.6632$. The previous equations define the key steps in the evaluation procedure of the crack growth resistance curve. By measuring the instantaneous compliance during unloading of the specimen (see Fig. 2), the current crack length follows directly from solving the above expression for μ.

Nondimensional Plastic Eta Factors

SE(T) Fracture Specimens

Based upon the plastic component of the area under the load *vs.* displacement curve (see Fig. 2), Ruggieri [15] provided improved nondimensional η-factors for the analyzed clamped SE(T) specimens with varying H/W-ratios. Further, Paredes and Ruggieri [16] examined the effecst of weld strength mismatch on fracture toughness measurements defined by J and CTOD fracture parameters using SE(T) specimens and arrived at a set of nondimensional η-factors for this crack configuration as a function of the mismatch ratio, M_y. Figure 5 displays provide factors η_J derived from CMOD (η_J^{CMOD}) and LLD (η_J^{LLD}) for the clamped SE(T) specimens with varying a/W-ratios and different mismatch levels for a groove size, $2h = 15$mm. In these plots, the solid symbols correspond to the compute η-values whereas the lines represent fitting curves to the numerical data.

The results given by the plots of Fig. 5 allow expressing the η-factors for the analyzed clamped SE(T) specimens with $H/W = 10$ in the form

$$\eta(a/W) = C_0 + C_1(a/W) + C_2(a/W)^2 + C_3(a/W)^3 \quad (16)$$

where the coefficients C_k are function of the mismatch level, *i.e.*, $C_k = f(M_y)$, valid in the range $0.2 \le a/W \le 0.7$ and $1.0 \le M_y \le 1.5$ as follows

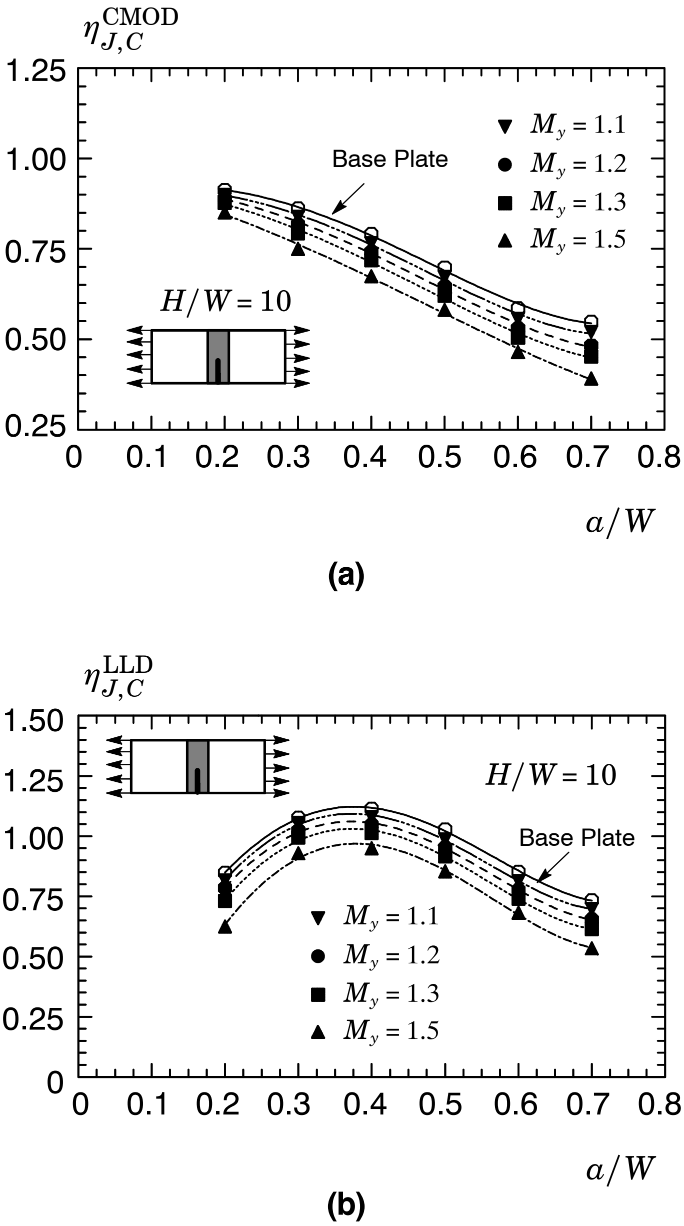

Figure 5 *Variation of η-factor to determine J with increased crack size (a/W-ratio) for the clamped SENT specimens with different levels of strength mismatch: (a) CMOD; (b) LLD.*

- Coefficients C_k for η_J^{CMOD}:

$$C_0 = 0.6960 - 0.2411 M_y + 0.2888 M_y^2$$

$$C_1 = 2.2141 + 2.7164 M_y - 3.0284 M_y^2$$

$$C_2 = -3.3160 - 12.1180 M_y + 9.1392 M_y^2$$

$$C_3 = 0.8558 + 11.2970M_y - 7.6189M_y^2$$

- Coefficients C_k for η_J^{LLD}:

$$C_0 = -0.8380 + 1.1698M_y - 0.8782M_y^2$$

$$C_1 = 10.4110 - 2.4038M_y + 2.7719M_y^2$$

$$C_2 = -12.5970 - 9.0348M_y + 0.0200M_y^2$$

$$C_3 = 2.4767 + 13.2410M_y - 3.1169M_y^2$$

SE(B) Fracture Specimens

For the tested SE(B) fracture specimens, Donato and Ruggieri [21] provide a set plastic of η-factors for homogeneous materials which are displayed in Figs. 6. To facilitate manipulation of the previous results to estimate J in fracture testing, a polynomial fitting of the functional dependence of the η-factors and on a/W for varying hardening properties based upon a least square scheme is given as follows.

$$\eta_J^{LLD} = -17.260(a/W)^2 + 9.946(a/W) + 0.383 \quad (17)$$
$$\text{all } n \quad ; \quad 0.05 \le a/W \le 0.3$$

$$\eta_J^{LLD} = 0.127(a/W) + 1.816 \quad (18)$$
$$\text{all } n \quad ; \quad 0.3 < a/W \le 0.7$$

$$\eta_J^{CMOD} = 0.341(a/W)^2 - 2.111(a/W) + 3.6496 \quad (19)$$
$$\text{all } n \quad ; \quad 0.15 \le a/W \le 0.7$$

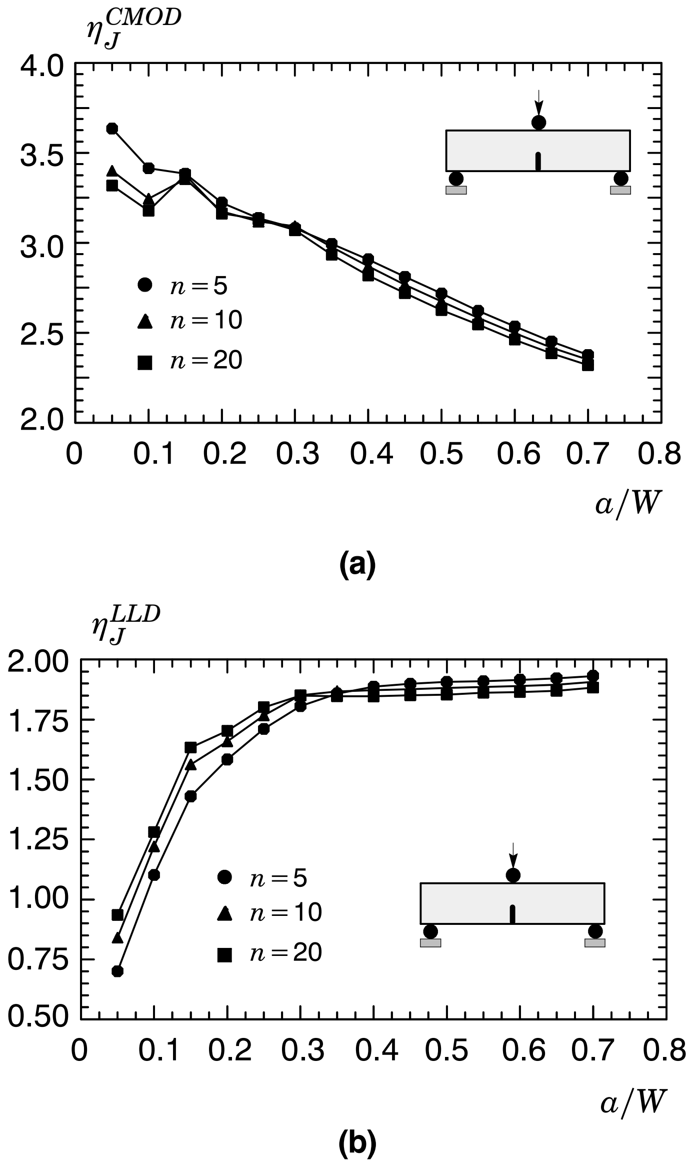

Figure 6 *Variation of plastic η_J derived from CMOD and LLD with increased a/W-ratio and varying hardening properties for the 3P SE(B) fracture specimen.*

Crack Growth Resistance Results

This section now describes the evaluation of ductile tearing properties for the tested X80 pipeline girth weld from laboratory measurements of load and CMOD for the clamped SE(T) specimens and the 3P bend SE(B) specimens with cente notched welds. The clamped SE(T) specimens have $a/W = 0.4$ and $H/W = 10$ with thickness $B = 14.8$ mm, width $W = 14.8$ mm and clamp distance $H = 148$ mm (refer to Fig. 1(a)). The SE(B) specimens have $a/W = 0.25$ with thickness $B = 14.8$ mm, width $W = 14.8$ mm and spam $S = 4W$ (refer to Fig. 1(b)). Figure 7 shows the measured load-displacement curve (as described by CMOD) for both test specimens.

Evaluation of the crack growth resistance curve follows from determining J and Δa at each unloading point of the measured load-displacement data. Based upon the previous results for the η-factors displayed in the plots of Fig. 5 with $M_y = 1.1$, the present analysis employs η_J^{CMOD} and η_J^{LLD} to estimate the plastic component of the J-integral, J_p. Figures 8-9 present the measured crack growth resistance curves for the tested pipelines girth weld. Figure 5 displays the J vs. Δa curves for for tested clamped SE(T) and 3P SE(B) specimens based upon η-factors for homogeneous materials. Figure 6 shows the resist-

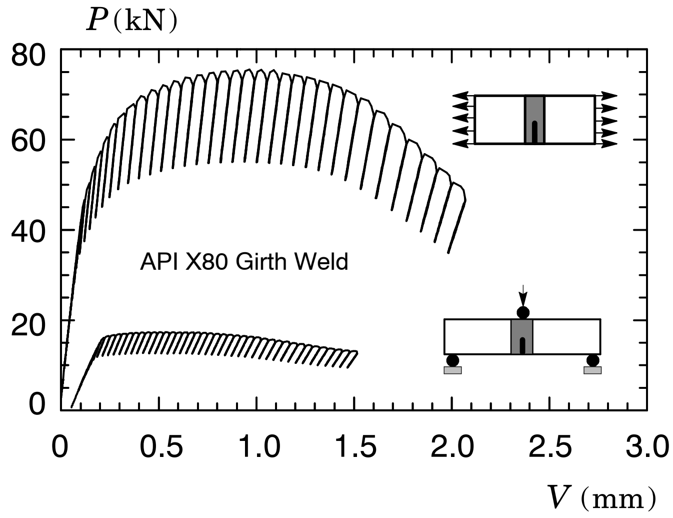

Figure 7 *Measured load-CMOD curve for the tested X80 pipeline girth weld using clamped SE(T) specimens with a/W = 0.4 and 3P SE(B) specimens with a/W = 0.25.*

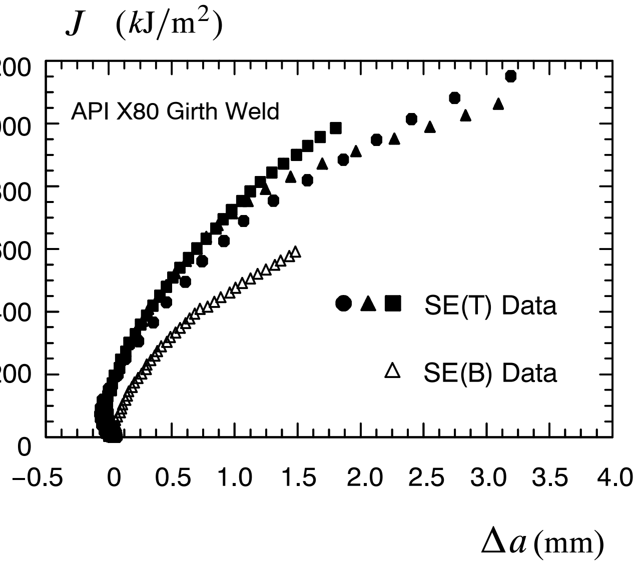

Figure 8 *Experimental R−curves for tested clamped SE(T) and 3P SE(B) specimens based upon η-factors for homogeneous materials (20°C).*

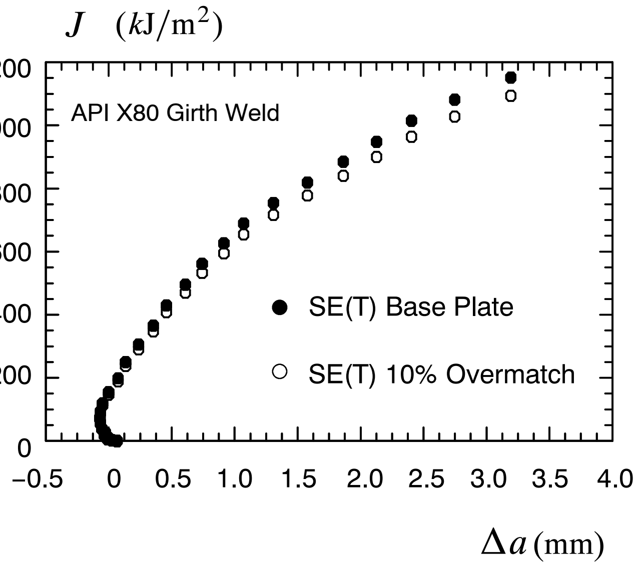

Figure 9 *Experimental R−curves for tested clamped SE(T) specimen based upon η-factors for homogeneous materials and overmatched welds (20°C).*

ance curves for one of the tested clamped SE(T) specimens based upon η-factors for homogeneous materials and overmatched welds. The significant features associated with these plots include: (1) The shallow-crack SE(B) specimen provides an *R*-curve which, albeit slightly more conservative, exhibits levels of J-values comparable to the levels of J corresponding to the deeply-cracked SE(T) specimen at a fixed amount of crack growth, Δa; (2) Use of the η-factors specifically derived for overmatched materials in the estimation procedure for J_p does provide a better description of the ductile tearing behavior for the material; here, use of the η-factors for homogeneous materials (*i.e.*, not taking into account the degree of weld strength overmatch) leads to nonconservative estimates of the *R*-curve (we should emphasize that the larger the levels of weld strength mismatch the larger the degree of nonconservativeness).

DISCUSSION AND CONCLUDING REMARKS

This work presents an investigation of the ductile tearing properties for a girth weld made of an API 5L X80 pipeline steel using experimentally measured crack growth resistance curves ((J-Δa curves). Testing of the pipeline girth welds utilized side-grooved, clamped SE (T) specimens and 3P bend SE(B) specimens with a weld centerline notch to determine the crack growth resistance curves based upon the unloading compliance (UC) method using a single specimen technique. This experimental characterization provides additional toughness data which serve to evaluate crack growth resistance properties of pipeline girth welds using SE (T) and SE(B) specimens with weld centerline cracks. Additional work is in progress to further validate the use of shallow-crack SE(B) specimens as an alternative fracture specimen to measure crack growth properties for pipeline girth welds. Ongoing investigation also focuses on establishing robust correlations between J and CTOD for stationary and growing cracks in SE(T) and SE(B) fracture specimens.

Acknowledgments

This investigation is supported by the Brazilian Scientific Council for Research and Technology (CNPq) (Grant 304132/2009-8) and by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP Grant 2009/54229-3). The authors acknowledge Tenaris-Confab and Lincoln Electric Brasil for providing support for the experiments described in this work. The authors also acknowledge the encouragement and useful discussions provided by Sergio Kojima (Tenaris-Confab) and Antonio C. Souza (Lincoln Electric Brasil).

References

[1] Hutchinson, J. W., ''Fundamentals of the Phenomenological Theory of Nonlinear Fracture Mechanics,'' *Journal of Applied Mechanics*, Vol. 50, pp. 1042-1051, 1983.

[2] Anderson, T. L. *Fracture Mechanics: Fundaments and Applications - 3rd Edition*, CRC Press, New York, 2005.

[3] Det Norsk Veritas. "Fracture Control for Pipeline Installation Methods Introducing Cyclic Plastic Strain". Recommended Practice DNV-RP-F108, 2006.

[4] Shen, G. and W.R. Tyson, "Crack Size Evaluation Using Unloading Compliance in Single−Specimen Single-Edge-Notched Tension Fracture Toughness Testing", *Journal of Testing and Evaluation*, Vol. 37 (4), paper ID JTE102368, 2009.

[5] Cravero, S. and Ruggieri, C., "Estimation Procedure of *J*-Resistance Curves for SE(T) Fracture Specimens Using Unloading Compliance", *Engineering Fracture Mechanics*, Vol. 74, pp. 2735-2757, 2007.

[6] Nyhus, B., Polanco, M and Ørjasæter, O., ''SENT Specimens as an Alternative to SENB Specimens for Fracture Mechanics Testing of Pipelines.'' *in* ASME International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2003), American Society of Mechanical Engineers, Cancun, Mexico, 2003.

[7] Cravero, S. and Ruggieri, C., "Correlation of Fracture Behavior in High Pressure Pipelines with Axial Flaws Using Constraint Designed Test Specimens - Part I: Plane-Strain Analyses," *Engineering Fracture Mechanics*, Vol. 72, pp. 1344-1360, 2005.

[8] Silva, L. A. L., Cravero, S. and Ruggieri, C., "Correlation of Fracture Behavior in High Pressure Pipelines with Axial Flaws Using Constraint Designed Test Specimens - Part II: 3-D Effects on Constraint," *Engineering Fracture Mechanics*, Vol. 73, pp. 2123-2138, 2006.

[9] Shen, G., R. Bouchard, J. A. Gianetto and W. R. Tyson, "Fracture Toughness Evaluation of High-Strength Steel Pipe", *in* ASME PVP 2008 Pressure Vessel and Piping Division Conference (PVP 2008), American Society of Mechanical Engineers, Chicago, IL, 2008.

[10] Park, D. Y., Tyson, W. R., Gianetto, J. A., Shen, G and Eagleson, R. S., "Evaluation of FRacture Toughness of X100 Pipe Steel Using SE(B) and Clamped SE(T) Single Specimens," *in* ASME International Pipeline Conference (IPC 2010), American Society of Mechanical Engineers, Calgary, Canada, 2010.

[11] Fernandes, P. E. A., *HAZ Notch Toughness of an API X80 Steel Weldment Fabricated by SMAW and FCAW Welding Processes*, Ph. D. Thesis, University of São Paulo, 2011 (in Portuguese).

[12] American Petroleum Institute. "Fitness-for-Service", API RP-579-1 / ASME FFS-1, 2007.

[13] American Society for Testing and Materials, "Standard Test Method for Measurement of Fracture Toughness", ASTM E1820, 2008.

[14] Cravero, S. and Ruggieri, C., "Further Developments in *J* Evaluation Procedure for Growing Cracks Based on LLD and CMOD Data", *International Journal of Fracture*, Vol. 148, pp. 387-400, 2008.

[15] Ruggieri, C., "Further Results in *J* and CTOD Estimation Procedures for SE(T) Fracture Specimens - Part I: Homogeneous Materials," *Engineering Fracture Mechanics*, (In Press), 2011.

[16] Paredes, M. and Ruggieri, C., "Further Results in *J* and CTOD Estimation Procedures for SE(T) Fracture Specimens - Part II: Weld Centerline Cracks," *Engineering Fracture Mechanics*, (Submitted for Publication), 2012.

[17] Sumpter, J. D. G. and Turner, C. E., "Method for Laboratory Determination of J_c," *Cracks and Fracture*, ASTM STP 601, American Society for Testing and Materials, pp 3-18, 1976.

[18] Tada, H, Paris, P. C. and Irwin, G. R., "The Stress Analysis of Cracks Handbook", 3rd Edition, American Society of Mechanical Engineers, NY, 2000.

[19] Saxena, A., "Nonlinear Fracture Mechanics for Engineers", CRC Press, Boca Raton, 1998.

[20] Ruggieri, C., "FRACTUS2D: Numerical Computation of Fracture Mechanics Parameters for 2-D Cracked Solids," EPUSP, University of São Paulo, 2011.

[21] G. H. B. Donato and C. Ruggieri, "Estimation Procedure for J and CTOD Fracture Parameters Using Three-Point Bend Specimens" in *6th International Pipeline Conference - IPC 2006*, Anais CD-ROM, Calgary, Canadá, 2006.

[22] International Organization for Standardization, "Metallic Materials – Unified Method of Test for the Determination of Quasistatic Fracture Toughness", ISO 12135, 2002.

[23] Cravero, S., *Development of Evaluation Procedures for J-R Curves of SE(T) Fracture Specimens Using the Unloading Compliance Method*, Ph. D. Thesis, University of São Paulo, 2007 (in Portuguese).