THE PLASTIC ETA FACTOR IN EXPERIMENTAL MEASUREMENTS OF FRACTURE TOUGHNESS FOR TENSILE SE(T) SPECIMENS[1]

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Abstract

This work investigates application of the η-factor (which bears direct connection with laboratory toughness measurements) on accurate and robust estimates of J for pin loaded and clamped single edge notch tension (SE(T)) specimens using load-displacement records. Very detailed non-linear finite element analyses for plane-strain models provide the evolution of load with increased load-line displacement and crack mouth opening displacement to define the applied load as a separable function dependent upon crack geometry and material deformation. The procedure enables determining the corresponding separation parameters for each specimen geometry thereby allowing evaluation of factor η derived from a load separation analysis. The study reveals that η-factors based on load-line displacement (LLD) are very sensitive to plasticity changes at locations remote from the crack-tip region. In contrast, η-factors based on crack mouth opening displacement (CMOD) appear less affected by remote crack-tip plasticity. Overall, the present results provide a strong support to use η-based procedures in toughness measurements for clamped SE(T) fracture specimens.

Key-words: Structural integrity; Welded joints; Pipeline steel weldments; Fracture toughness; J-Integral.

O FATOR PLÁSTICO *ETA* EM MEDIÇÕES EXPERIMENTAIS DE TENACIDADE UTILIZANDO ESPÉCIMES DE TRAÇÃO SE(T)

Resumo

Este trabalho apresenta uma investigação sobre a aplicabilidade de fatores plásticos η (os quais possuem relação direta com medições experimentais de tenacidade) em estimativas robustas e acuradas da Integral *J* utilizando espécimes SE(T) fixados por pinos e garras. Análise não lineares por meio do método de elementos finitos fornecem a variação de carga versus deslocamento definindo a área plástica e os parâmetros de separação de carga. Os estudos revelam que os fatores η baseados em LLD são mais sensíveis a efeitos de plasticidade remota do que os fatores η correspondentes baseados em CMOD. Os resultados apresentados fornecem um forte suporte à utilização de procedimentos para medição de tenacidade baseados em fatores η utilizando espécimes SE(T) fixados por garras.

Palavras-chave: Integridade estrutural; Juntas soldadas; Soldas em aços para tubulações; Tenacidade à fratura; Integral *J*.

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1 INTRODUCTION

Conventional testing standards to measure cleavage fracture resistance of structural steels, including pipeline and pressure vessel steels, most often employ three-point bend SE(B) and compact C(T) specimens containing deep, through cracks ($a/W \gtrsim 0.45\sim0.5$). However, structural defects (e.g., blunt corrosion, slag and nonmetallic inclusions, weld cracks, dents at weld seams, etc.) in pressurized piping systems are very often surface cracks that form during fabrication or during in-service operation.[1] These crack configurations generally develop low levels of crack-tip stress triaxiality which contrast sharply to conditions present in deeply cracked specimens. Recent defect assessment procedures advocate the use of geometry dependent fracture toughness values so that crack-tip constraint in the test specimen closely matches crack-tip constraint for the structural component. In particular, fracture toughness values measured using single edge notch tension (SE(T)) specimens appear more applicable for characterizing the fracture resistance of pressurized pipelines and cylindrical vessels than standard, deep notch fracture specimens under bend loading. The primary motivation to use SE(T) fracture specimens in defect assessment procedures of cracked pipes is the strong similarity in crack-tip stress and strain fields which drive the fracture process for both crack configurations.[2]

Current evaluation procedures for toughness measurements, such as the J-integral and the crack tip opening displacement (CTOD), focus primarily on developing single specimen estimation schemes which essentially relates the plastic contribution to the strain energy (i.e., the plastic work per unit uncracked ligament of the deformed cracked body) with J. Such methodologies employ a plastic η -factor introduced by Sumpter and Turner[3] to relate the macroscale crack driving force (J and CTOD) to the area under the load versus load line displacement (or crack mouth opening displacement) for cracked configurations (see also refs. [4,5]). Because of its relative ease with which the load-displacement records can be measured in conventional test specimens, the method is most suited for testing protocols measuring fracture toughness such as ASTM E1820.[6] Another related approach to determine J from load-displacement records which shares much in common with the previous outlined methodology adopts a load separation analysis proposed by Paris et al.[7] to evaluate η for conventional fracture specimens. Here, a key assumption is that load can be represented as the product of a crack geometry function (G) and a material deformation function (H) so that factor η is proportional to the crack geometry function. Sharobeam and Landes[8] employed the load separation concept to develop an experimental procedure to determine η-factors for selected crack geometries.

This study addresses the significance of the η -factor (which bears direct connection with laboratory toughness measurements) on accurate and robust estimates of the J integral for pin-loaded and clamped single edge notch tension (SE(T)) specimens using load-displacement records. Very detailed non-linear finite element analyses for plane strain models provide the evolution of load with increased load-line displacement and crack mouth opening displacement to define the applied load as a separable function dependent upon crack geometry and material deformation. The analyses reveal that η -factors based on load-line displacement (LLD) are very sensitive to plasticity changes at locations remote from the crack-tip region. In contrast, η -factors based on crack mouth opening displacement (CMOD) appear less affected by remote crack-tip plasticity. Overall, the present results

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provide a strong support to use η-based procedures in toughness measurements for clamped SE(T) fracture specimens.

2 J ESTIMATION PROCEDURE

Evaluation of the J-integral from laboratory measurements of load-displacement records is most often accomplished by considering the elastic and plastic contributions to the strain energy for a cracked body under Mode I deformation[9] as follows

$$J = Je + Jp \tag{1}$$

where the elastic component, J_e, is given by

$$Je = \frac{K_I^{\,2}}{E'} \tag{2}$$

Here, the elastic stress intensity factor, K_I, is defined for a SE(T) specimen as

$$K_I = \frac{P}{B_N \sqrt{W}} \Im(a/W) \tag{3}$$

where P is the applied load, B_N represents the net-section specimen thicknes, W is the specimen width and F(a/W) defines a nondimensional stress intensity factor dependent upon specimen geometry, crack size and loading condition (pin-loaded vs. clamped ends). For the SE(T) specimens analyzed here, Cravero and Ruggieri[2] provide analytical expressions for the nondimensional stress intensity factors F(a/W).

The plastic component, J_p , is conveniently evaluated from the plastic area under the load-displacement curve as:[10]

$$Jp = -\int_0^{\Delta p} \left(\frac{\partial P}{\partial a} \right) d\Delta p = \frac{\eta_J}{b} \int_0^{\Delta p} P d\Delta p = \frac{\eta_J A_p}{b} \tag{4}$$

where A_p is the plastic area under the load-displacement curve (which represents the plastic work, U_p), P denotes the applied load, Δ_p defines the plastic component of loadline displacement (LLD or Δ) and b is the uncracked ligament. In the above expression, factor η_J represents a nondimensional parameter which describes the effect of plastic strain energy on the applied J. Figure 1 illustrates the procedure to determine the plastic area to calculate J from a typical load-displacement curve. It should be noted 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. While factors η_J derived from each curve possess a different character they serve equally as a means to determine J_P from laboratory measurements of load-displacement records; here, these quantities are denoted η^{LLDJ} and η^{CMODJ} .

An alternative approach to evaluate the plastic component of the J-integral, J_P , from laboratory testing of conventional fracture specimens derives from the load separation method proposed by Paris et al.[8] Based upon dimensional analysis arguments, they proposed a separable form for the load, *P*, represented as the product of a crack geometry function (*G*) and a material deformation function (*H*) expressed by

$$P = G(a/W) \cdot H(\Delta p/W) \tag{5}$$

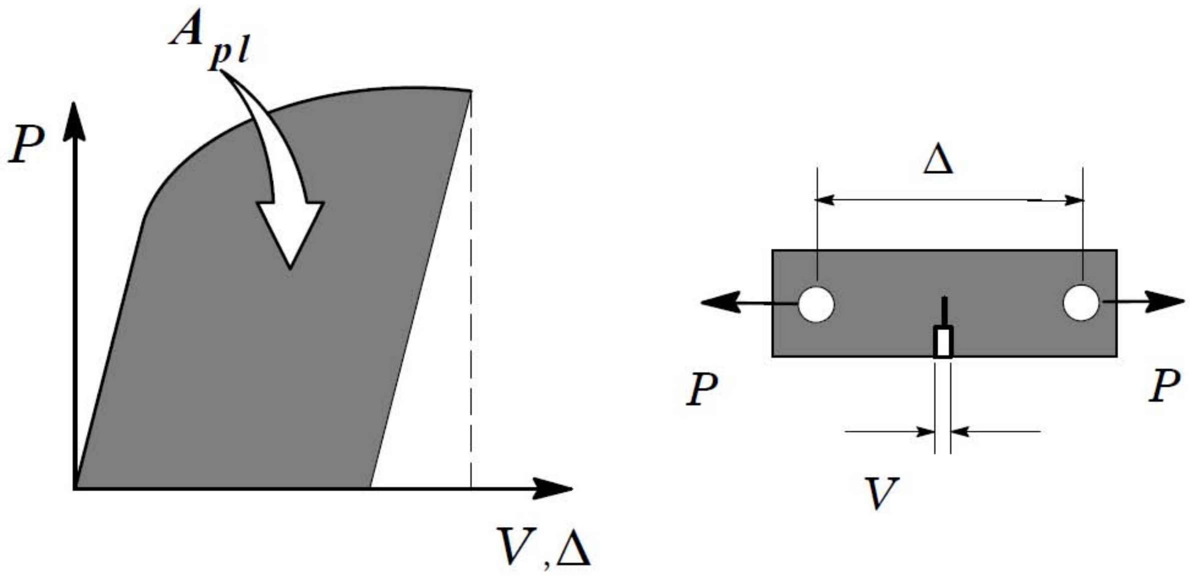

Figure 1 – Definition of the plastic area vs. load-displacement (CMOD or LLD) curve.

To arrive at a convenient procedure to evaluate factor η_J based on the load separation concept, the above Eq. (5) is used in Eq. (4) so that the integral form of J_P resolves to an alternative definition for the plastic factor η^{LLDJ} in the form

$$\eta_J^{LLD} = -\frac{(b/W)}{G(a/W)} \cdot \frac{\partial G(a/W)}{\partial (a/W)} = \frac{(b/W)}{G(b/W)} \cdot \frac{\partial G(b/W)}{\partial (b/W)} \tag{6}$$

A similar expression also applies when the specimen displacement is characterized by the CMOD. By assuming a constant relationship between the plastic components of LLD, Δ_p, and CMOD, V_p, and making use of the relationship[11]

$$\Delta p = ha \cdot Vp \tag{7}$$

where h_a is a parameter dependent on crack size and relatively independent of loading and material properties, factor η^{CMODJ} is simply expressed as

$$\eta_J^{CMOD} = \frac{(b/W)}{G(b/W)} \cdot \frac{\partial G(b/W)}{\partial (b/W)} \cdot ha(b/W) \tag{8}$$

The above resulting forms of the load separation model to evaluate factor η_J expressed by the above Eqs. (6) and (8) requires the knowledge (or, at least, a convenient choice) of the function *G* for the cracked configuration under analysis. Sharobeam and Landes[8] developed an experimental procedure to determine factor η_J for planar fracture specimens in which the crack geometry function *G* is described by a power law.

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2.1 Finite Element Procedures

Detailed finite element analyses are performed on plane-strain models for a wide range of 1-T SE(T) specimens (*B*=25.4 mm) and conventional geometry with *W*=2*B*. The analysis matrix includes specimens with *a/W*=0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and *H/W*=6. Here, *a* is the crack size specimen, *W* is the specimen width and *H* is the distance between the pin loading or clamps. The analyses also consider the effect of loading conditions, pin-loaded ends *vs.* clamped ends; these specimens are denoted as SE(T)$_P$ and SE(T)$_C$. Figure 2(b) shows the geometry and specimen dimensions for the analyzed crack configurations.

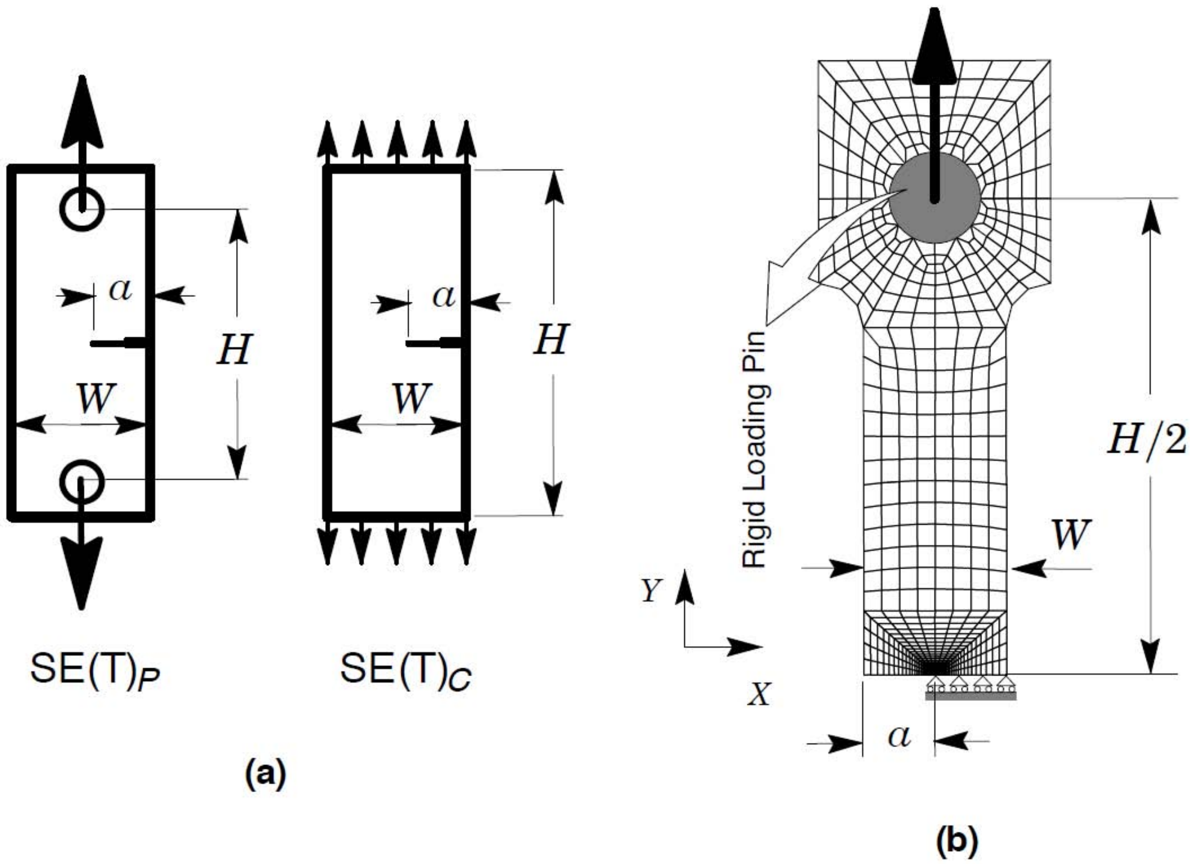

Figure 2 – a) Geometry for analyzed SE(T) fracture specimens with pin load and clamp conditions; b) Finite element model used in plane-strain analyses of the deeply cracked SE(T) specimen with a/W=0.5

Figure 2(b) shows the finite element model constructed for the plane-strain analyses of the deeply-cracked SE(T) specimen with *a/W*=0.5. All other crack models have very similar features. Symmetry conditions permit modeling of only one-half of the specimen with appropriate constraints imposed on the remaining ligament. A typical half-symmetric model has one thickness layer of 1241 8-node, 3-D elements (2678 nodes) with plane-strain constraints imposed (*w*=0) on each node. The finite element models for the pin-loaded specimens are loaded by a rigid pin at the specimen end holes to allow rotation of the specimen and to simulate contact between the loading pin and the loading hole. The numerical models for the clamped specimens are loaded by displacement increments imposed on the loading points.

The finite element code WARP3D[12] provides the numerical solutions for the plane-strain analyses reported here. Evaluation of the *J*-integral derives from a domain integral procedure[13] which yields *J*-values in excellent agreement with estimation schemes based upon η -factors for deformation plasticity [9] while, at the same time, retaining strong path independence for domains defined outside the highly strained material near the crack tip.

Evaluation of factor η requires nonlinear finite element solutions which include the effects of plastic work on J and the load-displacement response. These analyses utilize an elastic-plastic constitutive model with J_2 flow theory and conventional Mises plasticity in small geometry change (SGC) setting. The numerical solutions employ a simple power- hardening model to characterize the uniaxial true stress-logarithmic strain in the form

$$\frac{\varepsilon}{\varepsilon ys} = \frac{\sigma}{\sigma ys} \quad \varepsilon \le \varepsilon ys \; ; \; \frac{\varepsilon}{\varepsilon ys} = \left(\frac{\sigma}{\sigma ys}\right)^n \quad \varepsilon > \varepsilon ys \tag{9}$$

where σ_{ys} and ε_{ys} are the yield stress and strain, and n is the strain hardening exponent. The finite element analyses consider material flow properties representing a typical pipeline and pressure vessel grade steels with E=206 GPa, ν=0.3, σ_{ys}=460 MPa and n=8. This material was employed by Sharobeam and Landes[8] in their experimental studies using load separation analyses to determine J in conventional fracture specimens.

2.2 Load Separation in Se(T) Fracture Specimens

Paris et al. [7] and later Sharobeam and Landes[8] introduced a separation parameter, S_k , defined as a ratio of load for specimens with different crack ligament measured at a fixed value of plastic displacement, Δ_p, in the form

$$S_K = \left[\frac{P(bk)}{P(bo)}\right]_{\Delta p} \tag{10}$$

where $P(b_k)$ and $P(b_0)$ are the load for specimens with crack ligament size b_k and b_0 in which subscript "0" represents a reference specimen size. Within this approach, the load is separable (*i.e.*, it can be described in a separable form such as Eq. (5)) if the load ratio, S_k , is constant over the full range of plastic displacement.[7,8] A similar definition for the load ratio also applies when the plastic component of CMOD, represented by V_p, is used. These quantities are denoted S^{LLD}_k and S^{CMOD}_k .

This section examines the load separation behavior for the pin-load and clamped SE(T) specimens described previously. Here, evaluation of the separation parameter follows from determining the load ratio, S_k , for each specimen geometry based upon the fracture specimen with a/W=0.5 as the reference configuration (b_0=25.4 mm in the present context). Since the choice of b_0 is rather arbitrary,[7,8] the separation behavior is essentially similar for other values of b_0 as the reference specimen size.

Consider first the evolution of S^{LLD}_k with plastic load-line displacement, Δ_p, normalized by the crack ligament size, b_k , for the pin-load and clamped SE(T) specimen displayed in Figures 3(a) and 3(c). At very low deformation levels, the elastic component of load-line displacement, Δ_e, has a magnitude which is comparable with the corresponding magnitude of the plastic component, Δ_p, thereby affecting the computed S^{LLD}_k –value for all specimen geometries and loading conditions (pin-load and clamp); note, however, that since the specimen with a/W=0.5

is taken as the reference configuration, its S^{LLD}_k -value is unaffected. After this short transient, the load ratio S^{LLD}_k is essentially constant for deeply cracked specimens (a/W>0.4). For the moderate-to-shallow crack configurations (a/W<0.3), parameter S^{LLD}_k displays a little sensitivity on plastic displacement, particularly for the clamped SE(T) specimens. Now direct attention to the variation of S^{CMOD}_k with the plastic component of CMOD, V_p, normalized by the cracked ligament size, b_k , for the pin-load and clamped SE(T) specimen shown in Figures 3(b) and 3(d). While the general trends are essentially similar to the previous plots in which the load lratio is constant for deeply cracked configurations, the sensitivity of S^{CMOD}_k on V_p for shallow crack specimens is more pronounced.

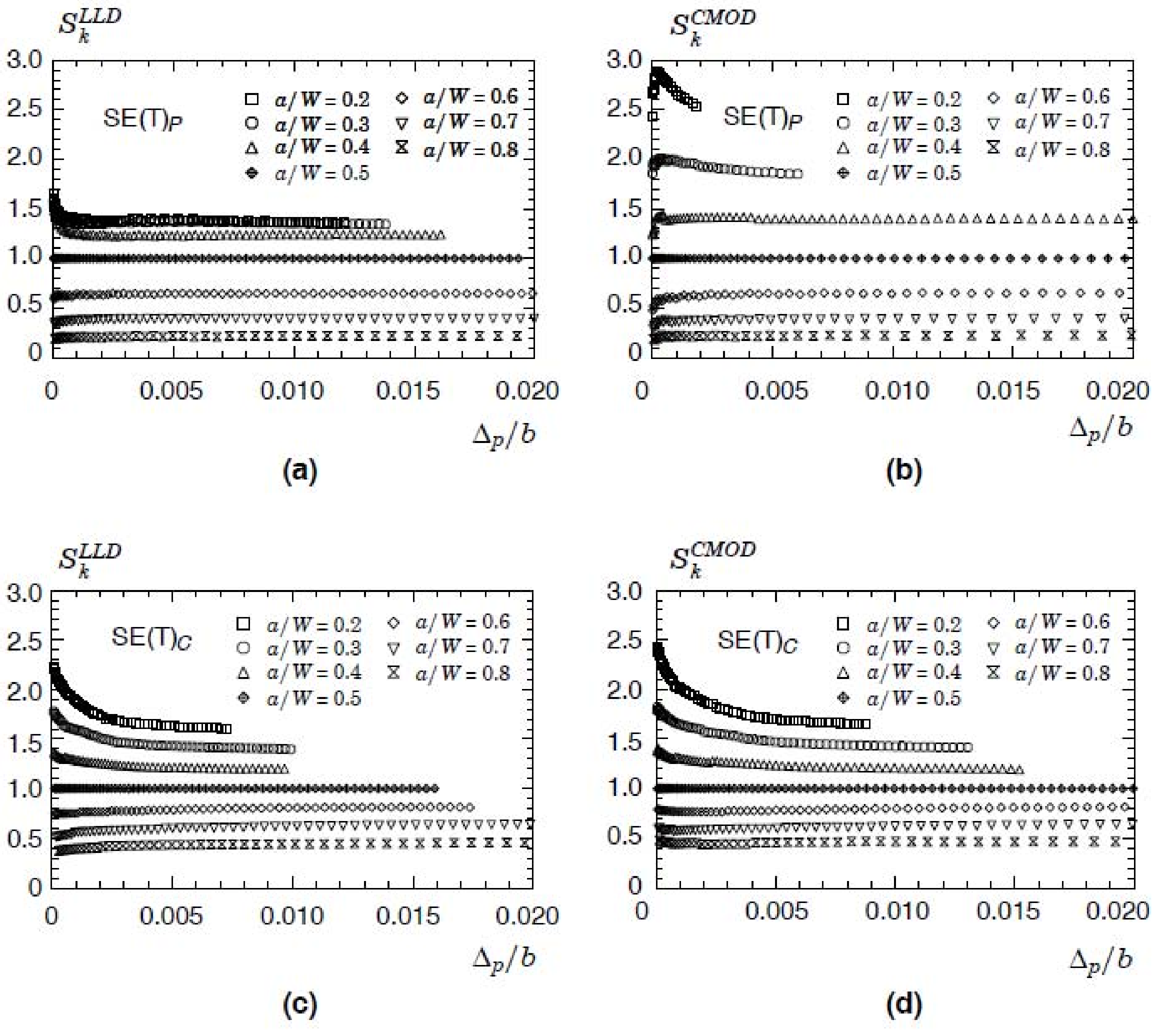

Figure 3 - Variation of load ratio, Sk, with increased plastic LLD and CMOD for the SE(T) specimens: (a,b) Pin-loaded condition; (c,d) Clamp condition.

2.3 Plastic *Eta*-Factors

The procedures outlined earlier to estimate J from load-displacement records provide the basis to evaluate the nondimensional η-factors for the analyzed SE(T) specimens with varying geometry and different loading conditions. The analyses include determining factor η based upon the plastic work defined by the plastic component of the area under the load *vs.* LLD curve or the load *vs.* CMOD curve (Figure 1) or determining the η-factor using the load separation method.

Before proceeding with the assessment of the two methodologies for evaluation of factor η, a convenient choice for the function $G(b/W)$ (and its derivative) is required so that Eq. (6) (and, equivalently, Eq. (8)) can be solved. Using the procedure proposed by Sharobeam and Landes,[8] construction of the function $G(b/W)$ follows directly from evaluating $S_k(b/W)$ for each specimen geometry and loading condition in the form $G(b/W)= \beta S_k(b/W)$ where β is a constant.

Figure 4 shows the variation of $S_k(b/W)$ with increased values of b/W-ratio (decreased values of a/W-ratio) for the pin-loaded and clamped SE(T) specimens with plastic displacements measured in terms of LLD or CMOD. To facilitate manipulation of the derivative appearing in Eqs. (6) and (8), it proves convenient to define a functional relationship for $S_k(b/W)$ by an appropriate fitting of the individual computed S_k-values. In these plots, the solid symbols are the S_k -values for each b/W-ratio whereas the lines represent the corresponding fitted curves derived from a standard least square procedure. Here, we adopt two fitting functions to describe the dependence of S_k on b/W: *i*) a power law model defined by $S_k = A(b/W)^m$ in which A and m are constants as proposed by Sharobeam and Landes[8] and *ii*) a 3-*th* order polynomial fitting. The trends are clear. The polynomial fitting provides good agreement with each computed individual S_k -value for all analyzed crack configurations and load conditions. In contrast, the power law fitting does not provide a close correspondence with the computed data set for the pin-loaded SE(T) specimen, particular for shallow crack sizes (increased b/W-ratios). However, the power law fitting curve matches quite well the variation of S_k with b/W for the clamped SE(T) specimens.

Figure 5 provides the η-factors derived from LLD and CMOD for the pin-loaded (denoted as $\eta_{LLDJ,P}$ and $\eta_{CMODJ,P}$) and clamped SE(T) specimens (referred to as $\eta_{LLDJ,C}$ and $\eta_{CMODJ,C}$) with varying a/W-ratios. These nondimensional η-values are derived from three different procedures: *i*) computation of the plastic work defined by the plastic component of the area under the load *vs.* LLD curve or the load *vs.* CMOD curve − see Fig.1 and Eq. (4); *ii*) computation of the load separation parameter, S_k , using a power law fitting (PLF) and *iii*) computation of the load separation parameter, S_k , using a 3-*th* order polynomial fitting (3PF).

Consider first the results displayed in Figures 5(a) and 5(c) for the pin-loaded specimens. The significant features include: *i*) a reasonable agreement is observed between the η-values derived from the plastic area approach and the load separation procedure using a polynomial fitting for the analyses based upon LLD records; *ii*) the η-factors derived from the plastic area method and the load separation procedure using a polynomial fitting differ largely in the shallow crack range for the analyses based upon CMOD records; however, the agreement is slight better for deeply cracked specimens; *iii*) the η-factors derived from the load separation analysis using a power law fit is independent of crack size for both LLD or CMOD-based displacement records.

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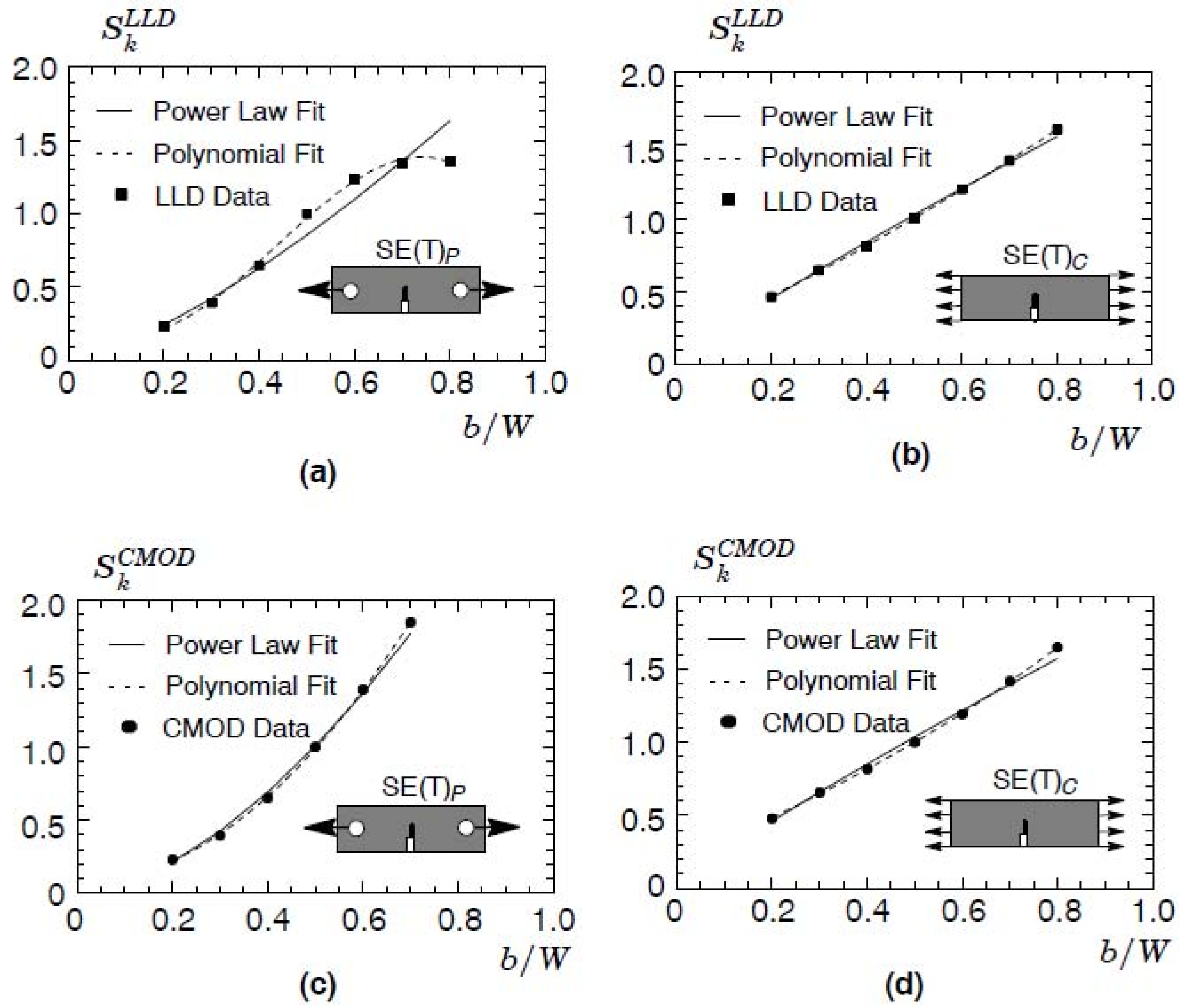

Figure 4 – Load ratio, Sk, with b/W-ratio for pin-loaded and clamped SE(T) specimens: (a,b) LLD records; (c,d) CMOD records.

Consider next the results shown in Figures 5(b) and 5(d) for the clamped specimen. A different picture now emerges. The η-factors based upon the plastic area approach agree well with the corresponding values derived from the load separation procedure using a polynomial fitting for both analyses using LLD and CMOD records. The approach based upon a power law fit to describe the the variation of S_k with b/W also produces a constant η-factor which is nevertheless reasonably close to the other η-values obtained from different procedures.

One salient feature of the previous results is the independence of factor η on crack size for any condition analyzed. As already hinted before, this is not unexpected and can be easily understood by the following argument. The assumption of a power law in the form $S_K = A(b/W)^m$ adopted by Sharobeam and Landes[8] with parameters A and m translates directly into a constant η-factor which is equal to the power law coefficient, m. Such conclusion is in stark contrast with previous work conducted by other researchers (see, *e.g.*, [2,14]) which reveal a rather strong dependence of factor η_J on crack size, particularly for moderate-to-shallow cracks (a/W<0.3).

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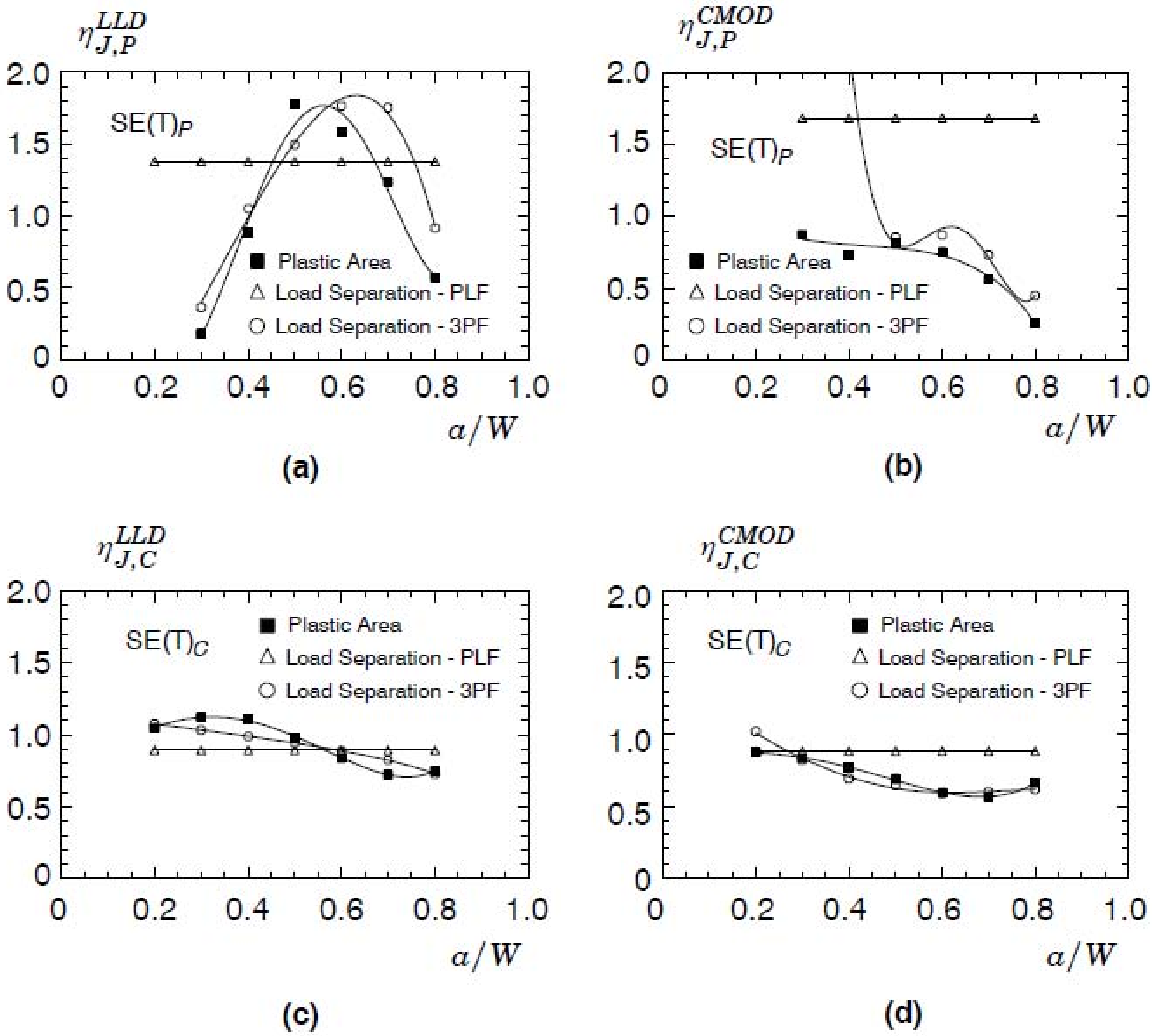

Figure 5- Variation of plastic η-factor with a/W-ratio derived from different estimation procedures for pin-loaded and clamped SE(T) specimens: (a,c) LLD records; (b,d) CMOD records.

4 CONCLUDING REMARKS

This work addresses the significance of the *η* methodology in estimation procedures applicable to determine fracture toughness parameters from laboratory measurements of load-displacement data using SE(T) fracture specimens. The analyses consider *J* estimation techniques for pin-loaded and clamped SE(T) specimens and include: *i*) estimating *J* from plastic work and *ii*) estimating *J* from load separation analysis. The study reveals that *η*-factors based on load-line displacement (LLD) are very sensitive to plasticity changes at locations remote from the crack-tip region. In contrast, *η*-factors based on crack mouth opening displacement (CMOD) appear less affected by remote crack-tip plasticity. Overall, the present results provide a strong support to use *η*-based procedures in toughness measurements for clamped SE(T) fracture specimens.

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