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FRACTURE TOUGHNESS TESTING OF A PRESSURE VESSEL STEEL USING CLAMPED SE(T) SPECIMENS AND THE NORMALIZATION METHOD

Vitor Scarabeli Barbosa

Felipe Ezsias Fiumarelli

Claudio Ruggieri

Polytechnic School of Engineering, University of São Paulo

scarabeli@usp.br; felipezsias@usp.br; claudio.ruggieri@usp.br

Abstract. *This work addresses an exploratory application of the normalization method to determine crack growth resistance curves for a typical pressure vessel steel and a clad pipe girth weld using clamped SE(T) specimens. A primary objective is to verify the effectiveness of the methodology in providing accurate descriptions of the ductile properties for the tested materials using clamped SE(T) specimens. Fracture toughness testing conducted on an A285 Gr C pressure vessel steel provides the load-displacement data from which J -resistance curves are evaluated on the basis of the normalization procedure. For the tested pressure vessel steel, the normalization method produces ductile tearing responses in terms of $J - \Delta a$ curves which are in good agreement with experimentally measured crack growth responses derived from the UC procedure.*

Keywords: *J -integral, crack growth resistance curve, clamped SE(T) specimen, normalization method*

1. INTRODUCTION

Quantitative engineering analyses of the structural response to ductile tearing associated with large plastic deformation and high intensity loads remain essential in more accurate assessments of the remaining strength capacity of metallic engineering structures containing crack-like flaws. Most high grade, high toughness structural and pressure vessel steels often undergo significant stable crack growth prior to final instability, often accompanied by large increases in fracture toughness, as conveniently characterized by the J -integral (Hutchinson, 1983; Kanninen and Popelar, 1985; Anderson, 2005), over the first few mm of stable crack extension. To include the potential strong effects of ductile tearing on toughness, conventional and advanced defect assessment procedures, such as BS 7910 (British Institution, 2013) and API 579 (American Petroleum Institute, 2016), among others, rely on the direct application of crack growth resistance ($J - \Delta a$) curves (also termed R -curves) to specify critical flaw sizes and appropriate inspection intervals for in-service structural components. A particular case of interest lies in the fail-safe operations of the infrastructure for production and transportation of oil and natural gas in more hostile environments, including very deep water offshore hydrocarbon reservoirs. Advances in existing technologies favor the use of C-Mn steel pipelines either clad or mechanically lined with corrosion resistant alloys (CRA), such as ASTM UNS N06625 Alloy 625 (American Society for Testing and Materials, 2009, 2011), for the transport of crude oil and natural gas containing corrosive contaminants, such as CO_2 and H_2S . Due to the dissimilar nature of these materials, more 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 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 the high tension stresses and strains.

Much current research now centers on the utilization of single edge notched tension, SE(T), specimens (also often termed SENT configurations) under fixed grip conditions to measure experimental crack growth resistance curves as the crack-tip stress and strain fields which drive the fracture process in this crack configuration are similar to the corresponding fields at weld circumferential flaws in pipeline girth welds. Recent and on-going work to develop testing procedures for clamped SE(T) specimens focus on the evaluation of J -resistance curves based on the unloading compliance (UC) method using a single specimen. However, while used effectively in routine fracture testing programs for ductile materials, the UC method can become highly problematic when it is not feasible to measure crack extension during the test, such as in aggressive environments or under high loading rate and high test temperatures. In an effort to simplify the crack growth resistance test procedure, an alternative test protocol, commonly known as the normalization method, for directly determining a J -resistance curve from load versus displacement records has also been employed as an effective procedure

to produce crack growth resistance curves which are equivalent to $J - \Delta a$ data derived from the UC method. However, the methodology relies heavily on accurate values of load, crack size and displacement experimentally measured at the end of test, which, in turn, can introduce large uncertainty in the resulting fitting of the normalized load-displacement curve.

This work explores the use of the normalization method to determine crack growth resistance curves for a typical pressure vessel steel. A primary objective is to verify the effectiveness of the methodology in providing accurate descriptions of the ductile properties for the tested materials using low constraint fracture specimens under predominantly tensile loading. Fracture toughness testing conducted on an A285 Gr C pressure vessel steel provides the load-displacement data from which J -resistance curves are evaluated on the basis of the normalization procedure. For the tested pressure vessel steel, the normalization method produces ductile tearing responses in terms of $J - \Delta a$ curves which are in good agreement with experimentally measured crack growth responses derived from the UC procedure.

2. EVALUATION OF $J - R$ CURVES USING THE NORMALIZATION METHOD

2.1 Overview of the Normalization Procedure to Estimate Crack Extension

Development of the normalization method to direct evaluation of J -resistance curves from load-displacement records begins with consideration of the load separation method proposed in earlier work by Ernst et al. (1979; 1981). Based upon dimensional analysis arguments, they assumed a separable form of the applied load, P , as the product of a crack geometry function, G , and a material deformation function, H , expressed by

$$P = G\left(\frac{a}{W}\right) H\left(\frac{\psi_p}{W}\right) \quad (1)$$

where a is the crack length, W is the specimen width and ψ_p represents the plastic component of displacement here defined either in terms of load line displacement (LLD or Δ) or crack mouth opening displacement (CMOD or V). The above expression can be rearranged in the form

$$\hat{P} = \frac{P}{G(a/W)} = H\left(\frac{\psi_p}{W}\right) \quad (2)$$

in which it is understood that the normalized load, \hat{P} , is solely a function of material deformation in terms of ψ_p/W .

A key feature of the above expression is the coupling between the crack geometry and material deformation functions, such that, once G and H are known, the variation of load, crack length and displacement follows a unique relationship. Thus, Eq. (2) can advantageously be employed to develop a J -resistance curve from a single test record of load vs. displacement in which crack length remains as the only unknown to be determined.

The following steps describe the normalization procedure to evaluate $J - \Delta a$ data from experimental measurements of load-displacement records as presently implemented in ASTM E1820 (American Society for Testing and Materials, 2020) and illustrated in Fig. 1(a). The method was originally developed in terms of load-line displacement (LLD) data but it is equally applicable when crack mouth opening displacement (CMOD) records are measured in the fracture resistance test. Further details of the normalization method are described in American Society for Testing and Materials (2020) and in the representative works of Zhu and co-workers (Zhu and Joyce, 2007; Zhu *et al.*, 2009b,a).

1. Each load value P_k up to, but not including the maximum load, P_{max} , is normalized using the expression

$$\hat{P}_k = \frac{P_k}{WB[(W - a_{b,k})/W]^{\eta_{j,k}}} \quad (3)$$

where W is the specimen width, B represents the specimen thickness, η_j defines a nondimensional parameter describing the effect of plastic strain energy on the applied J and $a_{b,k}$ is the blunting corrected crack length at the $k - th$ datum point given by

$$a_{b,k} = a_0 + \frac{J_k}{2\sigma_f} \quad (4)$$

in which a_0 is the initial crack size, σ_f represents the flow stress defined by $(\sigma_{ys} + \sigma_{uts})/2$, with σ_{ys} and σ_{uts} denoting the material yield stress and ultimate tensile strength, and J_k is conventionally determined in terms of the elastic and plastic components as

$$J_k = J_{e,k} + J_{p,k} = \frac{K_{I,k}^2}{E'} + J_{p,k} \quad (5)$$

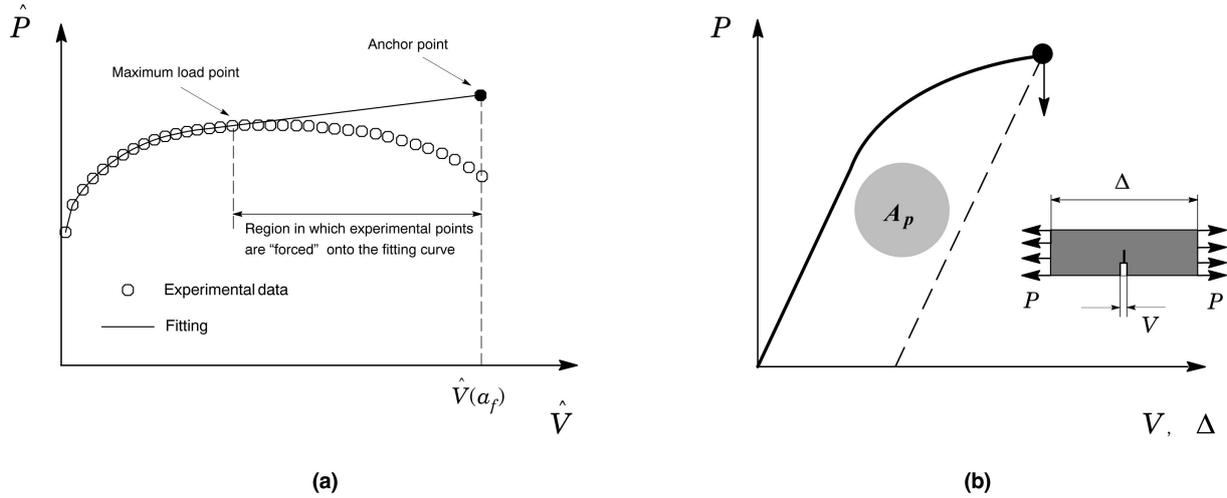


Figure 1. (a) Schematic illustration of the normalization procedure to evaluate $J - \Delta a$ data from experimental measurements of load-displacement records as presently implemented in ASTM E1820. (b) Schematic of J -evaluation procedure and definition of the plastic area under the load-displacement curve

where K_I defines the (Mode I) elastic stress intensity factor and $E' = E/(1 - \nu^2)$ with E and ν representing the (longitudinal) elastic modulus and Poisson's ratio. In the above, the plastic component of the J -integral, $J_{p, k}$, is conventionally determined using an incremental procedure given by ASTM E1820 (American Society for Testing and Materials, 2020) (see also Cravero and Ruggieri (2007a; 2007b).

- Each corresponding displacement, here defined in terms of CMOD (V), is normalized to yield a normalized plastic CMOD, \hat{V}_p , as

$$\hat{V}_{p, k} = \frac{V_{p, k}}{W} = \frac{V_k - P_k C_{CMOD, k}}{W} \quad (6)$$

where V_k is the total CMOD, $V_{p, k}$ is the plastic component of CMOD and C_{CMOD} is the specimen elastic compliance defined in terms of crack mouth opening displacement and the blunting corrected crack length.

- Since test data points after the maximum load are excluded from the fitting procedure, an end point to the curve is added by normalizing the point of maximum displacement using the final measured crack length in connection with previous Eqs. (3) to (6) - this point is often referred to as the "anchor" point (Graham, 2009) as indicated in Fig. 1(a).
- Using the normalized values of load and displacement defined by $(\hat{P}_k, \hat{V}_{p, k})$ pairs with $\hat{V}_{p, k} > 0.001$ up to, but not including the maximum load, added by the normalized end point, a normalized functional relationship between \hat{P} and \hat{V}_p is obtained by performing a nonlinear least square fitting to the normalized data in the form

$$\hat{P} = \frac{c_1 + c_2 \hat{V}_p + c_3 \hat{V}_p^2}{c_4 + \hat{V}_p} \quad (7)$$

in which c_1, c_2, c_3 and c_4 are the fitting parameters.

- Once the fitting parameters are determined, an iterative procedure to further adjust the crack length, a_k , is applied such as each point defining a $(\hat{P}_k, \hat{V}_{p, k})$ pair is forced to lie onto the fitting function expressed by Eq. (7), as indicated in Fig. 1(a). This can be accomplished by solving the nonlinear equations at each load-displacement data point given by each pair (P_k, V_k)

$$\frac{P_k}{WB [1 - a_k/W]^\eta} = \frac{c_1 + c_2 \hat{V}_p(a_k) + c_3 \hat{V}_p^2(a_k)}{c_4 + \hat{V}_p(a_k)} \quad \hat{V}_p(a_k) = \frac{V_k - P_k C_{CMOD, k}(a_k)}{W} \quad (8)$$

- Now, with the current crack length, a_k , thus determined, the amount of crack extension is simply obtained as $\Delta a_k = a_k - a_0$.

2.2 Evaluation of the J -Integral

Once the amount of crack extension is determined at each load-displacement data point, evaluation of the crack driving force, as characterized by the J -integral, proceeds using a conventional incremental procedure - see ASTM E1820 (American Society for Testing and Materials, 2020), Joyce (1996), Cravero and Ruggieri (2007a; 2007b), Zhu and Joyce (2012), Zhu (2014), Ruggieri (2017) and references therein for further details on the evaluation method for obtaining crack growth resistance curves. The methodology updates J in terms of its elastic component, J_e , and plastic component, J_p , at each k -th data point during the measurement of the load vs. displacement curve as

$$J_k = J_{e,k} + J_{p,k} \quad (9)$$

where the current elastic term is given by

$$J_{e,k} = \left(\frac{K_I^2}{E'} \right)_k \quad (10)$$

in which K_I is the elastic stress intensity factor for the cracked configuration at the k -th data point and $E' = E/(1 - \nu^2)$, where E and ν are the (longitudinal) elastic modulus and Poisson's ratio, respectively. For the SE(T) geometries discussed here, solutions for K_I can be found in Cravero and Ruggieri (2007a), Shen et al (2009) and BS 8571 (British Institution, 2018).

Now, directing attention to the evaluation of the plastic term, J_p^k , early methods to measure J -resistance curves adopted an incremental equation to estimate J_p based entirely on load-load line displacement (LLD) records which derives from the fundamental work of Ernst et al. (1981). However, when the crack growth response is measured in terms of load-crack mouth opening displacement (CMOD) records, Cravero and Ruggieri (2007b) and Zhu et al. (2008) introduced an incremental formulation to determine J_p to correct the measured load-displacement records for crack extension (see Anderson (2005), Kanninen and Popelar (1985) and Cravero and Ruggieri (2007b) in the form

$$J_p^k = \left[J_p^{k-1} + \frac{\eta_{CMOD}^{k-1}}{b_{k-1} B_N} (A_p^k - A_p^{k-1}) \right] \cdot \Gamma_k \quad (11)$$

with Γ_k defined by

$$\Gamma_k = \left[1 - \frac{\gamma_{LLD}^{k-1}}{b_{k-1}} (a_k - a_{k-1}) \right] \quad (12)$$

where factor γ_{LLD} is evaluated from

$$\gamma_{LLD} = \left[-1 + \eta_{LLD}^{k-1} - \left(\frac{b_{k-1}}{W \eta_{LLD}^{k-1}} \frac{d\eta_{LLD}^{k-1}}{d(a/W)} \right) \right] \quad , \quad (13)$$

where it is noted that A_p represents the plastic area under the load-displacement curve as illustrated in Fig. 1(b), B_N is the net specimen thickness at the side groove roots ($B_N = B$ if the specimen has no side grooves where B is the specimen gross thickness), a is the crack length, b denotes the uncracked ligament ($b = W - a$ where W is the width of the cracked configuration and a is the crack length).

In the above, the nondimensional parameters η_{CMOD} and η_{LLD} relate the plastic contribution to the strain energy for the cracked body with J in terms of load-crack mouth opening displacement (CMOD or V) data or load-load line displacement (LLD or Δ) data. For the clamped SE(T) specimens under consideration, Mathias et al. (2013) provide expressions to define η_{CMOD} and η_{LLD} derived from CMOD records in the form

$$\eta_{J-CMOD}^{SET} = 1.067 - 1.767 \frac{a}{W} + 7.808 \left(\frac{a}{W} \right)^2 - 18.269 \left(\frac{a}{W} \right)^3 + 15.295 \left(\frac{a}{W} \right)^4 - 3.083 \left(\frac{a}{W} \right)^5 \quad (14)$$

$$\eta_{J-LLD}^{SET} = -0.623 + 9.336 \frac{a}{W} - 4.584 \left(\frac{a}{W} \right)^2 - 47.963 \left(\frac{a}{W} \right)^3 + 87.697 \left(\frac{a}{W} \right)^4 - 44.875 \left(\frac{a}{W} \right)^5 \quad , \quad (15)$$

which are valid in the range $0.2 \leq a/W \leq 0.7$.

3. EXPERIMENTAL DETAILS

3.1 Material Description

The material utilized in the fracture resistance tests described next is a typical ASTM A285 Grade C (American Society for Testing and Materials, 2017) pressure vessel steel. Mechanical tensile tests (American Society for Testing

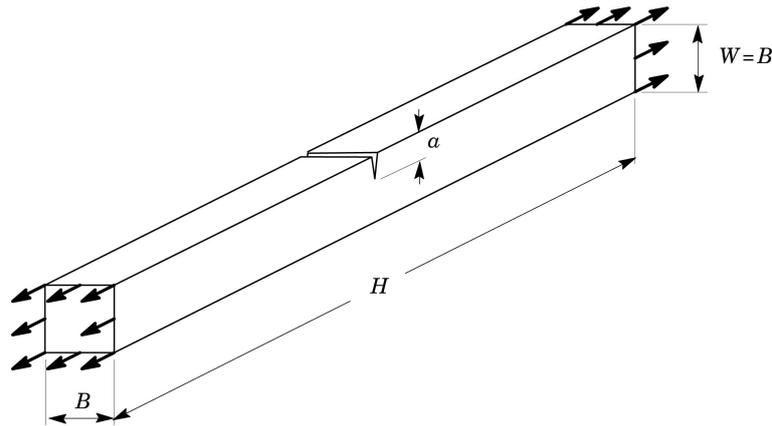


Figure 2. Geometry of tested clamped SE(T) specimens having $H/W = 10$ and $B \times B$ configuration with $a/W = 0.3$ and $a/W = 0.4$.

and Materials, 2016) performed on standard tensile specimens with 12.5 mm diameter extracted from the transverse plate direction at mid-thickness location provide the yield stress, $\sigma_{ys} = 230$ MPa, and tensile strength, $\sigma_{uts} = 446$ MPa, at room temperature ($T = 20^\circ\text{C}$). Based on Annex F of API 579 (American Petroleum Institute, 2007), the estimated Ramberg-Osgood strain hardening exponent for the tested steel is 5.3 ($\sigma_{uts}/\sigma_{ys} \approx 2$), which clearly indicates the high hardening behavior of the tested steel. Other mechanical properties for this steel include Poisson's ratio, $\nu = 0.3$ and Young's modulus, $E = 204$ GPa.

3.2 Specimen Geometries

Fracture resistance tests at room temperature using both the normalization method (NM) and the unloading compliance (UC) technique were performed on single edge-notched specimens, SE(T), with fixed-grip loading to measure tearing resistance curves in terms of $J - \Delta a$ data. The clamped SE(T) specimens illustrated in Fig. 2(a) have a fixed overall geometry and crack length, a , to specimen width, W , ratio defined by $a/W = 0.3$ with specimen thickness $B = 15$ mm, width $W = 15$ mm and clamp distance $H = 150$ mm ($H/W = 10$). An additional fracture specimen with same overall dimensions but $a/W = 0.4$ was also tested to provide another J -resistance curve against which ductile tearing behavior for the crack configuration with $a/W = 0.3$ can be compared.

All SE(T) fracture specimens were precracked in bending according to conventional techniques recommended in ASTM E1820 American Society for Testing and Materials (2020) and 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 with a 0.5 mm side-groove root radius) to promote uniform crack growth and tested following some general guidelines described in ASTM E1820 standard (2020). Records of load vs. crack mouth opening displacements (CMOD) were obtained from the specimens using a clip gauge mounted on knife edges attached to the specimen surface.

4. J-RESISTANCE RESULTS

4.1 $J - R$ Curves

The testing program described for the A285 steel considers two nominally identical specimens with $a/W = 0.3$ (refer to Fig. 2), but each one employed to produce a distinct J -resistance curve following different methods, namely, the UC procedure and the normalization method previously outlined. These test specimens are denoted PVS1-UC and PVS2-NM, respectively. Here, we observe that the specimen PVS2-NM was loaded up to a CMOD value of approximately 2 mm to obtain a better nonlinear fitting of normalized load vs. normalized plastic displacement. A third fracture specimen with nominally identical overall dimensions but with $a/W = 0.4$ was tested to measure an additional $J - \Delta a$ data based on the UC method - this specimen is denoted PVS3-UC. Figure 3 shows the load-crack mouth opening displacement (CMOD) curves for specimens PVS1-UC and PVS2-NM, in which the unloading-reloading steps are evident in the plot. Figure 4 displays the normalized load, \hat{P} , with increased normalized plastic CMOD, \hat{V}_p , for specimen PVS2-NM, in which the solid symbols represent the experimental data points defined from the procedure previously outlined. Here, the final crack length measurement is given in Table 1 next. The plot also includes the fitted curve described by Eq. (7) and the corresponding fitting coefficients, c_k , where it can be seen an excellent agreement between the fitted curve and experimental data points.

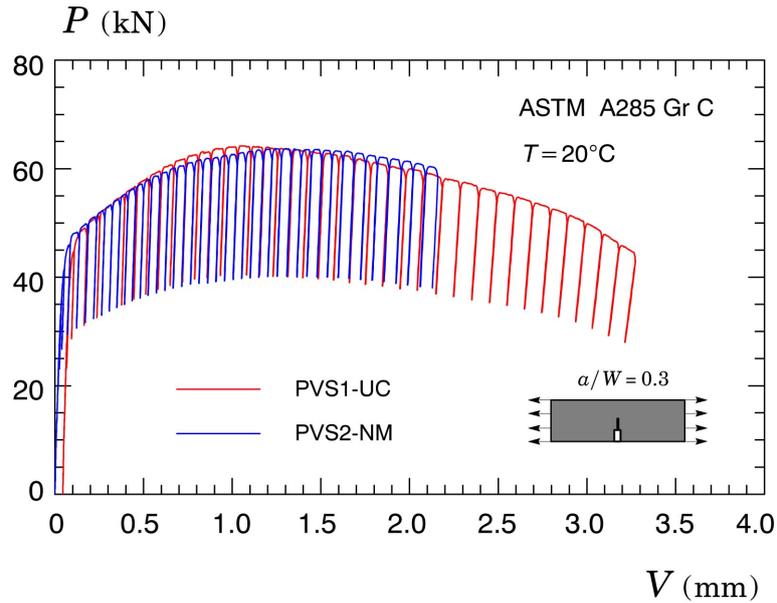


Figure 3. Measured load-CMOD curve for the A285 steel using clamped SE(T) specimens with $a/W = 0.3$.

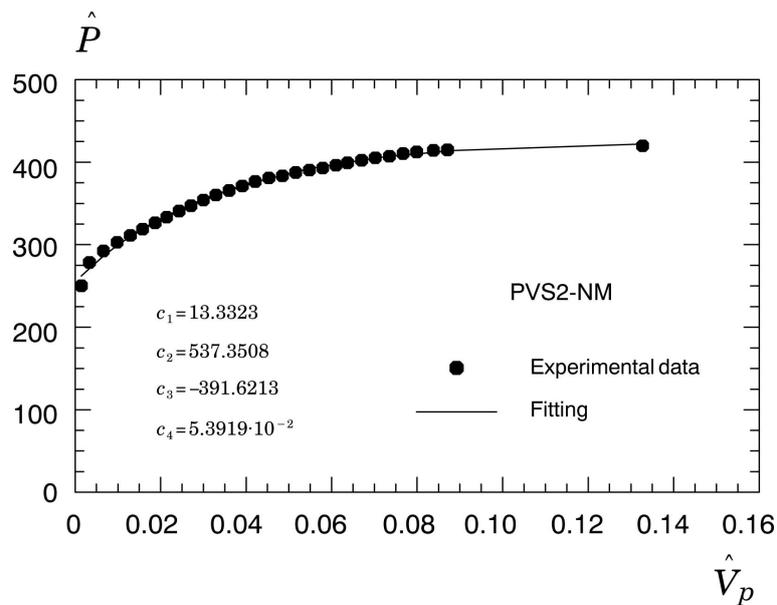


Figure 4. Normalized load, \hat{P} , with increased normalized plastic CMOD, \hat{V}_p , for specimen PVS2-NM.

Figure 5 shows the measured resistance curves for the tested crack configurations obtained from the UC procedure (specimens PVS1-UC and PVS3-UC represented by open symbols) and the normalization method (specimen PVS2-NM represented by solid symbol). Consider first the measured crack growth response based on the UC procedure. It is clear that the $J - R$ curves for the specimen configurations with $a/W = 0.3$ and $a/W = 0.4$ are virtually unchanged and can thus be regarded as independent of crack size, at least for this a/W -range. Now direct attention to the $J - \Delta a$ data for specimen PVS2-NM based on the normalization method. The agreement with the measured resistance curves derived from the UC procedure is remarkably close, indicating that the crack growth resistance properties and, thus, the fracture behavior are fully described by the normalization method in the range of $\Delta a \approx 2$ mm.

4.2 Crack Length Measurements

The accurate measurement of crack extension, particularly the final crack length, represents a key procedure in the normalization method. For all tested fracture specimens, evaluation of the physical crack extension follows the widely adopted 9-point average technique given by ASTM E1820 (2020). To mark the area of ductile crack extension at the end of the test, the area of the slow crack growth was identified by a conventional heat-tinting procedure for 20 minutes at

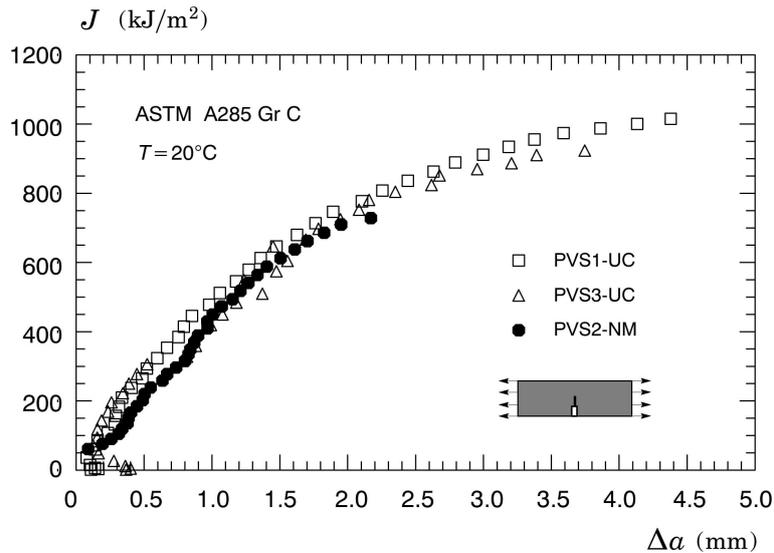


Figure 5. Measured resistance curves for the A285 steel obtained from the UC procedure and the normalization method.

$\approx 300^{\circ}\text{C}$ followed by breaking open the specimen after it is immersed in liquid nitrogen to produce cleavage fracture of the remaining specimen ligament. Then, the exposed crack front is thoroughly observed and measured by using a high resolution image of the fracture surface.

Figure 6 shows the crack surface for the specimen PVS2-NM, in which the optical crack front profile allows measuring ductile crack extension according to the 9-point procedure given by ASTM E1820 American Society for Testing and Materials (2020). This figure indicates key regions of the crack surface as follow: 1) the EDM notch; 2) the fatigue precrack front and 3) the final crack front. Both crack fronts of interest exhibit a somewhat irregular shape and a relatively small amount of crack front tunneling. Despite equipping the specimen with side-grooves, these features are relatively common in fracture resistance testing of tensile crack configurations extracted from welded joints.

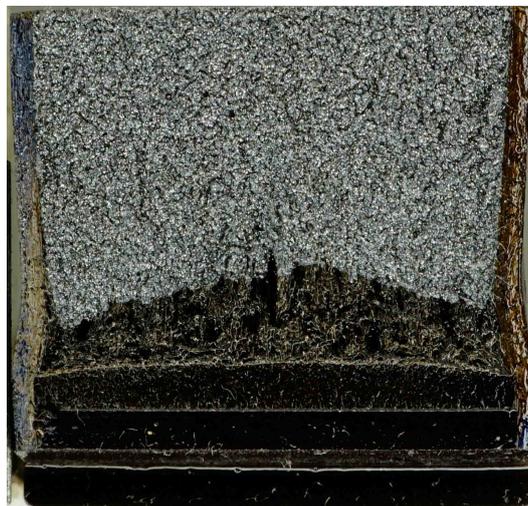


Figure 6. Crack surface for the specimen PVS2-NM indicating the fatigue precrack and the final crack fronts associated employed to measure ductile crack extension

Table 1 provides the initial and final crack length measured after the test by means of an optical method, including the measured and estimated crack extension for each tested specimen. By defining the deviation between the measured and estimated values of crack extension as $\Lambda = (\Delta a_{measured} - \Delta a_{estimated}) / \Delta a_{measured}$, it can be seen that predictions of the amount of ductile tearing based on the UC procedure underestimate the 9-point average crack extension by $\sim 20\%$. By contrast, predictions of crack extension derived from the normalization method are in much better agreement with experimental measurements - here, the level of accuracy is in the range of $\sim 5\%$. Table 1 also shows the ductile crack extension relative to the remaining crack ligament, $\Delta a/b_0$, in which $b_0 = W - a_0$. Observe that the amount of crack growth is $\sim 50\%$ of b_0 for specimens PVS1-UC and PVS3-UC, whereas is $\sim 19\%$ for specimen PVS2-NM.

Table 1. Crack lengths measured after the test by means of an optical method, including the measured and estimated crack extension for each tested specimen.

Material	Specimen	a_0 (mm)	a_0/W	a_f (mm)	Δa_{exp} (mm)	$\Delta a_{exp} / b_0$	Δa_{pred} (mm)	Λ (%)
A285 Gr C	PVS1-UC	4.39	0.29	9.95	5.56	0.52	4.38	21.2
	PSV2-NM	4.19	0.28	6.27	2.08	0.19	2.17	4.3
	PSV3-UC	5.77	0.38	10.38	4.61	0.50	3.75	18.7

5. CONCLUDING REMARKS

This study describes an exploratory application of the normalization method to evaluate J -resistance curves for a typical A285 pressure vessel steel using clamped SE(T) specimens and experimentally measured load-CMOD records. Fracture resistance curves for tested material were also evaluated from employing the unloading compliance procedure, which thus serve as baseline reference $J - \Delta a$ data against which the normalization method can be compared. The experimental investigation described in this work supports the following conclusions:

1. The normalization method is a relatively simple test procedure which can represent an effective alternative to the unloading compliance procedure in fracture resistance testing using clamped SE(T).
2. While the clamped SE(T) specimen is still a fracture specimen not widely standardized, the normalization method, as described in ASTM E1820 (2020), is equally applicable in obtaining valid $J - R$ curves provided an accurate set of plastic η -factors is available.
3. The fitted plasticity function, particularly in the region between the point of maximum load and the anchor point may potentially markedly affect the J -resistance curve obtained by the normalization method. Specifically, careful attention should be given to obtain accurate measurements of ductile crack extension as this measure is key to define the anchor point.

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