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J. Wainstein[1] and J. E. Perez Ipiña[2]

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Reference

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[1] Dpto. Mecánica, UNPatagonia SJB-CONICET, Ruta Prov.1 km 4, Comodoro Rivadavia, 9000 Chubut, Argentina

[2] GMF-LPM, UNComa-CONICET, Buenos Aires 1400, Neuquén 8300, Argentina (Corresponding author), e-mail: jwainste@ing.unp.edu.ar

ABSTRACT

The S_{pb} method estimates stable crack growth in fracture mechanics precracked specimens test. It compares the load ratio between a precracked specimen that exhibits stable crack growth and a blunt-notched specimen with apparent constant crack length when tested at constant displacement. When it was applied to very tough material, it was found that blunt-notched remaining ligaments varied by as much as 11.83 %, affecting visibly the results. Therefore, to apply the S_{pb} method to very tough material for which non-standard specimens could be used as coiled tubing, the methodology limits are investigated. In this work, particularly the effect of geometry changes through an incipient crack growth produced on the blunt-notched specimens for very tough materials is analyzed. Hence, a modified S_{pb} method is presented that takes into account the change in geometry of the blunt-notched specimens. Results provided in this paper are quite encouraging.

Keywords

J-integral, separability property, S_{pb} parameter, crack-length estimation, geometric variations

Nomenclature

a = crack length
a_0 = initial crack length
a_b = blunt-notched crack length
a_f = final crack length
a_p = precracked crack length
b = remaining ligament
b_b = blunt-notched remaining ligament
b_{b0} = blunt-notched initial remaining ligament
b_{bf} = blunt-notched final remaining ligament
b_p = precracked remaining ligament
b_{p0} = precracked initial remaining ligament
b_{pf} = precracked final remaining ligament
B = thickness
B_N = net thickness with side grooves
CC(T) = center cracked panel tension
C_i = compliance
C(T) = compact tension specimen
E = Young's modulus
G = geometry function
H = deformation function
J = J integral
J_{IC} = J value at crack-growth initiation
m = exponent S_{pb} method equation
P = applied load
P_b = blunt-notched applied load
P_p = precracked applied load
S = span
SE(B) = single edge notched bend specimen
SE(T) = single edge notched tension specimen
S_{pb} = separability parameter
UC = unloading compliance
v = displacement
v_{pl} = plastic component of displacement
W = width
η_{pl} = etha plastic factor
ν_m = crack opening displacement at notch mouth
σ_{ys} = yield strength

Introduction

Fracture toughness of ductile materials is often characterized by the *J*-integral concept [1–3] proposed by Rice [4]. The determination of characteristic values is generally performed through the construction of the resistance curve of the material (*J-R* curve). Stable crack growth has to be estimated for this purpose and different alternatives are available. The first method used was the multiple specimen technique developed by Begley and Landes [5] in which several identical specimens are loaded to obtain different amounts of crack growth. The crack lengths are then physically measured on the fracture surfaces after the specimens have been broken. This method is not always a practical one because large amounts of material and time are required for specimen preparation and testing. For this reason, considerable efforts were devoted to develop methods consuming less time and material as in ASTM E1820-08 [6–9]. The most common single specimen testing methodologies applied in the field of metals are the elastic-compliance and the electrical potential drop techniques. They require special equipment for on-line measurement of crack extension, are more difficult to implement and present limitations when applied to some materials or conditions [10–12].

The normalization method is another alternative that was first applied to metals [9,13,14]. This method is based on the load separation property developed by Ernst et al. [3], which allows to express the load as two multiplicative functions, the geometry $G(b/W)$ and the deformation $H(\nu_{pl}/W)$ functions. Normalization method requires the assumption of a geometry function and the determination of the deformation function $H(\mathrm{v}_{pl}/W)$, which is a relationship between normalized load and normalized plastic displacement with a given functional form. In this way, a normalized calibration curve, P_N versus ν_{pl}/W is obtained for each tested specimen. The deformation function depends on flow strength, hardening characteristics and other materials features, i.e., it is material dependent.

Another single specimen method, S_{pb}, has been developed [15] and successfully applied to fracture toughness of metals and polymers characterization [16–18], including high load rate conditions [19]. This concept was originally proposed for several other related applications: to determine the η_{pl} factor in pre-cracked specimens, to set up the limits of validity in load separation and to determine the stable crack-growth initiation parameter, J_{IC}, without the need of building the *J-R* curve [10,20–22].

The S_{pb} method, as normalization, is based on the existence of the load separation proposed by Ernst et al. [3].

$$P = G\left(\frac{b}{W}\right) \times H\left(\frac{\nu_{p_l}}{W}\right) \tag{1}$$

The S_{pb} parameter [13] is defined as the load ratio between two specimens at constant displacement, a precracked one that exhibits crack growth during its test and a blunt-notched specimen with constant crack length when tested.

$$S_{pb} = \left.\frac{P_p(b_p, \nu_{pl})}{P_b(b_b, \nu_{pl})}\right|_{\nu_{pl}} = \left.\frac{G_p\left(\frac{b_p}{W}\right) \cdot H\left(\frac{\nu_{pl}}{W}\right)}{G_b\left(\frac{b_b}{W}\right) \cdot H\left(\frac{\nu_{pl}}{W}\right)}\right|_{\nu_{pl}} \tag{2}$$

Sharobeam and Landes [13] studied the load separability property in several precracked specimen geometries (C(T), SE(B), CC(T), and SE(T)), as well as in different materials. For situations when the geometry function, $G(a/W)$, can be fitted by a potential function

$$G\left(\frac{b}{W}\right) = \left(\frac{b}{W}\right)^m \tag{3}$$

they proved that the S_{pb} parameter adopts the following expression:

$$S_{pb} = \left.\frac{P_P}{P_b}\right|_{\nu_{Pl}} = \left(\frac{b_p}{b_b}\right)^m \tag{4}$$

then

$$a_p = W - b_p = W - b_b\left(S_{pb}\right)^{1/m} \tag{5}$$

where:

$m = \eta_{pl}$ [13].

Even if both normalization and S_{pb} may appear as very similar options, the S_{pb} method has the appealing advantage of only requiring the assumption of one hypothesis, i.e., a geometry function, which is indeed well known for several configurations [15,16]. It is also a simple method that uses only two specimens to determine the *J-R* resistance curve of a material. It does not need supplementary devices to estimate crack growth during the fracture test. It only compares the load record of a precracked and a blunt-notched specimens.

It has been already used for standard and non-standard specimens. Following, we detail different cases where it was used. Wainstein et al. [19] used for dynamic conditions where the final crack length is not available. Wilson and Mani [23] used to determine the plastic work factor (η_{pl}) for the double edge notch tension (DENT) geometry for power-law hardening materials. An integrity assessment of thin-walled tubular components, was made using S_{pb} method by Samal and Sanyal [24]. The fracture resistance behavior of these tubes cannot be evaluated using standard ASTM techniques. It is because of the inability of these axially cracked specimens to meet the stringent plane strain requirement as a result of their geometry and the high ductility of the zirconium alloy used for their fabrication. Moreover, the measurement of crack growth during the testing by conventional methods is a cumbersome process and sometimes it is not possible to use them because of the small size of these specimens. Alternative methods such as the load-separation technique are suitable for these types of situations. Bao and Cai [25] modified the load separation parameter S_{pb} method to eliminate the effect of the reference blunt cracked specimen on *J*-resistance determination. On the other hand, Likeb et al. [26] used S_{pb} method to develop the load separation for new pipe-ring notched bend specimens. An approach for determining the plastic load line displacement (η_{pl} LLD) and the plastic crack mouth opening displacement (η_{pl} CMOD) correction factors for pipe-ring notched bend specimens was made. The estimated plastic factors are possible to use in estimation approach based on load versus displacement test. The η_{pl} factors could be applied for fracture toughness testing of pipeline materials when standard specimens cannot be applied. The effect of the notch tip radius on the η_{pl} factors was analyzed. Matvienko and Muravin [27] used the load-separation concept to determine the mixed mode plastic η_{pl} and COD η_{pl} factors for the tension plate with an inclined center through thickness crack for power law hardening materials. Kim et al. [28] also employed the load separation method to measure the η_{pl}-factor, the growing crack length and the applied *J*-integral during the course of the test of small curved CT specimen of Z-2.5 Nb pressure tube material. The effect of the notch tip radius of the notched (reference) CT specimen on the separation parameter was analyzed to predict the crack growing length in the precracked specimen.

None of the cited examples of S_{pb} method uses analyzes the effect of geometry changes through an incipient crack growth produced on the blunt-notched specimens for very tough materials during the fracture tests.

Therefore to apply the S_{pb} method to very tough material for which non-standard specimens could be used [29], the methodology limits are being studied by the authors. Specially, the effect of blunt-notched geometry changes on stable crack-growth estimation in high-fracture-toughness steels. Two steels with different *R*-curve behaviors were tested. One was a very-high-crack-growth-resistance material that did not show a significant load drop during tests. The other one was a high-crack-growth-resistance material that displayed a conventional load drop after maximum load. Crack-growth estimations were compared with those obtained by applying the unloading compliance method—used as reference method—and fracture surface measurements.

A methodology to take into account the geometry changes in blunt-notched specimens is proposed together with a new formulation of the S_{pb} method to estimate crack growth using this blunt-notched geometry changes.

Materials and Methods

Tests were carried out on two micro-alloyed steels used for piping, called in this paper material B and material C [1], **Table 1** shows some mechanical properties of the tested materials. Three-point single edge notch specimens SE(B) were cut out from each material, with $B/W = 0.55$ and $S/W = 4$. Precracked

TABLE 1 Materials mechanical properties.

Material	σ_{ys} (MPa)	σ_{uts} (MPa)	Elongation (%)
B	544	559	13
C	473	547	18

TABLE 2 Specimens configurations.

	Precracked (PC)				Blunt Notched (BN)			
Material	Specimen	B (mm)	W (mm)	a_o (mm)	Specimen	B (mm)	W (mm)	a_o (mm)
B	BS1	10.1	20.1	9.60	BBN1	10.1	20.1	15.7
	BS2	10.1	20.1	9.43	BBN1j	10.1	20.17	15.03
	BS3	10.1	20.1	9.50	BBN2j	10.1	20.18	12.1
C	CS1	13.7	27.3	13.3	CBN1	13.7	27.3	20.0
	CS2	13.7	27.3	13.4	CBN1j	13.7	27.6	20.6
	CS3	13.7	27.4	13.3	CBN2j	13.7	27.5	16.5

(PC) and blunt-notched (BN) specimens were prepared. **Table 2** shows the specimen matrix.

Fracture toughness tests were carried out in precracked specimens of both materials. Load, load line, and crack mouth displacements were recorded (**Fig. 1**).

During the fracture tests, multiple unload–reload cycles were made to apply the unloading compliance method. Once each test was completed, the slopes of every unload–reload event were determined, which are in every case the specimen compliance at that displacement. The crack lengths were calculated for all the obtained compliances by means of the relationship given by the standard for three point-bending specimens [6]:

$$\left(\frac{ai}{W}\right) = [0.999748 - 3.9504u + 2.9821u^2 - 3.21408u^3 + 51.51564u^4 - 113.031u^5] \tag{6}$$

with

$$u = \frac{1}{\left[\frac{B_e W E C_i}{S/4}\right]^{1/2} + 1}$$

FIG. 1 Fracture toughness test for a precracked specimen, material B.

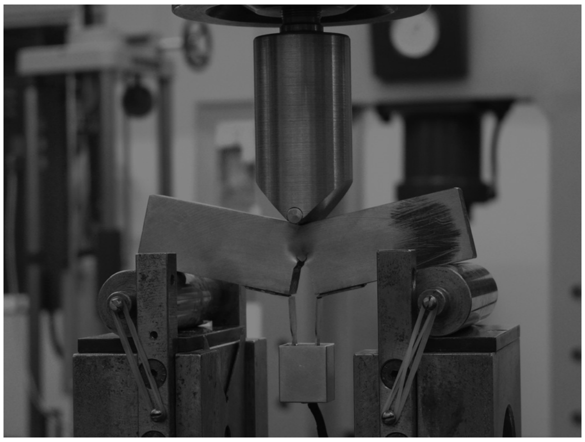
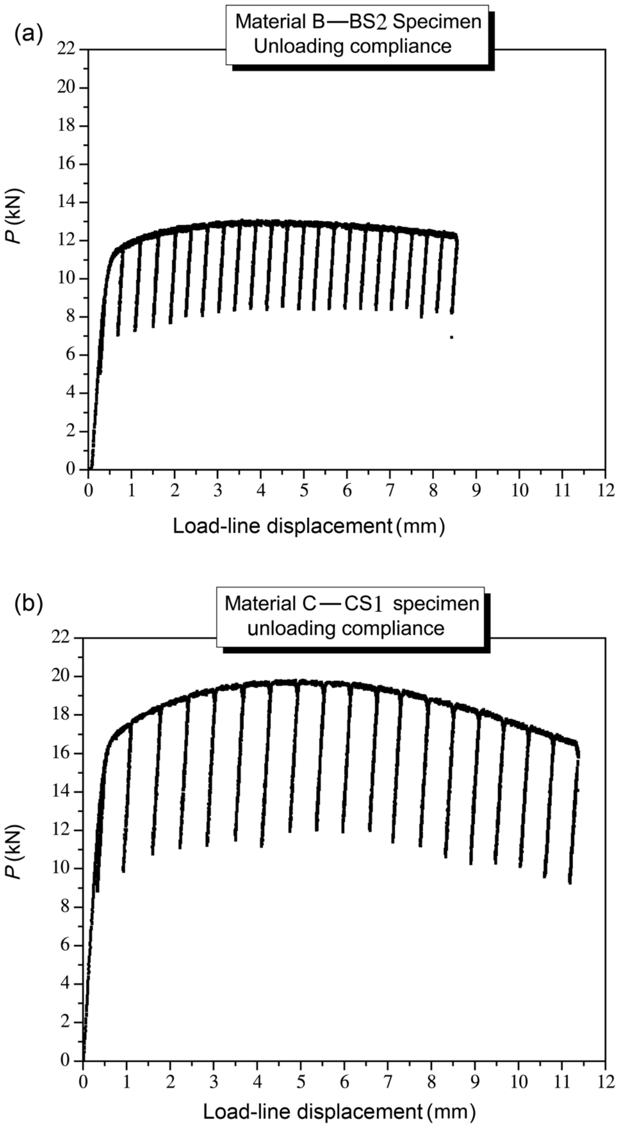


FIG. 2 Load versus load line displacement records with load–reload sequences: (a) material B-BS2 specimen and (b) material C-CS1 specimen.



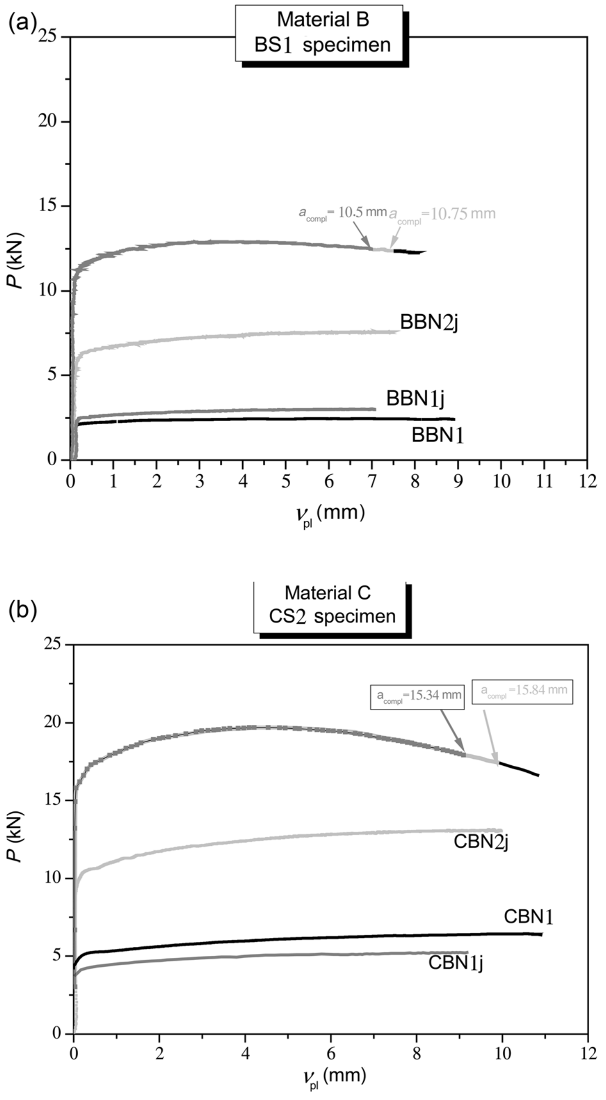
$C_i = (\Delta\nu_m/\Delta P)$ on an unloading–reloading sequence, and

ν_m = crack opening displacement at notched edge, $B_e = B - (B - B_N)^2/B$.

The stable crack growth for an unload–reload event corresponds to the difference between actual and initial crack lengths. Measurements of initial and final crack length on the fracture surfaces were used also as references. Load versus load line displacement records, used to apply the S_{pb} method, were "cleaned up" taking out the unload–reload events.

Three blunt-notched specimens were tested for each material. Different a/W ratios were used to analyze the influence of blunt-notched a/W on the S_{pb} crack-length estimations. Blunt-notched geometrical changes were measured after testing, especially the remaining ligament.

FIG. 3 Load versus plastic load line displacement: (a) material B and (b) material C.



Results and Discussion

ANALYSIS OF BLUNT-NOTCHED GEOMETRY VARIATION

Fig. 2 shows load versus load line displacement records of two precracked specimens, corresponding to each material, with their unload–reload cycles.

Fig. 3 shows the resulting load versus plastic load-line displacement records corresponding to a precracked specimen (after cleaning it up) and three blunt-notched specimens for each material.

These figures also show that blunt-notched specimens CBN1j, BBN1j, CBN2j, and BBN2j did not reach the final plastic displacement that the precracked one reached. After the first blunt-notched test, it was noted that the specimen presented some stable crack growth. Hence, blunt-notched tests were

FIG. 4 S_{pb} versus v_{pl}: (a) BS3 specimen and (b) CS1 specimen.

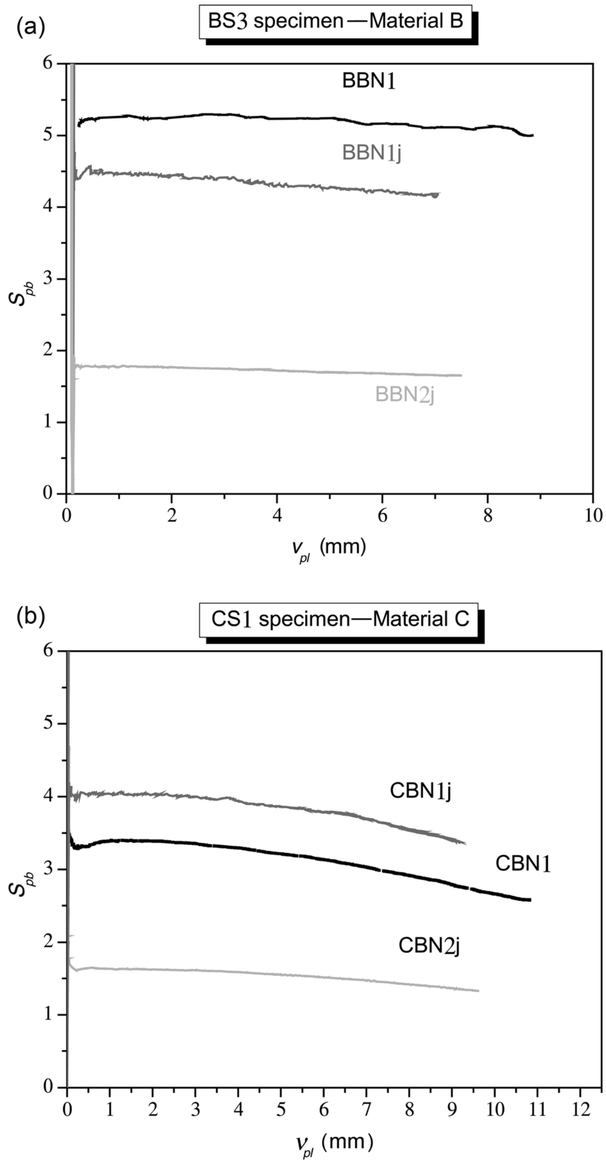


TABLE 3 Estimated crack growth obtained by S_{pb} method and unloading compliance.

Material	Spec	Δa (S_{pb})	Δa (UC)	Δa Estimation Differences (%)	Δa (S_{pb})	Δa (UC)	Δa Estimation Differences (%)	Δa (S_{pb})	Δa (UC)	Δa Estimation Differences (%)
		BBN1 ($a/W = 0.78$)			BBN1j ($a/W = 0.74$)			BBN2j ($a/W = 0.59$)		
B	BS1	0.38	1.27	−70.0	0.55	1.11	−50.4	0.44	1.06	−58.4
	BS2	0.37	1.50	−75.3	0.60	1.24	−51.6	0.55	1.36	−59.5
	BS3	0.26	1.03	−74.7	0.36	1.01	−64.3	0.35	1.05	−66.6
		CBN1 ($a/W = 0.73$)			CBN1j ($a/W = 0.74$)			CBN2j ($a/W = 0.60$)		
C	CS1	2.07	2.78	−25.5	1.12	1.82	−38.4	1.10	2.10	−47.6
	CS2	2.21	2.98	−25.8	0.98	2.29	−57.2	1.41	2.52	−44.0
	CS3	2.00	2.86	−30.0	1.30	2.29	−43.2	1.31	2.29	−42.7

repeated, paying special attention to the notch root with a microscope. These tests were stopped when an incipient stable crack growth was observed or when the maximum load was reached (**Fig. 3**).

To apply the S_{pb} method, blunt-notched specimen has to reach at least the same plastic displacement than the precracked did. Because this was not the case for BBN1j, CBN1j, CBN2j, and BBN2j blunt-notched specimens, precracked load-plastic displacement records were used up to displacements corresponding to each blunt-notched final plastic displacement used. Then, as it is shown on **Fig. 3**, the precracked curve was used as three different precracked specimens, each of which had the plastic displacement reached by the corresponding blunt-notched specimen (indicated with different colors, i.e., light gray, gray and black, on the precracked load-displacement curve). The precracked final plastic displacement in each case corresponded to an unloading point, which represents a determined crack length, used as final crack length.

CRACK-LENGTH DETERMINATION

To evaluate the a/W blunt-notched influence on the S_{pb} method, three blunt notched with different a/W were used.

Fig. 4 shows an example of the obtained S_{pb} values as a function of the plastic component of displacement, for

FIG. 5

(a) CBN1 tested specimen and (b) rounded notch root with some stable crack growth.

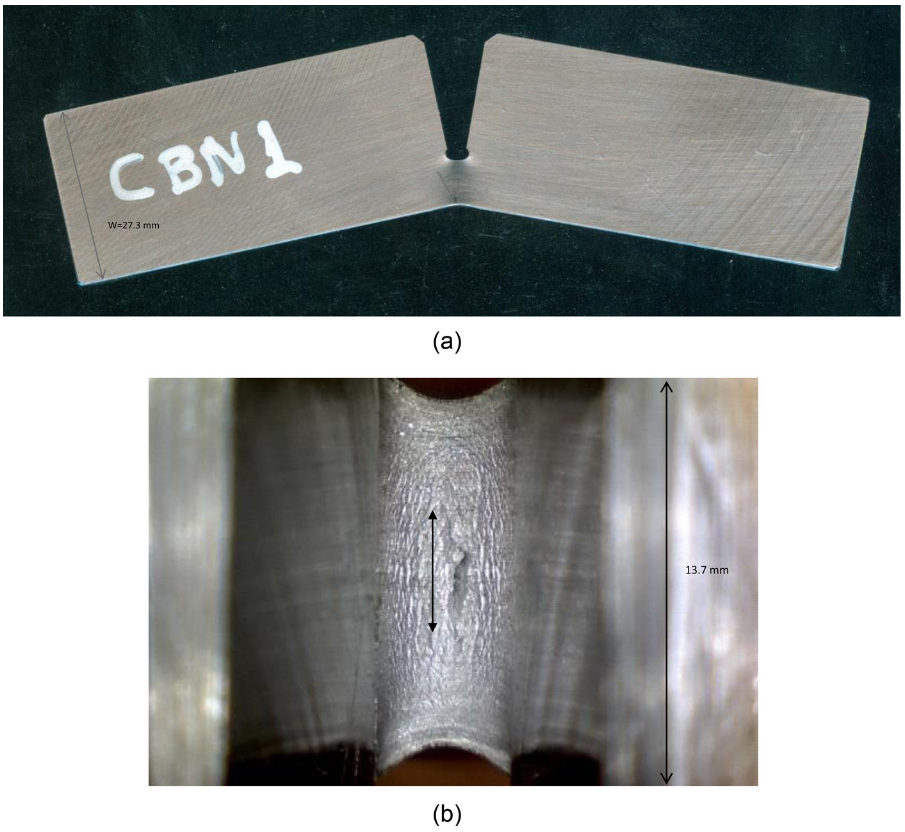
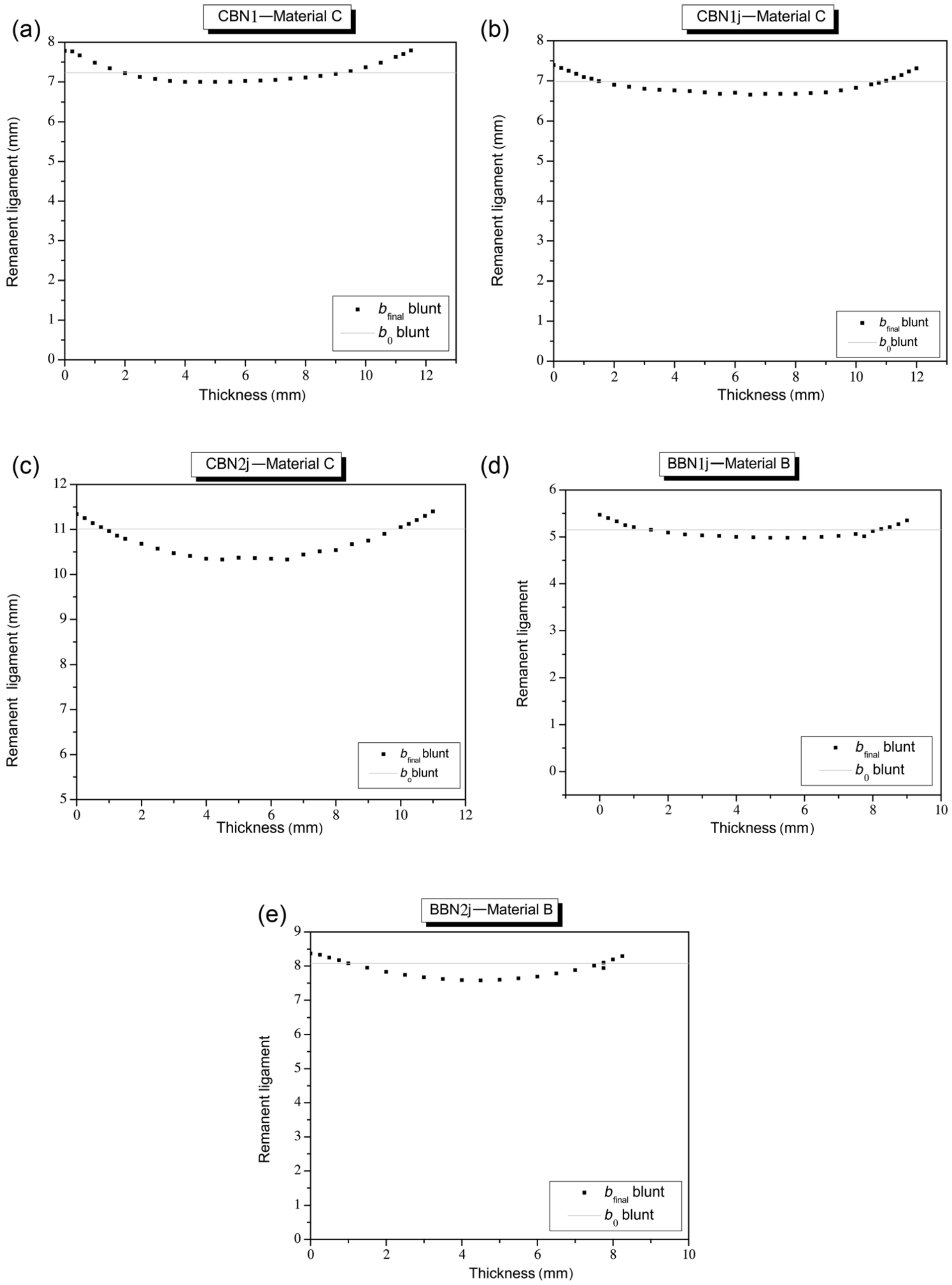


FIG. 6

BN remaining ligaments (a) CBN1, (b) CBN1j, (c) CBN2j, (d) BBN1j, and (e) BBN2j.



specimens BS3 and CS1. Different S_{pb} records were obtained for the same precracked specimen with different blunt-notched specimens. S_{pb} is larger as the difference between both crack lengths is larger.

Stable crack growth was determined for each precracked specimen using three blunt-notched specimens with different a/W ratios. The crack lengths for every point of the load-displacement record of the precracked specimens were obtained. **Table 3** shows stable crack growths determined by S_{pb} and unloading compliance methods. It can be seen that differences in Δa estimations given by S_{pb} and unloading compliance methods were in the worst cases larger than 70 %, the crack growths were always underestimated by the S_{pb} methodology.

To analyze blunt-notched specimen role on S_{pb} method behavior, final dimensions, especially blunt-notched remaining ligaments, were measured on the specimens after tested. BBN1 was not available for the measurements because it had been discharged after the tests. The measurements were made on specimens BBN1j, BBN2j, CBN1, CBN1j, and CBN2j. **Figs. 5** and **6** show the obtained results.

Fig. 5 shows a blunt-notched specimen tested and the notch root showing some stable crack growth. **Fig. 6** shows remaining

TABLE 4 BN remaining ligaments variations.

Specimen	a/W	b_{bo} (mm)	b_{bf} (mm)	(%) Difference $b_{bo} - b_{bf}$
BBN1j	0.74	5.10	4.98	−2.35
BBN2j	0.60	8.10	7.58	−6.41
CBN1	0.73	7.30	7.00	−4.10
CBN1j	0.74	7.00	6.65	−5.00
CBN2j	0.60	11.0	10.3	−6.36

ligaments measured on blunt-notched specimens. Red lines show initial remaining ligaments length. A remaining ligament variation from the initial one was found in all the specimens measured, when it is supposed that it did not change. There were smaller remaining ligaments in most specimens, but at the surfaces. From these measurements, a final remaining ligament for every blunt-notched specimen was obtained. **Table 4** shows that the smaller the a/W ratio, the larger was the reduction on the remaining ligament. The final crack lengths were estimated by means of Eq 5 modified with the measured final remaining ligaments: b_{bf}

$$a_p = W - b_p = W - b_{bf}\left(S_{pb}\right)^{1/m} \tag{7}$$

Table 5 and **Fig. 7** show the recalculated crack-growth values.

On **Fig. 7**, black, blue, and magenta bold lines represent the crack-length estimations for the same precracked specimen, but using different blunt-notched specimens. The figure also shows square points for compliance crack-length estimation, and bold points for the final crack length used for every blunt-notched specimen. Half bold points represents the new final crack lengths estimated using the new final remaining ligament measured on each blunt-notched specimen.

It can be seen in **Fig. 7** and **Table 5** that crack-growth differences obtained with S_{pb} method using corrected b_b and that determined by unloading compliance are notably lower than those estimated with the original remaining ligament of blunt-notched specimens.

The effect of correcting b_{bf} on blunt-notched specimens is interpreted as taking into account actual conditions on b_b and this implies better final crack-length estimation on precracked specimens, improving the performance of the methodology. On the other hand, the a/W effect of blunt-notched specimens on crack-length estimation of precracked specimens was visibly reduced in both materials, obtaining better results in final crack length in almost all cases. These results demonstrated that the assumption of blunt-notched geometry constancy could induce large errors of estimation in S_{pb} method. This can be important when high-toughness materials, such as material B, are tested. Moreover, when very large displacements are applied to the blunt-notched specimens, some stable crack growth will occur and some additional important errors can be introduced and they will not easily be eliminated or minimized.

This variation in blunt-notch geometry should be taken into account also for any method which use blunt-notched specimens like key curve method, because the same kind of error could occur.

Authors developed a corrected S_{pb} method using the results shown above. Following the modified S_{pb} method is proposed.

MODIFIED S_{PB} METHOD

A modified S_{pb} method is proposed that takes into account blunt-notched geometry variation evidence. It involves the following recommendations:

- Blunt-notched specimens must be tested in the first place to know the maximum plastic displacement that precracked record will have to display.
- Final remaining ligament of the blunt-notched specimen have to be measured after tested, to determine b_{bf}. Hence, a new m is calculated using the following calibration points (S_{pb}cte, b_{po}/b_{bo}), (S_{pb} final, b_{pf}/b_{bf}), and the theoretical point [1,1].
- No plastic displacements lower than v_{pl}min/W, will be considered to avoid values too influenced by the errors introduced when two very close values are subtracted (v_{total} close to v_{el}). v_{pl}min is the first v_{pl} at $S_{pb} = $ cte. This value represents the beginning of separability property

TABLE 5 Final crack length and stable crack growth obtained with corrected BN final remaining ligament.

Spec	Δa (Corrected S_{pb})	Δa (UC)	Δa Estimation Differences (%)	Δa (Corrected S_{pb})	Δa (UC)	Δa Estimation Differences (%)	Δa (Corrected S_{pb})	Δa (UC)	Δa Estimation Differences (%)
		BBN1			BBN1j			BBN2j	
BS1	—	1.27	—	1.14	1.11	2.70	0.90	1.06	−15.1
BS2	—	1.50	—	1.10	1.24	−11.3	1.37	1.36	0.73
BS3	—	1.03	—	0.60	1.01	−40.6	0.91	1.05	−13.3
		CBN1			CBN1j			CBN2j	
CS1	2.31	2.78	−16.9	1.75	1.82	−3.84	2.01	2.10	−4.28
CS2	2.44	2.98	−18.1	1.67	2.29	−27.0	2.38	2.52	−5.55
CS3	2.31	2.86	−19.2	2.04	2.29	−10.9	2.25	2.29	−1.74

validity within a range $\nu_{pl}\text{min}/W < \nu_{pl}/W < \nu_{pl}\text{max}/W$ [23].

- The S_{pb} equation has to take into account the variation of blunt-notched remaining ligament. A linear variation of the remaining ligament is proposed to be used in Eq 5.

$$b_p = b_b(S_{pb})^{1/m} \tag{8}$$

$$b_b = W_b - a_{bi}\left(1 - \frac{\nu_{pli}}{\nu_{pltot}}\right) + a_{bf}\left(\frac{\nu_{pli}}{\nu_{pltot}}\right) \tag{9}$$

Using this new formulation of S_{pb} method, crack-length estimations were recalculated. Results are shown in **Fig. 8**. In bold lines, crack-length estimations for traditional S_{pb} method of a unique precracked specimen are shown. Each blunt-notched specimen used gives as a result different crack-length estimations for the same precracked specimen. Different colors, i.e., black, gray, and light gray represent different crack-length estimations for each blunt-notched specimens used. Circle curves show modified S_{pb} method results for the same pre-cracked specimen and the different blunt-notched specimens

FIG. 7

Crack length versus plastic displacement using corrected b_b: (a) CS1, (b) CS2, (c) CS3, (d) BS1, (e) BS2, and (f) BS3.

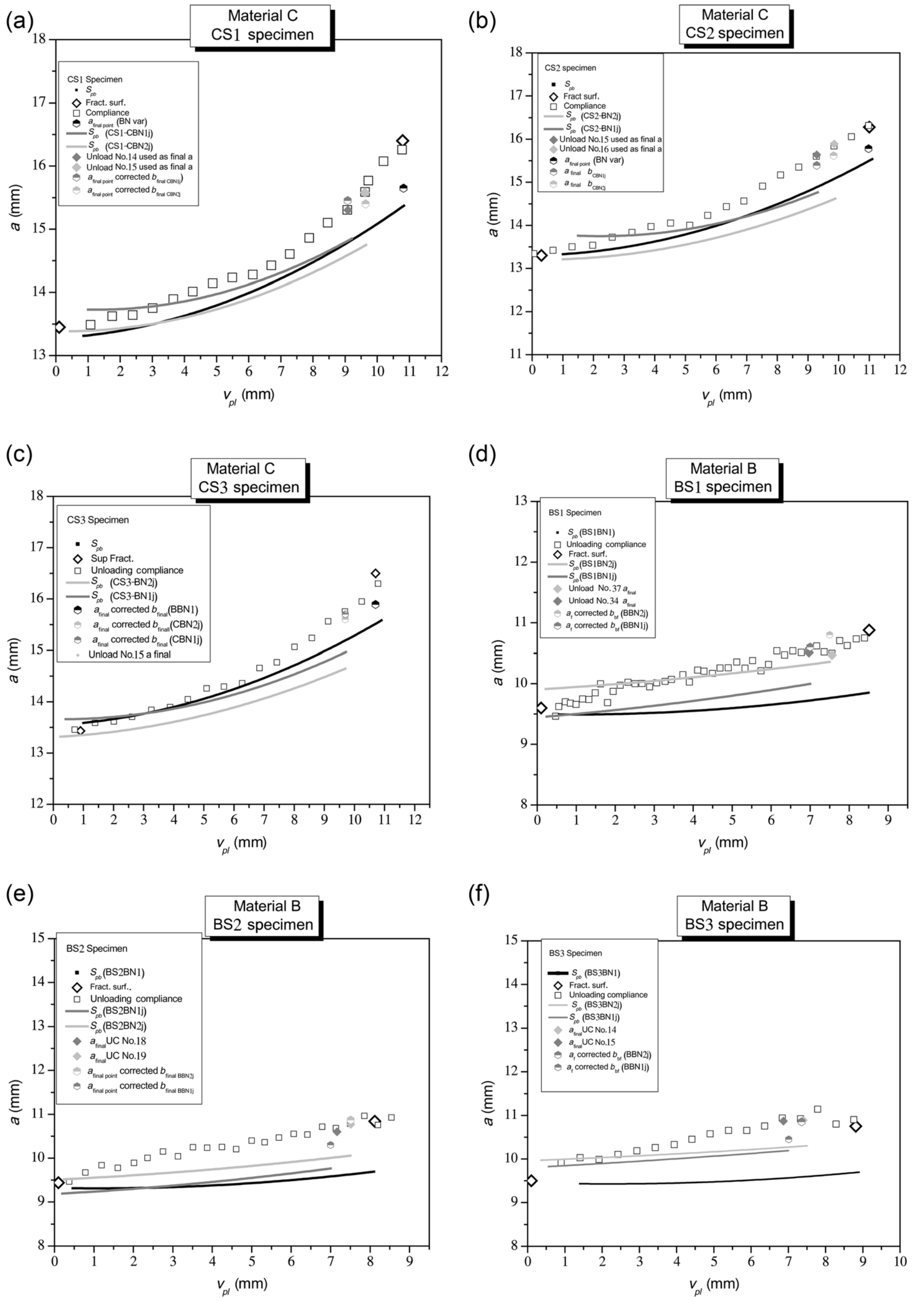
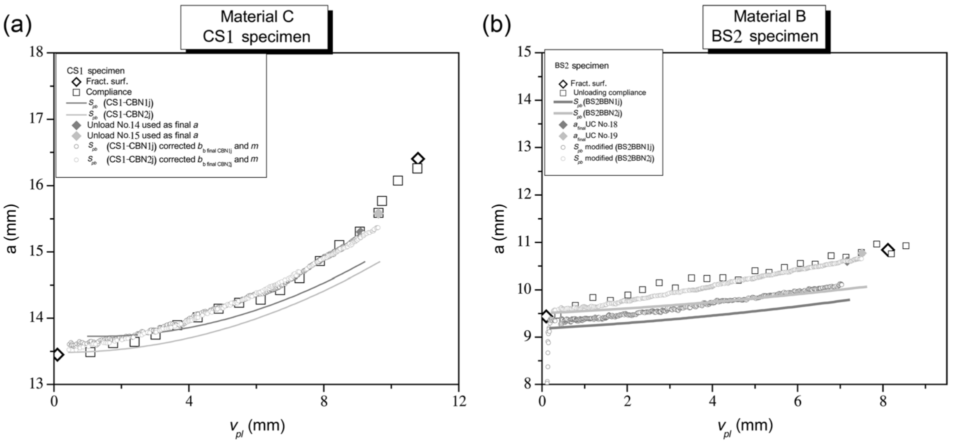


FIG. 8

Corrected S_{pb} method compared with traditional S_{pb} method and unloading compliance method: (a) CS1 specimen material C and (b) BS2 specimen material B.



used. It can be seen that modified S_{pb} method has a better performance than traditional S_{pb} methodology, showing almost the same estimated values of crack length than compliance method used as reference.

It can also be seen on **Fig. 8**, that using the modified S_{pb} method, the blunt-notched specimen b_b/W effect of estimating different crack lengths for blunt-notched specimens for the same precracked specimen decrease for both materials, especially for material C.

Using these new crack lengths versus plastic displacement curves, *J-R* curves were determined and compared with those obtained by compliance method (**Fig. 9**). The *R* curves obtained by using the modified S_{pb} method agree very closely with those from unloading compliance method used as reference.

For comparison purposes both graphics have the same scale. It can be seen that material B is the tougher material (**Fig. 9b**). It is so tough that the recommended by ASTM E1820-08 blunting line does not intercept the *R* curve. For this reason, a BS 7448-4 [30] blunting line was also used for this material. It seems more appropriate because it agrees better with the first part of the compliance *J-R* curve [30]. A J_{IC} value of approximate 1800–2000 kJ/m^2 was determined, giving more evidence of the large toughness of this material.

Fig. 9a also shows material *J-R* curves determined using S_{pb}, modified S_{pb} and compliance methods. It can be seen the different behavior estimated by traditional S_{pb} and corrected S_{pb} method. The traditional S_{pb} method, not taking into account blunt-notched geometry variation, predicts a tougher material.

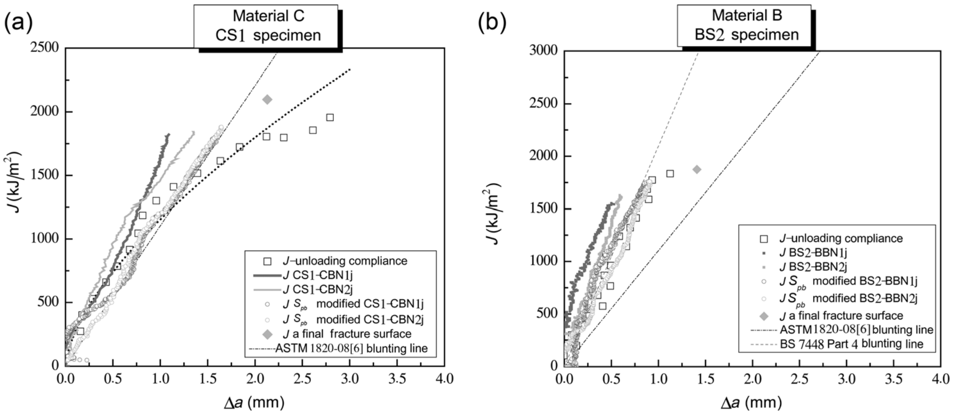
An important variation in the *R*-curves could be appreciated according to the different blunt-notched specimen used using traditional S_{pb} method. This was not the case for modified S_{pb} method, showing similar behavior besides the blunt-notched specimen used. Also modified S_{pb} method determines *J-R* curves similar to compliance method which is the reference method.

Conclusions

S_{pb} methodology limits were studied by the authors, particularly its application to very tough materials. The effect of blunt-notched geometry changes on stable crack-growth estimation

FIG. 9

J-R curves: (a) material C and (b) material B.



was evaluated. A methodology to take into account the geometry variation in blunt-notched specimens was proposed together with a new formulation of the S_{pb} method to estimate crack growth using this blunt-notched geometry alterations.

Summarizing all the results obtained in this work, it could be seen that

- Blunt-notched specimens varied their geometry during the tests, resulting in a different final remaining ligament than the original one.
- Δa obtained with corrected b_{bf} presented a better agreement with the ones determined with unloading compliance.
- Fracture toughness tests that use blunt-notched specimens and perform important displacements must consider the no constancy of remaining ligament and some sort of correction have to be implemented.
- The S_{pb} method can be applied up to displacements that produce incipient crack initiation and growth at the bottom of the blunt-notched specimen.
- A modified S_{pb} method was presented that takes into account the change in geometry in the blunt-notched specimens, no initial v_{pl} values are considered and the whole *J-R* curve—including the blunting line—is obtained.
- A modified S_{pb} method works very well with both tough materials determining *J-R* curves similar to compliance *R* curves used as reference method. Authors consider that more experimental tests ought to be done.

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