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S_{PB} AND *DCPD* METHODS APPLIED TO COILED TUBINGS SPECIMENS

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Abstract. *J-R curves in thin walled tubes, as coiled tubing, can not be obtained from standardized specimens. Stable crack growth methods must be adapted to non-standard geometries. S_{pb} and Potential Drop estimates stable crack growth in fracture toughness tests of different standardized specimen geometries. In this work, both methods were applied to non-standard coiled tubing specimens and compared. The S_{pb} geometry function was experimentally obtained testing four-point bending coiled tubing specimens as well as the calibration curve for direct current potential drop method. This methodology can be applied to any metal tube geometry.*

Keywords: ***S_{pb}*** *Method, Coiled Tubing, DC Potential Drop Method, Crack Length Estimation*

1. INTRODUCTION

Coiled Tubings are thin walled steel tubes of 25 to 89 mm in diameter and several thousand meters long. They are used in oil and energy industries to provide a number of production tasks and maintenance services. They suffer plastic deformation during unwinding of the reel, passing through a *goose neck* arch guide and an injection unit. Strain levels are about 2-3%, making the tubing fails by low cycle fatigue in around 100 wrap-unwrap cycles. The fracture behavior of a component is necessary to know in order to assess the integrity of structures containing crack like defects. For pipe materials with high toughness, elastic-plastic fracture mechanics (EPFM) provides realistic estimates of the fracture performance of cracked pressurized pipes. *Coiled tubings* made of high strength low alloy (*HSLA*) steel behaves in a ductile manner at working temperatures in and out the well. Fracture toughness of ductile materials is often characterized by the *J*-integral concept (Ernst and Paris 1980, Paris et.al. 1980, Ernst et.al. 1981) proposed by Rice (Rice, 1968). The determination of characteristic values is generally performed through the construction of the material resistance curve (*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 (Begley and Landes, 1972) 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 (ASTM E1820 2008, Bakker 1985, Schwalbe et.al. 1985, Herrera and Landes 1990). The most common single specimen testing methodologies applied in the field of metals are the elastic-unloading 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 (Chung and Williams 1991, Grellman and Seidler 2001).

S_{pb} method, has been developed (Cassanelli et al. 2001, Wainstein et al 2003) and successfully applied to fracture toughness of metals and polymers characterization (Wainstein et al 2004), including high load rate conditions (Wainstein et al 2007). 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 (Chung and Williams 1991, Bernal et al 1995 and 1999). The S_{pb} method, as normalization, is based on the existence of the load separation proposed by Ernst (Ernst et al 1981).

$$P = G\left(\frac{a}{W}\right) \times H\left(\frac{v_{pl}}{W}\right) \tag{1}$$

where G(a/W) is the geometry function and $H(\nu_{pl}/W)$is the derfomation properties function.

The S_{pb} parameter (Sharobeam and Landes 1993) 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.

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

Sharobeam and Landes (Sharobeam and Landes 1993) 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

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

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

$$S_{pb} = \left.\frac{P_P}{P_b}\right|_{v_{Pl}} = \left(\frac{a_p}{a_b}\right)^m \tag{4}$$

The direct current potential drop (DCPD) method represents one of the possibilities to measure crack length during fracture mechanics testing. The DCPD method works based on the occurrence of an electrical potential drop caused by the crack in the specimen when a direct current of a sufficient value passes through the whole specimen cross-section. The disturbance magnitude is a function of crack length. Advantages and problems related to the application of DCPD method were discussed (Cerný et al. 1998, Cerný 2004). The method requires a calibration curve which relates crack length with the corresponding potential drop. This curve can be obtained numerically or experimentally.

The, S_{pb} method is a simple technique for crack length estimation usually applied to standard specimens in fracture mechanics tests. The aim of this work was studying the applicability of this methodology for *coiled tubings* specimens. Due to *coiled tubing* diameter and thickness, no standard specimens can be used. To avoid this limitation coiled tubing segments of 1m long approximately were tested in four-point bending configuration. The geometry function was experimentally obtained from testing blunt notched *coiled tubing* specimens with different 2C/D ratios. Once the geometry function was determined, the S_{pb} Method was used to estimate stable crack growth on a *coiled tubing*s fracture mechanic test. Results were compared with those obtained by applying the potential drop method -used as reference method- and fracture surface measurements.

2. MATERIAL AND METHODS

Test specimens were cut-out from two coiled tubings materials called A and B, and consisted of coiled tubing segments, of 1m long approximately, with through wall circumferential cracks, machined by a milling machining process. Two crack front configurations were tested, precracked (PC) and blunt notched (BN) in order to apply the S_{pb} method.

Four point bending loading was applied to all specimens in a Wolpert Universal Testing Machine at room temperature. Only the precraked specimens were fatigue precracked (2-10mm at each side) before performing the fracture tests. This ensured a sharp crack tip. The geometric details of the tested specimens are given in Tab. 1.

Table 1. Details of test specimen

Mat.	Blunt Notched					Pre cracked				
	Spec.	Out diameter [mm]	Wall thickness [mm]	2C [mm]	W [mm]	Spec.	Out diameter [mm]	Wall thickness [mm]	$2C_0$ [mm]	W [mm]
A	CTABN1	51.1	5.30	91.0	160.2	CTAPC1	51.1	5.3	74.5	160.2
	CTABN2	51.1	5.30	96.0	160.2					
	CTABN3	51.1	5.30	77.5	160.2	CTAPC2	51.1	5.3	72.5	160.2
	CTABN4	51.1	5.30	83.5	160.2					
B	CTBBN12	51.1	5.30	102	160.2	CTBPC1	51.1	5.3	72.6	160.2
						CTBPC2	51.1	5.3	72.2	160.2

Load, load line displacement and crack mouth potential drop were recorded during the tests.

The DCPD calibration curve which relates crack arc length with the corresponding potential drop was determined using several coiled tubing specimens, with different stationary crack arc lengths and 30A current was applied to them. The potential drop was measured for every blunt notched specimen. Once the potential drop calibration curve was determined, fracture tests of precracked and blunt notched specimens were conducted.

After testing, specimens were heat tinted and then cooled for fracture broken. The initial and final crack arc lengths were measured on the fracture surface,

The Potential Drop calibration curve is shown in Fig 1. The potential drop measured was normalized with the current density in order to be independent of the coiled tubing diameter.

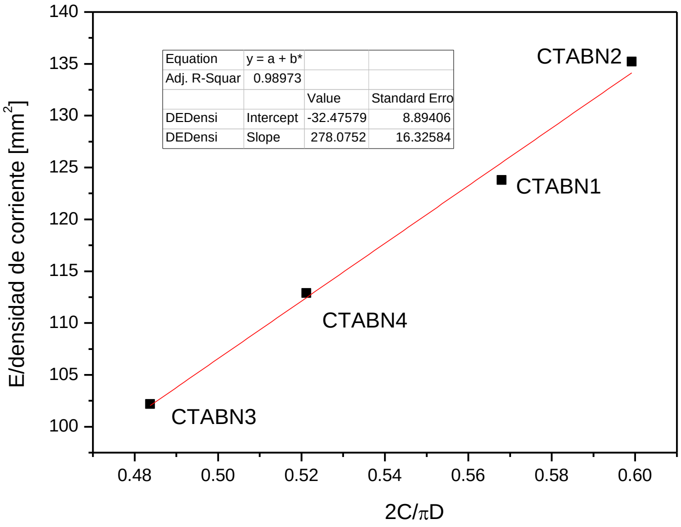


Figure 1. Potential drop calibration curve

2.1 Geometry function G(a/W) determination

The blunt notched specimens described in Tab.1 were tested up to maximum load in order to determine the geometry function for coiled tubings. Fig. 2 shows the load *vs*. plastic displacement records of material A.

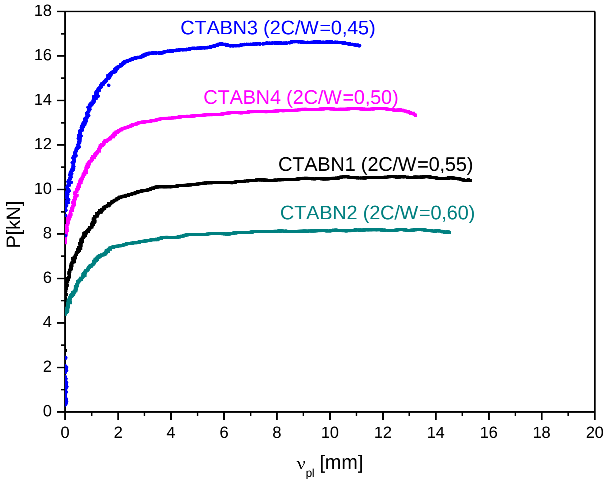


Figure 2. Load vs plastic displacement blunt notched specimens.

Figure 3 shows the S_{ij} parameters calculated from the load ratio between two blunt notched specimens at constant displacement. The separability parameter is almost constant for the whole range of plastic displacement, except for a limited region at the beginning of plastic behavior. The S_{ij} parameter constancy evidence the existence of the separability property for this material and configuration for a wide range of crack lengths.

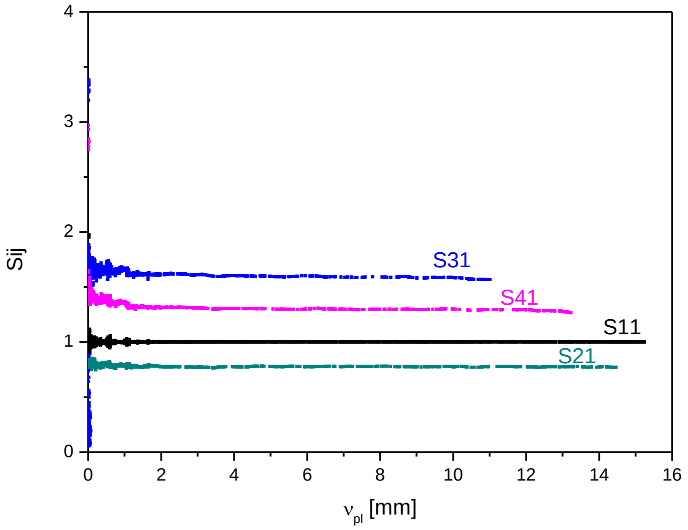


Figure 3. S_{ij} parameter vs plastic displacement

Figure 4 shows the geometry function determined (Sharobeam and Landes 1991) fitting a potential function to the S_{ij} vs. bo/W values. This allowed the use of the S_{pb} method for 4P bend coiled tubing testing.

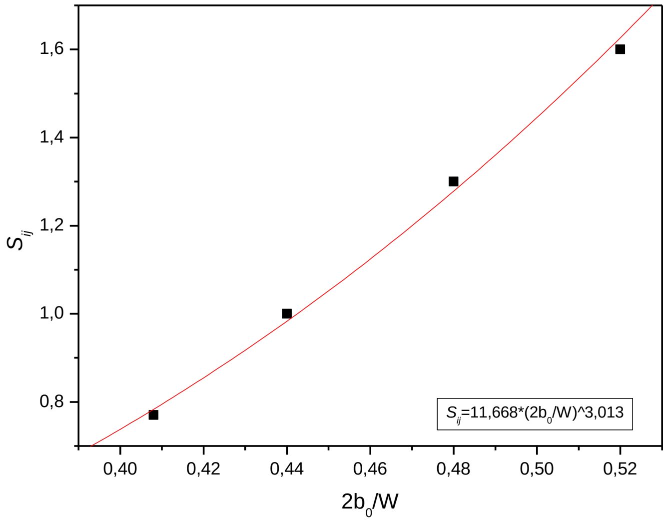


Figure 4. Sij vs b_0/W

3.3 The Use of S_{pb} method for coiled tubing specimens

Precracked and blunt notched coiled tubing specimens were tested. A testing scheme in four-point bending with potential drop implementation is shown in Fig. 5a. Figs. 5b and 5c show the fracture surfaces of precracked and blunt-notched specimens respectively.

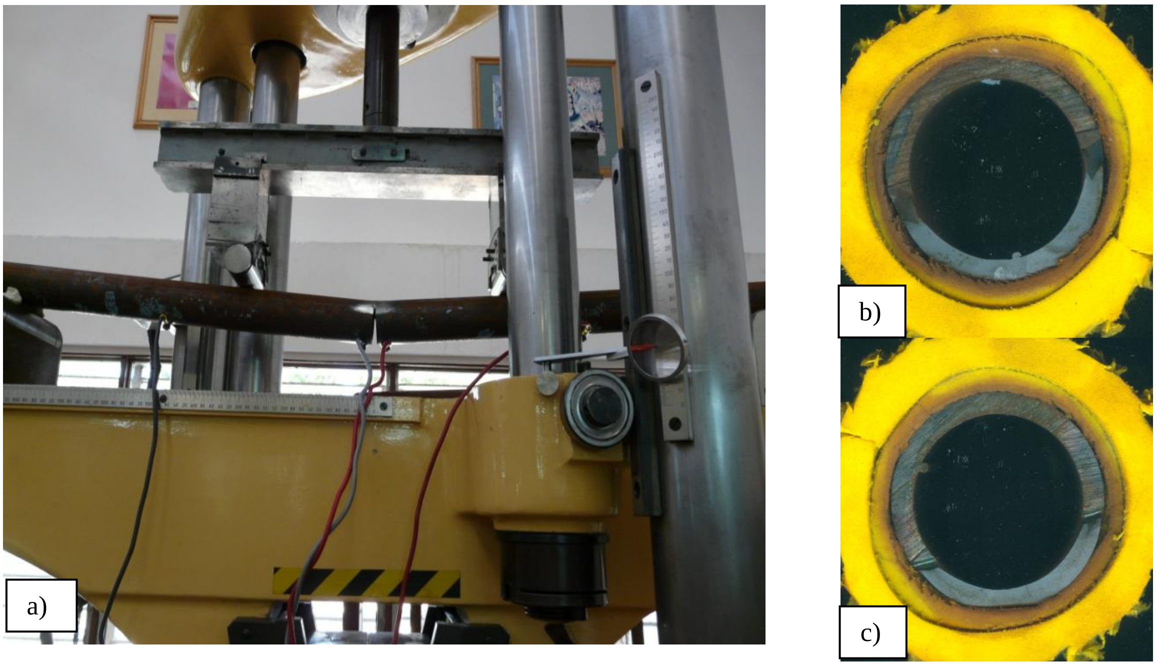


Figure 5. a) Precracked coiled tubing fracture test.
b) Precracked Coiled tubing fracture surface. c) Blunt notched coiled tubing fracture surface

Figure 6 shows the load vs plastic displacement obtained for both configurations and both materials.

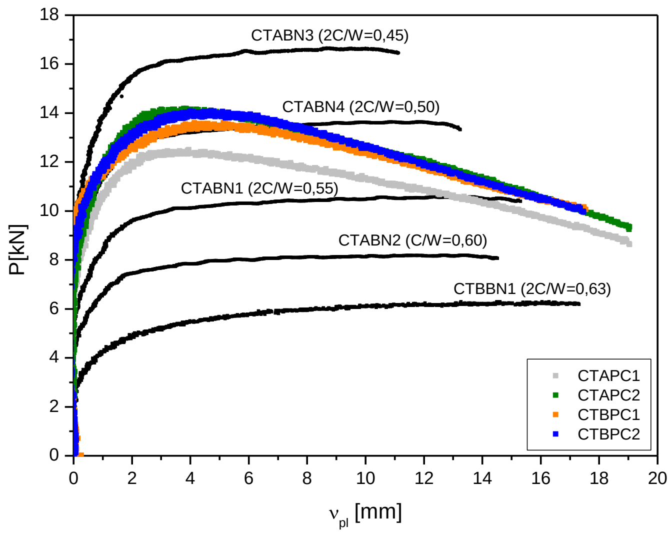


Figure 6. Load vs plastic displacement for precracked and blunt notched coiled tubing specimens.

According to the S_{pb} method definition, it is required that the blunt notched specimens should have at least the same plastic displacement than the precracked specimens. Fig. 6 shows that none of the blunt notched specimens fulfill this requirement for Material A. Instead, for material B, CTBBN1 presented the same plastic displacement than the precracked specimens CTBPC1 and CTBPC2. Hence, the S_{pb} method was applied only to material B.

Blunt notched specimens Material A began to suffer an incipient crack growth and the tests had to be stopped at a lower plastic displacement than the already tested precracked specimens. This method limitation was already noted in a previous paper (Wainstein, Perez Ipiña 2015).

S_{pb} parameter was determined as shown in Figure 7.

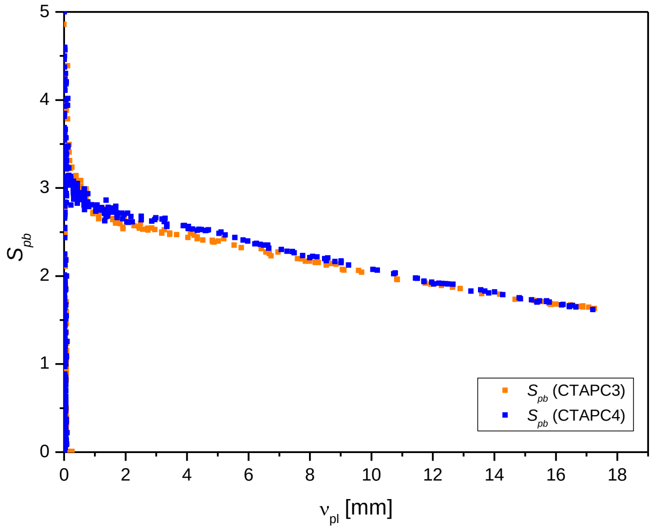
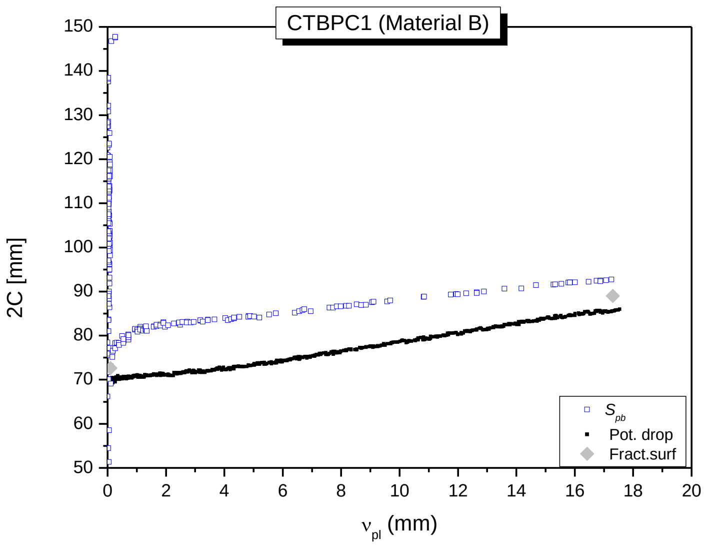


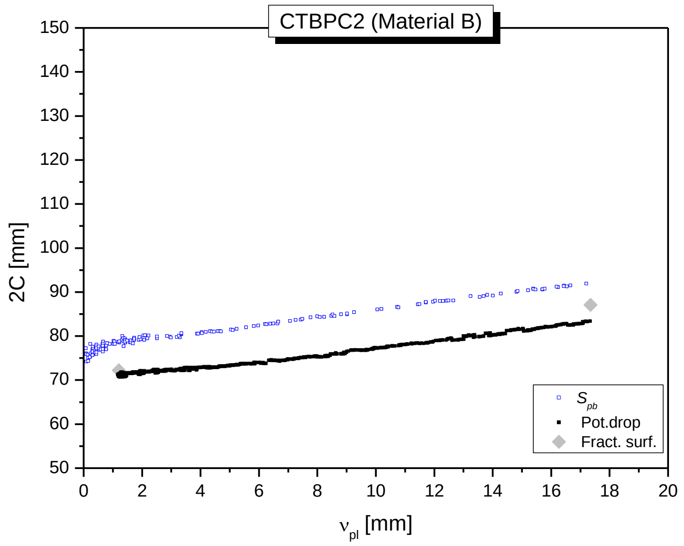
Figure 7. S_{pb} parameter vs plastic displacement.

Crack lengths for every point of the load vs. plastic displacement curves were determined by applying Eq. (4).

Figure 8 shows crack lengths obtained by the S_{pb} method together with potential drop and fracture surface measurements.



(a)



(b)

Figure 8. Crack lentghs obtained by S_{pb} method, potential drop and fracture surface measurements.
a) CTBPC1, b) CTBPC2

S_{pb} method overestimated initial, intermediate and final crack length for both specimens, while PD slightly underestimated the crack lengths.

This was the first attempt on using S_{pb} method for coiled tubing specimens and some reasons for this behavior can be cited and then studied to avoid them. Measurements on *coiled tubings* fracture surface for final crack lengths were not simple (Fig. 5 b). Blunt notched fracture surfaces showed an incipient crack growth (Fig. 5c), affecting the crack length estimation (Wainstein and Perez Ipiña, 2015). As it also occurs in standardized specimens, the crack growth initiation that corresponds to the beginning of constancy on S_{pb} parameter is not well defined and requires a methodology improvement.

Table 2. Stable crack growth estimated by S_{pb} method, Potential drop method and fracture surface measurements

Specimen	Δ2C *Fract.Surf* [mm]	Δ2C *Pot. Drop* [mm]	Δ2C S_{pb} [mm]	% Diff. (S_{pb} -*FS*)	%Dif (PD-*FS*)
CTBPC1	16,9	16,7	16,2	4,10	2,89
CTBPC2	15,0	13,8	12,7	15,3	8,00

In spite of the difficulties found, S_{pb} method estimated stable crack growth quite well when the indetermination of the crack growth initiation is avoided (see slopes in Fig 8). Tab. 2 shows the differences on stable crack growth determined by S_{pb} method, Potential drop method and fracture surface measurements. The differences in S_{pb} were lower than 5% when compared to the physical stable crack growth for one of the specimens, and about 15% for the second. The differences between DCPD and the physical measurements were lower.

Authors considered that more work ought to be done in applying S_{pb} method for tubes specimens, in special with *coiled tubing*s specimens.

3. CONCLUSIONS

S_{pb} method was applied to *coiled tubings* specimen configuration for the first time.

The geometry function was determined using blunt notched coiled tubing specimens . Improvements in the definition of stable crack growth beginning are necessary

Potential drop was also used and a calibration curve was also constructed. *DCPD* appears to give better results than *Spb*..

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