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On the Line Method apparent fracture toughness evaluations: Experimental overview, validation and some consequences on fracture assessments

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ABSTRACT

This paper analyses the capacity of the Line Method to provide evaluations of the apparent fracture toughness, which is the fracture resistance exhibited by materials in notched conditions. With this aim, the experimental results obtained in 555 fracture tests are homogeneously presented and compared to the Line Method evaluations. It is remarked that the Line Method provides adequate estimates of the apparent fracture toughness, and also that it conveniently addresses the physics of the notch effect. All this makes the Line Method a valuable scientific and engineering tool for the fracture assessment of materials containing notches.

1. Introduction

The load-bearing capacity of structural components is generally conditioned by the presence of stress risers such as cracks, notches, welded joints, corners. These stress risers take very different forms, and different approaches have been proposed to deal with the structural integrity of such components. This paper is focused on the notch-type defects (particularly, U-shaped notches), which may appear in structural components due to design details, mechanical damage, corrosion defects or fabrication defects.

When notches are blunt, it is overly conservative to proceed on the assumption that they behave like sharp cracks and to apply Fracture Mechanics criteria (i.e., such an assumption may lead to unnecessary repairs or replacements, or to structural oversizing). In fact, as has been widely shown in the literature (e.g., [1–9]), components with non-sharp defects or notches exhibit an apparent fracture toughness that is greater than that obtained for cracked components. This generally has direct consequences on the load-bearing capacity of the structural components and also on their structural integrity assessments [4].

The literature (e.g., [7,8]) shows that there are two main failure criteria in the notch theory: the global criterion and the local criteria. The global criterion is analogous to the ordinary fracture mechanics approach, and establishes that fracture takes place when the notch stress intensity factor (K_ρ) reaches a critical value (K_ρ^c), where K_ρ defines the stress and strain fields in the vicinity of the notch tip, whereas K_I defines such fields in the crack tip. This approach is of unquestionable significance, but its application is very limited because of the lack of analytical solutions for K_ρ or/and standardized procedures for the experimental definition of K_ρ^c.

Meanwhile, local criteria are based on the stress–strain field at the notch tip. The most important ones are the Point Method (PM) and the Line Method (LM), both of them being methodologies of the Theory of Critical Distances (TCD) that can easily generate evaluations of the apparent fracture toughness exhibited by notched components. The resulting expression of the LM is particularly simple, and provides similar predictions to those generated by the PM [9]: therefore, for the sake of simplicity, the analysis here is focused on the LM estimations.

In any case, the evaluations provided by the LM (or the PM) have been validated for different materials (a sound review may be found in [9]), but such predictions have not been treated homogeneously and, therefore, they are not directly comparable. The aim of this paper is to provide a homogenous analysis of a high number of apparent fracture toughness tests (555) performed on notched specimens under very different conditions (different materials, notch radii, testing specimens, testing temperatures, parameter calibration processes, etc.), providing a general validation of the LM. This allows general conclusions to be made concerning the use and the validity of the apparent fracture toughness evaluations obtained from the LM.

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Nomenclature

K_{mat}	material fracture toughness	σ_u	ultimate tensile strength
K_{mat}^N	apparent fracture toughness	σ_0	material strength parameter (the inherent strength)
K_I	stress intensity factor	DBTZ	Ductile-to-Brittle Transition Zone
K_ρ	notch stress intensity factor	FE	Finite Elements method
K_ρ^c	critical notch stress intensity factor	LM	Line Method
L	material critical distance	LS	Lower Shelf
M	fitting parameter in Eq. (9)	PM	Point Method
r	distance from the notch tip	TCD	Theory of Critical Distances
ρ	notch radius	US	Upper Shelf
σ	applied stress		

2. Theoretical background: the Line Method and apparent fracture toughness evaluations

The Theory of the Critical Distances (TCD) comprises a group of methodologies with a common aspect: they all use a characteristic material length parameter (the critical distance) when performing fracture assessments [9,10]. The origins of the TCD are located in the middle of the twentieth century [11,12], but in the last two decades this theory has had a wider development, providing answers to different scientific and engineering problems (e.g., [3,6,13–20]).

The above-mentioned length parameter is generally referred as the critical distance, L, and in fracture analyses it follows the equation [9]:

$$L = \frac{1}{\pi}\left(\frac{K_{mat}}{\sigma_0}\right)^2 \tag{1}$$

where K_{mat} is the material fracture toughness obtained for cracked specimens, and σ_0 is a characteristic material strength parameter, named the inherent strength. The last parameter (σ_0) is usually larger than the ultimate tensile strength (σ_u) and must be calibrated, although σ_0 coincides with σ_u in those situations where there is a linear-elastic behaviour at both the micro and the macro scales (e.g., fracture of ceramics and certain rocks).

There are different methodologies, within the TCD, allowing fracture analyses to be performed [9], such as the Point Method (PM), the Line Method (LM), the Imaginary Crack Method (ICM) and the Finite Fracture Mechanics (FFM). In any case, the evaluations made by these methodologies are very similar [9], and both the PM and the LM are particularly simple. Therefore, from now on, this theoretical overview is focused on these two methodologies.

The PM establishes that fracture occurs when the stress reaches the inherent strength, σ_0, at a distance from the defect tip equal to $L/2$ [12,21,22]. Therefore, the failure criterion is:

$$\sigma\left(\frac{L}{2}\right) = \sigma_0 \tag{2}$$

The LM assumes that fracture occurs when the average stress along a certain distance, $2L$, reaches the inherent strength, σ_0 [11,22–24]. Therefore, the LM expression is:

$$\frac{1}{2L}\int_0^{2L} \sigma(r)dr = \sigma_0 \tag{3}$$

Moreover, both the PM and the LM provide expressions for the apparent fracture toughness (K_{mat}^N) exhibited by notched components. In the case of U-shaped notches (as those analysed in this paper) both the PM and LM may be applied considering the linear-elastic stress distribution at the notch tip provided by Creager and Paris [25], which is equal to that ahead of the crack tip but displaced a distance equal to $\rho/2$ along the x-axis, which is located in the notch midplane and has its origin at the crack tip [9,25]:

$$\sigma(r) = \frac{K_I}{\sqrt{\pi}}\frac{2(r+\rho)}{(2r+\rho)^{3/2}} \tag{4}$$

where K_I is the stress intensity factor for a crack with the same size as the notch, ρ is the notch radius and r is the distance from the notch tip to the point being assessed. Eq. (4) was derived for long thin notches (i.e., notch depth $\gg$ notch radius) and is only valid for small distances from the notch tip ($r \ll$ notch depth).

If the PM is applied, Eq. (2) may be combined with Eq. (4), giving [9]:

$$K_{mat}^N = K_{mat}\frac{\left(1+\frac{\rho}{L}\right)^{3/2}}{\left(1+\frac{2\rho}{L}\right)} \tag{5}$$

By considering the LM, Eq. (3), together with Eq. (4), we get [9]:

$$K_{mat}^N = K_{mat}\sqrt{1+\frac{\rho}{4L}} \tag{6}$$

This has implications from a practical point of view, given that it reduces the fracture analysis of a notched component to an equivalent situation of a cracked component, with the only particularity of considering K_{mat}^N instead of K_{mat}. Thus, fracture occurs when:

$$K_I = K_{mat}^N \tag{7}$$

Analogously, the authors have demonstrated [4,26] that notches may be analysed by using Failure Assessment Diagrams and substituting K_{mat} with K_{mat}^N in the definition of the K_r coordinate of the assessment point, which is defined as the ratio between the applied stress intensity factor (K_I) and the material fracture resistance (K_{mat} for cracks and K_{mat}^N for notches) [27–29].

Both Eqs. (5) and (6) have been validated in a number of papers (many of them are summarized in Ref. [9]), covering a wide range of materials.

However, the corresponding observations have been diverse or contradictory. In some cases a critical radius has been found below which the notch effect is negligible [38,39], whereas in other cases such a critical radius has not been detected [6,37]. On some occasions, the apparent fracture toughness remains approximately constant above a certain notch radius [6,9,38], and the experimental results differ from the LM or PM predictions (which predict a monotonically increasing fracture resistance when increasing the notch radius), whereas in other cases the experimental results continuously increase with the notch radius [9,37,39]. Some results of the apparent fracture toughness are conservative [2,9], whereas the predictions for other cases perfectly fit the experimental results or are non-conservative [3,6,9]. All this makes it necessary to undertake a sound analysis of the K_{mat}^N evaluations provided by