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Some default values to estimate the critical distance and their effect on structural integrity assessments

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ABSTRACT

When the structural integrity of notched components is analysed, it is generally assumed that notches behave as cracks, something which generally provides overconservative results. Thus, it is necessary to derive models that take into account the higher fracture resistance developed by structural materials when notches (and not cracks) are present. In this sense, the use of the Theory of Critical Distances (TCD) for the estimation of the apparent fracture toughness (K_c^N) observed in notched components has been validated for different types of materials, such as ceramics, polymers, composites and metals. The estimations, for U-shaped notches, arise from the combination of the TCD with the Creager-Paris stress distribution ahead of the notch tip, and apply a notch correction factor to the material fracture toughness observed in cracked conditions (K_c). Such correction only depends on the geometry (notch radius) and the material critical distance (L). The latter is the critical issue when applying the TCD, given that it generally requires calibration through experimental results and simple statistics (best fitting), or through a combination of experimental results with finite elements modelling. This paper provides some default safe values of the material inherent strength that may be used to derive safe estimates of the corresponding value of L, without any further calibration, to be finally used in the apparent fracture toughness predictions and subsequent structural integrity assessments.

1. Introduction

1.1. Notch effect

There are many situations where the defects responsible for structural failure are not necessarily sharp. If defects are blunt, it is excessively conservative to proceed on the assumption that the defects behave like sharp cracks, combined with the use of the sharp crack methodology generally based on Fracture Mechanics, given that notched components develop a load-bearing capacity that is greater than that developed by cracked components.

For the brittle failure, fracture mechanics establishes that the critical situation is reached when the applied stress intensity factor (K) is equal to the material fracture toughness (K_c):

$$K = K_c \tag{1}$$

However, notched subject components to less critical situations, given that the corresponding stress field at the defect tip are less severe to those existing at the crack tip. In practical terms this could be taken into account by considering a larger fracture resistance when the notch radius does not tend to zero.

Therefore, the particular nature of notches makes it necessary to develop specific methodologies for fracture analysis that take into account their lower tensional demands. In this sense, the analysis of the fracture behaviour of notches can be performed using different criteria. Some of them are related to each other, so it is not straightforward to establish the frontiers between them. A tentative list should include, among others, the Critical Distance methodologies [1–8], the Global Criterion [9,10], Process Zone models (e.g., [11–15]), statistical models (e.g., [16,17]), mechanistic models (e.g., [18]), the Strain Energy Density (SED) criterion (e.g., [19–36]), etc. The former methodologies have been successfully applied to different failure mechanisms (e.g., fracture, fatigue) and materials, and are particularly simple to implement in structural integrity assessments (e.g., [2,5,37–46]). A brief description of them is shown below.

1.2. The Theory of Critical Distances

The Theory of Critical Distances (TCD) is a group of methodologies which have in common the use of the material toughness and a length parameter that depends on the material (the critical

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length, L) [1,47]. The origins of the TCD are located in the middle of the twentieth century with the Neuber [48] and Peterson [49] publications, but its greater development have been produced the last two decades, establishing the applicability of the TCD to different types of materials (e.g., metals, ceramics, polymers, composites), processes (fracture and fatigue, principally) and conditions (e.g., linear-elastic versus elastoplastic). The above mentioned length parameter is usually known as L (the critical distance) and it is defined by the following expression:

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

where K_c is the material fracture toughness and σ_0 is a characteristic strength parameter (known as the inherent strength) that is generally higher than the ultimate tensile strength (σ_u) and requires calibration. When the material behaviour is fully linear-elastic σ_0 is equal to σ_u.

Among the methodologies that compose the TCD, the Point Method (PM) and the Line Method (LM) are distinguished by both their simplicity and their applicability [1].

The Point Method (PM) is the simplest approximation and it assumes that failure occurs when the stress at a specific distance from the notch tip ($L/2$) is equal to the inherent strength. Therefore, the resulting failure criterion is:

$$\sigma\left(\frac{L}{2}\right) = \sigma_0 \tag{3}$$

Alternatively, the Line Method (LM) assumes that failure occurs when the mean stress through a specific length ($2L$) is equal to the inherent strength. Thus the expression for the LM is:

$$\frac{1}{2L}\int_0^{2L} \sigma(r)dr = \sigma_0 \tag{4}$$

Predictions using the LM are slightly different than those obtained by means of the PM [50], but both methods generate estimates which are reasonably similar to experimental data.

Both the PM and the LM can be applied to predict the apparent fracture toughness (K_c^N) developed in notched conditions [1]. If the PM is used, is necessary to consider the stress distribution on the notch tip, according to the proposal of Creager and Paris for U-shaped notches [50], which is equal to the stress distribution on the crack tip, but displaced a distance equal to half the notch radius:

$$\sigma(r) = \frac{K_I}{\sqrt{\pi}}\frac{2(r+\rho)}{(2r+\rho)^{3/2}} \tag{5}$$

Considering this stress distribution, the failure conditions of the PM (Eq. (3)) and the definition of the critical length (Eq. (2)), and establishing that failure occurs when K_I is equal to K_c^N, the resulting expression is:

$$K_c^N = K_c \frac{\left(1+\frac{\rho}{L}\right)^{3/2}}{\left(1+\frac{2\rho}{L}\right)} \tag{6}$$

Similarly, the application of the LM provides the Eq. (7) which, as can be observed, is simpler than Eq. (6) and provides similar predictions of the apparent fracture toughness. For these reasons, this is the expression that will be applied in this paper.

$$K_c^N = K_c\sqrt{1+\frac{\rho}{4L}} \tag{7}$$

1.3. Failure Assessment Diagrams

Failure Assessment Diagrams (FADs) are one of the main engineering tools for the assessment of fracture-plastic collapse in cracked components (e.g., [34,51–53]). These diagrams allow the simultaneous assessments of fracture and plastic collapse by using two normalised parameters, K_r and L_r, whose expressions are:

$$K_r = \frac{K_I}{K_c} \tag{8}$$

$$L_r = \frac{P}{P_L} \tag{9}$$

K_r evaluates the component against fracture and it is defined by the ratio of K_I to K_c, K_I being the stress intensity factor, and K_c being the material fracture resistance. L_r evaluates the component against plastic collapse and it is defined by the ratio P to P_L, P being the applied load and P_L being the limit load.

Once the assessment point representing the cracked component being analysed is described by K_r and L_r coordinates, it is necessary to define the limiting conditions. This is done by defining the Failure Assessment Line (FAL), whose general expression is:

$$K_r = f(L_r) \tag{10}$$

Finally, if the assessment point is located above the FAL, the component is considered to be under unsafe conditions, whereas if the assessment point is located below the FAL it means that the component is considered to be under safe conditions. The critical situation (failure condition) is that in which the assessment point lies exactly on the FAL. Fig. 1 shows an example of the three different possible situations.

2. Materials and methods

In order to provide default values of the critical distance to be used in structural integrity assessments, a deep review of the existing bibliography has been made. L values have been obtained for steels, aluminium alloys, polymers, ceramic materials, composites and rocks.

2.1. Steels

The first group of materials that will be analysed is formed by different types of steel (structural and high resistance steels) working at different temperatures (Lower Shelf or Ductile-to-Brittle-Transition-Zone). The corresponding L values have been obtained from [1,43,44,47,54,55] and are gathered in Table 1.

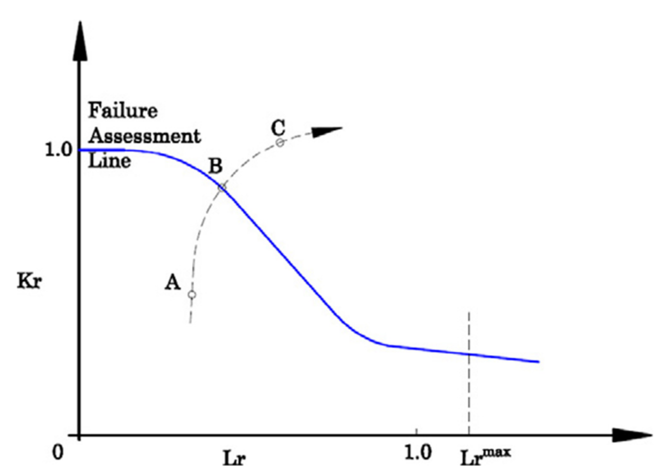

Fig. 1. FAD analysis (initiation), showing three possible situations: A, safe condition; B, critical condition; C, unsafe condition.