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Assessment of notched structural steel components using failure assessment diagrams and the theory of critical distances

V. Madrazo, S. Cicero *, T. García

Dpto. Ciencia e Ingeniería del Terreno y de los Materiales, Universidad de Cantabria, Av/Los Castros s/n, 39005 Santander, Cantabria, Spain

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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. The proposal of this paper consists, on the one hand, in the application of the theory of critical distances for the estimation of the notch fracture toughness and, therefore, for the conversion of the notched situation into an equivalent cracked situation in which the material develops a higher fracture resistance. On the other hand, once the notch fracture toughness has been defined, the assessment is performed using the failure assessment diagram methodology, and assuming that the notch effect on the limit load is negligible. The methodology has been applied to 336 CT notched fracture specimens made of two different structural steels, covering temperatures from the corresponding lower shelf up to the upper shelf, providing satisfactory results and a noticeable reduction in the overconservatism derived from the analyses in which the notch effect is not considered.

1. Introduction: Notch effect, the theory of critical distances and failure assessment diagrams

There are many situations where the defects responsible for structural failure are not sharp. Actually, notched components develop a fracture resistance that is greater than that developed by cracked components (e.g., [1–7]) and this, generally, is directly related to the load-bearing capacity of the component. Hence, the development of an adequate methodology for the assessment of the notch effect would reduce the conservatism in many practical situations.

There are two main failure criteria in notch theory: the global fracture criterion and local fracture criteria [2,3]. The global criterion establishes that failure occurs when the notch stress intensity factor reaches a critical value, K_ρ^c:

$$K_\rho = K_\rho^c \tag{1}$$

This approach is totally analogous to that used in cracks, but its application is very limited because of the lack of analytical solutions for K_ρ (as there are for K_I) or/and standardized procedures for the experimental definition of K_ρ^c.

Local criteria are based on the stress field on the notch tip. Among them, the Point Method (PM), the Line Method (LM) and the Finite Fracture Mechanics stand out [8], all of them being different versions of the theory of critical distances (TCD) and, then, using a characteristic material length parameter (the critical distance, L) when performing fracture assessments [8]:

* Corresponding author.
E-mail address: ciceros@unican.es (S. Cicero).

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

K_c is the material fracture toughness and σ_0 is a characteristic material strength parameter (the inherent strength) that must be calibrated. Only in those materials with linear-elastic behaviour at both the macro and the micro scales (e.g., ceramics), does σ_0 coincide with the ultimate tensile strength (σ_u) [8].

The notch analysis following these methodologies is relatively simple. For example, the PM [9] establishes that fracture occurs when the stress reaches the inherent strength (σ_0) at a distance from the defect tip equal to $L/2$:

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

For its part, the LM [10] assumes that fracture occurs when the average stress along a distance equal to $2L$ (starting from the defect tip), reaches the inherent strength, σ_0:

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

The basics of the FFM, a little more complex and based on the Griffith theory [11], can be found in [8,12].

When fracture toughness is determined by using notched specimens, and the equations provided by the standards (e.g., [13]) for the definition of the material fracture toughness are applied, the corresponding measured fracture resistance may be noticeably higher than the fracture toughness (e.g., K_c) obtained in normalised cracked specimens, given that, as mentioned above, the load-bearing capacity of the notched material is higher than that developed by the same material when it is cracked. This fracture resistance developed by the material in notched conditions is generally referred to as the apparent fracture toughness or notch fracture toughness, K_c^N.

The different methodologies belonging to the TCD can be applied to the analysis of the load-bearing capacity of components containing notches. Moreover, these methodologies may generate predictions of the notch fracture toughness $\left(K_c^N\right)$ exhibited by components containing U-shaped notches [14]. If the PM is used, it is necessary to consider the stress distribution on the notch tip provided by Creager and Paris [15], which is equal to that ahead of the crack tip but displaced a distance equal to $\rho/2$ along the x-axis:

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

In [7], the Creager–Paris distribution and FE results are compared, providing reasonably similar predictions of the stress field on the notch tip. Considering both the condition defining the PM (Eq. (3)) and the definition of the critical distance L (Eq. (2)), and establishing that failure takes place when K_I is equal to K_c^N, Eq. (6) may be easily obtained [8]:

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

Analogously, the application of the LM provides the following equation:

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

Further details on the TCD, its different proposals for notch effect analysis, and the comparison between the corresponding predictions, can be found in the literature (e.g., [8,16]).Finally, failure assessment diagrams (FADs) constitute one of the main engineering tools for the assessment of fracture-plastic collapse processes in cracked components (e.g., [17–21]). These diagrams present a simultaneous assessment of both fracture and plastic collapse processes by using two normalised parameters, K_r *y* L_r, whose expressions are:

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

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

P being the applied load, P_L being the limit load, K_I being the stress intensity factor, and K_c the material fracture resistance measured by the stress intensity factor. Therefore, L_r evaluates the structural component situation against plastic collapse, and K_r evaluates the component against fracture. Once the component assessment point is defined through the coordinates (K_r,L_r), it is necessary to define the component limiting conditions (i.e., those leading to final failure). With this purpose, the Failure Assessment Line (FAL) is defined, so that if the assessment point is located between the FAL and the coordinate axes, the component is considered to be under safe conditions, whereas if the assessment point is located above the FAL, the