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Assessment of notched structural components using Failure Assessment Diagrams and the Theory of Critical Distances

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ABSTRACT

This paper illustrates the need to develop specific methodologies for the assessment of notched structural components. These are usually analysed under the assumption that notches behave as cracks, providing results that may be overconservative. The proposal consists, on the one hand, in the application of the Theory of Critical Distances for the estimation of the apparent fracture toughness, and for the conversion of the notched situation into an equivalent cracked situation in which the material develops a higher fracture resistance (the apparent fracture toughness). On the other hand, once the apparent fracture toughness has been defined, the assessment is performed using the Failure Assessment Diagram methodology, and assuming that the notch effect on the plastic collapse load is negligible. The methodology has been applied to notched fracture specimens made of PMMA and Al7075-T651, providing satisfactory results and a noticeable reduction in the overconservatism derived from analyses in which the notch effect is not considered.

1. Introduction: notches and Failure Assessment Diagrams

1.1. An introduction to notches

There are many situations where the defects that are, or might be, responsible for structural failure are not necessarily sharp. This is the case, for example, of mechanical damage, corrosion defects or fabrication defects. If such defects are blunt, it is overly conservative to proceed on the assumption that the defects behave like sharp cracks, coupled with the use of the sharp crack methodology generally based on Fracture Mechanics, given that, actually, notched components develop a load-bearing capacity that is greater than that developed by cracked components. However, it is a common engineering practice to assess notches as if they were cracks. The main reasons for this practice are probably two: on the one hand, fracture mechanics is a well-known, established scientific and engineering tool, with easily available analytical solutions and materials characterisation standards that provide the parameters and the material properties involved in the analysis; in contrast, there are no such well-known established theories, analytical solutions or characterisation standards for the analysis of notches. Hence, despite the corresponding assumed overconservatism, it is far simpler to consider that notches behave as cracks.

For the brittle failure of a crack, fracture mechanics establishes that the critical situation is reached when the applied stress, σ, multiplied by the square root of the crack length is equal to a constant (here called k_1) related to the material fracture toughness [1]:

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Nomenclature

Principal symbols

a	crack size
B	specimen thickness
E	Young's modulus
$f(L_r)$	function of L_r defining FAD
J	J integral
J_e	elastic component of J
K_C	material fracture toughness measured by stress intensity factor
K_r	fracture ratio of applied elastic K_I value to K_C
K_I	stress intensity factor
K_{IC}	plane strain fracture toughness
K_{IN}	apparent fracture toughness
K_ρ	notch stress intensity factor
K_ρ^c	critical notch stress intensity factor
L	material critical distance
L_r	ratio of applied load to yield or proof load
P	applied load
P_L	yield or proof load
ρ	notch radius
σ_u	ultimate tensile strength
σ_y	yield stress
σ_0	inherent strength
$\sigma_{0.2}$	0.2% proof strength

Principal abbreviations

FAD	Failure Assessment Diagram
FAL	Failure Assessment Line
FE	Finite Elements
FFM	Finite Fracture Mechanics
LM	Line Method
PM	Point Method
PMMA	Polymethyl methacrylate
SSY	Small Scale Yielding
TCD	Theory of Critical Distances

$$\sigma\sqrt{\mathrm{a}} = k_1 \tag{1}$$

However, notches subject components to less critical situations that may be expressed through Eq. (2):

$$\sigma \cdot \mathrm{a}^{\alpha} = k_2 \tag{2}$$

where the exponent α is a constant.

The stress distribution at the region ahead of a notch tip may be represented in a bi-logarithmic plot, as shown in Fig. 1, where three regions can be distinguished [2,3]. Region I corresponds to a nearly constant stress zone, region II is a transition zone, and region III is a zone where stresses follow the expression:

$$\sigma_{\mathrm{yy}} = \frac{K_\rho}{(2\pi r)^{\alpha}} \tag{3}$$

where K_ρ is the notch stress intensity factor and α is a material constant for a given notch radius.

The literature gathers a number of analytical solutions of the elastic stress distribution at the notch tip (e.g., [2–9]), the solution proposed by Creager and Paris [9] being the most significant from the fracture analysis point of view.

There are two main failure criteria in notch theory: the global fracture criterion and local fracture criteria [10,11]. The global criterion establishes that failure occurs when the notch stress intensity factor reaches a critical value, K_ρ^c, which depends on the notch radius and the material:

$$K_\rho = K_\rho^c \tag{4}$$

K_ρ defines the stress and strain fields in the vicinity of the notch tip, as shown in Eq. (3). This approach, of an unquestionable significance, is totally analogous to that used in cracks, but its application is very limited because of the lack of analytical solutions for K_ρ (in contrast with the case of K_I, e.g., [12–15]) or/and standardised procedures for the experimental definition