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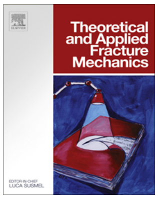

On the assessment of U-shaped notches using Failure Assessment Diagrams and the Line Method: Experimental overview and validation

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ABSTRACT

This paper analyses the structural integrity of components containing U-shaped notches by combining Failure Assessment Diagrams and the Line Method correction for notch effects. With this objective, the experimental results obtained in 555 fracture tests are homogeneously evaluated in the same Failure Assessment Diagram, with and without applying the Line Method notch corrections, and covering a wide range of materials such as PMMA, Al7075-T651, four different structural steels (S275JR, S355J2, S460M and S690Q) tested at different temperatures from the Lower Shelf up to the ductile-to-brittle transition zone, and two rocks (granite and limestone). It is demonstrated that the proposed methodology generally produces significant reductions in the conservatism associated to notch effects, yet providing safe predictions.

1. Introduction

The structural integrity assessment of components containing cracks may be addressed using the Failure Assessment Diagram (FAD) methodology, which allows a simultaneous assessment against fracture, plastic collapse and their corresponding interaction. However, the integrity assessment (and the load-bearing capacity predictions) of structural components containing notches using the same methodology leads to generally overconservative results, given that the fracture resistance developed by a given material in notched conditions may be much higher than that developed in cracked conditions (e.g., [1–8]). Notches (and stress risers, in general) can take very different forms. This paper is focused on U-shaped notches, which may appear in structural components due to design details, mechanical damage, corrosion defects or fabrication defects, among others [9,10].

The authors have published a number of papers analysing the notch effect in different materials (e.g., [3–5,11,12]), and have also provided a model for the structural integrity assessment of notches by using the FAD methodology and the Line Method (LM) correction for the consideration of notch effects [13,14]. This model has been validated individually for different materials (e.g., PMMA and Al7075-T651 [13], and structural steels S275JR and S355J2 [14]), but the results are not directly comparable, given that the Failure Assessment Line (FAL) defining the critical situation in the corresponding FAD depends on the material tensile properties, so that the FAL used in the above mentioned research varies with the material being analysed.

The aim of this paper is to extend the validation of the proposed methodology for the structural integrity of U-shaped notches, by including a wider scope of materials (those mentioned above plus structural steels S460M and S690Q, and two rocks – limestone and granite) and also by providing a homogenous analysis of all of them, that is, analysing all the different materials and experimental results in the same FAD. The tests cover very different conditions (different materials, notch radii, testing specimens, testing temperatures, parameter calibration processes, etc.), summing 555 structural integrity assessments and providing a general validation of the methodology.

With all this, Section 2 presents some theoretical background about FADs and the LM, Section 3 describes the materials being analysed and the assessment model (materials and methods), Section 4 provides the results and the corresponding discussion and, finally, Section 5 gathers the main conclusions.

2. Theoretical background: Failure Assessment Diagrams and the Line Method

2.1. Failure Assessment Diagrams

Failure Assessment Diagrams (FADs) constitute one of the main engineering tools for the assessment of fracture-plastic collapse processes in cracked components. As explained in [15], they were

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Nomenclature

J	applied J-integral
J_e	elastic component of J
K_{mat}	material fracture toughness (mean value)
$K_{\text{mat}0.95}$	material fracture toughness associate to a 95% confidence level
K^N_{mat}	apparent fracture toughness
K_I	stress intensity factor
K_r	fracture ratio of applied K_I to fracture resistance (e.g., $K_{\text{mat}}, K^N_{\text{mat}}, \ldots$)
L	material critical distance
L_r	ratio of applied load to limit load
r	distance from the notch tip
ρ	notch radius
σ	applied stress
σ_{ref}	reference stress
σ_u	ultimate tensile strength
σ_Y	yield stress
σ_0	material strength parameter (the inherent strength)
CFF	Conservatism Factor of Failure
DBTZ	Ductile-to-Brittle Transition Zone
FAD	Failure Assessment Diagram
FAL	Failure Assessment Line
FE	Finite Element method
LM	Line Method
LS	Lower Shelf
PM	Point Method
TCD	Theory of Critical Distances

first introduced by Dowling and Townley [16] and Harrison et al. [17], and were derived from the modified version of the strip yield model [18,19] proposed by Burdekin and Stone [20]. In the last decades, they have been introduced in the most important structural integrity assessment procedures (e.g., [21–24]), led by the R6 procedure [23].

For a given structural component containing a crack, FADs present a simultaneous assessment of both fracture and plastic collapse processes by using two normalised parameters, K_r and L_r, whose expressions are:

$$K_r = \frac{K_I}{K_{\text{mat}}} \tag{1}$$

$$L_r = \frac{P}{P_L} \tag{2}$$

P being the applied load, P_L being the limit load, K_I being the stress intensity factor, and K_{mat} being the material fracture resistance measured by the stress intensity factor (e.g., K_{IC}, K_{Jc}, etc.). L_r may also be expressed following Eq. (3), which is totally equivalent to Eq. (2) [22]:

$$L_r = \frac{\sigma_{\text{ref}}}{\sigma_Y} \tag{3}$$

σ_{ref} being the reference stress, obtained by multiplying Eq. (2) by the yield stress, and σ_Y being the material yield stress.

L_r evaluates the structural component situation against plastic collapse, and K_r evaluates the component against fracture, the assessed component being represented by a point of coordinates (K_r,L_r). Once the component assessment point is defined through these coordinates, it is necessary to define the component limiting conditions (i.e., those leading to final failure). To this end, 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 component is considered to be under unsafe conditions. The critical situation (failure condition) is that in which the assessment point lies exactly on the FAL. Fig. 1 shows an example with the three different possible situations when performing fracture initiation analyses.

In any case, the FAL follows expressions which are functions of L_r:

$$K_r = f(L_r) \tag{4}$$

From an engineering point of view, and beyond the origins of the FAD based on the strip yield model, the $f(L_r)$ functions are actually plasticity corrections to the linear-elastic fracture assessment ($K_I = K_{\text{mat}}$), whose exact analytical solution is:

$$f(L_r) = \sqrt{\frac{J_e}{J}} \tag{5}$$

J being the applied J-integral and J_e being its corresponding elastic component [15].

The analysis is limited by the cut-off, which corresponds to the load level causing the plastic collapse of the analysed component. This cut-off is defined by the maximum value of L_r (see $L_r^{\max}$ in Fig. 1), which depends on the material flow stress (usually the average value of the yield stress and the ultimate tensile strength).

In practice, structural integrity assessment procedures (e.g., [21–24]) provide approximate solutions to Eq. (5), which are defined through the tensile properties of the material. These approximate solutions are generally provided hierarchically, that is, defining different levels on which the more defined the material stress–strain curve, the more approximate are such solutions to Eq. (5). For instance, [21] defines an Option 0 (Basic) FAL, which does not require any tensile data, whereas Option 1 (Standard) requires both the yield or proof strength and the ultimate tensile strength, and Option 3 is defined through the full stress–strain curve (Option 2 in [21] is dedicated to a mismatch analysis). As an example, Option 0 for those materials which display or may be expected to display a yield plateau (discontinuous yielding), is defined by the following equations:

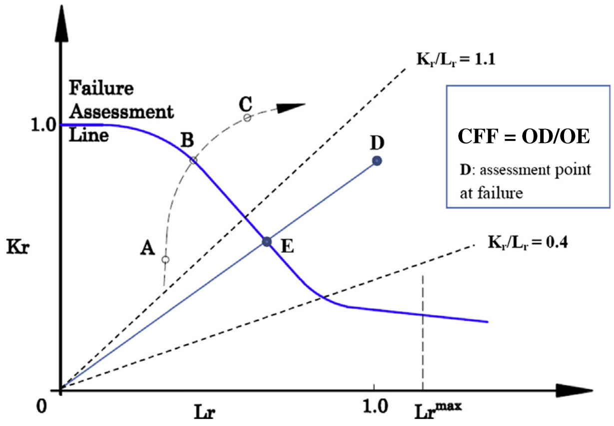

Fig. 1. FAD analysis showing three possible situations: A, safe conditions; B, critical condition; and C, unsafe conditions.