A SIMPLE METHOD FOR THE ASSESSMENT OF REDUNDANT CRACKED STRUCTURES IN ELASTIC-PLASTIC REGIME

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A method for the evaluation of the crack driving force and the assessment of the integrity of redundant cracked structures is proposed. The method is a combination of the classical linear elastic theory and the GE-EPRI elastic-plastic engineering approach, so it applies to materials that break in the elastic-plastic regime. The application of the method is illustrated through the resolution of a realistic example: a continous cracked pipe composed of austenitic stainless steel.

INTRODUCTION

Some of the methods currently used for the assessment of cracked structures of high toughness materials have been classified by Milne (1). These methods are included in Elastic-Plastic Fracture Mechanics (EPFM), hence, the parameters used to define the crack driving force are either the J-integral or the crack tip opening displacement (CTOD). The stability analysis is performed by comparing the applied crack driving force on the structure to the fracture resistance of its constituent material. These procedures are limited to the evaluation of flawed sections, without considering their inclusion into framed structures. However, the stress distribution of redundant structures varies according to the stiffness of their elements. As the stiffness of cracked elements changes depending on the length of the cracks they contain, the stress distribution in the structure is modified by the crack propagation. Hence, the objective of this paper is the presentation of an approach for the assessment of high toughness redundant cracked structures, considering the interaction between stress distribution and crack propagation.

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THEORETICAL BASIS

To assess the integrity of cracked structures, the crack driving force, as a function of the applied loads, must be known to be compared to the fracture resistance of the material. The parameter that will be used to define the crack driving force in the proposed approach will be the J-integral and the fracture resistance of materials will be characterized through its fracture resistance curve or J_R curve.

The proposed method is based on the consideration that the effects of cracks are limited to the section containing them. Hence, considering the existence of only one cracked section, the structure can be divided into two parts for its assessment:

- The first part is composed of the complete structure except the cracked section. Assuming the absence of other cracks, it has been considered that this part behaves in the elastic regime and is assessed through the classical linear elastic theory.

- The second part is the cracked section. This part breaks in the elastic-plastic regime and must be assessed through the EPFM. The proposed procedure makes use of the GE-EPRI engineering approach published by Kumar et al. in the early 80's (2).

The general methodology has been developed for the evaluation of beams subjected to vertical loads, so axial efforts will not be considered, although its inclusion would not change the logic of the procedure. For this application, the forces acting between the two parts are a bending moment, M, and a shear force, Q. If the deformation caused by the shear force is neglected, the values of M and Q can be calculated making the movements of the structure and those of the cracked section compatible. Once the forces applied on the the cracked section are known, the crack driving force, J integral, is evaluated through the GE-EPRI approach formulation and then a classical stability analysis can be performed.

PRACTICAL APPLICATION

In order to illustrate the applications of the approach presented, in this paragraph a realistic example, defined from the materials and geometry of an in-service industrial piping system, will be solved.

Definition

The material considered is the weld metal from a manual metal arc weldment between austenitic stainless steels whose properties, obtained by Gorrochategui et al. (3), are summarized below:

Modulus of elasticity, E = 181 GPa
Yield stress, σ_y = 353 MPa
Tensile strength, σ_u = 488.7 MPa
Ramberg-Osgood law, $\varepsilon/\varepsilon_y = \sigma/\sigma_y + 2.908\,(\sigma/\sigma_y)^{6.49}$
J_R curve, $J_R = 511.39\,\Delta a^{0.6363}$ (J in kN/m and a in mm)

The geometrical configuration of the example is the continous pipe defined in Figure 1a, where $L_1 = L_2 = 6$ m and c = 1.5 m. The pipe, whose mean radius is R = 595 mm and its thickness is t = 30 mm, contains a circumferential through-the-wall crack in its mid-section whose length is 2 a, and is subjected to two symmetric vertical loads, P, in its central opening.

Formulation

The rotation at the end of the beam next to the cracked section of the first part for this configuration is expressed as:

$$\theta_0 = \frac{P}{E \cdot I} \cdot \left(\frac{c^2}{2} + \frac{c \cdot L_2}{3} \right) - \frac{M}{E \cdot I} \cdot \left(\frac{L_1}{2} + \frac{L_2}{3} \right) \tag{1}$$

The rotation of the cracked section, θ_c, caused by a bending moment for the studied geometry in elastic-plastic regime was formulated by Zahoor in reference (4).

The compatibility condition between the movements of the two parts of the structure considered in the model leads to the following equation:

$$2\,\theta_0 = \theta_c \tag{2}$$

Solving this equation, the value of the bending moment acting on the cracked section, M, is calculated. Then, the crack driving force applied on this section, J_{app}, can be evaluated through the equations provided in reference (4).

The formulation developed up to this point considers that the first part of the structure, the complete structure except the cracked section, behaves in linear elastic regime. However it is possible that, caused by the crack propagation during the loading process, the bending moment in the sections placed on the central supports reaches its limit value. From this point, the static configuration of the system changes to that shown in Figure 1b, where it has been assumed that the sections where the bending moment reaches its limit value behave as plastic hinges. The limit moment is defined as:

$$M_{lim} = 2\,(\sigma_y + \sigma_u)\,R^2\,t \tag{3}$$

This is an isostatic system where the bending moment applied upon the cracked section is:

$$M = P\,c - M_{lim} \tag{4}$$

whose knowledge again permits the calculation of the applied J integral.

Results

Figure 2 shows the crack driving force diagram used for the stability analysis of the example. This diagram contains three different families of curves:

- wide solid lines define the material J_R curve for different initial crack lengths
- narrow solid lines define the crack driving force for different values of the applied load P according to the continous pipe model
- narrow dashed lines are equivalent to the above family according to the model acting after the formation of plastic hinges in the central supports.

The valid zone of the last two families of curves is, for a given P value, the one that has higher values of J_{app}, because the curves represent the acting static model only in those zones.

According to Figure 2, the values contained in Table 1 are obtained as the maximum load that the pipe is able to bear as a function of the initial crack length, a_0.

TABLE 1 - Load-bearing capacity of the pipe.

a_0 (mm)	467.3	350.5	233.7	116.8
P_{max} (MN)	17.0	18.2	19.6	21.1

As a comparison, the loads that would induce the formation of the first plastic hinge and the instability of the uncracked structure are 21.7 and 23.8 MN respectively. These values are very close to those calculated for the cracked structure, principally for the shortest cracks.

CONCLUSION

A method for the assessment of high toughness redundant cracked structures that break in the elastic-plastic regime has been presented. However, as the adopted hypothesis and the plastic collapse load have an important influence on the results, either an experimental or numerical validation that covers a wider spectrum of materials and structural configurations is needed. An experimental work, carried out by Gorrochategui, whose results validate the proposed methodology, has recently been finished and published in reference (5).

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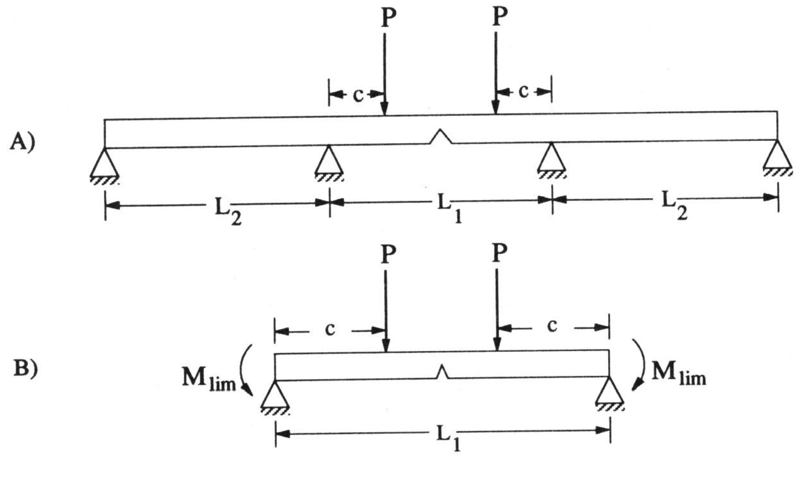

Figure 1 Static configurations of the studied example.

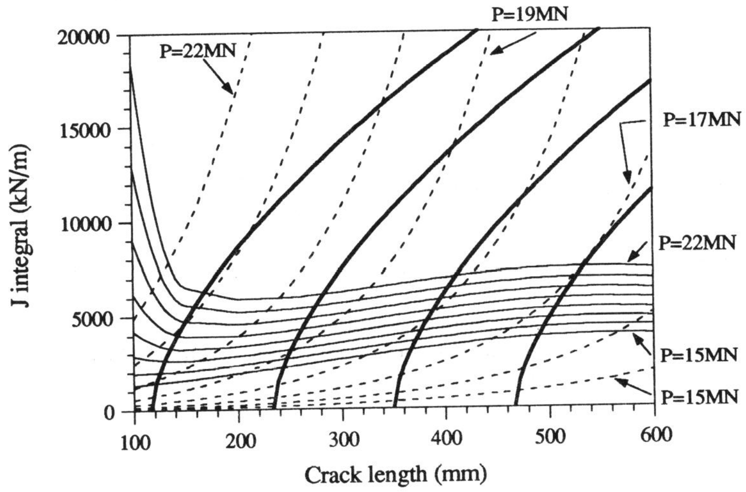

Figure 2 Crack driving force diagram.