M. Touzet, M. Lamazouade, M. Puiggali
Laboratoire de Mécanique Physique UMR CNRS 5469,Université Bordeaux 1, 351 cours de la Libération 33405, France

INTERACTION BETWEEN 3D STRESS CORROSION CRACKS

ABSTRACT

To predict the time to failure of a structure due to stress corrosion crack network, overall crack growth behavior must be studied. When many cracks are initiated in an enclosed area, neighboring cracks may affect the stress field ahead the crack tips and then affect their crack growth rates. The interactions between cracks depend on their relative positions and on their sizes. The present work presents the experimental behavior of crack networks by in-situ observations and proposed a finite element analysis of interacting 3D cracks.

Key words: *stress corrosion cracks, fracture mechanics, stress intensity factors, finite elements analysi.*

INTRODUCTION

Multiple cracking is one of the most common problems found in many engineering structures in service (pipelines, pressure vessels, aircraft components). These cracks frequently observed in stress corrosion and fatigue corrosion nucleate on the surface and propagate both on the surface and in the bulk of the material, leading to the final fracture.

When such crack colonies are observed, the effect of interactions between cracks induces complex growth behaviour of each crack. In order to analyze the effect of interactions between stress corrosion and fatigue-corrosion cracks, many experimental studies were performed to estimate crack growth rate and evaluate time to failure. Because of the complexity of the collective crack growth, some authors have considered that initiation and propagation of cracks could be regarded as a stochastic process and therefore, they have used a statistical approach to simulate multiple crack initiation and propagation. Recently, Kamaya [1] showed that it was possible to take into account interactions between stress corrosion propagating cracks by calculating the Stress Intensity Factors (SIFs) of interacting crack tips. This author considered that a line could approximate the crack shape so that crack propagation in depth is not considered. However, these problems are three-dimensional and the 2D idealization that is well suited for the description of short cracks behaviour drastically simplifies the actual behaviour of longer cracks.

Thus, the accurate calculation of stress intensity factors of 3D surface cracks has been recognized as an important problem in fracture mechanics and has been the focus of attention of many researchers. Irwin published the first engineering estimation of SIF for a semi-elliptical surface crack under remote tension. Then, several numerical techniques were used to calculate SIFs with and without interactions. One of them called “Equivalent Domain Integral” method [2, 3] is particularly suitable to study 3D interacting cracks.

Nevertheless, theoretical studies concerns coplanar or stacked surface cracks associated with symmetric configurations. In fact, experimental studies and observations of crack colonies show that distribution of crack lengths is very heterogeneous because the initiation of cracks is a progressive process and induces non symmetric crack configurations. These particular situations have to be studied in order to elaborate a mechanical modelling reliable to the lifetime of a service structure.

EXPERIMENTAL OBSERVATIONS

Quantitative characterization of surface cracks evolution are obtained by in-situ observations with a CCD camera through a corrosion cell. Results of slow strain rate tests on a 304L stainless steel in hot chloride magnesium were presented in [4-5] and reminded in Fig.1. One main result concerns the link between crack initiation and crack propagation. The first initiated cracks remain the longest ones during the entire test and the cracks initiated at the end of the test are frequently stopped. Surface crack propagation rate of each crack is a function of its initiation time.

These results mean that if a crack is initiated at the beginning of the test when the number of cracks is low, its propagation will be easy and it will not be affected by the shielding effect. On the contrary, at the end of the tests, when a microcrack is initiated, its propagation can be modified by the presence of a mesocrack in its neighboring.

a) b)

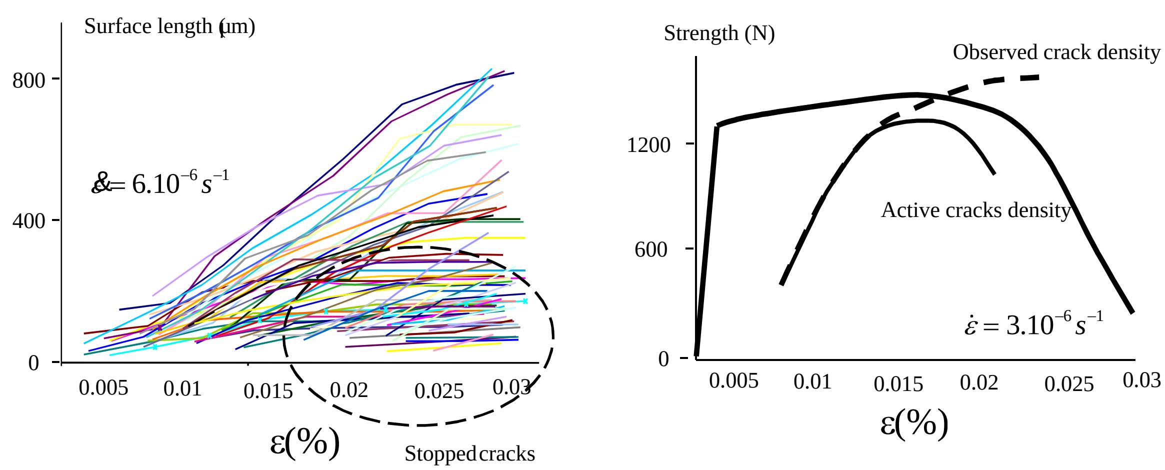


Fig. 1. Surface cracks distribution: a) length of all observed cracks and b) density of all observed cracks and density of active cracks (without stopped cracks)

Consequently, to study the impact of interactions on crack propagation, it is necessary to determine the stress field at each 3D crack tip and to compare numerical results obtained for symmetric and non symmetric configurations.

THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

Let's consider two semi-circular surface cracks in an infinite plate subjected to remote uniform tensile stress. In order to determine stress intensity factors (SIFs), *J*-integral is calculated, with SAMCEF [6], using the Equivalent Domain Integral (EDI) [2, 3] method.

A semi-infinite solid was assumed to contain two semi-circular surface cracks. Let's denote *2a* the surface length, *a* the depth and ϕ the parametric angle used to describe the position along the crack front. Cracks were subjected to uniform tensile stress $\sigma_{xx} = \sigma_0$ at $x \to \infty$ perpendicular to the plane of the cracks.

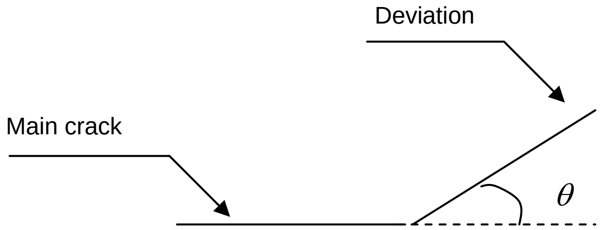
Twenty-node isoparametric three dimensional brick elements were used in this study. In order to model the square root singularity at the crack front the collapsed elements with quarter-point nodes proposed by Barsoum [7] were employed.

The mode I interaction processes are quantified by calculation the interaction factor defined by :

$$\gamma = \frac{K_I(d)}{K_I(d_\infty)}$$

where $K_I(d)$ and $K_I(d_\infty)$ represent respectively the mode I SIFs with and without interaction processes.

In some cases, when the crack tips closely approach, the SIF in mode II K_{II} is introduced. Therefore, the direction of propagation of the crack is given by the maximum tangential stress theory, which was first proposed by Erdogan and Sih [8]: the crack advances in the direction in which the tensile stress at the crack tip is maximum. This hypothesis relates the stress intensity factors K_I and K_{II} to the direction of propagation θ as shown in Fig. 2.



$$\theta = 2\arctan\left(\frac{K_I - \sqrt{K_I^2 + 8K_{II}^2}}{4K_{II}}\right)$$

Fig. 2. Local direction of crack propagation

NUMERICAL RESULTS

Coplanar configuration

This section discusses the interaction of two semi-circular coplanar cracks in a semi-infinite plate subjected to remote tension. This configuration does not induce mixed mode behaviour, the mode I is only involved.

The interaction factor γ along the crack front between two semi circular-cracks is reported in Fig. 3. Results are given for identical cracks (black solid line) and for a large (grey solid line) and a small crack (black dotted line) for a relative distance between the cracks of $d_x / a = 1/2$. Results obtained by Carpinteri [9] and Murakami [10] are also plotted for identical cracks.

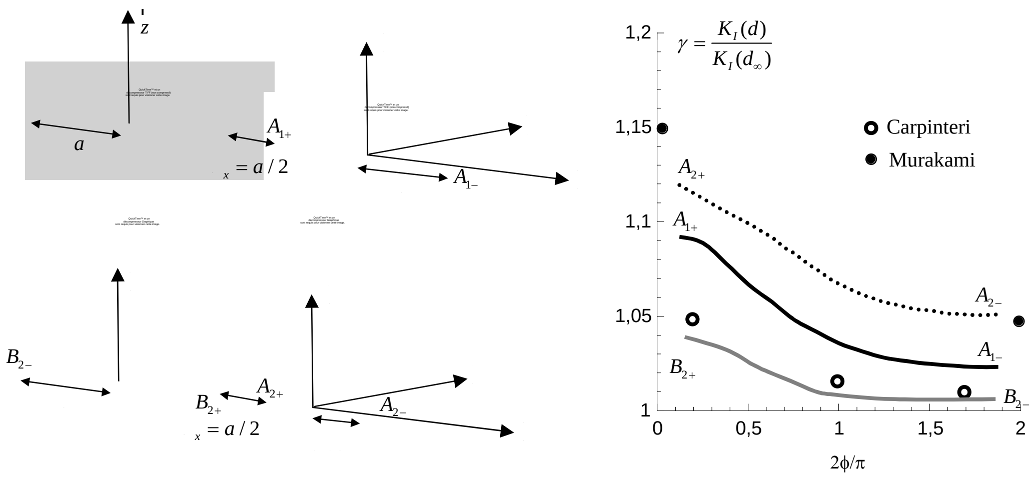


Fig. 3. Variation of the amplification factor γ along the crack front for two identical semi-circular coplanar cracks and for two different semi-circular coplanar cracks. The distance between the cracks is $d = a/2$

Note that SIFs values obtained along the crack front are in good agreement with those obtained by other authors because the difference doesn't not exceed 5%. Results show that the maximum amplification effect is obtained for the interacting crack tip (point A_{1+}) for identical cracks. This amplification effect is more significant for the small crack (point A_{2+}) but it also exists for the longest crack (B_{2+}).This result means that a small amplification value obtained on a long crack can induce a significant variation of the crack length still accentuated by the decrease of the distance between cracks.

Stacked configuration

This configuration induces mixed mode behaviour, -ie- the interacting cracks result in two fracture modes I and II. Results reported in Fig. 4 displays the variations of the interaction factor γ and the deviation angle θ for two different semi-elliptical stacked cracks. The vertical distance between cracks is $d_z / a = 1$.

In the classical symmetric stacked crack configuration, the interactions due to the smallest crack on the larger one are not significant. The shielding effect induced by the largest crack on the smallest one is illustrated by the value of the interacting factor lower than 1.

In real crack network, symmetric configurations are never seen and dissymmetrical configurations better describe progressive damage evolution. In this case, the behaviour of the two cracks is modified. The interactions induce a shielding effect on the smallest crack and an amplification effect on the larger one. The angle of deviation of the long crack is very low in the non interacting zone (B_{2-}). These results means that the stress intensity factor at the crack tip of the longer crack is higher that for the same isolated one.

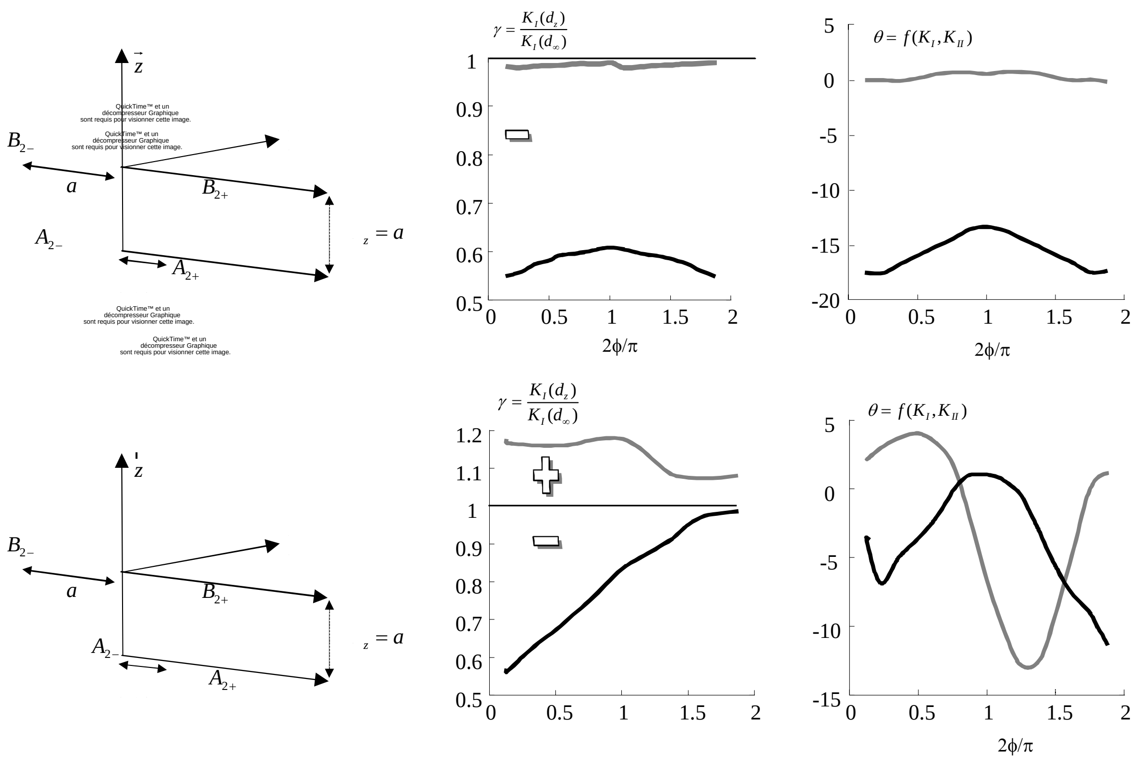


Fig. 4. Variation of the amplification factor γ and the deviation angle θ along the crack front for two semi-circular stacked cracks in symmetric and non-symmetric configurations. The distance between the cracks is $d_z = a$

This result is very important because it means that a dissymmetric configuration simultaneously induces shielding effect on the small crack and amplification on the longest one. Then, in this situation, modifications of the growth rate of the long crack can occur in comparison with the growth rate of the isolated crack.

CONCLUSIONS

Experimental investigations of crack colonies showed that initiation of cracks is a very progressive process that induces non-symmetrical crack configurations. Some particular situations issued from experimental observations have been studied by a numerical approach.

The finite element analysis was performed on three-dimensional semi-circular surface cracks in coplanar and stacked configurations. The simulations were conducted in order to compare symmetrical and dissymmetrical situations of interacting cracks.

For some real dissymmetrical configurations, the stress field around the crack tip of a long crack is modified by the presence of a short one.

In conclusion, all dissymmetrical situations induces amplification effect on the long crack. Then, first initiated long cracks can be amplified by small cracks in all configurations and propagation rates of these long cracks can be accelerated by successive interactions.

REFERENCES

1. Kamaya M., Totsuka N. Influence of interaction between multiple cracks on stress corrosion crack propagation. Corrosion science, 2002, 44, pp. 2333-2352.
2. Raju I.S., Shivakumar K.N. An equivalent domain integral method for three-dimensional mixed-mode fracture problems. Engineering fracture mechanics, 1992, 42(6), pp. 935-959.
3. Nikishkov G.P., Atluri S.N. Calculation of fracture mechanics parameters for an arbitrary three-dimensional crack, by the 'equivalent domain integral' method. International journal for numerical methods in engineering, 1987, 24, pp. 1801-1821.
4. Le Poulain F., Touzet M., Puiggali M. and Aubert. I, Mechanical behavior of a solid with many stress corrosion growing cracks. Journal of material science, 2005, 40, pp. 1-11.
5. Touzet M., Le Poulain F, Puiggali M and Aubert. I Incremental self-consistent scheme applied to stress corrosion cracks. Mechanics of materials, 2006, 38, pp. 620-632.
6. Murakami Y., Nemat-Nasser S. Interacting dissimilar semi-elliptical surface flaws under tension and bending. Engineering Fracture Mechanics, 1982, 16(3), pp. 373-386.
7. Carpinteri A., Brighenti R., Vantadori S. A numerical analysis on the interaction of twin coplanar flaws. Engineering fracture mechanics, 2004, 71, pp. 485-499.
8. Samcef-V10, User's manual.
9. Barsoum R.S. Triangular quarter-point elements as elastic and perfectly-plastic crack tip elements. Int. J. numer. Meth. Engng, 1977, 11, pp. 85-98.
10. Erdogan F., Sih G.C. On the crack extension in plates under plane loading and transverse shear. J. Basic Engineering, 1963, 85, pp. 519-527.