Modeling of Defect Front Evolution During its Propagation in Fatigue

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Abstract On the basis of experimental results led on thick plates in three point bending and on thick tubes under internal pressure, containing the same type of surface defect of semi-elliptic form, one proposes to describe a simple numerical method allowing to predict the defect geometry evolution during their propagation. This method known under the name of global approach is based on the assumption that the real crack front minimizes the potential energy. Thus, the calculation of the energy release rate from the experimental data in our possession allowed us to propose a method to follow the evolution of the two semi-axes of the crack during its propagation in fatigue without having recourse to the use of a propagation law.

1 INTRODUCTION

The life time of structures and the installations at high security, we obliged to preview the evolution of cracks that's exist or being developed during the service field. This could be doable by theory prediction, by numeric simulation or by mechanical tests. One of cracks forms which are nearest to present on the mechanical structures, are on a helical shape, it means, semi-elliptic. The prediction of the evolution in the shape of himself type of defect during its propagation in fatigue, present a particular complexity by the fact of its geometry and by the difficulty in the choice of a law of fissuration of fatigue in three dimensions that takes to its account the mechanical parameters majority (bound to the material) and geometric (bound to the defect).

Since loan of a half century several researchers tried to foresee the evolution of surface cracks during their propagation in fatigue, especially those of semi-elliptic shape. The quasi-totality of these works was about shortcomings contained in plates and in tubes charged cyclically in flexion three and four points [1 to 9] or in plates charged in traction [10 to 21]. In spite of the number and the recorded work quality, the problem always remains posed. What to make for example, in the case of a semi-elliptic defect propagating itself in a partition of a thick tube under internal pressure?

A synthesis of results brought back by the literature relative to plates under a loading of flexion or traction and cylinders solicited in flexion and under internal pressure [22 to 26] already give us a suspicion's answer on counts:

- to the change in the defect's shape during its propagation [22 and 23],
- to the type of criteria to the of the approach used for the spoliation of test results [23, 27 and 28].
- to degrees of such or such empiric relation validity established in the goal to foresee the evolution in the shape of this type of shortcoming during their propagation in fatigue [23].

In this paper, we intends from a numeric simulation based on the method of finite elements, in addition of test results, leads on the thick plates in flexion three points and on the thick tubes under internal pressure to review the problem.

2 EVOLUTION OF THE SEMI-ELLIPTIC CRACK FORMED

For a semi-elliptic shape surface crack (figure 1) contained in a tube, can from experimental results are published. Y.S. Yoo and K. Ando [24], achieved tests on tubes of different geometric dimensions in presence of cracks semi-elliptic different dimensions circumferential loaded in flexion four points. The two authors noticed that for all configurations studied the report of the two demi-axis, a/c offers toward one slightly tilted asymptote, consolidated around values 0.7 and 0.9. These results have been given as a function to a/t ratio.

V.N. Shlyannikov, A.V. Tchadaev V.A and. Kalatchev [25], achieved a numeric survey on the semi-elliptic crack progression contained in a cylinder. Different geometric dimensions of the cylinder and the defect have been used. These authors adapted an approach based on the detection of the rupture's zone damage and the factor of constraint intensity calculated by the analytic expression of Newman and Raju [29]. They conclude that, the report of the two demi-axis of ellipsis a/c offer toward a value asymptotic understood between 0.46 and 0.52. These results have been given as a function to the report of the thickness to the interior ray of the cylinder (t/Rint).

X.B. Linen and R.A Smith [26], proposed a general method that follows the change of shape of cracks in three dimensions. Their method can be applied at any defect of surfaces and in particular the semi-elliptic shape shortcomings contained in any type of structures. The two authors use the factor of constraint intensity local and one laws of Paris - Erdogan type propagation to follow the progression of certain numbers of points of the crack forehead (figure 1).

Table 1. Conditions of fatigue test [1 and 23]

Designation	Tube	Plaque
Thickness [mm]	25	50
Diameter rxterior [mm]	250	-
Diameter interior	200	-
Length [mm]	500	500
Width [mm]	-	100
Maximal load	500 bars	90 kN
Load ratio : $R = \frac{P_{min}}{P_{max}}$	0.3	0.1, 0.3 et 0.5
Nature of test	Oiled	ambient
distance between supports [mm]	-	480

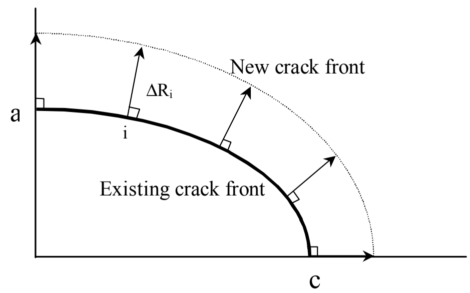


Figure 1. Crack growth prediction using local approach [26].

Boukharouba and al. [1, 22, 23 and 30], published the experimental results achieved on tubes under internal pressure and on plates in flexion three points. The specimens of test have the same defect are manufactured in a steel to high limit of elasticity, the 35 NCDV12S and tests have been achieved in conditions summarized in the table (1). In the case of tube the experimental results published, show that the crack propagates itself as the ratio of the two demi-axis ellipsis a/c offers toward one almost horizontal asymptote, in the value of a/c ratio depends a lot of the initial dimension of the defect. Results have been given as a function to a/t ratio. Authors conclude that this variation is close to the one gotten on plates fissured loaded in traction.

3 METHODE OF CALCULATION

We noticed the lack of physical justification and the practices insufficiencies in the quoted approach use to foresee the change of the geometric shape of surface cracks during their propagation in fatigue. Besides, we also noticed the dispersion of results and by same time a contradiction while using him of the different empiric relations. Us, we propose to use the global approach as criteria of propagation of the crack while doing call to the principle of minimization of the potential energy ∏ of the structure fissured, or to a maximization of the rate of restitution of energy G.

The principle is simple, a semi-elliptic crack of initial dimensions (a_1, c_1) propagating itself of an increment ΔA offers toward a final shape of dimension (a_2, c_2). This final shape restraint minimizes the potential energy of the structure fissured. While applying this principle, we can put a procedure of follow-up of the change of the geometric shape of the crack in place during its propagation (figure 2), without having recourse to a law of propagation. The calculation of the potential energy ∏ (equation 1) of the two fissured structures (plate and tube) takes in consideration the following points:

- the initial defect is defined solely by its two demi-axis (a_0, c_0),
- a quarter of the structure was modified (symmetry of the geometric and the loading in relation to the crack),
- the crack remains semi-elliptic during its propagation, what is verified experimentally [1 and 23],
- the material is linear elastic.

$$\prod = U - W \tag{1}$$

where:

W: Outside forces work,

U: elastic strain energy.

For the code of calculation the following formula is used:

$$W = \sum F_i \cdot q_i = \{q\}^T [K]\{q\} \tag{2}$$

where:

F : exterior load,

q : displacements,

K : matrix de rigidity.

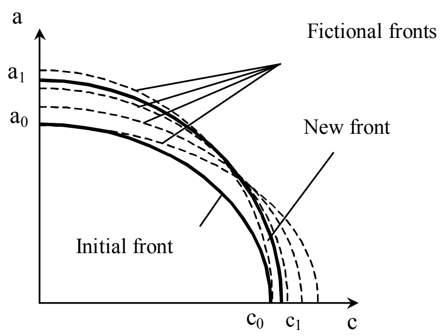


Figure 2. Fictional and real progressions of the crack.

It is necessary to suppose several possible fictive foreheads (a_i, c_i) having the same increment ΔA (figure 2) in relation to the initial forehead. For every fictive forehead it is necessary to calculate the variation of the potential energy Δ∏ or the restitution rate of the energy G. while using the method of disruption:

$$\Delta W = -\{q\}^T [\Delta K] \cdot \{q\} = -\sum F_i \cdot q_i \tag{3}$$

$$G = -\frac{d\Pi}{dA} \approx -\frac{\Delta\Pi}{\Delta A} = \frac{1}{2} \cdot \frac{\Delta W}{\Delta A} \tag{4}$$

The goal is to get a value of the potential energy for every fictive forehead. These values lead to a variation of this potential energy that can be represented by a parabola. By a smoothing of points of calculation and interpolation we determine the minimum of the potential energy rate (figure 3), what we draw the new forehead of the crack by the (a_1, c_1). Of this manner, we can recreate the forehead of fissuration until the critical dimension.

An example of calculation results compared to the experimental data is represented in figures (4 and 5). We notice that in the two cases of figures the precision is a very substantial degree.

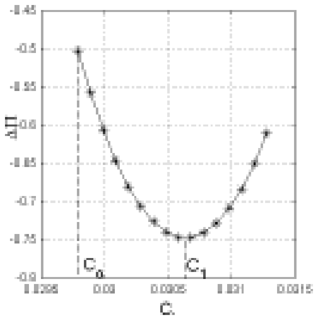


Figure 3. Variation of the potential energy for the different fictive foreheads.

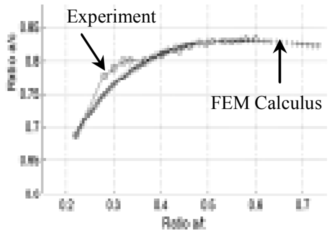


Figure 4. Evolution the crack's shape in the case of a tube under internal pressure.

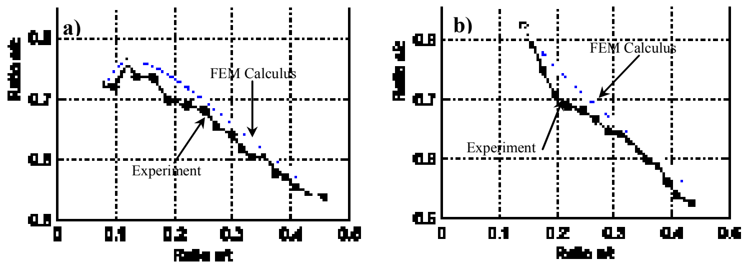
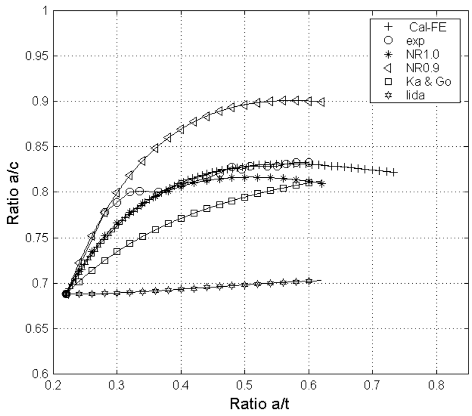


Figure 5. Evolution the crack's shape in the case of a plate in flexion three points.

4 DISCUSSION

Figures (6 and 7) give a comparison between the experimental results, those gotten while using a numeric simulation based on the global approximation and those gotten by the different empiric relation use given in the literature. We notices that these results are very dispersed. Predictions given by formulas of Iida [31] and those of Mahmoud [32 and 33] using the correlation of Newman Raju and [35] $C_c=0.9^m$. C_a, are very far of the experimental results and that, in the two cases of figures.

The relation of Groner and al. [34] under estimation the progression of the crack in depth in the case of a tube and overestimates it in the case of a plate in flexion three points. On the other hand, the one proposed by Mahmoud [32 - 33] while using $C_c=C_a$ [35], gives a good prediction of change in the crack's shape in the two cases of figure, but offers little toward one asymptote inclined toward the end, in the case of a tube. To the descended of these results we propose two empiric models (equation 6 and 7) describing the evolution respectively in the shape of a semi-elliptic defect in the case of a tube under internal pressure and in the case of a plate in flexion three points.



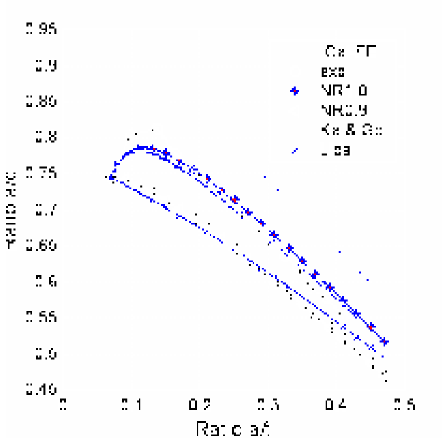


Figure 6. Case of a tube under internal pressure

Figures 7. Case of a plate in flexion three points

Case of a tube under internal pressure

$$\left(\frac{a}{c}\right)_i = 0.9 - 0.075\left(\frac{a}{t}\right)_i + \lambda_{Bt}\left(\frac{a}{t}\right)_i^{-2} \quad (6a)$$

With:

$$\lambda_{Bt} = \left(\frac{a_0}{c_0} + 0.075\left(\frac{a_0}{t}\right) - 0.9\right)\cdot\left(\frac{a_0}{t}\right)^2 \quad (6b)$$

Case of a plate in flexion three points

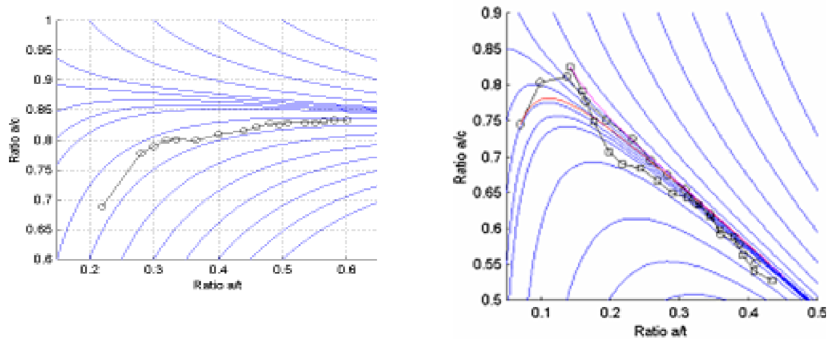
$$\left(\frac{a}{c}\right)_i = 0.915 - 0.85\left(\frac{a}{t}\right)_i + \lambda_{Bp}\left(\frac{a}{t}\right)_i^{-2} \quad (7a)$$

With:

$$\lambda_{Bp} = \left(\frac{a_0}{c_0} + 0.85\left(\frac{a_0}{t}\right) - 0.915\right)\cdot\left(\frac{a_0}{t}\right)^2 \quad (7b)$$

The tracing of evolution curves from these two models for different ratios of two demi-axis compared to the experimental results is illustrated respectively by figures (8 and 9). It is noticed that:

- the change of shape of a defect contained in a thick plate in traction or in a thick tube under pressure would give the same type of evolution, to see face (6),
- the shape with which propagates itself this type of defect depends on its initial size and the type of solicitation (traction, flexion, pressure, etc.),
- during the propagation, initially elliptic defect remained elliptic but non homothetic in the case of flexion. On the other hand, its shape offers toward a stable shape (ratio a/c becomes constant during the propagation) in the case of traction and in the case of the internal pressure,
- from the value of a/c = 0.80, in the case of a plate in flexion three points, the propagation this fact a lot more in surface that one depth,
- in the case of a tube under internal pressure, the value of ratio a/c = 0.85, represent a limit in the change in the crack's shape. This limit is symbolized by an asymptotic to curves joining the variation ratio a/c as a function to a/t. in other words, the propagation in surface and in depth will make itself with the same increment represented by ratio a/c.



case of a tube under internal pressure   case of a plate in flexion

Figure 8. Drawn of model proposed for the prediction of the shape evolution of semi-elliptic cracks.

5 CONCLUSION

The objective of this survey was double, in the first place, we wanted to go up that can predict us comfortably the evolution in the defect's shape propagating itself in a partition of a thick tube or a thick plate and that, from a simple numeric simulation, using the geometric dimensions of the defect solely. Among advantages of using this simulation based on the global approach we mentions:

- non recourse to the experience seen some determining the relation between the crack size and the cycles number to the propagation in fatigue, necessary in case of utilizing of the local approximation and semi local [1, 23],
- non recourse to the use of a propagation law that permits to go back up to the profile adapted by the crack after or during the propagation [1, 28]. Generally these laws of propagation are adapted badly or their validities are not verify indeed for cases 3D,
- the description of all crack forehead (faces) and no two points of the forehead (the deepest point and in surface), as in the case of the local and semi-local approach,
- the good concordance between results of the simulation and of by the experience and that, to least cost in relation to all other methods of calculations or prediction.

In second place to propose two empiric models of simulation permits to predict the evolution in the shape of a semi-elliptic defect propagating itself in the partition of a tube under internal pressure and in the thickness of a plate in flexion three points. The exploitation of these two models permits us, to go back up to the shape adapted by the elliptic defect during its propagation in fatigue without the recourse to tests costing expensive excessively especially in the case of tubes under internal pressure. It's sufficient therefore, to determine by one of non destructive control methods the initial notch of the defect to define its profile thereafter during its propagation in fatigue.

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