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T. BOUKHAROUBA* and G. PLUVINAGE**

Crack Propagation in a Cylinder Submitted to Internal Pressure

* USTHB IGM BP. 32 El-Alia, Bab-Ezzouar Alger - Algérie.
** LFM Université de Metz, Ile du Saulcy 57045 Metz - France.

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ABSTRACT : The fatigue propagation of a semi-elliptical surface crack in a pipe submitted to internal pressure is always an open question although a number of numerical works. Crack front evolution is generally predicted by empirical relationships.
This fatigue propagation in the case of a pipe submitted to an internal pressure have been obtained using a special device allowed to produce an internal pressure up to 700 bars. Crack aspect ratio evolution is similar to those of a crack in plate submitted to tension.

Introduction

Propagation of a semi-elliptical crack is oftently observed on the failure surface of engineering structures like pipes, bolts, plates, pressure vessels etc... Several investigators have pointed out that the fatigue propagation of surface flaws in metallic plates are significantly affected by the crack shape change for any kind of loading. The semi-elliptical form is preserved during the whole growth but the aspect ratio of the part through defects changes (figures 1a and 1b).

The results from literature show that these flaws tend to follow a common propagation path in the diagram of the crack aspect ratio a/c against the relative crack depth a/t. As it can be seen on figure (1) the ratio a/c first increases until a maximum and decreases quasi linearly and tends to an asymptote, independent of the initial value of a/c and a/t ratios.

Several authors have proposed empirical relationships for crack aspect ratio versus relative crack depth which will be shown further. The safety of a pressure vessel can be asserted using the fracture criterion "leak before break" which needs to know the geometrical evolution of a crack during crack propagation. This evolution is relatively complex as it can be seen on figure (2). At the beginning, crack growths faster in the direction of thickness. After, this stage the propagation is more important in the transverse direction (1 to 3).

Therefore, the prediction of life duration and fracture conditions need to know the following points :

- How the evolution of the crack geometry ?
- What is the crack growth governing law ?
- Is this governing law a function of the stress intensity factor and what is the nature of such a SIF (local, average, global) ?
- Are the coefficients of the law intrinsic to the materials ?

The first point will be examined in this paper, the other are described in (2). Crack front evolution during propagation can be observed on the fracture surface by the shape of the front lines.

These lines show the different steps of crack evolution and result from overload during cyclic loading. A typical example can be seen on figure (2) where the evolution of a surface crack in a steel pipe submitted to internal pressure is easily observed (1 to 3).

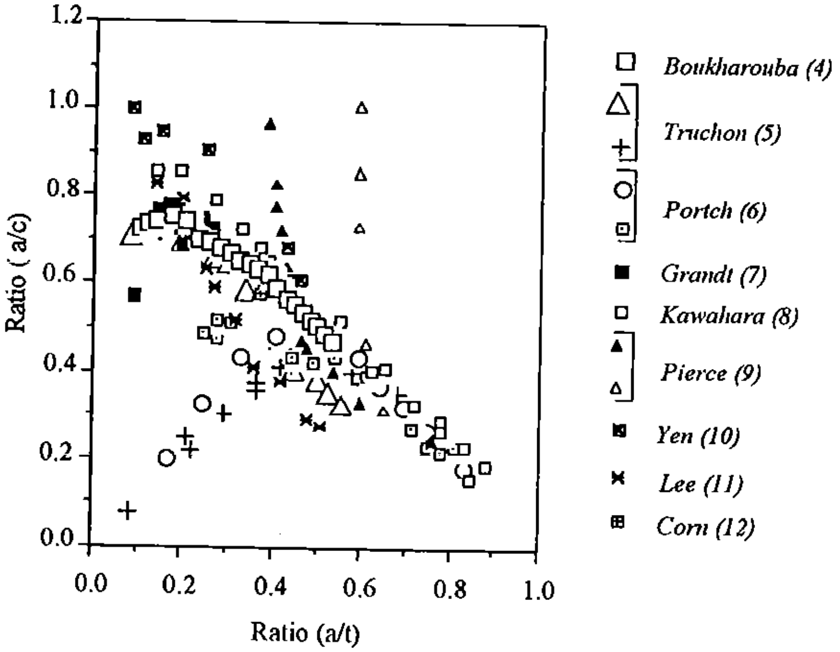

Fig.1a Evolution of crack aspect a/c versus normalised crack depth a/t in bending.

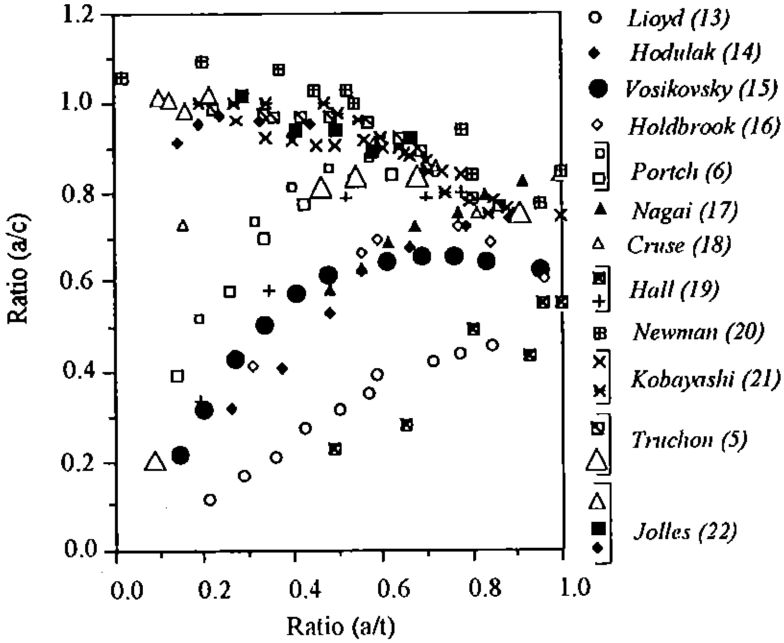

Fig.1b Evolution of crack aspect a/c versus normalised crack depth a/t in tension.

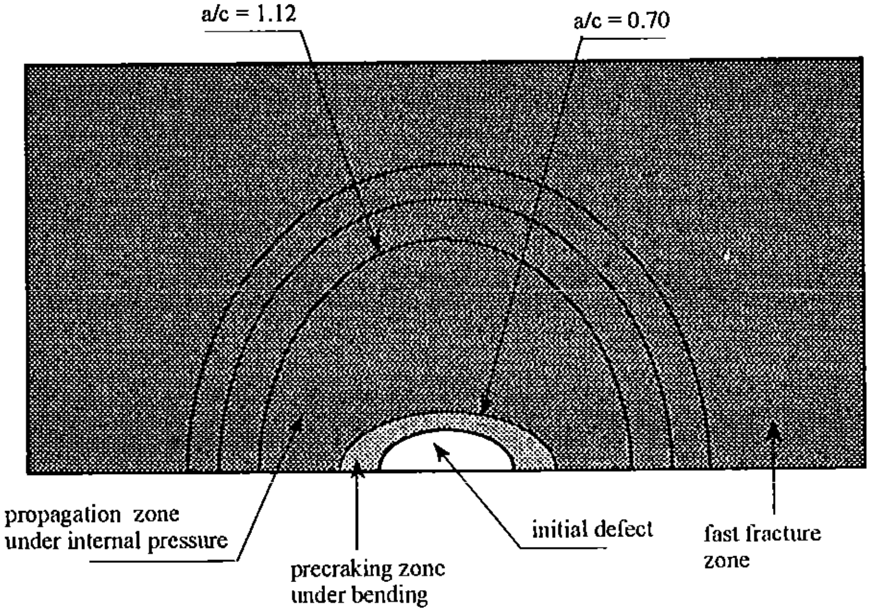

Fig.2 Evolution of crack aspect in a pipe submitted to an internal pressure (1 and 3).

Experimental Study

Tests have been performed on a special device built in the laboratory and able to submit a thick pipe to a high pressure (up to 70 MPa).

Experimental device

Internal pressure is produced by an autonomous apparatus, monitoring by the electronic device of an hydraulic fatigue machine. The hydraulic pressure is get from this fatigue machine (figure 3).

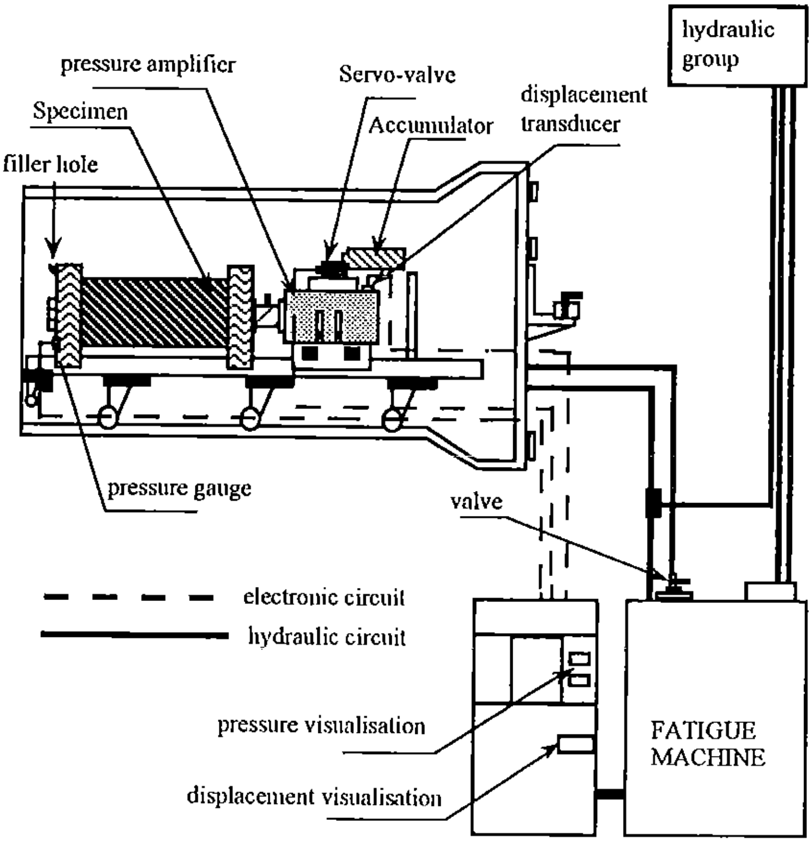

Fig.3 Special device to applied pressure (up to 700 bars) to a thick pipe

This device is constituted with :

- a pressure amplifier (ratio 3.2) monitoring by a servo-valve, which give from the initial pressure (210 bars) the necessary one,
- one LVDT coupled with the pressure amplifier which allows to measure the actuator displacement up to 60 mm,
- a pressure transducer situated on the floppy of the pipe specimen gives the pressure values in the range of 0 - 700 bars,,
- a servo-valve monitoring by the electronic device
- a specimen of pipe's shape,
- one carriage supporting device.

Material and Specimen

The material used for the tests is a 35 NCDV 12 steel (French standard) with thermal treatment. Its mechanical characteristics are given in table (1).

Crack is initiated from a surface notch situated in the middle of the internal wall of the pipe. The specimen has a 500 mm length, an outer diameter of 250 mm and a wall thickness of 25 mm.

Table 1- Mechanical characteristics of the 35 NCDV 12 steel.

yield stress	ultimate stress	elongation	toughness	parameters of the crack propagation law	
Re 0,2 (MPa)	Rm (MPa)	A%	K_{IC} (MPa$\sqrt{m}$)	C	m
1282	1433	11	103	9.2 E-9	2.77

Stress Intensity Factor for a Pipe Submitted to Internal Pressure

Few works have been done to compute the value of the local stress intensity factor in a pipe submitted to an internal pressure. A listing of authors is given in table (2). Finite elements method has been generally used but also the weight functions and the boundary integral method. The results are presented using the following general relationship :

$$K_I(\Phi) = \frac{p R_{int}}{t} \sqrt{\frac{\pi a}{Q}} . M\left(\frac{a}{t}, \frac{a}{c}, \frac{R_{int}}{t}, \Phi\right) \tag{1}$$

With : M geometrical correction factor for a crack in pressurised pipe
p internal pressure
Q shape factor for an elliptical crack
Φ eccentricity angle of the ellipse
R_{int} internal radius of the pipe
a and c semi-axex of the elliptical crack
t thickness of the pipe wall

Table 2 - Works on pressure tubes for SIF calculations.

authors	date	ref.	method	range of validity			
				a/t	a/c	t/R_{int}	results
Kobayashi & al	1977	(23-24)	FDP	.25 to .8	.34	0.1	graph
Helliot & Labbens	1979	(25)	EIB	.25 to .8	.34	1.1	graph
McGowan & al	1979	(26)	FEM	.25 to .8	.34	1.1	graph
Newman & Raju	1980	(27-28)	FEM	.2 to .8	.2 to1	0.1and 0.25	equation
Boukharouba & al	1995	(1)	FEM	.46 to .7	.7 to 1.12	.25	graph

(WF) : Weight function, (BIE) : Boundary integral equation and (FEM) : finite elements method.

Few differences have been found between these results. They are only valid for particular geometrical conditions. No experimental determination of the local stress intensity factor have been made.

Boukharouba and al (1 to 3) have analysed the experimental results of the fatigue crack growth of a surface semi-elliptical crack in a steel pipe. These experiments shows that in the case of a pipe submitted to an internal pressure, the evolution of the crack shape is different from the case of pure tension or bending. After a transient stage, the crack shape becomes quasi semi-circular and keeps this geometry during all the crack propagation.

The evolution of crack aspect ratio a/c versus relative crack depth can reach a horizontal asymptote like for a crack in tension and for a value a/c = 1, which corresponds to a semi-circular crack (figure 4).

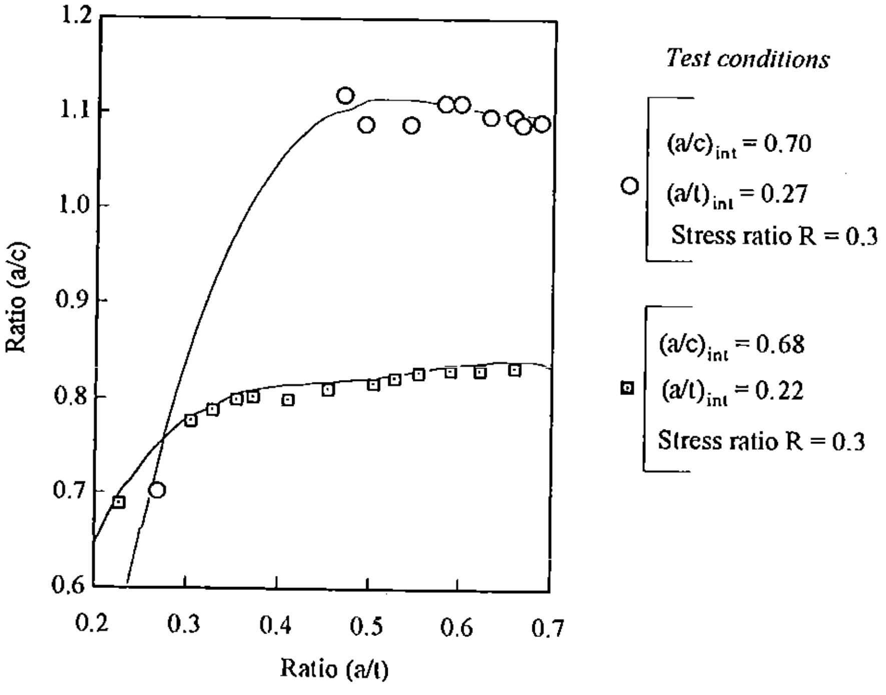

Fig.4 **Crack aspect ratio a/c evolution versus depth ratio a/t, case of pipe under internal pressure**

Results from two tests are reported in figure (4) it crack aspect ratio a/c is plotted versus non dimensional depth a/t. These two results are obtained for two different initial conditions $(a/c)_{int}$ et $(a/t)_{int}$.

Empirical equation for tensile loading

No empirical relationships relative to the evolution of the crack aspect ratio with crack depth for pipe under internal pressure are proposed in the literature. Available results are only relative to plate under tension or bending. Due to the fact that the crack aspect ratio evolution is similar for a plate in tension and a pipe under internal pressure, only empirical relationships relative to plate in tension are listed in table (3).

Case of a pipe submitted to internal pressure

In case of a pipe submitted to an internal pressure, the evolution of the crack shape is different from the case of pure tension or bending (2 to 4). After a transient stage, the crack shape becomes quasi semi-circular and keeps this geometry during all the crack propagation (figure 4). We have compared our experimental results to the empirical relationships proposed for tensile loading (table 3). A new empirical relationship is proposed in order to fit the experimental results.

$$\left(\frac{a}{c}\right)_i = \left(A + 0.07\left(\frac{a}{t}\right)_i\right) - \left(0.000727\left[\left(\frac{a}{t}\right)_i - \lambda_B\right]^{-2.6}\right) \qquad (2)$$

The A parameter in equation (2) defines the initial crack aspect ratio. For the first test A = 1.1 and the defect has an initial semi-elliptical shape with initial ratio a/c = 0.70 and a/t = 0.27 to reach a semi-circular final shape. In the second test A = 0.75, the initial defect is always semi-circular with a/c = 0.68 and a/t = 0.22. This equation is a modified form of Iida relationship. In this case, A has a constant value equal to 0.78.

A comparison of the prediction of these empirical laws has been established and can be seen in figures (5a and 5b). We can notice that these laws are sensitive to the initial crack aspect ratio.

Table 3. Empirical equations for the prediction of the evolution of the ratio a/c given in the literature. Tensile case

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$$\left(\frac{a}{c}\right)_{i+1} = \left[1.1 - 0.35\left(\frac{a}{t}\right)_{i+1}\right] \cdot \left[1 - \left(\frac{a}{t}\right)_{i+1}\right]^4 \left(1.1 - \lambda_P\right) \tag{3a}$$

Portch* (6) the relationship (2a) is valid for $\left(a/t\right)_{i+1} \geq T$

$$\left(\frac{a}{c}\right)_{i+1} = I\left(\frac{a}{t}\right)_{i+1} \quad \text{for} \quad \left(\frac{a}{c}\right)_{i+1} < T \tag{3b}$$

$$I = \frac{\left(a/c\right)_i}{\left(a/t\right)_i} \quad \text{and} \quad T = \frac{4.05 - I}{3\left(I + 0.35\right)} \tag{3c}$$

Gomer**(29)

$$\left(\frac{a}{c}\right)_i = \left[0.98\left(\frac{a}{t}\right)_i - 0.06\left(\frac{a}{t}\right)_i^2\right]\left\{\left(\frac{a}{t}\right)_i^2 + \lambda_G\left[0.06\left(\frac{a}{t}\right)_i\right]\right\}^{-0.5} \tag{4}$$

Iida*** (30)

$$\left(\frac{a}{c}\right)_i = \left[0.78 - 0.07\left(\frac{a}{t}\right)_i\right] \pm 0.0834\left[\left(\frac{a}{t}\right)_i - \lambda_I\right]^{-2.6} \tag{5}$$

Carpinteri**** (31)

$$\left(\frac{a}{c}\right) = a_0 + a_1\left(\frac{a}{t}\right) + a_2\left(\frac{a}{t}\right)^2 + a_3\left(\frac{a}{t}\right)^3 + a_4\left(\frac{a}{t}\right)^4 \tag{6}$$

(*): If T is calculated from (3c), relationship (3b) is used for the full range of $0 < T < 1$. In this case λ_{Π} is calculated from (3a) using the initial (a/t) and (a/c) values. If $0 < T < 1$ then equation (2b) is used for the range $0 < (a/t)_i < T$.

(**) : λ_G is calculated from the initial values of a and c.

(***) : λ_I is a constant calculated using the initial values of a/c and a/t. The plus sing is for $a/c > 0.78 + 0.07\ a/t$ and the minus sing for $a/c < 078 - 0.07\ a/t$.

(****) : The parameter a_i depends on crack shape and m values.

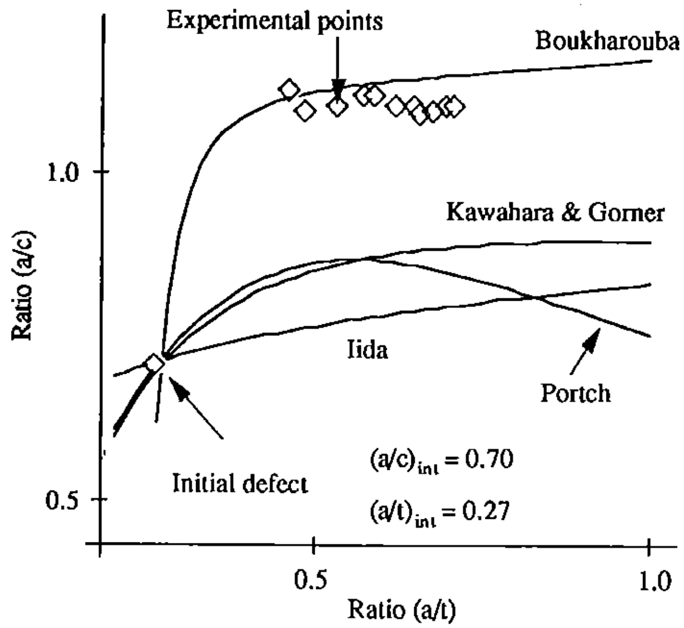

Fig.5a Crack aspect ratio evolution dering crack.propagation.

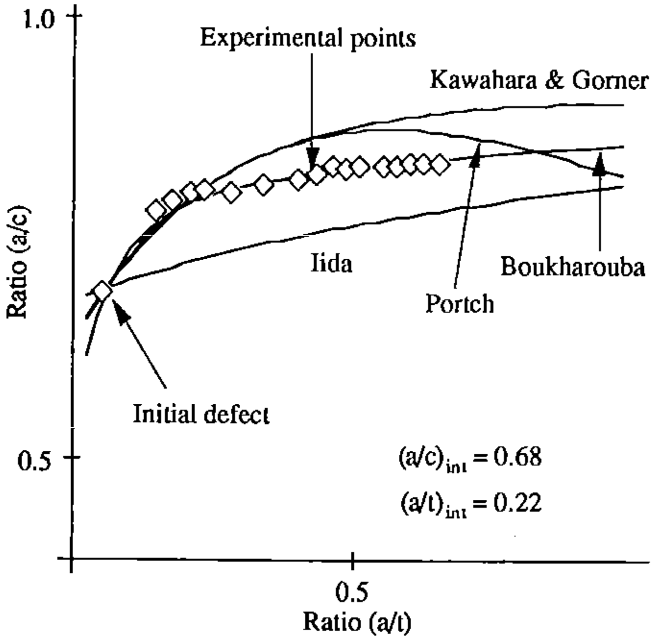

Fig. 5b Crack aspect ratio evolution dering crack.propagation.

Conclusion

Crack aspect ratio for semi-elliptical surface crack in a pipe submitted to an internal pressure is similar to those of a plate in tension. The a/c ratio increases with a/t and trends to an asymptotic value. This evolution is different for a semi-elliptical surface crack in bending.

The empirical law to describes this evolution is very sensitive to initial conditions. For a semi-elliptical surface crack in a pipe submitted to an internal pressure, a new empirical relationship is proposed derived from those proposed by Iida (30) for a case of plate in tension.

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