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FLOW RATE MEASUREMENT IN CRACKED PLATES UNDER TENSION. CORRELATION WITH CRACK OPENING DISPLACEMENT

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ABSTRACT

The paper describes an experimental investigation performed on 4 fatigue cracked plate specimens made of 316 L steel subjected to tensile load.

1.INTRODUCTION

The study is a part of a programme carried out on the behalf of the French Safety Authority (IPSN).
The experimental study presented in this paper is part of a program which aims to correlate the flow measurement through cracks with the geometrical measured dimensions of these ones (length, shape and opening).

2.DESCRIPTION OF THE EXPERIMENTAL PROCEDURE. CRACKING

This stage of the tests consists to initiate and make propagated a notch machined on the surface in a plane plate. The crack is propagated under cyclic tensile solicitation. The propagation is stopped when the crack opens and reaches a given length. All along the test, the opening displacement on the machined notch side is recorded.

2.1Test pieces

The geometry of the five pieces tested is indicated on the drawing of figure 1.
The test piece material is 316 SPH steel whose mechanical characteristics are given in the section A3.1S of RCC-MR. [1].

E = 192 000 MPa, Sy = 275 MPa, Su = 582 MPa

2.2 Experimental device

The test machine is driven in cyclic imposed force (frequency ≈ 200Hz).
The applied loading is the same for each specimen.
The crack opening displacement is given by a clip-gauge extensometer mounted on supports added on both sides on the face which has the machined notch.
The propagation on both faces of the test piece is followed with gauges glued on the crack plane.

3.DESCRIPTION OF CRACKING RESULTS

The figure 2 brings together the dimensions of initial notchs and final cracks obtained for the test pieces 2, 3, 4 and 5.
On figure 3, the graphic evolution of the opening as a function of the effort is represented, keeping only the part corresponding to the first loading and the last unloading.
It has been tried to use the formula for through thickness crack given by Tada (1973) [2] to establish a relation between the opening δ of a crack and the applied tensile effort F.
The rigidity values calculated with this formula are compared to experimental values coming from figure 3. The graphic comparison is reproduced in figure 4. It is clearly distinguished that for a given crack size, the calculated rigidities are higher that the actual rigidities, except for the test piece n° 4. There is some "3 D effect" of the crack due to the local bending induced by the presence of a part through thickness crack in an overall membrane stress state.

4.DESCRIPTION OF FLOW RATE MEASUREMENTS

In this experimentation stage, the water flow rate is measured through the cracks produced in varying the tensile effort and the pressure in the fluid for each test piece.
The test piece is mounted on a tensile machine. The effort is kept constant during a flow rate measurement.
The used water is demineralized and degased. Is is pushed at constant pressure by a capacity.

4.1 Flow rate measurement

The water passing through the crack is collected into a graduated beaker. The flowed water volume V is obtained as a function of the measurement duration given by a chronometer. The mean flow rate is calculated with the formula :

$$Q = V / t$$

For each test piece, the nine different measurements are done with decreasing loading, i.e. in the order given by table 1.
Proceeding so, we begin to measure the higher flows, which are less submitted to blocking. When the loadings decrease, we can reach flow values where blocking takes place, i.e. non constant flow values and even null flows.

5.RESULTS OF FLOW RATE MEASUREMENTS. INTERPRETATIONS

A graphic illustration of these results is shown on figure 5. We have represented on a logarithmic axes system the flow rate measurements Q versus applied pressure P for different tensile efforts. These measurements are represented by points.

5.1 Flow rate/pressure correlation

The figure 5 allows to adjust straight lines joining the flow values Q versus pressure P at constant tensile efforts F for the test pieces 2, 3 and 4. The slopes found for each straigth line are calculated. The indicated slope is the ratio :

$$\text{slope} = \log P / \log Q$$

Such graphic adjustments allow to consider the existence of a relation between P and Q which is of the form :

$$Q = K\, P^{\alpha}$$

where K is a constant and α is an exponent ranging between 0.6 and 0.8 for the test piece n° 2, which is the most cracked and leads to higher flow rates, and ranging between 2 and 1.1 for the test pieces.3 and 4. There values are given in the table 2.

5.2 Flow rate/opening correlation

We have represented on figure 6, the flow rate values measured versus opening δ recorded by the extensometer for the applied effort with the effort/opening low obtained at the last propagation cycle. This quantity comprises the residual opening (which can be estimated for a null tensile effort) and the practically linear elastic opening due to the monotonous loading applied during a flow rate measurement.

We can adjust straight lines joining the representative points for a pressure P and a given test piece. The slopes of adjusted straight lines are indicated on figure 6. At last if we admit a relation of the form :

$$Q = K\delta^{\alpha}$$

the α value is ranged between 2.2 and 3.2 for the test piece n° 2 ; 5 and 9 for the test piece n° 4 and 3.1 and 3.7 for the test piece n° 3. There values are given in the table 2.

5.3 Formula of leakage flow

5.3.1 Laminar regime

When dealing with a conduct, it is usual to calculate the Reynold's number with the formula :

$$R = u.D / \nu$$

where :
u is the mean velocity of the fluid in he considered section, D is the section diameter, ν is the kinematic viscosity.
In order to apply the above formula we can turn to use the hydraulic parameter of the section, which is estimated by the ratio of 4 times the area over the perimeter of the ellipse (with $a >> \delta$).

$$D = (\pi \, a \, \delta/4) / 2 \, a = \pi\delta / 2.$$

With the same assumptions, it is possible to calculate the flow velocity u from the flow Q with the formula :

$$u = Q / \pi \, a \, \delta/4$$

At last we get the formula :

$$R = 2Q / a \, \nu$$

For the test piece n° 2 we find, taking a water kinematic value : $\nu = 10^{-6}$ m^2/sec, for the two extreme measured flows :(Q = 120 ml / mn, R = 80), (Θ = 1815 ml / mn, R = 1210).
These two values indicate the flow regimes are located in the viscous laminar domain.

5.3.2 Verification of a flow formula

The experimental results can be compared to the laminar massic flow Poiseuille's formula given for a flow by parallel and rectilinear thin jets between two plane plates.

$$Q = b^3 \, a \, P / (12 \, \nu \, e)$$

where b is the distance between the two planes. Assuming that the breach area has an ellipsoidal shape, the value b giving the same hydraulic diameter is calculated for the ellipse and the rectangle of length a. It is found :

$$b = \pi\delta / 4$$

from which comes the laminar flow Poiseuille's formula :

$$Q = (\pi^3 / 768) (\delta^3 \, a \, P / \nu \, e) \approx 0.04 (\delta^3 \, a \, P / \nu \, e)$$

This formula makes appear a power of 1 between flow rate and pressure, of 3 between flow rate and opening for experimental correlations is reminded in the table 2. The flow rate is calculated using the values a, d, P and e of the test. The results are presented in the table 3 and compared to the experimental results.
It can be seen the calculated flow rate is always higher than the experimentally measured flow rate.
The flow rate formula applies better when the flow rate is higher.
This formula and the margins found for the test piece n° 2 indicate that if we want to use the flow rate measurement and the above formula to evaluate a crack dimension, knowing

all the other necessary data, we result in an underestimate ranging between 8 to 15 times on the defect size. On the opening value we underestimate from 2 to 2.5 times the actual opening.

6.CONCLUSIONS. RECAPITULATION

The experimental study consists to produce through cracks by fatigue and to measure the flow rates of water through these cracks under mechanical loading effect.
Within the conditions of performed tests, it appears the calculation of dimensions for a through crack, with a known flow rate leakage, requests a great deal of prudence.

REFERENCES

[1] RCC-MR. Règles de conception et de construction des matériels mécaniques des îlots nucléaires RNR. Design and construction rules of mechanical materials for FNR sites. AFCEN edition, june 1985.

[2] Tada. The stress analysis of cracks handbook. Del Research Corporation. Hellertown, Pennsylvania, 1973.

ORDER	EFFORT (kN)	PRESSURE (bar)
1 2 3	75	5 3 1
4 5 6	37.5	5 3 1
7 8 9	0	5 3 1

TABLE 1 : ORDER FOR FLOW RATE MEASUREMENTS

EXPONENTS	CALC.	TESTS			
		T.p. 2	T.p. 3	T.p. 4	T.p. 5
Q/DP	1	0.6-0.8	1.3-2	1.1-1.8	*
Q/δ	3	2.2-3.2	3.1-3.7	5 - 9	*

* *null flow.*

TABLE 2 : VALUES OF EXPONENTS FOR CORRELATIONS BETWEEN FLOW RATES AND PRESSURE OR CRACK OPENING.

P	TEST PIECE n° 2				TEST PIECE n° 3				TEST PIECE n° 4				TEST PIECE n° 5			
		Q cal	Q exp	Q cal / Q exp		Q cal	Q exp	Q cal / Q exp		Q cal	Q exp	Q cal / Q exp		Q cal	Q exp	Q cal / Q exp
1 3 5	103	1311 3934 6556	120 320 475	11 12 13.8	14	1.18 3.55 5.93	0 0 0	- - -	24	10.95 32.8 54.7	0 0 0.023	- - 23.78	7.8		0 0 0	
1 3 5	142.5	3472 10417 17362	400 830 1180	8.7 12.5 14.7	36.4	20.8 62.5 104	0.022 0.168 0.48	103 372 216	31.8	25.4 76.4 127	0.712 5.4 12.9	35.4 14.1 9.8	24.2		0 0 0	
1 3 5	179	6882 10417 17361	715 1295 1815	9.6 8.04 9	59.0	88.7 266 444	3.33 11.5 25.26	26.6 23.1 17.5	39.6	49.2 147.5 246	19.50 58.7 116.6	2.5 2.5 2.1	-		0 0 1.02	

TABLE 3 : VERIFICATION OF A FLOW RATE FORMULA.

ΔP in bar
δ in μm
Q in ml/min.

ac in mm
* extrapolated value
\- undefined value

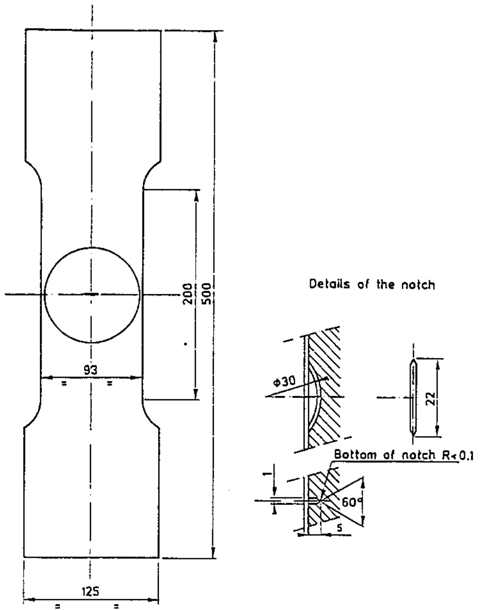
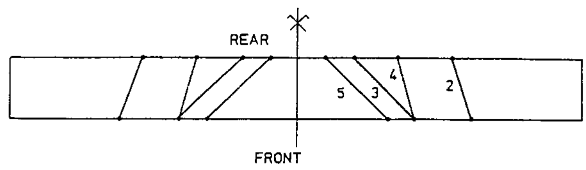


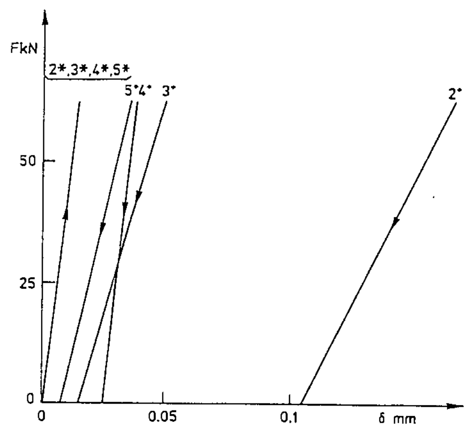
Fig. 1 - GEOMETRY OF THE TEST PIECES



TEST PIECE NUMBER	NUMBER OF CYCLES AT END OF TEST	FINAL NOTCH mm	
		Front ai	Rear ae
2	2320800	57.39	50.26
3	2684000	38.6	18.5
4	2794000	38.47	32.84
5	5372000	29.5	9

Initial notch :
ai = 5 mm
depth = 22.4 mm

Fig.2 FINAL CRACK CONDITIONS



* Initial crack
\+ Final crack

Fig. 3 - EFFECT OF CUMULATIVE OPENING DISPLACEMENT

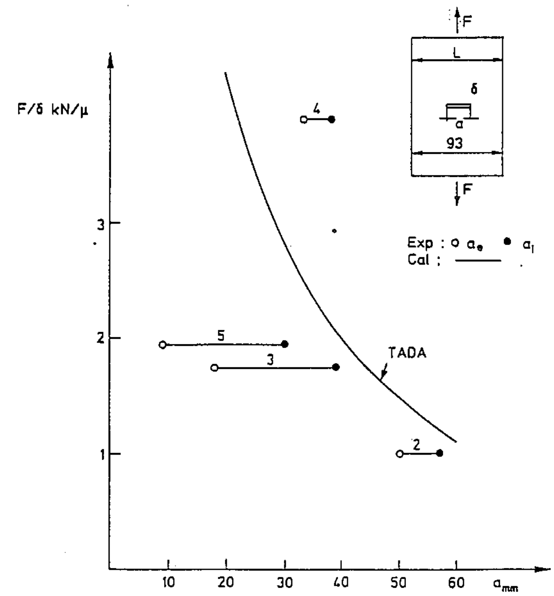


Fig. 4 - DIAGRAM GIVING THE ELASTIC RIGIDITIES

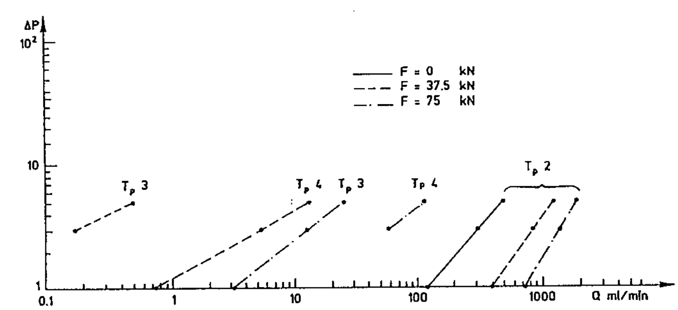


Fig. 5 - FLOW RATE-PRESSURE CORRELATION

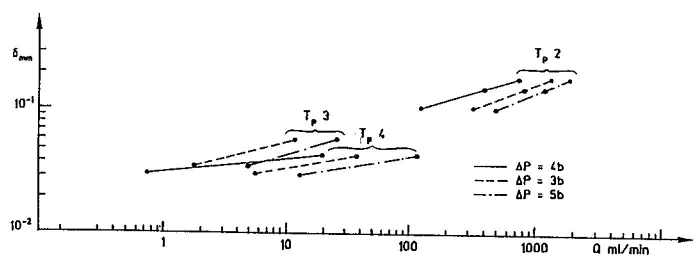


Fig. 6 - FLOW RATE-OPENING CORRELATION