DUCTILE FRACTURE ANALYSIS OF CIRCUMFERENTIALLY SURFACE CRACKED PIPES UNDER BENDING

P. Le Delliou *, E. Meister **

EDF has conducted two bending tests on 406 mm diameter pipes containing a circumferential constant depth surface crack. This paper describes the experimental results and the fracture analyses performed with simplified and finite element methods. J-estimation schemes are generally conservative but not very accurate. Moreover they are presently limited to pipes with a mean radius to thickness ratio of 10.

INTRODUCTION

In 1986, Electricité De France started a program on fracture of carbon and stainless steel cracked pipes. The purpose of the program was to develop a better understanding on pipe fracture behaviour in order to evaluate leak before break (LBB) concept and to improve in service flaw assessments. The experimental grid involved 168 and 406 mm outer diameter pipes loaded in four point bending. Most of the tests concerned circumferential through-wall cracks with total angles ranging between 30° and 120° [1]. Only two tests were made on 406 mm diameter pipes containing constant depth circumferential surface crack, one on a carbon steel pipe and the other one on a stainless steel pipe. This paper describes the experimental results and the fracture analyses performed with simplified methods and finite element calculations.

* Electricité De France (EDF), Direction des Etudes et Recherches,
Dpt MTC, Les Renardières, 77250 MORET s/LOING, FRANCE

** Electricité De France (EDF), Direction des Etudes et Recherches,
Dpt MMN, 1, av. du Général de Gaulle, 92141 CLAMART, FRANCE

EXPERIMENTS

Description of pipe tests

The material is A42 carbon steel (similar to ASTM A106 Gr. B) for the first pipe and AISI 316 austenitic steel for the second pipe. Outer diameter of both pipes is 406 mm. Wall thickness is 21 mm for the carbon steel pipe ($R/t = 9.2$, where R is the mean radius) and 40.5 mm for the stainless steel one ($R/t = 4.5$). Total length of the pipe specimens is 8.5 m. The stainless steel specimen is made of a central piece (length 0.75 m) welded in the center of carbon steel moment arm pipes. The tests were conducted under four point bending load (inner span = 2 m, outer span = 8 m) at 300°C and quasi-static loading rate (displacement rate of the ram : 3 mm/min).

The surface crack had a length of 120°, and a depth-to-thickness ratio of 0.666 (figure 1). The flaw was made by electric discharge machining.

The data collected during the experiments were : applied load, ram displacement, COD at the center of the crack, rotations of the pipe, pipe diameter variations (for ovalization) and d-c electric potential drop measurements. These potential drop measurements were not very successfull, because it was impossible to detect crack initiation.

Applied load versus ram displacement curves are presented in figures 4 and 5, while COD versus ram displacement curves are given in figures 6 and 7.

Material characterization

The material characterization tests consisted of chemical analyses, tensile tests and J-resistance tests. The true stress - true strain curves are given in figure 2. The following J-R curves have been adopted for the calculations :

- carbon steel : $J_{0.2} = 122$ kJ/m^2 and $J = 273.8\ (\Delta a)^{0.66}$,
- stainless steel : $J_{0.2} = 1370$ kJ/m^2 and $J = 1330\ (\Delta a)^{0.71}$,

the crack extension Δa being in mm. $J_{0.2}$ is the value of J at a crack extension of 0.2 mm.

ANALYSES

Finite element calculations

For symmetry reasons only a quarter of the pipe is modelled. The model is built up with three-dimensional 20-node elements, containing 9000 nodes for the stainless steel pipe and 13700 nodes for the carbon steel pipe (figure 3). The non-linear calculations are conducted on a CRAY YMP computer with the finite element program PERMAS. The 3-D J-integral is calculated along the crack front using the G-THETA method developed by EDF [2]. Comparisons with experiments are made, for a given displacement, on the applied load and the crack opening displacement. A good agreement is observed between computed and experimental loads (figures 4 and 5), particularly for the carbon steel pipe. The COD values are considerably underestimated by the calculations (figures 6 and 7), probably because large deformation occurs in the ligament.

Engineering fracture mechanics methods

The R6 approach [3] was applied to calculate the maximum moment using the following expressions for the limit load :

$$M_L = 4\,\sigma_y\,R^2 t\,(\sin\beta - \frac{1}{2}.\frac{a}{t}.\sin\theta) \quad \text{with} \quad \beta = \frac{1}{2}(\pi - \frac{a}{t}.\theta)$$

and for the stress intensity factor [4] :

$$K_I = \sqrt{\pi a}\,\sigma_b\,F_b = \frac{\sqrt{\pi a}\,R}{I}\,F_b\,.\,M$$

$$\text{with } F_b = 1.1 + \frac{a}{t}.[-0.09967 + 5.0057\,(\frac{a}{t}.\frac{\theta}{\pi})^{0.565} - 2.8329\,(\frac{a}{t}.\frac{\theta}{\pi})]$$

where R, t, a and 2θ are the mean radius, the thickness of the pipe, the crack depth and the crack angle, respectively. The expression for F_b was developed for a R/t ratio of 10. Comparisons with FE results showed that it gives a correct value for the carbon steel pipe (R/t = 9.2) but not for the stainless steel one (R/t = 4.5). The maximum moment predicted by the R6 rule is conservative for both tests : carbon steel pipe : 484 kN.m (exp. 566 kN.m), stainless steel pipe : 1019 kN.m (exp. 1041 kN.m).

The other simplified methods, aimed to calculate the J integral, have been applied only to the carbon steel pipe, because they are presently available for a R/t ratio of 10. EPRI method is described in [4,5] while SC.TNP and SC.TKP methods are described in [6]. These methods rely on a Ramberg-Osgood fitting of the tensile curve and a decomposition of J in 2 components : $J = J_e + J_p$ (the elastic component is neglected in SC.TNP and SC.TKP methods). The R-O parameters used for the carbon steel pipe are the following :

$\sigma_0 = \sigma_y = 183$ MPa, $\alpha = 2.14$ and $n = 4.17$.

Comparison of J versus bending moment curves is shown in figure 8. All the methods are conservative compared with FE results, except SC.TNP.

CONCLUSIONS

Fracture analyses were performed on two surface cracked pipe experiments. Finite element method gives a good estimation of the load-displacement curve but underestimates the COD-displacement one. Simplified methods generally overestimate J value compared with FE results, and hence conservatively predict instability load. However, these methods are presently limited to pipes with radius to thickness ratio of 10.

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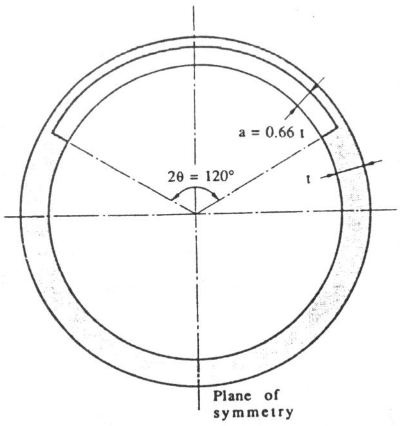

Fig. 1 Schematic of crack geometry

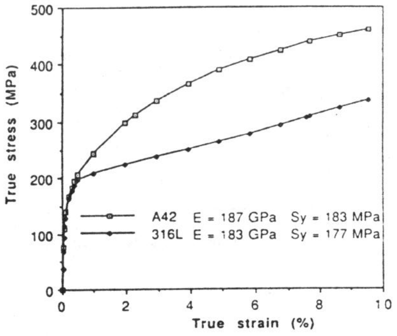

Fig. 2 True strain - true stress curves at 300°C

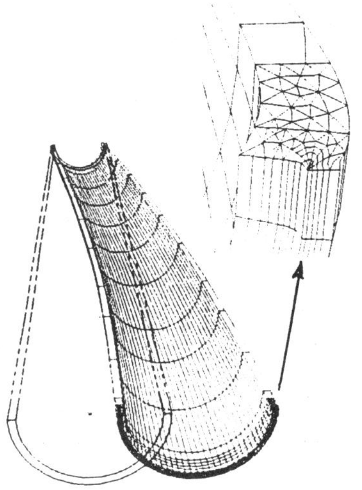

Fig. 3 Deformed view of the finite element mesh (carbon steel pipe)

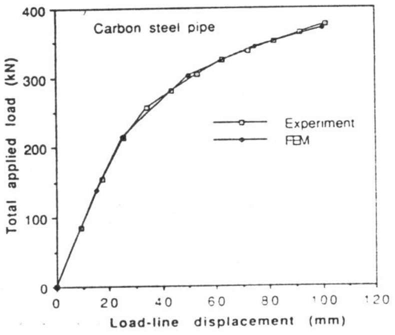

Fig. 4 Load versus load-line displacement (carbon steel pipe)

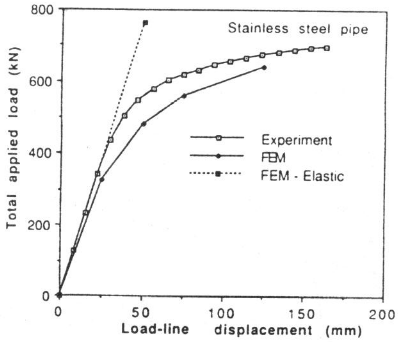

Fig. 5 Load versus load-line displacement (stainless steel pipe)

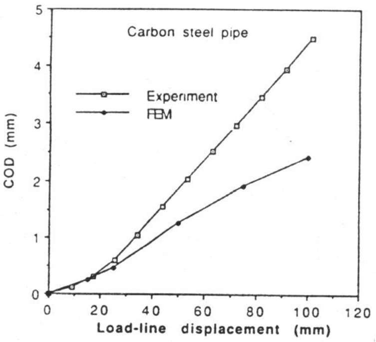

Fig. 6 COD versus load-line displacement (carbon steel pipe)

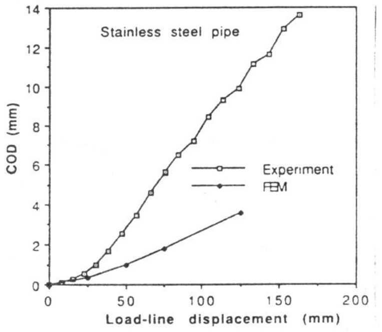

Fig. 7 COD versus load-line displacement (stainless steel pipe)

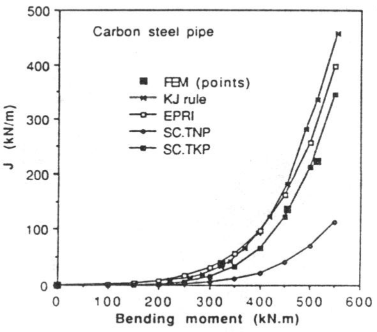

Fig. 8 J versus bending moment (carbon steel pipe)