Experimental Investigation of Crack Stability and Propagation in Piping under Bending

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ABSTRACT

This paper describes recent results obtained during an experimental investigation with tubes under bending load. These tests are carried out in France in CEA at Saclay in collaboration with FRAMATOME and Electricité de France in order to establish and validate criteria to perform leak before break analysis for primary circuit of PWR made with 316L steel.

The cracks are through-wall. 14 specimens were tested with prefatigue cracks. Initiations take place a long time before maximal bending load. A considerable striction occurs (reduction of thickness = 0.5). The behavior is somewhat different between larger cracks (angles > 60 degrees) and smaller cracks. Reduction of classical "flow stress" is necessary if limit load analysis is used to predict initiation and maximal load. Between initiation and maximal load the experimental value of J varies by a factor larger than 10.

1 INTRODUCTION

During the past few years, important work was performed for development of non linear techniques to assess degraded nuclear piping. A reference study was made at Battelle's Laboratories (Kanninen et al. 1982); practical experimental procedures are available (Zahoor et al. 1981) and (Wilkowski et al. 1981) to treat the particular problem of circumferentially cracked pipe in bending.

It was decided to check the validity of those results to predict the behavior of cracks during initiation and propagation on representative piping components.

First results of this experimental study has been already presented (Moulin et al. 1989a) in the case of evaluation of crack initiation (Moulin et al. 1989b, and Touboul et al. 1989) in the case of evaluation of crack propagation and for elbows. The present paper underlines recent results concerning: influence of the experimental definition of initiation in the test, influence of the reduction of thickness during propagation, the consequence on J evaluation and adjustment of flow stress for the limit analysis.

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2 DESCRIPTION OF TESTS

A more complete description of the experiments can be found in the previously referenced paper. Figure 1 recalls the four points bending experimental device used. The straight tubes have through thickness cracks ranging from 15 degrees to 150 degrees (total center angle).

Before monotonic bending load is applied the machined notchs are fatigue precracked under cyclic bending load inferior to 1/4 of the calculated limit load.

The main experimental results are the recordings of curves giving the evolution of bending moment, in the crack section, as a function of total rotation measured close to the crack section (figure 2). The reduction of bending moment is continuous with initial crack angle. Worth noting are the crossing of curves for crack angles between 30 and 60 degrees. This indicates a particular behavior in this region. Maximal bending moment is not reached for $\theta < 30$ degrees with the experimental device.

To detect initiation of crack and to measure then crack propagation, the electric potential drop method is used during the test. This parameter, as a function of rotation, is used to define a calibration curve. Beach markings of crack fronts during crack propagation are obtained by partial unloadings. Each marked front is visible after rupture of the specimen in the cracked section. The cracked area is measured by a planimeter on pictures made of the cracked section. The cracked area is then converted to a crack length Δa by dividing the area value by nominal thickness t of the tube. A calibration straight line is determined by this method. This straight line is extrapolated to the origin ($\Delta a = 0$) in order to find the electric potential drop value for initiation. The amount of crack propagation obtained at maximal bending moment is ranging from 4 to 6 mm. The higher values are obtained with the smallest cracks.

The figure 3 is a schematic representation of the cracked section after rupture of the specimen. Worth noting is the dramatic evolution of striction that begins close to fatigue precracked front. The thickness is reduced from 8.3 mm to 4.5 mm. The striction is then constant after 5 mm of crack propagation. For propagation less than 5 mm the effect of striction is larger than the effect of crack propagation, as far as changes of geometry near the crack tip are concerned.

3 VERIFICATION OF CRITERIA BASED ON LIMIT ANALYSIS

Formulas to predict instant of initiation, instant of maximal bending moment are checked.

It is easy to demonstrate that a simple limit bending moment for a circular cracked geometry is given by the equation:

$$M_L = 4 R^2 t \left(\cos \frac{\theta}{4} - \frac{1}{2} \sin \frac{\theta}{2}\right) S_L \qquad (1)$$

In this equation, R and t are respectively mean radius and thickness of the pipe, θ is the initial total angle of the through thickness crack and S_L is the material limit stress. This value S_L must be a characteristic value coming from the tensile curve of the material of the specimen.

Results are presented here, considering the maximal bending moment.

Comparisons of formula given by equation (1) and experimental results M_{exp} are performed by calculation of the ratio:

$$\frac{M_{exp}}{4\ R^2 t} \qquad (2)$$

and the geometrical function:

$$\cos\frac{\theta}{4} - \frac{1}{2}\sin\frac{\theta}{2} \qquad (3)$$

Material data are obtained from a tensile curve drawn from a traction specimen extracted from the massive part of the concerned tube. The S_L value is calculated by a combination of yield stress S_y and ultimate tensile stress S_u. Conventionally the flow stress S_f concept is used. This stress is the mean value of S_y and S_u:

$$S_f = \frac{S_y + S_u}{2} \qquad (4)$$

Comparisons are given graphically in figure 4 for maximal bending moment. In this diagram the limit load evaluation is conservative - the formula underpredicts the actual bending moment - if the representative point of coordinates (M_{exp}/Rt^2,θ) is located above the curve drawn, corresponding to theoretical function given by equation (3).

Examination of figure 4 shows that the estimation is not conservative. A reduction of 15% of the flow stress is necessary. This means that the following equation must be used to calculate maximal bending load in our cases:

$$M_{max} = 0.85\ S_f\ 4\ R^2 t\ (\cos\frac{\theta}{4} - \frac{1}{2}\sin\frac{\theta}{2}) \qquad (5)$$

It is worth noting that this reduction is almost equal to the reduction of the limit bending moment (equation 1) caused by the propagation obtained at the experimental maximal bending load. This point will be addressed again in the remaining of the paper.

4 VERIFICATION OF J CRITERION FOR INITIATION

The second criterion "experimental J" is evaluated from the bending moment M - angle of rotation φ plot obtained from experiments (see figure 2) - according to the "one specimen method". This method (see for example Zahoor, 1981) relies on the existence of a scale function named here H. This function H(θ) describes the effect of crack length on the bending moment versus rotation curve only by the change in the scale of the axis concerning the bending moment. Then the evolution of J is calculated by the equation:

$$J = \frac{1}{Rt}\ \frac{H'(\theta)}{H(\theta)}\int_0^{\varphi} M\ d\varphi \qquad (6)$$

where $H'(\theta) = \dfrac{\partial H(\theta)}{\partial \theta}$.

It was checked that this scale function actually exists from the experimental results.

The normalized bending moment (with tube $\theta = 0$) is compared with the scale function deduced from the limit analysis (equation (3)) in figure 5. It seems that experimental points can be gathered in two families: small angles ($\theta \leqslant 30$) which are close to the theoretical curve and large angles ($\theta > 30$) which are above the theoretical curve. However, the experimental points are on 2 straight lines, the slope of which are close to the slope of the theoretical curve. This remark implies that the use of equation (3) for the scale function in equation (6) will give unconservative evaluation of experimental J.ΔA 15% reduction is necessary to achieve a good correlation between experimental points and theoretical curve.

The J calculated at the point of initiation ranges from 0.26 to 0.10 MN/m when crack varies from 30 to 150 degrees. It seems that this value is decreasing as a function of initial crack angle. A non negligible scattering is also obtained (factor 2 for $\theta = 120$ degrees).

5 EVALUATION OF DUCTILE TEARING

The comparison of J. a curves between tubes and small CT specimens has been presented (Moulin, 1989b). The discrepancy between the two geometries is large. A ratio equal to 4 between the two corresponding slopes was shown. Crack propagations in CT specimens are limited to 1.5 mm. For such small crack propagation it was verified that, like for tubes, the effect of striction is very important. This localized striction is not taken into account for the evaluation of experimental J. In order to go in this direction, the crack propagation data were reevaluated by considering the reduced thickness instead of the nominal thickness. This operation results in an increase by a factor of two on crack length. This procedure was confirmed by the measurement of the final crack (arc length measurement with a flexible rule) on some tubes. Figure 6 gives the evolution of the experimental bending moment load as a function of the actualized crack angle for two tubes. These curves are compared with the theoretical limit bending moment given by equation (1) with the flow stress as a limit stress. The 3 curves follow the same slope after same propagation. This observation indicates that this equation can predict conservatively the evolution of the bending moment during large ductile propagation when the reduction in thickness is constant.

6 CONCLUSIONS

Further interpretations of results give an earlier definition of crack initiation in the tests and an increase in the experimental evaluation of the crack propagation because of the large reduction of thickness. The reduction of thickness in the cracked section is stabilized after some amount of propagation.

Procedures to calculate J before initation are validated. Adjustments to use limit analysis for the prediction of maximal bending moment are given. During large ductile propagation the bending moment can be calculated with a limit load equation if the real crack propagation is taken into account.

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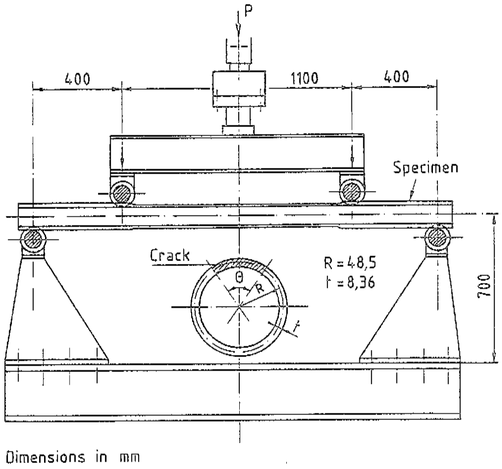

Fig. 1 - EXPERIMENTAL TEST DEVICE FOR STRAIGHT PIPES

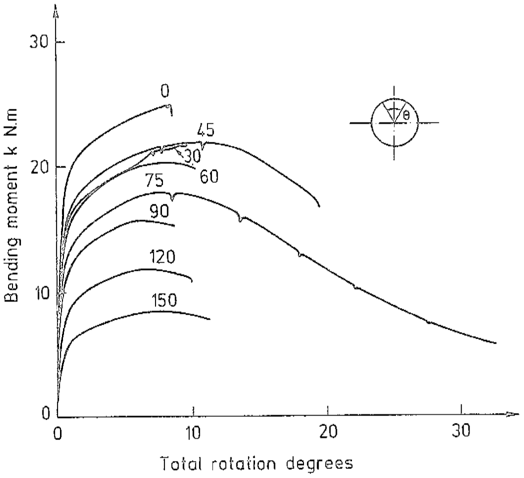

Fig. 2 - BENDING MOMENT VERSUS ROTATION FOR TUBES WITH DIFFERENT TOTAL CRACK ANGLE

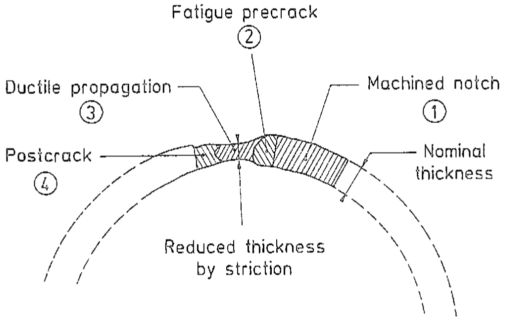

Fig. 3 - EVOLUTION OF STRICTION WITH PROPAGATION

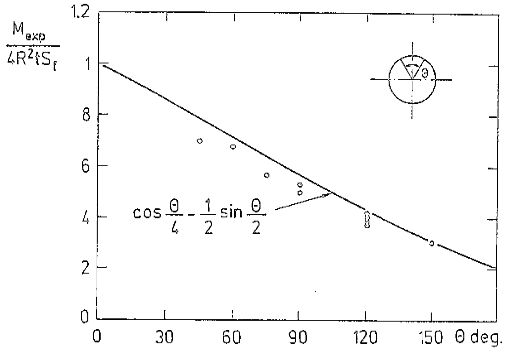

Fig. 4 - VERIFICATION OF A LIMIT LOAD ESTIMATION OF MAXIMAL EXPERIMENTAL BENDING MOMENT

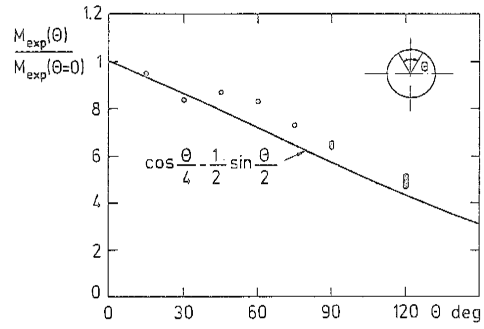

Fig. 5 - VERIFICATION OF EXPERIMENTAL SCALE FUNCTION FOR ROTATION = 6 DEGREES

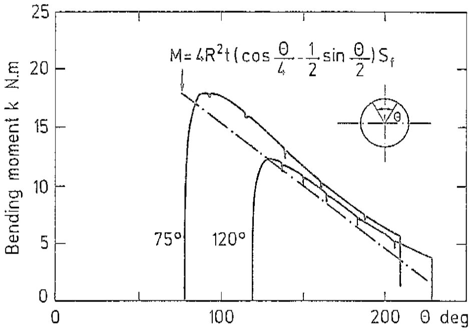

Fig. 6 - VERIFICATION OF LIMIT LOAD FOR EXPERIMENTAL BENDING MOMENT IN LARGE PROPAGATION