Evaluation of Critical Sizes of Part-Through Cracks on 3 Inch Austenitic Stainless Steel Pipings

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SUMMARY

The COMMISSARIAT A L'ENERGIE ATOMIQUE, FRAMATOME, ELECTRICITE DE FRANCE and NOVATOME have undertaken two experimental programs with a view to validate a failure criterion applicable to part-through pipe defects . In both programs the corresponding tests are conducted on small diameter austenitic stainless steel pipes. These programs are described together with the analyses carried out.

AQUITAINE III program

The testsare conducted on Z3 CND 17-12 equivalent to AISI 316L - stainless steel pipes. The longitudinal or circumferential part-through cracks, are spark-eroded, geometries of the defects are :

. longitudinal crack : length from 0.3 to 2D, depth from 0.6 to 0.8 t,

. circumferential crack : angle from 130 to 240°, depth from 0.7 to 0.9 t

These tests are conducted either under the pressure and temperature conditions of a Pressurized Water Reactor, on the **COMMISSARIAT A L'ENERGIE ATOMIQUE's AQUITAINE II** facility, or at ambient temperature under hydrostatic pressure.

Ten tests were conducted and analyzed using the flow stress criterion. The test-calculation comparison primarly concerned the behavior of the part-through defects and gave rise to the following conclusions :

. the radial instability pressure for the part-through defect can be estimated correctly with the criterion used. There the flow stress σ^* is near to the material ultimate stress σ_u .

This results is valid for deep flaws for which the main failure mode is the plastic collapse of the small ligament, then the calculated flow stress is well above the value usually considered $\sigma^* = \frac{1}{2.4} (\sigma_y + \sigma_u)$ which is more adapted to larger ligament where the tearing instability generally occures before the plastic collapse.

CRACK INSTABILITY TESTS

The test pipes are made from AISI 316 stainless steel. Their geometrical characteristics are :

Outside diameter 80 mm, thickness 5 mm, length 480 mm

These pipes are provided with part-through defects 400 mm long x 3-4 or 4.5 mm deep which are spark-eroded.

The tests are conducted at room temperature. The load imposed is an internal hydrostatic pressure combined with a longitudinal traction or compression proportional to the pressure value. This longitudinal load is one of the program study parameters.

The results obtained show that :

. the use of the flow stress criterion to predict the bursting pressure leads to values for this stress which are very high, on the order of the ultimate stress σ_u ; result comparable with the result obtained on the **AQUITAINE III program.**

. the axial load superposed on the internal pressure is very little effect on the bursting pressure.

INTRODUCTION

In recent years considerable analytical and experimental work has been done on the behavior of axial or circumferential cracks in pipes, and various applicable failure criteria have thus been defined. For simple geometries such as straight pipes, the analyses are generally based on simplifying assumptions concerning material behavior, such as disregarding the biaxiality of the stress field in applying the criterion, or the known stress distribution in the cracked section.

In order to assess the conservatism of the available simple criteria, two experimental pipe failure programs were undertaken jointly by the **Commissariat à l'Energie Atomique (CEA), Framatome, Electricité de France** and **Novatome** to compare analysis and test results.

1. THE AQUITAINE III PROGRAM

The objective of this program is to qualify suitable failure criteria for austenitic stainless steel pipes for the purpose of estimating the critical size of part-through longitudinal and circumferential flaws. The program includes two phases :

- Tests on CT and CCT specimens of the following parameters :

  . notch root radius (CT50 specimens).

  . scale effects (CCT specimens)

  The test resuts |1| show that the scale effect on the $J_R/\Delta a$ strength curve is negligible.

- Tests on 1:10 scale pipes representative of PWR primary coolant pipes. These tests are discussed below.

1.1 Description

The test characteristics are as follows :

1.1.1 Material

Z3 CND 17-12 austenitic stainless steel (equivalent to AISI 316L steel). Refer to Table 1 for mechanical properties.

1.1.2 Geometry

Pipe dimensions : inside diameter 76.3 mm, initial thickness 6.15 mm. The tube outer surface was remachined to close thickness tolerances in the flaw zone; refer to Table 2 for the complete test thickness values.

Internal longitudinal or circumferential flaws were machined by spark-erosion, with bottom radïi ranging from 0.05 to 0.1 mm.

1.1.3 Experimental conditions

Two types of tests were conducted :

- high-temperature tests in the AQUITAINE II facility |2| :

  The cracked test section was installed between two vessels filled with subcooled water at 320 °C (figure 1) and subjected to pressure loading. The maximum test pressure was 18.5 MPa.

- Room-temperature tests :

  The test section was subjected to hydrostatic pressure by means of a pump, with the following loading configuratlons :

  . pressure only

  . pressure + 4 point bending (figure 2) : after first applying the pressure load, the tube was tested to failure by appling the flexure load.

1.1.4 Instrumentation

Measurement data was acquired principally for the following :

- loading parameters (pressure, bending load, fluid and metal temperatures for the high-temperature tests),
- deformation of the ligament.

Tables 2 and 3 summarize the tests performed and the results observed.

1.2 Analysis of Test Results

1.2.1 Tests with Longitudinal Defects

Most of the data obtained involve the radial stability of the defects. The test results were analyzed on the basis of Battelle's flow stress criterion |3| :

$$\sigma_h = \sigma^* \left(\frac{t/a \; - \; 1}{t/a - 1/M}\right)$$

where σ_h : **circumferential failure stress**

t : pipe thickness

a : defect depth

M : elastic amplification factor

The initial defect dimensions were determined for the flow stresses proposed in reference |3|, i.e. $\sigma^* = 1/2.4\,(\sigma_y + \sigma_u)$.

The first test results showed that for the defects studied this estimate was very conservative. The bursting pressures gave σ^* values ranging from $1.1\,\sigma_u$ to $1.2\,\sigma_u$.

This result is related to the geometry of the cracked section : i.e. small diameter pipes with very deep defects (a/t ratios = 0.65 - 0.85), with the ligament dimension on the order of the COD. Under these conditions the radial instability of the crack is due to plastic collapse of the ligament with no prior defect growth. Microscopic examination showed no signs of incipient cracking in the ligament at stress levels near the ultimate stress.

For penetrating defects, the commonly used criterion is :

$$\sigma_h = \frac{\sigma^*}{M}$$

No conclusion can be drawn from test results as to whether the previously defined σ^* value is valid for this geometry. It may be noted that the experimental works reported in the literature |4, 5| indicate flow stress values between the elastic limit and the ultimate stress in the following form :

$$\sigma^* = \frac{\sigma_y + \sigma_u}{k} \quad \text{or} \quad \sigma^* = \sigma_y + k\,(\sigma_u - \sigma_y).$$

1.2.2 Tests with Circumferential Defects

The radial stability of part-through defects was also analyzed using the flow stress. The stress field is assumed to be linear in the cracked section |6|; this stress is a combination of :

- the axial force due to pressure distributed over the remaining cross section,
- the pressure-induced bending moment resulting from the offset position of the center of gravity with respect to the pipe centerline,
- additional applied bending moments.

The following results were obtained for the two loading configurations :

- **Pressure stresses only :**

  The bursting pressure for the room-temperature test was predicted within 5 % by the relation : $\sigma^* = 1.2\sigma_u$.

  Conversely, the bursting pressure estimates for the high-temperature tests were pessimistic, probably because of the experimental device itself : the bending due to displacement of the neutral axis was hindered by the test section supporting conditions.

- **Combined pressure and bending stresses :**

  The previous analysis based on the assumption of a linear stress distribution in the test section provided conservative estimates for the room-temperature experiment. Another approach was thus attempted : allowance was made for a plastic hinge in the cracked section |7| (figure 3). In this case, failure occurs when the limit moment is reached :

$$M_L = 4 \ \sigma^* \ R^2 e \ [\cos \alpha - \frac{a}{2t} \sin \theta]$$

and

$$\alpha = \frac{a}{2t} \theta + \frac{\pi R}{4t} \left(\frac{P}{\sigma^*}\right)$$

where **P : internal pressure**

R : mean radius

This analysis gives a limit moment value comparable to the measured experimental moment, with a flow stress value approximating the ultimate stress.

2. INFINITE LONGITUDINAL DEFECT TESTS ON TUBES

This program was primarily designed to study the effects of the axial load together with internal pressure loading on the bursting pressure of a tube with a longitudinal crack.

2.1 Description

2.1.1 Material

The test sections were made of AISI 316 austenitic stainless steel.

2.1.2 Geometry

Pipe dimensions : 80 mm outside diameter, 5 mm thick, 480 mm long.

Longitudinal defects were spark-machined over the full length of ten tubes with a 0.2 mm groove root radius. Table 4 indicates the defect depths.

2.1.3 Experimental Conditions

The test pieces at room temperature were subjected simultaneously to internal pressure and to an axial tensile or compression load proportional to the internal pressure. Refer to Figure 4 for the test schematic.

2.1.4 Instrumentation

Measurement data included the internal pressure and axial load, as well as the tube deformation at various points. The test characteristics are summarized in Table 4.

2.2 Results

During the tests, the stress loading was increased until tube failure occurred. The bursting pressures are listed in Table 4.

It may be noted that the ultimate stress value constitutes a lower limit on the flow stress σ^*. Thus, for tests with only pressure loading, σ^* may be estimated as follows :

$$1.2\,\sigma_u < \sigma^* < 1.4\,\sigma_u$$

This result is consistent with the AQUITAINE III test findings. The introduction of an axial load modified the bursting pressure by a maximum of 15 % in these tests.

3. CONCLUSION

The test results show that the widely used flow stress criterion,

$$\sigma^* = \frac{1}{2.4}(\sigma_y + \sigma_u)$$

is too conservative for very deep defects with ligaments on the order of the COD; in this case the ultimate stress is more representative. This result cannot be transposed to a full scale PWR primary coolant pipe, since when the ligament is thicker the pipe failure mode changes. Stable crack growth generally precedes plastic collapse.

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Table 1 : Mechanical characteristics of Z3 CND 17-12 steel

Temperature (°C)	Yield Strength (MPa)	Ultimate Strength (MPa)
20	211.5	521
320	139.2	407.5

Table 2 : Aquitaine III program - Test characteristics

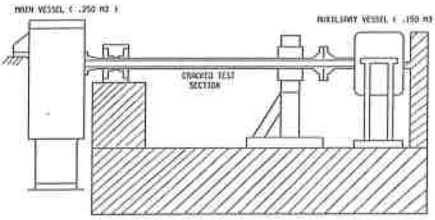
	Test	Geometry of the cracked pipe section			Experimental conditions	
		Thickness (mm)	Depth (mm)	Length (mm or degrees)	Temperature (°C)	Loading
Axial crack	1-1	5.95	4.00	30	320	Pressure
	1-2	5.95	4.80	30	320	Pressure
	1-3	5.65	4.80	80	20	Pressure
	1-4	5.5	4.50	180	320	Pressure
Circumferential crack	2-1	5.95	4.20	130	320	Pressure
	2-2	5.65	4.70	130	320	Pressure
	2-3	5.1	4.50	240	320	Pressure
	3-1	5.35	4.65	180	20	Pressure
	3-2	5.35	4.65	180	20	Pressure 18.6 MPa + 4 point bending

Table 3 : Aquitaine III program. Predicted and experimental crack behavior

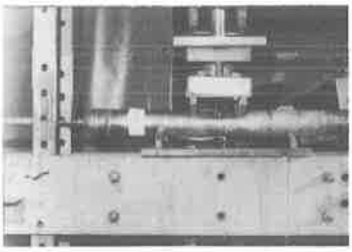
Test	Value of σ^* used for prediction	Predicted behavior	Experimental behavior
1-1	$\frac{1}{2.4}(\sigma_y + \sigma_u)$	Stability for p = 16 MPa	Stability for p = 16 MPa
1-2	$\frac{1}{2.4}(\sigma_y + \sigma_u)$	Leak for p = 15 MPa	Stability for p = 18.5MPa
1-3	$1.2\ \sigma_u$	Leak for p = 19.5 MPa	Leak for p = 19.5 MPa
1-4	$1.2\ \sigma_u$	Burst pressure 13.9 MPa Instability of the through - wall crack	Burst pressure 12.9 MPa Instability of the through wall crack
2-1	$\frac{1}{2.4}(\sigma_y + \sigma_u)$	Stability for p = 16 MPa	Stability for p = 16 MPa
2-2	$\frac{1}{2.4}(\sigma_y + \sigma_u)$	Leak for p = 12.4 MPa	Stability for p = 18.5MPa
2-3	$1.2\ \sigma_u$	Burst pressure 14.8 MPa Instabilités of the through wall crack	Stability for p = 17.2MPa
3-1	$1.2\ \sigma_u$	Leak for p = 28.4 MPa	Leak for p = 29.2 MPa
3-2	$1.2\ \sigma_u$	Leak for bending moment : 1100 N. m	Leak for bending moment : 3450 N.m

Table 4 : Test characteristics

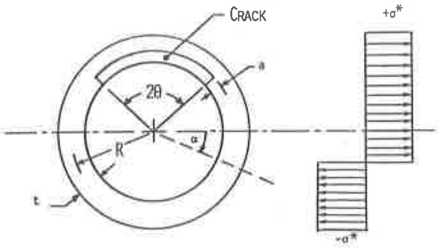
Test	Crack location	Crack depth (mm)	Imposed axial load/axial force due to pressure	Burst pressure (MPa)
1	Inside surface	4	0	21.6
2	Inside	4	- 2	20.4
3	Inside	4	- 1	20.0
4	Inside	4	1	18.8
5	Inside	4.5	0	10.4
6	Inside	4	- 2	20.0
7	Inside	4	1	18.3
8	Inside	3	0	36.5
9	Outside surface	4	- 1	17.0
10	"	4.5	0	9.6



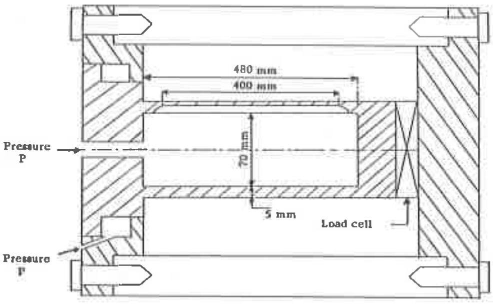
<u>Figure 1</u> : Test section on AQUITAINE II facility



<u>Figure 2</u> : Four – point bending



<u>Figure 3</u> : Plastic hinge in the cracked section



<u>Figure 4</u> : Test section for combined pressure and axial force