Fatigue crack growth on a straight pipe element under sodium thermal shocks

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ABSTRACT

Accurate predictions of subcritical fatigue crack growth are an important element in the leak-before-break demonstration of reactor piping systems. In fast breeder reactors several opposing factors affect the geometric evolution of the crack. Some are unfavorable (thermal shocks which induce bending and peak stresses; circumferential weld seams which also result in residual bending stresses; creep effects in high temperature loops) while others are favorable (thin gauge pipe walls; high fracture toughness of the 316 L Steel used).

The authors first describe the FORTUNA test device used to apply cyclic thermal shocks on a straight pipe section submitted to a combination of primary membrane and bending stresses. The pipe element includes two circumferential cracks, one of which is located in a circumferential weld seam.

Finite-element calculations of crack growth are then discussed, using linear elastic fracture mechanics and defect linespring type shell elements to allow low cost crack geometry updating.

The analysis shows that thermal shocks resulting in equi-biaxial bending across the pipe wall should be one of the most severe loading configurations for leak-before-break demonstration. The experimental results will provide a basis for comparison.

1 INTRODUCTION

One of the essential safety options of future fast breeder reactors is demonstrated leak-before-break capability for the secondary circuit piping.

For the purpose of this demonstration the pipe is assumed to have a defect and the shape evolution of the defect is analyzed under the effect of operating loads. The crack size must not reach circumferential extent which would allow quillotine failure under a sudden incidental load such as a design basis earthquake.

Various opposing factors affect the radial geometric evolution of a crack. Unfavorable phenomena include :

. thermal shocks which induce tensile stresses on the inner surface and compression stresses on the outer surface (thermal peak effects may also significantly increase the stress intensity factor).

. circumferential weld seams resulting in similar stress loading (maintained stresses which can be particularly detrimental in high temperatures creep situations).

Other factors may be considered favorable :

. the thin gauge pipes used in fast breeder reactors;

. the good high temperature fracture toughness of the steel grade used (316 L).

To assess the relative importance of these factors, a simple experimental device was necessary that would be representative of actual stress loading conditions on sodium piping in fast breeder reactors.

2 TEST DEVICE

2.1 Design Principles

The test device is designed to investigate fatigue or creep-fatigue crack growth in a straight pipe section subjected to cyclic thermal shock loading and to a combination of primary membrane and bending stresses.

Thermal shocks are obtained by injecting cold sodium into the pipe after prior temperature stabilization with hot sodium inside and outside the test element.

The primary stress loading is a constant force applied parallel to but at a certain distance from the pipe centerline to induce both bending and tensile loads in the test section. The primary mechanical loading principle is illustrated in Figure 1.

Thermal loading initially consists of repeated thermal shocks under negligible creep conditions (cold sodium temperature 200°C, hot sodium temperature 400°C). Subsequently hot pipes will be examined with high temperature residence times to allow for creep effects; the cold and hot sodium temperatures will be 350°C and 600°C, respectively.

Major test specifications include the following :

. Material :	316 L stainless steel
. Pipe outside diameter :	252 mm
. Thickness :	12 mm
. Length :	1500 mm
. Tensile load rating :	210.7 KN

2.2 Description

The test device (Figure 2) is mounted on the cover of a large sodium pot 2200 mm in diameter. The cover supports an 850 mm diameter flange from which the fixed components are suspended. This assembly comprises a cylindrical heat insulated vessel sustaining the loads exerted on the test mockup mounted inside the vessel. The annular gap between the test mockup and the inner wall of the heat insulated shell contains six immersion heaters to maintain the hot sodium temperature at the test value (400-600°C) around the outer surface of the test mockup; the internal sodium is heated by thermal conduction.For each thermal shock, cold sodium is circulated by a submerged electromagnetic pump located beneath the test vessel.

The removable portion of the test device is the test mockup comprising an upper gripper cover through which the off-center tensile load is transmitted, and a lower connection to the outer shell; the mockup contains an inert core to limit the sodium volumes involved in the cold shock tests.

3 OPERATING PROCEDURE

The initial test will be run to acquire thermal data on a defect-free tube mockup. Figure 3 shows the thermocouple layout on the first mockup with special implants welded onto the tube containing thermocouples placed parallel with the tube wall. These thermocouples are specially intended to monitor thermal peak effects.

The pure fatigue test program with cold sodium at 200°C and hot sodium at 400°C will include two series of tests : one with reduced primary stress loading (approx 70 KN) and the second at the nominal loading (210 KN). The thermal cycling rate will be 100 cycles per day.

The test mockup itself includes two semi-elliptical circumferential internal cracks (Figure 4) located 200 mm apart on the generatrix corresponding to the maximum bending stress. One of the cracks is located in a circumferential weld seam, and will thus also be subjected to residual welding stresses. The incipient cracks are produced by separate fatigue stress by cyclic tensile loading on a press.

After each series of tests the mockup will be removed and submitted to destructive examination to observe the evolution of the defect shape during propagation under fatigue loading.

4 FATIGUE CRACK GROWTH CALCULATIONS

A number of preliminary calculations of fatigue crack growth have been performed using linear elastic fracture mechanics. The dimensions of the initial defect were estimated by prior analysis using, for example, the solutions defined for flat plates by Raju & Newman [1]. In order to calculate the crack evolution, however, the cyclic variation of K (due to the thermal shocks which constitute the cyclic portion of the stress loading) must be assessed not only for the initial defect geometry but also for all of the geometric configurations taken by the crack during fatigue growth.

Thirty-six calculations were thus performed for combinations of the following geometries :

. a = 5,6,7,8,9 and 9,6 mm
. c = 20,30,40,60, 80 and 120 mm

Were a : maximum semi-elliptical defect depth,
c : defect half-width (an arc length, as the crack is circumferential),
and were the initial defect dimensions were a = 5 mm and c = 20 mm.

The calculations were performed using the CASTEM 2000 code from the CEA's CASTEM system. The semi-elliptical defect was modeled with linespring elements, i.e. Shell elements for which the rigidity is parameterized according to the relative depth of a surface crack [2] [3]. The remainder of the structure was modeled with 3-node shell elements. The simplicity of this elastic shell analysis model and the structure of the code used make parameter calculations easy. The stress intensity factor at the edge of the defect was estimated by the virtual crack extension method. The geometry is shown in Figure 5 :

. Boundary conditions : face (A) : x 0 y symetry
face (B) y 0 z symetry

. Loading : 100°C linear wall temperature gradient
. Young's modulus : $E = 165\ 000$ MPa
. Linear thermal expansion coefficient :
$\alpha = 18.33 \times 10\text{-}6$ °C-1
. Poisson coefficient : $\nu = 0.3$
. Modelized height : $H = 150$ mm
. Mean radius : $R = 120$ mm.

Figures 6 and 7 are examples of the meshes used calculations where $c = 20$ mm and $c = 120$ mm, respectively.

All the calculations were performed by modeling the crack with 10 linespring elements, constituted by a line of double nodes in the lower lefthand portion of the mesh. For the fatigue crack growth calculation the propagation rate was calculated at points A and B (Figure 5) using a conventional Paris relation :

$$v_r = \frac{da}{dN} = C\ [\Delta K\ (\frac{a}{t}, c)_{\text{radial}}\ ]^m$$

$$v_c = \frac{dc}{dN} = C\ [\Delta K\ (\frac{a}{t}, c)_{\text{edge}}\ ]^m$$

After N cycles the radial propagation becomes vR N = a and the circumferential propagation vc N = c. The calculation is iterated for the new defect geometry where $a = a + \Delta a$ and $c = c + \Delta c$. The defect is assumed to remain semi-elliptical, allowing the results of the parameter calculations to be used.

The results obtained using an envelope Paris law for the material at 400°C (da/dN mm/cycle = 3.22×10^{-8} $(\Delta K)^{3.26}$ $(\text{MPa}\sqrt{\text{m}})$ are illustrated in Figure 8, showing the evolution of a/t versus 2c. Figures 9 and 10 show the KI values reached at points A and B during the crack propagation (boldface lines), superimposed on the above-mentioned parameter calculation results (iso-c curves). It may be seen that despite the defect enlargement the edge stress intensity factor rises except at the end of the propagation phase where the crack enlargement factor predominates. Conversely, the radial stress intensity factor systematically diminishes.

These results confirm that thermal shock loading which induces pure bending stresses should be one of the most unfavorable cases for the leack-before-break demonstration.

5 CONCLUSION

The test device described in this paper is a simple design that can nevertheless be used to investigate fatigue and creep-fatigue growth of a defect under loading conditions representative of those encountered in fast breeder reactor secondary piping systems.

The initial parameter calculations of fatigue crack growth confirm the importance of thermal loading in leak-before-break analysis and provide a basis for the first series of tests.

These calculations will be renewed in greater detail on the basis of the experimental thermal loads (3-D massive element calculations). Comparison with the experimental results will permit qualification of fatigue crack growth prediction methods or the development of new methods if necessary.

REFERENCES

[1] J.C. Newman and I.S. Raju. Analysis of Surface Cracks in Finite Plates under Tension or Bending Loads. NASA Technical Paper N° 1578 (1979).

[2] E. de Langre and L.Ebersolt The Use of a New Linespring Shell Element for Elastic Surface Crack Analysis. To be published in : Fatigue and Fracture of Engineering Materials and Structures.

[3] L.Ebersolt and A.Combescure Finite Element Analysis with a Special Fracture Linespring Element. SMIRT 9; Lausanne, BG 1/8.

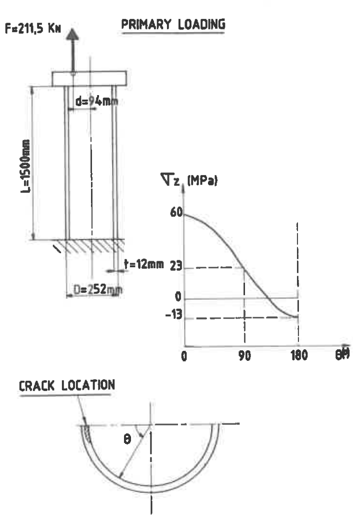

Figure 1
Primary loading schematic

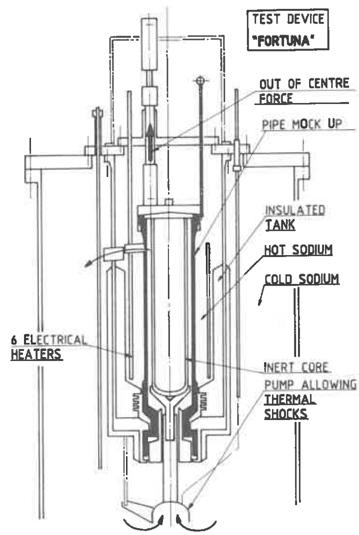

Figure 2
The FORTUNA test device

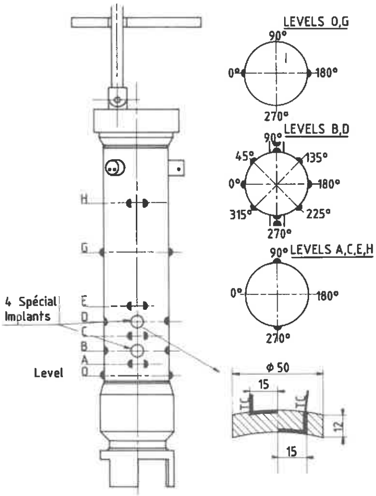

Figure 3
Thermal instrumentation
of the pipe mock up

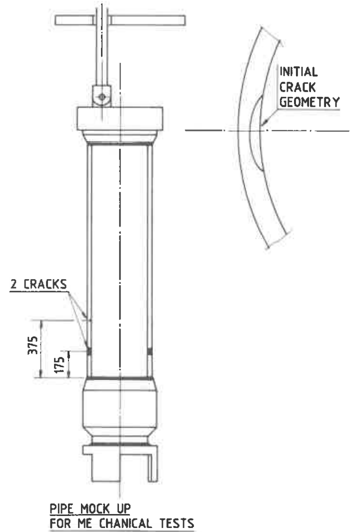

Figure 4
Pipe mock up for mechanical
testing

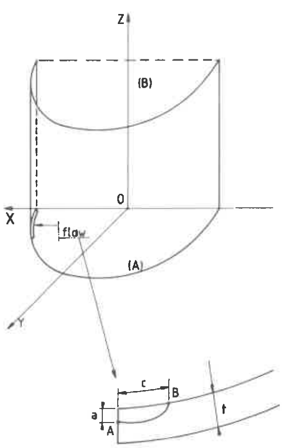

Figure 5
Geometry modelization and
boundary conditions

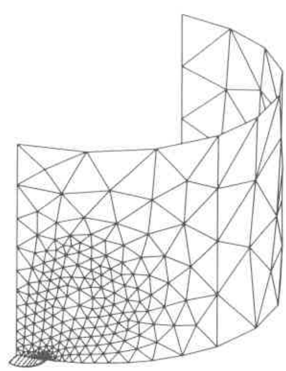

Figure 6
Mesh for a = 5 and c = 20

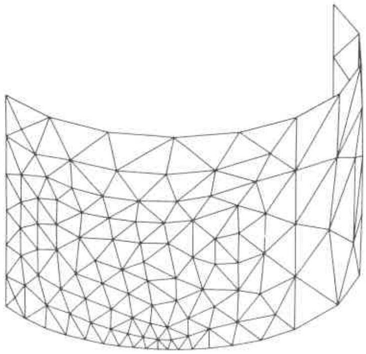

Figure 7
Mesh for a = 5 and c = 120

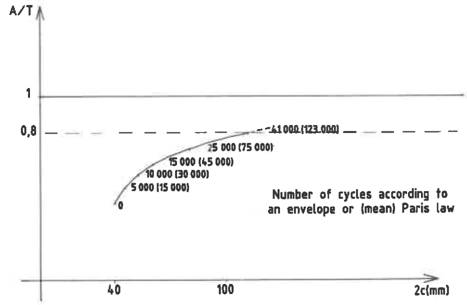

Figure 8
a/t ratio versus 2c during crack propagation

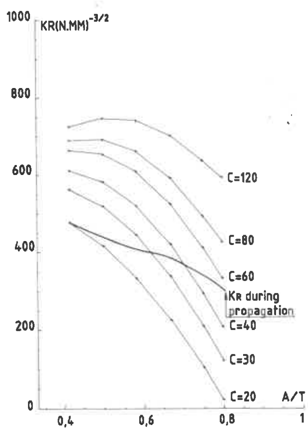

Figure 9
K_r values reached during propagation

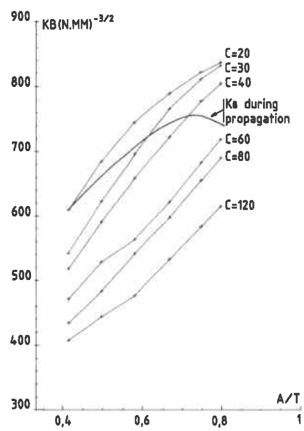

Figure 10
K_{edge} values reached during crack propagation