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Numerical simulations of crack opening areas for leak before break applications in LMR components

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ABSTRACT : The application of the Leak Before Break (LBB) concept to Liquid Metal Reactor (LMR) components is sometimes delicate due to the low level of primary loads (pressure, gravity) compared to thermal gradients. This is unfavorable for the flow rate.

When applying procedures based on simplified analytical methods, the calculated flow rate for a critical through-wall defect is often very low and the conclusion is that the component does not verify the LBB concept.

FRAMATOME-NOVATOME has undertaken several studies in order to take into account more accurately the effects of bending stresses due to an axial thermal gradient and residual welding stresses in the evaluation of the leak area for a through-wall circumferential defect in a cylindrical structure, typical of LMR's vessel.

The main results issued from three-dimensional finite element calculations are the following:

- for a welding process giving tension on the skins of the vessel and compression in the inner part, the effect of residual stresses on the leak area is negligible,
- for a long defect, the leak area given by simplified analytical methods is pessimistic.

All these results allow the verification of the LBB concept for the studied case. They will contribute to the development of LBB methodology for LMR components.

1 INTRODUCTION

In the framework of Leak Before Break (LBB) concept, one of the main technical points concerns the evaluation of the leak area and the detection of the leak.

The main goal of this paper is to describe the investigations carried out by FRAMATOME-NOVATOME on a LMR component, on the topic of leak area evaluation.

Thermomechanical computations were conducted to estimate leak area, considering normal operating sollicitations, for a through-wall circumferential defect located in the weld area of a cylindrical component.

Loading is characterised by a low level of membrane stresses, and significant bending stresses due to an axial thermal gradient and to the welding process, which is unfavorable to the flow rate and to the detection of the leak, because of the closure tendancies of the through-wall defect and the low differential pressure of the fluid.

A simplified approach [1] to take into account bending stresses on leak area was too pessimistic.

In order to solve this problem, the basic idea on which work was carried out is the following : for a long crack the bending stress effects due to thermal gradient and welding would decrease and the defect opening would be sufficient for leak detection.

Therefore, the subject of this study is to quantify this phenomenon and to derive the evaluation of the minimum length which gives, under operating conditions, leak area sufficiently high and thus a detectable leak by the presently used detection facilities.

These investigations were conducted on a cylindrical component using three-dimensional finite element calculations with the computer code SYSTUS [2], and general conclusions were drawn.

2 GENERAL APPROACH OF THE LBB ANALYSIS

The objective of LBB analysis is then to verify that a hypothetical propagation of defects will give rise to through-wall cracks, detectable before being critical, even though a fracture mechanics analysis shows that these defects cannot become critical. A description of the procedure is given by [1]. The demonstration of the validity of the LBB concept is based on leakage flow calculation, leakage detection capabilities and fracture mechanics analysis. The size of the minimal detectable through-wall defect has to be determined.

3 MODELLING CONSIDERATIONS

3.1 Finite element discretization

The structure investigated is a cylindrical component, whose radius/thickness ratio, close to 400, is typical of a LMR main vessel.

To limit the size of the problem, only a part of the structure is used in the analysis (see fig.1).

As is usual, the through wall crack is modelled using double nodes, each couple of nodes being linked through special elements.

The length of the crack could vary through the choice of the stiffness of these elements. A very weak stiffness corresponds to nodes of the cracked zone and a very high stiffness is chosen for the nodes belonging to the uncracked zone.

For example to model the uncracked structure, the stiffness of all the special elements was taken to a very high value.

To modelise the behaviour in the thickness, four layers of elements are considered to be sufficient.

Computations were carried out using the computer code SYSTUS[2].

First, 8 noded-brick-elements were used. Analysis is conducted using several cracks lengths with a regular mesh size:
L = 424, 650, 874, 1100, 1324, 1550, 1774, 2000 mm.

For a reason explained later, computations were performed again using high performance 20-noded-brick-elements and a reduced-integration.

However this analysis was limited to only the following crack lengths : 400, 1000, 1400 mm. Results obtained by the two modelisations were compared.

Another feature introduced in this analysis was that the size of crack tip elements was reduced to 0.5% of the half crack length and that $1/r^{1/2}$ strain field singularity (r : distance from the crack tip) associated with linear elasticity was modelled by placing the mid-side nodes at the 1/4 of the edges leading away from the crack tip.

The boundary conditions were imposed in order to respect the symmetry conditions. Moreover one node (A) was completely restrained to eliminate rigid body motion along axial direction during loading (see fig.1).

3.2 Material characteristics

The constitutive material is the 316 austenitic stainless steel used for most LMR structures. The analysis was conducted considering mechanical properties at 400°C given by RCC-MR [4] (1S material).

The weld material is not modelled explicitly, since it does not affect the global behaviour of the structure [5].

4 LOADING CONDITIONS

The crack opening area for leakage calculations was estimated under normal operating conditions (the transient conditions are not considered), the applied stresses are small with respect to the yield stress of the material. Consequently, the results obtained here are based essentially on elastic analysis. The full loading included:

- mechanical loads, giving a uniform axial tensile stress of 40 MPa
- axial thermal gradient, giving a maximum bending stress equal to 140 MPa
- residual stresses in welding area

4.1 Axial thermal gradient

Due to a non-linear distribution of the axial thermal gradient, bending stresses develop which opens the crack at one side of the shell (external surface) and closes it at the other side (internal). For a long crack length this effect would decrease.

The 8-noded-brick-elements overestimate these stresses because of their too rigid behaviour under bending load. However displacements and the crack opening area were considered sufficiently accurate though somewhat pessimistic.

This was confirmed (see fig. 2) by comparison with results obtained using 20-noded-brick-elements which are more accurate due to the presence of mid-side nodes.

4.2 Residual welding stresses

The residual welding stresses were evaluated by a simplified procedure using the work of The Welding Institute summarized by LEGGATT [5].

From this document we chose the case study corresponding to cylindrical component, circumferential crack, full penetration butt weld.

The yield stress of weld material at service temperature, defined as 0.2 per cent plastic strain, was considered for the maximum value of residual welding stress field in the uncracked structure.

The welding residual stresses were simulated using :

- an initial strain field for axial stress component,
- a fictive internal pressure, for hoop stress.

These two loadings were applied in the weld area and their intensity and distribution were determined in order to respect the residual stress field given in [5] for an axisymmetrical structure without crack.

The presence of a through-wall crack in the shell structure results in a redistribution of the stresses mainly for axial stresses perpendicular to the crack, which would be carried from the cracked region, into the surrounding structure.

The bending stresses decrease and so does the closure effect due to compressive stresses in the center of the thickness.

5 ANALYSIS OF RESULTS

Considering the minimum crack opening (even closure) at mid-crack-length, we undertook computations for several crack lengths and then we calculated leak area as a function of crack length.

5.1 Crack opening under normal operating conditions

The variation of crack opening δ versus crack length is shown on fig. 2, where δ represents the crack opening obtained in the analysis at the middle of the crack, on the side submitted to compression.

It is the presence of membrane tensile stresses which accounts for the separation (opening) of the crack lips.

In the initial calculation, the tensile loading was applied as a membrane stress controlled loading (40 MPa). The corresponding crack opening displacement is overestimated for long crack lengths, because the length of the structure modelled is not sufficient as regards the crack length.

The real situation for long crack lengths is between stress controlled and displacement controlled.

Therefore, another computation was performed under displacement controlled loading for a crack of 1000 mm length. Finally, a more exact curve was deduced for the variation of δ versus crack length (see "more exact" opening in fig. 2) by interpolation between stress controlled and displacement controlled results.

The result is that crack closure is observed for short cracks and crack opening begins to appear for a crack length equal to 1000 mm.

For longer cracks, the crack opening δ increases rapidly.

5.2 Calculation of leak area

The crack opening areas are computed by integrating the local crack opening displacements along the modelled half length of the crack.

In our analyses the crack opening area correlates very well with the elliptical shape. Crack opening areas were calculated on three planes corresponding to inside / middle / outside surfaces of the structure; after that, only the lowest value was retained.

5.3 Residual weld stress effects

The behaviour of the through-wall cracks was also investigated under residual weld stresses only. For each crack length analysed, the crack closure due to compressive residual stresses in the inner part of the thickness, was found to be negligible (see fig.3).

Detailed investigations on the welding process and then a numerical analysis, using a specific computer code like SYSWELD, could be performed to simulate with accuracy the residual welding stress field. However, due to the results obtained, this step was not necessary.

It confirms that this kind of stresses, localized in the weld area, considering their low energetic level, gives low closure effects.

5.4 Thermal bending stress effect

Fig. 3 shows the closure effect versus crack length under the stresses due to the axial thermal gradient only (on compressive side). The main results are :

- for long through wall cracks, the closure as function of crack length, does not increase. The maximum closure is relative to the crack length value of about 1300 mm.
- above 1300 mm, closure decreases because of the stress redistribution due to the crack extension (the bending stresses disappear on the crack lips) and because of the shorter remaining ligament (where the bending stresses continue to act).

5.5 Fitness of simplified crack opening dispacement (COD) expression

In order to estimate the COD δ under a combined membrane and bending stresses (respectively called σ_m and σ_b), Toyosada & Nagai [3] introduced the idea of "effective stress" σ_{eff} . A lower bound value of the COD can be expressed as follows : $\delta = 4\ a\ (\sigma_m - K_I\sigma_b)/E$ where $K_I \approx 0.37$, a is the half crack length, E the Young's modulus.

Due to the presence of very high bending stresses as compared to membrane stresses, the crack would remain closed according to this expression if $\sigma_m < 0.37\sigma_b$. The objective here is to show that this expression is conservative.

In order to check this simplified method, we present numerical results, in the same form as used by the simplified approach. K_I parameter (see fig.4) decreases quickly versus crack length ($K_I=0.2$ when L=1400mm for the geometry and loading considered). The simplified method [3] underestimates bending effect until the crack length value of 700 mm, and overestimates it for cracks longer than 700 mm.

These conclusions are valid for a cylindrical vessel with a high radius/thickness ratio and a bending stress/tensile stress ratio close to 3. Parametric studies would have to be continued in order to extend these results to other geometry and loading cases.

6 CONCLUSION

Numerical simulations using a finite element model were performed in order to evaluate more accurately crack opening area on a LMR cylindrical component under normal operating conditions.

The main results obtained by parametric computations of leak area are described as follows :

- for the type of geometry and loads considered (including mechanical, thermal gradient and welding stresses) detectable leak areas are obtained when crack lengths are above 1000 mm,
- residual welding stress effect is negligible on leak area,
- axial thermal gradient produces significant crack closure, but this effect decreases when crack length increases,
- the crack opening expression given by [3] is pessimistic.

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Figure 1. General mesh of the cracked vessel

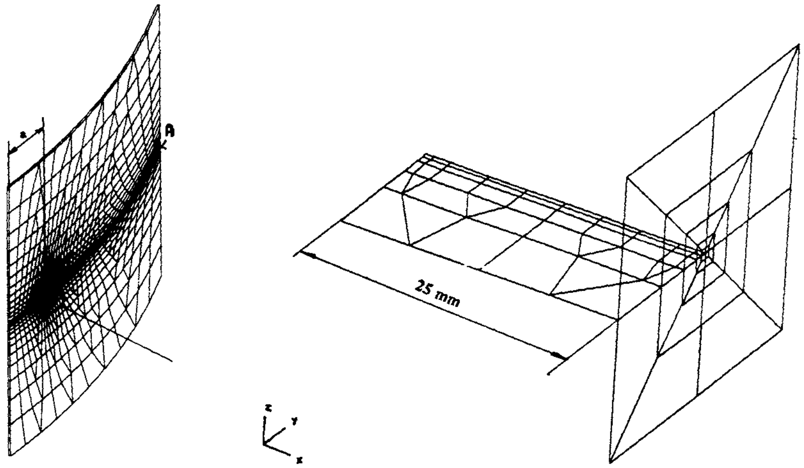

Figure 2. Center crack opening displacement curve

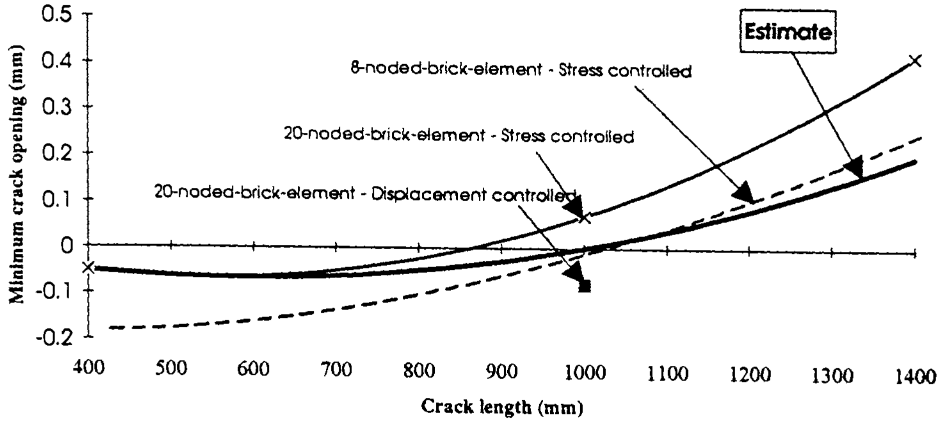

Figure 3. Crack closure under welding residual stresses or thermal gradient load

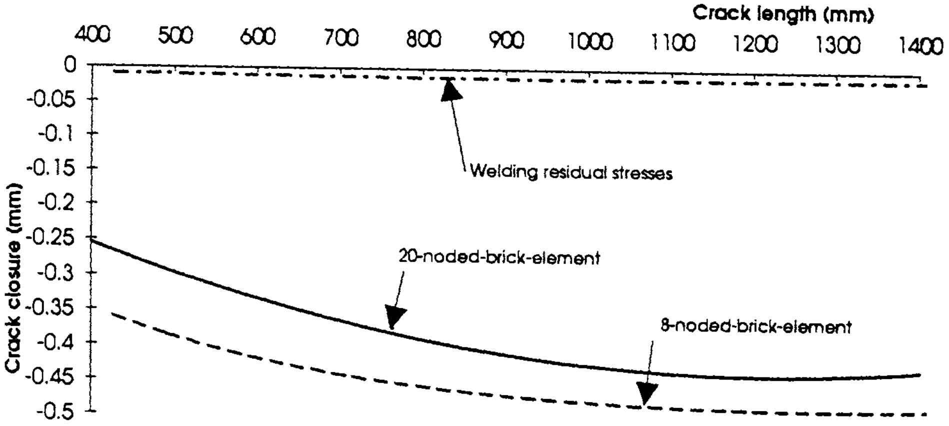

Figure 4. Fitness of simplified approach under bending stresses