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THREE DIMENSIONAL FATIGUE PROPAGATION MODELING OF A NOZZLE CORNER CRACK

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ABSTRACT

The problem of nozzle corner fatigue crack propagation has been addressed since more than 25 years (Broekhoven, 1975, Kobayashi, 1979). The high stress concentration in a nozzle corner under pressure and thermal shocks, make necessary the check of fatigue crack initiation and propagation risks in such a zone. Most of the integrity studies carried out over 40 years of service do include fatigue crack propagation assessments. However a realistic analysis of the crack extension is a complex three-dimensional problem. The fatigue growth is driven by the Stress Intensity Factor (SIF) values along the crack front. These SIF depend not only on the crack size but also on its shape and the location along the crack front. Therefore the crack shape is likely to change continuously.

The current practice for stress intensity factors calculation consists in using influence functions established for a given type of crack front shape (semi-elliptical) and which take into account only in-depth stress gradients. This leads for instance to an overestimation of the crack extension and is not able to take into account the protective role of a thermal sleeve. The aim of the present study is to get through 3 dimensional finite element computations of the SIF, a more realistic estimate of the fatigue crack propagation of nozzle corner cracks. Namely, a reliable description of the crack shape evolution was expected for analyzing the risk of break through and examining the feasibility of non destructive examinations.

Keywords: Fatigue Crack Propagation, Nozzle Corner Crack, 3D Finite Element model.

1. INTRODUCTION

The nozzle corner is a location of high stress concentrations (PVRC, 1987), furthermore nozzles are subjected to pressure and thermal shocks, making necessary to analyze fatigue crack initiation and propagation risks in this zone. The problem is how to assess surface crack propagation over the plant life in such complex shaped structures.

The nozzle connecting the Chemical and Volume Control System (CVCS) to the Reactor Coolant System (RCS) experiences large thermal-hydraulic transients at start up as well as at shut down. Crack propagation studies are required in these CVCS nozzles. To avoid the conservatisms of the commonly used methodology, a new and more realistic approach has been developed. This methodology is based on Finite Element computations of the SIFs at each step of the crack propagation. Our study has involved about 6000 3D computations of the cracked nozzle, therefore careful attention has been paid in simplifying the remeshing techniques and in computing SIFs.

The present paper underlines the difficulties of the problem, explains the weaknesses of the commonly used approach and describes the specific features of the new methodology. Finally, the improvements brought by this new methodology are shown through a comparison of fatigue crack growth predictions of a CVCS nozzle corner crack using the two methods.

2. THREE DIMENSIONAL FATIGUE CRACK PROPAGATION

The fatigue crack growth rate (FCGR) of a macrocrack is commonly assumed to be controlled by the range of the stress intensity factor ΔK. It has been shown by Paris (1963), on the basis of experiments and later confirmed by many researchers, that FCGR of various materials is proportional to a power of ΔK. In our study, we selected two severe initial conditions: the existence of an initial crack, resulting from some initiation phase, was postulated and no ΔK threshold below which cracks do not propagate was considered. This is the stage II of the fatigue crack propagation, where the crack grows under the primary action of maximum principal stress. The crack path has been shown to be essentially perpendicular to the maximum stress direction (Erdogan, 1963). In a nozzle, the macrocrack is more likely to appear and to propagate in the longitudinal plane of the auxiliary pipe containing the primary pipe axis. Such a crack is loaded in mode I and this case is the most severe one. Since the highest value of the applied stress intensity factor range is far below the material fracture toughness, the FCGR remains in the stage II all along the plant life.

Having in mind all these conditions, we may consider that fatigue crack propagation is governed by a Paris-Forman (1967) type law of the form:

$$\frac{da}{dN} = C\left[\frac{K_{\max} - K_{\min}}{1 - f\left(\dfrac{K_{\min}}{K_{\max}}\right)}\right]^m \qquad (1)$$

Where C and m are constant depending on the material and the environment and f ($R = K_{min} / K_{max}$) is a function established from experiments for different R ratios. The SIFs K_{max} and K_{min} represent respectively the minimum and the maximum values of a SIF during a load cycle. The problem of definition and combination of cycles will not be addressed in this study; the standard approach (RCCM, 2000) will be used.

Applying such a FCGR law for modelling the propagation of a surface crack under thermomechanical load variations, requires answering the following difficult questions:

- What is the direction of crack propagation?
- How to define the crack growth rate in 3D?
- What is the validity of the application of the FCGR law at the surface?
- How to perform SIF computations?
- How to integrate the FCGR on a 3D crack front?

The main problem in 3D crack growth is the influence of the sliding of the crack faces in directions normal (mode II) or parallel (mode III) to the crack front. These modes characterized by K_{II} and K_{III} SIFs make the cracks deviate from their local tangential plane and trend to become nearly perpendicular to the tensile stress (Pook, 1979, Hurd, 1982). In mode I+II loading case, the crack deviation could be assessed on a basis of a maximum energy release criterion (Lemaitre, 1985, chap. 8). For mode III cracks, the proof is more difficult to obtain since the energy release has to be computed on branched crack with a vanishing extension (Bui, 1978) requiring in mode III, 3D models. However in 3D configurations, along the crack front a mode II loading becomes frequently a mode III one. Once the deviation is assessed, the crack propagates in mode I and the Paris law may be applied.

Fatigue is a local phenomenon, therefore crack branching criteria and fatigue crack growth rate laws have to be applied locally, that is using a local variation of the SIF (Varfolomeyev, 1990).

Along 3D crack fronts, the SIFs are defined in an orthogonal coordinate system defined by the normal and the tangent to the crack front in the local tangential plane and the normal to this plane (binormal axis). From above, the cracks will grow in a mode I plane. In this plane, we assume that the crack extents in the direction normal to the crack front to be consistent with the measurements in establishing the FCGR law.

Fatigue propagation laws are established from tests on through-wall cracked standard specimens where the extension is measured normally to the crack front. For 3D configurations, except at points where the crack intersects the surface, plane stress specimens are more representative. However, if plasticity is contained, the FCGR law established on specimens should apply on 3D configurations. If the load variations correspond to remote stress being small compared to the yield stress, then surface corrections may be ignored. Otherwise, a small correction may be applied to the constant C in Paris Law (Newmann & Raju, 1981, Varfolomeyev, 1990), accounting for the slowing down at the surface due to higher crack closure effects connected with the increase of plastic zone in plane stress state.

In our case, since a plane mode I crack is considered, the crack will remain plane and only mode I SIF need to be computed. This is the problem addressed by our paper. It should be emphasized that the SIF computation problem is coupled with the fatigue crack growth problem since SIFs depend not only on the crack size but also on its shape, the considered location along the crack front and the stress gradients. The problem of the crack shape evolution in fatigue has been addressed by a very large number of researchers (Shah and Kobayashi, 1972, Newmann & Raju, 1981, Truchon & Lieurade., 1981, Robisson et al., 1982, Jolles et al. 1983, Wu, 1985, Muller et al., 1986, Lin & Smith, 1997). But in most of the cases, only simple configurations were considered, allowing relatively simple answers. The very classical configuration is the plate containing a semi-elliptical surface crack loaded in mode I under tension or / and bending. The results may be summarized as follows:

- The crack remains almost semi-elliptical (Muller, 1986) under such type of loading, provided that the crack is not too deep compared to the plate thickness.
- In most of the cases, an asymptotic regime of crack shape evolution (characterized for the ellipse by its aspect ratio: a/c =depth/half length) is reached after a period depending on the initial shape and the type of loading. Under tension the asymptotic behaviour is stable: the crack front tends to be almost semi-circular, but under bending the ratio of the semi-ellipse axes is changing continuously (Truchon, 1981, Muller 1986).
- The influence of Paris exponent value on the crack shape change is secondary (Lin & Smith 1999).
- The reduction of fatigue crack growth rate at the edge is not always observed (Lin & Smith 1999).

All these studies have been conducted to derive empirical crack front shape evolution laws (see Mahmoud 1986 for a review) which could reduce the prediction of surface crack fatigue growth to a 1D analysis at the deepest point. Transposition to pipes is not straightforward: local tension prevails in mechanical bending not under thermal shock (Watanabe, 1981, Yagawa, 1979).

This self similar crack growth behaviour is no more observed in complex shaped geometries like corner cracks at holes (Wilhem, 1981), cracked nozzles (Smith, 1981). Several factors are likely to explain such behaviour: bending to tensile ratio changes due to stress concentration effects, stress gradient orientations changes in the nozzle thickness, surface effects are important. Therefore corner crack shape in nozzles is likely to change continuously with crack growth.

3. CLASSICAL COMPUTATIONS OF FATIGUE CRACK PROPAGATION

Computation of SIFs for cracks in complex shaped geometries is a difficult problem since obtaining reliable K values along the front requires one hand a local fine mesh in the planes normal to the front as well as along the front itself and one the other hand a large number of elements for modeling the 3D structure. For the much simpler problem of a surface crack in a plate under uniform tension, in 1979 a large disagreement was observed between solutions obtained by several investigators (Hodulak, 1979). Numerical interpretations dated before the 1980's of surface crack fatigue growth test results should be taken with caution. Few investigators have addressed the question of accuracy estimation. A detailed analysis of the SIF computation for semi-elliptical cracks in cylinder conducted by Heliot et al. (1979) has shown that simplified formulae may be rather inaccurate, namely close to the surface. These authors estimated the accuracy around 5%. Today, using nice refined mesh for a 3D cracked structure an accuracy of less than 3% should be expected on SIF estimates.

Computing SIFs for many different cracks corresponding to changes of size and shape during fatigue crack growth, was impossible in the eighties, several simplifications of the fatigue nozzle crack growth problem were proposed:

- The influence function technique is used. This technique allows deriving the SIFs from the computation of stress distributions on the sound structure. In a first step SIFs have to be computed on the cracked geometry for elementary stress distributions corresponding to the terms of a polynomial function. These elementary SIF are the influence functions and owing to the superposition principle, SIFs corresponding to any polynomial stress distribution may be obtained by linear combinations of stress terms and the influence functions. The use of these techniques implies that stress distributions are fitted by polynomials, a set of crack shapes and sizes for which influence functions are computed is selected, and influence functions or SIFs values have to be interpolated at each step of crack growth.

- The crack front shape is modeled by a portion of ellipse or a straight line.
- The influence functions are computed for a simpler geometry: a plate or a corner crack in a perforated plate (Perez, 1986).

Two examples of simplified approaches are presented below.

3.1. The equivalent plate model

A common approach consists in considering a configuration which is locally (i. e. around the crack) symmetrical with respect to a line which, in most of studies, is the bisecting line of the corner. This line starts from the nozzle corner to the nearest point of the outer surface. A further step in the simplification, the "equivalent plate model" (Kobayashi, 1979) is currently used. In this model, influence functions are computed for a semi-elliptical surface crack in a plate under the normal stressed distribution acting along the selected line of symmetry of the sound nozzle. The load is applied on the corner crack defined by the segment of ellipse lying in the nozzle corner. As suggested by Kobayashi, the cracked plate could be oriented normally to the steepest stress gradient, but this direction may differ according to the considered loading. Therefore the bisecting line is selected in most of the applications of this method. The plate thickness is as thick as the nozzle along this bisecting line.

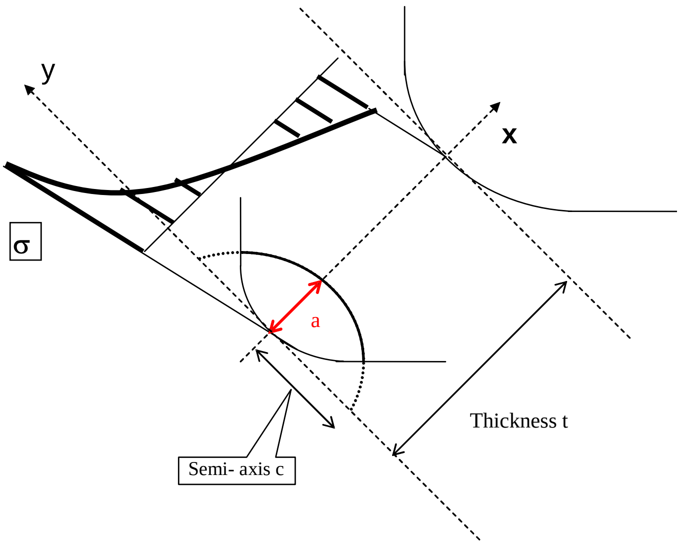

Fig. 1: Scheme illustrating the equivalent plate model

3.2. The envelope nozzle corner crack model

This approach (Robisson, 1982) uses also the influence function method to calculate SIFs, but the influence functions are computed for more representative configurations, i. e corner cracks in a given nozzle. Furthermore, normal stress distributions in the nozzle corner section are fitted by a polynomial of two spatial coordinates accounting for stress gradients along the bisecting line (X axis) of the corner section and along the Y axis normal to the bisecting line in the crack plane. The stress fit is given by the following polynomial function:

$$\sigma\left(X,Y\right)=\sum_{i,j}\sigma_{ij}\left(\frac{X}{t}\right)^{i}\left(\frac{Y}{t}\right)^{j} \qquad (2)$$

where t is the thickness of the nozzle cross section along the X axis.
The SIFs is determined by the expression:

$$K_I\left(s\right)=\frac{2}{\pi}\left[\sum_{i,j}\sigma_{ij}\,h_{ij}(s)\left(\frac{a'}{t}\right)^{i+j}\right]\sqrt{\pi\,a'} \qquad (3)$$

where

- s is the abscissa along the crack front and a' the radius, i. e. the distance between the origin and the crack front along the X axis.
- The influence functions h_{ij} are the SIF corresponding to each elementary loading $\left(\frac{X}{t}\right)^i \left(\frac{Y}{t}\right)^j$ applied on the crack area in the uncracked structure. For the deepest cracks a 10 term fit (i + j " 3) has been used, and a 5 term fit for the smallest cracks.

In this approach the crack growth is predicted by the value of the SIF at the deepest point. The aim of the paper is to determine what shape of crack is to be selected for obtaining trough the application of this simplified approach, envelopes of cracks resulting from fatigue propagation in the nozzle corner. The demonstration, limited by its empirical nature, relies on two hypotheses:

- The pressure is the dominant loading
- Along fatigue crack fronts, the SIF is almost constant.

The paper compares the behaviour of seven cracks, all symmetrical with respect to the bisecting line, but with different depth and shapes. Four cracks are quarter circular cracks with different radius and depth, one with two bumps and two are semi-elliptical as shown in figure 2.

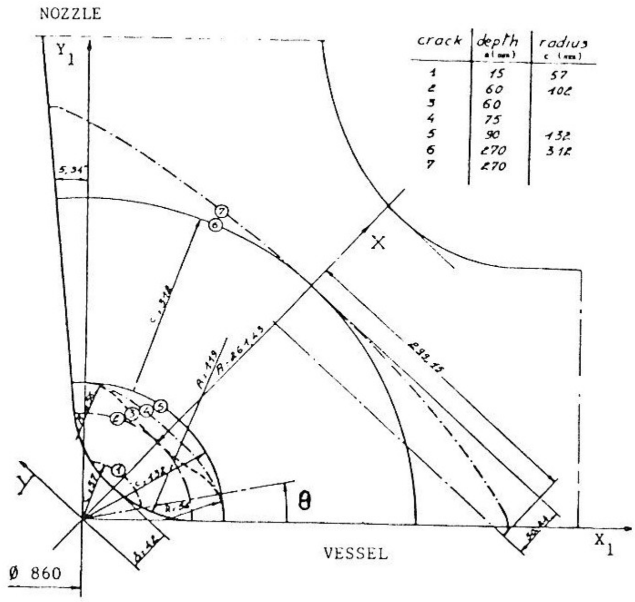

FIGURE 2 : NOZZLE CORNER CRACKS

Fig. 2: Nozzle corner cracks considered in (Robisson, 1982)

It appears from the comparison of SIF distributions along the crack front that for the two chosen semi-elliptical cracks the SIF crack front distribution is rather uniform. Finally the authors recommend distinguishing two families of corner cracks depending if the crack radius is smaller or not than the radius of the nozzle. If the crack is small, an elliptical crack with a depth 3 times smaller than the other semi-axis is recommended. For larger crack a more flat semi-elliptical crack should be preferable (aspect ratio of 10).
A similar approach, based on different crack shape envelopes, has been recently proposed by Yigeng and Shutao (1991).

3.3. Limitations of the simplified approaches

Both approaches resort to the influence function method which presents two major drawbacks:

- The location, shape and size of the cracks defined for the computation of influence functions have to be selected before any crack growth computation.
- The computed crack propagation is symmetrical with respect of a selected line (bisecting lie or line of highest stress gradients).

The equivalent plate model, considers usually only in-depth stress gradients. This leads to an overestimation of the crack extension and is not able to take into account the protective role of a thermal sleeve. The approximations of the equivalent plate model lead to quite acceptable predictions provided the surface crack is oriented in the direction of the steepest stress gradient and stress gradient do not change too much during crack growth. This may not be the case for large propagations.

The envelope nozzle corner crack approach hypotheses are restricted to pressure dominant loadings and assumes that on crack front resulting from fatigue propagation, the SIF is almost constant, which is certainly not the case in the shape evolution phase. In this approach crack growth is predicted by the value of the SIF at the deepest point and the crack shape is fixed to get envelope propagation. This may lead to larger overestimate than in the equivalent plate model.

4. FRAMATOME-ANP METHOD FOR FATIGUE CRACK PROPAGATION SIMULATION

The aim of the present study is to get a more realistic estimate of the fatigue crack propagation of nozzle corner cracks. Namely, a more accurate description of the crack shape evolution was expected for analyzing the risk of break through and examining the feasibility of non destructive examinations. This approach departs from the French standard scheme for fatigue crack propagation assessments (Beaud, 2003) on three points: initiation phase has been neglected, SIF are computed on the actual crack front whose shape and plastic zone size corrections are not considered for the considered thermal dominant type of loadings.

The present method consists in an algorithm for fatigue crack growth computation from finite element computed SIFs and a set of tools for ensuring fast but accurate SIF determination. The flexibility and the user's friendliness of these tools is an important point since for such kind of fatigue analysis, about 300 load combinations have to be taken into account, requiring the 3D computation of about 6000 cracked structures.

4.1. Fatigue crack growth assessment

The basic idea is to use the Finite Element method at discrete steps (called reference steps) of the fatigue crack growth computation. However this cannot be achieved for each increment of growth. Therefore the following assessment technique for crack propagation has been implemented in a monitoring software of the Finite Element code SYSTUS (SYSTUS, 2005):

- At each of these reference steps, the nozzle with its initial crack, or the crack computed from the previous step, is modelled by Finite Elements and SIFs are computed for all the loading combinations.
- Then a parent crack is defined by homothetic transformation of the reference front (see Fig. 3). Again, for all the loading combinations, SIFs are computed along the parent front. The homothetic transformation is applied to the reference crack with a ratio of 1.1, except if the propagation is so fast that more refined steps are required.
- At each node of the reference front crack extension is computed along the normal to this front in the crack plane (since the crack propagates in mode I). The extensions are obtained by integration of the Paris-Forman law for a set of cycles ΔN corresponding to one year of service.

$$\int_{a_0}^{a_f} \frac{da}{\left[\dfrac{K_{\max} - K_{\min}}{1 - f\left(\dfrac{K_{\min}}{K_{\max}}\right)}\right]^m} = C\,\Delta N \qquad (4)$$

Integration is performed using an actual value of the SIF. This actual value is derived by linear interpolation between the value at the current node and the SIF value at the intersection of the normal to the parent front.

- The load combinations will be defined following Miner's rule at the node for which the distance to the outer surface of the nozzle is the smallest.
- The crack growth computation is stopped at the end of the year in the course of which the actual front goes beyond the parent front. Then an envelope of the actual crack front is defined and remeshed, constituting the next reference front.
- Thus, the meshing of reference and parent front is repeated for each of these blocks of years up to the end-of-life of the plant.

This technique presents several difficulties like front remeshing which could not have been automated. Most of these problems are described with their corresponding remedies in the next paragraph.

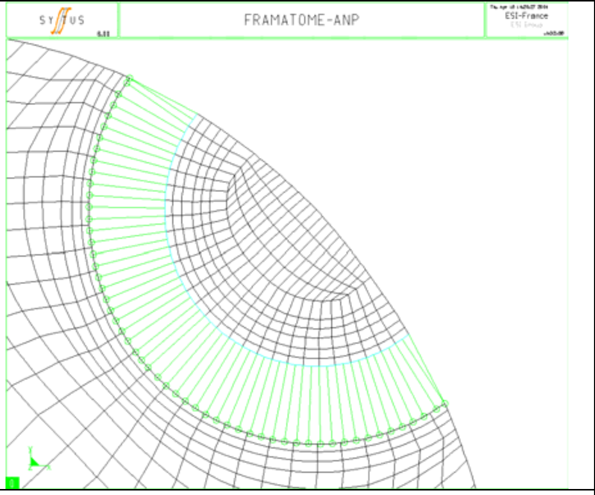

Fig. 3a: Lines normal to the reference crack

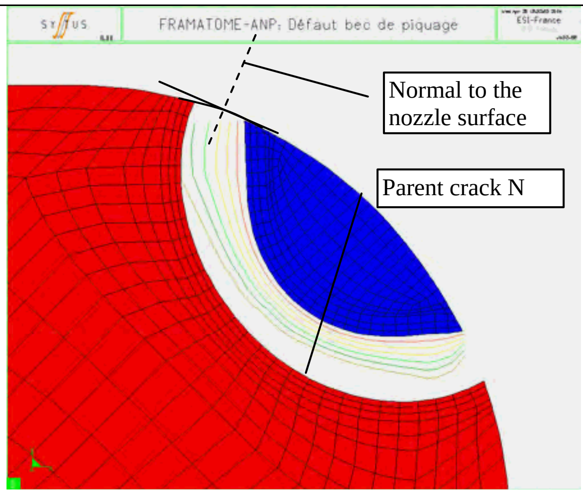

Fig. 3b: Reference, parent and actual cracks

4.2. Meshing the cracks and computing Stress Intensity Factors

The meshing techniques developed by Framatome-ANP and ESI in SYSTUS for crack modelling have been noticeably improved for propagating cracks. The shape of the initial crack is usually taken as a part of ellipse, and for such type of crack a special module has been developed in SYSTUS since years. The module removes a group of elements (sound block) in the mesh of the sound structure, builds a cracked block of elements having the same envelope as the sound mesh and inserts the cracked block in the sound structure. However, after some crack growth, the shape of the actual crack is considerably different, and new tools have been implemented in SYSTUS for meshing any planar crack. Crack fronts are fitted by connected B-splines (kinds of flexible strips used to create smooth curves), allowing representing any front shape. The continuity of the tangents at the connection of front segments is a recommendation. When a crack propagates much less close to the nozzle surface, the front forms a sharp angle with the surface. This may lead to an underestimation of the real value of the SIFs and makes difficult the meshing of the new front. In such a case, a local envelope of the actual crack is obtained by extrapolation of the front from a part which is close to this area but present a more regular variation of curvature. The new reference front is therefore an envelope of the last actual front. Since the length of the new reference front may be much larger than the previous one, extra nodes may be added for keeping almost a constant density of nodes all along the front.

The discretization of the parent crack front is defined by the intersection of normal lines to the reference front with the new front. The connection of the parent front with the nozzle edge is defined by extrapolation along the tangent of the front.

The SIFs were computed from the displacements which is must faster than using domain integrals since stress do not need to be computed. However, this require a well suited crack front mesh according to the following rules: the cracked block is meshed with quadratic elements, along the front the mesh is sufficiently refined to give SIF values close to those obtained by a domain integral method (at least 20 elements along the front), each element face containing a primary node of the front is normal to the front, the crack tip mesh is radial with a constant angular spacing of 22.5 degrees. The selection of all of these parameters has been validated by comparison with J integral computations (see § 4.3 on validation). H. D. Bui (Bui, 1978) has proven that the relationship between the crack opening displacement (COD [u]) and the SIF established in plane strain is valid in 3D provided that the displacement (u_z in mode I) is computed in a plane normal to the crack. Therefore, SIFs have been derived through the following formula:

$$K = \frac{E}{1-\nu^2}\frac{\sqrt{2\,\pi}}{8}\frac{[u_z]}{\sqrt{r}} + O(r) \quad (5)$$

where r is the distance to the crack front in the front normal plane, E is Young's modulus and ν Poisson's ratio. At the edge, a plane stress state prevails, and neglecting any effect on the stress singularity (Benthem, 1977), the value of m is simply set to zero complying with the plane stress expression of (5).

4.3. The plastic zone size correction problem

The crack-tip stress field is singular, which induces a local yielding, even if the global behavior of the cracked structure remains elastic. For small scale yielding conditions, G. R. Irwin (1962) proposed a plastic zone size correction to the SIF which accounts for the increase of the energy release rate J due to small scale yielding. Under cyclic loading, this correction is given by the following formula:

$$r_y = \frac{1}{k\pi}\left(\frac{\Delta K}{2\sigma_y}\right)^2 \qquad (6)$$

If the SIF K is expressed in MPa√m, and the conventional yield limit σ_y in MPa, r_y is obtained in m. The coefficient k value is set to 6 for plane strain and 2 in plane stress. If strain hardening is accounted for, a flow stress may be used instead of the yield limit: $\sigma_f = \frac{R_{p0,2} + R_m}{2}$ (7).

However applying such a plastic zone correction to SIFs in fatigue crack growth simulations is questionable for two main reasons:

- Fatigue propagation laws are derived from experimental measurements described in terms of the elastic K value without accounting for small scale yielding. These measurements are validated if yielding is so small the plastic zone correction is less than one hundredth than the ligament size (local thickness w minus crack depth a) as expressed by the condition:
  - $$w - a > \frac{4}{\pi}\left(\frac{K_{max}}{\sigma_f}\right)^2 \qquad (6)$$
- Thermomechanical loading may induce yielding in the nozzle corner, even without any crack. This will modify the stress distribution and thermal strains will induce lower stress levels than for a linear elastic behavior. In another fatigue crack growth analysis in the same CVCS nozzle, we have shown for two cracks sizes (10 and 23 mm) under dominant thermal loading that elastic K values are larger than the elastoplastic equivalent SIF values derived from the J integral trough the formula $K_{eq} = \sqrt{E' J}$ (7).

For these two reasons, there is no need to apply any plastic zone size correction to the SIFs in fatigue crack growth calculations.

There is another limitation on yielding which guarantee that propagation remains in stage II. The condition bears on the maximum value of the SIF:

$$K_{\max} < 0{,}7 K_{Jc} \quad (8)$$

This limitation has been developed for duplex stainless steels under mechanical loadings and is very conservative for austenitic steels.

In our case, all the validity conditions for applying Paris law without any plastic zone size corrections and without entering stage III propagation are met.

4.4. Validation of the new approach

The present FE based approach for fatigue crack propagation simulation has been validated on three points: accuracy of the SIF computational method, quality of the nozzle corner crack SIF computation, check of the fatigue propagation algorithm.

The accuracy of the SIF computational method has been estimated by comparing J values (Fig. 4) obtained using the Crack Opening Displacement formula (5) and the J-K relationship (7) with values computed using the domain integral method G_THETA (Destuynder, 1981). The latter method is much less sensitive to the mesh refinement and stability of the integration is checked by comparing results obtained on several integration domains. Figure 4 gives for a pressure loading applied on 2 mm deep semi-circular crack, the SIF results obtained by G_THETA method on two contours and the SIF derived from CODs. The G_THETA results obtained on the two domains are identical. Close to the surface, the crossings of the curves mark the plane strain to plane stress evolution. The J values from COD are very close to those obtained with the domain integral method.

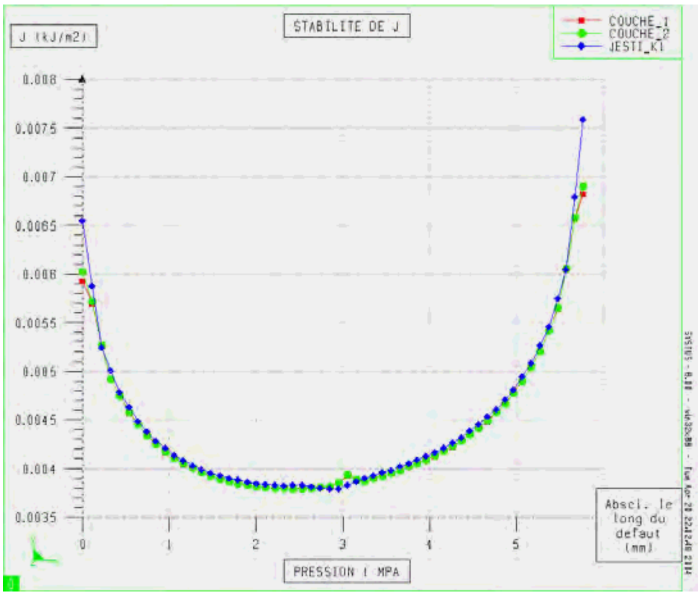

Fig. 4: SIF variations along the crack front using COD (diamonds) and G_THETA methods

Several tests have been conducted on the mesh refinement around the crack front for the same semi-circular crack. We deduced from the results the following recommendations:

- The number of elements along the front has to be greater than 20
- If the quality rules given in 4.2 are verified, then the SIF evolution along the front is smoother as shown on Figures 5a and 5b.

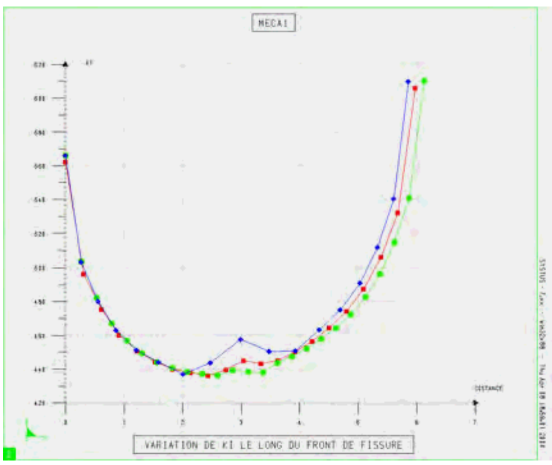

Figure 5a : Influence of the number of elements on the SIF evolution along the crack front

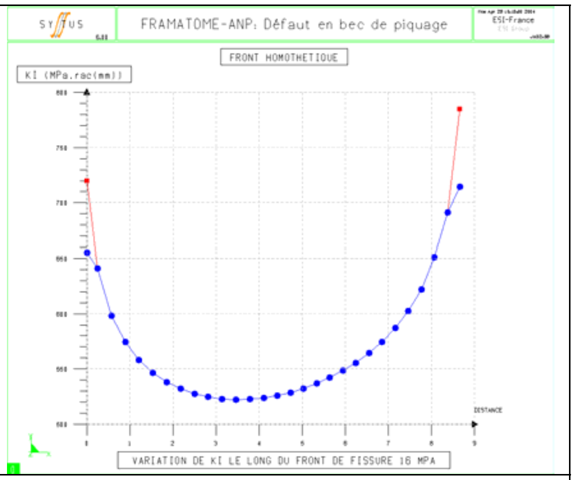

Figure 5 b : Influence of a regular variation of crack front tangents on SIF evolutions along the crack front

On similar cracked nozzles, the quality of the SIF computation has been checked by comparing SYSTUS computations with results of the PVRC study (1981) on pressurized reinforced nozzles containing a corner crack in the longitudinal symmetry plane.

Finally, the fatigue propagation algorithm has been checked by comparing the results with another in-house software based on the equivalent plate model. For a given crack and a given node, the same combination of loads has been selected in the two softwares and a 5% difference has been found on the SIFs. Such a difference is to be expected when comparing SIF obtained from refined FE computations and SIF computed with influence functions established for a surface cracked plate. We have also checked that the linear interpolation of SIFs between reference and parent crack front do not have an influence on the crack growth estimate.

4.5. Advantages of the new approach

The main advantage of the FE crack propagation simulation method is its ability to predict changes in shape and preferred directions of crack extension. If, as in our case, loadings induce unsymmetrical stress distributions, the steepest stress gradient of which is time dependent. This is illustrated in § 6.

The approach allows predicting large crack growth more accurately than using influence functions. Three reasons support this affirmation: for crack size greater than half the thickness, the influence functions vary much more rapidly making interpolations less accurate, for large cracks the effect of the shape of the structure is greater, and for a given depth, crack areas predicted using influence functions are larger. One may expect to obtain a smaller crack extension along the bisector where the remaining ligament is the smallest.

5. NOZZLE CONFIGURATION

The present study concerns the fatigue crack propagation analysis of a nozzle corner crack in the nozzle connecting the chemistry and volumetric control system pipe (CVCS) and the Reactor Coolant System. The CVCS is aimed to control the RCS water volume and chemistry.

5.1 Geometry

The inner and outer diameters of the reinforced part of the nozzle are respectively 65.6 and 177 mm. The outer diameter of the thermal sleeve is 60.6 mm. The nozzle corner radius is 8 mm and the distance from the corner centre and the outer surface is about 92 mm.

The initial defect is located in the longitudinal plane of symmetry, since mode I pressure stress are higher for this location. This defect has a part elliptical crack front of aspect ratio of 5 and is 2 mm deep.

5.2 Material characteristics

The nozzle as well as the thermal sleeve is forged in austenitic stainless steel (Z3 CND 17.12 with controlled nitrogen and molybdenum (RCC-M, 1997). In the nozzle corner, base metal minimum values have been selected for the yield stress, which are:

Sy = 255 MPa at 20 °C and Sy = 144 MPa at 300 °C

At 300°C Young's modulus value E is 176500 MPa, and the fracture toughness $J_{0,2}$ = 137 kJ/m^2. Thermal characteristics may be found in the RCC-M code (1997). The thermal conductivity of the water lying between the sleeve and the nozzle has been enhanced.

The Fatigue Crack Growth Rate law to be used for analysis of austenitic stainless steel components in PWR environment is as follows (Le Duff, 1996) and has been selected from the RSEM (RSEM addenda, 2000). In the following formula, SIF K is in MPa√m and the crack length a in mm.

$$\frac{da}{dN} = 1.8\ 10^{-9}\ \left(\Delta K_{eff}\right)^4 \quad \Delta K_{eff} = \Delta K\ f(R) \quad (9)$$

(9b)	$K_{min} < K_{max} < 0$	$K_{min} < 0 < K_{max}$	$K_{min} > 0$
f (R) R = K_{min}/K_{max}	$\frac{1}{3}$	$\max\left(\frac{1}{3};\frac{1}{1-\frac{R}{2}}\right)$	$\frac{1}{1-\frac{R}{2}}$

The initiation phase has been neglected.

5.3 Loadings

The CVCS nozzles are subjected to the same pressure transient as the RCS. Therefore only thermal shocks caused by mass flow variations are of interest. 37 thermal transients and their associated pressure variations have been considered. These transients are those of the CVCS line and the cold leg. Letdown and charging flows temperature variations have been accounted for. The exchange coefficients have been determined experimentally. A detailed analysis of the thermal exchange conditions in the volume between the thermal sleeve and the nozzle under the support ring has been performed. A thermal hydraulic analysis of tests results on a CVCS nozzle mock-up, specific exchange conditions have been defined for this volume, accounting of the shielding effect of the thermal sleeve. Namely the mixing rate is lower than without the sleeve on about a zone of 10 mm under the ring. The thermal exchange coefficient is still high in this zone. A barycentric interpolation is applied to obtain local values of the thermal exchange coefficient.

The moment loadings of the primary pipe and the CVCS line have been neglected, since generating low value of stresses compare to thermal stresses.

6. CRACK GROWTH OVER FORTY YEARS OF SERVICE

The equivalent plate model and the FE fatigue crack growth simulation have been applied to the fatigue crack growth of the same initial nozzle corner defect.

6.1 Finite element models

In both cases, temperature fields have been computed on a 3D uncrackced model (Figs 6a, 6b, 6c) meshed with linear elements. In the 37 transients, 300 instants have been selected accounting for maximal values of the trough thickness temperature gradient, the inner wall value of the quadratic temperature fit and the difference between the inner wall temperature and the mean value.

The selected temperature fields are projected on the nozzle corner crack models which are meshed with quadratic elements (Fig. 6d shows a typical mesh of the cracked zone for the postulated crack). The thermomecanical computations are performed on these quadratic models considering thermal dependent mechanical properties.

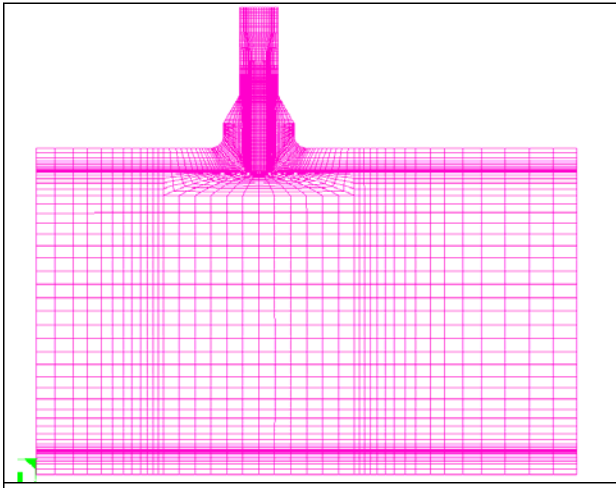

Fig. 6a: Mesh of half primary pipe and nozzle

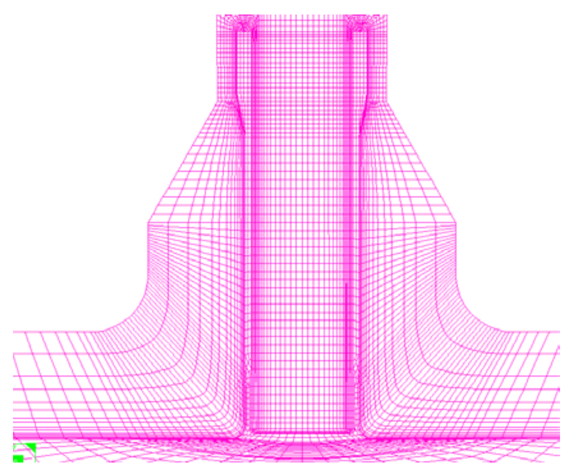

Fig. 6b: Mesh of half nozzle

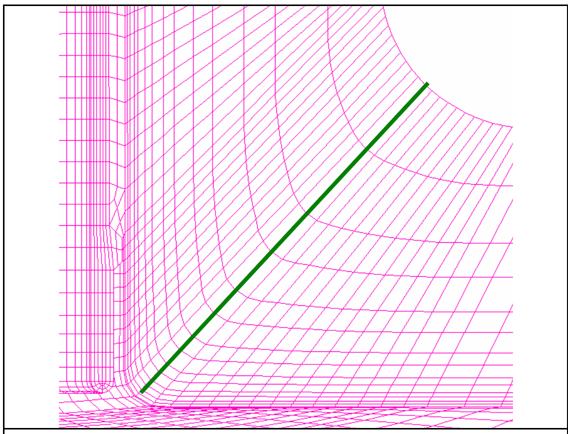

Fig. 6c: Zoom on the nozzle corner mesh

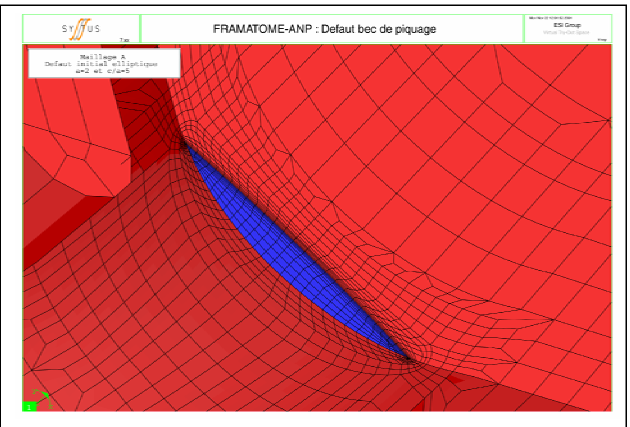

Fig. 6d: Initial crack

6.2 Crack growth results

The fatigue computations have been conducted without plastic zone size correction and considering a classification of transients following a decreasing order of SIF range ΔK.

For the considered configuration, the stage II condition (8) is always verified since the maximum SIF value is about 76 $MPa\sqrt{m}$ which is less than 104 $MPa\sqrt{m}$, value of $0{,}7*K_{JC}$.

After 40 years of service, the initial defect has grown from 2 mm to 27.5 mm along the bisecting line, which represents less than one third of the local thickness along this line. The crack propagation over the last 4 years is represented in Figure 7. The crack growth is more important on the primary side (42 mm) than on the auxiliary side (22.5 mm). This is the result of the shielding effect of the thermal sleeve. Such an unsymmetrical crack growth could not be evidenced with the simplified approaches. All along the years, the maximum ΔK_{eff} value is almost constant along the bisecting (Fig. 8), which explains the linear propagation observed in Fig. 9.

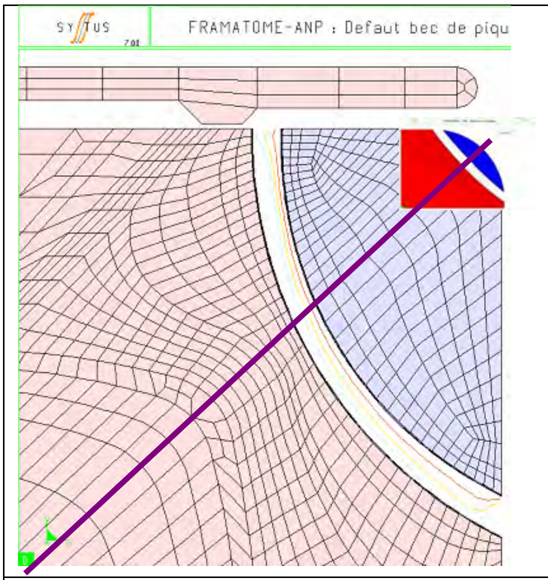

Fig. 7: Mesh of half primary pipe and nozzle

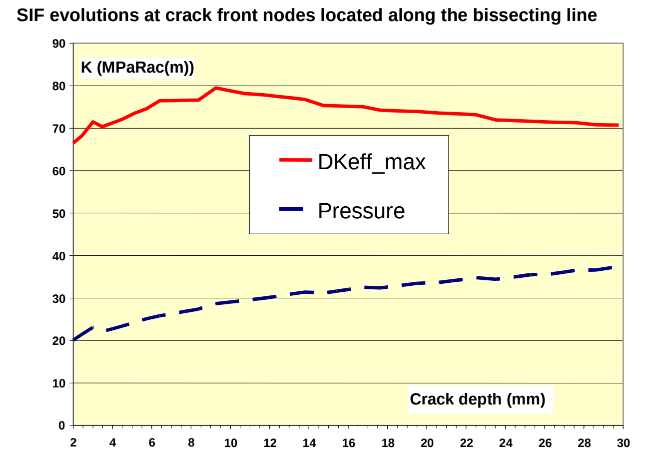

Fig. 8: SIF evolutions along the bisecting line

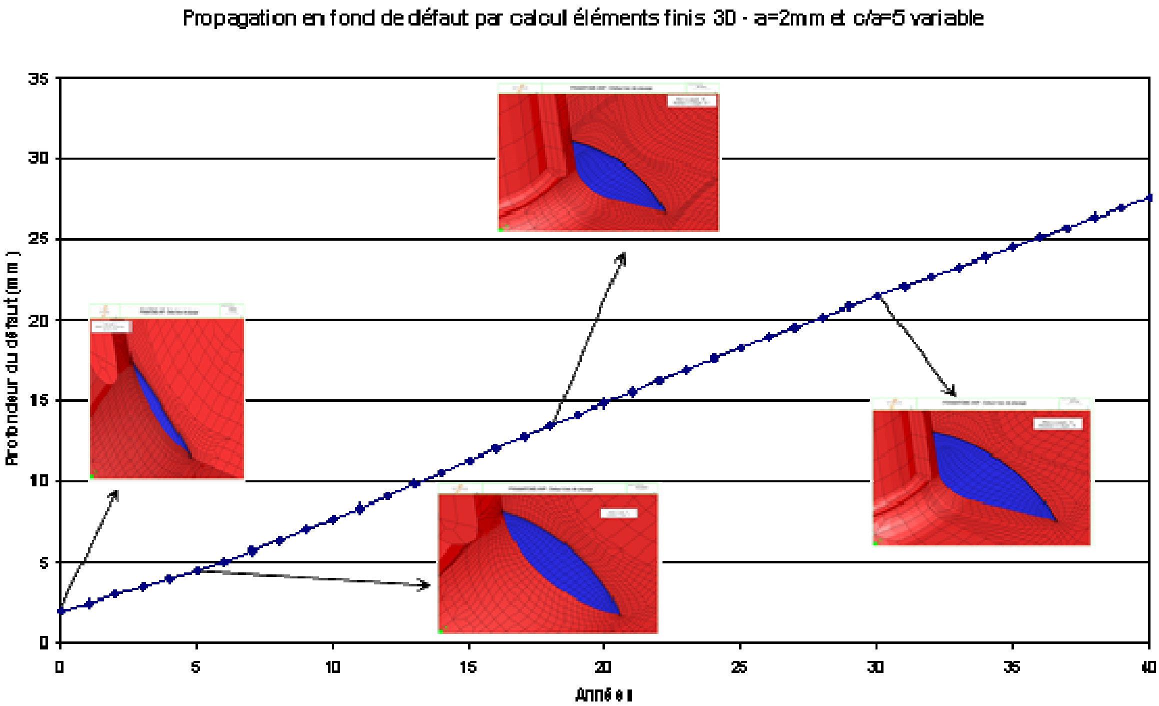

Fig. 9 Crack growth at nodes located along the bisecting line

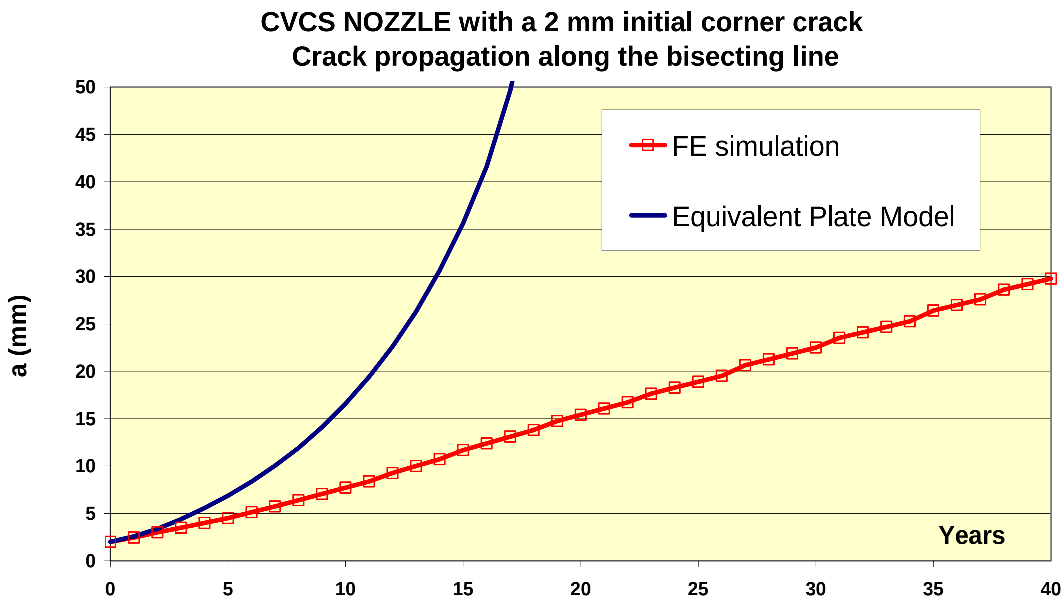

Fig.10 Crack growth at nodes located along the bisecting line

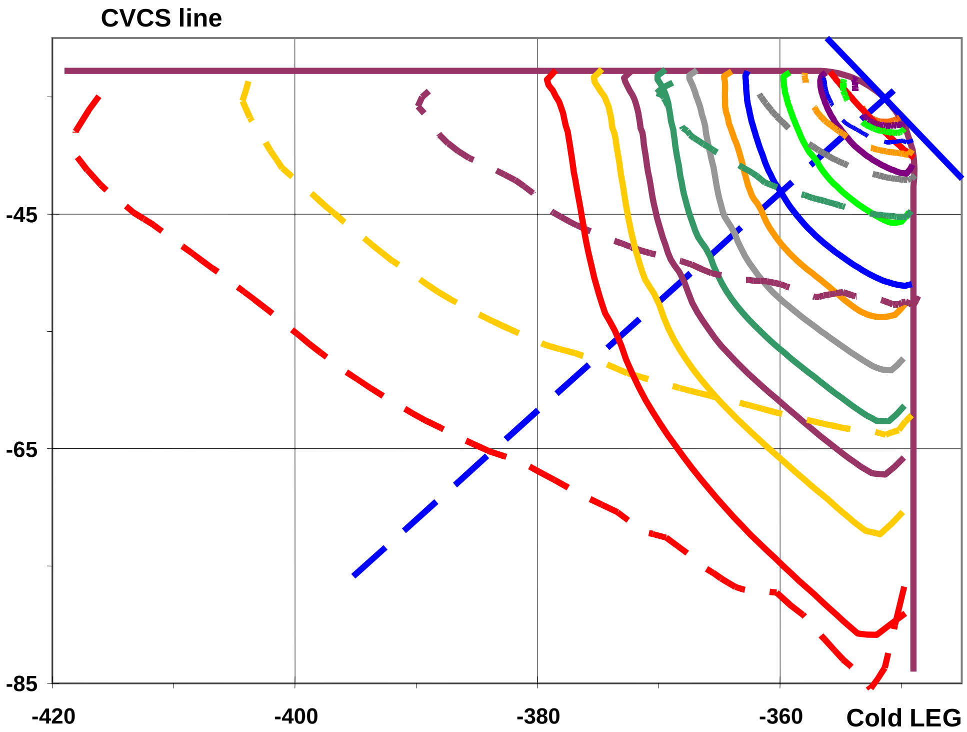

Fig. 11 FE simulation and Equivalent plate Model (dotted lines) crack growth predictions

Figures 10 and 11 illustrate differences in predictions using the FE simulation or the Equivalent Plate Model:

- The crack propagation along the bisecting line is far much faster using the Equivalent Plate Model. The FE simulation gives a more comforting result, since the propagation rate is constant.
- The crack propagation predicted by the FE crack propagation simulation method is non symmetrical. The extents on the cold leg side are quite similar, but the propagation predicted by FE simulation is much lower on the CVCS side.

These comparisons make evident the conservative nature of the predictions obtained with the equivalent plate model and its unsuitability to handle non symmetrical evolutions of the crack shape under fatigue loading.

7. CONCLUSIONS

A numerical simulation of fatigue crack growth based on the combination of Finite Element modelling at discrete steps of the fatigue crack growth and interpolations techniques has been presented. This method is particularly suited in stress concentrations areas subjected to time dependent unsymmetrical stress distributions.

This method cannot be applied without an important effort for meshing the cracks. This has been made possible with the development of performing meshing tools. The efficiency of the algorithm allowed handling more than 6000 computations of cracked structures. However, the method presents two main advantages:

- Realistic prediction of the crack front evolution as illustrated by the application to the Chemical and Volume Control System (CVCS) nozzle where the symmetrical partly semi-elliptical nozzle corner crack extents towards the primary pipe taking the form of a quarter of an ellipse.
- Realistic prediction of the damage as shown by the comparisons with the predictions given by the equivalent plate model. The present method shows that extension rate along the bisector is constant along the bisecting line, when the equivalent plate method gives a highly non-linear rate of growth. Furthermore, the FE simulation evidences the shielding effect of the thermal sleeve.

This promising technique has been also applied to different type of problems mixed mode fatigue crack growth (Curtin, 1998), fatigue crack growth in surface cracked plates (Lin & Smith, 1999), influence of residual tress fields on fatigue crack propagation (Courtin, 2003). The present application deals with a much complex structure subjected to a lot of transients, showing the ability of the approach to solve industrial problems.

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REFERENCES

Broekhoven M. J. G. & Van de Ruijenbeek M.G., 1975, "Fatigue crack extension in nozzle junctions: comparisons of analytical approximations with experimental data", Trans 3rd Conf. in Reactor Technol. , London, G4/7
Kobayashi, A. S., Emery, A. F, Lowe, W. J. and Antipas A, 1979, "A procedure for Estimating the Stress Intensity Factor of a Flattened Surface Crack at a Nozzle Corner". Jour. of Pres. Vessel Technology, ASME, Vol. 101, pp. 181-183
J. L. McLean, January 1987. PVRC Report Grant Nrs 84-20 & 85-8, Project P110-5 prepared for Pressure Vessel Research Committee. Review and Critical evaluation of data on nozzle corner cracks. Final report.
Paris, P. C., 1963, « The Fracture Mechanics Approach to Fracture », Proc. Of the 10th Sagamore conference, Syracuse University Press.
Erdogan, F., Sih, G. C., 1963, Journal of Basic Engineering, vol. 85, N°4, pp. 519-527.
Forman A. G.., 1967, Journal of Basic Engineering, vol. 89, pp. 459-469.
RCC-M, 1997 & addenda 1998, 2000, “Design and construction rules for mechanical components of PWR nuclear islands”, AFCEN, Paris
Pook, L. P. and Sharples J. K., 1979, Int. Jour. of Fracture, **15**, p. R223.
Pook, L. P. and Greeman, A. F., 1979, in Fracture Mechanics, ASTM STP 677, American Society for Testing and Materials, pp. 23-25.
Hurd, N. J. and Irwing, P. E., 1982, “Factors Influencing Propagation of Mode III Fatigue Cracks under Torsional Loading”, Design of Fatigue and Fracture Resistant Structures, ASTM STP 761, P. R. Abelkis and C. M. Hudson Eds, American Society for Testing and Materials, pp. 212-233.
Lemaitre, J., Chaboche, J. L., 1985, « Mécanique des matériaux solides », Bordas Ed., Paris.
Bui, H. D., 1978, « Mécanique de la rupture fragile », Masson Ed. , Paris.
Varfolomeyev, I. V. and Vainshtok, V. A., 1990, “Discussion on surface crack growth criteria under cyclic loading”, Int. Jour. of Fracture 46, pp. R25-R33.
Newmann, J. C. and Raju, I. S., 1981, Engng. Fracture Mechanics, Vol. 15, pp. 185-192.
Truchon, M. and Lieurade, H.-P., 1981, "Experimental Study of Surface Crack Propagation in an E36 steel", in Advances in Fracture Research, Fracture, ICF5, vol. 1, pp. 31-39.
Jolles, M. & Tortoriello, V., 1983, « Geometry variations during fatigue crack growth of surface flaws », Fracture mechanics, ASTM STP 791 Vol 1, In Lewis J., Sines G. editors, American Society for Testing and Materials, pp. 297-307.
Shah R. C. and Kobayashi A. S., 1972, “Stress Intensity Factors for an Elliptical Crack Approaching the Surface of a Plate in Bending”, ASTM STP 513, Part I, American Society for Testing and Materials, 3-21.
Robisson, F., Doule, A., Heliot, J., Flamand, F. and Pellissier-Tanon, A., 1982, PVRC Report, "Effect of shape and depth of cracks on stress intensity factor at nozzle corner", PVP Vol. 58, ASME.
Wu, S. X., 1985, « Change of surface during fatigue growth », Engng. Fracture Mechs., 22, pp. 897-913.
Muller, H. M., Muller S., Munz D. and Newmann, J., 1986, ”Extension of Surface Cracks During Cyclic Loading“, ASTM STP 905, American Society for Testing and Materials, pp. 625 – 643.
Lin, X. B. and Smith, R. A., 1997, “An improved Numerical Technique for Simulating the Growth of Fatigue Planar Cracks”, Fatigue and Fracture of Engineering Materials and Structures, Vol. 20, 10, p. 1363-1373.
Lin, X. B. and Smith, R. A., 1999, “Finite element modeling of fatigue crack growth of surface cracked plates”, 3 parts, Eng. Fract. Mechs., 63, pp503-556.
Mahmoud, M. A and Hossein, A.., 1986, "Assessment of Stress Intensity Factor and Aspect Ratio variability of Surface Cracks in Bending Plates". Engng. Fract. Mechs, Vol. 24, N°2, pp. 207-221.
Watanabe, T., Hasegawa, Y. and Katsumoto K. , 1981, "Fatigue tests on defective circumferential welded pipe joints", in Advances in Fracture Research, Fracture, ICF5 vol. 1, Cannes, pp.41-48.
Yagawa G., Ichimiya, M., Ando, Y., 1979, Theoretical and Experimental Analysis of Semi-elliptical Surface Cracks Subject to Thermal Shock”, Fracture Mechanics, ASTM STP 677, C. W. Smith Editor, American Society for Testing and Materials, pp. 381-398.
Wilhem, D., Fitzgerald J., Carter, J. and Dittmer D., 1981 “An empirical approach for determining K for surface cracks”, in Advances in Fracture Research, Fracture, ICF5 vol. 1, Cannes, pp.11-21.

Smith, C. W., 1981. "Observation on Prediction of non-similar subcritical crack Growth and Stress Intensity Distributions", in Advances in Fracture Research, Fracture, ICF5 vol. 1, Cannes, pp.3-10.
Hodulak, L. , Kordish, H., Kunzelmann S. and Sommer E., 1979,“Growth of Part-Trough Cracks“, Fracture mechanics, ASTM STP 677, C. W. Smith Editor, American Society for Testing and Materials, pp. 399-410.
Heliot, J., Labbens, R. and Robisson, F., 1980, "Influence functions for stress intensity factors at nozzle corner", Fracture Mechanics, ASTM STP 743
Perez R., Tritsch, D. E. and Grandt F. Jr., 1986, "Interpolative estimates of stress intensity factors for fatigue crack growth predictions", Technical note, Eng. Fract. Mechs, 24, N°4, pp.629-633.
Yigeng, Xu and Shutao, Cai, 1991, "Assessment of the Fatigue Life in Relation to Cylinder-Nozzle Corner Cracks". Int. J. Pres. Ves. & Piping, **46**, 411-422.
Beaud, F., Musi, S., Faidy, C., 2003, “Industrial Models for Thermal Fatigue Crack Initiation and Propagation in Mixing Zones of Piping Systems”, SMiRT 17 conference, Prague Aug. 17-22, paper F02-5.
SYSTUS, User’s manual 2005, ESi-Group, France.
Benthem, J. P., 1977, "State of stress at the vertex of a quarter-infinite crack in a half-space". Int. J. of Solids and Structures, 13, 479-492.
Irwin, G. R., 1962, "The Crack Extension Force for a Part Through Crack in a Plate". Trans of ASME, Jour. of Applied Mechanics, Vol. 29, pp. 651-654.
Destuynder Ph., Djaoua M., 1981, “Sur une interprétation mathématique de l’intégrale de Rice en théorie de la rupture fragile”, Math. Meth. In Applied Sciences, N°3.
Le Duff J. A., Ould P., Bernard J. L., 1996, "Fatigue crack initiation and propagation in austenitic stainless steels for light water reactors", Int. J. Pres. Ves. & Piping 65, pp. 241-253.
RSE-M, 1997 & addenda 2000, « Surveillance and in-service inspection rules for mechanical components of PWR nuclear islands”, AFCEN, Paris.
Courtin, S., 2004, “Propagation de fissures de fatigue dans une géométrie de gorge de vilebrequin en présence de contraintes résiduelles”, Université de Poitiers, France.
Curtin T. J., Adey R. A., W. Baynham, J. M., Marais, Ph.., 1998, "Fatigue Crack Growth Simulation for Complex Three-Dimensional Geometry and Loading". Proceedings from the 2nd Joint NASA/FAA/DoD Conference on Aging Aircraft, Williamsburg, VA.