G22/1*

Evaluation of Crack Opening Times and Leakage Areas for Longitudinal Cracks in a Pressurized Pipe

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INTRODUCTION

This study presents a method of evaluating the minimum time to crack opening as well as the maximum leakage areas in the case of longitudinal through-wall cracks in a cylinder with an internal pressure. The objective is to arrive at a realistic enveloping hypothesis for the conventional longitudinal break of a Steam Generator (S.G.) entry elbow through the application of the proposed method on the hot leg of French PWR's. In fact, the present hypotheses consider the existence of a longitudinal through crack of length equal to the outer diameter (D_o) of the piping with :

. leakage area = fluid section ($\pi D_i^2/4$) $\simeq$ 5000 cm^2
. time to crack opening of 1 ms.

These conventional values are too conservative and do not seem to be compatible between each other. Fortunately, the fracture mechanics theories presently available permit to evaluate an upper bound to the leakage areas for cracks in piping. Moreover, a synthesis of recent studies in fracture dynamics allows to determine the minimum crack opening times. This study is thus composed of four steps :

a) Proposal of a computational model to evaluate upper bound of leakage areas in pipes under pressure.

b) Validation of the model with respect to certain number of experimental and/or computational results.

c) Application of the model to S.G. entry-elbows of FRAMATOME designed PWR's, using the hypothesis of an existing through crack of length equal to external diameter of the pipe.

d) Synthesis of studies in fracture dynamics to evaluate the maximum crack opening velocities in order to determine the minimum crack opening times.

This will reduce the over conservatism existing in the present hypothesis in the evaluation of jet forces in longitudinal break related to the S.G. entry-elbow.

SMiRT 11 Transactions Vol. G (August 1991) Tokyo, Japan, © 1991

COMPUTATIONAL MODEL FOR UPPER BOUND OF LEAKAGE AREA IN A PRESSURIZED CYLINDER

The approach presented here is similar to the one described earlier (BHANDARI, FAIDY, ACKER - 1989).

LINEAR ELASTIC THEORY

Starting from the definition of the Strain Energy Release Rate G as

$$G = -\frac{1}{2t}\frac{\partial p}{\partial a}$$

where P is the Potential Energy and 2a the crack length in a structure of thickness t, one can show that for the case of a uniform applied stress, σ, the crack opening area A is related to G through the relation :

$$G = \frac{\sigma}{4}\left(\frac{\partial A}{\partial a}\right)$$

or

$$A = \frac{A}{\sigma E'}\int_0^a K_I^2\ (x)\ dx \text{ ----------------------------- } [1]$$

where K_I is Stress Intensity Factor (SIF), E', ν have usual significance.

In the case of an infinite plate with a central crack of length 2a,

$$K_I = \sigma\ (\pi\ a)^{1/2}$$

and the crack opening area (COA) becomes :

$$A_0 = 2\ \sigma\ \ \pi\ a^2/E'$$

(In the following $E' = E$ will be considered).

Case of a Cylindrical Shell

In general, for the case of a through crack of length 2a in a pipe subjected to a uniform stress σ, the SIF can be written as :

$$K_I = M\ (\lambda)\ \sigma\ \sqrt{\pi\ a}$$

where M represents the amplification factor (bulging factor) and λ, the shell parameter ; R, t being respectively the radius and thickness of the pipe.

Using equation (1), the COA, A_c, in non-dimensional form becomes :

$$\alpha\ (\lambda) = \frac{A_c}{A_0} = \frac{2}{\lambda^2}\int_0^\lambda M^2\ (\lambda)\ \lambda\ d\lambda \text{ ----------------- } [2]$$

Depending on the expression of $M(\lambda)$ used, various cases can be considered :

. WÜTHRICH (1983) uses results concerning $M(\lambda)$ of ERDOGAN and KIBLER (1979)

. TADA-PARIS Method (1983) : In this case, results of $M(\lambda)$ come from an approximation of the following solution (ROOKE, 1976)

$$K_p = F_p \sigma_p \sqrt{\pi a} \quad \text{for the pressure stress } \sigma_p$$

where $F_p = (1 + 0.3225 \lambda_I^2)^{1/2}$ for $(0 \leq \lambda_1 \leq 1)$

$= 0.9 + 0.25 \lambda_1$ for $(1 \leq \lambda_1 \leq 5)$

and $\lambda_1 = a/\sqrt{Rt}$

Integrating this expression, one obtains

$$\alpha_p = 1 + 0.16 \lambda_I^2 \quad \text{for } (0 \leq \lambda_1 \leq 1)$$

$$= 0.2/\lambda_I^2 + 0.81 + 0.30 \lambda_1 + 0.03 \lambda_I^2 \text{ for } (1 \lambda_1 \leq 5)$$

. BARTHOLOME-KASTNER Method (BARTHOLOME et al. 1986, KASTNER, 1981) : The B-K method uses an approximation of the expression given by WÜTHRICH (1983) which is of the form :

$$\alpha(\lambda) = A_c/A_0 = 1 + 0,1 \lambda + 0,16 \lambda^2$$

However, their results are based on an approximate expression of the crack displacement field (asymptotic solution) in a plate which gives COA as :

$$(A_0)_{B-K} = 7.54 \sigma a^2/E$$

with respect to theoretical value of

$$A_0 = 2 \pi \sigma a^2/E$$

This shows that the B-K method is already considering the opening area 20% higher than the theoretical elastic value.

. PROPOSED METHOD : A comparative study shows that all the above methods give nearly the same results with respect to $\alpha(\lambda)$ since they all use the same basic formulation (ERDOGAN-KIBLER, 1979). In the method proposed here we retain the expression of $\alpha(\lambda)$ used by TADA-PARIS Method (1983).

PLASTICITY EFFECTS

The effect of plasticity is to give the crack opening and areas greater than those in elastic case. To take account of these effects, one can use :

- either one of available analytical models like DUGDALE, IRWIN
- or an approach based on J-integral
- or any numerical method like Finite Elements. However the cost of computation in this case is certainly much larger than any simplified method unless one has EPRI-handbook type solutions obtained from numerical results (KUMAR & al., 1984)

IRWIN Plasticity model : this model uses the elastic solution with an effective crack length

$$a_{eff} = a_0 + r_y$$

where a_0 is the initial crack length and

$$r_y = \frac{1}{\beta \pi} \left[\frac{K}{\sigma_y} \right]^2 \quad ; \quad \begin{array}{l} \beta = 2 \text{ in Plane-stress conditions} \\ \quad = 6 \text{ in Plane-strain conditions.} \end{array}$$

. TADA-PARIS Method : is based on IRWIN-model in plane-stress. The effective crack angle is given by :

$$\theta_{eff} = \theta_0 + \frac{K^2}{(2 \pi R \sigma_y^2)}$$

which is obtained using an iterative approach.

. BARTHOLOME-KASTNER Method : also uses IRWIN-model, however σ_y is replaced by σ_F (Flow-Stress) of the material ($\sigma_F = (\sigma_y + \sigma_u)/2$).

The asymptotic solution in the case of an infinite plate with a central crack of length $2a_0$ subjected to a uniform stress, σ, gives the displacement field which when integrated gives the opening area in non-dimensional form as

$$\gamma = \frac{A}{A_0} = \frac{1 - x^3}{(1 - x^2)^2} \quad ; \quad x = \left[\frac{\sigma}{\sigma_F} \right] \Big/ \sqrt{2}$$

representing a correction factor accounting for the plasticity effects.

(Note : The above expression for γ represents the present version of the B-K method (BARTHOLOME et al. (1986)) and gives a value higher than the preceding version (KASTNER, 1981)

$$\gamma = (1 + x^2)^{3/2} - (x^2)^{3/2}$$

The difference in the two versions is due to the fact that KASTNER et al. (1981) do not update the value of K after plasticity correction).

. JAERI Method (ISOZAKI, 1988) is a modification of the PARIS-TADA Method replacing σ_y by a flow-stress σ_F^* defined as follows

$$\sigma_F^* = \left[\frac{3 \sigma_y + \sigma_u}{4} \right]$$

The results thus obtained correlate well with experimental data obtained on 3", 6" and 12" pipes with 60°, 90° and 150° angle cracks.

. <u>DUGDALE Plasticity Model</u> : IRWIN-Plasticity Model is valid for small-scale-yielding conditions unless the fracture parameters are updated after the plasticity effets. DUGDALE-Model has a more extended application.

The effective length of the crack in GRIFFITH configuration is given by :

$$a_{eff} = a_0 \ \mathrm{Sec} \left(\frac{\pi}{2} s \right) \quad ; \quad s = \sigma/\sigma_F$$

Integrating the displacement field given by this model one can write opening area in a non-dimensional form

$$\gamma\ (s) = A_{el}\text{-}p_l/A_{el}$$

<u>Case of non-uniform loading</u> : one of the problems of this model is that it is applicable under uniform loading conditions since parameter s represents the ratio of uniform stress to the flow stress. This difficulty can be overcome by using reference stress concept (PENNY, 1971)

$$\sigma^* = \frac{\text{applied load}}{\text{limit load } (\sigma_F)} \ . \ \sigma_F$$

Thus whatever the applied loading condition, on can associate a reference stress σ^* to it and the parameter

$$s = \frac{\sigma^*}{\sigma_F} = \frac{\text{applied load}}{\text{limit load } (\sigma_F)}$$

can be obtained to apply the DUGDALE model.

<u>Plasticity Effects in Cylindrical Shells</u> : to a first approximation, one can combine plasticity and bulging effects through a multiplicative function γ (s) . α (γ) which would give opening area as (WÜTHRICH, 1983)

$$A = \gamma\ (s)\ .\ \alpha\ (\lambda)\ A_0$$

This relation does not account for the interaction between plasticity and bulging since both phenomena are considered independently. It is therefore not conservative from the point of view of the objectives enunciated in the beginning since we are looking for an upper bound for crack areas and one must take into account the interaction mentioned above.

One conservative approach in this sense would be to consider

$$A_c = \gamma\ (s^*)\ \alpha\ (\lambda^*)\ A_0$$

where λ^* and s^* are respectively the shell parameter and the DUGDALE Model parameter which take into account the interaction between curvature and plasticity.

One could for example consider

$$s^* = M\ (\lambda^*)\ \sigma/\sigma_F \quad , \quad \alpha = \alpha\ (\lambda^*)$$

which accounts for the effect of plasticity on curvature, where

$$\lambda^* = \lambda \Big/ \text{Cos} \left(\frac{\pi}{2} \cdot \frac{M\sigma}{\sigma_F} \right)$$

which accounts for the effect of curvature on plasticity by considering the applied stress magnified by the factor M.

However, this approach puts too much margin of conservatism : in many cases, it might conclude that the crack is unstable whereas in reality the experiment might show the contrary.

To evaluate a reasonable upper bound for the crack area, it is proposed :

. to take into account the interaction between plasticity and curvative effects as a first approximation i.e.

$$s = M(\lambda)\ \sigma/\sigma_F \ , \ \alpha = \alpha\ (\lambda^*)$$

where

$$\lambda^* = \lambda \Big/ \text{Cos} \left(\frac{\pi}{2} \cdot \frac{\sigma}{\sigma_F} \right)$$

. to bound crack area by considering the crack opening uniform all over its surface equal to its value at the center, 2 δ, i.e.

$$A_c = 2\ \delta * 2\ a_0$$

. and to validate this method through available experimental and/or computational results.

. B-K METHOD OF EVALUATING UPPER BOUND LEAKAGE AREA

It might be interesting to note the procedure adopted by BARTHOLOME et al. (1986) to compute the "maximum" leakage areas using the following two steps:

1) Compute the crack area

$$A_c = \gamma(s)\ .\ \alpha(\lambda)\ .\ A_0$$

which does not take into account the interaction between plasticity and curvature (but, as we have seen earlier, is already 20 % higher through the use of an asymptotic solution rather than the exact solution for A_0).

2) Multiply A_c by a factor of 3

$$(A_c)_{max} = 3 * A_c$$

In the following will be shown a comparison of this method with the proposed one on some experimental results.

VALIDATION OF THE PROPOSED METHOD

Validation of the proposed method is done using experimental results obtained in West Germany at the MPA Institute in Stuttgart (reported by Bartholome et al. (1986)). It concerns four tests on large piping :

. 3 tests at room temperature on German material 20 Mn Mo Ni 155
. 1 test at 155°C on material 22 Ni Mo Cr 37.

Table I shows the experimental results and their comparison with B-K method as well as proposed method.

One can see that the proposed method gives conservative results and closer to the reality than the empirical B-K method. In particular, B-K method does not distinguish between tests 3 and 4 (table I) while the proposed method shows the tendencies observed experimentally.

Nevertheless, B-K method also gives conservative results and can be used to compute "maximum" leakage areas under the condition that the limit load of the structure is not attained.

EVALUATION OF MAXIMUM CRACK OPENING AREAS FOR POSTULATED LONGITUDINAL CRACKS IN FRENCH PWR HOT LEG

Geometry : This study is conducted with a minimum nominal diameter (S.G. side) of 787.4 mm and with thickness ranging from 60 mm to 110 mm. The length of the defect is conventionally considered equal to outside diameter of pipe.

Material properties : According to the French Code (RCC-M-1988) the material Z3 CN 20-09 (M 3403) used in French PWR hot leg, has minimum properties at 343°C (temperature of hot leg) as : σ_y = 117 MPa, σ_u = 403 MPa, E = 172 GPa.

In this presentation, computation is also made using a value of σ_y = 174 MPa.

The fracture mode retained is plastic instability under applied pressure.

Loading : As a first step and for this simplified study, the only loading considered is internal pressure of P = 15.5 MPa (normal operating pressure).

Results : A parametric study shows that it is necessary to have a minimum thickness to garantee protection against plastic instability of a pipe having a defect of length equal to outside diameter of the pipe. This value is situated at a level of

71.8 mm (for σ_y = 117 MPa)
and 67.0 mm (for σ_y = 174 MPa).

This shows that all the pipes having thickness greater than 71.8 mm would not under go the postulated fracture mode even if we consider the minimum properties of the material.

Fig. 1 shows the results relative to Crack Opening Areas (COA) obtained using two methods (Proposed Method and B-K Method). It is observed that the maximum value of COA is about 200 cm^2 corresponding to the minimum thickness of 72 mm.

EVALUATION OF MINIMUM CRACK OPENING TIMES

Scenario concerning pipe break : As mentionned earlier, the presently used hypothesis is to consider an opening corresponding to a longitudinal defect of length equal to the external diameter of the pipe.

However, the presence of such a defect, postulated conventionally, is possible only due to a process which one must not ignore. Two cases can occur :

. According to the first, one can consider a through-wall crack existing from the beginning. In that case, a leak would have certainly taken place (unless the crack is very small) and its presence certainly detected.

. According to second case, one can suppose that a surface cracks exist and a through crack is obtained when its ligament breaks ; in that case the crack could propagate as follows :

- if the toughness of the material is sufficiently high, the crack will arrest when it attains a stabilized length from the postulated conventional defect.

- if the toughness of the material is not sufficient, the crack will continue to grow till the opening section is stabilized at a value equal to the pipe section.

The second scenario is more plausible and in any case envelops the first one if the postulated reference defect is greater than the through-wall defect susceptible to exist from the beginning. It is this scenario which will be retained in this study.

Initial reference defects : In a specific internal study on fabrication defects, two types of defects have been proposed :

. a realistic envelopping defect
. an exceptional defect.

In this generic study, it is sufficient to consider the exceptional defect which is characterized by a length of 120 mm and a depth of 5 mm.

The scenario forseen would suppose that at time $t = 0$, the ligament breaks and the defect becomes through-wall defect. Its propagation will be studied upto the length when the COA becomes stabilized. (One should observe that with the known loading conditions, it can be shown that the defect will not propagate to become a through-wall crack. Conservatism exists even at this level).

Study of Break-Propagation-Velocity : This study is based on two experimental investigations on the dynamics of break propagation :

. one conducted at the French Atomic Energy Commission in CADARACHE (ELF 1982, 1983) on a stainless steel material

. one conducted at MPA, Stuttgart, FRG on ferritic steels (MPA Tests 1985)

ELF EXPERIMENTS : Three tests (29,30 and 33) were conducted on a pipe with external diameter $D_e = 88.9$ mm ; thickness $t = 3.09$ mm ; length of pipe $L = 2230$ mm, on a SS Å 312, at a temperature of 235°C.

The objective here was to validate the device measuring the longitudinal break propagation rates with respect to visual measurements using an ultra-rapid camera. During the experiment, rates of break opening were also measured.

The three tests gave a mean velocity of break-propagation of 96 m/s (70 m/s in test 29 ; 119 m/s in test 30 ; 99 m/s in test 33).

The mean velocity of opening of break in test 30 is of the order of 58 m/s.

To evaluate the minimum times of break openings, we would retain a value of 60 m/s for the break opening velocity (the break propagation velocity is two times this value i.e. 120 m/s).

<u>MPA EXPERIMENTS</u> : These tests are conducted in the frame work of Leak-Before-Break program, on large pipes (D ≃ 800 mm, t = 47.5 mm) on two types of defects (surface defects, through-wall defects) in air and water environment, at room as well as high temperature (155°C, 245°C, 300°C).

In all about 15 tests are performed. Rate of break-propagation were measured, for surface cracks, in both the radial (rupture of ligament) as well as longitudinal direction.

The results show that the velocity to break the ligament for the case of surface cracks is of the order of 250 m/s ; however when the break is open its rate of propagation has a mean valve of about 40 m/s or when the defect becomes unstable after arrest, it is about 95 m/s (see figure 2).

These studies show that for computation of minimum break-opening times, propagation velocity of 120 m/s is conservative and break-opening velocity, taken as half of propagation velocity, of 60 m/s would also be conservative.

<u>Determination of stabilized defects</u> : The evaluation of stabilized defects made earlier (see table II) shows that, except for the elbow of thickness 72 mm, all the postulated defects stabilize at a minimum value of 1010 mm.

Moreover, if one considers the depressurization at the break level, when the fluid flows through the break, as has been shown by a certain number of studies in the literature, all the postulated conventional defects stabilize, under the saturation pressure, to a minimum value of 975 mm.

<u>Minimum crack opening time</u> : In the preceding paragraphs, we have evaluated :

. maximum break opening velocity of the order of 60 m/s,
. length of the reference defect at the moment of break opening (120 mm)
. minimum length of stabilized defects beyond the postulated conventional defect equal to the external diameter of pipe (1010 mm for nominal pressure, 975 mm for saturation pressure).

The minimum break-opening times, tm, can be determined by computing the time necessary for the reference defect (120 mm) to become minimum stabilized defect with maximum opening velocities (60 m/s). This leads to tm ≃ 14.75 ms for minimal pressure (except for elbow of thickness 72 mm) and tm ≃ 14.25 ms for saturation pressure.

This minimum time is associated with a maximum break opening area of 200 cm^2.

One should note that break opening velocity (60 m/s) considered in this study is based on heuristic considerations that this value is about half of break propagation velocity. Although, it is confirmed by test-ELF 30, analysis of more experimental data is certainly necessary to support this conclusion.

However it seems that the value of 15 ms is also used reasonably in some establishments to evaluate jet forces from postulated breaks.

Nevertheless, more studies are certainly necessary to reinforce the findings.

CONCLUSION

This study presents a simple method of computing maximum leakage areas.

The method has been validated on large scale experimental results obtained by MPA in Stuttgart, Germany. It is applied to obtain leak areas A_c on the Steam-Generator entry elbows by postulating a conventional defect of length equal to external diameter of pipe using plastic instability as the fracture mode. The results show that the presently used hypothesis of A_c = 5000 cm^2 are not justified since the maximum value of A_c is of the order of 200 cm^2.

A stability analysis using J_{IC} = 100 kJ/m^2 and dJ/da = 60 MPa shows that all the conventional defects (except for the elbow of thickness 72 mm) arrest and become stabilized after some crack growth under nominal operating pressure. However, if depressurization due to fluid flow through the break is considered, all the conventional defects become stabilized under the saturation pressure.

In all the cases, the maximum opening area remains about 200 mm^2.

Further, minimum times of crack openings have been evaluated using :

. maximum value of opening velocity
. maximum value of initial reference defect
. minimum value of stabilized conventional postulated defect.

This minimum time is of the order of 15 ms associated with the maximum opening area of about 200 cm^2.

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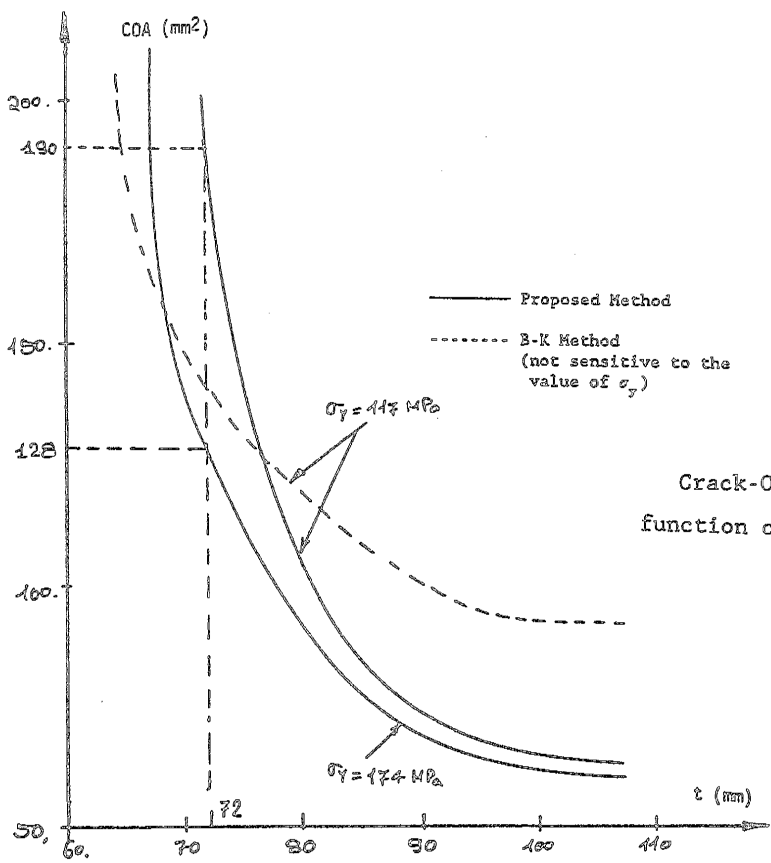

FIGURE 1

Crack-Opening Area as a function of pipe thickness

TEST		1	2	3	4
MPA n°		BVZ 010	BVZ 011	BVZ 012	BVS 010
GEOMETRY	D_o mm	797.5	798	798	792
	t mm	47.6	47.5	47.5	47.6
	2a mm	730	1105	1285	1480
LOADING	Pressure in MPa	23.8	14.8	13.95	6.82
MATERIAL PROPERTIES	Material	20 Mn Mo Ni 155			22NiMoCr37
	Temperature	20°C	20°C	20°C	155°C
	σ_y MPa	520	515	515	420
	σ_u MPa	633	632	632	544
	E MPa	204000	204000	204000	190000
CO AREA in mm^2	Test	7748	15600	60000	42100
	B-K Method	15418	41667	69144	66532
	Proposed Method	17342	37883	71745	48800

TABLE I

TABLE II

Thickness of the elbow in mm	Nominal Pressure p = 155 bar			Saturation Pressure p = 117.5 bar	
	Defect length at initiation in mm	Stabilized defect in mm	COA cm^2	Stabilized defect in mm	COA cm^2
72	375	*	*	980	100
78	425	1095	205	975	75
80	440	1045	145	975	75
96	570	1010	75	985	45

* Postulated conventional defect is greater than the critical defect COA would be equal to Pipe Section.

$$J_{IC} = 100\ kJ/m^2\ ;\ \frac{dJ}{da} = 60\ MPa \qquad \approx 3\ daJ/cm^2\ \text{(Resilience)}$$