Reliability analysis of low alloy ferritic piping steels
B- Effect of both pre-service and in-service inspections

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ABSTRACT. *A probabilistic fracture mechanics model of structural reliability is described that considers failure to occur as the result of subcritical and catastrophic growth of pre-existing cracks that escape detection. The model considers cracks to be two-dimensional and is capable of treating many of the input parameters as random variables and can consider arbitrary inspection schedules. Numerical results for two-dimensional cracks in a weld joint in a large reactor pipe show that the ratio of failure rates is not highly dependent on the initial crack distribution, even for this more general case. Thus, it appears that an assessment of the relative benefit of in-service inspection does not require accurate knowledge of the initial crack distribution.*

1. INTRODUCTION

This paper describes modifications to pc-PRAISE to provide capabilities for probabilistic analysis of fatigue-crack initiation and growth. This expanded version of the software is referred to as Version 4.2. The PRAISE code was originally developed to provide a probabilistic treatment of the growth of crack-like weld defects in piping due to cyclic loading [1]. This treatment of fatigue-crack growth was later expanded to include the initiation and growth of stress corrosion cracks [2]. The software was then made to run on a personal computer for ease and economy of use [3]. The purpose of the efforts reported herein is to expand the capabilities of PRAISE to include a probabilistic treatment of fatigue-crack initiation. The current capabilities for analyzing fatigue-crack growth are then used to calculate the crack penetration in the pipe wall. The schematic diagram of the steps in the piping reliability calculations by pc-PRAISE are presented in Fig. 1.

2. DESCRIPTION OF GENERAL MODEL

The components of a probabilistic fracture mechanics model of structural reliability that considers the realistic case of two-dimensional cracks are presented in Fig. 1, which also shows the interrelationship of the various components. The approach is applicable to a wide variety of two-dimensional cracks, but the case of semi-elliptical surface cracks of arbitrary aspect ratio in a body of finite thickness will be considered here. Such a crack is shown schematically in the upper left corner of Fig. 1, and is characterized by two dimensions *a* and *b*. The model depicted in Fig. 1 is described in detail in [3], so only a brief review will be presented here.

The procedures shown in Fig. 1 are applicable to a given location in a structure, such as a weld of volume V. The as-fabricated crack size distribution is combined with the nondetection probability to provide the post-inspection distribution. The manner in which the cracks that escape detection grow is then calculated by fracture mechanics techniques. The cumulative probability of failure at any time is simply the probability of having a crack at that time equal to or larger than the critical crack size, [3].

The crack size distribution at the time of the first in-service inspection (ISI) can be calculated. This pre-inspection distribution is combined with the non- detection probability to provide the post-inspection distribution. Fracture mechanics calculations then proceed up to the next ISI, at which time the procedures are again applied. Calculations of the failure probability for the general model are performed numerically because of the complexity of the fracture mechanics calculations of the growth of two-dimensional cracks as well as the complicated bivariate nature of the crack size distribution, [2, 4].

A specific example of results from the general model will be presented later along with a discussion of inputs to the model.

3. PRAISE MODIFICATIONS

Modifications were made to pc-PRAISE to consider the initiation of cracks and their subsequent growth to become through-wall. For initiation, the PNNL subroutine for initiation was used in conjunction with Monte Carlo simulation to estimate the probability of initiation as a function of time. The subroutine provides results for constant stress amplitude, whereas the stress histories to be considered have cyclic stresses of different amplitudes. The Miner's rule was used to account for these more complex stress histories.

These modifications were explained in the first part (A- Baseline case), of this study.

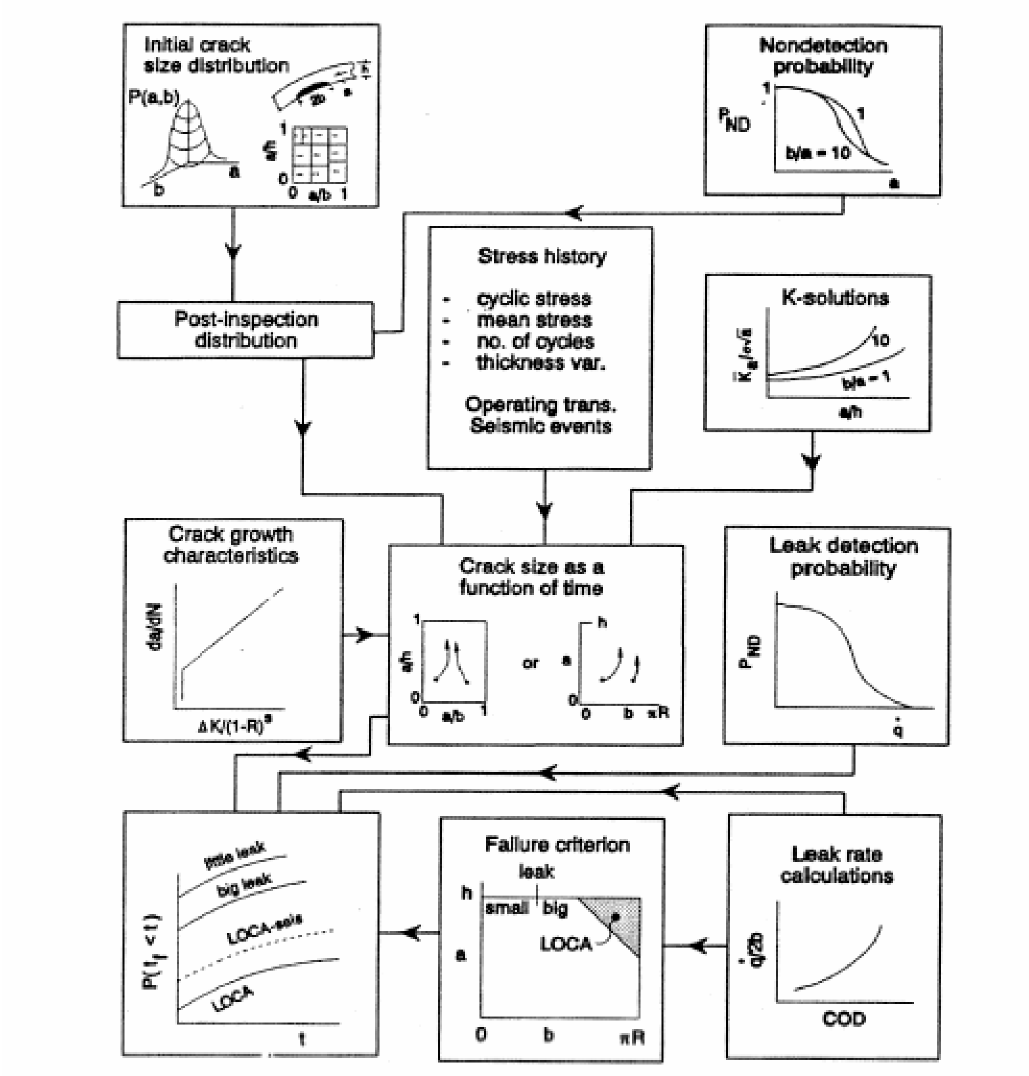

Figure 1. Schematic diagram of piping failure probability calculation as performed by pc-PRAISE.

4. EXAMPLE

The example problem of the previous section was analyzed using 18 initiation sites with a multiplier on t, of 3 and using (b_0-a_0) as the random variable describing the size of the initiated cracks. The effect of pre-service and in-service is shown in Fig. 2.

5. PROBABILITY RESULT

In addition to probability of crack initiation, the probability of a leak (through-wall crack), is evaluated. Analyses were performed for no circumferential variation of the stresses. The results provide information on the relative leak-to- break probability for situations with and without variations of stress on the surface. Such information is useful in leak-before-break assessments.

Table1. Example of crack-Linking Information Printed out in pc-Praise at Time60 Years

pcinitiation

TIME (YRS)	TOTAL INITIATED CRACKS	FIRST INITIATED # OF CRACKS	PROBABILITY
2	0	0	0.0000E+00
4	0	0	0.0000E+00
6	0	0	0.0000E+00
8	0	0	0.0000E+00
10	0	0	0.0000E+00
12	0	0	0.0000E+00
14	1	1	1.0000E-06
16	2	2	3.0000E-06
18	9	9	1.2000E-05
20	14	14	2.6000E-05
22	24	24	5.0000E-05
24	42	42	9.2000E-05
26	78	78	1.7000E-04
28	112	112	2.8200E-04
30	184	184	4.6600E-04
32	247	247	7.1300E-04
34	363	363	1.0760E-03
36	431	430	1.5060E-03
38	604	604	2.1100E-03
40	816	813	2.9230E-03
42	1020	1019	3.9420E-03
44	1284	1278	5.2200E-03
46	1615	1607	6.8270E-03
48	1842	1828	8.6550E-03
50	2229	2209	1.0864E-02
52	2613	2596	1.3460E-02
54	3207	3150	1.6610E-02
56	3584	3525	2.0135E-02
58	4210	4120	2.4255E-02
60	4783	4669	2.8924E-02

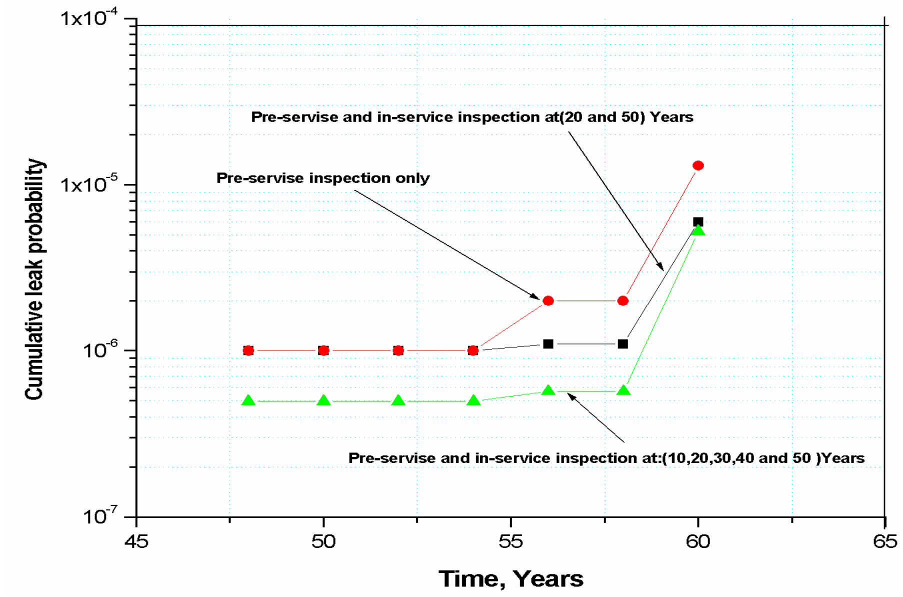

Figure 2. Effect of pre-service and in-service inspection on the cumulative failure probability

For no circumferential stress variation, the stresses were taken to be axisymmetric, and the results are for times extending to 60 years. Fig. 2 provides a plot of these results. No results are plotted for the DEPB probability because no such failures occurred in the 100 trials performed. Provisions were added to the pc-PRAISE output to summarize the linking of cracks, which is described here. The results for this example problem with no stress gradient are considered. Table1 provide an example of the information in pc-PRAISE on crack initiations, and a summary of crack initiation and linking. Such results are printed out. The benefit effect of (ISI) is shown in Fig. 2.

For each evaluation time that is a multiple of 10. Hence, the crack-linking information is printed out for 20, 40, 50 and 60 years. Table2 includes the crack-linking information at 40 and 60 years. The results are summarized on a crack-by-crack basis, so information is lost regarding cracks on a weld-by-weld (trial-by-trial) basis.

Cracks in the depth range of 0.95<a/h< 99% are mostly through-wall cracks, which are of particular interest. Table entries for this range of depths provide information on the length distribution of through-wall cracks and how many cracks linked to form them. Any cracks that grew to become leaks before 60 years also appear in the Table2. Table3 summarizes results on a weld-by-weld (trial-by-trial) basis. The number of individual cracks involved is net given, but only the sum of the surface lengths.

Table2. Example of crack-Linking Information Printed out in pc-Praise at Time 40 and60 Years

```
At time (yrs)    40.00

    .00< a/h <=    .30

 % circumf.   [ ALL ]|[  1  ][  2  ]
     .0- 20.0    2925|    2925     0
   20.0- 40.0       0|       0     0
   40.0- 60.0       0|       0     0

    .30< a/h <=    .60

 % circumf.   [ ALL ]|[  1  ][  2  ]
     .0- 20.0       4|       4     0
   20.0- 40.0       0|       0     0

    .60< a/h <=    .80

 % circumf.   [ ALL ]|[  1  ][  2  ]
     .0- 20.0       0|       0     0
   20.0- 40.0       0|       0     0

    .80< a/h <=    .95

 % circumf.   [ ALL ]|[  1  ][  2  ]
     .0- 20.0       0|       0     0
   20.0- 40.0       0|       0     0

    .95< a/h <= 99.00

 % circumf.   [ ALL ]|[  1  ][  2  ]
     .0- 20.0       0|       0     0
   20.0- 40.0       0|       0     0
```

```
At time (yrs)    60.00

    .00< a/h <=    .30

 % circumf.   [ ALL ]|[  1  ][  2  ][
     .0- 20.0   28924|   28923     1
   20.0- 40.0       0|       0     0

    .30< a/h <=    .60

 % circumf.   [ ALL ]|[  1  ][  2  ][
     .0- 20.0     361|     360     1
   20.0- 40.0       0|       0     0

    .60< a/h <=    .80

 % circumf.   [ ALL ]|[  1  ][  2  ][
     .0- 20.0      26|      26     0
   20.0- 40.0       0|       0     0

    .80< a/h <=    .95

 % circumf.   [ ALL ]|[  1  ][  2  ][
     .0- 20.0      10|      10     0
   20.0- 40.0       0|       0     0

    .95< a/h <= 99.00

 % circumf.   [ ALL ]|[  1  ][  2  ][
     .0- 20.0      13|      13     0
   20.0- 40.0       1|       1     0
```

Table3. Crack Size data sorted on a Weld by Weld basis 40 and 60 Years

At 40 years

	>0	>0.3h	>0.6h	>0.8h	>.95h
0 - 20%	2925	4	0	0	0
20-40%	0	0	0	0	0

At 60 years

	>0	>0.3h	>0.6h	>0.8h	>.95h
0 - 20%	28945	410	49	23	13
20-40%	1	1	1	1	1

6. Conclusions

A probabilistic fracture mechanics model of structural reliability is summarized that considers cracks to be two-dimensional such as semi-elliptical surface cracks. The model uses a fatigue initiate crack and crack growth model to grow initiating, semi-elliptical, fabrication defects. Critical flaw sizes for pipe breaks are based on a net section collapse criteria of fracture. Numerical results obtained for a weld in a large reactor pipe are then presented for randomly distributed material properties. ISI was seen to generally not have a large influence on the cumulative failure probabilities. The leak and DEPB failure rates are obtainable from the numerical results and are cast in terms of the ratio of failure rates with and without ISI. The results show this measure of the relative benefit of ISI is virtually independent of the initial crack size distribution and also is not strongly dependent on the failure mode considered. Thus, even in the more general case it appears that the benefit of ISI can be assessed without detailed knowledge of the initial crack size distribution. As a conclusion, using the initiation only show a weakly cumulative probability of leak in the ferritic components, than it will be better to combine the effect of the initiation with a pre-existing crack.

7. References

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