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Development of simplified analysis procedure for cracks in elbows

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ABSTRACT

The objective of this effort was to see if a simple relationship could be developed between cracks in straight pipe and cracks in elbows. If such a geometric relationship could be developed, then a simple multiplier could be applied to the straight-pipe solutions that are already used in standards such as the ASME or other codes. In order to accomplish this, solutions from elbow and straight pipe EPFM analyses were used along with experimental data. Comparisons were made to circumferential surface-cracked elbow data from the IPIRG-2 program, and an axial surface-cracked elbow test conducted by EDF. The comparisons showed that there was a simple multiplier on the straight pipe solution, which was linearly related to the ASME B_2 stress index for elbows.

INTRODUCTION

A significant amount of experimental and analytical efforts have been expended over the years to develop validated fracture mechanics analyses for axial or circumferential cracks in straight pipe. However, there has been comparatively little efforts for the evaluation of cracks in elbows. Due to the stress indices for elbows, they are frequently the highest stress location in a piping loop. The efforts in the Second International Piping Integrity Research Group (IPIRG-2) program[1,2] involved developing a GE/EPRI based analyses for axial and circumferential surface cracks in elbows. In the GE/EPRI type of J-estimation scheme, finite element analyses are used to calibrate functions representing elastic and plastic contributions to J. The axial cracks were located on the flank (side) of the elbow, and on the inside surface where the highest stress occurs of the elbow being bent in the opening mode. The circumferential internal surface crack was centered on the extrados, where the elbow under bending in the closing direction opens the crack.

The efforts in Reference 1 involved conducting a large matrix of finite element analyses to develop a J-estimation scheme in the spirit of the GE/EPRI methodology. Even though a number of variables were considered (such as crack depth, R_m/t, and strain-hardening exponents), these analyses were limited to one crack length, in-plane bending, and long radius 90-degree elbows. There are a significant number of other variables that make the development of such solutions a seemingly formidable task for all pipe fittings and loading combinations. The lack of such solutions for a wider variety of problems, in combination with the desire to have a codifiable approach, led to the pursuit of a simplified solution.

BASIC PREMISE OF SIMPLIFIED ANALYSES

In the development of fracture mechanics relationships for cracked in pipes, Folias[3] first proposed a geometric multiplier between the elastic stress-intensity factor for an axial through-wall crack in a straight pipe, and the same length of crack in an infinite flat plate.

One of the most remarkable aspects of this relation is that it was based on linear elastic fracture mechanics which has also been found to be applicable in the EPFM and limit-load regions, even though there was no rigorous theoretical proof to that effect. The experimental results demonstrating the validity of these expressions however are overwhelming[4], and have been used in many codes and standards criteria.

From this type of analogy, it was postulated that a surface crack in a straight pipe would give some M-factor relative to a similar size surface crack in a flat plate, and similarly for a surface crack in an elbow. It follows that there will therefore exist a relationship between a surface-crack in an elbow and the same size crack in a straight pipe where using such a relationship, the circumferential surface-cracked pipe solutions that currently exist in code and standards procedures could readily be modified to be applied to elbows. This will of course depend on the crack orientation in the elbow. To check the feasibility of this approach, the IPIRG-2 J-estimation schemes[1] developed for surface cracks in elbows were used. The details of this approach and a separate validation with elbow experimental data are presented below.

DEVELOPMENT OF ANALYSIS PROCEDURE

Following the desire to develop a simple failure avoidance analysis that could be readily codified, three general steps were used to assess this approach:

(1) J versus moment curves were generated for the same size crack in both a straight pipe and a comparable elbow.
(2) From these calculations, the ratio of the moment for the straight pipe to that for the elbow case at the same value of applied J was determined. This moment ratio was found to be virtually independent of the applied J level for J_{Ic} values of typical nuclear piping steels.
(3) The moment ratio at constant applied J values was then compared with the ASME stress indices. This was done for pipe and elbows with different R_m/t ratios.

Axial Surface Crack Along Elbow Flank

For this crack geometry case, the elbow axial flank surface-crack solution for combined pressure and bending from Reference 1 was compared with the solution for a circumferential crack in a straight pipe under pressure and bending.

For the cracked-elbow J versus moment calculations, the SC.ELB3 analysis method developed during the IPIRG-2 program[1] was used. The circumferential surface-cracked straight-pipe analyses used were SC.TNP1, SC.TNP2, SC.TKP2, and SC.ENG2. The SC.TNP1 analysis has been found to give the best agreement with experimental maximum loads[5]. The SC.TNP2, SC.TKP2, and SC.ENG2 J-estimation schemes were determined to agree better with J values from FEM analyses than the SC.TNP1 analysis, but these three analyses tend to underpredict experimental maximum loads when using L-C oriented C(T) specimen J-R curves. It is believed that the inaccuracy of these three analyses in predicting maximum loads may be due to anisotropy differences between the L-C oriented crack growth and the fact that surface cracks grow in the L-R direction. The L-R direction is typically higher in toughness. Additionally, there is some evidence that the constraint in a C(T) specimen is much higher than for a surface crack in a pipe, hence the apparent toughness for the surface-cracked pipe is higher than from the C(T) specimen.

The elbow analyses used 90-degree bends, with a bend radius (R_{el}) equal to $1.5R_m$ (a long radius elbow). The calculations were done using the A106 Grade B carbon steel elbow stress-strain curve from this program and a non-growing crack for J values up to 2.0 MJ/m^2 (11,400 $in\text{-}lb/in^2$). The calculations were done for pressure levels corresponding to a hoop stress of 122.5 MPa (17.77 ksi) which is the S_m value for a number of commonly used stainless and carbon piping steels[1] at 288 C (550 F). An example of the results of the J versus moment calculations is given in Figure 1 for an R_m/t value of 5.

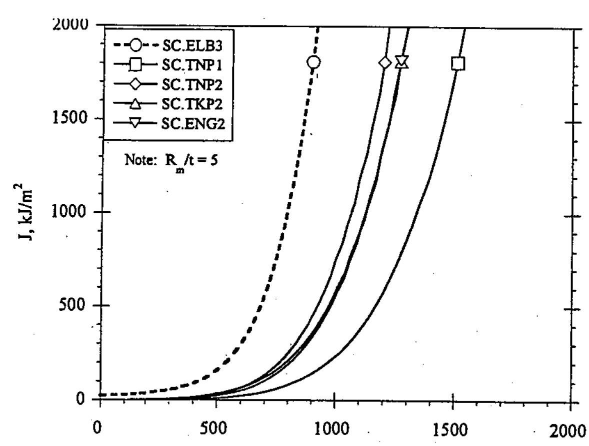

Figure 1 J versus moment calculations for axial, flank, surface crack (SC.ELB3 analysis) in an elbow and various straight-pipe circumferential crack J-estimation schemes

The next step was to construct a plot of the ratio of the moments for the straight pipe to that for the elbow at the same J values, i.e., $(M^{pipe}/M^{elbow})|_J$. The variation of this ratio with applied J is illustrated in Figure 2. A key aspect of this figure is that after some plasticity occurs, the moment ratio becomes constant. This can also be shown mathematically using the GE/EPRI methodology[2]. In Figure 2, it should be noted that the plastic part of J dominates the moment ratio for $J_{applied}$ values of generally greater than 100 kJ/m^2 (570 in-lb/in^2) which bounds the toughness range of typical nuclear piping material, except perhaps some aged CF8M steels.

The final step was to compare the moment ratios in Figure 2 to the stress indices for the elbows. Since the elbow was under bending, the B_2 and C_2 indices were used. These stress indices give stress multipliers for the location in the piping product where the stresses are the highest. For the case of an elbow under bending, the stresses are the highest along the flank of the elbow normal to the axial direction, i.e., the crack location for this evaluation.

Figure 3 shows a comparison of the $(M^{pipe}/M^{elbow})|_J$ values with the B_2 and C_2 stress indices. Four aspects need to be pointed out from this figure.

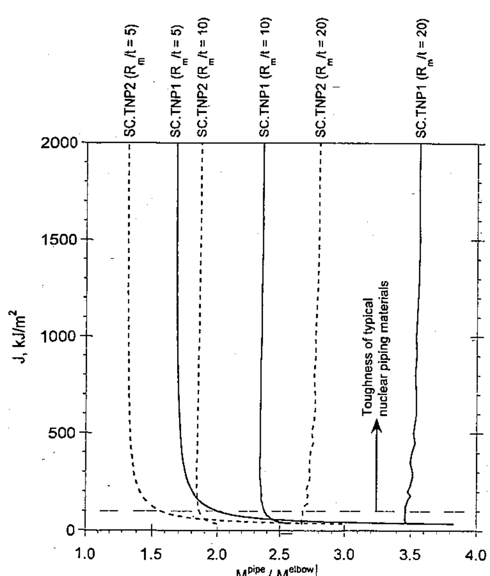

Figure 2 Comparison of J versus moment for circumferential, surface-cracked, straight pipe to moment for axial, flank, surface-cracked elbow at the same J values $(M^{pipe}/M^{elbow}|_J)$

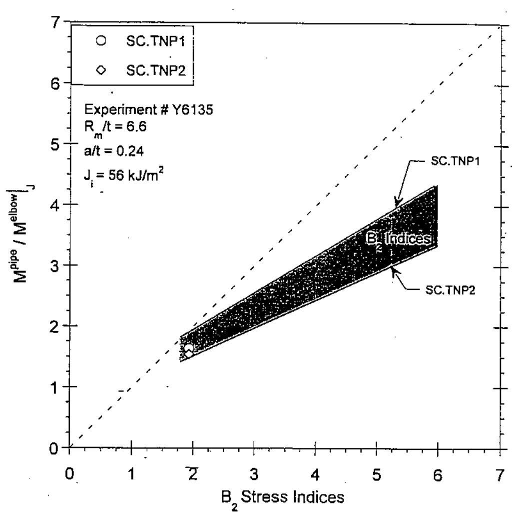

Figure 3 Comparison of ASME elbow stress indices to ratio of moment for circumferential, surface-cracked, straight pipe to moment for axial, flank, surface-cracked elbow at the same J values $(M^{pipe}/M^{elbow}|_J)$, and EDF data

- First and most importantly, the linear scatter bands show that the stress indices are greater than $(M^{pipe}/M^{elbow})|_J$ values.
- Secondly, there is a linear trend of the B_2 or C_2 stress indices with $(M^{pipe}/M^{elbow})|_J$.
- Thirdly, the upper bound occurred when using the SC.TNP1 straight-pipe analyses, and the lower bound comes from the SC.TNP2 analyses.
- Finally, the scatter in the moment ratio for J values of 100 to 2,000 kJ/m^2 (570 to 11,430 in-lb/in^2) is reflected by the symbols with the lines between them.

Comparison of Elbow Axial Surface Crack Failure Avoidance Criterion with Elbow Axial Surface Crack Experimental Data

To validate the use of this failure avoidance approach, it was desirable to compare this approach with experimental data. There are limited experimental results for axial, flank, surface cracks in elbows where there is good documentation of all the variables in the experiment. An elbow test by Electricité de France (EDF) was a well documented case(6). In this test, crack initiation occurred, but the experiment was stopped prior to reaching maximum load. Although the strain-hardening exponent (n) at the EDF material is similar to that used in developing the linear relationships in Figure 3, it was felt that this was a significant test of this failure avoidance criteria due to the following differences between this experiment and the analyses used to develop Figure 3.

- The crack length was slightly shorter
- The crack depth was much shallower, a/t of 0.24 versus 0.5, and
- The toughness was 56 kJ/m^2 (320 in-lb/in^2) which is lower than the 100 kJ/m^2 (570 in-lb/in^2) limit used in creating Figure 3.

Calculations were made with the SC.TNP1 and SC.TNP2 straight-pipe analysis methods to get the M^{pipe} value at crack initiation, and the experimental moment at crack initiation was used for the M^{elbow} value. The experimental moment ratio values are also shown in Figure 3 in comparison with the failure avoidance criteria. Considering the differences in material and crack size between the experiment and the case used to develop the linear relationships in Figure 3, the agreement is remarkably good.

Circumferential Surface Crack Centered Along the Extrados of an Elbow

In this crack geometry case, the circumferential elbow surface-crack solution for combined pressure and bending was compared with the solution for a circumferential crack in a straight pipe under pressure and bending. The development of the failure avoidance criteria is very similar to the elbow axial surface-crack case. Some noteworthy differences are:

- For a long circumferential crack in the elbow, the peak J value is 45 degrees from the center of the crack, whereas for a straight pipe, the peak J value is at the center
- The B_2 and C_2 indices are stress multipliers for the location corresponding to the flank (side or crown) of the elbow. For the circumferential crack, it is logical to expect that the stress indices would be less sensitive to the moment ratios at constant J values than were found in the axial crank case.

For the development of the J versus moment curves, there were two elbow analyses available (SC.ELB1 and SC.ELB2) from Reference 1. Both of these analyses were GE/EPRI type fits developed through a matrix of the same finite element solutions, but they have different reference moments and hence different h_1 functions. Differences between the two solutions should only occur for values interpolated between the FEM cases.

The elbow analyses used 90-degree bends, with a bend radius (R_{el}) equal to $1.5R_m$. The calculations were done using the A106-90 (Grade B) carbon steel elbow stress-strain curve from the IPIRG-2 program and a non-growing crack. The parameters were the same as for the axial crack, except the circumferential crack length was 180 degrees. (The SC.ELB1 and SC.ELB2 analyses were only developed for this crack length.) The calculations were done for the same pressure levels as the axially oriented crack elbow analyses.

The next step was to construct a plot of the straight pipe to elbow moments at the same J values, i.e., $(M^{pipe}/M^{elbow})|_J$. As with the elbow axial flank surface-cracked elbow case, this moment ratio reaches a constant value after some plasticity, similar to the trend seen in Figure 2. A comparison of the moment ratios with the elbow stress indices for J values larger than 100 kJ/m^2 (570 in-lb/in^2) is shown in Figure 4 using the SC.ELB1 analysis. Observations from this figure are:

- The results of the calculations were virtually identical using either the SC.ELB1 or SC.ELB2 solutions. This was because the case used was close to a finite element run used to define the h_1 functions.

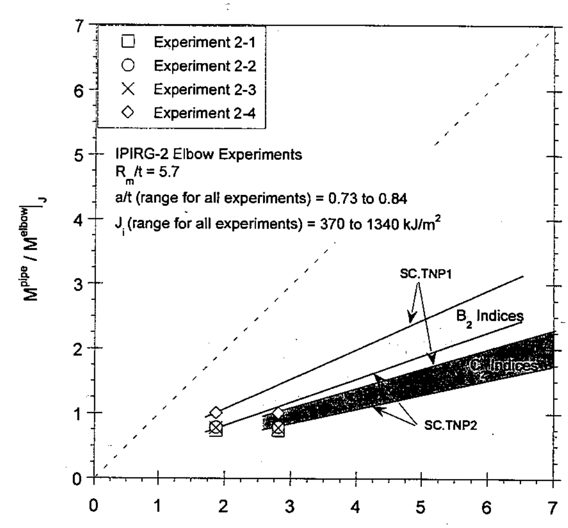

Figure 4 Comparison of ASME elbow stress indices to ratio of moment for circumferential, surface-cracked, straight pipe to moment for circumferential, extrados, surface-cracked elbow at the same J values ($M^{pipe}/M^{elbow}|_J$), using SC.ELB1 analysis, and comparison to IPIRG experiments

- As with the axial elbow crack case, the linear scatter bands show that the stress indices are greater than $(M^{pipe}/M^{elbow})|_J$ values.
- Secondly, there is a linear trend of the B_2 or C_2 stress indices with $(M^{pipe}/M^{elbow})|_J$.
- Thirdly, the upper bound again occurred when using the SC.TNP1 analyses.

Based on the analyses shown in Figure 4, the best prediction of elbow moment would use the SC.TNP1 straight-pipe solution and the B_2 stress indices.

Comparison of Elbow Circumferential Extrados Surface Crack Failure Avoidance Criterion to Experimental Data

As a first step in validating the use of this failure avoidance approach, a comparison with the IPIRG-2 elbow experimental data(2) was conducted. There were four experiments that can be used to help validate the elbow circumferential surface-crack failure avoidance criterion, two on an A106-90 (Grade B) elbow and two on a stainless steel WP304L elbow. The two experiments for each material were the companion quasi-static and pipe system experiments. These experimental conditions were close to the same assumptions used in the analyses used to develop the "elbow circumferential flaw failure avoidance" curve. The differences between these experiments and the analyses used to develop Figure 4 were:

- The crack depths for the experiments were much deeper,
- The elbows in the experiments started with some known out-of-roundness,
- The stainless steel elbow had a lower strain-hardening exponent.

Calculations were made with the SC.TNP1 and SC.TNP2 straight-pipe analysis methods to get the M^{pipe} values at crack initiation, and the experimental moments at crack initiation were used for the M^{elbow} values. The experimental moment ratio values are also shown in Figure 3 in comparison with the scatter band from the analyses predictions and the 1:1 failure avoidance criteria. As in the axial elbow crack case, the agreement is remarkably good.

DISCUSSION

To use the information in Figures 3 and 4 in an actual fracture evaluation, two approaches could be followed. The first is the simplest, but perhaps too conservative. Because the B_2 indices are closer to the 1:1 moment ratio line than the C_2 indices, more accurate predictions would be made using the B_2 indices. This approach is to simply take the ASME Section III stress indices and use them directly, where M^{elbow} is equal to M^{pipe}/B_2.

Alternatively, one could define a new parameter, called Υ^f_x (where f is the type of fitting, and x is for the crack orientation) that fits the data in Figures 3 and 4. Using this parameter, the elbow moments are M^{elbow} is equal to M^{pipe}/Υ^f_x.

Generally the experimental results agreed better with the SC.TNP2 Υ^e_c values, except for the one IPIRG-2 stainless steel circumferential surface-crack elbow experiment which agreed better with the SC.TNP1 Υ^e_c value. The better agreement with the SC.TNP2 Υ^e_c values may be due to the fact that both the SC.TNP2 and SC.ELB J-estimation schemes agree closely with FEM moment versus J predictions. Hence, the ratio of the two methods may be a more accurate value of Υ^e_c. Using the SC.TNP1 based Υ^e_c values would be slightly more conservative than the SC.TNP2 $\Upsilon^e_{a,c}$ values, yet still reasonably accurate. The resulting equations are:

$$\Upsilon^e_a = 0.601B_2 + 0.755 \text{ (for axial, flank, surface-cracked elbow)} \qquad (1)$$

$$\Upsilon^e_c = 0.465B_2 + 0.136 \text{ (for circumferential, extrados, surface-cracked elbow)} \qquad (2)$$

CONCLUSIONS

This approach of relating the surface-cracked elbow crack-driving force to the circumferential surface-cracked straight-pipe crack-driving force appears to be a promising method. However, to confirm the practicality of the approach, further validation is needed. For example, the elbow radius of curvature is a variable that would directly affect the B_2 indices, so it needs to be established if the same relationship is applicable to short radius elbows, or bends with larger radii that are used in the oil and gas industry.

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