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MECHANISTIC FRACTURE EVALUATION OF SAN ONOFRE UNIT 1 MAIN STEAM LINE PIPE CONTAINING A POSTULATED THROUGH-WALL CRACK

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1. INTRODUCTION

1.1 Background

Presently, the Main Steam Line Break (MSLB) evaluation of the Pressurized Water Reactor (PWR) system is carried out by postulating non-mechanistic circumferential (guillotine) breaks in which the pipe is assumed to rupture along the full circumference of the pipe. This can result in overly conservative steam pressure loading in the containment. It is, therefore, highly desirable to be realistic in the postulation of main steam line breaks. Presented in this report is the result of an anlaytical study carried out toward establishing that a non-mechanistic type break will not occur within the main steam line and, therefore, possibility of containment structure overpressurization will be precluded.

1.2 Scope and Objective

The general purpose of this investigation is to show that a circumferential flaw which is larger than any flaw that would be present in the main steam line is stable under the worst combination of plant loadings. The fracture criteria proposed for the analysis will examine the local and global stability. The global analysis is carried out by performing a static elastic-plastic finite element analysis of a straight piece of the main steam line pipe containing a circumferential flaw and subjected to internal pressure and external loading. ADINA (1-1) computer code is used for the ~~fintie~~ finite element analysis. The elastic-plastic finite element analysis results are used to obtain an estimate for the J integral, which is required for the local stability evaluation.

2. INITIAL FLAW

It is well known that initial flaw*geometry is one of the three pieces of fundamental data needed for a fracture mechanics evaluation of a given component. The other two data are stress field and material properties. Conceivably, the initial flaw geometry to be assumed in a fracture mechanics evaluation of a component would depend on several factors, namely, fabrication, examination testing and inspection. One of the rational means of establishing an initial flaw geometry is from the knowledge of the probability of missing (or detecting) a given size flaw.

Figure 2-1 shows schematically how one would find an initial flaw size, given the probability of missing (or detection of) a given size flaw. The probability of missing a very small flaw will be nearly unity whereas the probability of missing a through-wall flaw will be nearly zero. Contrarily the probability of detection of a very small flaw and a through wall flaw would be nearly zero and unity, respectively. However, no data quantifying these probabilities is yet available for main steam line piping.

Although examination and inspection experiences do not tell us anything about the size of flaws that have been missed, these experiences do provide some qualitative ideas about the sizes. The ASME Boiler and Pressure Vessel Code (BPVC) Section XI (2-1) specifies that flaws longer than 1/4 inch and deeper than 9 percent of the pipe wall shall be repaired during preservice examination. Similarly, during inservice inspection, Section XI requires that flaws longer than 0.55 inch and deeper than 11 percent of the pipe wall shall be repaired.

It has been shown in reference 2-2 that if one assumes that the largest initial crack is a semielliptical flaw of length 2-1/4 inch and 3/8 inch depth, the growth of the crack will be very small for the 40 year design life of the plant.

In this analysis a through wall circumferential flaw of 10 inch length is used conservatively (Figure 2.2).

*Flaw and crack are used interchangeably and mean the same in fracture mechanics evaluation.

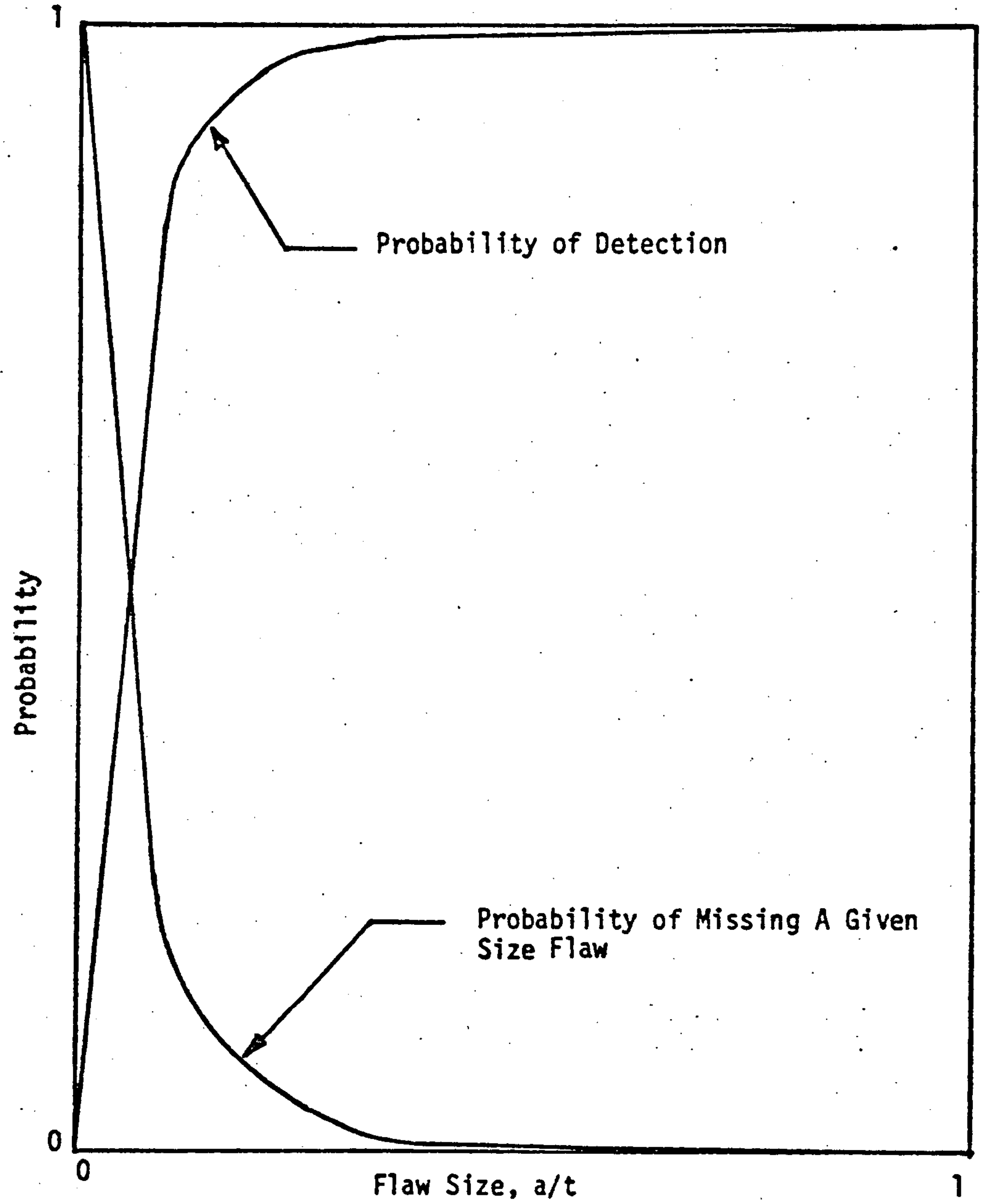


Figure 2.1 Schematic Illustration of Probability Associated with Detecting or Missing a Given Size Flaw.

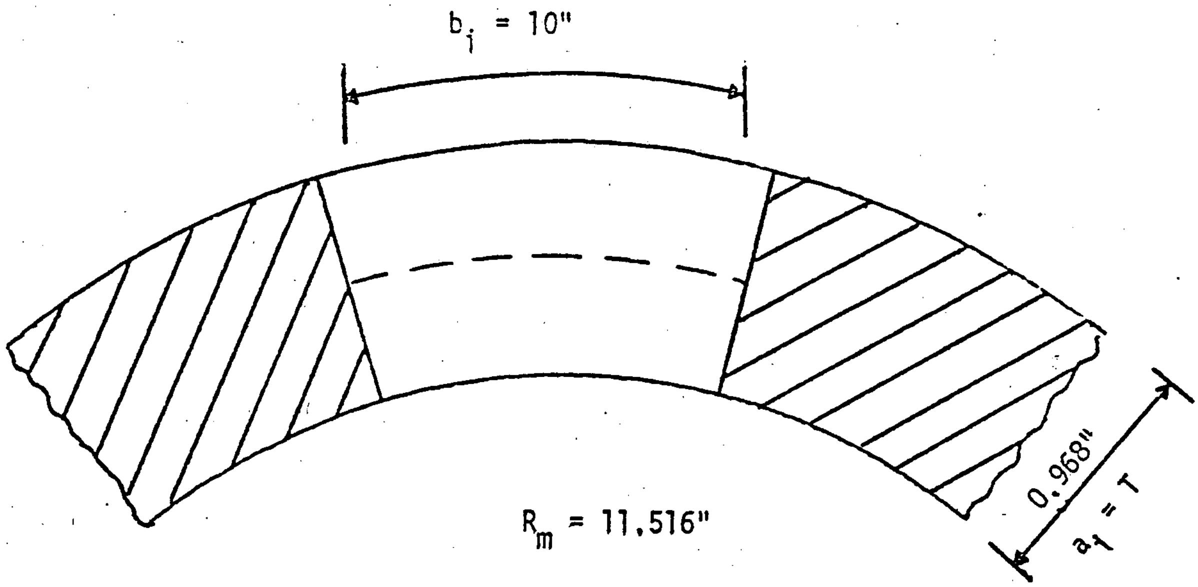


Figure 2.2 - Flaw Shape and Size

3. MATERIAL PROPERTIES

The MSL pipe is made of SA106 Gr B carbon steel material and the size is 24 inch schedule 60. The material properties of SA106 Grade B were obtained from ASME Section III (3-1). Table 3-1 lists those properties. In order to perform the elastic plastic analysis a bilinear stress strain curve as shown in Figure 3-1 was used. (3-1, 3-2).

TABLE 3-1

MATERIAL PROPERTIES

Property (500°F)	Material SA106B
Young's Modulus (psi)	26.4×10^6
Poisson's Ratio	0.3
Yield Point (psi)	28300
Strain hardening Modulus (psi)	0.268×10^6

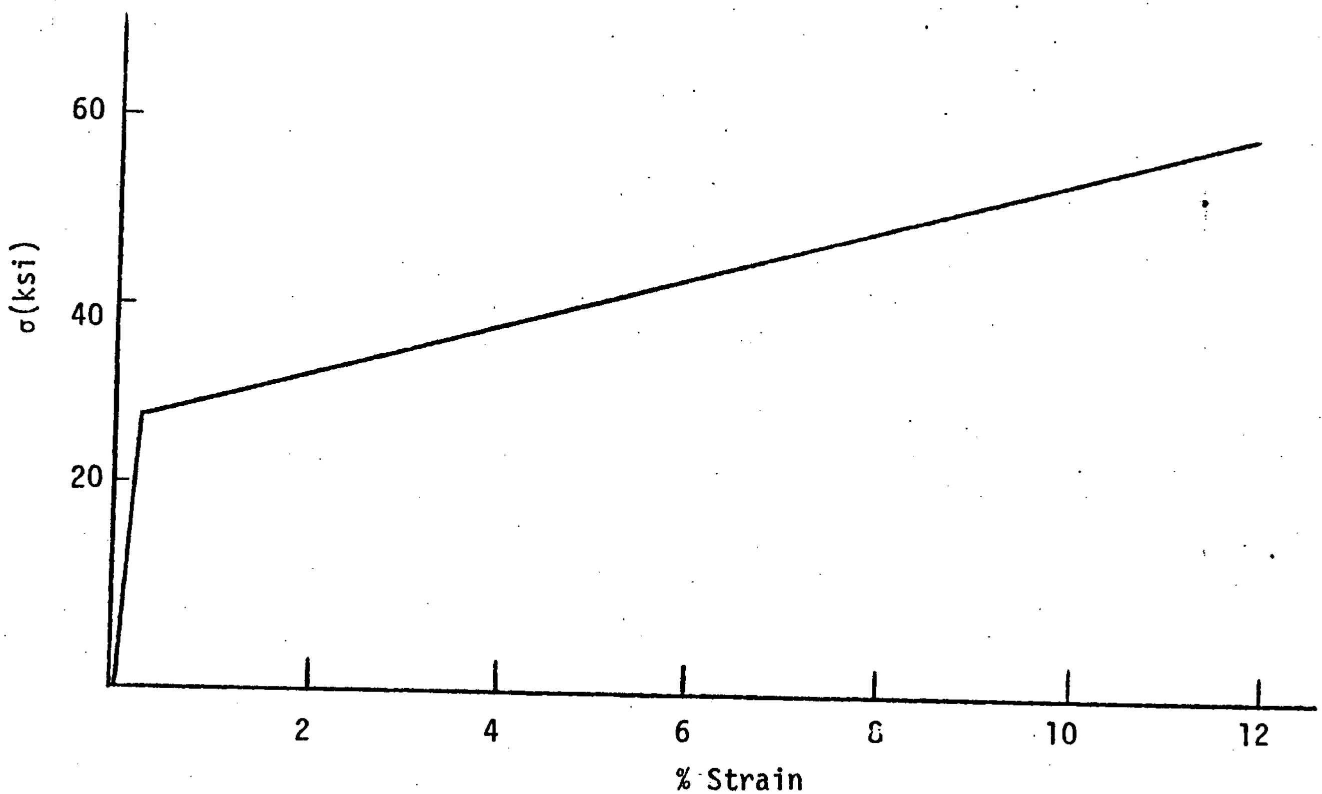


Figure 3-1 Bilinear Stress Strain Curve

4. FAILURE CRITERIA FOR FLAWED PIPES

4.1 General Considerations

Linear elastic fracture mechanics has been accepted as a basis for establishing the fracture capacity of structures made of high-strength low-toughness materials. Active research is being carried on in industry, universities as well as other research organizations to establish fracture criteria for ductile materials. Criteria, being investigated, include those based on J integral initiation toughness, equivalent energy, crack opening displacement, crack opening stretch, crack opening angle, net-section yield, tearing modulus and void nucleation. Several of these criteria are discussed in a recent ASTM publication [4-1].

A practical approach based on the ability to obtain material properties and to make calculations using the available tools, was used in selecting the criteria for this investigation. The ultimate objective is to show that the secondary pipe containing a conservatively assumed circumferential through-wall flaw is stable under the worst combination of postulated and operating condition loads within acceptable engineering accuracy. With this viewpoint, two mechanisms of failure, namely, local and global failure mechanisms should be considered.

4.2 Global Failure Mechanism

For a tough ductile material if one assumes that the material is notch insensitive, then the global failure will be governed by plastic load. Extensive literature is available on this subject. The recent PVRC study [4-2], in critically reviewing the literature as well as data from several hundred tests on pressure vessel heads, nozzles, pipes, elbows and tees, discusses the details of analytical methods, assumptions and methods of correlating experiments and analysis.

A schematic description of the plastic behavior and the definition of plastic load is shown in Figure 4.1. For a given geometry and loading, the plastic load is defined to be the peak load reached in a generalized load versus displacement plot and corresponds to the point of instability.

A simplified version of this criterion, namely, net section yield criterion has been successfully used in the prediction of the load carrying capacity of pipes containing gross size through-wall flaws [4-2] and was found to correlate well with experiment. This criterion can be summarized by the following relationship:

$$W_a < W_p \qquad (4\text{-}1)$$

where W_a = applied generalized load

W_p = calculated generalized plastic load

In this report, Wp will be obtained by an elastic-plastic finite element analysis of the pipe containing a given size flaw. For a pipe with high $\frac{d}{t}$ ratio and ductile material, the global failure will be the governing mechanism of failure (4-2). For the size of initial flaw proposed in section 2, it is expected that the global plastic load will give a more realistic estimate of the ultimate strength than that provided by the local criteria (i.e. J integral) based loads.

4.3 Local Failure Mechanism

The local mechanism of failure is primarily dominated by the crack tip behavior in terms of crack-tip blunting, initiation, extension and finally crack instability Depending on the material properties and geometry of the pipe, flaw size, shape and loading, the local failure mechanisms may or may not govern the ultimate failure.

The stability will be assumed if the crack does not initiate at all. It has been accepted that the initiation toughness, measured in terms of J_{IN} from a J-integral resistance curve is a material parameter defining the crack initiation. If, for a given load, the calculated J-integral value is shown to be less than J_{IN} of the material, then the crack will not initiate.

If the initiation criterion is not met, one can calculate the tearing modulus as defined by the following relation.

$$T_{app} = \frac{dJ}{da} \quad \frac{E}{\sigma_f^2} \tag{4-2}$$

where T_{app} = applied tearing modulus

E = modulus of elasticity

σ_f = flow stress = $(\sigma_y + \sigma_u)/2$

a = crack length

σ_y, σ_u = yield and ultimate strength of the material, respectively.

In summary, the local crack stability will be established by the two step criteria:

$$J < J_{IN} \tag{4-3}$$

$$T_{app} < T_{mat}, \; J \geq J_{IN} \tag{4-4}$$

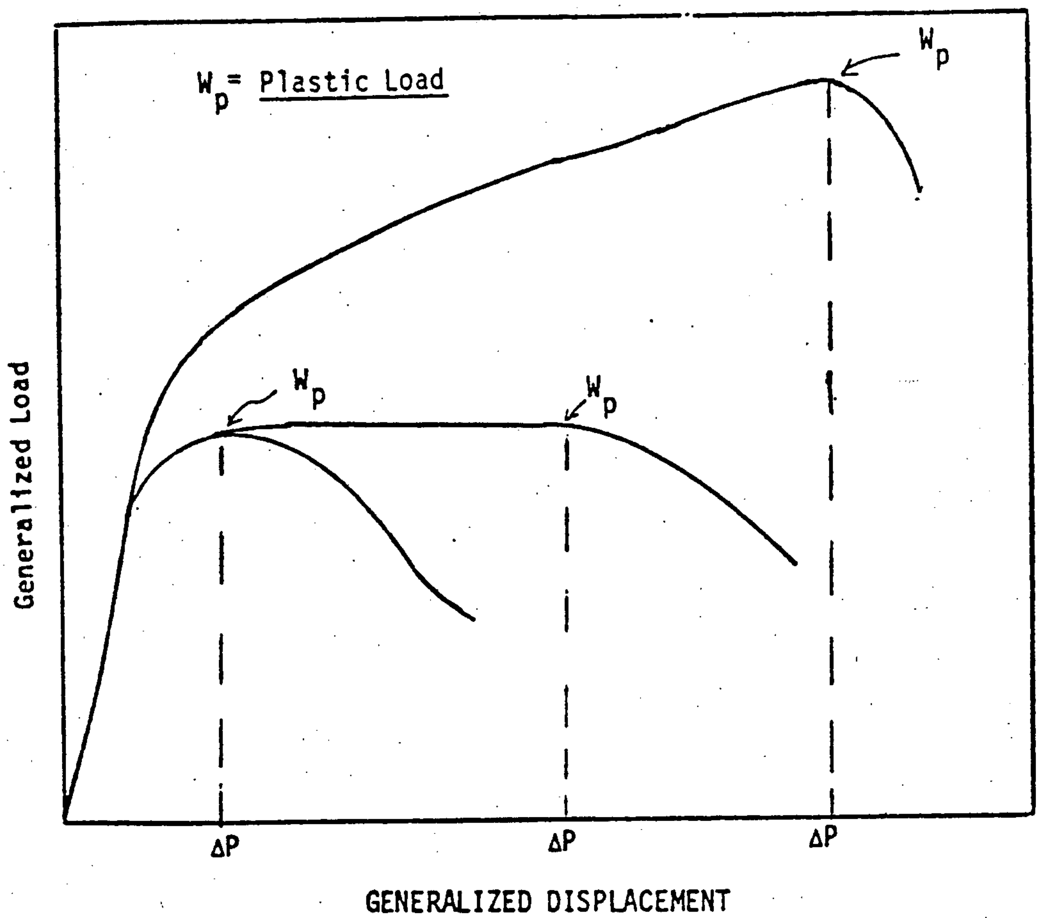


FIGURE 4.1 Typical Load - Deformation Behavior

5. FINITE ELEMENT ANALYSIS OF MAIN STEAM LINE PIPE USING ADINA

5.1 Static Analysis of Precracked Pipe

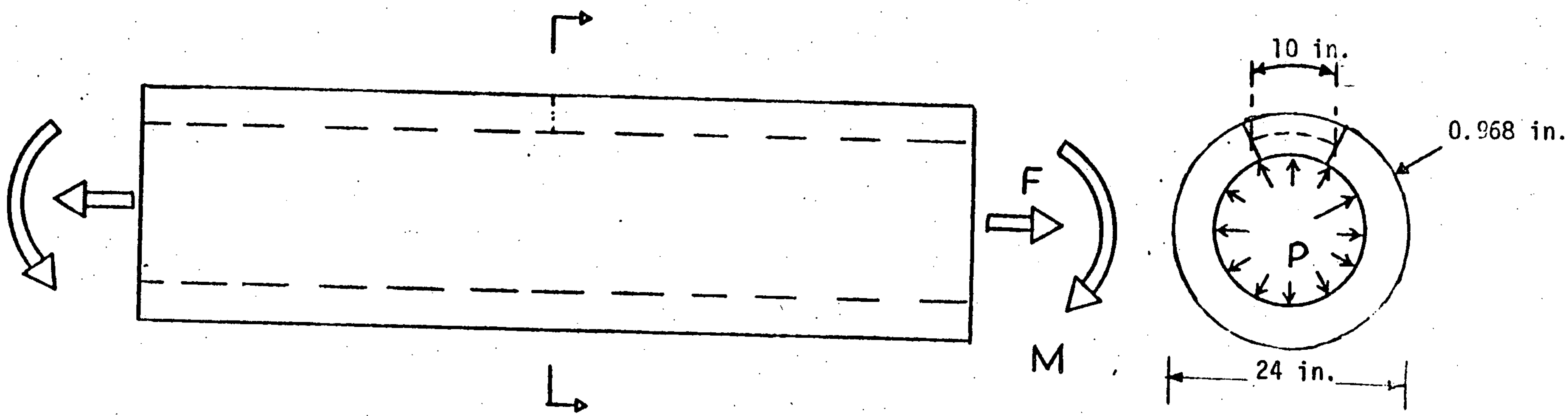
The objective of the finite element analysis is to compute the response to applied load on the main steam line pipe. The geometry of the pipe and the loadings are shown in Figure 5-1. The loadings consist of internal pressure, external bending moment and axial force due to internal pressure acting on the closed end of the pipe.

The length of the main steam line was chosen to be 187 inches. A circumferential through wall 10 inches long crack was postulated and used in the model. Taking advantage of the symmetry, one quarter of the pipe was modeled. Three dimensional variable node isoparametric shell elements were used to model the pipe. Elements were defined by the mid surface node specification. Eight node elements were specified in the vicinty of the crack and four node elements were used away from the crack. Five node (mixed) elements were used for transition. Figure 5-2 shows the finite element model used in the analysis. Figure 5-3 shows the area in the vicinity of the crack.

The material representing the model pipe was assumed to obey von Mises' yield condition and isotropic hardening law. Values of 26.4×10^3 ksi, 2.68×10^2 ksi and 28.3 ksi were used, respectively, for elastic modulus, strain hardening modulus and yield strength.

In performing the elastic-plastic finite element analyses the steam pressure of 710 psia[5-1] and the associated axial loads were applied in 4 equal steps. An external bending moment of 10580 in-kips was then superimposed in 7 equal steps while the pressure was maintained constant. The stiffness was reformulated at every 3rd loading step.

The maximum external moment load of 10580 in-kips used in ADINA calculations is a factor of 3.6 greater than the maximum applied moment of 2880 in-kips[5-2] on the main steam line pipe. This applied moment includes the thermal expansion moment, moment due to dead weight, design basis earthquake and turbine valve closure. Figure 5-4 shows the variation of pipe end slope with increasing pipe moment. It is notable that the slope of the curve is postive at the applied load level: This shows that the cracked pipe is stable under this loading.



$P = 710$ PSI

$F = 0.27 \times 10^6$ lbs

$M = 10.58 \times 10^6$ in-lbs

FIGURE 5-1 MAIN STEAM LINE PIPE

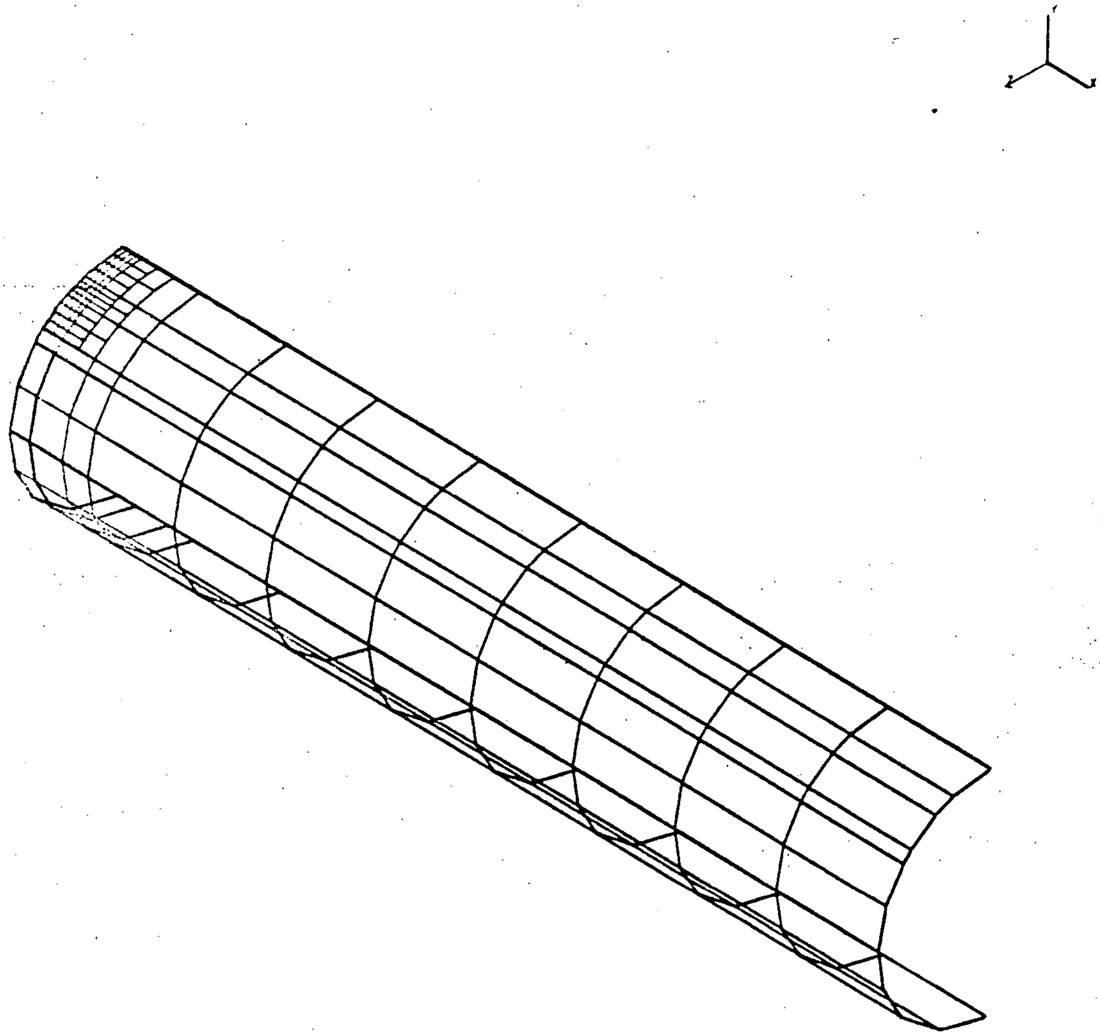


Figure 5-2 Finite Element Model

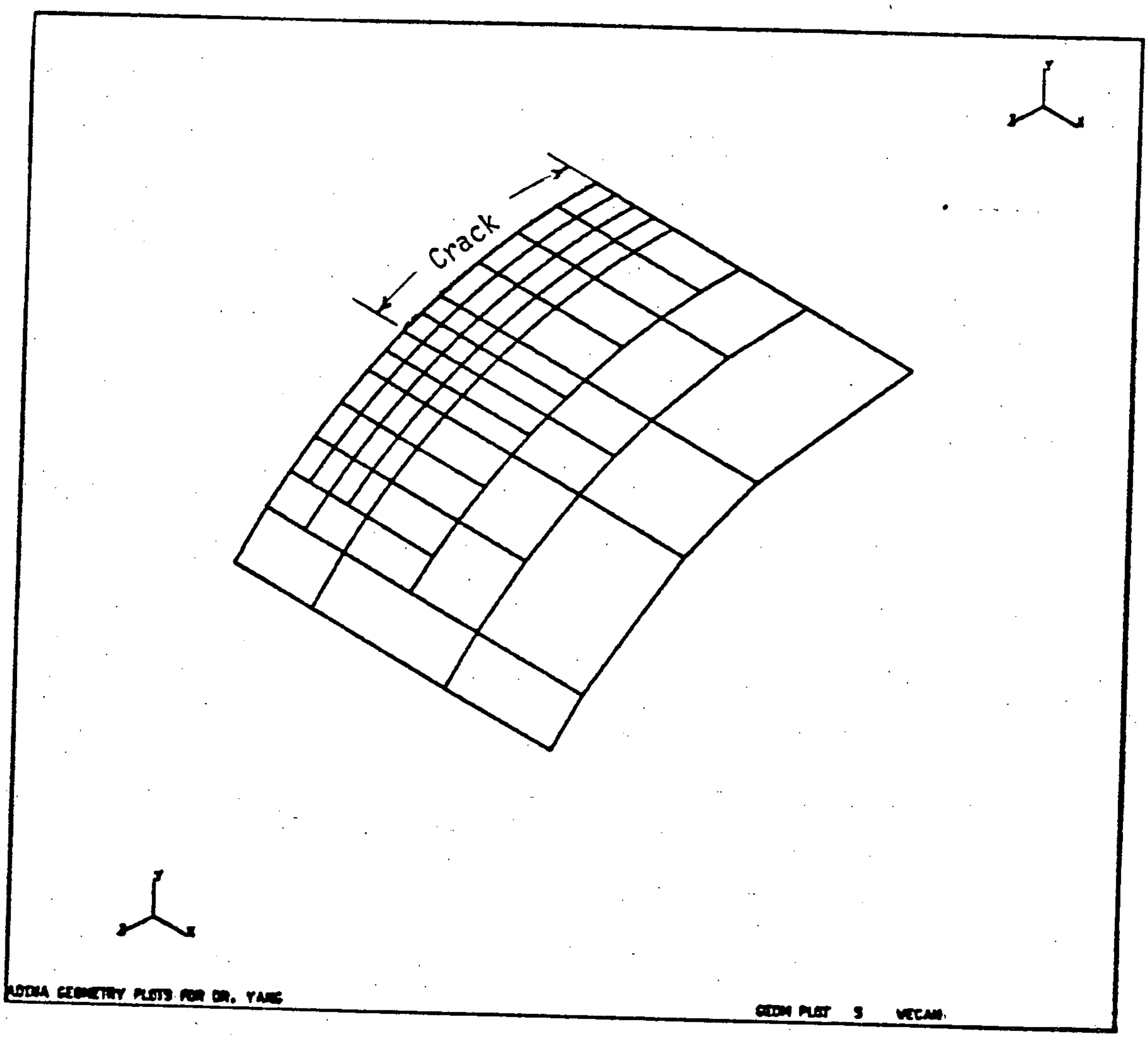


Figure 5-3 Details of Finite Element Model in the Vicinity of Crack

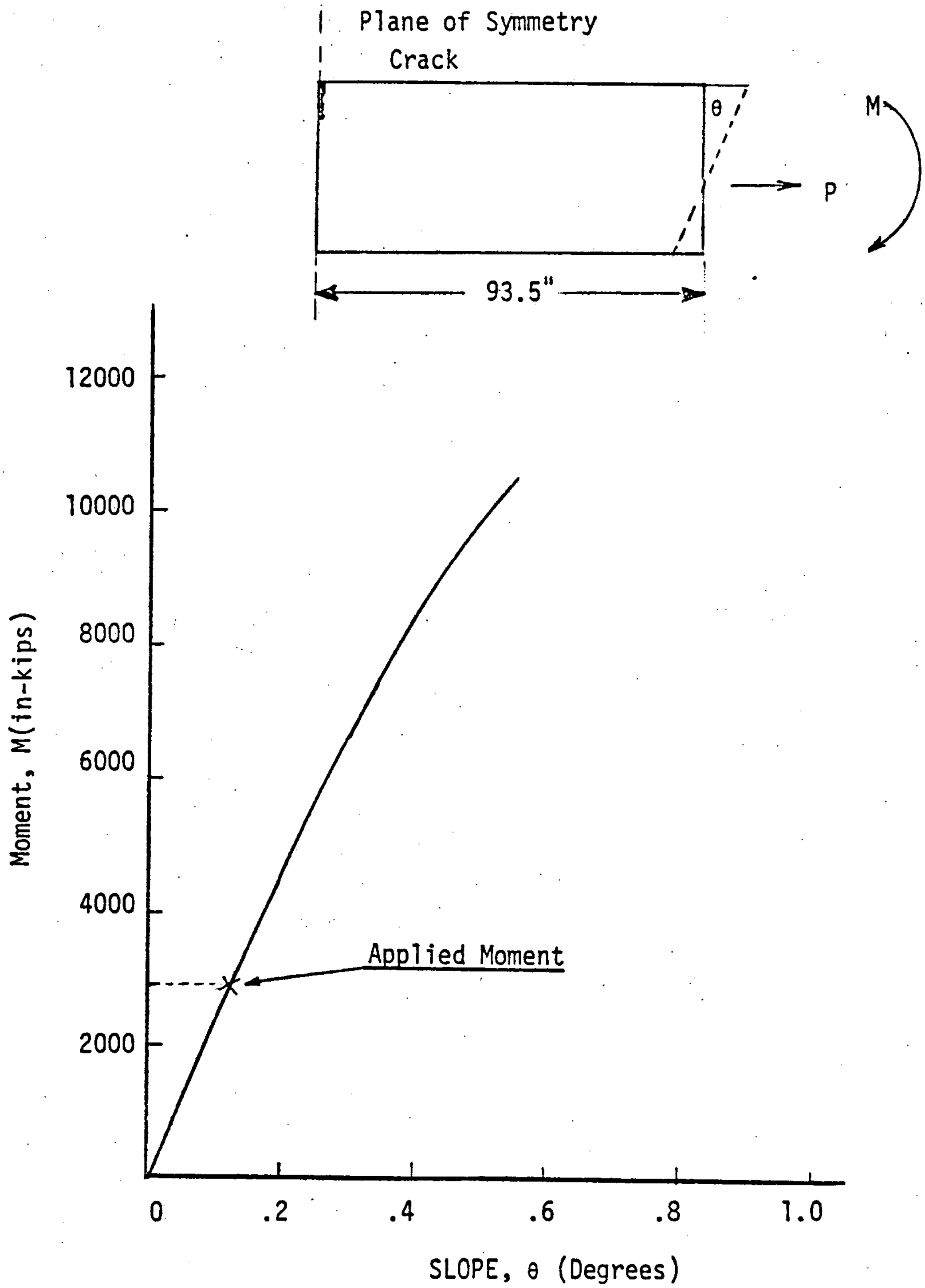


Figure 5-4   Variation of Pipe End Slope with Applied Static Moment

6. FRACTURE MECHANICS EVALUATION OF MAIN STEAM LINE PIPE

6.1 Global Criteria

The general global criterion specified in section 4-2 requires that

$$W_a < W_p \qquad (4\text{-}1)$$

where W_a = applied generalized load

W_p = calculated generalized plastic load.

For the static loading, ADINA finite element elastic plastic calculations show that the moment carrying capacity of the main steam line pipe containing a 10 inch through wall circumferential flaw is at least 10580 in-kips for a given steam pressure of 710 psi.

The generalized plastic load W_p is then at least 10580 in-kips for the given pressure of 710 psi. The applied generalized load W_a is 2880 in-kips for a given pressure of 710 psi. Therefore, the criterion given by equation 4-1 is satisfied.

6.2 Local Criteria

The general local criteria specified in Section 4-3 require that

$$J < J_{IN} \qquad (4\text{-}2)$$

An estimate for the J integral can be obtained based on the following approximate relation, using the finite element analysis results:

$$J = \frac{\pi}{8r} [E^1 \delta_e^2 + E^T \delta_p^2] \qquad (6\text{-}1)$$

where δ_e, δ_p = elastic and plastic displacement of the quarter-point node behind the crack tip, respectively.

r = distance between crack tip and the quarter-point node

E^1 = E, $E/1-\nu^2$ for plane stress and plane strain, respectively.

E^T = Strain-hardening modulus.

It should be noted that the above expression is strictly applicable only to a crack in a two-dimensional bilinear elastic medium. One would expect that this would give reasonable estimate for the bilinear elastic-plastic case where unloading does not occur.

For the present case, the J-integral value of 51 in-lb/in^2 is obtained corresponding to a load of 3034 in-kips using equation (6-1). Since the maximum applied generalized load [5-2] is 2880 in-kips (<3034) this calculated J integral value of 51 in-lb/in^2 can be considered as the maximum resulting J from the applied loads.

The value of J_{IN} for the SA106B is available at 425°F and varies between 674 in-lb/in^2 (6-1) and 1096 in-lb/in^2 (unpublished Westinghouse results). Clearly, the calculated J value of 51 in-lb/in^2 is very small compared to J_{IN}. Therefore, equation (4-2) is satisfied.

7. SUMMARY AND CONCLUSIONS

7.1 Summary

The objective of this investigation was to examine mechanistically, under realistic and yet sufficiently conservative assumptions, whether a crack which was assumed to appear instantaneously, in the main steam line pipe of San Onofre Unit 1, would become unstable and lead to a full circumferential break when subjected to the worst possible combination of plant loadings. The scope of this investigation included:

- Postulating a circumferential through-wall flaw.
- Performing static elastic-plastic finite element analysis of the cracked pipe using the ADINA Code.
- Evaluation of global criteria based on plastic instability load.
- Obtain an estimate of J integral to evaluate the local criterion.

7.2 Conclusions

Based on the analysis the following conclusions are drawn.

- A 10 inch long through wall circumferential flaw in the main steam line pipe will be stable globally and locally.

- Under the worst combination of loadings including the effects of design basis earthquake, thermal expansion, dead weight and turbine valve closure, a realistically postulated flaw will not propagate around the circumference and cause a guillotine break.

REFERENCES

1-1 ADINA - A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis, MIT Report 82448-1.

2-1 ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, 1977.

2-2 Fatigue Crack Growth Evaluation for San Onofre Unit 1 Main Steam Line Pipe, WCAP 9808, October 1980.

3-1 ASME, SECTION III, Nuclear Power Plant Components, 1977.

3-2 1977 Annual Book of ASTM Standards, Part 1, Steel Piping, Tubing and Fittings.

4-1 J. D. Landes, et. al., Editors, Elastic-Plastic Fracture, STP-668, ASTM, Philadelphia, PA. 19109, Nov. 1977.

4-2 Mechanical Fracture Predictions for Sensitized Stainless Steel Piping with Circumferential Cracks, EPRI-NP-192, September 1976.

5-1 Westinghouse Technical Manual #T.M. 1440-C77, "Vertical Steam Generator for Southern California Edison Company, San Onofre Nuclear Generating Station.

5-2 San Onofre Nuclear Generating Station, Unit 1, Bechtel Job No. 1400-006, Input to Westinghouse on Main Steam Line Fracture Mechanics Analysis, B/SCE-80-066, September 15, 1980, A. Sanders to E. Donovan.

6-1 A. Goldberg et. al., "Evaluation of Cracking in Feedwater Piping Adjacent to the Steam Generators in Nine Pressurized Water Reactor Plants" Lawrence Livermore Laboratory Report UCRL 53000 NUREG/CR-16-3 October 1980.