① EPRI-217-1-TR6
② PB-247 518

PB-247 518

AN ENGINEEFING FRACTURE MECHANICS ANALYSIS OF THE PILGRIM I NOZZLE-TO-PRESSURE VESSEL WELD DISCONTINUITIES

P. M. Besuner

Failure Analysis Associates

Prepared for:

Electric Power Research Institute

October 1975

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

352086

Analysis of the Pilgrim I Nozzle-to-Pressure Vessel Weld Discontinuities

PB 247 518

EPRI

EPRI 217-1
Technical Report
October 1975

Keywords:
Reactor Safety
Nondestructive Testing
Nuclear Reactors
Inspection Reliability
Quality Assurance

Prepared by
Failure Analysis Associates
Palo Alto, California

ELECTRIC POWER RESEARCH INSTITUTE

BIBLIOGRAPHIC DATA SHEET

1. Report No. EPRI 217-1 ·No.6·

2.

3. Recipient's Accession No.

4. Title and Subtitle

Analysis of the Pilgrim I Nozzle-to-Pressure Vessel Weld Discontinuities

5. Report Date

October 1975

6.

7. Author(s)

P. M. Besuner

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Failure Analysis Associates
Palo Alto, CA

10. Project/Task/Work Unit No.

RP 217-1

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

Electric Power Research Institute
Palo Alto, CA

13. Type of Report & Period Covered

TECHNICAL REPORT

14.

15. Supplementary Notes

Continuing research

16. Abstracts

The influence function (IF) method for calculation of stress intensity factor $K_I(a)$ is applied to the case of a semicircular surface crack, of radius "a", used to model a discontinuity revealed by in-service inspection of a nozzle-to-shell weld in the Pilgrim I pressure vessel. The K_I calculations obtained in Section 2 for two complex thermal stress distributions and a combined stress distribution encountered in the nozzle weld, are compared with previous calculations based upon the "Evaluation of Flaw Indications" method described in the ASME Boiler and Pressure Vessel Code. It is shown that a substantial difference exists between the $K_I(a)$ values calculated by the Code method and the IF method, except, coincidentally, in the vicinity of the specific flaw size (a=0.9") revealed by inspection of the Pilgrim vessel. For crack sizes substantially greater than 1.0", $K_I(a)$ values calculated by the Code method are significantly larger than those calculated by the IF method. The IF method has the potential to improve and affect the conclusions of future analyses of structures with imperfections.

17. Key Words and Document Analysis. 17a. Descriptors

Reactor safety
Nondestructive testing
Nuclear reactors
Inspection reliability
Quality assurance

17b. Identifiers/Open-Ended Terms

17c. COSATI Field Group

PRICES SUBJECT TO CHANGE

18. Availability Statement

Release Unlimited

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 22

22. Price 3.50

P087-3204 NTIS $11.45 [illegible] 11-24-86

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

AN ENGINEERING FRACTURE MECHANICS ANALYSIS OF THE PILGRIM I NOZZLE-TO-PRESSURE VESSEL WELD DISCONTINUITIES

Research Project 217-1
(FAA-75-4-7)

Technical Report 6

October 1975

Prepared by

Failure Analysis Associates
750 Welch Road
Palo Alto, California 94304

Author
P. M. Besuner

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

Project Manager
F. Gelhaus

ia

NOTICE

TABLE OF CONTENTS

LIST OF FIGURES

Preceding page blank

1. SUMMARY

The influence function (IF) method for calculation of stress intensity factor $K_I(a)$ is applied to the case of a semicircular surface crack, of radius "a", used to model a discontinuity revealed by in-service inspection of a nozzle-to-shell weld in the Pilgrim I pressure vessel. Calculated K_I values are a key input to fatigue and static fracture mechanics analyses. The IF method for determining K_I, the development and application of which have been documented previously (3), has the capability to accurately and efficiently account for complex geometries, stress fields, and three-dimensional aspects of crack growth.

The K_I calculations obtained in Section 2 for two complex thermal stress distributions and a combined stress distribution encountered in the nozzle weld, are compared with previous calculations (1) based upon the "Evaluation of Flaw Indications" method described in Section XI, Appendix A of the ASME Boiler and Pressure Vessel Code (2).

The IF method, as fully detailed in (3) and outlined briefly in Section 2, models the stress field to any degree of accuracy desired rather than with the single straight line approximation used in the Code method. It is shown that a substantial difference exists between the $K_I(a)$ values calculated by the Code method and the IF method except, coincidentally, in the vicinity of the specific flaw size (a=0.9") revealed by inspection of the Pilgrim Vessel.

For crack sizes substantially greater than 1.0 inch, $K_I(a)$ values calculated by the Code method are significantly larger than those calculated by the IF method. Since the Code method values have been shown previously to predict more-than-adequate residual fatigue lifetime and static strength for the vessel, the smaller K_I values computed by the IF method do not alter the major conclusions reached in (1). In fact, a static failure and fatigue analysis, performed in Section 3, does show a significant increase in the already large static failure safety margins computed in (1) while the fatigue calculation is virtually unaffected.

It is concluded that the IF method has the potential to improve and to affect the conclusions of future Section XI analyses of structures with imperfections. In future Section XI analysis where higher accuracy is required, because of combinations of larger cracks, lower temperatures and higher working stresses, the IF method should be useful for evaluation of the integrity of pressure vessels, piping, and other structures. The Code (2) already recognizes the need for improvements and states (Article A-3300, Item (c)): "Note that (Code) Equation (1) is only a recommended procedure for determination of K_I. More sophisticated techniques may be used providing the methods and analyses are documented. In many cases, involving complex geometries and stress distributions, the methods outlined above may be inadequate, and more sophisticated techniques should be used." The influence function method has been shown (3-5) to be both accurate and efficient for highly non-linear stress fields and has also been computerized to calculate fatigue crack length as a function of number of load cycles.

2. STRESS INTENSITY FACTOR CALCULATIONS

2.1 The Influence Function Method

This section applies the influence function (IF) method to compute the stress intensity factor $K_I(a)$ for three complex loadings of the semi-circular surface crack, of radius "a", illustrated in Fig. 1. According to (1), and as specified by Article A-2000 of Section XI, this crack conservatively models the "discontinuity" region revealed by in-service, ultrasonic inspection of the nozzle-to-shell weld in the Pilgrim I reactor pressure vessel.

The IF method uses only the stress in the uncracked solid to compute the crack-induced redistribution of the elastic stress field. Details of the IF method are available elsewhere (3-5) and, for completeness, only two relevant equations are given below. The expressions for stress intensity factors at the maximum depth $(\overline{K}_x)$* and at the surface $(\overline{K}_y)$* portions of the circular crack front in Fig. 1 are given by

$$\overline{K}_i = 2(\pi a)^{-3/2} \int_{-a}^{a} \int_{0}^{\overline{y}_{max}} f(x_e)\ (1 + \frac{2i^2}{a^2\alpha})\alpha^{1/2}\sigma_{zz}\ (x,y)\ dy\ dx \qquad (1)$$

for $i = x,y$

$$\overline{y}_{max} = (1 - x^2/a^2)^{1/2}, \quad \alpha = 1 - (x^2 + y^2)/a^2$$

$$\overline{x}_{max} = (1 - y^2/a^2)^{1/2}$$

$$x_e = x/(a\overline{x}_{max})$$

where $f(x_e) = (1 + x_e)^{1/2}\ (1.3188 - 0.7884\ x_e + 0.1768x_e^2) \qquad (2)$

---

* The accent mark ($\overline{\ }$) denotes that $\overline{K}_i$ is a specifically weighted average of the K(s) function along the i^{th} portion of the crack front, s.

is a crack surface correction factor derived from analogous two-dimensional edge crack solutions. Finally, $\sigma_{zz}(x,y)$ is the uncracked stress (i.e., stress in the uncracked structure at, and normal to, the crack locus).

As derived and demonstrated in Appendix B of (3), Equation 1 is a good engineering approximation (i.e., expected errors are approximately 5%) of the stress intensity factors for arbitrary stress fields for the case of sufficiently small a/t, where t = 6" is the vessel shell thickness as shown in Fig. 1. The ASME Code (2) circular crack solutions indicate that the finite thickness effect may be neglected for a/t less than 2/3 so that Equations 1 and 2 are applied only in the range 0 < a < 4" in this report. The current Code requires that when more than one K value is computed, the maximum value should be used. In the calculations below for all considered values of a and σ_{zz}, we compute

$$\overline{K}_y\,(a) > \overline{K}_x\,(a) \tag{3}$$

so that we may simplify the K factor notation below to $\overline{K}_y(a) = K_I(a) = K(a)$.

2.2 K(a) Solutions for Three Uncracked Stress Fields $\sigma_{zz}(x,y)$

Figures 2, 3 and 4 illustrate the uncracked stress distributions, calculated in (1), of the form $\sigma_{zz}(x,y) = \sigma_{zz}(x) = \sigma(x)$ where, as shown in Fig. 1, x is the distance from the free surface. Figure 2 plots the maximum combined loading $\sigma(x)$ distribution, used by (1) to compute $K_{max}(a)$ so that the allowable or minimum critical crack depth a_c can be computed from $K_{max}(a_c)=K_c$, where K_c is the allowable or minimum critical stress intensity factor value for brittle failure. Figure 3 plots the peak transient thermal stress calculated in (1) as caused by a 506^{o}F step change in reactor vessel feedwater (FW) temperature. According to the calculations in (1), this type of thermal transient, with a 446^{o}F step change, is the most important cyclic stress component of the shutdown operation, which is the major contributor to fatigue crack propagation. Figure 4 illustrates the highly nonlinear thermal stress distribution caused by a 100^{o}F step change in reactor pressure vessel (RPV) temperature. We consider the RPV thermal stresses in order to compare the K(a) calculations for IF and Code methods for a highly nonlinear stress field. The three stress distributions were each fit with ten linear segments, as shown schematically in Fig. 5, for substitution into Equation 1 to compute K(a) numerically with computer program IFS3-3 which is referenced in Table I of (3). The stress distributions were also fit with 5 and with 20 linear segments and all 5- and 20-segment computed values of K(a) differed by less than 3% from the 10-segment values.

Figures 2 to 4 compare the K(a) calculated by the IF method with two other methods of stress intensity factor computation. The other two methods are: the Code method and the IF method using a single straight line approximation to the actual uncracked stress field. For any given crack depth "a", this line is a secant approximation drawn between $\sigma(a)$ and $\sigma(0)$ on the "σ vs. a" plot as in Fig. 5. The IF method was used to compute K(a) with the secant line stress field in order to quantify only that portion of the total difference in calculated K(a) that results from approximating the actual stress field with a single secant line. Note the significant differences in the IF method curves introduced by the secant approximation. up to 16% for the combined stress distribution in Fig. 2 and up to 28% and 250% for the thermal stress distributions in Figs. 3 and 4, respectively.

In reviewing the Code analysis in (1) for K, no curve for M_b values (bending correction factors for surface cracks) for the appropriate a/L = 0.5 and for the highest value of K around the semicircular crack (the surface location in this case) was available in Fig. A-3300-5 of (2).* However, by utilizing the Code method and the dashed line in Fig. A-3300-5 of (2) for an elliptical crack of aspect ratio, a/L = 0.3, FAA was able to reproduce the K values reported in (1) and shown in Figs. 2 to 4. As evidenced in Figs. 2 to 4, the K(a) values reported in (1) for a/L = 0.5 do not coincide with the IF-secant stress field K(a) values for any of the three analyzed stress distributions. The greatest differences between the secant-based K(a) curves occur for the highly non-linear RPV thermal stress distribution where the K(a) values in (1) are: 1) when 0 < a < 0.7", 30-40% smaller, 2) when a is near 1", almost the same, and 3) when a > 1.5", up to 40% larger than the IF calculated K(a) for the secant stress field.

3. RELEVANCE OF K(a) TO ALLOWABLE CRACK DEPTH AND FATIGUE CRACK GROWTH CALCULATIONS

3.1 Fatigue Crack Growth

Stating that its analysis is conservative, Reference (1) estimates that the crack modeling the weld discontinuity can grow from its initial a = 0.9" to a final size a = 1.0" under stress cycles induced by 40 years of operational load transients. Because the shutdown operation occurs

*October 1975 Footnote:
It is now known that this confusion was caused by the 1973 Summer addenda of the Code which incorrectly labeled a curve "a/L = 0.5" rather than the correct "a/L = 0.3" which appears in later published Code editions.

frequently, it is expected to cause about 60% of the total fatigue growth, $\Delta a = 0.1"$. As stated previously, the major cyclic stress component of shutdown is due to a 446 ^{o}F step change in FW temperature during shut down. This thermal transient produces cyclic stresses which are 446/506 = 0.88 times the stresses calculated by finite element methods (1) for a 506 ^{o}F step change in FW temperature and reproduced in Fig. 3 of this report.

Since K calculations using the IF method and the Code method in (1) are essentially equal for "a" near 1", the amount of fatigue crack growth, $\Delta a = 0.1"$, predicted by each method would also be equal. However, noting from (2) that the upper bound growth rate is

$$\frac{da}{dN} \propto \{\Delta K(a)\}^{3.726} \propto K(a)^{3.726} , \qquad (4)$$

significantly different crack growth rates would be predicted for "a" values much different from 1". The following table uses (4) to compute the ratio of crack growth rates for the two methods that would be predicted at three different crack sizes.

a (in)	$K^{(1)}$ (Ksi(in)$^{1/2}$)	$K^{(2)}$ (Ksi(in)$^{1/2}$)	$(da/dN)^{(2)}/(da/dN)^{(1)} = \left[K^{(2)}/K^{(1)}\right]^{3.726}$
0.5	12.9	15.3	$1.186^{3.726} = 1.9$
1.0	19.1	20	$1.047^{3.726} = 1.2$
3.0	36	26.5	$0.736^{3.726} = 0.32$

(1) refers to calculations in Ref. (1)

(2) denotes IF method results in this report, Fig. 3.

Clearly, the use of the influence function method for stress intensity factor calculations will, in general, affect $\frac{da}{dN}$.

3.2 Allowable Maximum Crack Depth

Arguments are presented in (1) for computing the allowable crack depth a_c from

$$K_{max}(a_c) = 63.2 \text{ ksi} \sqrt{\text{in}} \tag{5}$$

for metal temperatures greater than 180^{o}F. Application of (5) and Fig. 2 shows that the allowable crack depth computed in (1) is approximately $a_c = 2.4"$ while the IF method calculates $a_c = 3.2"$. This difference between allowable crack sizes is significant. Although the Pilgrim I flaw evaluation was conservative, FAA believes that the IF method should be considered for future fracture mechanics analyses that require greater accuracy.

4. CONCLUSIONS

(1) The influence function (IF) method accurately computes stress intensity factors $K_I(a)$ for many specified stress distributions in the uncracked solid, including highly non-linear stress distributions.

(2) The current ASME Code recommended procedure for computing $K_I(a)$ may yield results which differ considerably from more accurate calculations, depending on the shape of complex stress distributions and upon any necessity for extrapolation to obtain geometric correction factors from incomplete sets of curves in the Code.

(3) The allowable crack depth in the Pilgrim I vessel feedwater nozzle weld was computed with the IF method to be 3.2 inches as compared to 2.4 inches using the Code method.

(4) Fatigue analysis of the 0.9 inch indication found in the Pilgrim I vessel is not strongly affected by an improved K analysis. However, fatigue analysis for crack depths significantly larger or smaller than 0.9 inches and for many other problems would be significantly affected.

(5) The computerized influence function method can economically provide accurate end-of-life and critical flaw size calculations, as specified in the Code, even when highly non-linear stress distributions are present and when Code approximations are inadequate.

REFERENCES

1. "Evaluation of 1974 ISI Results for Pilgrim 1 RPV Nozzles," Tech. Rept. #-1836, Teledyne Materials Research (July 1974).

2. Rules for Inservice Inspection of Nuclear Power Plant Components, Section XI, ASME Boiler and Pressure Vessel Code (Dec. 1974).

3. Besuner, P. M., "The Influence Function Method for Fracture Mechanics and Residual Fatigue Life Analysis of Cracked Components Under Complex Stress Fields," Technical Report for Electric Power Research Institute, Contract #RP217-1, Failure Analysis Associates, April 1975 (in preparation).

4. Cruse, T. A. and Besuner, P. M., "Residual Life Prediction for Surface Cracks in Complex Structural Details," Journal of Aircraft (to appear).

5. Besuner, P. M., "Residual Life Estimates for Structures with Partial Thickness Cracks," ASTM Eighth National Symposium on Fracture Mechanics, Providence, 1974 (accepted for publication).

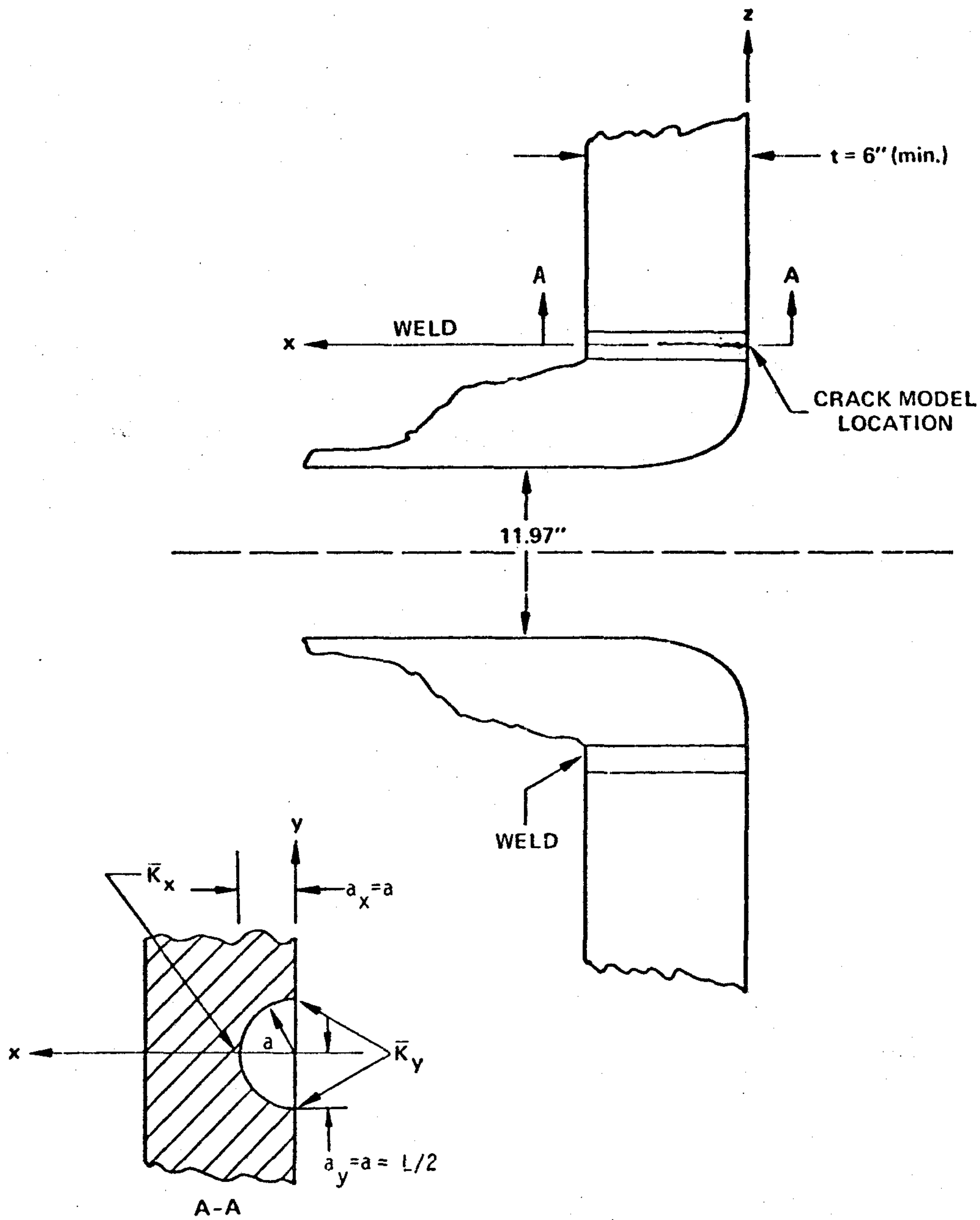

Fig. 1. SCHEMATIC OF NOZZLE GEOMETRY AND CRACK MODEL OF DISCONTINUITY

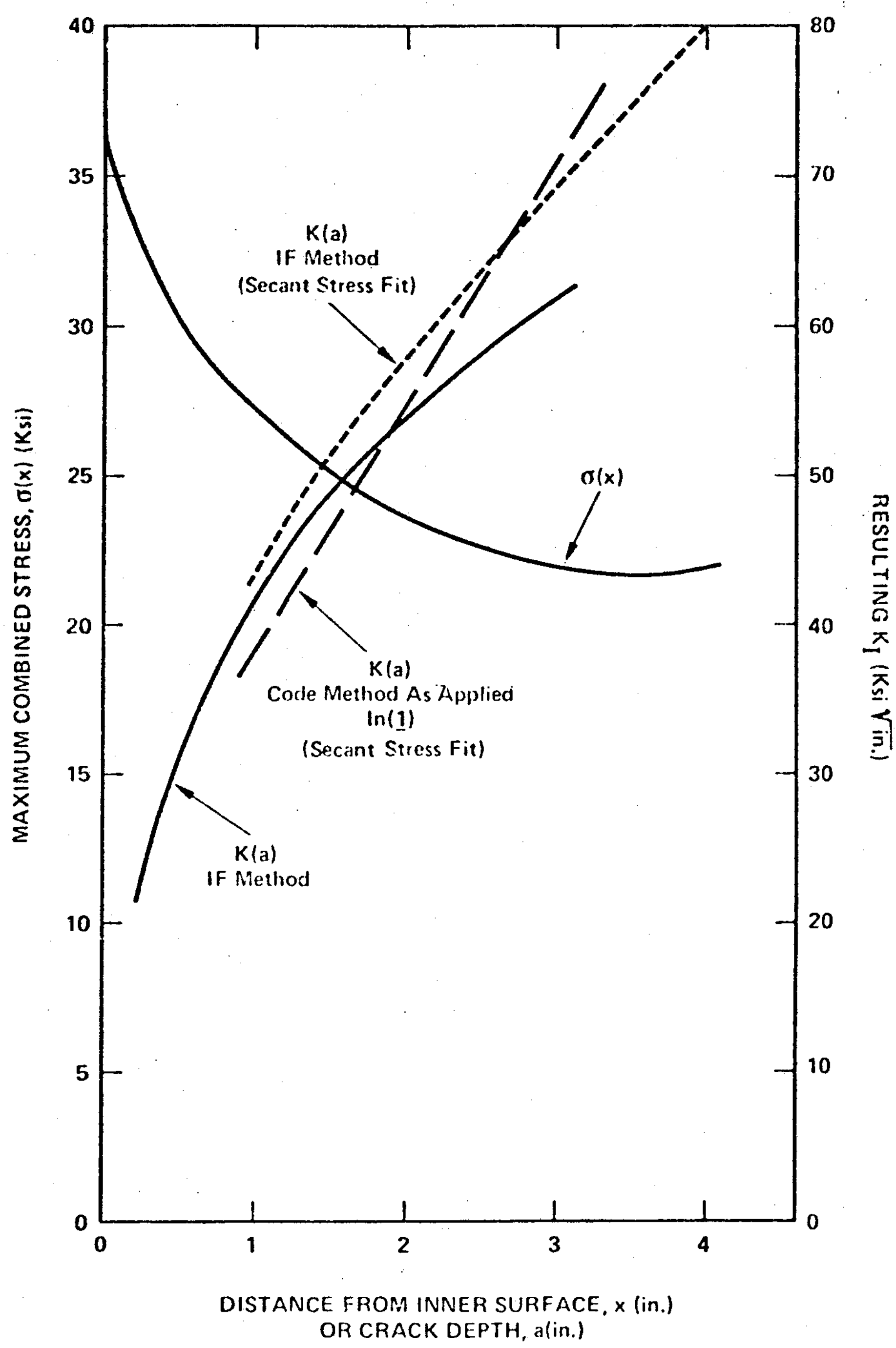

FIG. 2. COMPARISON OF THE STRESS INTENSITY FACTORS CALCULATED BY THE IF AND CODE METHODS FOR A COMBINED STRESS DISTRIBUTION IN THE FEEDWATER NOZZLE WELD OF THE PILGRIM I VESSEL

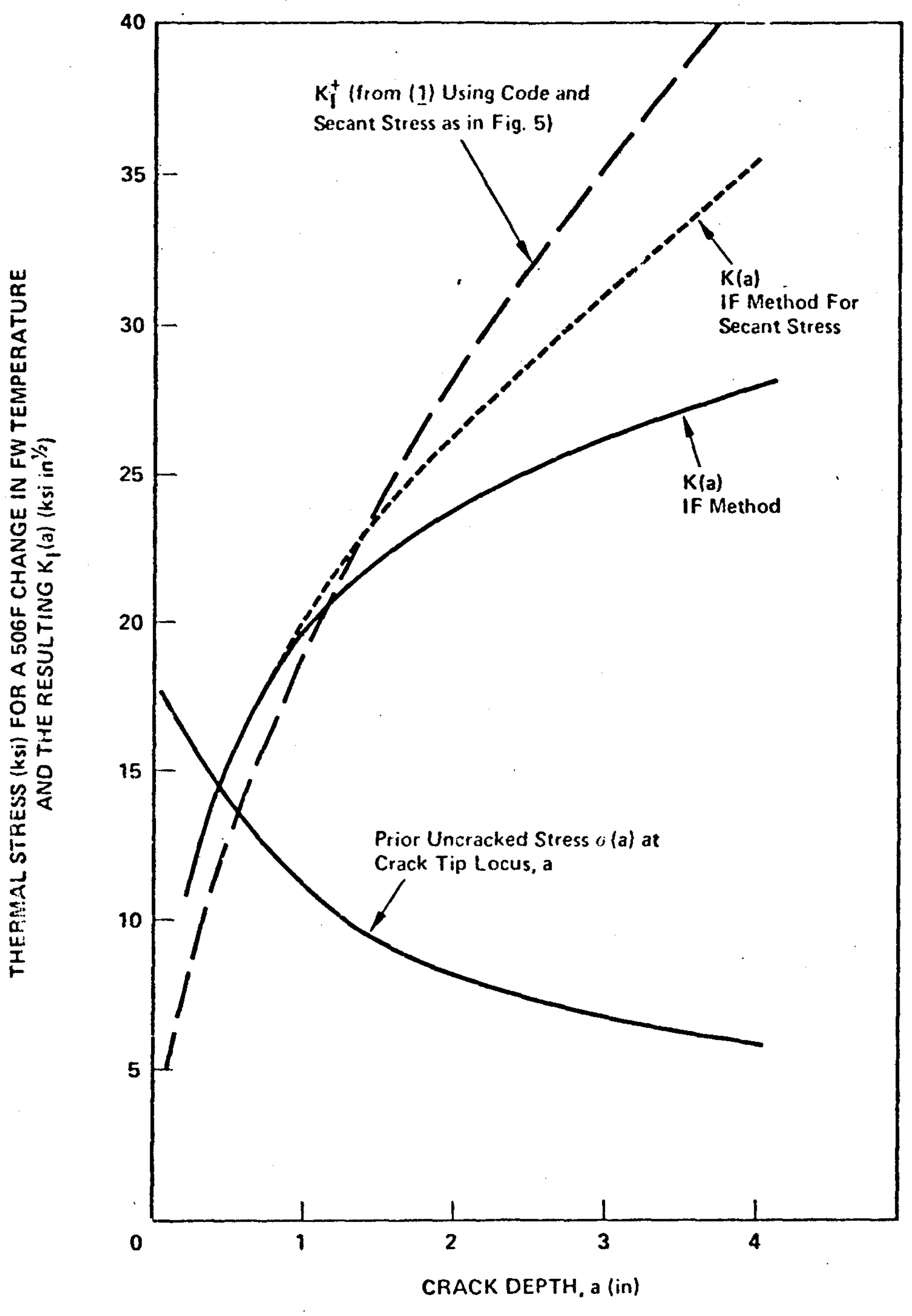

FIG. 3. COMPARISON OF THE STRESS INTENSITY FACTORS CALCULATED BY THE INFLUENCE FUNCTION METHOD AND THE APPROXIMATE ASME CODE METHOD FOR THE FW THERMAL STRESS DISTRIBUTION IN THE PILGRIM I FEEDWATER NOZZLE WELD

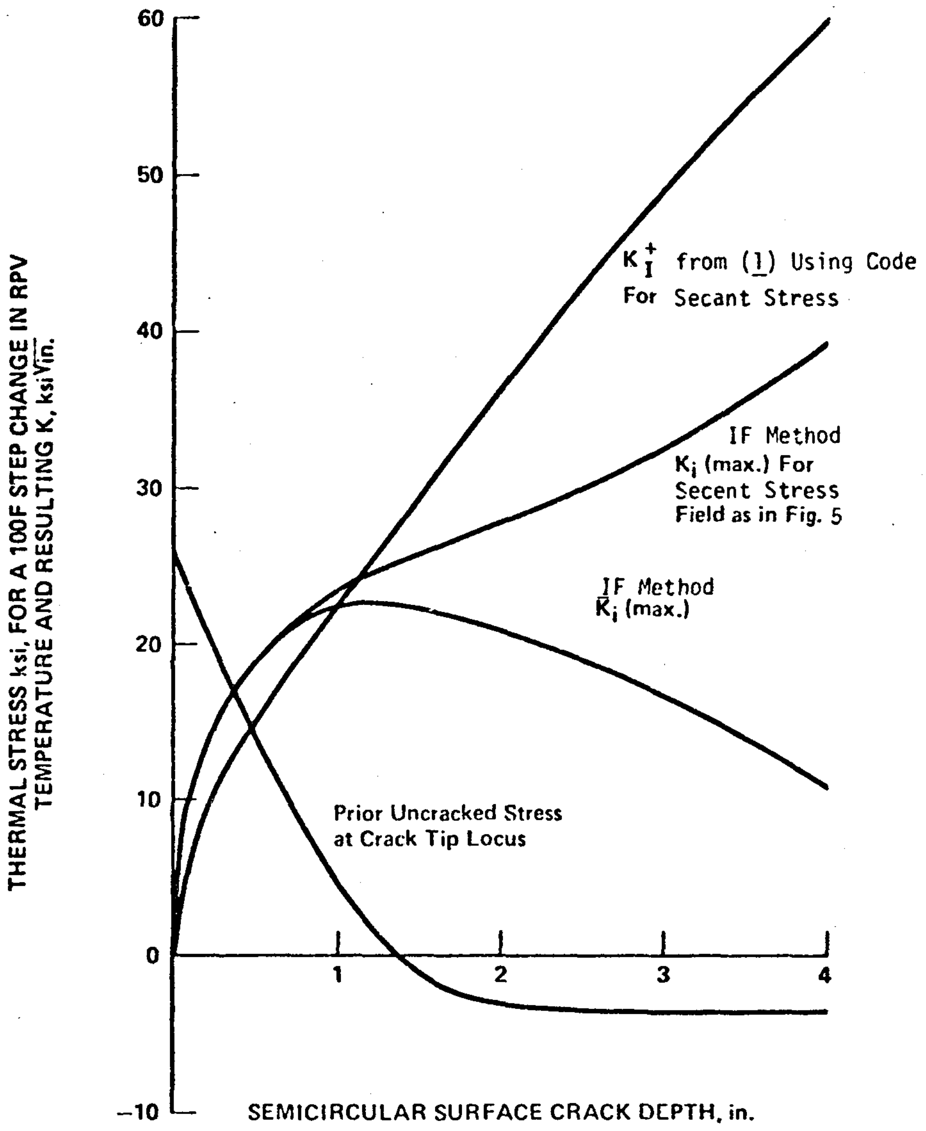

Fig. 4 COMPARISON OF THE STRESS INTENSITY FACTORS CALCULATED BY THE INFLUENCE FUNCTION METHOD AND THE APPROXIMATE ASME CODE METHOD FOR THE RPV THERMAL STRESS DISTRIBUTION IN THE PILGRIM I FEEDWATER NOZZLE WELD.

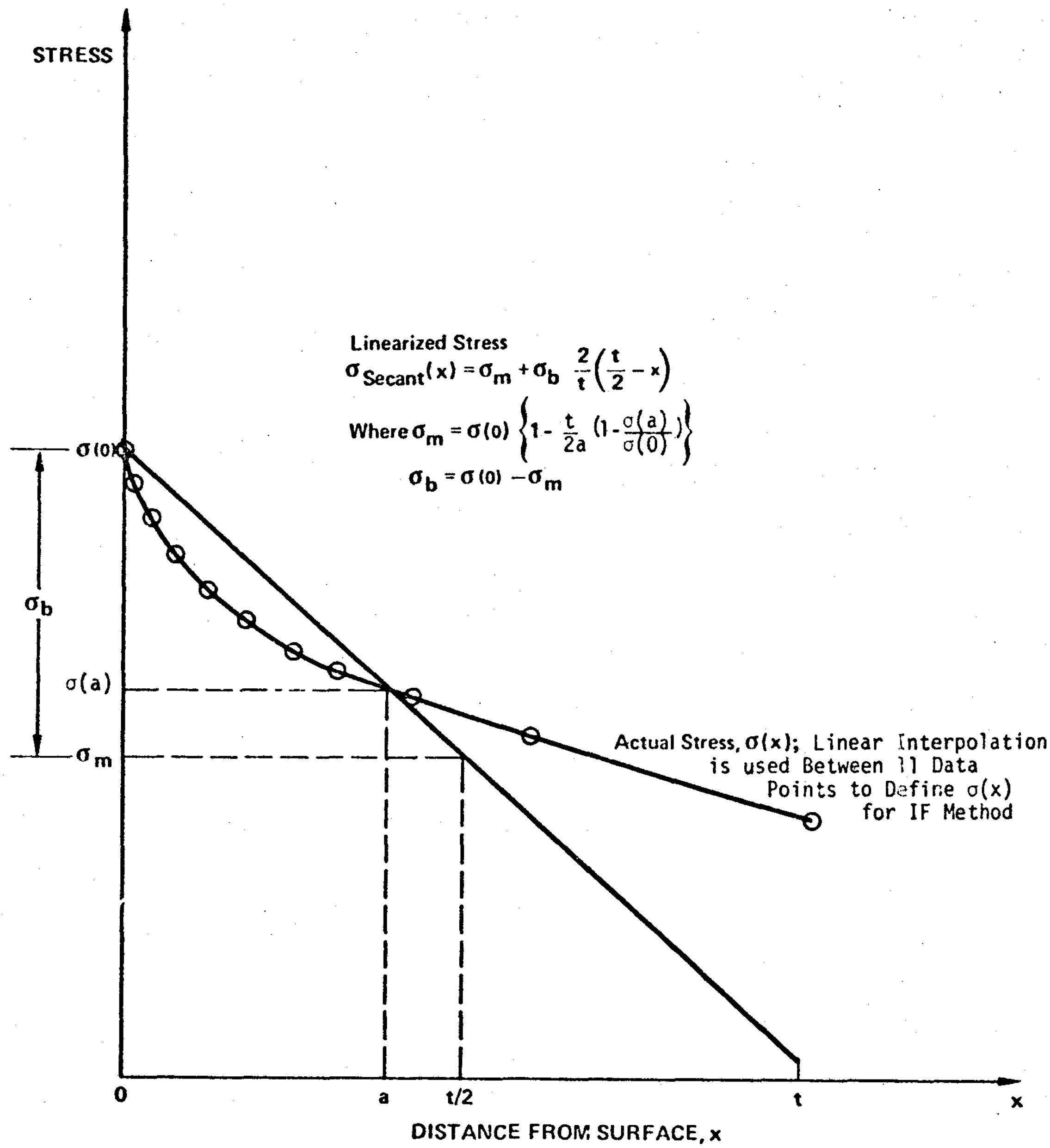

Fig. 5. COMPARISON OF THE TEN LINEAR SEGMENT APPROXIMATIONS TO THE ACTUAL STRESS FIELD USED IN THE IF METHOD WITH THE SINGLE SECANT APPROXIMATION IN THE CODE METHOD.