May 10, 2006

MEMORANDUM TO: John A. Grobe, Director
Division of Component Integrity
Office of Nuclear Reactor Regulation

FROM: Kimberly A. Gruss, Branch Chief ***/RA/***
Flaw Evaluation and Welding Branch
Division of Component Integrity

SUBJECT: APPROVAL OF TRAVEL AND PUBLICATION OF A PAPER PROPOSED FOR THE 14TH INTERNATIONAL CONFERENCE ON NUCLEAR ENGINEERING (ICONE-14) TAC NO. MC8181

Simon C. F. Sheng, has authored a paper titled, “Stress Intensity Factors for a Crack Emanating Non-radially from a Circular Hole Under Arbitrary Loading,” which was accepted for publication and presentation at the 14th International Conference on Nuclear Engineering (ICONE-14). A copy of the paper is attached. This memorandum requests your approval of publication of the paper in the ICONE-14 Proceeding and approval of Simon Sheng’s travel to Miami, Florida to attend the meeting on July 17-20, 2006, and to present his paper there.

The paper has been prepared in accordance with COM-207, Revision 1, “Procedures for Reviewing and Approving Speeches, Papers, and Journal Articles by NRR staff,” and Nuclear Regulatory Commission (NRC) Management Directive (MD) 3.9, “NRC Staff and Contractor Speeches, Papers, and Journal Articles on Regulatory and Technical Subjects.” The paper does not contain implications with respect to new or unresolved policy issues. The onsite registration fee for an author is $675, and the travel expenses are expected to be less than $2000.

The Director of Division of Engineering, Michael E. Mayfield, approved the submittal of the abstract on September 5, 2005, in accordance with Office Instruction COM-207, Revision 1.

As required by MD 3.9 and COM-207, NRC Form 390 is also attached.

Approval: ______***/RA/***_______
John A. Grobe, Director
Division of Component Integrity

Enclosures:
1. ICONE Paper
2. NRC Form 390

CONTACT: Simon Sheng, DCI/CFEB
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ENCLOSURE 1: ICONE PAPER

Proceedings of ICONE 14
14th International Conference on Nuclear Engineering
July 17-20, 2006, Miami, FL USA

ICONE14-89019

STRESS INTENSITY FACTORS FOR A CRACK EMANATING NON-RADIALLY FROM A CIRCULAR HOLE UNDER ARBITRARY LOADING

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ABSTRACT

Stress intensity factors are found for a crack emanating from a circular hole in an elastic solid which is in a state of plane deformation resulting from loads applied at infinity or pressure applied internally at the faces of the crack and the hole. The results, including Mode-I (opening) and Mode-II (shearing) stress intensity factors, are obtained numerically by means of a dislocation model which conveniently allows for general loading and, consequently, can easily handle the case where a crack emanates non-radially from a hole. Good agreement is found with published values for the special case when the crack is radial and the loading consists of remote tension and uniform pressure at the surface of the hole. Also included in the present paper are results for the case when both the hole and the crack are pressurized. Although the subject elastic solid is an infinite medium, the results of this paper serve as good estimates when the hole is relatively small in a finite component and is distant from the component edge. Since in most circumstances a real crack does not orient itself radially from a hole, this paper provides analysts information to decide whether Mode-II fracture needs to be considered in assessing the structural integrity of a component with a hole. Similarly, when the problem is 3-dimensional, the results of this paper imply that Mode-III (tearing) fracture may also need to be considered.

1. INTRODUCTION

The study of the problem of a crack emanating from a fastener hole was originated from the aircraft industry's concern, as indicated in the paper by Gran (1971) and that by Grandt (1975). However, this problem is also of interest to the nuclear industry because bolting-hole connections appear in many nuclear structures, systems, and components (SSCs). One idealization of this problem, which is concerned with a crack originating at the edge of a circular hole in an infinite plate was first solved by Bowie (1956). He used a conventional Kolosov-Muskhelishvili potential formulation involving a complex mapping function to map the crack-hole geometry into a unit circle. A boundary collocation method, which follows more or less the conventional approach, has also been used. Newman (1971) solved many symmetric (with respect to geometry and loading) crack-hole problems, where complex-series stress functions were constructed to satisfy the boundary condition exactly on the crack surfaces and approximately on the hole.

J. Tweed and D.P. Rooke (1976, 1973) used the Mellin transform to reduce the same problem to a singular integral equation. They then solved the equation numerically by the method of Erdogan and Gupta (1972). Although they claimed their results are of a higher degree of accuracy than Bowie's results, the authors did not substantiate this point.

A.F. Grandt Jr. (1975) used a completely different approach to solve this problem. His method is based on the work by Rice (1972), which can be explained, in Grandt's words, as "Once the displacement field and stress intensity factor are known for one geometry and loading (case 1), K_I may be obtained for any other symmetric loading applied to the same crack geometry (case 2)." The application of this method is limited for two reasons. First, it can only be used to extend a solved problem to include cases with different loadings. Second, it needs information about the derivative of the crack opening displacements, which as a rule is not readily available.

To the author's best knowledge, all published papers using the dislocation model addressed problems with a crack in an infinite boundary, such as that by Atkinson (1972), Erdogan (1974), and Sheng (1981), except for the one by Sheng (1987). There, the author extended the application of this method to a classical stress analysis of a finite medium (without cracks). In spite of its success in solving related crack problems, methods based upon dislocation density modeling have not been applied to the area of current interest. Here the author uses the method to calculate stress intensity factors for a crack emanating non-radially from a circular hole subjected to three types of loading. The first type (type I) is uniform remote tension which does not need to be perpendicular to the crack. The second type (type II) is a uniformly pressurized cracked hole, which has implications for problems in hydraulic fracture. The third type (type III) is internal pressure applied to the hole but with the crack surface traction free, which may be considered as the crack originating from an interference fit in the hole.

Since in reality a crack is very unlikely to be initiated and propagated precisely along the line of symmetry, the author formulates the problem in such a way that the crack is not located on this line. The problem with type II loading is shown in Fig. 1, where (t_1, w_1) and (t_2, w_2) represent the two ends of a crack of length d; R represents the radius of the hole; and p represents internal pressure of the hole and the crack-face pressure. The location and orientation of the crack are defined by parameters α and γ, as shown in Fig. 1. Results for the special case where $\alpha = 0$ and $\gamma = 0$ are compared with figures taken from papers by Bowie, Grandt, and Tweed (1976).

2. FORMULATION

The problem with type III loading is a special case of the problem with type II loading shown in Fig. 1. Accordingly, the latter will be used as an example to describe the method the author uses here. The analysis is based upon superposition of two problems. The configuration and loading for the first problem (Prob. I) is similar to that in Fig. 1, but without the crack. Thus, in Prob. I, surface traction is developed along the crack locus.

In the second problem (Prob. II, Fig. 2) all applied loads are removed. Instead, there is a continuous distribution of dislocations along the crack locus. The author requires that the tangential components of the surface traction induced by this distribution cancel their counterparts in Prob. I, while the negative normal components of the surface traction differ from their positive counterparts in Prob. I by the pressure p. The solutions of these two problems are added to give the solution of the problem depicted in Fig. 1.

The stress field for an infinite medium with a pressurized hole was given in Muskhelishvili's book (1954). The solution for a single dislocation in the presence of a circular inclusion was solved by Dundurs (1964). This paper considers the limiting case where the inclusion reduces to a hole. By a simple manipulation, Dundurs's solution can be used as a Green's function which is to be integrated over the crack locus for a continuous distribution of dislocations. In this manner, two singular integral equations are obtained which relate the tangential and normal components of the surface traction to the dislocation density components $b_t(t_0)$, and $b_w(t_0)$.

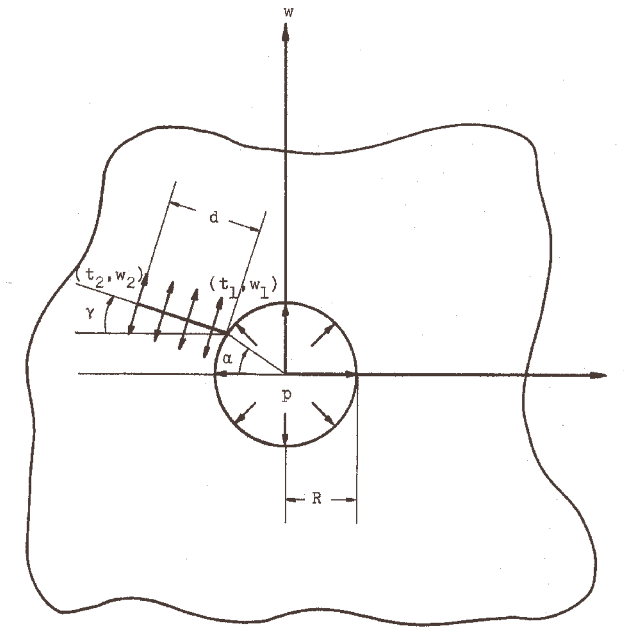


Figure 1 Pressurized crack emanating non-radially from a pressurized circular hole

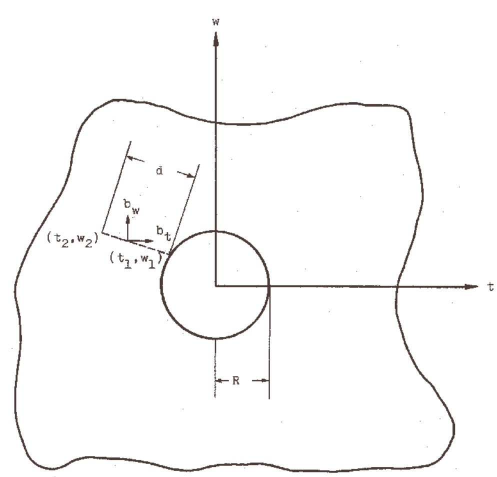


Figure 2 Geometry showing distribution of dislocations along the crack locus

The details of the mathematical derivation are given in the author's 1981 paper and will not be reproduced here. The resulting integral equations are

$$\pi p_1(t) = \int_{t_2}^{t_1} \{2[\frac{\sin\gamma}{t_0 - t} f_1(t_0) + \frac{\cos\gamma}{t_0 - t} f_2(t_0)] + k_{11} f_1(t_0) + k_{12} f_2(t_0)\} \frac{dt_0}{\cos\gamma} \quad (1)$$

$$\pi p_2(t) = \int_{t_2}^{t_1} \{2[\frac{\cos\gamma}{t_0 - t} f_1(t_0) - \frac{\sin\gamma}{t_0 - t} f_2(t_0)] + k_{21} f_1(t_0) + k_{22} f_2(t_0)\} \frac{dt_0}{\cos\gamma}$$

where $p_1(t)$ and $p_2(t)$ denote the normal and tangential components of the surface traction along the crack locus; $f_1(t_0)$ and $f_2(t_0)$ are the dislocation density components taking the negative sign, i.e., $f_1(t_0) = - b_t(t_0)$ and $f_2(t_0) = - b_w(t_0)$; and k_{11}, k_{12}, k_{21}, and k_{22}, which are functions of t and t_0, denote the non-singular portion of the contribution to the surface traction components p_1 and p_2 at t from the dislocation density functions f_1 and f_2 at t_0. In terms of stresses, the surface traction components assume the following forms:

$$[p_1(t)]_i = -(\sigma_{tt})_i \sin^2\gamma - (\sigma_{tw})_i \sin 2\gamma - (\sigma_{ww})_i \cos^2\gamma$$

$$[p_2(t)]_i = -\tfrac{1}{2}[(\sigma_{tt})_i - (\sigma_{ww})_i]\sin 2\gamma - (\sigma_{tw})_i \cos 2\gamma \quad (2)$$

for problem with type I and type III loading, where i = I or III. For type II loading, the author has

$$[p_1(t)]_{II} = -(\sigma_{tt})_{II} \sin^2\gamma - (\sigma_{tw})_{II} \sin 2\gamma - (\sigma_{ww})_{II} \cos^2\gamma - p$$

$$[p_2(t)]_{II} = -\tfrac{1}{2}[(\sigma_{tt})_{II} - (\sigma_{ww})_{II}]\sin 2\gamma - (\sigma_{tw})_{II} \cos 2\gamma \quad (3)$$

The quantities $(\sigma_{tt})_i$, $(\sigma_{ww})_i$, and $(\sigma_{tw})_i$ (i = I, II, or III) appeared in the above two equations are stress components obtained from solutions to Prob. I, which are available in Muskhelishvili's book. Because the crack is absent in Prob. I, it can be solved (though not in closed form) for essentially arbitrary loading by classical methods.

In order to maintain single-valuedness of the displacement for points to the left of (t_2, w_2), two more equations are needed. They are

$$\int_{t_2}^{t_1} \frac{1}{\cos\gamma} f_1(t_0) dt_0 = 0$$

$$\int_{t_2}^{t_1} \frac{1}{\cos\gamma} f_2(t_0) dt_0 = 0$$

(4)

$$h_j(\xi) = 2 f_j(\xi)(1-\xi)^{1/2}(1+\xi)^{1/2} \quad (j = 1, 2)$$

3. NUMERICAL METHOD AND STRESS INTENSITY FACTORS

To further simplify the formulation, the author introduces the functions:

$$\xi = -[\frac{2t_0 - (t_1 + t_2)}{t_1 - t_2}] \quad (5)$$

where ξ is given by

(6)

$$\pi p_1(\bar{\xi}) = \int_{-1}^{1} [\frac{-\sin\gamma}{\xi - \bar{\xi}} h_1 - \frac{\cos\gamma}{\xi - \bar{\xi}} h_2 + \frac{d}{4} k_{11} h_1 + \frac{d}{4} k_{12} h_2] \frac{d\xi}{(1-\xi)^{1/2}(1+\xi)^{1/2}}$$

$$\pi p_2(\bar{\xi}) = \int_{-1}^{1} [\frac{-\cos\gamma}{\xi - \bar{\xi}} h_1 + \frac{\sin\gamma}{\xi - \bar{\xi}} h_2 + \frac{d}{4} k_{21} h_1 + \frac{d}{4} k_{22} h_2] \frac{d\xi}{(1-\xi)^{1/2}(1+\xi)^{1/2}}$$

Hence, the integration interval $[t_2, t_1]$ for t_0 becomes [1, -1] for ξ. Using (5) and (6) and changing the integration interval from [1,-1] to [-1,1], Equation (1) can be put in a form which is convenient for numerical integration:

(7)

where d is the length of the crack.

Similarly, the single-valuedness condition takes the form:

(8)

Since there is no stress singularity at the point (t_1, w_1), Equation (5) results in two more conditions:

$$h_j(-1) = 0 \quad (j = 1, 2) \tag{9}$$

Equation (7), (8), and (9) comprise the system upon which the numerical work is based.

A numerical method due to Ioakimidis and Theocaris (1977) reduces (7) to 2(n-1) linear algebraic equations with 2n unknowns (n is the number of abscissas for the numerical integration). Unfortunately, (8) and (9) give four equations instead of two. Therefore, two equations have to be discarded.

It is clear that (9) concerns dislocation densities at a point, whereas (8) concerns dislocation densities along the entire crack locus. If two equations have to be dropped, (9) will be the first choice. The numerical results which are discussed later confirms the rationale. The stress intensity factors at the crack tip (t_2, w_2) are defined by

$$\begin{aligned} K_I &= \lim_{t \to t_2} [2(t_2 - t)/\cos\gamma]^{1/2}\, p_1(t) \\ K_{II} &= \lim_{t \to t_2} [2(t_2 - t)/\cos\gamma]^{1/2}\, p_2(t) \end{aligned} \tag{10}$$

By a procedure similar to the one employed by Erdogan (1974), the author arrives at

$$\begin{aligned} \frac{K_I(t_2)}{p(\pi d)^{1/2}} &= \frac{1}{2^{1/2}}[\sin\gamma h_1(1) + \cos\gamma h_2(1)] \\ \frac{K_{II}(t_2)}{p(\pi d)^{1/2}} &= \frac{1}{2^{1/2}}[\cos\gamma h_1(1) - \sin\gamma h_2(1)] \end{aligned} \tag{11}$$

4. RESULTS AND DISCUSSION

The results for the stress intensity factors for various d/R values are tabulated in Table 1 for the three types of loading considered here. Also listed in this table are results taken from the literature. Bowie's results in Table 1 are generated from the following equation suggested by Grandt,

$$\frac{K_I}{p(\pi d)^{1/2}} = \frac{0.8733}{0.3245 + d/R} + 0.6762 \tag{12}$$

which was based on a least squares approximation to Bowie's original solution. The remaining cited results are inferred indirectly from figures. Therefore, an error as large as ± 3% may occur.

Since the difference among the results of various investigators for type I loading is small, the author plots only Bowie's results along with the author's results in Fig. 3. Figures 4 and 5 contain similar plots for the remaining load cases. Tweed's results (1976) are presented in Fig. 5 for comparison. To the author's knowledge, the results illustrated in Fig. 4 are new.

It is interesting to note from Table 1 that the current results are very close to those of Tweed (1976), which may be due to the fact that although the approaches are different, they probably end up with very similar singular integral equations. Furthermore, even though the author dropped two equations, (9), no significant effects are experienced for stress intensity factors for any value of d/R.

Table 1 Summary of stress intensity factors $K_I/p(\pi d)^{1/2}$ for three types of loading considered

	Type I				Type II	Type III	
d/R	Bowie	Grandt	Tweed	Author	Author	Tweed	Author
.01	3.29	----	3.28	3.33	2.22	1.10	1.10
.05	3.01	----	3.01	3.04	2.11	1.02	1.02
.10	2.73	2.62	2.73	2.78	1.99	.938	.937
.30	2.07	2.08	2.03	2.09	1.67	.700	.698
.50	1.74	1.68	1.65	1.73	1.48	.560	.551
.75	1.49	1.38	1.45	1.46	1.33	.440	.432
1.0	1.34	1.23	1.28	1.31	1.23	.358	.352
1.25	1.23	1.15	----	1.20	1.15	----	.294
1.50	1.15	1.12	----	1.13	1.10	----	.251
1.75	1.10	1.04	----	1.07	1.06	----	.218
2.00	1.05	1.00	----	1.03	1.02	----	.192

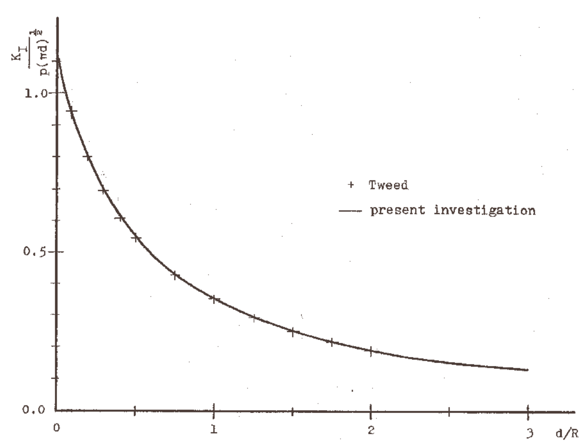
$$\int_{-1}^{1} h_1 \frac{d\xi}{(1-\xi)^{1/2}(1+\xi)^{1/2}} = 0$$

$$\int_{-1}^{1} h_2 \frac{d\xi}{(1-\xi)^{1/2}(1+\xi)^{1/2}} = 0$$

Figure 4 Stress intensity factors for a crack emanating from a circular hole subjected to hydraulic pressure (Type II loading)

Figure 3 Stress intensity factors for a crack emanating from a circular hole in remote tension (Type I loading)

Figures 6 and 7 show the variation of $K_I/p(\pi d)^{1/2}$ and $K_{II}/p(\pi d)^{1/2}$ for □ = 5 E when the dimensionless crack length d/R is varied from .01 to 3.0. In this



calculation, the variable □ is set to be zero. These two figures reveal that when the crack is offset from the radial line by only a small amount, K_{II} may be as large as 15% of K_I under Type III (bolting pressure) load. This implies that, depending on the specific engineering applications, K_{II} may not be negligibly small.

As a conclusion, the author emphasizes that except for the present method and collocation method, none of the methods mentioned in this paper can be used or extended to solve the problem with a crack extending non-radially from a circular

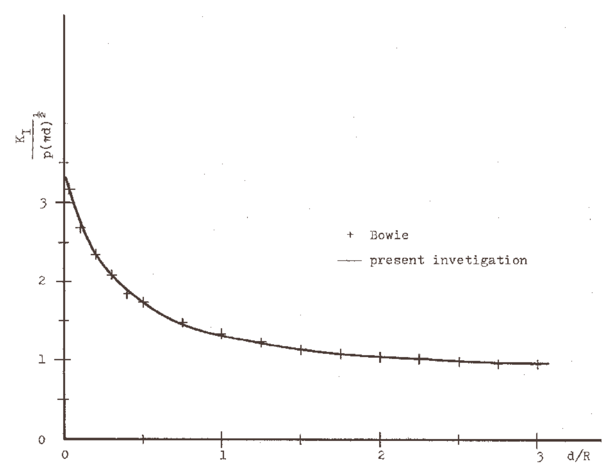


Figure 5 Stress intensity factors for a crack emanating from a circular hole with uniform pressure applied to hole only (Type III loading)

hole. The dislocation model thus furnishes a versatile tool for the analysis of cracked hole problems. Since the current approach results in a reasonable number of linear algebraic equations, complex schemes in matrix manipulations which are common in finite element method codes are not necessary here. Consequently, most commercial software without complex schemes in solving a system of linear algebraic equations can be used here. For example, Newman (1971) used 160 coefficients in the stress function to bring his results within 2 percent of Bowie's approximate solution. Since the problem he dealt with was symmetric about both coordinate axes, more coefficients are likely needed for the problem with only one crack emanating from the hole. He has to solve a system of at least 160 equations. For the current study, 20 abscissa points are used to get the results listed in Table 1. This means the author has a linear algebraic system of only 20 equations to solve.

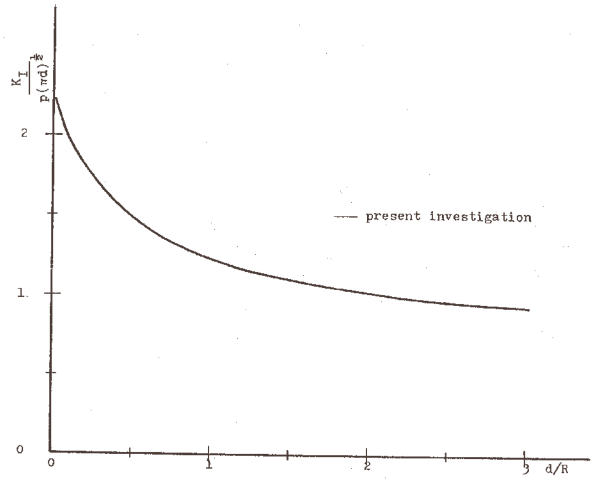


Figure 6 Opening-mode stress intensity factors for a crack emanating non-radially from a circular hole

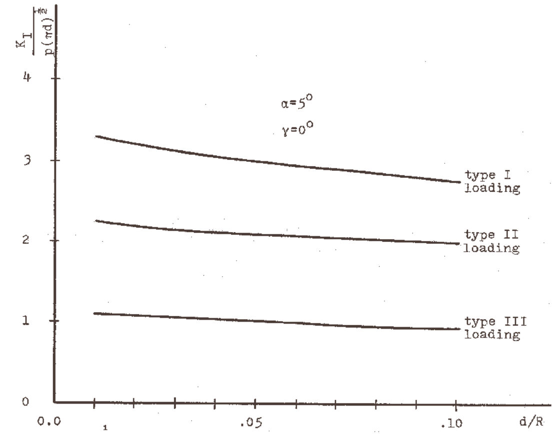
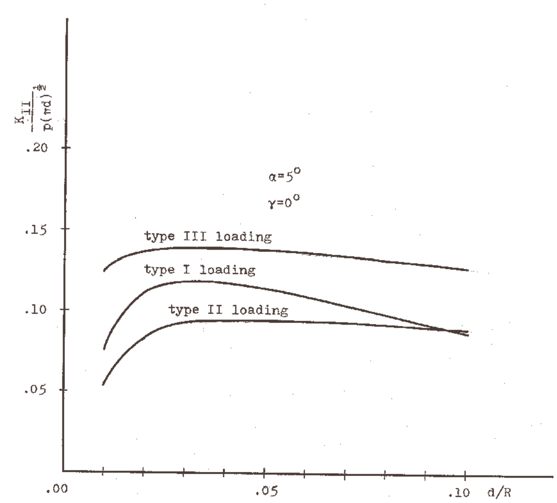


Figure 7 Shearing-mode stress intensity factors for a crack emanating non-radially from a circular hole



Although information about stress intensity factors for a new problem is of interest in itself, the author's ultimate objective goes beyond this. It is to reexamine the established fracture mechanics methodologies which calculate crack growth and use failure criteria based on only Mode I fracture. In recent years, an approach of also considering K_{II} and K_{III} has been developed to evaluate the crack growth of a flaw in reactor vessel control rod drive mechanism (CRDM) nozzles, as evidenced by the NRC-sponsored work of Rudland (2003) and the nuclear industry-sponsored work of Broussard (2003); and pressurizer heater sleeves, as evidenced by a non-proprietary Westinghouse report (2003). Theoretically, this approach of considering K_{II} and K_{III} can also be used in establishing the failure criteria for elastic-plastic fracture mechanics (EPFM) applications. However, due to the high ductile material property of the CRDM and pressurizer heater penetrations, limit load analysis had been used to develop their failure criteria, and the new approach of considering K_{II} and K_{III} in addition to K_I had been applied to only crack growth calculations for these two applications.

5. CONCLUSION

Stress intensity factors K_I and K_{II} are found for a crack emanating from a circular hole in an infinite elastic solid under three types of loading conditions, using a dislocation model. The results indicate that a slight out of symmetry regarding component geometry and loading could result in K_{II} values which are not as small as originally thought for many applications. Therefore, it may be worthwhile to consider K_{II} and K_{III} in estimating the crack growth for SSCs other than CRDM and pressurizer heater penetrations.

Although considering K_{II} and K_{III} in the crack growth calculation represents an improvement over the conventional approach of considering only K_I, this new approach does not address all effects caused by K_{II} and K_{III}. Sheng (1981) pointed out that whenever a significant K_{II} exists, the crack will grow off its original orientation after initiation (i.e., $K_I \$K_{Ic}$, where K_{Ic} is the plane strain fracture toughness). Likewise, it is reasonable to assume that K_{III} also plays a role in determining the crack growth path. So far, consideration of K_{II} and K_{III} in determining the crack growth path has not been attempted in nuclear industry applications. The need to further modify this new approach to include crack direction change should be judged by operating experience. In other words, operating experience will determine whether the conventional approach with its specific structural (safety) factors, which does not consider crack path change, is adequate to assess structural integrity of nuclear SSCs.

6. REFERENCES

Atkinson, C., 1972, "The Interaction Between a Crack and an Inclusion," International J. of Engineering Science, Vol. 10 (127-136).

Rroussard, J. and Gross, D., 2003, “Welding Residual and Operating Stress Analysis of RPV Top and Bottom Head Nozzles,” Conference on Vessel Penetration Inspection, Crack Growth and Repair (NUREG/CP-0191), March 2004.

Bowie, O. L., 1956, "Analysis of An Infinite Plate Containing Radial Cracks Originating from the Boundary of an Internal Circular Hole," J. of Mathematics and Physics, Vol.35 (60-71).

Dundurs, J. and Mura, T., 1964, "Interaction Between an Edge Dislocation and a Circular Inclusion," J. of Mechanics and Physics of Solids, Vol.12 (177-189).

Erdogan, F., Gupta, G. D., and Ratwani, M., 1974, "Interaction Between a Circular Inclusion and an Arbitrarily Oriented Crack," ASME J. of Applied Mechanics, Vol. 41(1007-1013).

Erdogan, F. and Gupta, G. D., 1972, "On the Numerical Solution of Singular Integral Equations," Q. Appl. Math. Vol.29 (525-534).

Gran, R. J., Orazio, F. D., Paris, P. C., Irwin, G. R. and Hertzberg, R., 1971, "Investigation and Analysis Development of Early Life Aircraft Structure Failures," Technical Report AFFDL-TR-70-149, Wright-Patterson Air Force Base, Ohio.

Grandt, A. F. Jr., 1975, "Stress Intensity Factors for Some Through-Cracked Fastener Holes," International J. of Fracture, Vol. 11 (83-94).

Muskhelishvili, N., 1954, Some Basic Problems of the Mathematical Theory of Elasticity, Noordhoff, Groningen.

Newman, J. C., "An Improved Method of Collocation for the Stress Analysis of Cracked Plates with Various Shaped Boundaries," 1971, NASA Technical Note, TND-6376.

Rice, J. R., 1972, "Some Remarks on Elastic Crack-Tip Stress Fields," International J. of Solids and Structures, Vol. 8 (751-758).

Rudland, D., Wilkowski G., Wang Y., and Norris W., 2003, “Analysis of Weld Residual Stresses and Circumferential Through-Wall Crack K-solutions for CRDM Nozzles,” Conference on Vessel Penetration Inspection, Crack Growth and Repair (NUREG/CP-0191), March 2004.

Sheng, C. F., 1987, “Boundary Element Method by Dislocation Distribution,” ASME J. of Applied Mechanics, Vol. 54 (105-109).

Sheng, C. F. and Wheeler, L., 1981, "Crack Path Prediction for a Kinked Crack in the Neighborhood of a Circular Inclusion in an Infinite Medium," ASME J. of Applied Mechanics, Vol. 48 (313-319).

Theocaris, P. S. and Ioakimidis, N. I., 1977, "Numerical Integration Methods for the Solution of Singular Integral Equations," Q. of Applied Mathematics, Vol. 35 (173-183).

Tweed, J. and Rooke, D. P., 1976, "The Elastic Problem for an Infinite Solid Containing a Circular Hole with a Pair of Radial Edge Cracks of Different Lengths," International J. of Engineering Science, Vol. 14 (925-933).

Tweed, J. and Rooke, D. P., 1973, "The Distribution of Stress Near the Tip of a Radial Crack at the Edge of a Circular Hole," International J. of Engineering Science, Vol. 11 (1185-1195).

WCAP-16180-NP, 2003, “Operability Assessment for Combustion Engineering Plants with Hypothetical Circumferential Flaw Indications in Pressurizer Heater Sleeves.”

ENCLOSURE 2: NRC FORM 390