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Abstract

A problem of particular interest in pressure vessel technology is the calculation of accurate stress-intensity factors for semielliptical surface cracks in cylinders. Computing costs for direct solution techniques can be prohibitive when applied to three-dimensional (3-D) geometries with time-varying boundary conditions such as those associated with pressurized-thermal-shock. An alternative superposition technique requires the calculation of a set of influence coefficients for a given 3-D crack model that can be superimposed to obtain mode-I stress-intensity factors. Considerable economy can be achieved in this approach because the only direct 3-D solutions required are those used to calculate the influence coefficients. This report presents stress-intensity-factor influence coefficients (SIFICs) for axially oriented finite-length semielliptical inner-surface flaws with aspect ratios [total crack length to crack depth (a)] of 2, 6, and 10 for clad cylinders having an internal radius to wall thickness (t) ratio of 10. SIFICs are computed for flaw depths in the range of $0.01 \leq a/t \leq 0.5$ with particular emphasis on shallow flaws ($a/t \leq 0.1$), and two cladding thicknesses. This is the first step of an ongoing task in the Heavy-Section Steel Technology Program that has the objective of developing a data base of validated SIFICs for a wide range of axially and circumferentially oriented finite-length semielliptical inner-surface flaw geometries for a range of clad vessel geometries. The incorporation of this SIFIC data base into fracture mechanics codes such as FAVOR, will facilitate the generation of fracture mechanics solutions for a wide range of flaw geometries as may be required in structural integrity assessments of pressurized water and boiling water reactors.

1. Introduction

Several techniques have been employed by analysts to calculate accurate stress-intensity factors for semielliptical surface cracks in cylinders. Solution techniques that have been applied to this problem include direct three-dimensional (3-D) calculations using a finite-element method.[1,2] However, computing costs for this direct approach can be prohibitive when applied to 3-D geometries with time-varying boundary conditions such as those associated with pressurized-thermal-shock. Several investigators[3–5] have focused on an alternative superposition technique that requires calculation of a set of influence coefficients for a given 3-D crack model. In this technique, the crack surface of a specified geometry is subjected to four stress distributions in the radial direction: uniform, linear, quadratic, and cubic. Stress-intensity-factor influence coefficients (SIFICs) obtained from these solutions are then superimposed to obtain mode-I stress-intensity factors for other stress distributions, such as those due to internal pressure or thermal shock. Considerable economy can be achieved in this approach because the only direct 3-D solutions required are those used to calculate the influence coefficients.

The Heavy-Section Steel Technology Program at the Oak Ridge National Laboratory currently has the objective of developing a data base of validated SIFICs for a wide range of axially and circumferentially oriented finite-length semielliptical inner surface flaw geometries for a range of clad vessel geometries. The incorporation of this SIFIC data base into fracture mechanics codes such as FAVOR,[6] will facilitate the generation of fracture mechanics solutions for a wide range of flaw geometries as may be required in structural integrity assessments of pressurized water and boiling water reactors.

In this report, SIFICs are presented for axially oriented finite-length semielliptical inner-surface flaws with aspect ratios [total crack length (2c) to crack depth (a)] of 2, 6, and 10 for clad cylinders having an internal radius (R_i) to wall thickness (t) ratio of 10. The SIFICs are computed for flaw depths in the range of $0.01 \leq a/t \leq 0.5$ with particular emphasis on shallow flaws ($a/t \leq 0.1$) and cladding. SIFICs are computed for two cladding thicknesses [t = 3.96 mm (0.156 in.) and t = 6.35 mm (0.25 in.)]. This report first outlines the technique for computing the SIFICs. Next, results from the application of the superposition technique are compared with direct 3-D finite-element solutions. Finally, the calculated SIFICs are compared with results obtained by other investigators for $a/t \geq 0.2$ (SIFICs for shallow flaws from other sources were not available for comparison).

2. Superposition Technique

The stress-intensity factor (K_I) is calculated by a superposition technique proposed by Bueckner,[7] and illustrated in Fig. 1. Instead of calculating the cracked structure using the actual loads, the calculation is performed with a distributed pressure applied to the crack surfaces only. This pressure is opposite in sign, but equal in magnitude and distribution, to the stresses along the crack line that are calculated for the uncracked structure with the actual loads applied. For an arbitrary stress distribution, such as that shown in Fig. 1, and for the case of a 3-D semielliptical flaw, the truncated stress distribution is approximated with a third-order polynomial as indicated by Eq. (1):

$$\sigma(a') = C_0 + C_1(a'/a) + C_2(a'/a)^2 + C_3(a'/a)^3 , \tag{1}$$

where $\sigma(a')$ is the stress normal to the crack plane at radial position a', and a' and a are defined in Fig. 2. The K_I values are calculated for each of the individual terms (stress distributions) in Eq. (1) and are then added to obtain the total K_I value as indicated by Eq. (2):

$$K_I(a) = \sum_{j=0}^{3} K_{Ij}(a) = \sum_{j=0}^{3} C_j \sqrt{\pi a} K_j^*(a) , \tag{2}$$

where

$$K_j^*(a) = K_{Ij}'(a)/(C_j' \sqrt{\pi a}) . \tag{3}$$

Values of $K_{Ij}'(a)/C_j'$ are calculated for each of the normalized stress distributions corresponding to each term in Eq. (1) (see Fig. 3), using the 3-D finite-element analysis and an arbitrary value of C_j', such as unity. The quantity $K_j^*(a)$ is referred to as the influence coefficient and, as indicated by Eq. (3), is dimensionless. Once the influence

coefficients are obtained, they can be used with any values of C_j to obtain corresponding values of $K_I(a)$.

For 3-D flaws, $K_j^*(a)$ values can be calculated for several points along the crack front, in which case Eq. (2) becomes

$$K_I(\phi) = \sum_{j=0}^{3} C_j \sqrt{\pi a} K_j^*(\phi) \ , \tag{4}$$

where ϕ is the elliptical angle denoting the point on the crack front, and the crack-depth notation (a) has been dropped.

The presence of a thin layer of stainless steel cladding on the inner surface of reactor pressure vessels has a significant effect on the K_I values for inner-surface flaws because of very high thermal stresses generated in the cladding during a thermal transient. When using coefficients for 3-D flaws, it is necessary to represent the stress distribution in the uncracked cylinder with a third-order polynomial, and thus the discontinuity in the thermal stress at the clad-base material interface presents a problem. To accommodate the stress discontinuity associated with the cladding, influence coefficients were calculated for the cladding stresses alone; the corresponding K_I value can then be superimposed on the K_I value due to the stresses in the base material. As indicated in Fig. 4, this is accomplished by first calculating a K_I value for a continuous-function stress distribution obtained by a linear extrapolation of the stress distribution in the base material into the cladding. Then a K_I value is calculated for a stress distribution in the cladding which is obtained by subtracting the extrapolated distribution from the actual distribution in the cladding, which is also assumed to be linear. The total K_I value is simply the sum of the two. Because the stress distribution in the cladding is essentially linear, only a first-order polynomial is used for the cladding coefficients.

3. Calculation of SIFICs (K_j^*)

For the present study, K_j^* values were computed using the ABAQUS[8] finite-element code. ABAQUS is a nuclear quality assurance certified (NQA-1) code which employs a virtual crack extension method for the computation of the J-integral. A 3-D finite-element model was generated for each crack depth and aspect ratio. The analysis matrix included a crack depth range from 2.16 mm to 108.0 mm (0.085 in. to 4.25 in.) (crack depth/vessel thickness ratio of 0.01 to 0.5), and three different aspect ratios (2c/a) of 2, 6, and 10. A total of 39 finite-element models and over 200 analyses were required to generate the K_j^* values.

The 3-D finite-element model of a vessel with an axial, inner-surface, semielliptical flaw was generated with the ORMGEN[9] mesh generating program. A typical finite-element mesh from this study is shown in Fig. 5 (6:1 axial flaw with a/t of 0.2). This model has 10792 nodes and 2255 twenty-noded isoparametric elements. The mesh refinement was increased (more nodes and elements) near the crack tip for models with shallower flaws. From symmetry conditions, only one-fourth of the vessel is included in the finite-element model. The vessel in Fig. 5 has a thickness (t) of 216 mm (8.5 in.) (including the cladding), internal radius (R_i) of 2184 mm (86.0 in.), and length (ℓ) of 4699 mm (185.0 in.).

In the process of calculating the SIFICs, careful attention was paid to using adequately converged finite-element meshes and an appropriate cylinder length. The number of elements in the circumferential and axial directions, and around the crack front was increased, one at a time, to the point where addition of one element changed the value of K_I by less than one percent. The resultant converged meshes for a 180°, half-length segment of the cylinder had ~11500 degrees of freedom. With regard to cylinder length, a minimum incremental length of the cylinder that could be added to the length of the flaw to negate end effects was estimated from Eq. (5) (Ref. 10):

$$\ell = 2\pi / \beta , \tag{5}$$

where

$$\beta^4 = 3(1-\nu^2) / (R_i^2 t^2) , \tag{6}$$

and ν is Poisson's ratio. For the cylinder radial dimensions given in Fig. 5, $\ell \approx 3353$ mm (132 in.). From previous studies,[5] the appropriate length for a cylinder with a 6:1, inner-surface, semielliptical flaw (a/t = 0.2) was 1.4 times the estimated value, so a cylinder length of 4699 mm (185 in.) was used in these analyses. A second analysis was performed on a cylinder in which the length of the cylinder was doubled. The K_I values around the crack front changed less than one percent.

The adequacy of using SIFICs was investigated by calculating K_I values by both the superposition and direct ABAQUS finite-element techniques. The first comparison was for the 6:1 semielliptical flaw with a/t = 0.075 and the thermal loading through the vessel wall as indicated in Fig. 6. Representative material properties were used for these analyses and are given in Table 1. The results of this comparison analysis indicate a maximum

Table 1. Material properties for cylinder analyses

Material Property	Base	Clad
Thermal Conductivity (k)	41.54 W/m•K (24 Btu/hr•ft•°F)	17.31 W/m•K (10 Btu/hr•ft•°F)
Specific Heat (c_p)	502.4 J/kg•K (0.12 Btu/lb•°F)	502.4 J/kg•K (0.12 Btu/lb•°F)
Density (ρ)	7833 kg/m^3 (489 lb/ft^3)	7833 kg/m^3 (489 lb/ft^3)
Young's Modulus (E)	193.05 GPa (28000 ksi)	186.16 GPa (27000 ksi)
Coefficient of Thermal Expansion (α)	1.449E-05 /°C (0.805E-05 /°F)	1.638E-05 /°C (0.910E-05 /°F)
Poisson's Ratio (ν)	0.30	0.30

Heat transfer coefficient : 1816 W/m^2•K (320 Btu/hr•ft^2•°F)

difference of ≈ 2 % along the crack front (Fig. 7). The second comparison was for a 10:1 semielliptical flaw with a/t = 0.5 and the same loading. The results, given in Fig. 7, show good agreement.

Two analyses were performed on a clad cylinder with $R_i/t = 10$, t = 108 mm (4.25 in.), and a = 10.8 mm (0.425 in.) with uniform and quadratic loading so a comparison of SIFICs could be made for vessels with the same R_i/t and a/t ratios. The SIFICs around the crack front had less than 0.02 % difference between the analyses of the two cylinders (thicknesses of 216 mm and 108 mm).

Tables 1–8 in Appendix A give the results of this study in terms of non-dimensionalized K_j^* values for axial flaws. Each set of angular values represents a separate finite-element analysis where the plane strain relation $K = \sqrt{(JE/(1-\nu^2))}$ was used to calculate K from J. The K value was then normalized by dividing the value by $\sqrt{\pi a}$, and using a stress load of unity. While English units were utilized to compute the K_j^* values, the nondimensionalized K_j^* values in the tables are appropriate for any consistent set of units (English, SI, etc.).

4. Comparison With Other Investigators

A comparison of some of the 3-D influence coefficients generated in this study with similar coefficients obtained by other investigators[3,4] is shown in Figs. 8–10. To compare the coefficients with those obtained from Raju and Newman,[3] the influence coefficients in Figs. 8 and 9 represent K_j^* values multiplied by $\sqrt{Q}$, where the shape factor (Q) is the square of the complete elliptic integral of the second kind. The shape factor for an elliptical crack is approximated by the following equation:

$$Q = 1 + 1.464\,(a/c)^{1.65} \quad . \tag{7}$$

As indicated in Figs. 8 and 9, the coefficients being compared pertain to axially oriented, inner-surface flaws in a long cylinder with a/t = 0.2 and 0.5; and aspect ratios of 2:1 and 10:1. The coefficients in Fig. 10 (Ref. 4) are K_j^* values for an aspect ratio of 6:1 and a/t = 0.5. The results of all the comparisons indicate good agreement.

The other investigators[3,4] did not publish SIFICs for the shallower flaw depths so a comparison could not be made for a/t ratios less than 0.2.

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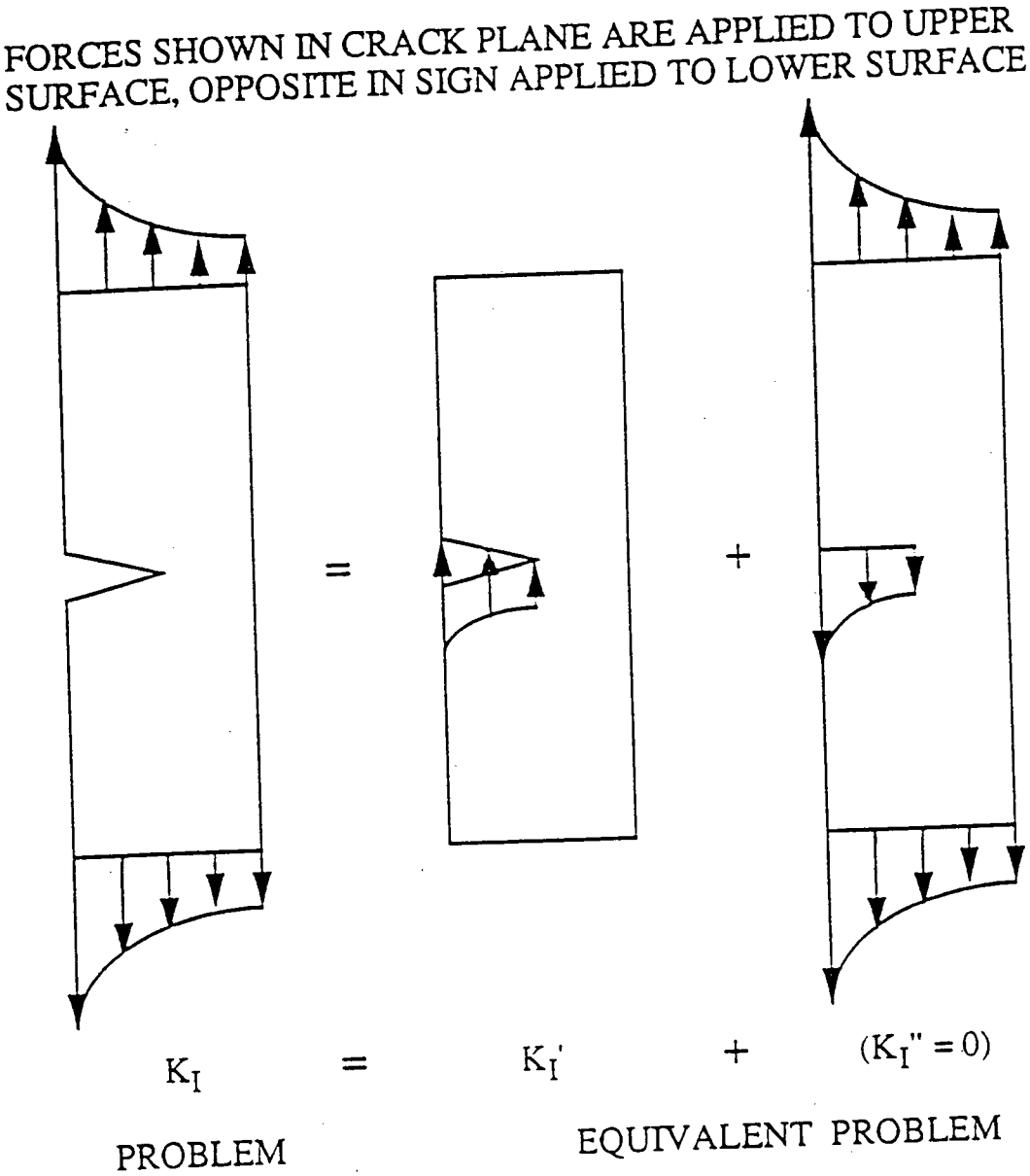


Figure 1 Graphical representation of method for calculating K_I using equivalent problem

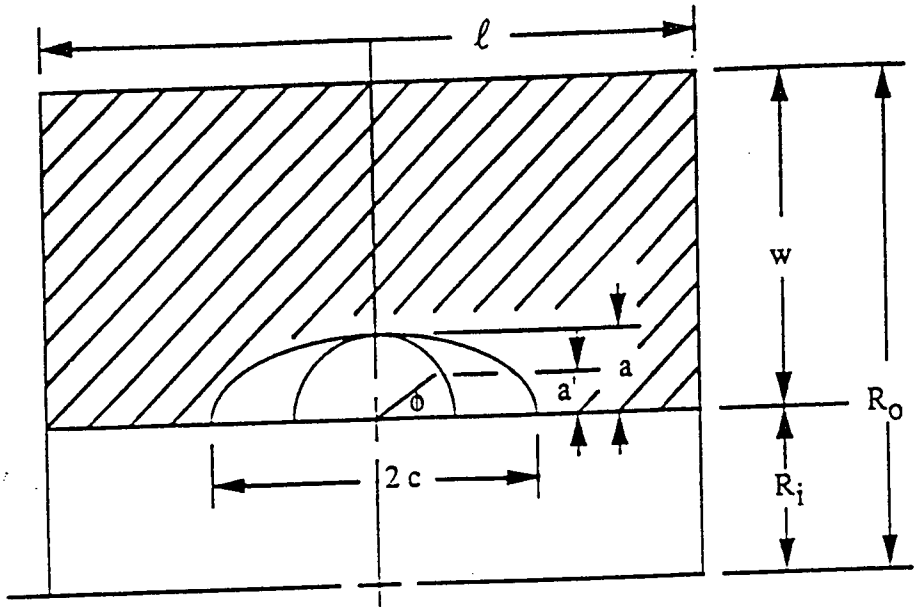


Figure 2 Axially oriented semielliptical flaw on inner surface of cylinder

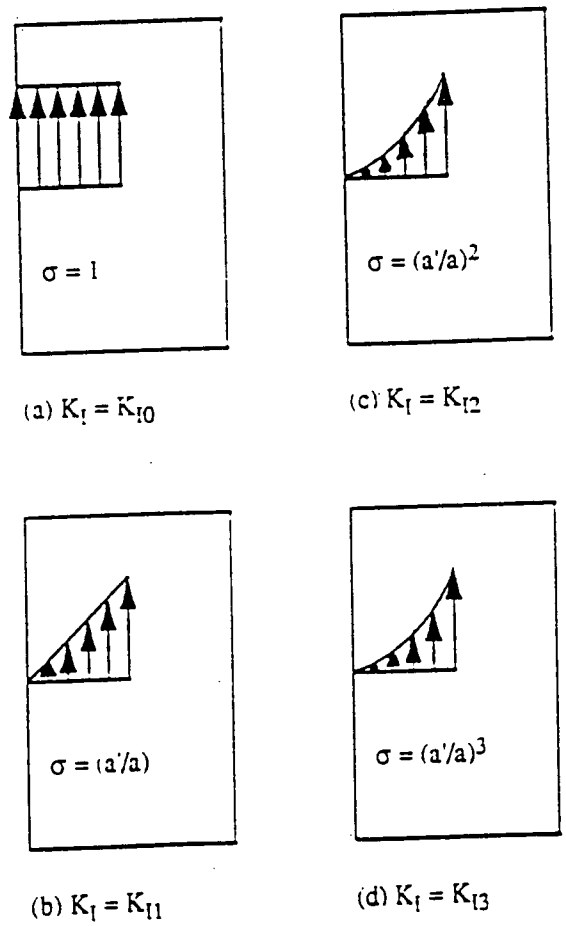


Figure 3 Crack-surface loading cases for determining 3-D flaw influence coefficients

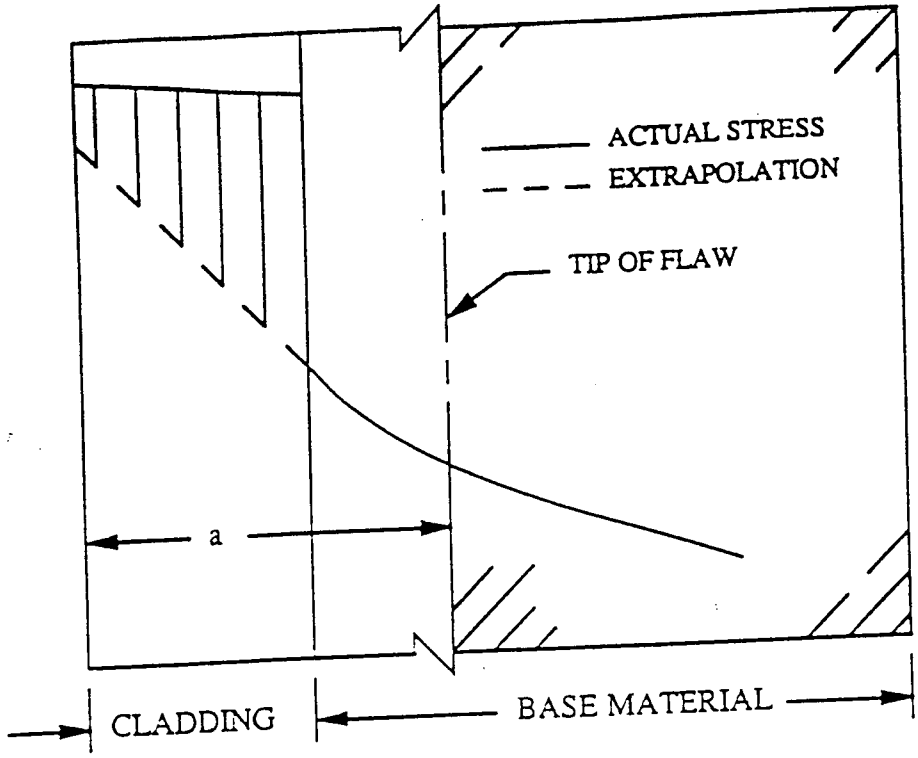


Figure 4 Stress distributions used in superposition techniques for including effect of cladding on K_I

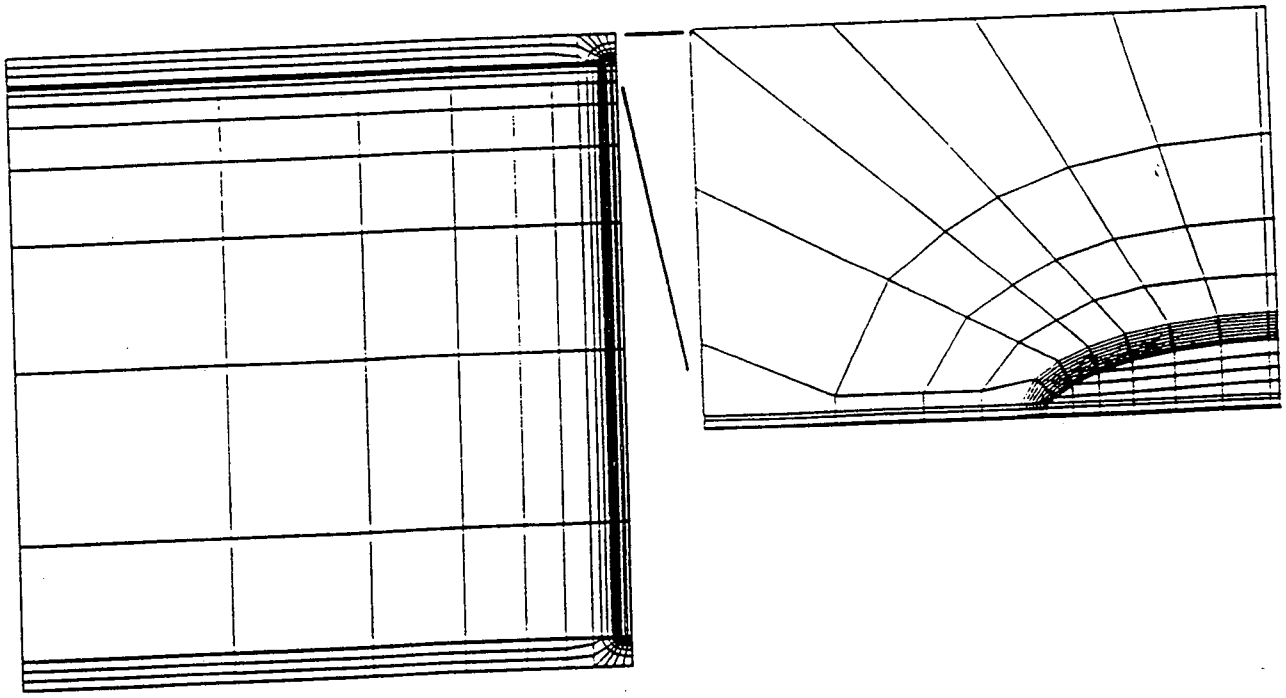


Figure 5 Finite-element model of the clad cylinder

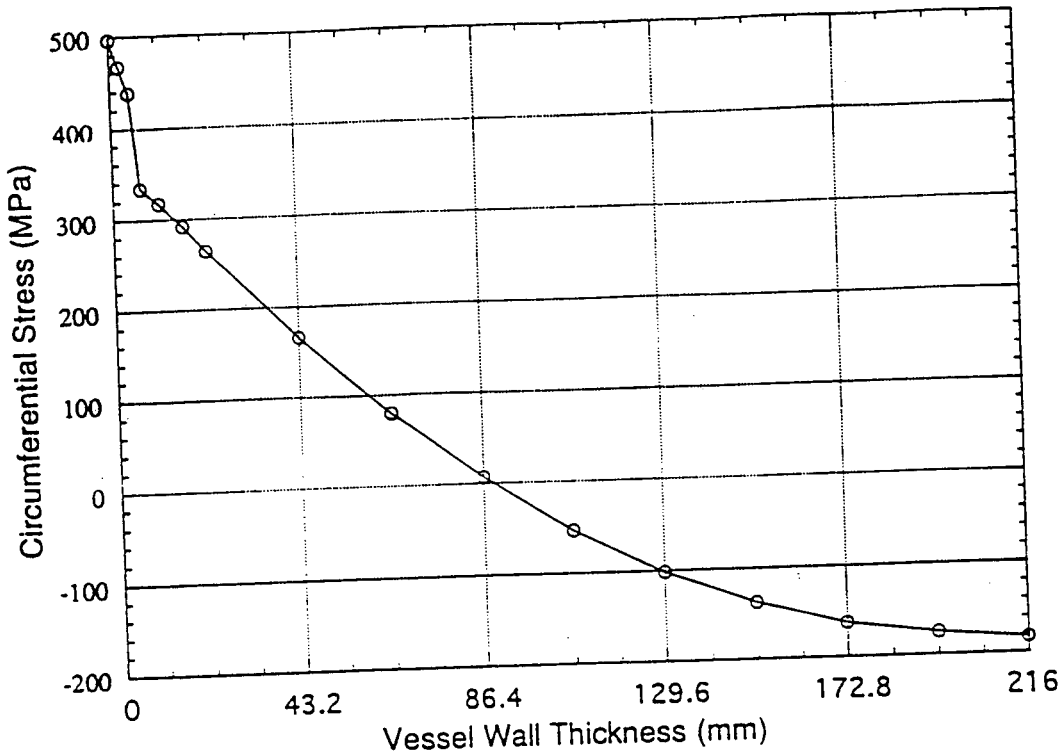


Figure 6 Thermal stress profile in clad cylinder used to calculate K_I

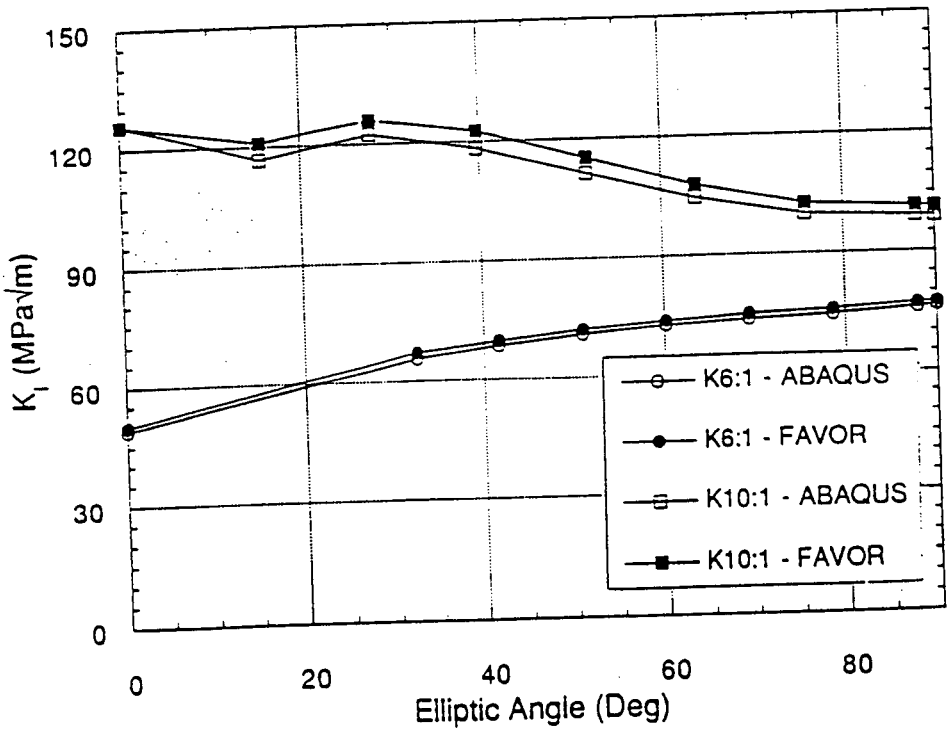
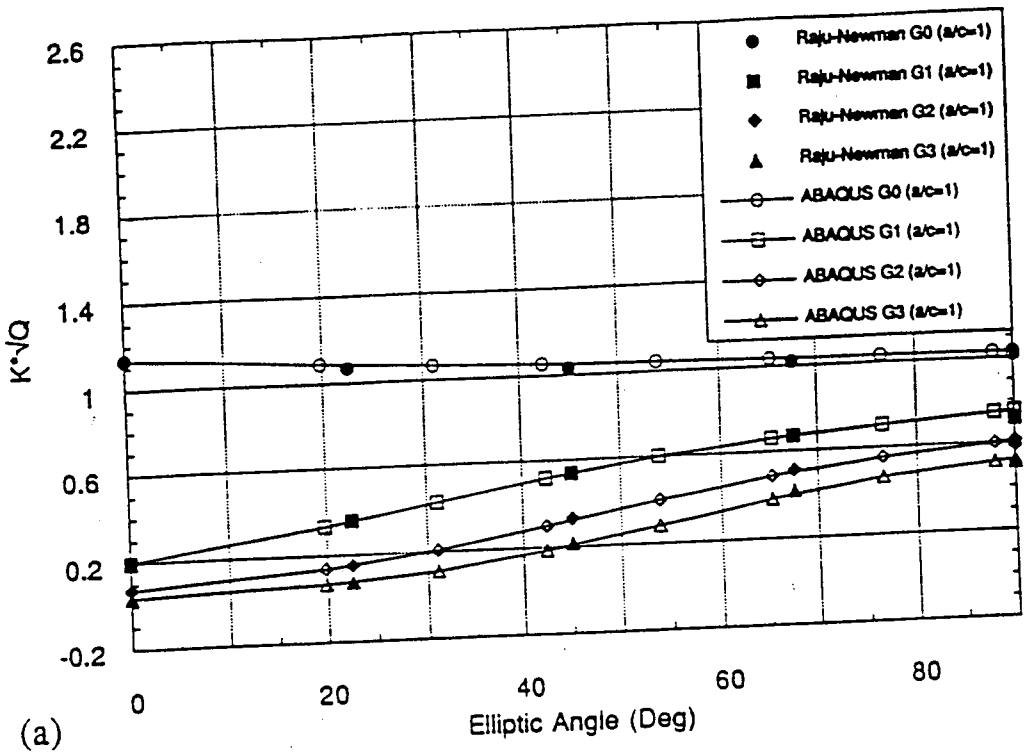
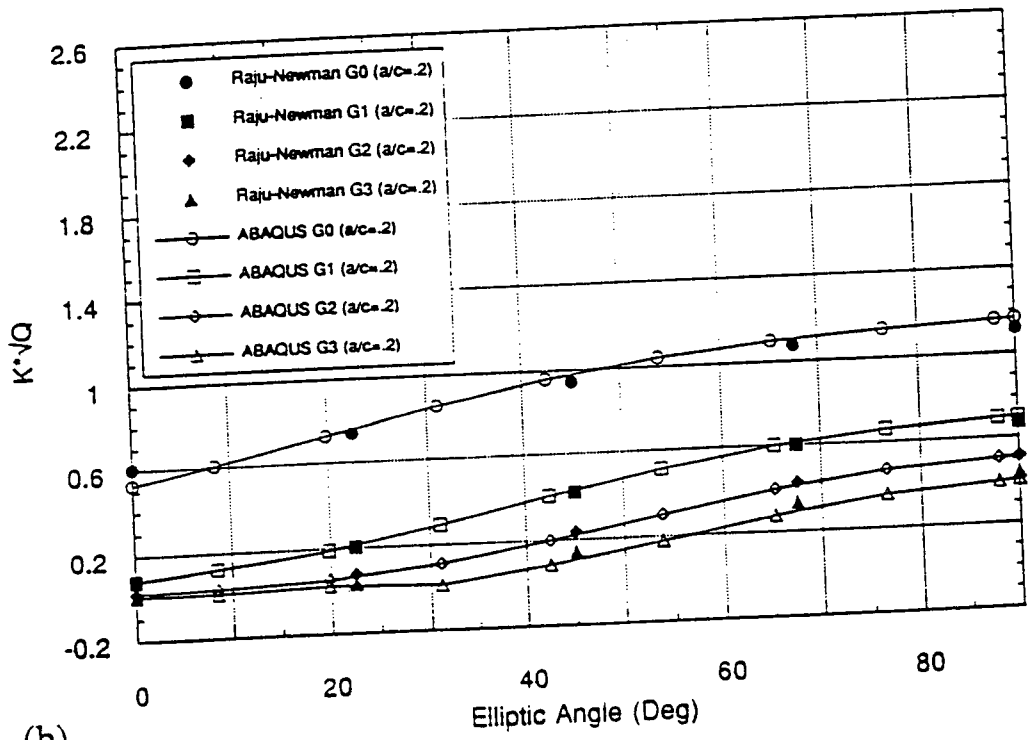


Figure 7 Comparison of KI values calculated by superposition and direct ABAQUS finite-element techniques for axially oriented 6:1 and 10:1 flaws (a/t = 0.075 and 0.5, respectively) in clad cylinder during severe thermal transient

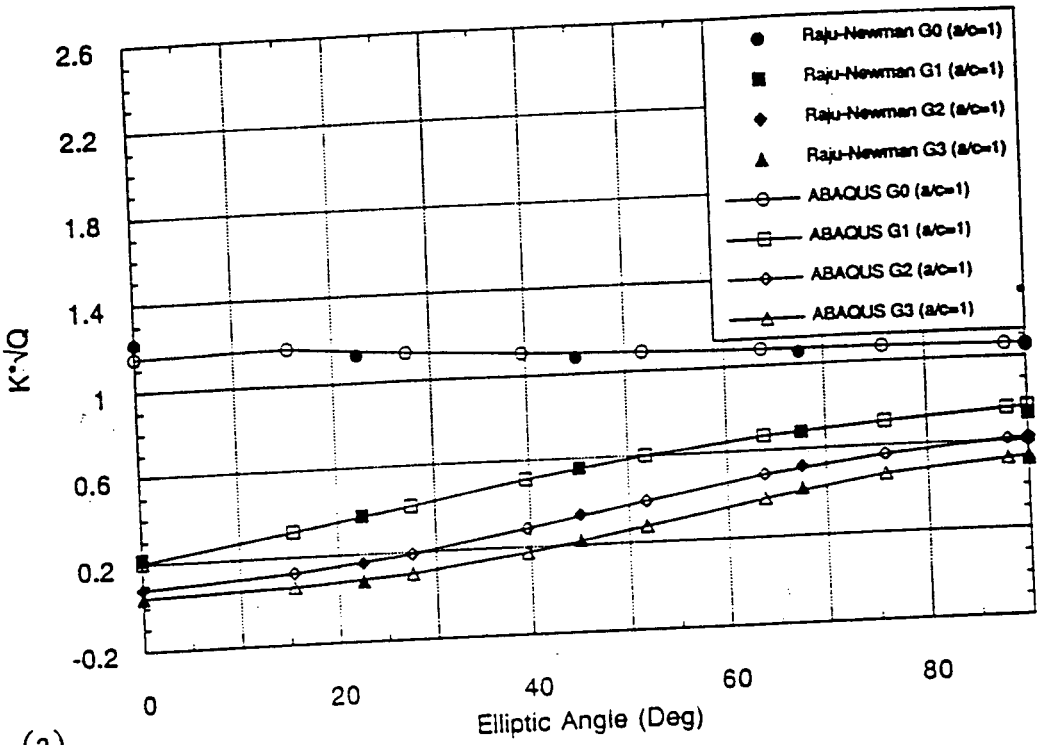


(a)

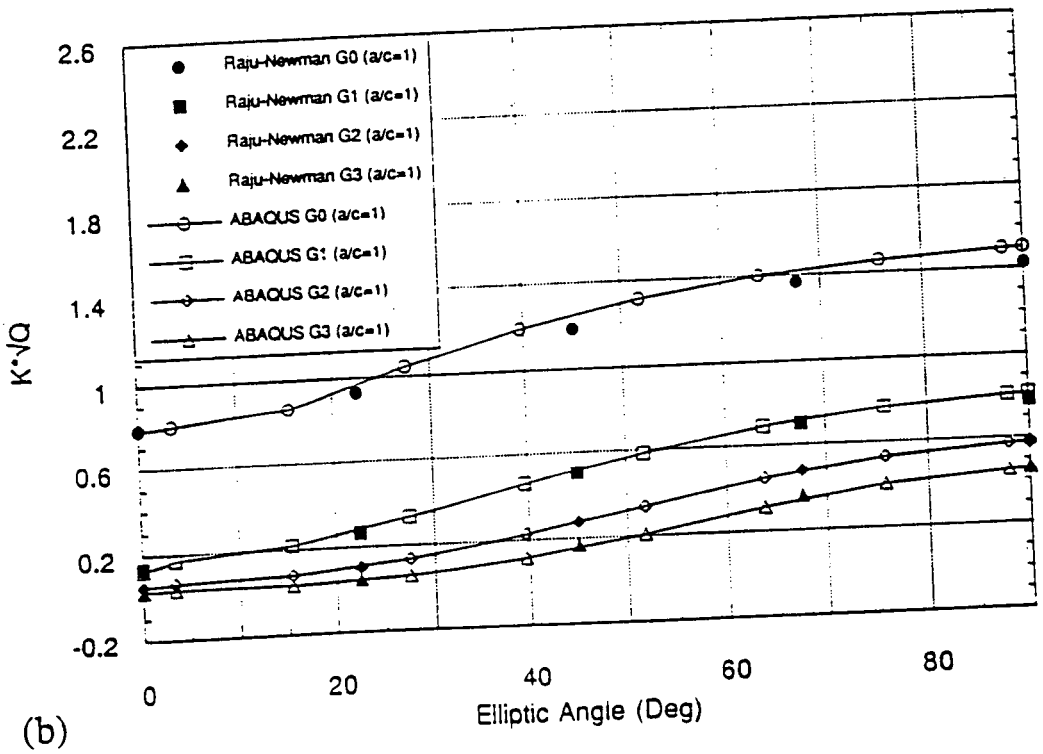


(b)

Figure 8 Influence coefficients for axially oriented semielliptical flaws (a/t = 0.2) on inner surface of cylinder: (a) 2:1 aspect ratio; (b) 10:1 aspect ratio



(a)



(b)

Figure 9 Influence coefficients for axially oriented semielliptical flaws (a/t = 0.5) on inner surface of cylinder: (a) 2:1 aspect ratio: (b) 10:1 aspect ratio

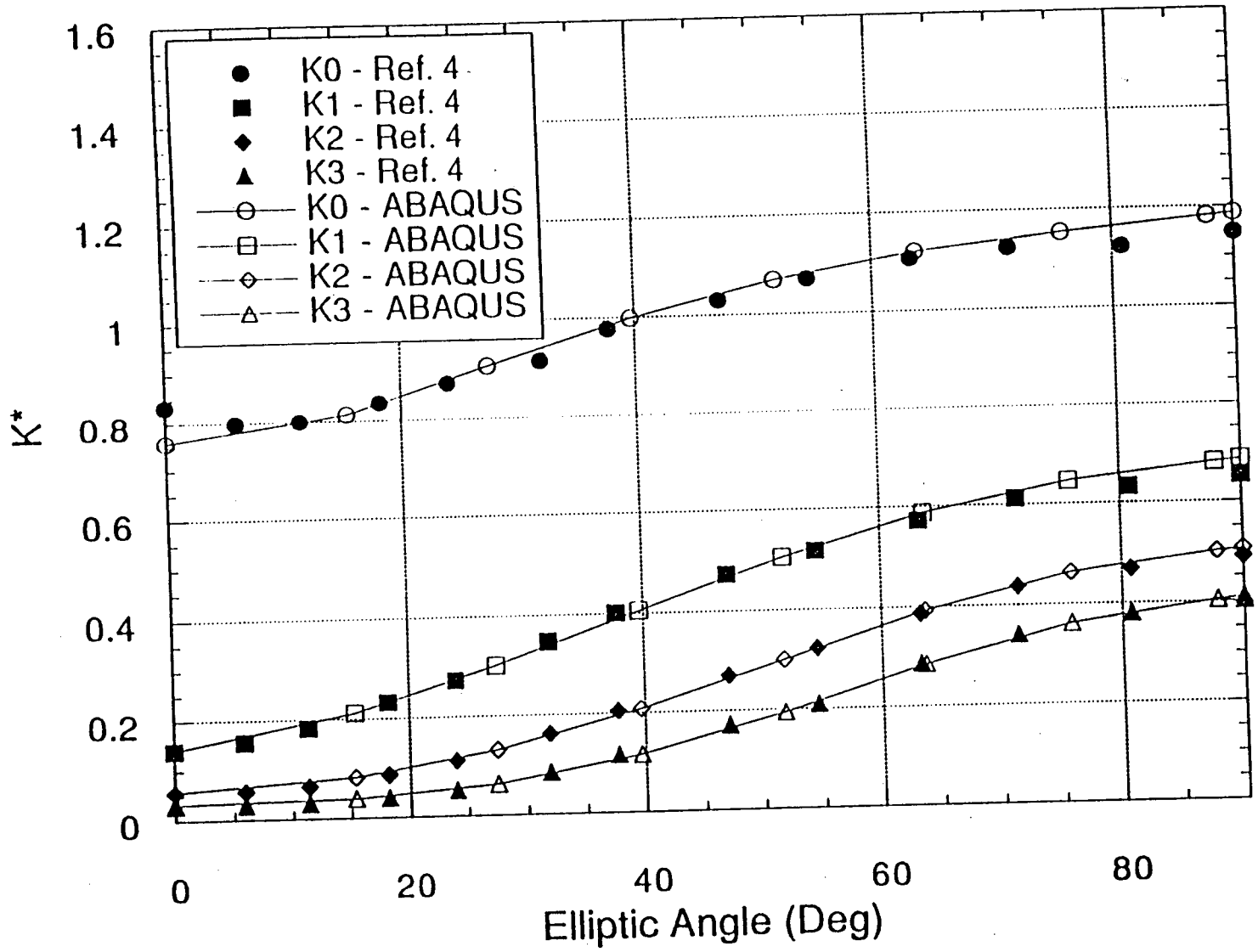


Figure 10 Influence coefficients for an axially oriented semielliptical flaw with a/t = 0.5 and 6:1 aspect ratio

Appendix A

Stress-Intensity-Factor Influence Coefficients For Axially Oriented Finite-Length Inner-Surface Flaws

Stress-intensity-factor influence coefficients are included in Tables A.1 – A.8 for axially oriented, inner-surface flaws in a cylinder with surface length-to-depth ratios of 2:1, 6:1, and 10:1, and with t = 216 mm (8.5 in.) (including the cladding), R_i = 2184 mm (86.0 in.), and ℓ = 4699 mm (185.0 in.). Also, there are coefficients for two cladding thicknesses, 6.35 mm (0.25 in.) and 3.96 mm (0.156 in.). Figures A.1 – A.3 are graphs of the influence coefficients at the deepest point on the crack front vs. a/t for the clad cylinder for each aspect ratio.

Table A.1 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.01$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.76431	0.15336	0.061480	0.034155	0.76431	0.15336	0.76431	0.15336
	2.3700	0.75397	0.16453	0.062254	0.031969	0.75397	0.16453	0.75397	0.16453
	16.600	0.69027	0.19214	0.079032	0.040464	0.69027	0.19214	0.69027	0.19214
	30.800	0.66906	0.26392	0.12664	0.068891	0.66906	0.26392	0.66906	0.26392
	45.000	0.65995	0.33527	0.19622	0.12443	0.65995	0.33527	0.65995	0.33527
	59.200	0.65298	0.39301	0.26935	0.19797	0.65298	0.39301	0.65298	0.39301
	73.400	0.65116	0.43425	0.32946	0.26755	0.65116	0.43425	0.65116	0.43425
	87.600	0.64934	0.46343	0.36613	0.30966	0.64934	0.46343	0.64934	0.46343
	90.000	0.64903	0.46837	0.37232	0.31678	0.64903	0.46837	0.64903	0.46837
6:1	0.0000	0.66980	0.13372	0.047876	0.023841	0.66980	0.13372	0.66980	0.13372
	2.3700	0.66747	0.13358	0.043464	0.019177	0.66747	0.13358	0.66747	0.13358
	16.600	0.65352	0.17022	0.054629	0.0084953	0.65352	0.17022	0.65352	0.17022
	30.800	0.74120	0.26918	0.10858	0.028931	0.74120	0.26918	0.74120	0.26918
	45.000	0.82712	0.38061	0.19901	0.099912	0.82712	0.38061	0.82712	0.38061
	59.200	0.89305	0.48081	0.30173	0.19671	0.89305	0.48081	0.89305	0.48081
	73.400	0.93816	0.55865	0.38889	0.28996	0.93816	0.55865	0.93816	0.55865
	87.600	0.97003	0.59448	0.43479	0.34103	0.97003	0.59448	0.97003	0.59448
	90.000	0.97541	0.60112	0.44253	0.34964	0.97541	0.60112	0.97541	0.60112
10:1	0.0000	0.51516	0.089849	0.019506	0.0056700	0.51516	0.089849	0.51516	0.089849
	2.3700	0.52863	0.093816	0.010198	0.0045670	0.52863	0.093816	0.52863	0.093816
	16.600	0.60953	0.14618	0.032898	0.0046444	0.60953	0.14618	0.60953	0.14618
	30.800	0.76189	0.25848	0.059893	0.019119	0.76189	0.25848	0.76189	0.25848
	45.000	0.88851	0.38852	0.17053	0.066027	0.88851	0.38852	0.88851	0.38852
	59.200	0.97886	0.50680	0.28973	0.13600	0.97886	0.50680	0.97886	0.50680
	73.400	1.0332	0.59260	0.38870	0.24902	1.0332	0.59260	1.0332	0.59260
	87.600	1.0635	0.63461	0.43864	0.30668	1.0635	0.63461	1.0635	0.63461
	90.000	1.0687	0.64172	0.44708	0.31642	1.0687	0.64172	1.0687	0.64172

Table A.2 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.0184$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.77707	0.15544	0.061263	0.033720	0.77707	0.15544	0.77707	0.15544
	2.3700	0.76679	0.16653	0.062084	0.031604	0.76679	0.16653	0.76679	0.16653
	16.600	0.69995	0.19378	0.078909	0.040274	0.69995	0.19378	0.69995	0.19378
	30.800	0.67682	0.26592	0.12666	0.068881	0.67682	0.26592	0.67682	0.26592
	45.000	0.66663	0.33791	0.19645	0.12457	0.66663	0.33791	0.66663	0.33791
	59.200	0.65954	0.39659	0.26982	0.19818	0.65954	0.39659	0.65954	0.39659
	73.400	0.65668	0.43757	0.32956	0.26729	0.65668	0.43757	0.65668	0.43757
	87.600	0.65383	0.46741	0.36648	0.30956	0.65383	0.46741	0.65383	0.46741
	90.000	0.65336	0.47246	0.37271	0.31670	0.65336	0.47246	0.65336	0.47246
6:1	0.0000	0.65341	0.12750	0.043132	0.020688	0.65341	0.12750	0.65341	0.12750
	2.3700	0.65354	0.12792	0.037667	0.015719	0.65354	0.12792	0.65354	0.12792
	16.600	0.65431	0.16841	0.045253	0.020792	0.65431	0.16841	0.65431	0.16841
	30.800	0.75785	0.27140	0.099264	0.026032	0.75785	0.27140	0.75785	0.27140
	45.000	0.85154	0.38748	0.19193	0.085288	0.85154	0.38748	0.85154	0.38748
	59.200	0.91965	0.49213	0.29767	0.18685	0.91965	0.49213	0.91965	0.49213
	73.400	0.96347	0.56881	0.38691	0.28260	0.96347	0.56881	0.96347	0.56881
	87.600	0.99402	0.60920	0.43406	0.33530	0.99402	0.60920	0.99402	0.60920
	90.000	0.99918	0.61603	0.44203	0.34420	0.99918	0.61603	0.99918	0.61603
10:1	0.0000	0.52450	0.092006	0.019423	0.0065237	0.52450	0.092006	0.52450	0.092006
	2.3700	0.53832	0.095891	0.0093893	0.0052567	0.53832	0.095891	0.53832	0.095891
	16.600	0.62134	0.14887	0.039019	0.0053367	0.62134	0.14887	0.62134	0.14887
	30.800	0.77749	0.26226	0.049520	0.021725	0.77749	0.26226	0.77749	0.26226
	45.000	0.89886	0.39196	0.16374	0.075012	0.89886	0.39196	0.89886	0.39196
	59.200	0.98200	0.50947	0.28345	0.12711	0.98200	0.50947	0.98200	0.50947
	73.400	1.0334	0.59525	0.38271	0.24238	1.0334	0.59525	1.0334	0.59525
	87.600	1.0628	0.63726	0.43272	0.30047	1.0628	0.63726	1.0628	0.63726
	90.000	1.0678	0.64436	0.44117	0.31029	1.0678	0.64436	1.0678	0.64436

Table A.3 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.05$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.70062	0.13347	0.045253	0.022293	0.59616	0.17142	0.59793	0.21200
	31.000	0.68055	0.27556	0.13062	0.069875	0.61472	0.27804	0.23825	0.11945
	40.500	0.67005	0.32316	0.17823	0.10786	0.38592	0.20846	0.17521	0.089528
	50.000	0.66338	0.36729	0.23101	0.15763	0.26832	0.14666	0.14604	0.075448
	59.400	0.65851	0.40428	0.28177	0.21211	0.22639	0.12386	0.12943	0.067097
	68.900	0.65437	0.43225	0.32453	0.26267	0.20558	0.11195	0.11919	0.061809
	78.400	0.65289	0.45148	0.35543	0.30142	0.19434	0.10540	0.11380	0.058996
	87.900	0.65141	0.47177	0.37869	0.32725	0.18618	0.10061	0.10841	0.056184
	90.000	0.65108	0.47625	0.38383	0.33296	0.18437	0.099550	0.10723	0.055560
6:1	0.0000	0.51258	0.10011	0.026975	0.0099697	0.47858	0.18607	0.44376	0.17695
	31.000	0.76402	0.27526	0.099844	0.021627	0.69976	0.34616	0.33637	0.16560
	40.500	0.82338	0.35203	0.16178	0.071692	0.52833	0.27000	0.29221	0.14705
	50.000	0.87489	0.42886	0.23547	0.13652	0.44537	0.23154	0.27135	0.13686
	59.400	0.91492	0.49680	0.30971	0.20953	0.41704	0.21480	0.25881	0.13042
	68.900	0.94402	0.55095	0.37474	0.27936	0.40010	0.20452	0.25088	0.12627
	78.400	0.96435	0.58869	0.42254	0.33371	0.39066	0.19881	0.24685	0.12414
	87.900	0.98424	0.61114	0.44855	0.36272	0.38376	0.19458	0.24283	0.12200
	90.000	0.98864	0.61611	0.45431	0.36912	0.38222	0.19365	0.24194	0.12152
10:1	0.0000	0.42399	0.075154	0.011952	0.0084639	0.37300	0.16270	0.32277	0.14675
	31.000	0.78118	0.26111	0.044396	0.016244	0.71328	0.34511	0.37156	0.18177
	40.500	0.86800	0.35007	0.12614	0.056097	0.57811	0.30047	0.33344	0.16710
	50.000	0.93214	0.43683	0.21083	0.081688	0.50127	0.25827	0.30862	0.15497
	59.400	0.98117	0.51366	0.29425	0.17161	0.47103	0.24041	0.29297	0.14704
	68.900	1.0168	0.57496	0.36676	0.25086	0.45049	0.22852	0.28316	0.14201
	78.400	1.0399	0.61682	0.41918	0.31067	0.43966	0.22213	0.27760	0.13913
	87.900	1.0572	0.63894	0.44571	0.34082	0.43147	0.21727	0.27204	0.13625
	90.000	1.0610	0.64383	0.45158	0.34749	0.42966	0.21620	0.27081	0.13561

Table A.4 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.075$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.69719	0.13409	0.045344	0.022258	0.60388	0.20970	0.51139	0.20373
	32.300	0.68269	0.28441	0.13713	0.074704	0.25035	0.12659	0.13814	0.063186
	41.600	0.67307	0.33090	0.18471	0.11362	0.18668	0.096107	0.10843	0.053597
	50.900	0.66644	0.37333	0.23639	0.16322	0.15671	0.081410	0.092341	0.046722
	60.100	0.66151	0.40877	0.28562	0.21666	0.13948	0.072612	0.082582	0.042051
	69.400	0.65735	0.43554	0.32683	0.26571	0.12882	0.067044	0.076470	0.039012
	78.600	0.65584	0.45388	0.35647	0.30302	0.12322	0.064083	0.073262	0.037387
	87.900	0.65431	0.47356	0.37901	0.32802	0.11756	0.061094	0.070019	0.035741
	90.000	0.65397	0.47801	0.38410	0.33367	0.11628	0.060416	0.069291	0.035373
6:1	0.0000	0.49878	0.099174	0.025742	0.0087691	0.43638	0.17121	0.35723	0.16235
	32.300	0.77153	0.28459	0.10150	0.018132	0.35566	0.17668	0.20760	0.098821
	41.600	0.82896	0.36004	0.16418	0.072888	0.31051	0.15693	0.18793	0.093330
	50.900	0.87807	0.43429	0.23684	0.13826	0.28911	0.14611	0.17726	0.088723
	60.100	0.91582	0.49935	0.30893	0.21003	0.27622	0.13932	0.17025	0.085296
	69.400	0.94336	0.55116	0.37171	0.27791	0.26803	0.13496	0.16566	0.082971
	78.600	0.96251	0.58711	0.41750	0.33017	0.26381	0.13270	0.16325	0.081720
	87.900	0.98195	0.60884	0.44268	0.35821	0.26618	0.13373	0.16471	0.082250
	90.000	0.98637	0.61375	0.44836	0.36454	0.26671	0.13397	0.16503	0.082371
10:1	0.0000	0.36765	0.076520	0.011334	0.0095111	0.31237	0.14077	0.23136	0.12668
	32.300	0.79646	0.27608	0.048806	0.025438	0.39396	0.19451	0.23383	0.11190
	41.600	0.87750	0.36271	0.13103	0.052714	0.35332	0.17768	0.21589	0.10719
	50.900	0.93907	0.44686	0.21495	0.088956	0.32821	0.16506	0.20259	0.10118
	60.100	0.98467	0.51999	0.29571	0.17591	0.31222	0.15678	0.19350	0.096729
	69.400	1.0179	0.57822	0.36539	0.25243	0.30216	0.15154	0.18764	0.093789
	78.600	1.0394	0.61782	0.41541	0.30970	0.29642	0.14854	0.18425	0.092051
	87.900	1.0563	0.63908	0.44092	0.33864	0.29063	0.14550	0.18082	0.090292
	90.000	1.0602	0.64388	0.44667	0.34517	0.28932	0.14481	0.18005	0.089896

Table A.5 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.1$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.71454	0.13260	0.045664	0.022954	0.57641	0.21694	0.48608	0.21063
	27.200	0.68699	0.25595	0.11583	0.059677	0.20604	0.10164	0.11553	0.051814
	37.300	0.67620	0.30814	0.16397	0.095238	0.14595	0.073495	0.086591	0.042347
	47.400	0.66902	0.35740	0.21980	0.14526	0.11913	0.060797	0.071714	0.036056
	57.500	0.66349	0.39903	0.27514	0.20282	0.10413	0.053399	0.062859	0.031846
	67.700	0.65899	0.43084	0.32278	0.25810	0.095024	0.048785	0.057419	0.029153
	77.800	0.65714	0.45249	0.35737	0.30110	0.090256	0.046337	0.054580	0.027727
	87.900	0.65528	0.47448	0.38274	0.32940	0.085495	0.043883	0.051740	0.026302
	90.000	0.65490	0.47906	0.38801	0.33529	0.084504	0.043375	0.051153	0.026002
6:1	0.0000	0.55291	0.094589	0.026779	0.011033	0.45691	0.17862	0.37979	0.17032
	27.200	0.74113	0.24184	0.083647	0.010929	0.27814	0.13714	0.16439	0.078556
	37.300	0.81101	0.32365	0.14390	0.053136	0.23966	0.12025	0.14657	0.072816
	47.400	0.86896	0.40703	0.21967	0.11769	0.22093	0.11106	0.13649	0.068294
	57.500	0.91486	0.48260	0.29945	0.19420	0.20992	0.10546	0.13011	0.065160
	67.700	0.94836	0.54370	0.37132	0.27024	0.20295	0.10187	0.12598	0.063080
	77.800	0.97071	0.58594	0.42444	0.33029	0.19924	0.099937	0.12379	0.061948
	87.900	0.99136	0.61027	0.45279	0.36205	0.19554	0.098004	0.12159	0.060822
	90.000	0.99566	0.61532	0.45869	0.36864	0.19477	0.097600	0.12113	0.060583
10:1	0.0000	0.41707	0.070680	0.013151	0.0063520	0.35153	0.15558	0.28601	0.14381
	27.200	0.75170	0.22760	0.041417	0.017196	0.31018	0.15077	0.18649	0.089271
	37.300	0.84850	0.32058	0.11596	0.056948	0.27426	0.13687	0.16903	0.083868
	47.400	0.92239	0.41488	0.20166	0.067412	0.25225	0.12628	0.15664	0.078207
	57.500	0.97887	0.49998	0.29023	0.16185	0.23868	0.11948	0.14857	0.074254
	67.700	1.0196	0.56867	0.36950	0.24727	0.23005	0.11510	0.14334	0.071641
	77.800	1.0459	0.61582	0.42773	0.31323	0.22517	0.11260	0.14037	0.070129
	87.900	1.0645	0.64012	0.45675	0.34621	0.22028	0.11011	0.13739	0.068624
	90.000	1.0683	0.64517	0.46279	0.35307	0.21927	0.10959	0.13678	0.068312

Table A.6 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.2$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.72319	0.12740	0.046452	0.024500	0.47053	0.20441	0.39134	0.19468
	19.800	0.69460	0.21367	0.088533	0.044409	0.12966	0.062882	0.071411	0.031389
	31.100	0.67940	0.27283	0.13335	0.072765	0.080268	0.039442	0.047754	0.022886
	42.500	0.67129	0.33201	0.19246	0.12029	0.061415	0.030619	0.037646	0.018698
	53.800	0.66536	0.38322	0.25548	0.18159	0.051986	0.026123	0.032047	0.016093
	65.200	0.66040	0.42281	0.31216	0.24492	0.046547	0.023453	0.028711	0.014457
	76.500	0.65828	0.44980	0.35429	0.29633	0.043730	0.022034	0.026988	0.013596
	87.900	0.65613	0.47487	0.38365	0.32924	0.040887	0.020606	0.025249	0.012726
	90.000	0.65574	0.47949	0.38906	0.33530	0.040364	0.020342	0.024924	0.012566
6:1	0.0000	0.62518	0.10148	0.033635	0.016634	0.42340	0.18929	0.35423	0.17856
	19.800	0.69914	0.19389	0.066266	0.018589	0.15698	0.073882	0.092813	0.043345
	31.100	0.78123	0.27967	0.11830	0.045197	0.12744	0.062843	0.078585	0.038806
	42.500	0.85619	0.37461	0.19466	0.10145	0.11640	0.058049	0.072445	0.036158
	53.800	0.91528	0.46417	0.28261	0.17989	0.11020	0.055080	0.068711	0.034357
	65.200	0.95786	0.53827	0.36633	0.26515	0.10623	0.053098	0.066270	0.033142
	76.500	0.98570	0.58997	0.43012	0.33597	0.10407	0.051999	0.064963	0.032479
	87.900	1.0095	0.61872	0.46357	0.37325	0.10190	0.050891	0.063639	0.031813
	90.000	1.0139	0.62402	0.46974	0.38012	0.10150	0.050688	0.063397	0.031692
10:1	0.0000	0.50584	0.076958	0.021545	0.0085158	0.36792	0.17987	0.31430	0.16421
	19.800	0.69374	0.18287	0.050195	0.024903	0.17400	0.077612	0.10646	0.049965
	31.100	0.81548	0.27954	0.10672	0.011238	0.14876	0.072756	0.092540	0.045734
	42.500	0.91517	0.38683	0.19022	0.082960	0.13682	0.068040	0.085448	0.042605
	53.800	0.99068	0.48806	0.28659	0.16996	0.12955	0.064608	0.080987	0.040441
	65.200	1.0447	0.57197	0.37853	0.26284	0.12494	0.062328	0.078126	0.039018
	76.500	1.0798	0.63058	0.44863	0.33966	0.12246	0.061078	0.076608	0.038252
	87.900	1.1027	0.66007	0.48324	0.37830	0.11996	0.059814	0.075071	0.037482
	90.000	1.1070	0.66550	0.48962	0.38541	0.11950	0.059580	0.074790	0.037339

Table A.7 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.3$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.72349	0.12697	0.048227	0.026060	0.40399	0.18788	0.33355	0.17574
	17.400	0.70818	0.20325	0.083141	0.042185	0.10169	0.049092	0.055738	0.024894
	29.100	0.68985	0.26422	0.12595	0.068270	0.058271	0.028385	0.034402	0.016369
	40.900	0.68013	0.32636	0.18537	0.11447	0.042754	0.021103	0.026283	0.012963
	52.600	0.67314	0.38057	0.25051	0.17651	0.035635	0.017736	0.022128	0.011048
	64.400	0.66751	0.42275	0.31011	0.24232	0.031681	0.015818	0.019708	0.0098715
	76.100	0.66501	0.45156	0.35481	0.29656	0.029650	0.014804	0.018460	0.0092496
	87.900	0.66248	0.47766	0.38549	0.33096	0.027604	0.013779	0.017206	0.0086207
	90.000	0.66203	0.48231	0.39094	0.33708	0.027237	0.013599	0.016980	0.0085112
6:1	0.0000	0.66534	0.11168	0.040786	0.021601	0.37986	0.18113	0.31524	0.16722
	17.400	0.71518	0.18978	0.068302	0.027155	0.11749	0.054187	0.068969	0.032172
	29.100	0.80369	0.27713	0.11789	0.051195	0.092539	0.045280	0.057088	0.028113
	40.900	0.88561	0.37583	0.19384	0.10417	0.084663	0.042086	0.052799	0.026311
	52.600	0.95053	0.47034	0.28412	0.18241	0.080611	0.040196	0.050371	0.025152
	64.400	0.99750	0.54933	0.37186	0.27039	0.078060	0.038942	0.048803	0.024375
	76.100	1.0280	0.60458	0.43939	0.34479	0.076682	0.038235	0.047972	0.023958
	87.900	1.0534	0.63494	0.47456	0.38383	0.075290	0.037521	0.047131	0.023534
	90.000	1.0579	0.64034	0.48082	0.39078	0.075043	0.037398	0.046980	0.023456
10:1	0.0000	0.56151	0.085158	0.028798	0.014104	0.34445	0.16785	0.28974	0.15348
	17.400	0.70667	0.17594	0.051742	0.015895	0.12787	0.058724	0.077505	0.036900
	29.100	0.84823	0.27615	0.10446	0.015701	0.10999	0.054028	0.068387	0.033865
	40.900	0.96246	0.38933	0.18770	0.081784	0.10241	0.050937	0.064006	0.031911
	52.600	1.0507	0.49820	0.28751	0.16868	0.098390	0.049025	0.061575	0.030727
	64.400	1.1149	0.58957	0.38485	0.26508	0.096104	0.047891	0.060176	0.030031
	76.100	1.1565	0.65342	0.45969	0.34616	0.095023	0.047336	0.059529	0.029703
	87.900	1.1826	0.68523	0.49646	0.38688	0.093934	0.046775	0.058875	0.029371
	90.000	1.1873	0.69089	0.50300	0.39413	0.093740	0.046676	0.058759	0.029311

Table A.8 Influence coefficients for semielliptical surface crack on the inside of a cylinder: $R_i/t = 10$ and $a/t = 0.5$

		Unclad Cylinder				Cladding			
Aspect Ratio	Elliptic Angle	K0 - uniform	K1 - linear	K2 - quadratic	K3 - cubic	K0 (t=.25)	K1 (t=.25)	K0 (t=.156)	K1 (t=.156)
2:1	0.0000	0.73590	0.13195	0.052789	0.029231	0.32707	0.16206	0.27208	0.15042
	15.400	0.74632	0.20297	0.083352	0.043010	0.078913	0.037468	0.044537	0.020279
	27.500	0.71893	0.26349	0.12365	0.067162	0.041675	0.019997	0.024740	0.011716
	39.600	0.70394	0.32690	0.18268	0.11212	0.028807	0.014034	0.017835	0.0087384
	51.700	0.69324	0.38278	0.24910	0.17450	0.023440	0.011535	0.014710	0.0073016
	63.700	0.68489	0.42648	0.31077	0.24211	0.020572	0.010164	0.012942	0.0064505
	75.800	0.68067	0.45639	0.35739	0.29854	0.019061	0.0094171	0.012017	0.0059907
	87.900	0.67645	0.48332	0.38912	0.33412	0.017553	0.0086699	0.011092	0.0055309
	90.000	0.67571	0.48800	0.39462	0.34029	0.017293	0.0085413	0.010930	0.0054515
6:1	0.0000	0.75803	0.14208	0.058511	0.033254	0.32196	0.16333	0.26758	0.14878
	15.400	0.81355	0.21296	0.083111	0.039951	0.090547	0.041106	0.053788	0.025285
	27.500	0.90777	0.30213	0.13166	0.064546	0.069811	0.033946	0.043257	0.021289
	39.600	0.99793	0.40494	0.20790	0.11626	0.064693	0.032072	0.040462	0.020142
	51.700	1.0692	0.50431	0.30046	0.19465	0.062364	0.031029	0.039072	0.019488
	63.700	1.1204	0.58794	0.39183	0.28500	0.060783	0.030263	0.038090	0.019004
	75.800	1.1534	0.64675	0.46290	0.36265	0.059825	0.029770	0.037515	0.018714
	87.900	1.1818	0.67931	0.50003	0.40351	0.058870	0.029280	0.036940	0.018424
	90.000	1.1867	0.68497	0.50647	0.41060	0.058703	0.029195	0.036839	0.018374
10:1	0.0000	0.66568	0.11856	0.048640	0.028270	0.30205	0.15563	0.25403	0.14049
	15.400	0.82186	0.20827	0.076656	0.032556	0.097197	0.043552	0.059496	0.028437
	27.500	0.99495	0.31629	0.13076	0.056404	0.085818	0.041968	0.053569	0.026530
	39.600	1.1379	0.43967	0.21628	0.11183	0.083257	0.041338	0.052143	0.025982
	51.700	1.2513	0.56007	0.32124	0.19794	0.082685	0.041144	0.051834	0.025848
	63.700	1.3354	0.66229	0.42539	0.29774	0.082572	0.041097	0.051779	0.025821
	75.800	1.3900	0.73423	0.50636	0.38340	0.082572	0.041097	0.051779	0.025821
	87.900	1.4234	0.77021	0.54629	0.42667	0.082572	0.041097	0.051779	0.025821
	90.000	1.4292	0.77645	0.55322	0.43418	0.082572	0.041097	0.051779	0.025821

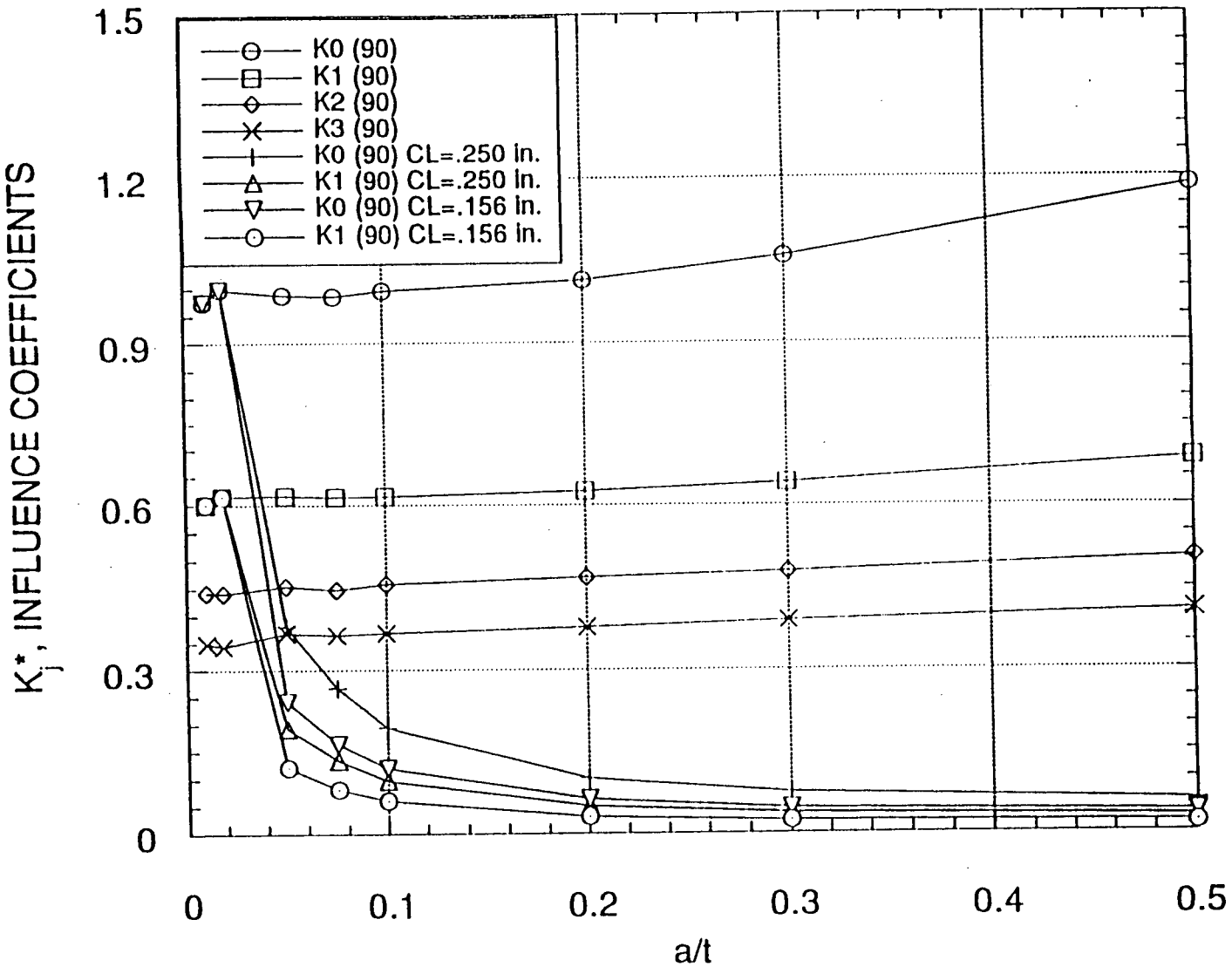


Figure A.2 Influence coefficients for 6:1 axially oriented inner-surface flaws at $\phi = 90°$

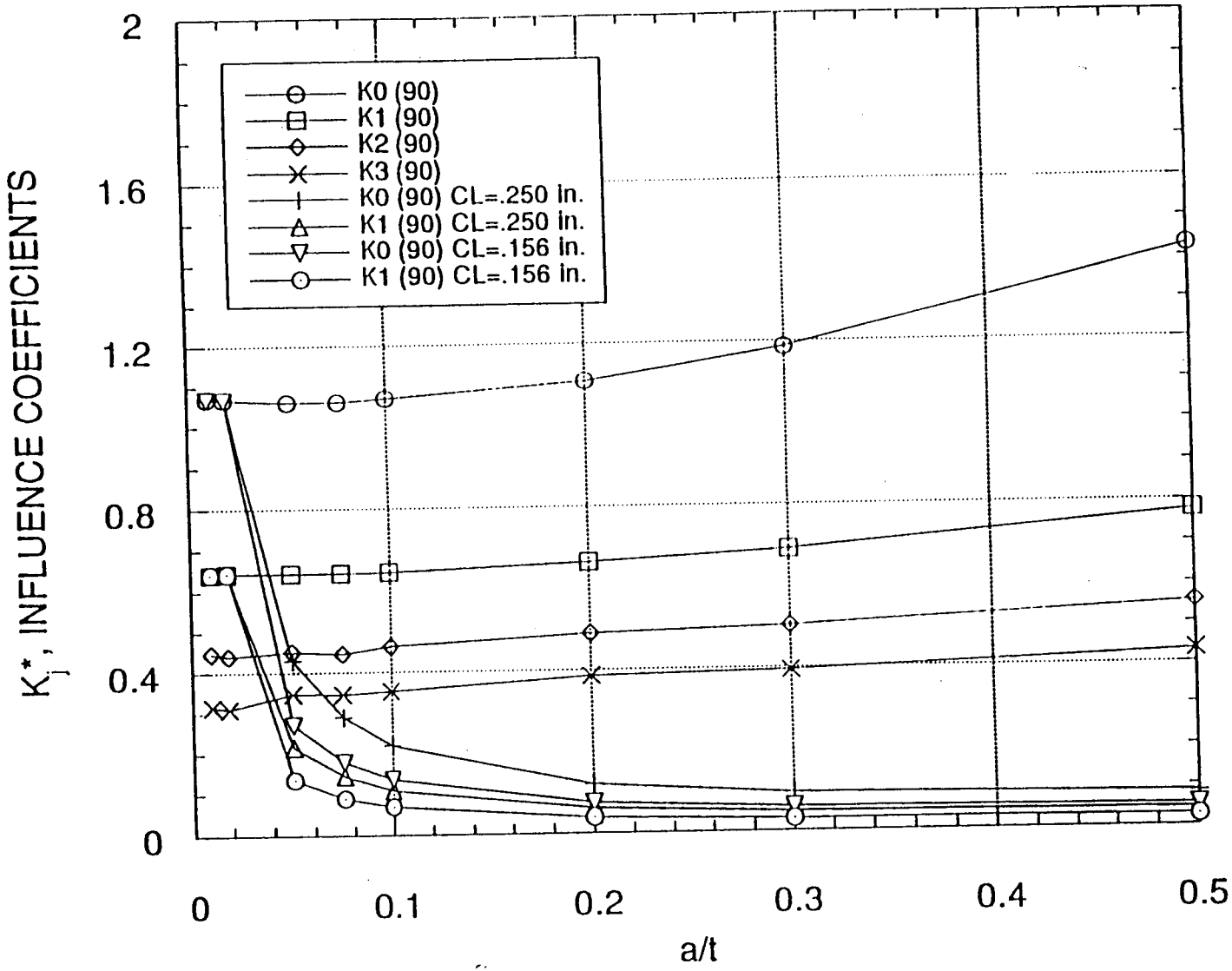


Figure A.3 Influence coefficients for 10:1 axially oriented inner-surface flaws at $\phi = 90°$

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