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IN AN ORTHOTROPIC STRIP

by

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ABSTRACT

The plane elastostatic problem of internal and edge cracks in an infinite orthotropic strip is considered. The problems for the material types I and II are formulated in terms of singular integral equations. For the symmetric case the stress intensity factors are calculated and are compared with the isotropic results. The results show that because of the dependence of the Fredholm kernels on the elastic constants, unlike the crack problem for an infinite plane, in the strip the stress intensity factors are dependent on the elastic constants and are generally different than the corresponding isotropic results.

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1. INTRODUCTION

In plane elastostatic problems for an infinite orthotropic medium containing a line crack [1-3] or a series of collinear cracks [4] it was shown that the stress intensity factor is identical to that found for isotropic materials. However, if the geometry of the medium is bounded, it is expected that in orthotropic solids the material constants would influence the stress intensity factors. A bounded specimen geometry which is sufficiently simple for the purpose of analysis and at the same time is of sufficient practical interest is that of a long strip containing internal or edge cracks. The main objective of the present paper is by considering this problem to give some idea about the degree of influence of the material orthotropy on the stress intensity factors. The equivalent isotropic case is one of the more widely studied crack problems in technical literature (see, for example, [5-13]).

2. FORMULATION OF THE PROBLEM

Consider the plane problem for the orthotropic strip shown in Figure 1. Referring to, for example [14], the equilibrium equations for an orthotropic plane may be expressed as

\[ \beta_1 \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \beta_3 \frac{\partial^2 v}{\partial x \partial y} = 0 \right. \]

\[ \left. \frac{\partial^2 v}{\partial x^2} + \beta_2 \frac{\partial^2 v}{\partial y^2} + \beta_3 \frac{\partial^2 u}{\partial x \partial y} = 0 \right. \]  

where \( u, v \) are the \( x, y \)-components of the displacement vector and
for generalized plane stress, and

\[ \beta_1 = \frac{E_{11}}{(1-\nu_{21}\nu_{21})G_{12}}, \quad \beta_2 = \frac{E_{22}}{E_{11}}, \quad \beta_3 = 1 + \nu_{21}\beta_1 \]  

for plane strain. Here, \( E_{ij}, \nu_{ij}, G_{ij} \) are the engineering elastic constants, \((i,j) = (1,2,3)\), the indexes \((1,2,3)\) corresponding to the directions \((x,y,z)\), and the matrix \((b_{ij})\) is given by

\[ (b_{ij}) = B = A^{-1}, \quad A = (a_{ij}), \quad (i,j) = (1,2,3), \]  

\[ a_{ii} = 1/E_{ii}; \quad a_{ij} = -\nu_{ij}/E_{ii} = a_{ji}, \quad (i \neq j) \]

The solution of the problem shown in Figure 1 may be obtained by using the standard superposition technique. Thus, for the purpose of evaluating the stress intensity factors and obtaining information relevant to the fracture of the solid, it is sufficient to consider the problem in which statically self-equilibrating crack surface tractions are the only external loads.

To solve the differential equations (1) let

\[ u(x,y) = \frac{2}{\pi} \int_0^{\infty} [f_1(\alpha,x)\cos\alpha y + g_1(\alpha,y)\sin\alpha x]d\alpha, \]

\[ v(x,y) = \frac{2}{\pi} \int_0^{\infty} [f_2(\alpha,x)\sin\alpha y + g_2(\alpha,y)\cos\alpha x]d\alpha. \]

Substituting from (5) into (1) the functions \( f_i \) and \( g_i \), \((i=1,2)\) are obtained as follows:
\[ f_1(\alpha, x) = \sum_j A_j(\alpha) e^{s_j \alpha x}, \quad f_2(\alpha, x) = \sum_j c_j A_j(\alpha) e^{s_j \alpha x}, \]

\[ g_1(\alpha, y) = \sum_j B_j(\alpha) e^{s_j \alpha y/\beta_5}, \quad g_2(\alpha, y) = \sum_j d_j B_j(\alpha) e^{s_j \alpha y/\beta_5}, \]

where \( s_1, \ldots, s_4 \) are the roots of the following characteristic equation:

\[ s^4 + \beta_4 s^2 + \beta_5 = 0, \quad s_3 = -s_1, \quad s_4 = -s_2, \]

and the constants \( \beta_4, \beta_5, c_j, \) and \( d_j, \) (\( j = 1, \ldots, 4 \)) are given by

\[ \beta_4 = (\beta_3 - \beta_1 \beta_2 - 1)/\beta_1, \quad \beta_5 = \beta_2/\beta_1, \]

\[ c_1 = -c_3 = (1 - \beta_1 s_3^2)/\beta_3 s_1, \quad c_2 = -c_4 = (1 - \beta_1 s_4^2)/\beta_3 s_2, \]

\[ d_1 = -d_3 = (s_1^2 - \beta_1 \beta_2^2)/\beta_3 s_1 \beta_5, \quad d_2 = -d_4 (s_2^2 - \beta_1 \beta_2^2)/\beta_3 s_2 \beta_5. \]

Assuming that \( x \) and \( y \) are axes of symmetry for loading as well as geometry, the unknown functions \( A_j(\alpha) \) and \( B_j(\alpha), \) (\( j = 1, \ldots, 4 \)) are determined from the following conditions:

\[ u(x, y) = 0, \quad v(x, y) = 0 \text{ for } y \rightarrow \infty, \]

\[ \sigma_{xx}(h, y) = 0, \quad \sigma_{xy}(h, y) = 0, \quad 0 \leq y < \infty, \]

\[ u(0, y) = 0, \quad \sigma_{xy}(0, y) = 0, \quad 0 \leq y < \infty, \]

\[ \sigma_{xy}(x, 0) = 0, \quad 0 < x < h, \]

\[ \sigma_{yy}(x, +0) = -p(x), \quad a < |x| < b, \quad \sigma_{yy}(x, -0) = 0, \quad b < |x| < h, \quad v(x, 0) = 0, \quad 0 \leq |x| < a, \quad b < |x| < h, \]

-4-
where the crack surface traction \( p(x) \) is a known function. The seven homogeneous conditions (9-12) may be used to eliminate seven of the unknowns and the mixed boundary conditions (13) would give a system of dual integral equations to determine the eighth. In this paper, defining a new unknown function

\[
\phi(x) = \frac{2}{\beta x} v(x,0) , \quad a < |x| < b , \quad (14)
\]

the problem is reduced to a singular integral equation by using the first equation of (13). From the second equation of (13) it is seen that

\[
\phi(x,0) = 0 , \quad 0 < |x| < a , \quad b < |x| < h ,
\]

\[
\int_{a}^{b} \phi(x) dx = 0 . \quad (15)
\]

Examining the roots of (7), it may be observed that

(i) for \( \beta_4 < 0, \beta_6 = \beta_4^2 - 4\beta_5^2 > 0 \) there are four real roots, \( s_1, s_2, s_3 = -s_1, \text{ and } s_4 = -s_2 \) \( (s_1 > 0, s_2 > 0) \); in this case the corresponding material will be classified as type I;

(ii) for \( \beta_6 < 0 \) the roots are complex, \( s_1 = \omega_1 + i\omega_2 = -s_3, \quad s_2 = \omega_1 - i\omega_2 = -s_4 \) \( (\omega_1 > 0, \omega_2 > 0) \) and the related material will be classified as type II; and

(iii) for \( \beta_4 > 0, \beta_6 > 0 \) the roots would be pure imaginary, \( s_1 = i\omega_3 = -s_3, \quad s_2 = i\omega_4 = -s_4 \).

In practice generally \( \beta_4 \) is negative. Therefore the problems of interest are those relating to materials type I and II only. This
classification seems to be necessary in order to pursue the formulation of the problem beyond equations (6) without introducing unnecessarily complicated complex algebra. Also, in this paper only the case of generalized plane stress will be considered. For plane strain it is sufficient to replace the quantities $E_x/(1-\nu_{xy}\nu_{yx})$, $E_y/(1-\nu_{xy}\nu_{yx})$, and $\nu_{yx}E_x/(1-\nu_{xy}\nu_{yx})$ by $b_{11}$, $b_{22}$, and $b_{12}$, respectively (see equation 4).

Because of symmetry considering only one quarter of the medium shown in Figure 1, and using the standard stress-displacement relations for plane stress, after somewhat lengthy but routine analysis, for material type I (i.e., for real $s_1$ and $s_2$) the problem may be reduced to the following integral equation:

$$
\int_a^b \left[ \frac{1}{t-x} + k_1(x,t) - k_1(x,-t) \right] \phi(t) dt = -\frac{\pi(1-\nu_{xy}\nu_{yx})}{2E_ym_{14}} p(x) , \quad a<x<b ,
$$

under the additional condition (15). Here the kernel is given by

$$
k_1(x,t) = \frac{1}{m_{14}} \int_0^\infty [K_1(x,\alpha)e^{-(h-t)\alpha^2/s_1} + K_2(x,\alpha)e^{-(h-t)\alpha^2/s_2}] d\alpha .
$$

The expressions for $K_1$, $K_2$, and $m_{14}$ are given in Appendix A.

For material type II the roots of the characteristic equation (7) are complex. Defining

$$
s_1 = \omega_1 + i\omega_2 = -s_3 , \quad s_2 = \omega_1 - i\omega_2 = -s_4 ,
$$

-6-
and, assuming that $\omega_1 > 0$, in this case the integral equation becomes

$$
\int_a^b \left[ \frac{1}{t-x} + \frac{1}{t+x} + k_2(x,t) - k_2(x,-t) \right] \phi(t) dt
$$

$$
= - \frac{\pi (1-\nu_{xy} \nu_{yx})}{2E \gamma_{14}} p(x) \quad , \quad a < x < b \quad ,
$$

(19)

again subject to condition (15). The kernel $k_2$ is given by

$$
k_2(x,t) = \int_0^\infty K_3(x,t,\alpha) e^{-\omega_1 \alpha (h-t)} d\alpha \quad ,
$$

(20)

where the function $K_3$ and the related constants $r_i$ are defined in the Appendix B.

One may note that in the special case of single internal crack, (i.e., for $a=0$, $b<h$) the integral equations (16) and (19) may be written as

$$
\int_a^b \left[ \frac{1}{t-x} + k_1(x,t) \right] \phi(t) dt = - \frac{\pi}{M_i} p(x) \quad , \quad -b < x < b \quad ,
$$

$$
i = 1, 2 \quad , \quad M_1 = \frac{2E \gamma_{14}}{1-\nu_{xy} \nu_{yx}} \quad , \quad M_2 = \frac{2E \gamma_{14}}{1-\nu_{xy} \nu_{yx}}
$$

(21)

where $i=1$ and 2 correspond to materials type I and II, respectively. In this case the single-valuedness condition (15) becomes

$$
\int_b^b \phi(x) dx = 0 \quad .
$$

(22)
3. STRESS INTENSITY FACTORS

The standard definition of the stress intensity factors at the crack tips a and b is

\[ k(a) = \lim_{x \to a} \sqrt{2(a-x)} \sigma_{yy}(x,0), \]

\[ k(b) = \lim_{x \to b} \sqrt{2(x-b)} \sigma_{yy}(x,0). \] (23)

To determine the asymptotic behavior of the cleavage stress \( \sigma_{yy} \) around the crack tips, first it may be observed that the index of the singular integral equations (16) and (19) is +1. Therefore, the solution is of the following form [15]:

\[ \phi(t) = f(t)[(t-a)(b-t)]^{\frac{-k}{2}}. \] (24)

Next, it should be pointed out that the left hand side of (16) and (19) gives \( \sigma_{yy}(x,0) \) for \( x \) outside the interval \((a,b)\) as well as within. Thus, making a change in variable

\[ x = \frac{b-a}{2}s + \frac{b+a}{2}, \quad t = \frac{b-a}{2}r + \frac{b+a}{2}, \] (25)

for example, (16) may be expressed as

\[ \frac{1}{\pi} \int_{1}^{1} \left[ \frac{1}{r-s} + k(s,r) \right] \psi(r) dr = \frac{q(s)}{M_1}, \quad \frac{b+a}{b-a} \leq \frac{2h-b-a}{b-a} \] (26)

where

\[ q(s) = \sigma_{yy}(x,0), \quad \psi(r) = \phi(t) = F(r)(1-r^2)^{-\frac{k}{2}}. \] (27)
and \(k(s, r)\) and \(F(r)\) are bounded functions. The objective is then to determine the asymptotic behavior of \(q(s)\) around \(s = i1, (|s| > 1)\) in terms of the unknown function \(F(r)\) which is obtained by solving the integral equation (26) in \(-1 < s < 1\) where \(q(s) = -p(x)\) is known. To do this let us assume that the bounded function \(F(r)\) can be represented by the following infinite series in Tchebyshev polynomials:

\[
F(r) = \sum_{n=0}^{\infty} A_n T_n(r).
\]

(28)

Substituting from (28) into (26) one obtains

\[
\sum_{n=0}^{\infty} A_n [G_n(s) + H_n(s)] = \frac{q(s)}{n+1}.
\]

(29)

\[
G_n(s) = \frac{1}{\pi} \int_{-1}^{1} \frac{T_n(r)dr}{(r-s)\sqrt{1-r^2}}, \quad H_n(s) = \frac{1}{\pi} \int_{-1}^{1} \frac{k(s, r)T_n(r)dr}{\sqrt{1-r^2}}.
\]

(30)

Here, \(H_n(s)\) is a bounded function. To determine \(G_n\) one may use the expression

\[
\frac{1}{\pi} \int_{-1}^{1} \frac{T_n(r)dr}{(r-z)\sqrt{1-r^2}} = \frac{(z^2-1)^n}{z^{2^n-1}}
\]

(31)

where \(z\) is the complex variable in the plane cut along \((-1, 1)\). Observing that on the real line \((z^2-1)^{\frac{1}{2}}\) is an odd function, from (30) and (31) it follows that

\[
G_n(s) = \frac{[s-\text{sgn}(s)\sqrt{s^2-1}]^n}{\text{sgn}(s)\sqrt{s^2-1}}.
\]

(32)

As \(s \to \pm 1\) (32) yields

\[
-9-\]
\[ Gn(s) = \frac{1}{\sqrt{s^2 - 1}} + R_1(s) \quad \text{if } s > 1 \]
\[ Gn(s) = \frac{(-1)^n}{\sqrt{s^2 - 1}} + R_2(s) \quad \text{if } s < -1 \]

(33)

where the functions \( R_1 \) and \( R_2 \) are bounded at \( s = \pm 1 \).

Now, observing that \( H_n(\mp 1) = \text{finite}, T_n(1) = 1, T_n(-1) = (-1)^n \), from (29) and (33) the asymptotic behavior of \( q(s) \) is found to be

\[ q(s) = \frac{F(1)}{\sqrt{s^2 - 1}} + R_3(s) \quad \text{if } s > 1 \]
\[ q(s) = \frac{F(1)}{\sqrt{s^2 - 1}} + R_4(s) \quad \text{if } s < -1 \]

(34)

where again the functions \( R_3 \) and \( R_4 \) are bounded at \( s = \pm 1 \). Going back to the original quantities by using (25) and (27), (34) becomes

\[ \sigma_{yy}(x,0) = \frac{F(1)\sqrt{x}}{\sqrt{2(x-b)}} + R_5(x) \quad \text{if } x > b \]
\[ \sigma_{yy}(x,0) = \frac{F(-1)\sqrt{x}}{\sqrt{2(a-x)}} + R_6(x) \quad \text{if } x < a \]

(35)

where the functions \( R_5 \) and \( R_6 \) are also bounded at \( x = b \) and \( x = a \). Thus, from (23) and (35) the stress intensity factors are found to be

\[ k(b) = -M_1F(1)\sqrt{x} \quad k(a) = M_1F(-1)\sqrt{x} \]

(36)

In the case of fully imbedded cracks the integral equations (16), (19) or (21) can always be reduced to the normalized form (26) and can be solved by using the technique described in [16].
4. EDGE CRACKS

In equations (16) and (19) the kernels \( k_1(x,t)-k_1(x,-t) \) and \( k_2(x,t)-k_2(x,-t) \) are bounded provided \( b<h \) (see Figure 1). For \( b=h \), that is in the case of edge cracks, the integral equations are still valid but these kernels do not remain bounded as \( x \) and \( t \) go to the end point \( b=h \) and, consequently, the singular behavior of the solution at \( x=b=h \) may no longer be described by (24). Expressing the kernels in (16) and (19) as

\[
   k_i(x,t) = k_{if}(x,t) + k_{is}(x,t), \quad (i=1,2)
\]

where \( k_{if} \) is bounded in the closed interval \([a,h]\), the unbounded parts \( k_{is}, (i=1,2) \) may be obtained from (17) and (20) by examining the asymptotic behavior of the integrals for large values of \( \alpha \). Thus, after some routine analysis we find

\[
k_{is}(x,t) = \frac{1}{m_{14}m_{15}} \left[ \frac{m_{16}}{s_1(h-x)+(h-t)\beta_5/s_1} + \frac{m_{17}}{s_2(h-x)+(h-t)\beta_5/s_1} \right] + \frac{m_{18}}{s_1(h-x)+(h-t)\beta_5/s_2} + \frac{m_{19}}{s_2(h-x)+(h-t)\beta_5/s_2} \quad \text{(37)}
\]

\[
k_{is}(x,t) = \frac{1}{r_{14}r_{19}} \left[ \frac{r_{25}\omega_2(t-x)}{\omega_2^2(t-x)^2 + \omega_1^2(2h-t-x)^2} \right] + \frac{r_{26}\omega_2(2h-t-x)}{\omega_2^2(2h-t-x)^2 + \omega_1^2(2h-t-x)^2} + \frac{r_{27}\omega_1(2h-t-x)}{\omega_2^2(t-x)^2 + \omega_1^2(2h-t-x)^2}
\]
where the constants $m_i$ and $r_i$ are given in the appendices. Thus, for example, the integral equation (16) may be expressed as

\[
\int_a^h \left[ \frac{1}{t-x} + \frac{1}{t+x} + k_1s(x,t) + k_1f(x,t) - k_1(x+t) \right] \phi(t) dt = - \frac{\pi}{M} p(x), \quad a < x < h.
\]  

In (39) for the purpose of asymptotic analysis transferring the terms involving the bounded kernels to the righthand side one may write

\[
\int_a^h \left[ \frac{1}{t-x} + k_1s(x,t) \right] \phi(t) dt = P_1(x), \quad a < x < h
\]  

where $P_1$ is a bounded function in $[a,h]$. Letting now

\[
\phi(t) = \frac{f_1(t)}{(h-t)^{\alpha}(t-a)^{\beta}}, \quad 0 < \text{Re}(\alpha,\beta) < 1,
\]  

where $f_1$ is $H$-continuous in $[a,h]$, and following the procedure outlined in [15], the characteristic equations for $\alpha$ and $\beta$ are found to be

\[
\cot \pi \beta = 0, \quad \beta = 1/2,
\]  

\[
-\cos \pi \alpha + \frac{1}{m_{14}m_{15}} \left[ m_{16}(s_5/s_3)^\alpha(s_1/s_5) + m_{17}(s_1/s_5) + m_{18}(s_2/s_5) + m_{19}(s_5/s_2)^\alpha(s_2/s_5) \right] = 0.
\]
Similarly, for material type II described by (19), assuming the solution again as given by (41), the characteristic equations become

\[ \cot \pi \beta = 0 \quad , \quad \beta = 1/2 \]  

(44)

\[
\cos \alpha + \frac{1}{r_{14}r_{19}} \left[ r_{29} + \frac{\omega_2 r_{25} - \omega_1 r_{27}}{\omega_1 + \omega_2} \cos(2\alpha \tan^{-1} \frac{\omega_2}{\omega_1}) \right. \\
- \left. \frac{\omega_1 r_{25} + \omega_2 r_{27}}{\omega_1 + \omega_2} \sin(2\alpha \tan^{-1} \frac{\omega_2}{\omega_1}) \right] .
\]  

(45)

At the imbedded crack tip \( x=a \) it is seen that the singularity has the expected \( 1/2 \) power. On the other hand, as in the isotropic case, (43) and (45) have no root for which \( 0<\text{Re}(\alpha)<1 \), meaning that at \( x=h \) there is no power singularity. One may also proceed and investigate the possibility of a logarithmic singularity for the solution. Thus, letting \( \alpha=0 \) in (41) and defining the sectionally holomorphic function

\[
F_1(z) = \frac{1}{\pi} \int_a^h \frac{\phi(t)}{z-t} \, dt 
\]  

(46)

we find [15]

\[
F_1(z) = \frac{f_1(a)e^{\pi i \beta}}{\sin \pi \beta} \frac{1}{(z-a)^\beta} + \frac{f_1(h)}{\pi(h-a)^\beta} \log(z-h) + P_2(z) , \\
\frac{1}{\pi} \int_a^b \frac{\phi(t)}{t-x} \, dt = \frac{f_1(a)\cot \pi \beta}{(x-a)^\beta} + \frac{f_1(h)}{\pi(h-a)^\beta} \log(h-x) + P_3(x) , \\
\frac{1}{\pi} \int_a^b \frac{\phi(t)dt}{t-(2h-x)} = F_1(2h-x) ,
\]  

(47)
where $P_2$ and $P_3$ are bounded at $x=h$ and have at most a singularity of lower order than $\beta$ at $x=a$. Substituting from (47) into (40), multiplying through by $(x-a)^{\beta}$ and letting $x=a$, it is found that $\cot \pi \beta = 0$, giving again $\beta = 1/2$. On the other hand, in the neighborhood of the end point $x=h$ one obtains

$$[1 - \frac{1}{m_{14} m_{15} h} (s_1 m_{16} + s_1 m_{17} + s_1 m_{18} + s_2 m_{19})] \log(h-x) + P_4(x) = P_1(x) \quad (48)$$

where $P_4$ contains all the bounded terms around $x=h$ on the left hand side of (40). Similarly, for the material type II one finds

$$[1 + \frac{1}{(\omega_1 + \omega_2) r_{14} r_{19}} (\omega_2 r_{25} - \omega_2 r_{26} - \omega_1 r_{27} - \omega_1 r_{28})] \log(h-x) + Q_4(x) = Q_1(x) \quad (49)$$

It turns out that, as in the case of isotropic materials [10], the coefficient of the logarithmic term in (48) and (49) is identically zero, meaning that the solution may not have logarithmic singularity at $x=h$. In the edge crack problem the integral equation (39) and the similar equation for the material type II are solved by defining

$$\phi(x) = \frac{f(x)}{\sqrt{x-a}} = F(s) \quad (50)$$

and by using the numerical technique described in [10]. In this case the stress intensity factor at $x=a$ becomes

$$k(a) = M_1 F(-1) \sqrt{2\xi} , \quad \xi = (h-a)/2 \quad (51)$$
5. RESULTS AND DISCUSSION

As an example the following two orthotropic materials will be considered:

Type I: \( E_x = 8 \times 10^6 \text{ psi} \ (55.16 \times 10^9 \text{ N/m}^2) \),
\( E_y = 24.75 \times 10^6 \text{ psi} \ (170.65 \times 10^9 \text{ N/m}^2) \),
\( G_{xy} = 0.7 \times 10^6 \text{ psi} \ (4.83 \times 10^9 \text{ N/m}^2) \),
\( \nu_{xy} = 0.036 \).

Type II: \( E_x = 3.1 \times 10^6 \text{ psi} \ (21.37 \times 10^9 \text{ N/m}^2) \),
\( E_y = 9.7 \times 10^6 \text{ psi} \ (66.88 \times 10^9 \text{ N/m}^2) \),
\( G_{xy} = 2.6 \times 10^6 \text{ psi} \ (17.93 \times 10^9 \text{ N/m}^2) \),
\( \nu_{xy} = 0.2 \).

Tables 1-3 show some of the calculated results for the stress intensity factors. In all the calculations it was assumed that the crack surface traction was constant, i.e.,

\[ \sigma_{yy}(x,0) = -p(x) = -p_0 \] (52)

which corresponds to uniform tension of the strip away from the crack region. Table 1 shows the results for an internal crack of length 2b (see Figure 1, \(a=0\)) which was found by solving (21). The stress intensity factors used in the tables are defined by (23) and are calculated by using (36) for internal and (51) for edge cracks. The stress intensity factors for symmetrically located two collinear cracks (Figure 1) are given by Table 2. Table 3 gives the results for symmetric edge cracks.
The tables also contain the stress intensity factors for the isotropic strip which are included for comparison. A close examination of the integral equations (16), (19), or (21) would indicate that in orthotropic materials since the Fredholm kernel \( k_1 \) or \( k_2 \) is heavily dependent on the material constants, the solution must also depend on the constants. On the other hand, in isotropic materials even though the structure of the integral equation is identical to that of (16) or (19) (see, for example, [10]), the kernel of the integral equation is independent of the elastic constants and the constants appear in the equation as a multiplying factor (in the form of \((1+\kappa)/4\mu\)) only. The stress intensity factors given in the tables indicate that the results for the orthotropic strip are indeed different than the isotropic results. The tables also show that for approximately the same modulus ratio \( E_y/E_x \) (in the example approximately 3/1), depending on the remaining constants, the materials may not only be of different type (I or II), also the stress intensity factors may be greater (in this case, in material type II) or smaller (in material type I) than the isotropic values. In orthotropic materials there are three independent material parameters, namely, \( G_{xy}/E_y \), \( E_x/E_y \), and \( \nu_{xy} \). Therefore, it does not seem to be feasible to make a systematic study and demonstrate the effect of the material orthotropy on the stress intensity factors. However, it appears that there exists a difference between isotropic and orthotropic results and in highly orthotropic materials it may be significant.

In solving this problem, the numerical analysis produced a somewhat unexpected result. First, it should be pointed out that the
results given in the tables are accurate to roughly three significant
digits, the remaining digits may not be accurate. On the other hand,
after rotating the material 90 degrees (i.e., taking the strip parallel
to the less stiff axis and the crack along the stiffer axis) and fully
expecting to obtain a different set of results, the print out for the
stress intensity factors came out to be identical - in all eight digits -
to the original values obtained for the strip which was parallel to the
stiff axis. Furthermore, the ratio of the function $F(r)$ defined by (27)
at all points in $-1 < r < 1$ for the 0 and 90 degree orientations was found
to be constant, indicating that the crack surface displacements for the
two cases are related by (see (14), (27), and (36))

$$v_0(x,0)M_0 = v_{90}(x,0)M_{90}$$

(53)

where the constant $M$ is defined by (21). This simply shows that the
kernels $k_1$ and $k_2$ which appear in the integral equations (16), (19),
and (21) remain invariant under a 90 degree rotation for a given ortho-
tropic strip.

Table 1. The stress intensity factor $k(b)/p_0\sqrt{b}$ for an internal crack
of length $2b$ in isotropic and orthotropic strips.

<table>
<thead>
<tr>
<th>b/h</th>
<th>Isotropic</th>
<th>Orthotropic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type I</td>
</tr>
<tr>
<td>-0</td>
<td>1.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>0.1</td>
<td>1.0060</td>
<td>1.0044</td>
</tr>
<tr>
<td>0.2</td>
<td>1.0246</td>
<td>1.0182</td>
</tr>
<tr>
<td>0.3</td>
<td>1.0578</td>
<td>1.0428</td>
</tr>
<tr>
<td>0.4</td>
<td>1.1094</td>
<td>1.0811</td>
</tr>
<tr>
<td>0.5</td>
<td>1.1869</td>
<td>1.1387</td>
</tr>
<tr>
<td>0.6</td>
<td>1.3033</td>
<td>1.2264</td>
</tr>
<tr>
<td>0.7</td>
<td>1.4888</td>
<td>1.3674</td>
</tr>
<tr>
<td>0.8</td>
<td>1.8160</td>
<td>1.6241</td>
</tr>
<tr>
<td>0.9</td>
<td>2.5809</td>
<td>2.2487</td>
</tr>
</tbody>
</table>
Table 2. The stress intensity factors $k(a)$ and $k(b)$ for symmetric collinear internal cracks in a strip.

<table>
<thead>
<tr>
<th>a/h</th>
<th>b/h</th>
<th>$k(a)/p_0\sqrt{\xi}$</th>
<th>$k(b)/p_0\sqrt{\xi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Isot. Type I</td>
<td>Type II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isot. Type I</td>
<td>Isot. Type I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k(a)/p_0\sqrt{\xi}$</td>
<td>$k(b)/p_0\sqrt{\xi}$</td>
</tr>
<tr>
<td>$-0$</td>
<td>0.4</td>
<td>$(-\infty)$</td>
<td>$(-\infty)$</td>
</tr>
<tr>
<td>0.1</td>
<td>0.5</td>
<td>$1.176$</td>
<td>$1.160$</td>
</tr>
<tr>
<td>0.2</td>
<td>0.6</td>
<td>$1.109$</td>
<td>$1.095$</td>
</tr>
<tr>
<td>0.4</td>
<td>0.8</td>
<td>$1.097$</td>
<td>$1.081$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.9</td>
<td>$1.127$</td>
<td>$1.104$</td>
</tr>
<tr>
<td>0.6</td>
<td>+1</td>
<td>$+1.600$</td>
<td>$+1.531$</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>$1.678$</td>
<td>$1.595$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.95</td>
<td>$1.194$</td>
<td>$1.160$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.98</td>
<td>$1.268$</td>
<td>$1.226$</td>
</tr>
<tr>
<td>0.5</td>
<td>+1</td>
<td>$+1.640$</td>
<td>$+1.600$</td>
</tr>
</tbody>
</table>

Table 3. The stress intensity factor $k(a)p_0\sqrt{\xi}$ for the case of symmetric edge cracks, $\lambda=(h-a)/2$.

<table>
<thead>
<tr>
<th>a/h</th>
<th>$k(a)/p_0\sqrt{\xi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isot. Type I</td>
</tr>
<tr>
<td></td>
<td>Isot. Type I</td>
</tr>
<tr>
<td></td>
<td>$k(a)/p_0\sqrt{\xi}$</td>
</tr>
<tr>
<td>0.1</td>
<td>2.980</td>
</tr>
<tr>
<td>0.2</td>
<td>2.218</td>
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<tr>
<td>0.3</td>
<td>1.907</td>
</tr>
<tr>
<td>0.4</td>
<td>1.742</td>
</tr>
<tr>
<td>0.5</td>
<td>1.640</td>
</tr>
<tr>
<td>0.6</td>
<td>1.600</td>
</tr>
<tr>
<td>0.7</td>
<td>1.574</td>
</tr>
<tr>
<td>0.8</td>
<td>1.567</td>
</tr>
<tr>
<td>0.9</td>
<td>1.576</td>
</tr>
<tr>
<td>0.98</td>
<td>1.582</td>
</tr>
</tbody>
</table>
REFERENCES


APPENDIX A

Expressions for the functions $K_1$ and $K_2$ and the constants $m_1$ (see equation 17) (material type I):

$$K_1(x, \alpha) = \frac{1}{2s_1m_{13}p(\alpha)} \left[ m_7 \cosh(\frac{s_2x}{\alpha}) \left( m_1m_{10}b_5 \tanh(s_2\alpha) \right) \right]$$

$$+ \frac{\cosh(\frac{s_2x}{\alpha})}{m_{11}m_{12}} - m_8 \cosh(\frac{s_2x}{\alpha}) \left( m_3m_{11}b_5 \right)$$

$$+ m_1m_9b_5 \tanh(s_2\alpha) \right] ,$$

$$K_2(x, \alpha) = \frac{1}{2s_2m_{13}p(\alpha)} \left[ m_7 \cosh(\frac{s_2x}{\alpha}) \left( -m_4m_{11}b_5 \right) \right]$$

$$\frac{\cosh(\frac{s_2x}{\alpha})}{m_{11}m_{12}} - m_8 \cosh(\frac{s_2x}{\alpha}) \left( m_3m_{11}b_5 \right)$$

$$\times \left( \frac{m_1m_9b_5 \tanh(s_2\alpha) + m_3m_{11}b_5} \right] ,$$

$$p(\alpha) = m_3m_{10} \tanh(s_2\alpha) - m_4m_9 \tanh(s_2\alpha) ,$$

$$m_1 = 1 + \nu y x s_1d_1/b_5 , \quad m_2 = 1 + \nu y x s_2d_2/b_5 , \quad m_3 = s_1 + \nu y x c_1 ,$$

$$m_4 = s_2 + \nu y x c_2 , \quad m_5 = \nu y x d_1s_1/b_5 , \quad m_6 = \nu y x d_2s_2/b_5 ,$$

$$m_7 = \nu y x s_1c_1 , \quad m_8 = \nu y x s_2c_2 , \quad m_9 = c_1s_1 - 1 ,$$

$$m_{10} = c_2s_2 - 1 , \quad m_{11} = d_1 - s_1/b_5 , \quad m_{12} = d_1 - s_2/b_5 ,$$

$$m_{13} = d_1 - d_2m_{11}/m_{12} , \quad m_{14} = (m_5 - m_6m_{11}/m_{12})/2m_{13} ,$$

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\[ m_{15} = m_3^m m_{10} - m_4^m m_9 \quad m_{16} = m_7^D (m_1^m m_{10} + m_4^m m_1) / 2s_1 m_{13} \quad m_{17} = -m_8^D (m_3^m m_{11} + m_4^m m_9) / 2s_1 m_{13} \quad m_{18} = -m_7^D m_{11} m_5 (m_4^m + m_2^m m_{10} / m_1^2) / 2m_3 s_2 \quad m_{19} = m_6^D m_{11} m_5 (m_3^m + m_4^m m_2 / m_1^2) / 2s_2 m_{13} \]

**APPENDIX B**

Expressions for the function \( K_3 \) and the constants \( r_i \) (see equation 20) (material type II):

\[
K_3(x, t, \alpha) = \frac{2}{\tau_1^D (\alpha)} \left[ -r_6 \sin(\omega_2 ax) \sinh(\omega_1 ax) + r_5 \cos(\omega_2 ax) \cosh(\omega_1 ax) \right] \cdot \left[ r_{16} \sin[\omega_2 a(h-t)] \right] \\
\cdot \left( r_9 \sin(\omega_2 ah) \cosh(\omega_1 ah) + r_{10} \cos(\omega_2 ah) \sinh(\omega_1 ah) \right) \\
- r_{18} (\frac{\omega_2}{\omega_1} \cos[\omega_2 a(h-t)] - \sin[\omega_2 a(h-t)]) \\
\cdot \left( r_1 \sin(\omega_2 ah) \sinh(\omega_1 ah) + r_2 \cos(\omega_2 ah) \cosh(\omega_1 ah) \right) \\
\right] + \left[ r_5 \sin(\omega_2 ax) \sinh(\omega_1 ax) + r_6 \cos(\omega_2 ax) \cosh(\omega_1 ax) \right] \\
\cdot \left[ r_{16} \sin[\omega_2 a(h-t)] \cdot (r_9 \cos(\omega_2 ah) \sinh(\omega_1 ah) \\
- r_{10} \sin(\omega_2 ah) \cosh(\omega_1 ah) + r_{18} (\frac{\omega_2}{\omega_1} \cos[\omega_2 a(h-t)]) \right]
\]
\[-\sin[\omega_2\alpha(h-t)] \cdot (-r_2 \sin(\omega_2\alpha)\sinh(\omega_1\alpha)) + r_1 \cos(\omega_2\alpha) \cosh(\omega_1\alpha)))\] 

\[Q(\alpha) = r_{19} \sinh(\omega_1\alpha)\cosh(\omega_1\alpha) + r_{20} \sin(\omega_2\alpha)\cos(\omega_2\alpha)\] 

\[s_1 = \omega_1 + \i\omega_2, \quad s_2 = \omega_1 - \i\omega_2, \quad \omega_1 > 0\] 

\[c_1 = \beta_7 + \i\beta_8, \quad c_2 = \beta_7 - \i\beta_8, \quad d_1 = \beta_9 + \i\beta_{10}, \quad d_2 = \beta_9 - \i\beta_{10}\] 

\[r_1 = \omega_1 + \i\nu_{xy}\beta_7, \quad r_2 = \omega_2 + \i\nu_{xy}\beta_8, \quad r_3 = 1 + \i\nu_{xy}(\omega_1\beta_9 - \omega_2\beta_{10})/\beta_5\] 

\[r_4 = \nu_{xy}(\omega_1\beta_{10} + \omega_2\beta_9)/\beta_5, \quad r_5 = \omega_1\nu_{xy}\beta_7, \quad r_6 = \omega_2\nu_{xy}\beta_8, \quad r_7 = \nu_{xy}(\omega_1\beta_9 - \omega_2\beta_{10})/\beta_5, \quad r_8 = r_4/\nu_{xy}, \quad r_9 = \omega_1\beta_7 - \omega_2\beta_8 - 1\] 

\[r_{10} = \omega_2\beta_7 + \omega_1\beta_8, \quad r_{11} = -\beta_10 + \omega_2/\beta_5, \quad r_{12} = \beta_9 - \omega_1/\beta_5\] 

\[r_{13} = -\beta_9 - \beta_{10}r_{12}/r_{11}, \quad r_{14} = -(r_7 + r_8r_{12}/r_{11})/2r_{13}\] 

\[r_{15} = r_4 - r_3r_{12}/r_{11}, \quad r_{16} = r_5r_6/4r_{13}\omega_1, \quad r_{17} = -r_{11} - r_{12}/r_{11}\] 

\[r_{18} = \omega_1 r_{17}/4r_{13}, \quad r_{19} = r_1 r_{10} - r_2 r_9, \quad r_{20} = r_2 r_{10} + r_1 r_9\] 

\[r_{21} = -r_6 r_{16} r_9 - r_6 r_{18} r_9 + r_5 r_{10} r_{16} + r_2 r_5 r_{18}\] 

\[r_{22} = (r_1 r_5 - r_2 r_5)r_{18}\omega_2/\omega_1\] 

\[r_{23} = -r_6 r_{10} r_{16} - r_2 r_6 r_{18} - r_5 r_9 r_{16} - r_1 r_5 r_{18}\] 

\[r_{24} = (r_2 r_6 + r_1 r_5)r_{18}\omega_2/\omega_1, \quad r_{25} = -r_{21} - r_{24}, \quad r_{26} = r_{21} - r_{24}\] 

\[r_{27} = r_{22} r_{23}, \quad r_{28} = r_{22} + r_{23}, \quad r_{29} = -(\omega_1 r_{28} + \omega_2 r_{26})/(\omega_1^2 + \omega_2^2)\] 

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Figure 1. Infinite strip with two internal cracks.