7-2015

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Louis Milton Brock

University of Kentucky, louis.brock@uky.edu

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CONTOURS FOR PLANAR CRACKS GROWING IN THREE DIMENSIONS: ILLUSTRATION FOR TRANSVERSELY ISOTROPIC SOLID

LOUIS MILTON BROCK

Three-dimensional dynamic steady state growth of a semi-infinite plane crack in a transversely isotropic solid is considered. Growth takes place on a principal plane with the material symmetry axis as one tangent. Fracture is brittle, and driven by compressive loads that translate on the crack surfaces. Translation speed is constant and subcritical, but direction with respect to the principal axes is arbitrary. An analytical solution is obtained, and examined in light of the dynamic energy release rate criterion for the case of a translating compressive point force. Introduction of quasipolar coordinates leads to a nonlinear first-order differential equation for the distance between force and crack edge. The equation depicts a crack edge that tends to the rectilinear away from the force. An analytical expression for the distance measured parallel to translation direction indicates a marked deviation from the rectilinear near the point force.

Introduction

A major goal of fracture mechanics is the determination of crack edge location. In 2D dynamic fracture, this requires an equation of motion for the crack tip [Freund 1990]. In a 3D study, such an equation must describe the crack contour. This goal has been achieved for semi-infinite crack growth in an unbounded isotropic solid [Brock 2015]. This paper extends the analysis to an unbounded transversely isotropic solid. For simplicity, the crack remains in its original plane, which is a principal plane. Moreover, crack growth is caused by compression loads on the crack surface that translate at constant subcritical speed in a fixed direction, and achieves a dynamic steady state.

Two-dimensional dynamic analyses of transversely isotropic half-spaces in which the material symmetry axis coincides with the surface normal essentially correspond to those for the isotropic case, e.g., [Scott and Miklowitz 1967]. As seen in sliding contact analysis [Brock 2013], elastic properties associated with principal planes other than that on the surface do influence 3D results but the solution forms resemble those for the isotropic case. When the surface normal is not the material symmetry axis, however, 3D solution forms are quite distinctive. Therefore, to enhance the effect of anisotropy, (a) the principal plane in this 3D illustration includes the axis of material symmetry, and (b) the fixed direction is arbitrary with respect to this axis.

Two-dimensional analyses of fracture for the general anisotropic solid in the dynamic steady state exist, of course. Indeed, the semi-infinite interface crack has been examined by Willis [1971]. Principal axes define both in-plane coordinates and interface, and the crack edge exhibits the well-known oscillatory behavior. Nevertheless, as in [Brock 2015] and the present study, a formula for crack extension based on dynamic energy release rate is developed.

Keywords: 3D, dynamic, criteria, analytic solution, crack contour, transverse isotropy, energy release.
Analysis begins by considering the unmixed boundary value problem for a discontinuity in displacement imposed over a semi-infinite plane area $A_C$ contained in an unbounded solid. This is of course a dislocation problem and is a standard [Willis 1971; Barber 1992] first step in fracture analysis. For efficiency in application to the title problem, this study considers a discontinuity that vanishes along area boundary $B_C$, vanishes at infinite distances from it, and translates with $A_C$ at constant subcritical speed $V$ in a fixed direction. A dynamic steady state ensues and allows use of a translating Cartesian basis. The transform solution is generated, but a quasipolar coordinate system is introduced in the inversion process. Expressions for normal traction on the plane of $A_C$ lead to a classical singular integral equation for the displacement discontinuity produced were $A_C$ a crack subject to a prescribed surface load. Imposition of a fracture criterion leads to a nonlinear first-order differential equation for the distance from a given point in $A_C$ to any point on (now) crack edge $B_C$.

Displacement discontinuity growth — governing equations

Consider an unbounded, transversely isotropic and linearly elastic solid. Cartesian basis $x = x(x_k)$ defines the principal material axes. The semi-infinite planar region $A_C (x_3 = 0, x_V < 0)$ with rectilinear boundary $B_C (x_V = 0)$ is subject to discontinuity

$$[u(u_k)] = U(U_k).$$

Here $k = (1, 2, 3)$, [] signifies a jump as travel from $x_3 = 0$— to $x_3 = 0+$ occurs, $u$ is the displacement field and discontinuity components $U_k = U_k(x_1, x_2)$. The $x_2$-direction defines the axis of material symmetry, and

$$x_V = x_1 \cos \theta + x_2 \sin \theta, \quad |\theta| < \frac{\pi}{2}.$$  \hspace{1cm} (2a)

The region translates in the positive $x_V$-direction at constant subcritical speed $V$. A dynamic steady state is achieved by $(U, A_C)$, and boundary $B_C$ may no longer be rectilinear. Displacement $u(u_k)$ and traction $T(\sigma_{ik})$ do not vary in the moving frame of $A_C$. Basis $x$ is therefore translated with $A_C$ so that $u_k = u_k(x)$, $U_k = U_k(x_1, x_2)$, $\sigma_{ik} = \sigma_{ik}(x)$, and the time derivative can be written

$$-V \partial V, \quad \partial V = \partial_1 \cos \theta + \partial_2 \sin \theta.$$  \hspace{1cm} (2b)

Here $\partial_k$ signifies $x_k$-differentiation. For convenience, $x = 0$ is located in the region of discontinuity, so that function $\Im(x_1, x_2) = 0, \sqrt{x_1^2 + x_2^2} \neq 0$ defines contour $B_C$ and the region can be defined as $(x_1, x_2) \in A_C$. Both $\Im$ and its gradient $\nabla \Im$ are continuous, and any line passing through $x = 0$ in the $x_1x_2$-plane can cross $B_C$ only once. For $x_3 \neq 0$, governing equations for $u(x_k)$ can be written as [Brock 2013]

$$\nabla \cdot T = C_{44} V^2 \partial_V^2 u,$$

$$[\sigma_{11}] = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{12} & C_{22} & C_{12} \end{bmatrix} \begin{bmatrix} \partial_1 u_1 \\ \partial_2 u_2 \end{bmatrix},$$  \hspace{1cm} (3a)

$$\sigma_{2k} = C_{44}(\partial_2 u_k + \partial_k u_2) \quad \text{for} \quad k = 1, 3, \quad \text{and} \quad \sigma_{31} = C_{55}(\partial_3 u_1 + \partial_1 u_3).$$  \hspace{1cm} (3b)
Here \((C_{11}, C_{22}, C_{12}, C_{13}, C_{44}, C_{55})\) are the elastic constants, and \(C_{13} = C_{11} - 2C_{55}\) [Jones 1999]. As reference quantities, we adopt shear modulus and shear wave speed

\[
\mu = C_{44}, \quad V_s = \sqrt{C_{44}/\rho}.
\] (4a)

Here \(\rho\) is mass density, and (4a) gives the dimensionless terms

\[
c = \frac{V}{V_s}, \quad d_1 = \frac{C_{11}}{C_{44}}, \quad d_2 = \frac{C_{22}}{C_{44}}, \quad d_5 = \frac{C_{55}}{C_{44}}, \quad d_{12} = \frac{C_{12}}{C_{44}}, \quad d_{13} = \frac{C_{13}}{C_{44}} = d_1 - 2d_5.
\] (4b)

In light of (1), conditions for \(x_3 = 0\) are

\[
[u_k] = U_k \quad \text{for} \quad (x_1, x_2) \in A_C, \quad [u_k] = 0 \quad \text{for} \quad (x_1, x_2) \notin A_C, \quad [\sigma_{3k}] = 0.
\] (5a)

Components \(U_k\) are not specified, but must be finite and continuous for \((x_1, x_2) \in A_C\). Therefore \(U_k = 0\) for \(\Im(x_1, x_2) = 0\), and \((u, T)\) should remain finite for \(|x| \to \infty, x_3 \neq 0\).

**General transform solution**

A double bilateral transform [Sneddon 1972] can be defined as

\[
\hat{F} = \int \int F(x_1, x_2) \exp(-p_1 x_1 - p_2 x_2) dx_1 dx_2.
\] (6)

Integration is along the entire \(\text{Re}(x_1)\)- and \(\text{Re}(x_2)\)-axes. Application of (6) to (3) gives

\[
\hat{u} = \hat{u}_5 + \hat{u}_+ + \hat{u}_-,
\] (7a)

\[
\hat{u}_5 = U_5^{(\pm)} \exp(-B_5 |x_3|), \quad \hat{u}_\pm = U_\pm^{(\pm)} \exp(-A_\pm |x_3|).
\] (7b)

In (7b) superscript \((\pm)\) signifies \(x_3 \geq 0\) and \(x_3 \leq 0\), respectively, and

\[
(U_5)_1^{(\pm)} = (\pm)B_5 V_5^{(\pm)}, \quad (U_5)_2^{(\pm)} = 0, \quad (U_5)_3^{(\pm)} = p_1 V_5^{(\pm)},
\] (8a)

\[
(U_\pm)_1^{(\pm)} = -(1 + d_{12})p_1 d_2 V_\pm^{(\pm)}, \quad (U_2)_2^{(\pm)} = d_1 (A_\pm + \Gamma_1) V_\pm^{(\pm)},
\] (8b)

\[
(U_\pm)_3^{(\pm)} = (\pm)(1 + d_{12})p_2 A_\pm V_\pm^{(\pm)}.
\] (8c)

Here \(V_5^{(\pm)}, V_\pm^{(\pm)}\) are arbitrary functions of \((p_1, p_2)\) and

\[
B_5 = \sqrt{-p_1^2 - \Gamma_0/d_5}, \quad T_5 = d_5 (p_1^2 - B_5^2),
\] (9a)

\[
\Gamma_0 = p_2^2 - c^2 p_\nu^2, \quad \nu_\nu = p_1 \cos \theta + p_2 \sin \theta,
\] (9b)

\[
A_\pm = \sqrt{-p_1^2 - \Gamma_\pm/d_1}, \quad \Gamma_\pm = \frac{1}{2} (M \pm \sqrt{M^2 - 4d_1 \Gamma_2 \Gamma_0}),
\] (9c)

\[
M = d_1 \Gamma_2 + \Gamma_0 - (1 + d_{12})^2 p_\nu^2, \quad \Gamma_1 = p_1^2 + \Gamma_0/d_1, \quad \Gamma_2 = d_2 p_2^2 - c^2 p_\nu^2.
\] (9d)

For bounded behavior as \(|x_3| \to \infty\), (7b) requires that \(\text{Re}(B_5, A_\pm) \geq 0\) in the cut complex \((p_1, p_2)\)-planes. Application of (6) to (3b), (3c) and (5) and substitution of (8) and (9) gives equations for \(V_5^{(\pm)}, V_\pm^{(\pm)}, V_-^{(\pm)}\) in terms of transforms \(\hat{U}_k\). The solutions are then used to generate expression (A.1)
for \((\hat{\theta}_{33}, \hat{\theta}_{31}, \hat{\theta}_{32})\) in plane \(x_3 = 0\). That the \(x_3\)-direction does not correspond to the material symmetry axis is clear from the different forms for (A.1b) and (A.1c).

**Transform inversion — general formulas**

In (5), inhomogeneous terms \((U_1, U_2, U_3)\) arise only for \((x_1, x_2) \in A_C\). In light of (A.1), therefore, the inversion operation corresponding to (6) gives \((\sigma_{33}, \sigma_{31}, \sigma_{32})\) for \(x_3 = 0\) as linear combinations of expressions

\[
\int \int U_k \, d\xi_1 \, d\xi_2 \, \frac{1}{2\pi i} \int dp_1 \, \frac{1}{2\pi i} \int P_k \, dp_2 \, \exp[p_1(x_1 - \xi_1) + p_2(x_2 - \xi_2)].
\]  

(10)

Here \(U_k = U_k(\xi_1, \xi_2)\) and \(P_k = P_k(p_1, p_2)\) is the corresponding coefficient. Double integration is over \(A_C\), and single integration is over the entire \(\text{Im}(p_1)\) and \(\text{Im}(p_2)\)-axes. After [Brock 2013; 2015], transformations are introduced:

\[
p_1 = p \cos \psi, \quad p_2 = p \sin \psi,
\]  

(11a)

\[
\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos \psi \sin \psi \\ -\sin \psi \cos \psi \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad \begin{bmatrix} \xi \\ \eta \end{bmatrix} = \begin{bmatrix} \cos \psi \sin \psi \\ -\sin \psi \cos \psi \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}.
\]  

(11b)

In (11a) and (11b), \(\text{Re}(p) = 0\), \(\text{Im}(p), x, y, \xi, \eta| < \infty\) and \(|\psi - \theta| < \frac{\pi}{2}\). Parameters \((p, \psi), (x, \psi; y = 0)\) and \((\xi, \psi; \eta = 0)\) resemble quasipolar coordinate systems, i.e.,

\[
d\xi_1 \, d\xi_2 = |\xi| \, d\xi \, d\psi, \quad dp_1 \, dp_2 = |p| \, dp \, d\psi.
\]  

(11c)

Use of (11) in (9) give

\[
\begin{align*}
\Gamma_0 &= p^2 C_0, & \Gamma_1 &= p^2 C_1, & \Gamma_2 &= p^2 C_2, & T_5 &= p^2 T_5, \\
\Gamma_\pm &= p^2 C_\pm, & M &= p^2 M, & A_\pm &= A_\pm \sqrt{p} \sqrt{-p}, & B_5 &= B_5 \sqrt{p} \sqrt{-p}.
\end{align*}
\]  

(12a)

Equation (12) is based on parameters that depend on \((c, \psi, \theta)\):

\[
\begin{align*}
C_0 &= \sin^2 \psi - c_V^2, & C_1 &= \cos^2 \psi + C_0/d_1, & C_2 &= d_2 \sin^2 \psi - c_V^2, \\
T_5 &= 2d_5 \cos^2 \psi + C_0, & c_V &= c \cos(\psi - \theta), \\
M &= d_1 C_2 + C_0 - (1 + d_1d_2)^2 \sin^2 \psi, & C_\pm &= \frac{1}{2} \left[ M \pm \sqrt{M^2 - 4d_1C_2C_0} \right], \\
B_5 &= \sqrt{\cos^2 \psi + C_0/d_5}, & A_\pm &= \sqrt{\cos^2 \psi + C_\pm/d_1}.
\end{align*}
\]  

(13a)

If \(\text{Re}(B_5, A_\pm) \geq 0\), terms in (7) are bounded when branches \(\text{Im}(p) = 0\), \(\text{Re}(p) < 0\) and \(\text{Im}(p) = 0\), \(\text{Re}(p) > 0\) are introduced for \(\sqrt{\pm p}\), respectively, such that \(\text{Re}(\sqrt{\pm p}) > 0\) in the cut \(p\)-plane. Behavior of \((B_5, A_\pm)\) therefore helps to define allowable speed for a particular solid.

**Transform inversion — transversely isotropic solid, allowable speed**

In view of [Payton 1983] and (4b), transversely isotropic solids can be categorized as follows, where we define \(\gamma = 1 + d_1d_2 - (1 + d_1d_2)^2\):

\[
\begin{align*}
\text{Re}(B_5, A_\pm) \geq 0, \quad \text{Cut } p\text{-plane.}
\end{align*}
\]  

(13d)
As an illustration, consider materials [Payton 1979] in particular, those which, like zinc, restrict speed for translation direction \( \theta \). Calculations of (15a) are presented in Tables 1 and 2 for values of \( \theta \).

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>0°</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_+(\theta) )</td>
<td>2.0564</td>
<td>1.9502</td>
<td>1.8149</td>
<td>1.6673</td>
<td>1.2762</td>
</tr>
<tr>
<td>( c_-(\theta) )</td>
<td>1.0</td>
<td>0.8805</td>
<td>0.7967</td>
<td>0.7061</td>
<td>1.0</td>
</tr>
<tr>
<td>( c_5(\theta) )</td>
<td>1.2823</td>
<td>1.2178</td>
<td>1.1498</td>
<td>1.0775</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 1. Dimensionless speeds for \( x_V \)-direction in \( x_1,x_2 \)-principal plane (zinc).

\[
\begin{align*}
2\sqrt{d_1d_2} & \leq \gamma \leq 1 + d_1d_2 & \text{for} & \quad 1 < d_1 < d_2, \\
d_1 + d_2 & \leq \gamma \leq 1 + d_1d_2 & \text{for} & \quad 1 < d_2 < d_1, \\
2d & \leq \gamma \leq 1 + d^2 & \text{for} & \quad 1 < d_1 = d_2 = d;
\end{align*}
\]

For \( |\psi - \theta| < \pi/2 \) and \( M^2 - 4d_1C_2C_0 \geq 0 \) Equations (13c) and (13d) hold, and \( A_\pm \) is real and nonnegative. For \( M^2 - 4d_1C_2C_0 \leq 0 \) however, the complex conjugates arise:

\[
A_\pm = \Omega_C \pm i\Omega_S, \tag{14a}
\]

\[
\Omega_C = \frac{1}{\sqrt{2}}\sqrt{A^2_\psi + \cos^2 \psi + M/2d_1} \geq 0, \quad \Omega_S = \frac{1}{\sqrt{2}}\sqrt{A^2_\psi - \cos^2 \psi - M/2d_1} \geq 0, \tag{14b}
\]

\[
A_\psi = [\cos^4 \psi + (M \cos^2 \psi + C_2C_0)/d_1]^{1/4}, \tag{14c}
\]

\[
A_+ + A_- = 2\Omega_C, \quad A_+A_- = A^2_\psi. \tag{14d}
\]

For \( |\psi - \theta| < \pi/2 \), \( c_V < c \) so that allowable speed for a given translation direction is defined by branch points of \( (A_\pm, B_5) \) on the positive Re\( (c) \)-axis for \( (\psi = \theta, |\theta| < \pi/2) \):

\[
c_\pm(\theta) = \sqrt{D_2 \pm \sqrt{D_2^2 - D_4}}, \quad c_5(\theta) = \sqrt{d_5 \cos^2 \theta + \sin^2 \theta}, \tag{15a}
\]

\[
D_2 = \frac{1}{2}(1 + d_1 \cos^2 \theta + d_2 \sin^2 \theta), \tag{15b}
\]

\[
D_4 = d_1 \cos^4 \theta + d_2 \sin^4 \theta + \gamma \sin^2 \theta \cos^2 \theta. \tag{15c}
\]

As an illustration, consider materials [Payton 1979]

III (zinc): \( d_1 = 4.2286, d_2 = 1.6286, d_5 = 1.6442, d_{12} = 1.3195, d_{13} = 0.9403 \).

I (beryl): \( d_1 = 4.11, d_2 = 3.62, d_5 = 2.0, d_{12} = 1.017, d_{13} = 1.055 \).

Calculations of (15a) are presented in Tables 1 and 2 for values of \( \theta \). Table 1 for zinc demonstrates that \( c_+(\theta) > c_5(\theta) \geq c_-(\theta) \). Table 2, however, shows that the relation between \( c_5(\theta) \) and \( c_-(\theta) \) is itself \( \theta \)-dependent. Although these are examples, the present study will focus on category III materials and, in particular, those which, like zinc, restrict speed for translation direction \( |\theta - \psi| < \pi/2 \) to the range \( 0 < c < c_-(\theta) \).

In view of this, and conditions on contour function \( \Im \), (10) assumes the form

\[
\frac{1}{i\pi} \int_{\psi} P_k \, d\psi \int_N d\eta \frac{\partial}{\partial x} \int_X d\xi \frac{\partial U_k}{\partial \xi}(\xi, \eta) \frac{1}{2\pi i} \int \frac{|p|}{p} \frac{\sqrt{-p}}{\sqrt{p}} \, dp \exp(p(x - \xi)). \tag{16}
\]
Table 2. Dimensionless speeds for \(x_V\)-direction in \(x_1x_2\)-principal plane (beryl).

<table>
<thead>
<tr>
<th>(\theta)</th>
<th>0°</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_+(\theta))</td>
<td>2.0278</td>
<td>1.9428</td>
<td>1.857</td>
<td>1.8514</td>
<td>1.9026</td>
</tr>
<tr>
<td>(c_-(\theta))</td>
<td>1.0</td>
<td>1.1326</td>
<td>1.1902</td>
<td>1.1469</td>
<td>1.0</td>
</tr>
<tr>
<td>(c_5(\theta))</td>
<td>(\sqrt{2})</td>
<td>1.3229</td>
<td>1.2247</td>
<td>1.118</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Symbols \((N, X, \Psi)\) signify integration over ranges \(|\psi - \theta| < \frac{\pi}{2}\), \(N^- < \eta < N^+\) and \(X_- < \xi < X_+\), respectively. In light of (A.1), (13d) and (14d), term \(P_k = P_k(\psi, \theta)\) is real-valued. The \(p\)-integration is along the positive side of the entire imaginary axis, and can be performed by use of Appendix B. Then, because \(U_k\) vanishes continuously on \(C\), (16) gives

\[
\frac{1}{\pi} \int_\Psi P_k d\psi \frac{\partial}{\partial x} \int_N d\eta \frac{1}{\pi} \int_X \frac{\partial U_k}{\partial \xi}(\xi, \eta) \frac{d\xi}{\xi - x}.
\]  

(17)

Limits \(N^\pm(\psi)\) in (17) are defined by

\[
\Im(\xi_1(\xi, N^\pm), \xi_2(\xi, N^\pm)) = 0, \quad \frac{dN^\pm}{d\xi} = 0.
\]

(18)

That is, for given \(\psi\), limits \(N^\pm\) are the maximum and minimum values of \(\eta\) on \(B_C\), and for given \(\eta\), limits \(X^\pm(\psi, \eta)\) locate the ends of lines that run parallel to the \(\xi\)-axis and that span \(A_C\). Conditions on \(B_C\) imply that these limits exist, are single-valued, and vary continuously in \(\psi\). Figure 1 gives a generic sketch for \(A_C\) and it is seen that, for semi-infinite \(A_C\), \(N^\pm(\psi) \to \pm \infty\) and \(|X_-(\psi, \eta)| \to \infty\) for certain ranges of \(\psi\).

In light of (7)–(12), traction in \(A_C\) itself, i.e., \(x_3 = 0, (x_1, x_2) \in A_C\), is

\[
\sigma_{3k} = -\frac{1}{\pi} \int_\Psi d\psi \int_N d\eta \frac{\partial}{\partial x} \int_X d\xi \delta(\xi, \eta) \sigma_{3k}(x_1(\xi, \eta), x_2(\xi, \eta)).
\]

(19)

Figure 1. Schematic of area \(A_C\) and contour \(B_C\).
In (19), $\delta$ is the Dirac function. Therefore, expressions for traction in $A_C$ can be obtained by matching the integrands of $(\psi, \eta)$-integration in (19) with combinations of those in (17). Moreover, $\xi$ in (17) and (19) is an integration variable representing parameter $x$ that itself depends on $(x_1, x_2)$ and $\psi$. As noted in connection with (11), coordinates $(x_1, x_2)$ can be replaced by $(x, \psi)$ for $y = 0$. Thus, every point $(x_1, x_2) \in A_C$ lies on an integration path $\eta = 0$ that passes through both limit points of the $\xi$-integral. Results of matching (17) and (19) give, therefore, expression (C.3).

Related crack growth problem: Basic results

Region $A_C$ is now a semi-infinite crack, i.e., translation speed $V$ is the crack growth speed, and $\Im(x_1, x_2) = 0$ is such that $B_C$ in Figure 1 is an arc of infinite length. The two crack surfaces are subjected to equal compressive stress $\sigma_{32} = \sigma_{31} = 0$, $\sigma_{33} = -\sigma^C_{33}$, where, for $(x_1, x_2) \in A_C$, $\sigma^C_{33}$ is nonnegative, finite, piecewise continuous and

$$\sigma^C_{33} \approx O((x_1^2 + x_2^2)^{-\chi}), \quad \sqrt{x_1^2 + x_2^2} \to \infty \quad \text{for} \quad \chi > 1. \quad (20)$$

Coupled singular integral equations for the $x$-derivatives of $(U_1, U_2, U_3)$ are provided by (C.3), with $(\sigma_{32}, \sigma_{31}) = 0$ and $\sigma_{33} = -\sigma^C_{33}$. Solution gives the derivatives and the functions themselves. If $\sigma^C_{33}$-values are largest near $(x_1, x_2) = 0$, it is reasonable to assume that any curvature of crack edge $B_C$ will produce an essentially concave profile with respect to this point. In view of the original conditions on $B_C$ then, $(U_1, U_2) = 0$ and two cases arise for $U_3$. Case $X_+ = x_+(\psi) > 0$, $X_- = -x_- (\psi)$ gives

$$\frac{\partial U_3}{\partial x} = \frac{1}{\sqrt{x_+ - x}} \frac{(vp)}{\pi} \int_x g_3 d\xi \sqrt{x_+ - \xi + x_-}, \quad (21a)$$

$$U_3 = \frac{1}{\pi} \int_x g_3 d\xi \ln \left| \frac{\sqrt{x_+ - x} \sqrt{\xi + x_-} - \sqrt{x_+ + x_-} \sqrt{\xi + x_-}}{\sqrt{x_+ - x} \sqrt{\xi + x_-} + \sqrt{x_+ + x_-} \sqrt{\xi + x_-}} \right|, \quad (21b)$$

$$g_3 = -\frac{2C_0}{\mu G_3} \sigma^c_{33}. \quad (21c)$$

Continuity of $B_C$ requires $x_+ (\frac{\pi}{2} - \theta) = x_- (\frac{-\pi}{2} - \theta)$. For $X_+ = x_+(\psi)$, $X_- \to -\infty$,

$$\frac{\partial U_3}{\partial x} = \frac{1}{\sqrt{x_+ - x}} \frac{(vp)}{\pi} \int_x g_3 d\xi \sqrt{x_+ - \xi}, \quad (22a)$$

$$U_3 = \frac{1}{\pi} \int_x g_3 d\xi \ln \left| \frac{\sqrt{x_+ - \xi} - \sqrt{x_+ - x}}{\sqrt{x_+ - \xi} + \sqrt{x_+ - x}} \right|. \quad (22b)$$

Continuity of $B_C$ now requires that $x_+(\theta \pm \frac{\pi}{2}) \to \infty$. Equations (21b) and (22b), as is appropriate, vanish continuously on $B_C$. Substitution of (21a) and (22a) into (17) and performing the $\xi$-integration for $x \notin X$ leads to, respectively, expressions for traction on plane $x_3 = 0$, $(x, \psi) \notin A_C$:

$$\sigma_{33} = \frac{1}{\pi \sqrt{x_+ - x} \sqrt{x_+ + x}} \int_x \sigma^C_{33} d\xi \sqrt{x_+ - \xi} \sqrt{x_+ + x_-}, \quad (23a)$$

$$\sigma_{33} = \frac{1}{\pi \sqrt{x_+ - x}} \int_x \sigma^C_{33} d\xi \sqrt{x_+ - \xi}. \quad (23b)$$
Critical speed: Illustration

Restriction \(0 < c < c_-(\theta)\) guarantees a bounded solution. In addition, (21b) and (22b) define crack surface separation, which should be nonnegative. Thus term \(C_0/G_3\) in (21c) should be negative and finite. The same condition arises in the isotropic limit

\[
d_1 = d_2 = d, \quad d_4 = d_5 = 1, \quad d_{12} = d_{13} = d - 2, \quad d = 2 \frac{1 - \nu}{1 - 2\nu}.
\]

Here \(\nu\) is Poisson’s ratio, and it can be shown that

\[
\begin{align*}
c_+ (\theta) &= \sqrt{d}, & c_- (\theta) &= c_5 (\theta) = 1, \\
A_+ &= A = \sqrt{1 - c_5^2/d}, & A_- &= B_5 = B = \sqrt{1 - c_5^2}, \\
G_3/C_0 &= -R/c_5^2 A, & R &= 4AB - (1 + B^2)^2.
\end{align*}
\]

In (24c), \(R \to 0 + (cV \to 0)\) and \(R = -1 (cV \to 1)\), which implies that \(R = 0 (cV V = c_R, 0 < c_R < 1)\). Thus, \(R\) is a Rayleigh function, \(V_R\) is the Rayleigh speed, and crack growth rate is restricted by \(0 < c < c_R\).

The situation is more complicated for the transversely isotropic solid: for \(\psi = \theta = 0\), \(G_3/C_0\) is negative for \(c < c_-\) and vanishes when

\[
4A_1 A_5 - (1 + A_2^2)^2 = 0, \quad (25a)
\]

\[
A_1 = \sqrt{1 - c^2/d_1}, \quad A_5 = \sqrt{1 - c^2/d_5}. \quad (25b)
\]

For the category III solid, in particular, \(G_3/C_0\) vanishes for \(\psi = \theta = \frac{\pi}{2}\) when

\[
\begin{align*}
\left[ 1 + (1 + d_{12})^2 - \sqrt{d_1 d_2 A_2 B} \right] B^2 + \sqrt{d_1 d_2 (1 - \sqrt{d_1 d_2 B^2})} A_2^2 &= 0, \quad (26a)
A_2 &= \sqrt{1 - c^2/d_2}, \quad B = \sqrt{1 - c^2}. \quad (26b)
\end{align*}
\]

Calculations for zinc give the roots of (25a) and (26a) as \(c_R \approx 1.16\) and \(c_R \approx 0.26\), respectively. However, Table 1 shows that the first root exceeds \(c_- (0)\). A similar result arose for sliding contact [Brock 2013]. That is, \(G_3/C_0\) plays the role of a Rayleigh function (cf. (25a) and (24c)) but its roots \(c_R\) may not give the minimum critical speed.

Brittle fracture parameter: Energy release (rate)

After [Griffith 1921] crack growth occurs when the rate of dynamic energy release matches that of potential energy decrease. For the 2D brittle crack, this criterion equates the rate per unit length (of crack edge) of energy release and negative of power per unit length generated in the crack plane [Willis 1971; Achenbach 1973; Freund 1990]. Here, total release rate \(\dot{G}_3\) and total power are considered. Affixed subscript “3” signifies the possibility that release rate in an anisotropic material depends on orientation of the fracture surface, e.g., here the surface normal aligns with the \(x_3\)-principal direction. Use of (8) for the dynamic steady state gives

\[
\dot{G}_3 = -V \int_{\psi} d\psi \left[ \left( \int_{-\infty}^{\infty} - \int_{X} \right) dx \sigma_{33} \partial_{\psi} U_3 + \int_{X} |x| dx \sigma_{33} \partial_{\psi} U_3 \right], \quad (27a)
\]
\[ \partial V = \cos(\psi - \theta) \frac{\partial}{\partial x} - \frac{\sin(\psi - \theta)}{|x|} \frac{\partial}{\partial \psi}. \]  

(27b)

To illustrate the form of \( \dot{D}_3 \) the \( \partial_V \)-operator is applied to case (23b):

\[
\partial_V U_3 = -\frac{(vp)}{\pi \sqrt{x_+ - x}} \int x g \left[ \sqrt{x_+ - \xi} \cos(\psi - \theta) - \frac{\sin(\psi - \theta)}{|x|} \cos(\psi - \theta) \frac{dx_+}{d\psi} \right] \\
+ \frac{\sin(\psi - \theta)}{\pi |x|} \int x \ln \left| \frac{\sqrt{x_+ - \xi} + \sqrt{x_+ - x}}{\sqrt{x_+ - \xi} - \sqrt{x_+ - x}} \right| \frac{\partial g_3}{\partial \psi}. \]

(28)

Equations (5a), (23b) and (28) imply that \( \dot{D}_3 = 0 \) in (27a). However (23b) and (28) are square-root singular for \( x \to x_+ + 0 \) and \( x \to x_+ - 0 \) respectively and, in the sense of a distribution [Achenbach and Brock 1973],

\[
\frac{H(x_+ - x)}{\sqrt{x_+ - x}} \frac{H(x - x_+)}{\sqrt{x - x_+}} = \frac{\pi}{2} \delta(x - x_+).
\]

(29)

Here \( H \) is the step function. Also, \( \dot{D}_3 \) is assumed invariant in (27a) with respect to its integrand. Singular behavior guarantees invariance in terms of \( x \), so that the integrand need only be constant in terms of \( \psi \). Therefore, for \( |\psi - \theta| < \frac{\pi}{2} \),

\[
\frac{\dot{D}_3}{\mu V_S} = -\frac{c C_0}{G_3} \left( \frac{G}{\mu} \right)^2 \frac{d}{d\psi} [x_+ \sin(\psi - \theta)], \quad G = \int x \frac{\sigma_{33}^C}{\sqrt{x_+ - x}} d\psi.
\]

(30)

Equation (30) is a nonlinear differential equation for \( x_+(\psi) \) based on (23), i.e., semi-infinite \( A_C \).

**Illustration: Point force**

Consider compressive point force loading

\[
\sigma_{31}^C = \sigma_{32}^C = 0, \quad \sigma_{33}^C = \frac{P \delta(r_0)}{2\pi r_0}, \quad r_0 = \sqrt{x_1^2 + x_2^2}.
\]

(31)

Here \( P \) is a force, so that traction \( \sigma_{33}^C \) is the axially symmetric Dirac function in standard polar coordinates. Function \( G \) in (30) for (31) is given in Appendix D. The right-hand side of (30) must be finite for \( |\psi - \theta| \to \frac{\pi}{2} \), and use of (13a), (C.2d) and (D.4b) gives

\[
x_+ \approx \sqrt{\frac{c \mu V_S}{2S D_3}} \frac{P}{2\pi \mu \sqrt{\cos(\psi - \theta)}} \quad \text{as} \quad |\psi - \theta| \to \frac{\pi}{2}.
\]

(32)

Terms in (32) are given by

\[
S = 4d_5 c_3' \tan^2 \theta + \frac{Q}{\Omega} \sqrt{d_1} \cos^2 \theta + T'^2 \left( \frac{Q}{\Omega} \frac{\sqrt{d_1} - \Omega}{D_4} \right),
\]

(33a)

\[
c_3' = \sqrt{d_5 \sin^2 \theta + \cos^2 \theta},
\]

(33b)

\[
Q = 1 + \frac{1}{D_4} \left( \sqrt{d_1} \sin^2 \theta + \frac{\cos^2 \theta}{\sqrt{d_1}} \right), \quad T' = \frac{2c_3'^2}{\cos \theta - \cos \theta},
\]

(33c)
\[
\Omega = \sqrt{\gamma \cos^2 \theta + 2 \sqrt{d_1 (\sqrt{d_1 \sin^2 \theta + D_4})}}, \quad (33d)
\]
\[
D_4 = \sqrt{d_1 \sin^4 \theta + d_2 \cos^4 \theta + \gamma \sin^2 \theta \cos^2 \theta}. \quad (33e)
\]

Equation (30) involves only \(x_+(\theta)\) itself for \(\psi = \theta\), i.e., the distance between point forces and crack edge measured in the direction of translation. In light of Appendix D, (30) can be solved algebraically as
\[
x_+(\theta) = F(c, \theta)L, \quad (34a)
\]
\[
F(c, \theta) = \sqrt{-cC_0/G_3}, \quad L = (P/2\pi)\sqrt{V_S/\mu\tilde{D}_3}. \quad (34b)
\]

Reference length \(L\) depends on a force/energy ratio. Term \(F(c, \theta)\) is dimensionless. Quantities \((C_0, G_3)\) come from (13), (14), (C.2d) and (C.3b) upon setting \(\psi = \theta\), \(c_V = c\). In view of (34) and invariance, (30) can be rewritten for \(|x - \theta| < \frac{\pi}{2}\) as
\[
-\frac{2C_0}{G_3x^3_+} \frac{d}{d\psi} [\sin(\psi - \theta)x_+] = \frac{F^2(c, \theta)}{cx^2_+(\theta)}. \quad (35)
\]

On the left-hand side of (35) we temporarily introduce \(z = x_+ \sin(\psi - \theta)\), which allows separation of variables. Integration in view of the asymptotic behavior noted above then gives \(x_+\) when \(\psi \neq \theta\):
\[
\frac{x^2_+(\theta)}{x^2_+(\psi)} = \frac{1}{c} F^2(c, \theta) \sin^2(\psi - \theta) \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{G_3 \, d\phi}{C_0 \sin^3(\phi - \theta)} \quad \text{for} \quad -\frac{\pi}{2} < \psi - \theta < 0, \quad (36a)
\]
\[
\frac{x^2_+(\theta)}{x^2_+(\psi)} = -\frac{1}{c} F^2(c, \theta) \sin^2(\psi - \theta) \int_{0}^{\frac{\pi}{2}} \frac{G_3 \, d\phi}{C_0 \sin^3(\phi - \theta)} \quad \text{for} \quad 0 < \psi - \theta < \frac{\pi}{2}. \quad (36b)
\]

Symbols \(\pm\) affixed to integral operators in (36) signify, respectively, integration ranges \(\psi < \phi < \theta + \frac{\pi}{2}\) and \(\theta - \frac{\pi}{2} < \phi < \psi\). Differentiation of (36) shows that \(dx_+/d\psi = 0\) for \(\psi = \theta\), i.e., crack edge and direction of point force translation are perpendicular directly ahead of the forces.

**Calculations**

Equation (36) and the asymptotic behavior noted for (32) indicate that, as in the isotropic case [Brock 2015], the crack edge \(B_C\) resembles those in Figure 2, where “\(x\)” denotes point force location. That is, it is a straight line at right angles to the translation/growth direction that is deformed by a bulge near the location \(x = 0\) of the translating point forces. Bulge size is characterized somewhat by the distance \(x_+(\theta)\) in (34). Therefore, values of dimensionless ratio \(F(c, \theta)\) are displayed in Table 3 for \(\theta = (0^\circ, 30^\circ, 45^\circ, 60^\circ, 90^\circ)\) respectively, and subcritical values of \(c\). Entries in Table 3 show that the bulge effect is enhanced by increase in extension speed \((c)\) and by deviation \((\theta)\) in force translation direction from the \(x_1\)-principal direction. Perhaps the latter behavior arises because \(d_2 < d_1\) \((C_{22} < C_{11})\).

**Some observations for more general loading**

Consider in place of (31) a finite, simply connected region \(A_0 \in A_C\) subjected to a finite and piecewise continuous pressure \(p_0\). The Green’s function for this case is obtained by replacing \((P, |x|)\) in (D.2)
Figure 2. Sketches of crack edge contour $B_C$.

with, respectively,

$$
\int \int_{A_0} p_0(u, \phi) |u| du d\phi,
$$

(37a)

$$
X = \sqrt{x^2 + u^2 - 2ux \cos(\phi - \psi)}.
$$

(37b)

Quasipolar coordinates $(u, \phi)$ lie in $A_0$ and, in consequence, the right-hand side of (D.3) is

$$
\frac{1}{\sqrt{z-x}} \frac{1}{Z^2 + \epsilon^2}, \quad Z = \sqrt{z^2 + u^2 - 2uz \cos(\phi - \psi)}.
$$

(38a)

Now $F_G(z)$ has three nonintersecting branch cuts, and the right-hand side of (D.4b) is

$$
\int \int_{A_0} \frac{d\phi}{\pi \sqrt{2}} \frac{p_0(u, \phi) |u| du}{Z_+ + x_+ - u \cos(\phi - \psi)} \quad \text{as} \quad \epsilon \to 0,
$$

(38b)

$$
Z_+ = \sqrt{x_+^2 + u^2 - 2ux_+ \cos(\phi - \psi)}.
$$

(38c)

Use of (38b) gives an equation for $x_+(\theta)$ that in general does not yield a closed-form result such as (34a). The result for $x_+$ when $|\psi - \theta| \to \frac{\pi}{2}$, however, is given by (32) with $P$ replaced by (37a). That is, asymptotic behavior of the crack edge depends only on total compressive load, not how that load may be distributed over a finite area.

<table>
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<th>$c$</th>
<th>$\theta$</th>
<th>$0^\circ$</th>
<th>$30^\circ$</th>
<th>$45^\circ$</th>
<th>$60^\circ$</th>
<th>$90^\circ$</th>
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<td>0.02526</td>
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<td>0.14</td>
<td>c &gt; $c_R$</td>
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</tbody>
</table>

Table 3. Crack edge location parameter $F(c, \theta)$ (zinc).
Some comments

This study extends a dynamic steady-state 3D analysis for an isotropic solid [Brock 2015] by illustrating semi-infinite crack growth in the principal plane of a transversely isotropic solid. Fracture is driven by compressive traction applied to the crack surfaces. An exact solution is possible and, upon introduction of a quasipolar coordinate system, gives a nonlinear first-order differential equation for the distance between a point on the crack plane and the crack edge. The distance function therefore defines the crack contour. The equation is studied for point force loading, so that distance can be chosen as that between forces and crack edge. Calculations show that the crack edge is rectilinear away from the point forces, and translates with them. Near the point forces, however, a bulge forms about them. Force-crack edge distance now increases with force translation speed, and increases are even more prominent as the translation direction aligns with the principal axis associated with the smaller elastic modulus.

These results are consistent with those of [Brock 2015]. Calculations of the distance (contour) function, however, require numerical evaluation of first integrals in (36); in [Brock 2015] analytical evaluation is possible. In addition these results are illustrations for a particular category of transversely isotropic solids [Payton 1983]. Nevertheless, general effects of transverse isotropy are emphasized, because the axis of material symmetry lies in the crack plane. These results are also consistent with those for sliding indentation on a half-space whose surface is the same principal plane [Brock 2013]: minimum critical growth rate may not be a Rayleigh speed. In closing, however, it should be mentioned that the possibility of energy release (rate) dependence on crack surface orientation was not exploited here.

Appendix A

For $x_3 = 0$:

$$\frac{\Gamma_0}{\mu} \hat{\sigma}_{33} = \hat{U}_3 \left[ 2d_5^2 p_1^2 B_5 + \frac{(\Gamma_1 - A_+ A_-)}{2A_+ A_- (A_+ + A_-)} \left( \frac{1}{2} T_5^2 + \Gamma_0 p_5^2 \right) + \frac{1}{2} T_5^2 \left( \frac{1}{A_+} + \frac{1}{A_-} \right) \right], \quad (A.1a)$$

$$\frac{\Gamma_0}{\mu} \hat{\sigma}_{31} = \frac{T_5}{2B_5} (T_5 \hat{U}_1 + p_1 p_2 \hat{U}_2) + \frac{d_5 p_1}{A_+ + A_-} \left[ (\Gamma_1 - A_+ A_-)(2p_1 \hat{U}_1 - p_2 \hat{U}_2) - \frac{\Gamma_0 p_2 \hat{U}_2}{d_1 (1 + d_{12})} \right], \quad (A.1b)$$

$$\frac{\Gamma_0}{\mu} \hat{\sigma}_{32} = \frac{p_1 p_2}{2B_5} (T_5 \hat{U}_1 + p_1 p_2 \hat{U}_2) - \Gamma_0 \left[ d_5 \frac{(1 + d_{12}) p_1 p_2}{A_+ + A_-} \hat{U}_1 + \frac{1}{2} \hat{U}_2 (A_+ + A_-) \right]$$

$$- \frac{\Gamma_1 - A_+ A_-}{A_+ + A_-} \left[ d_5 p_1 p_2 \hat{U}_1 + (p_2^2 + \Gamma_0) \frac{1}{2} \hat{U}_2 \right]. \quad (A.1c)$$

Appendix B

Consider the integral over the entire Im($p$)-axis:

$$\frac{1}{2\pi i} \int |p| \sqrt{-p} \sqrt{p} (A_R \mp i A_I) \exp(pX - (Y_R \mp i Y_I)\sqrt{-p} \sqrt{p}) \frac{dp}{p}. \quad (B.1)$$

Here $(A_R, A_I, X, Y_R, Y_I)$ are real constants, with $(X, Y_R, Y_I) \geq 0$, and $\mp$ signifies, respectively, Im($p$) > 0 and Im($p$) < 0. As noted in connection with (11) and (12), Re($\sqrt{\mp p}$) $\geq 0$ in the $p$-plane with branch cuts Im($p$) = 0, Re($p$) < 0 and Im($p$) = 0, Re($p$) > 0, respectively. In particular, for Re($p$) = 0+ and,
respectively, \( \text{Im}(p) = q > 0 \) and \( \text{Im}(p) = q < 0 \), we have

\[
\sqrt{-p} = \left| \frac{q}{2} \right|^{1/2} (1 \mp i), \quad \sqrt{p} = \left| \frac{q}{2} \right|^{1/2} (1 \pm i).
\] (B.2)

Use of (B.2) reduces (B.1) to

\[
\frac{1}{i\pi} \int_0^\infty \exp(-Y_R q) \left[ A_R \cos(X + Y_I) q - A_I \sin(X + Y_I) q \right] dq.
\] (B.3)

Performing the integration gives

\[
\frac{1}{i\pi} \int_0^\infty \exp(-Y_R q) \left[ A_R \frac{X + Y_I}{(X + Y_I)^2 + Y_R^2} - A_I \frac{Y_R}{(X + Y_I)^2 + Y_R^2} \right] dq.
\] (B.4a)

If factor \( \sqrt{-p}/\sqrt{p} \) in (B.1) is replaced by unity, the result becomes

\[
\frac{1}{i\pi} \int_0^\infty \exp(-Y_R q) \left[ A_R \frac{Y_R}{(X + Y_I)^2 + Y_R^2} + A_I \frac{X + Y_I}{(X + Y_I)^2 + Y_R^2} \right] dq.
\] (B.4b)

It is noted that

\[
\frac{1}{\pi} \frac{Y_R}{(X + Y_I)^2 + Y_R^2} \to \delta(X + Y_I) \quad \text{as} \quad Y_R \to 0 +.
\] (B.5)

Here \( \delta \) is the Dirac function.

**Appendix C**

For \( x_3 = 0, \ X_- < x < X_+, \ \psi \in \Psi \), i.e., \( x_3 = 0, \ (x_1, x_2) \in C \), we have

\[
\sigma_{33} = -\frac{\mu}{2\pi C_0} (vp) \int_x \frac{\partial U_3}{\partial x} \frac{G_3}{x - \xi} d\xi,
\] (C.1a)

\[
\sigma_{31} = -\frac{\mu}{2\pi C_0} (vp) \int_x \frac{\partial U_1}{\partial x} \frac{G_1}{x - \xi} d\xi - \frac{\mu}{2\pi C_0} (vp) \int_x \frac{\partial U_2}{\partial x} \sin 2\psi \frac{G_{12}}{x - \xi} d\xi,
\] (C.1b)

\[
\sigma_{32} = -\frac{\mu}{2\pi C_0} (vp) \int_x \frac{\partial U_1}{\partial x} \sin 2\psi \frac{G_{21}}{x - \xi} d\xi - \frac{\mu}{2\pi C_0} (vp) \int_x \frac{\partial U_2}{\partial x} \frac{G_2}{x - \xi} d\xi.
\] (C.1c)

Here \( U_k = U_k(\xi, \psi) \), \((vp)\) signifies the principal value, and for \( M^2 - 4d_1 C_2 C_0 > 0 \) we have

\[
G_1 = -\frac{T^2}{B_5} - 4d_5 \frac{A_+ A_+ + C_1}{A_+ + A_-} \cos^2 \psi,
\] (C.2a)

\[
G_2 = -\frac{\sin^2 2\psi}{2B_5} - C_0 (A_+ + A_-) + \frac{A_+ A_+ + C_1}{A_+ + A_-} (\sin^2 \psi - C_0),
\] (C.2b)
\[ G_{12} = G_{21} = -\frac{T_5}{2B_5} + \frac{2d_5}{A_+ + A_-} \left[ A_+ A_- + C_1 + (1 + d_{12}) \frac{C_0}{d_1} \right], \]  
\[ G_3 = 4d_5^2 B_5 \cos^2 \psi + \left( 1 + \frac{C_1}{A_+ + A_-} \right) \frac{T_5^2 + C_0 \sin^2 \psi}{A_+ + A_-} - \frac{T_5^2}{A_+ + A_-} (A_+ + A_-). \]  
(C.2d)

For \( M^2 - 4d_1 C_2 C_0 < 0 \) we have

\[ G_1 = -\frac{T_5^2}{B_5} - \frac{2d_5}{\Omega_C} (A_\psi^2 + C_1 \cos^2 \psi), \]  
\[ G_2 = -\frac{\sin^2 2\psi}{2B_5} - 2C_0 \Omega_C + \frac{1}{2\Omega_C} (A_\psi^2 + C_1) (\sin^2 \psi - C_0), \]  
\[ G_{12} = G_{21} = -\frac{T_5}{2B_5} + \frac{d_5}{\Omega_C} \left[ A_\psi^2 + C_1 + (1 + d_{12}) \frac{C_0}{d_1} \right], \]  
\[ G_3 = 4d_5^2 B_5 \cos^2 \psi + \frac{1}{2\Omega_C} \left( 1 + \frac{C_1}{A_\psi^2} \right) (T_5^2 + C_0 \sin^2 \psi) - \frac{2\Omega_C}{A_\psi^2} T_5^2. \]  
(C.3d)

Equations (13) and (14) govern equations (C.2) and (C.3), respectively. Term \( C_0 \) defined by (13a) may vanish for subcritical \( V \), but ratios of \( (G_1, G_2, G_{12}, G_{21}, G_3) \) with \( C_0 \) remain finite, e.g., for \( c_\psi^2 \rightarrow \sin^2 \psi \)

\[ \frac{G_3}{C_0} = 2d_5 \cos^2 \psi + \frac{1}{M_C} (4d_5^2 \cos^2 \psi + 2d_5^2 \sin^2 \psi) + 4d_5^2 \cos^2 \psi \left[ \frac{\cos \psi}{d_1 M_C (M_C + \cos \psi)} - \frac{1}{M_C} - \frac{1}{\cos \psi} \right] \]  
\[ - \frac{d_5^2}{d_1 M_C} \cos^3 \psi (m_+ \cos \psi + m_- M_C) \left[ 1 + \frac{1 + \cos \psi}{M_C (M_C + \cos \psi)} \right], \]  
\[ m_+ = 1 + d_1 + (1 + d_{12})^2, \quad m_- = \sin^2 \psi - \frac{2d_1(d_2 - 1)}{\gamma - 1 - d_1}, \]  
\[ M_C = \sqrt{\cos^2 \psi + \left[ \frac{1}{d_1} (\gamma - 1) - 1 \right] \sin^2 \psi}, \]  
\[ \gamma = 1 + d_1 d_2 - (1 + d_{12})^2. \]  
(C.4d)

**Appendix D**

In terms of quasipolar coordinates \( (x, \psi) \), (31) gives

\[ \sigma_{33}^c = P \frac{\delta(x)}{\pi|x|}, \quad |\psi| < \frac{\pi}{2}. \]  
(D.1)

Evaluation of \( G \) in (30) is obtained in terms of representation

\[ \sigma_{33}^c = P \frac{\epsilon}{\pi^2 |x| (x^2 + \epsilon^2)} \quad \text{as} \quad \epsilon \rightarrow 0. \]  
(D.2)

Function \( F_G(z) \) in the complex \( z \)-plane, where \( x = \text{Re}(z) \), is defined as

\[ F_G(z) = \frac{1}{\sqrt{z^2 - \epsilon_0^2} (z^2 + \epsilon^2) \sqrt{z - x_+}} \quad \text{for} \quad \epsilon_0 \approx 0. \]  
(D.3)
Here $F_G \approx O(z^{-3})$, $|z| \to \infty$ and exhibits branch cuts on the $\text{Re}(z)$-axis with branch points $z = (\pm \epsilon_0, x_\pm)$, and poles $z = \pm i \epsilon$. Thus integration over a closed contour that includes a portion $|z| \to \infty$, but excludes the poles and branch cuts, can be performed by residue theory. Setting $\epsilon_0 = 0$ then leads to the following expressions for $G$:

\begin{align}
G &= \frac{P}{\pi \alpha \sqrt{2(1 + \alpha)}} \frac{1}{x_+^{3/2}}, \quad \alpha = \sqrt{1 + \epsilon^2 / x_+^2}, \quad (D.4a) \\
G &= \frac{P}{2\pi x_+^{3/2}} \quad \text{as} \quad \epsilon \to 0. \quad (D.4b)
\end{align}

References


Received 29 Mar 2015. Revised 12 Jul 2015. Accepted 17 Jul 2015.

LOUIS MILTON BROCK: louis.brock@uky.edu
Department of Mechanical Engineering, College of Engineering, University of Kentucky, 265 RGAN, Lexington, KY 40506-0503, United States
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