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SOME TRANSIENT COUPLED THERMOELASTIC CRACK PROBLEMS

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This paper is concerned with determining the elastodynamic response of a plane strain medium containing a central crack deformed by the action of suddenly applied thermal and/or mechanical disturbances when the assumptions of the general theory of coupled thermoelasticity are assumed. Integral transform soultion is employed to reduce the governing equations into integral equations of Fredholm type. A numerical inversion technique is used to compute the dynamic stress-intensity factors when the faces of the crack are subjected to constant heat flux and/or mechanical loading. Attention is focused on the overshoot in the stress-intensity factor and its time interval for non-stationary temperature fields, and to what degree it is influenced by the mutual dependence of the temperature and displacement fields inherent in the coupled theory of thermoelasticity.

1. Introduction

Just as dynamic loading produce elastic waves, thermally activated disturbances and the accompanying heat conduction, generate thermoelastic waves which are transmitted through structural members. In isotropic solids there are two kinds of waves: A longitudinal wave and a transverse wave. Near an obstacle or a crack these waves are diffracted and reflected and give rise to high elevation of local stress which may trigger crack extension and eventual failure. The intensification of stress is usually measured by the stress-intensity factors which are functions of the crack and specimen geometries as well as the velocity and frequency of the travelling wave. Under dynamic loading the magnitude of the stress-intensity factor is larger than the corresponding statical one and, therefore, a knowledge of the overshoot in the stress-intensity factor is essential for a better understanding of the response and fracture behavior of structural components [1–3].

In an isotropic thermoelastic solid the thermal straining has no effect on the shear wave while two distinct dilatational waves exist [4–6]. One of these waves is similar in character to the elastic wave and the other is basically thermal in nature. Neither wave can exist without the other. At a crack tip these waves also cause high intensification of stress which may lead to breakdown of the structural element. To the best knowledge of the authors no dynamic solution to any thermoelastic crack problem is available in the literature. Several steady-state and uncoupled quasi-statical thermoelastic crack problems have been solved in the past [7–9].

The purpose of this paper is to investigate the propagation of elastic waves generated by thermal disturbances in a medium containing a central crack when the general theory of coupled thermoelasticity is employed. This theory takes into account the mutual influence of temperature and displacement fields. Its application is essential to a certain class of wave propagation problems in which there is an interaction between thermal and mechanical effects and where the major interest is concerned with thermoelastic damping. In using such a theory one can determine the nature of dynamic stresses produced by non-stationary temperature fields. Such results can be useful in the design of components which must withstand differential change in temperature.

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For a plane strain medium containing a central crack deformed by the application of suddenly applied thermal and/or mechanical disturbances, Laplace and Fourier transforms are used to reduce the problem to the solution of a Fredholm integral equation in the Laplace plane which is amenable to numerical treatment [10]. The dynamic stress-intensity factors are computed and displayed graphically for short time intervals for few materials. It is found that the overshoot in the stress-intensity factor is about 16–30% higher than the corresponding steady-state values. Also, the overshoot in the stress-intensity factor for non-stationary temperature fields tends to increase with increasing values of Poisson's ratio of the material. The thermoelastic coupling has negligible effect on the peak in the dynamic stress-intensity factor.

2. Basic equations

Neglecting body forces and internal heat sources, the governing equations of the linear coupled theory of thermoelasticity for an isotropic solid are [4]:

$$\mu \nabla^2 \vec{U} + (\lambda + \mu)\vec{\nabla} e - \alpha(3\lambda + 2\mu)\vec{\nabla} T = \rho \frac{\partial^2 \vec{U}}{\partial t^2}, \tag{1}$$

$$k\nabla^2 T - \rho c_v \frac{\partial T}{\partial t} = (3\lambda + 2\mu)\alpha T_0 \frac{\partial e}{\partial t}. \tag{2}$$

Equations (1) and (2) relate the displacement components, $\vec{U} = (U, V, W)$, to the temperature distribution, T, measured relative to the stress-free temperature, T_0. The constants, k, ρ and c_v appearing in the heat conduction equation denote, respectively, the thermal conductivity, mass density and the specific heat at constant volume of the solid. In eqs. (1) and (2), the dilatation has been denoted by e and ∇^2 stands for the usual Laplace operator while λ and μ are Lame's constants and α is the coefficient of linear expansion of the material.

It is convenient to use the following non-dimensional parameters for formulating plane problems in the $z = 0$ plane:

$$\begin{gathered} x = (c_1 x')/\kappa, \qquad y = (c_1 y')/\kappa, \qquad t = (c_1^2 t')/\kappa, \\ \theta = (T - T_0)/T_0, \qquad \beta^2 = \mu/(\lambda + 2\mu) = (c_2/c_1)^2, \\ u = \frac{\rho c_1^3 U}{(3\lambda + 2\mu)\alpha T_0 \kappa}, \qquad v = \frac{\rho c_1^3 V}{(3\lambda + 2\mu)\alpha T_0 \kappa}. \end{gathered} \tag{3}$$

Here, x', y' and t' are actual space and time variables, κ is the thermal diffusivity ($= k/\rho c_v$) and u, v and θ are, respectively, the normalized components of the displacement vector and the temperature field. Moreover, β designate the ratio of the velocities of the transverse and longitudinal waves in an infinite isothermal solid. In terms of the variables (3), eqs. (1) and (2) appear in the simplified scalar form:

$$\beta^2 \nabla^2 u + (1 - \beta^2)\frac{\partial e}{\partial x} - \frac{\partial \theta}{\partial x} = \ddot{u}, \qquad \beta^2 \nabla^2 v + (1 - \beta^2)\frac{\partial e}{\partial y} - \frac{\partial \theta}{\partial y} = \ddot{v}, \qquad \nabla^2 \theta - \dot{\theta} = \delta \dot{e}, \tag{4}$$

where a dot over a function indicates differentiation with respect to the normalized time variable and the dimensionless coupling constant, δ, designate the quantity

$$\delta = \frac{(3\lambda + 2\mu)^2 \alpha^2 T_0}{(\lambda + 2\mu)\rho c_v}. \tag{5}$$

In order to decompose the displacement components into potentials which govern the dilatational and shear waves, the following relations are usually used:

$$u = \frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial y}, \qquad v = \frac{\partial \phi}{\partial y} - \frac{\partial \psi}{\partial x}. \tag{6}$$

When relations (6) are introduced into (4), the following equations are obtained to determine the functions ϕ, ψ and θ.

$$\nabla^2\phi - \ddot{\phi} = \theta, \qquad \nabla^2\psi - \beta^{-2}\ddot{\psi} = 0, \qquad \nabla^2\theta - \dot{\theta} = \delta\nabla^2\dot{\phi}. \tag{7}$$

Equations (7) indicate that the pressure wave and the thermal field are mutually coupled while the shear wave remains unaltered by the thermal exposure. The stresses can be easily expressed in term of the potentials ϕ, ψ and θ. In particular, the components σ_y and τ_{xy}, normalized with respect to the quantity, $(3\lambda + 2\mu)\alpha T_0$, are given by the relations:

$$\sigma_y = \nabla^2\phi - 2\beta^2 \frac{\partial}{\partial x}\left(\frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial y}\right) - \theta, \qquad \tau_{xy} = \beta^2\left(2\frac{\partial^2\phi}{\partial x\,\partial y} - \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2}\right). \tag{8}$$

In the remaining part of the paper, eqs. (6)–(8) are used to determine the response of a structural member containing a central crack deformed by sudden exposure to changes in heat flux and/or mechanical loading while the region in the plane $y = 0$ outside the crack surfaces is insulated against the flow of heat.

3. Transient response

An infinite medium in plane strain contains a central crack of actual length $= 2a'$ and normalized length $(2a)$ with $a = c_1a'/\kappa$. Initially, the medium is undeformed, at rest and at a reference temperature, T_0. A sudden jump in the heat flux and/or loading is applied to the surfaces of the crack while the plane outside the crack is kept insulated. The aim is to find out the nature of the waves generated under the assumption of the coupled theory of thermoelasticity and, in particular, the nature of the crack tip stress field and the stress-intensity factor.

Assuming the origin of the coordinates (x, y, z) to coincide with the center of the crack, the boundary conditions for the thermally-induced deformations are:

$$\tau_{xy}(x, 0, t) = 0, \qquad \text{all } x, \text{ all } t, \tag{9a}$$

$$\frac{\partial\theta}{\partial y}(x, 0, t) = Q_0H(t), \tag{9b}$$

$$\sigma_y(x, 0, t) = 0, \qquad 0 \leq x \leq a, \quad \text{all } t, \tag{9c}$$

$$v(x, 0, t) = \frac{\partial\theta}{\partial y}(x, 0, t) = 0, \qquad x > a, \text{ all } t, \tag{9d}$$

in which, Q_0, is the constant amplitude of the heat flux applied at the crack surfaces and $H(t)$ is the Heavyside step function. Conditions (9) are to be supplemented by the usual requirement that all physical quantities must be bounded at large distances from the crack region. Alternatively, for load-induced deformation, eqs. (9b)–(9d) must be replaced by

$$\sigma_y(x, 0, t) = \sigma_0H(t), \quad 0 \leq x \leq a, \text{ all } t, \tag{10a}$$

$$v(x, 0, t) = 0, \qquad x > a, \text{ all } t, \tag{10b}$$

$$\frac{\partial\theta}{\partial y}(x, 0, t) = 0, \qquad \text{all } x \text{ and } t, \tag{10c}$$

where σ_0 is the specified stress across the crack surfaces.

Denoting the Laplace transform of a function, $f(x, y, t)$, by $\bar{f}(x, y, p)$, i.e.,

$$\bar{f}(x, y, p) = \int_0^\infty f(x, y, t)\, e^{-pt}\, dt$$

and using the assumed initial conditions, eqs. (7) are readily shown to transform into:

$$\nabla^2\bar{\phi} - p^2\bar{\phi} = \bar{\theta}\,, \qquad \nabla^2\bar{\psi} - (p^2/\beta^2)\bar{\psi} = 0\,, \qquad \nabla^2\bar{\theta} - p\bar{\theta} = \delta p \nabla^2\bar{\phi}\,. \tag{11}$$

An admissible integral solution of eqs. (11) bounded for large y is:

$$\bar{\phi} = \int_0^\infty [A_1(s, p)\, e^{-n_1 y} + A_2(s, p)\, e^{-n_2 y}] \cos(sx)\, ds\,, \qquad \bar{\psi} = \int_0^\infty A_3(s, p)\, e^{-n_3 y} \sin(sx)\, ds\,,$$

$$\bar{\theta} = \int_0^\infty [(m_1^2 - p^2)A_1(s, p)\, e^{-n_1 y} + (m_2^2 - p^2)A_2(s, p)\, e^{-n_2 y}] \cos(sx)\, ds\,, \tag{12}$$

where $A_j(s, p)$, $j = 1, 2, 3$, are unknown transform parameters and

$$n_j = \sqrt{s^2 + m_j^2},\ j = 1, 2, 3\,,$$
$$m_{1,2}^2 = \tfrac{1}{2}p[p + 1 + \delta \pm \sqrt{p^2 + 2(-1 + \delta)p + (1 + \delta)^2}]\,, \tag{13}$$
$$m_3^2 = p^2/\beta^2 = \frac{2(1 - \nu)}{1 - 2\nu}\, p^2\,,$$

with the provision that the s-plane being cut such that $n_j \geq 0$ for $0 \leq s < \infty$.

4. Thermal induced deformation

The application of Laplace transform to the boundary conditions (9) yields:

$$\bar{\tau}_{xy}(x, 0, p) = 0\,, \qquad \text{all } x\,, \tag{14a}$$

$$\frac{\partial\bar{\theta}}{\partial y}(x, 0, p) = Q_0/p\,, \quad 0 \leq x \leq a\,, \tag{14b}$$

$$\frac{\partial\bar{\theta}}{\partial y}(x, 0, p) = 0\,, \qquad x > a\,, \tag{14c}$$

and the mixed conditions

$$\bar{\sigma}_y(x, 0, p) = 0\,, \quad 0 \leq x \leq a\,, \tag{15a}$$

$$\bar{v}(x, 0, p) = 0\,, \quad x > a\,. \tag{15b}$$

Using eqs. (8), (12) and (13), it is readily confirmed, by utilizing conditions (14), that

$$A_2 = \frac{-1}{n_2(m_2^2 - p^2)} \left[\frac{2Q_0 \sin(as)}{\pi p s} + n_1(m_1^2 - p^2)A_1\right], \tag{16a}$$

$$A_3 = \frac{2s}{s^2 + n_3^2} \left[\frac{2Q_0 \sin(as)}{\pi p(m_2^2 - p^2)s} + \frac{m_1^2 - m_2^2}{m_2^2 - p^2}\, n_1 A_1\right]. \tag{16b}$$

With the help of relations (16), the stress and displacement components in the transformed plane can now be expressed in terms of integrals containing the transform parameter, $A_1(s, p)$, only. In particular:

$$\bar{v}(x,0,p)=\frac{m_3^2}{m_2^2-p^2}\int_0^\infty\left[(m_1^2-m_2^2)\frac{n_1A_1}{s^2+n_3^2}+\frac{2Q_0\sin(as)}{\pi spn_1}\right]\cos(xs)\,\mathrm{d}s\,, \tag{17a}$$

$$\begin{aligned}\bar{\sigma}_y(x,0,p)&=\int_0^\infty F(s,p)A_1\cos(xs)\,\mathrm{d}s\\&\quad-\frac{2Q_0}{\pi p(m_2^2-p^2)}\int_0^\infty\left(2\beta^2s^2+p^2-4\beta^2\frac{n_2n_3s^2}{s^2+n_3^2}\right)\frac{\sin(as)\cos(xs)}{n_2s}\,\mathrm{d}s\,,\end{aligned} \tag{17b}$$

where

$$F(s,p)=(2\beta^2s^2+p^2)\left[1-\frac{n_1(m_1^2-p^2)}{n_2(m_2^2-p^2)}\right]-4\beta^2\frac{n_1n_3s^2(m_2^2-m_1^2)}{(s^2+n_3^2)(m_2^2-p^2)}\,. \tag{18}$$

With a view toward simplifying the analysis, it is found convenient to make use of the notations:

$$\begin{aligned}B(s,p)&=(m_1^2-m_2^2)\frac{n_1A_1}{s^2+n_3^2}+\frac{2Q_0\sin(as)}{\pi ps(s^2+n_3^2)}\,,\\M(s,p)&=\frac{(m_2^2-p^2)(s^2+n_3^2)}{2(1-\beta^2)(m_2^2-m_1^2)p^2sn_1}F(s,p)\,,\\I^*(x,p)&=\int_0^\infty(2\beta^2s^2+p^2)(n_1^{-1}-n_2^{-1})\frac{\sin(as)\cos(xs)}{\pi s}\,\mathrm{d}s\,,\end{aligned} \tag{19}$$

such that $M(s,p)\sim 1+\mathrm{O}(s^{-2})$ for large s. The conditions in eqs. (15) can now be expressed as

$$\int_0^\infty sM(s,p)B(s,p)\cos(xs)\,\mathrm{d}s=\frac{(m_2^2-p^2)Q_0I^*(x,p)}{(1-\beta^2)p^3(m_2^2-m_1^2)}\,,\quad 0\leqslant x\leqslant a\,, \tag{20a}$$

$$\int_0^\infty B(s,p)\cos(xs)\,\mathrm{d}s=0\,,\quad x>a\,, \tag{20b}$$

with the solution [11]

$$B(s,p)=\int_0^a g(t,p)J_0(st)\,\mathrm{d}t\,, \tag{21}$$

where J_0 is the Bessel function of the first kind of order zero, and the auxiliary function, $g(t, p)$, is governed by

$$g(t,p)+\int_0^a g(u,p)K(u,t,p)\,\mathrm{d}u=\frac{Q_0(m_2^2-p^2)tI(t,p)}{(1-\beta^2)p^3(m_2^2-m_1^2)}\,, \tag{22}$$

in which

$$K(u,t,p)=t\int_0^\infty s[M(s,p)-1]J_0(st)J_0(su)\,\mathrm{d}s\,, \tag{23a}$$

$$I(t,p)=\frac{2}{\pi}\int_0^t\frac{I^*(x,p)}{\sqrt{t^2-x^2}}\,\mathrm{d}x\,. \tag{23b}$$

On account of the fact that eq. (22) has to be treated numerically, the following notations are introduced

$$t=ar\,,\quad u=a\,,\quad y=as\,,\qquad g(t,p)=\frac{aQ_0\sqrt{r}G(r,p)}{(1-\beta^2)p^3(m_2^2-m_1^2)}\,. \tag{24}$$

Then, it is readily shown that

$$G(r, p) + \int_0^1 G(\rho, p) L_1(a\rho, ar, p)\, \mathrm{d}\rho = \sqrt{r} I(ar, p) , \tag{25}$$

where

$$L_1(a\rho, ar, p) = \sqrt{r\rho} \int_0^\infty y \left[M\left(\frac{y}{a}, p\right) - 1 \right] J_0(yr) J_0(y)\, \mathrm{d}y , \tag{26a}$$

$$I(ar, p) = \frac{1}{\pi} \int_0^r \left(\frac{2\beta^2 y^2}{a^2} + p^2 \right) \left(\frac{1}{n_1} - \frac{1}{n_2} \right) \frac{\sin(y)}{y} J_0(yr)\, \mathrm{d}y , \tag{26b}$$

In the usual manner, the stress-intensity factor in the transformed plane is computed as

$$k_1(p) = Q_0 \sqrt{a} \frac{G(1, p)}{p} . \tag{27}$$

Hence, it follows that in the time domain and in actual units

$$\frac{k_1(t')}{\dfrac{(3\lambda + 2\mu)}{a' c_1} \kappa \alpha Q_0' a'^{3/2}} = \frac{1}{2\pi \mathrm{i}} \int_{\mathrm{Br}} \frac{G(1, p)}{p} \mathrm{e}^{pt'}\, \mathrm{d}p , \tag{28}$$

where Br denotes the Bromwich path of integration which is a line to the right-hand side and parallel to the imaginary axis in the p-plane. Equation (25) is solved numerically and the values of the function $G(1, p)$ are inserted in the relation (28). The Laplace inversion is then carried out numerically [12] to yield the dynamic stress-intensity factor.

5. Load-induced deformation

When the crack surfaces are opened out by the application of normal stress, the transformed boundary conditions are obtained from eqs. (10) as follows:

$$\bar{\tau}_{xy}(x, 0, p) = \frac{\partial \bar{\theta}}{\partial y}(x, 0, p) = 0 , \quad \text{all } x , \tag{29}$$

$$\bar{\sigma}_y(x, 0, p) = \sigma_0 / p , \qquad 0 \leqslant x \leqslant a , \tag{30a}$$

$$\bar{v}(x, 0, p) = 0 , \qquad x > a . \tag{30b}$$

The relations (29) can be used to express the unknown parameters A_2 and A_3 in term of A_1. Moreover, upon writing

$$D(s, p) = \frac{(m_2^2 - m_1^2) n_1 A_1(s, p)}{(m_2^2 - p^2)(s^2 + n_3^2)} , \qquad N(s, p) = \frac{(m_2^2 - p^2)(s^2 + n_3^2) F(s, p)}{2(1 - \beta^2) p^2 (m_2^2 - m_1^2) s n_1} , \tag{31}$$

where the function, $F(s, p)$, is defined in eq. (18), the conditions (30) are readily shown to render the following equations to determine the remaining unknown function $D(s, p)$:

$$\int_0^\infty s N(s, p) D(s, p) \cos(sx)\, \mathrm{d}s = \frac{\sigma_0}{2(1 - \beta^2) p^3} , \quad 0 \leqslant x \leqslant a , \tag{32a}$$

$$\int_0^\infty D(s, p) \cos(sx)\, \mathrm{d}s = 0 , \qquad x > a . \tag{32b}$$

Note that the function, $N(s, p)$, in eq. (31) has the asymptotic expansion $\sim 1 + \mathrm{O}(s^{-2})$ for large values of s. Inasmuch as the remaining analysis is similar to the previous case, only the result will be stated. The dynamic stress-intensity factor is computed in physical units as

$$k_1(t') = \frac{\sigma_0'\sqrt{a'}}{2\pi i} \int_{\mathrm{Br}} \frac{G(1, p)\, e^{pt'}}{p}\, dp\,, \tag{33}$$

where, in this case, $G(r, p)$ is governed by the integral equation

$$G(r, p) + \int_0^1 G(\rho, p) L_2(a\rho, ar, p)\, d\rho = \sqrt{r}\,, \tag{34}$$

and $L_2(a\rho, ar, p)$ denotes the integral

$$L_2(a\rho, ar, p) = \sqrt{r\rho} \int_0^\infty y\left[N\left(\frac{y}{a}, p\right) - 1\right] J_0(yr) J_0(y\rho)\, dy\,, \tag{35}$$

with

$$N\left(\frac{y}{a}, p\right) = \frac{1}{2(1-\beta^2)p^2}\left\{-4\beta^2 n_3\left(\frac{y}{a}\right) + \left[m_2^2 - p^2 - \frac{n_1}{n_2}(m_1^2 - p^2)\right] \frac{(2\beta^2 y^2/a^2 + p^2)(y^2/a^2 + n_3)}{n_1 \frac{y}{a}(m_2^2 - m_1^2)}\right\}, \tag{36}$$

In the remaining part of the paper the stress-intensity factor is computed to reveal the influence of dynamic effects inherent in the coupled theory of thermoelasticity.

6. Numerical results and discussion

The Fredholm integral eqs. (25) and (34) are solved numerically [10] and the resulting values of $G(1, p)$ are inserted into relations (28) and (33) to determine the dynamic stress-intensity factor. The Laplace inversion is then carried out using a five term series expansion in Legendre polynomials orthogonal in the interval $(-1, 1)$ by the scheme suggested in [12]. For thermal-induced deformation, Fig. 1 displays the variation of the stress-intensity factor, $k_1(t')/\gamma\alpha Q_0' a'^{3/2}$, $\gamma = (3\lambda + 2\mu)\kappa/a'c_1$, with

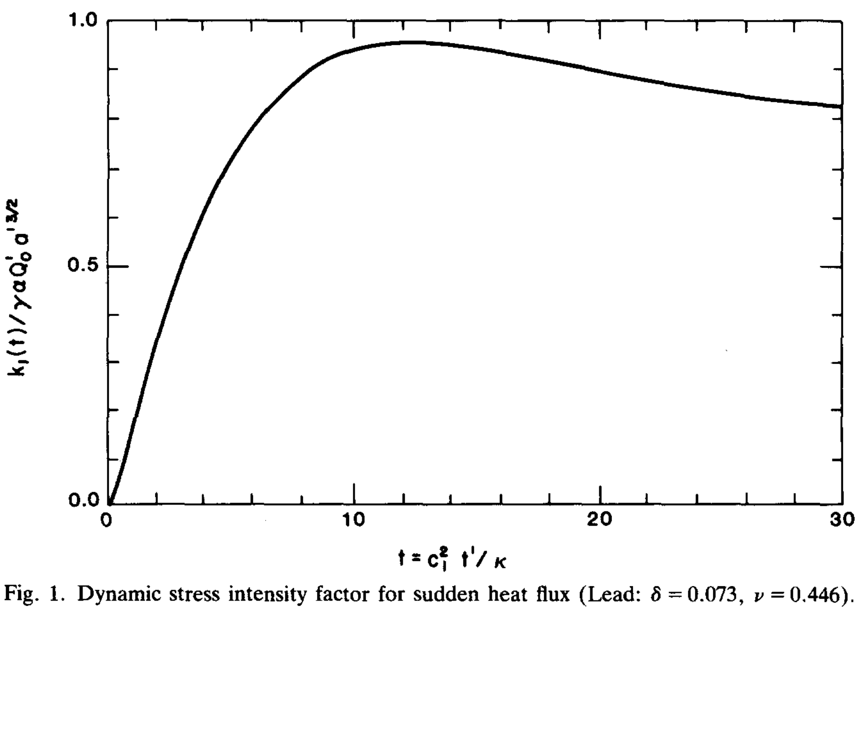

Fig. 1. Dynamic stress intensity factor for sudden heat flux (Lead: $\delta = 0.073$, $\nu = 0.446$).

time when the crack surfaces are opened out by the application of constant heat flux (Q_0'). The inertia effect is indicated through the rapid rise in the magnitude of the stress-intensity factor for short time interval and its eventual oscillation about the steady-state value. In this example (Lead with coupling parameter $\delta = 0.0729$ and Poisson's ratio $= 0.446$), the steady-state solution gives $k_1(t') = 0.83\gamma\alpha Q_0' a'^{3/2}$. The peak in the curve is about 16% higher than the steady-state value and is reached at time $t' = 13\ \kappa/c_1^2$ seconds. Figure 2 shows the same response in materials with different Poisson's ratios

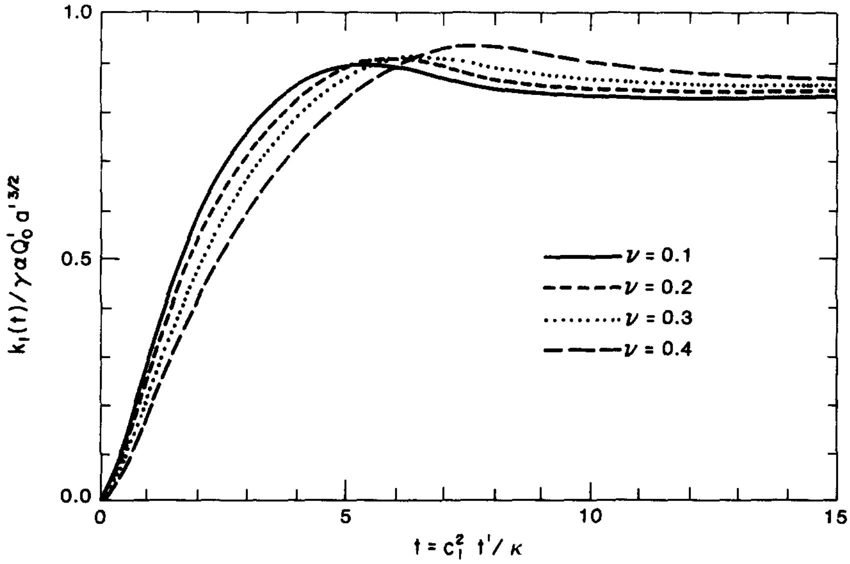

Fig. 2. Variations of dynamic stress intensity factor with time (constant heat flux, $\delta = 0$).

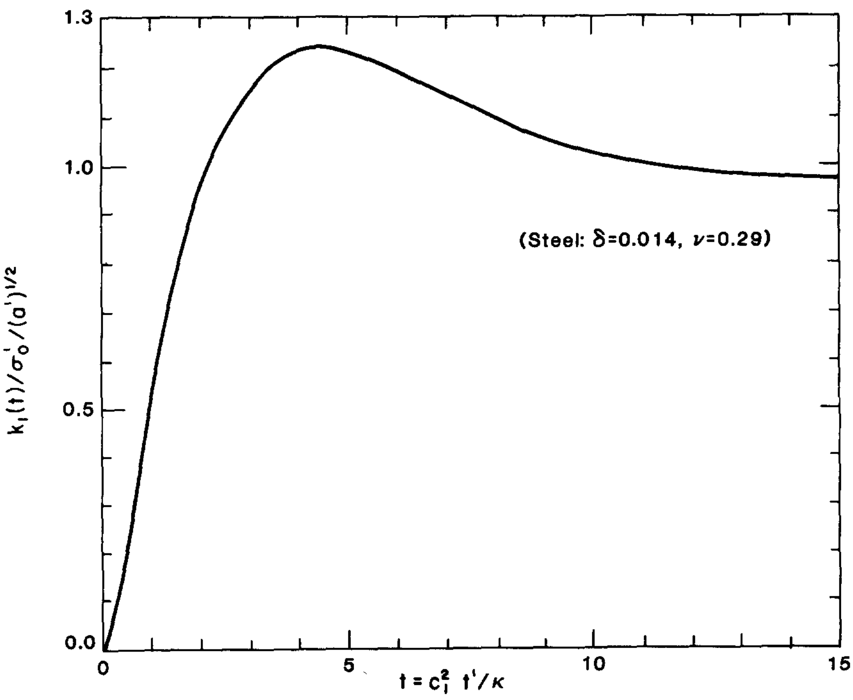

Fig. 3. Dynamic stress intensity factor as function of time. Impact normal loading.

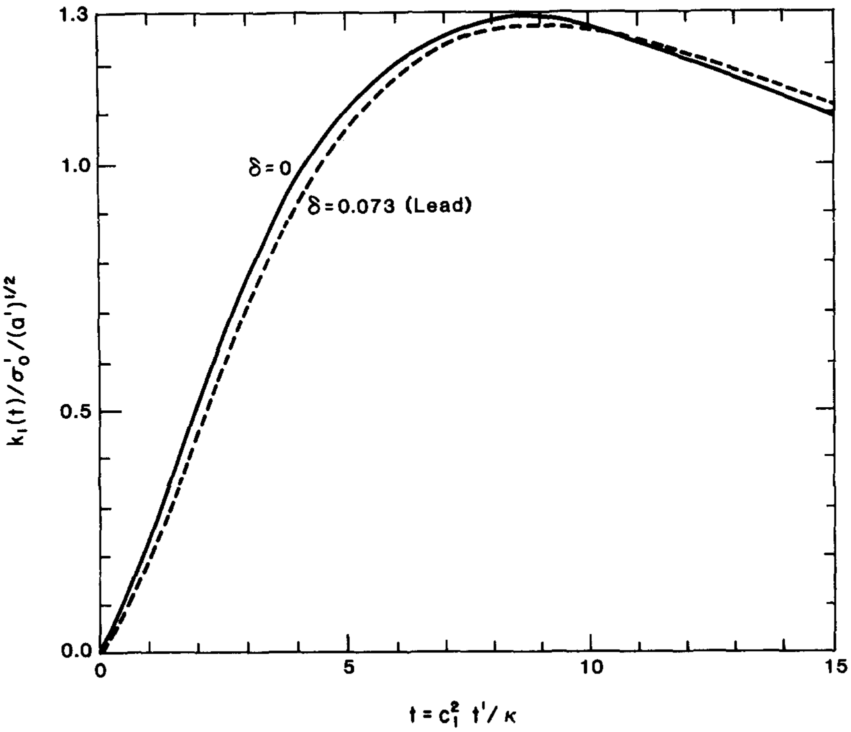

Fig. 4. Stress intensity factor versus time. Impact normal loading.

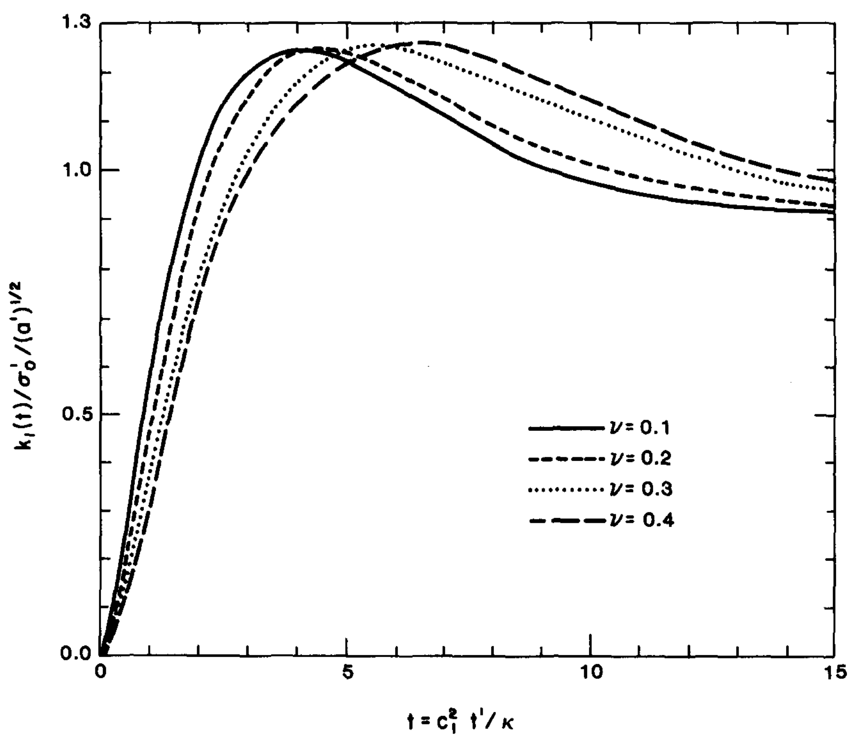

Fig. 5. Variations of stress intensity factor with time. Impact normal loading ($\delta = 0$).

and where the coupling parameter, δ, is set equal to zero. As the value of Poisson's ratio is increased, the peak in the stress-intensity factor is higher and is reached at a later time interval. Eventually, it oscillates about the corresponding steady-state solution.

For load-induced deformation, Fig. 3 reveals the variation of the dynamic stress-intensity factor with time using the coupled equations of thermoelasticity. Steel has been used to exhibit the behavior with $\delta = 0.014$ and $\nu = 0.29$. The crack surfaces are opened out by the application of constant normal stress of magnitude σ_0'. An overshoot of about 25% is observed at time $t' = 4\kappa/c_1^2$. The stress-intensity factor has also been computed for Lead when subjected to normal impact loading. Both situations with $\delta = 0.0729$ and $\delta = 0$ are used and the results appear in Fig. 4. No appreciable difference in the behavior is observed.

Finally, Fig. 5 shows the influence of Poisson's ratio on the stress intensity factor when $\delta = 0$ and constant normal loading. The overshoot can reach as high as 28% above the static value. There is a delay in the time interval at which the peak is reached for increase in the values of Poisson's ratio, and also a slight increase in the magnitude of the peak value itself.

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