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Quasi-static Planar Deformation in a Medium Composed of Elastic and Thermoelastic Solid Half Spaces Due to Seismic Sources in an Elastic Solid

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Abstract

A two-dimensional problem of quasi static deformation of a medium consisting of an elastic half space in welded contact with thermoelastic half space, caused due to seismic sources, is studied. Source is considered to be in the elastic half space. The basic equations, governed by the coupled theory of thermoelasticity, are used to model for thermoelastic half space. The analytical expressions for displacements, strain and stresses in the two half spaces are obtained first for line source and then for dip slip fault. The results for two particular cases, adiabatic conditions and isothermal conditions, are also obtained. Numerical results for displacements, stresses and temperature distribution have also been computed and are shown.

Key words: seismic sources, thermoelastic, quasi-static, deformation.

1. INTRODUCTION

The elasticity theory of dislocation was developed and applied by Steketee (1958), Rongved and Frasier (1958), and Maruyama (1964, 1966). The problems related to seismic sources in elastic media have been studied extensively by many researchers (Burridge and Knopoff 1964, Singh and Ben-Menahem 1969, Singh 1970, Sato 1971, Singh *et al.* 1973, Sato and Matsu'ura 1973, Jovanovich *et al.* 1974a, b; Freund and Barnett 1976, *etc.*). The detailed description about seismic sources is given in the classical texts: Aki and Richards (1980), Ben-Menahem and Singh (1981), Lay and Wallace (1995), and Stein and Wysession (2003).

Singh and Garg (1985) studied the static deformation of an isotropic multilayered half space by a normal line load and a shear line load. Singh and Garg (1986) described the representation of two-dimensional seismic sources and obtained the integral expressions for the Airy stress function in an unbounded medium due to various two-dimensional sources and represented the sources in terms of jumps across the plane through the sources. Garg and Singh (1987) extended the results of Singh and Garg (1985) by considering the multilayered half space as transversely isotropic. Pan (1989a, b) provided a unified solution of the static deformation of the transversely isotropic and layered half space by general surface loads. Rani *et al.* (1991) extended the work of Singh and Garg (1986) and obtained closed form analytical expressions for the displacements and stresses at any point of a uniform half space due to two-dimensional buried sources by applying the traction free boundary conditions at the surface of the half space.

Okada (1985, 1992) provided compact analytical expressions for the surface deformation and internal deformation due to inclined shear and tensile faults in a homogeneous isotropic half space. Heaton and Heaton (1989) obtained the deformation field induced by point forces and point force couples embedded in two Poissonian half spaces in welded contact. Singh *et al.* (1992) derived closed form expressions for displacements and stresses in two welded half spaces caused by two-dimensional sources. Many other researchers discussed source problems for different types of sources *viz.* Kumari *et al.* (1992), Singh *et al.* (1993, 2003), Garg *et al.* (1996, 2003), Tomar and Dhiman (2003), Kumar *et al.* (2005), Singh *et al.* (2005), and Madan *et al.* (2005).

Thermoelasticity deals with dynamical systems whose interactions with the surroundings include not only mechanical work and external work but also the exchange of heat. Theory of thermoelasticity studies the influence of temperature of an elastic medium on the distribution of stress and strain as well as the inverse effect of the deformation on the temperature distribution.

Attempts have been made to study source problems in thermoelasticity. However, most of such studies are attributed to internal and surface heat sources, (*e.g.*, Lanzano 1986a, b, Dziewonski and Anderson 1981, Rundle 1982, Small and Booker 1986, Abd-Alla 1995, Shevchenko and Gol'tsev 2001, Kit *et al.* 2001, Youssef 2006, 2009, 2010, Mallik and Kanoria 2008, Hou *et al.* 2008a, b, 2009, 2011, Kumar and Gupta 2009, Attetkov *et al.* 2009, *etc.*). Some authors have considered mechanical sources also; *e.g.*, Pan (1990) considered quasi-static governing equations of thermoelasticity and discussed the transient thermoelastic deformation in a transversely isotropic and layered half space by surface loads and internal sources. Kumar and Rani (2004) considered a dynamical two-dimensional problem of thermoelasticity and studied the deformation due to mechanical and thermal sources in generalized thermally conducting orthorhombic material. Ghosh and Kanoria (2007) derived analytical expressions for thermoelastic displacements and stresses in composite multi-layered media due to varying temperature and concentrated loads. Quasi-static deformation of a thermoelastic medium due to seismic sources or quasi static mechanical sources has not been studied so far.

For a realistic Earth model, it is appropriate to involve thermoelastic medium in the model. The study of quasi static deformation of a thermo- elastic medium, in welded contact with an elastic medium, due to seismic sources is important for its geophysical applications. The theory developed in this paper may find its applications in seismic faulting. When the source surface is very long in one dimension in comparison with the other, the use of two-dimensional approximations is justified and consequently calculations are simplified to a great extent and one gets a closed form of analytic solution. A very long strip source and a very long line source are the examples of such two-dimensional sources.

In this paper, quasi static deformation of a medium consisting of a homogeneous isotropic thermoelastic half space in welded contact with a homogeneous elastic half space, due to a line source and dip slip fault in an elastic half space, is studied. Numerical results for displacements, stresses and temperature distribution are presented graphically. The present problem is useful in the field of geomechanics where the interest is about the various phenomena occurring in the earthquakes and measuring of displacements, stresses, and temperature field due to the presence of certain sources.

2. FORMULATION OF THE PROBLEM

Consider a medium consisting of thermoelastic half spaces ($z \geq 0$) and an elastic half space ($z \leq 0$) which are in welded contact along the plane $z = 0$, as shown in Fig. 1. A line source parallel to the x-axis passing through the point $(0, 0, -h)$ in the elastic half space is considered.

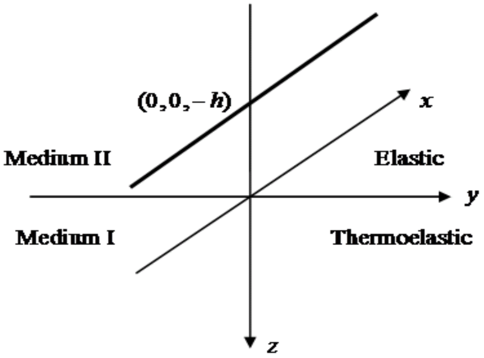

Fig. 1. A line source through the point $(0, 0, –h)$.

A two-dimensional plane strain problem in yz-plane is considered so that the displacement components can be written as:

$$u_i = u_i(y,z,t)\ ,\quad (i = y,z)\ ,\qquad u_x = 0\ . \tag{1}$$

3. BASIC EQUATIONS AND THEIR SOLUTIONS

3.1 For thermoelastic half space

The stress strain relations for a thermoelastic medium (Nowacki 1975) are given by:

$$\sigma_{ij} = \lambda\varepsilon_{kk}\delta_{ij} + 2\mu\varepsilon_{ij} - \beta\theta\delta_{ij}\ ,\quad i,j,k = x,y,z\ , \tag{2}$$

where σ_{ji} and ε_{ij} are components of stress and strain tensor, respectively, λ, μ are Lame's constants, $\beta = (3\lambda + 2\mu)\alpha_t$ is the thermoelastic coupling coefficient, θ is the temperature difference, and α_t is the coefficient of linear thermal expansion.

The stress components for a plane strain problem in the yz-plane are given by:

$$\sigma_{yy} = \lambda\varepsilon_{kk} + 2\mu\varepsilon_{yy} - \beta\theta\ , \tag{3a}$$

$$\sigma_{zz} = \lambda\varepsilon_{kk} + 2\mu\varepsilon_{zz} - \beta\theta\ , \tag{3b}$$

$$\sigma_{yz} = 2\mu\varepsilon_{yz}\ , \tag{3c}$$

where

$$\varepsilon_{kk} = \frac{1}{2(\lambda+\mu)}\left(\sigma_{yy} + \sigma_{zz} + 2\beta\theta\right)\ . \tag{3d}$$

The strain components can be represented as:

$$2\mu\varepsilon_{yy} = (1-\upsilon)\ \sigma_{yy} - \upsilon\sigma_{zz} + \alpha_0\theta \ , \tag{4a}$$

$$2\mu\varepsilon_{zz} = (1-\upsilon)\ \sigma_{zz} - \upsilon\sigma_{yy} + \alpha_0\theta \ , \tag{4b}$$

$$2\mu\varepsilon_{yz} = \sigma_{yz} \ , \tag{4c}$$

where $\upsilon = \dfrac{\lambda}{2(\lambda+\mu)}$ is Poisson's ratio and $\alpha_0 = (1-2\upsilon)\beta$.

The equations of equilibrium for thermoelastic medium, in the absence of body forces, are

$$\sigma_{yy,y} + \sigma_{yz,z} = 0 \ , \tag{5a}$$

$$\sigma_{zy,y} + \sigma_{zz,z} = 0 \ , \tag{5b}$$

and the compatibility equation is

$$\varepsilon_{yy,zz} + \varepsilon_{zz,yy} = 2\varepsilon_{yz,yz} \ . \tag{6}$$

Using Eqs. 4 and 5 in Eq. 6, we get

$$\nabla^2\left(\sigma_{yy} + \sigma_{zz} + 2\eta\theta\right) = 0 \ , \tag{7}$$

where

$$\eta = \frac{\alpha_0}{2(1-\upsilon)} = \frac{(1-2\upsilon)}{2(1-\upsilon)}\beta \ , \qquad \nabla^2 \equiv \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \ .$$

The heat conduction equation can be written as

$$\lambda_0\theta_{,ii} - \rho C_e\dot{\theta} - \beta T_0\dot{\varepsilon}_{kk} = 0 \ , \qquad \left(i,k = y,z\right) \ , \tag{8}$$

where λ_0 is the thermal conductivity, C_e is the specific heat, ρ is the density, and T_0 is the temperature at natural state.

The stress function U is defined as:

$$\sigma_{yy} = \frac{\partial^2 U}{\partial z^2} \ , \qquad \sigma_{zz} = \frac{\partial^2 U}{\partial y^2} \ , \qquad \sigma_{yz} = -\frac{\partial^2 U}{\partial y \partial z} \ . \tag{9}$$

Using Eqs. 3d and 9 in Eqs. 7 and 8, we get

$$\nabla^2\left(\nabla^2 U + 2\eta\theta\right) = 0 \tag{10}$$

and

$$\lambda_0\nabla^2\theta - \left(\rho C_e + \frac{\beta^2 T_0}{(\lambda+\mu)}\right)\dot{\theta} - \frac{\beta T_0}{2(\lambda+\mu)}\left(\nabla^2\dot{U}\right) = 0 \ . \tag{11}$$

Equations 10 and 11 imply that

$$\left(c\nabla^2 - \frac{\partial}{\partial t}\right)\nabla^2\theta = 0 \tag{12}$$

and

$$\left(c\nabla^2 - \frac{\partial}{\partial t}\right)\nabla^4 U = 0 \ , \tag{13}$$

where

$$c = \lambda_0\left[\rho C_e + \frac{\alpha_0{}^2 T_0}{\mu(1-2\upsilon)} - \frac{\alpha_0{}^2 T_0}{2\mu(1-\upsilon)}\right]^{-1} \ . \tag{14}$$

The general solution of Eq. 12 may be written as

$$\theta = \theta_1 + \theta_2 \ , \tag{15}$$

where

$$c\nabla^2\theta_1 = \frac{\partial\theta_1}{\partial t} \tag{16}$$

and

$$\nabla^2\theta_2 = 0 \ . \tag{17}$$

Similarly, the general solution of Eq. 13 can be expressed as:

$$U = U_1 + U_2 \ , \tag{18}$$

where

$$c\nabla^2 U_1 = \frac{\partial U_1}{\partial t} \tag{19}$$

and

$$\nabla^4 U_2 = 0 \ . \tag{20}$$

Equations 16, 17, 19, and 20, with the time dependence as $e^{-i\omega t}$, can be written as

$$\nabla^2\theta_1 + \frac{i\omega}{c}\theta_1 = 0 \ , \tag{21}$$

$$\nabla^2\theta_2 = 0 \ , \tag{22}$$

$$\nabla^2 U_1 + \frac{i\omega}{c}U_1 = 0 \ , \tag{23}$$

$$\nabla^4 U_2 = 0 \ , \tag{24}$$

where θ_1, θ_2, U_1, and U_2 are functions of y and z only.

Application of Fourier transform to Eqs. 21-24, solution of the resulting differential equations, inversion of Fourier transform and further simplification leads to

$$\theta = \int_0^\infty \left(A_1 e^{-mz} + A_2 e^{-kz}\right)\begin{pmatrix}\sin ky\\ \cos ky\end{pmatrix} dk \ , \tag{25}$$

$$U = \int_0^\infty \left(B_1 e^{-mz} + \left(B_2 + B_3 kz \right) e^{-kz} \right) \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} dk \ , \tag{26}$$

where

$$m = \left(k^2 - \frac{i\omega}{c} \right)^{1/2} , \quad \mathrm{Re}(m) > 0$$

and A_i, B_i may be functions of k. Equation 9 gives

$$\sigma_{yy} = \int_0^\infty \left(m^2 B_1 e^{-mz} + \left(B_2 k^2 - 2B_3 k^2 + B_3 k^3 z \right) e^{-kz} \right) \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} dk \ , \tag{27}$$

$$\sigma_{zz} = \int_0^\infty \left(B_1 e^{-mz} + \left(B_2 + B_3 kz \right) e^{-kz} \right) \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} \left(-k^2 \right) dk \ , \tag{28}$$

$$\sigma_{yz} = \int_0^\infty \left(mB_1 e^{-mz} + \left(\left(B_2 - B_3 \right) k + B_3 k^2 z \right) e^{-kz} \right) k \begin{pmatrix} \cos ky \\ -\sin ky \end{pmatrix} dk \ . \tag{29}$$

Making use of Eqs. 25 and 26 in Eqs. 10 and 11, we get

$$A_1 = -\frac{(m^2 - k^2)}{2\eta} B_1 = \frac{i\omega}{2\eta c} B_1 \ , \tag{30}$$

$$A_2 = \frac{2(\upsilon_u - \upsilon)}{\alpha_0} k^2 B_3 \ , \tag{31}$$

where

$$\upsilon_u = \upsilon + \frac{\alpha_0{}^2 T_0}{2\mu \left(\rho C_e + \frac{\alpha_0{}^2 T_0}{\mu(1-2\upsilon)} \right)} \ . \tag{32}$$

The displacement components can now be written as:

$$2\mu u_y = -\int_0^\infty \left(B_1 e^{-mz} + \left(B_2 + B_3 (2\upsilon_u - 2 + kz) \right) e^{-kz} \right) k \begin{pmatrix} \cos ky \\ -\sin ky \end{pmatrix} dk \tag{33}$$

and

$$2\mu u_z = \int_0^\infty \left(mB_1 e^{-mz} + \left(B_2 + B_3 (1 - 2\upsilon_u + kz) \right) k e^{-kz} \right) \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} dk \ . \tag{34}$$

The heat flux in z-direction is found as

$$q_z = -\lambda_0 \theta_{,z} = \lambda_0 \int_0^\infty \left(mA_1 e^{-mz} + kA_2 e^{-kz} \right) \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} dk \ . \tag{35}$$

3.2 For elastic half space

A homogeneous isotropic elastic medium can be characterized by the shear modulus (μ') and the Poisson's ratio (υ'). The plane strain problem for an isotropic elastic medium can be solved in terms of the Airy stress function Φ such that

$$\sigma'_{yy} = \frac{\partial^2\Phi}{\partial z^2}, \quad \sigma'_{zz} = \frac{\partial^2\Phi}{\partial y^2}, \quad \sigma'_{yz} = -\frac{\partial^2\Phi}{\partial y \partial z}, \tag{36}$$

where Φ satisfies the biharmonic equation

$$\nabla^2\nabla^2\Phi = 0 \tag{37}$$

and σ'_{ij} are the components of stress tensor.

Let there be a line source parallel to the x-axis passing through the point $(0, 0, -h)$ of the elastic half space ($z < 0$). The Airy stress function for a line source parallel to the x-axis passing through the point $(0, 0, -h)$ in an unbounded isotropic elastic medium (Singh and Garg 1986), can be expressed in the form

$$\Phi_0 = \int_0^\infty \left(S_1 + S_2 k\left|z+h\right|\right) e^{-k|z+h|} \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} \frac{dk}{k}. \tag{38}$$

The source coefficients S_1 and S_2 are independent of k.

The source coefficients for different types of sources, as given in Singh and Garg (1986), are given in Table 1. In this table, the upper sign is for $z > -h$, the lower sign is for $z < -h$ and

$$\alpha' = \frac{1}{2(1-\upsilon')}.$$

The Airy stress function for the elastic half space can now be written as

$$\Phi = \Phi_0 + \int_0^\infty \left(C_1 + C_2 kz\right) e^{kz} \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} dk, \tag{39}$$

where the unknowns C_1, C_2 are to be determined from the boundary conditions.

Using Eqs. 36, 38, and 39, the stresses are obtained as

$$\sigma'_{yy} = \int_0^\infty \left\{\left[S_1 + S_2\left(-2 + k\left|z+h\right|\right)\right] e^{-k|z+h|} + \left[C_1 + C_2\left(kz+2\right)\right] ke^{kz}\right\} \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} kdk, \tag{40}$$

$$\sigma'_{zz} = -\int_0^\infty \left[\left(S_1 + S_2 k\left|z+h\right|\right) e^{-k|z+h|} + \left(C_1 + C_2 kz\right) ke^{kz}\right] \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} kdk, \tag{41}$$

Table 1

Values of coefficients for different types of sources

Source	S_1	S_2	Upper or lower solution
Single couple (yz)	$\mp\frac{F_{yz}}{2\pi}$	$\pm\alpha'\frac{F_{yz}}{2\pi}$	upper
Single couple (zy)	$\pm\frac{F_{zy}}{2\pi}$	$\pm\alpha'\frac{F_{zy}}{2\pi}$	upper
Double couple (yz) + (zy) $F_{yz} = F_{zy} = D_{yz}$	0	$\pm\alpha'\frac{D_{yz}}{\pi}$	upper
Centre of rotation $F_{yz} = F_{zy} = R_{yz}$	$\pm\frac{R_{yz}}{\pi}$	0	upper
Dipole (yy)	$(1-\alpha')\frac{F_{yy}}{2\pi}$	$-\alpha'\frac{F_{yy}}{2\pi}$	lower
Dipole (zz)	$(1-\alpha')\frac{F_{zz}}{2\pi}$	$\alpha'\frac{F_{zz}}{2\pi}$	lower
Centre of dilatation (yy) + (zz) ($F_{yy} = F_{zz} = C_0$)	$(1-\alpha')\frac{C_0}{\pi}$	0	lower
Double couple (zz) – (yy) ($F_{yy} = F_{zz} = D'_{yz}$)	0	$\alpha'\frac{D'_{yz}}{\pi}$	lower

$$\sigma'_{yz} = \int_0^\infty \left\{ \pm\left[S_1 - S_2\left(1-k|z+h|\right)\right]e^{-k|z+h|} - \left[C_1 + C_2\left(1+kz\right)\right]ke^{kz} \right\} \begin{pmatrix} \cos ky \\ -\sin ky \end{pmatrix} kdk \ . \tag{42}$$

The corresponding displacement components are

$$2\mu' u'_y = \int_0^\infty \begin{bmatrix} \left\{-S_1 + S_2\left(2-2\upsilon' - k|z+h|\right)\right\}e^{-k|z+h|} \\ -\left\{C_1 + C_2\left(2-2\upsilon' + kz\right)\right\}ke^{kz} \end{bmatrix} \begin{pmatrix} \cos ky \\ -\sin ky \end{pmatrix} dk \tag{43}$$

and

$$2\mu' u'_z = \int_0^\infty \begin{bmatrix} \pm\left\{S_1 + S_2\left(1-2\upsilon' + k|z+h|\right)\right\}e^{-k|z+h|} \\ +\left\{-C_1 + C_2\left(1-2\upsilon' - kz\right)\right\}ke^{kz} \end{bmatrix} \begin{pmatrix} \sin ky \\ \cos ky \end{pmatrix} dk \ . \tag{44}$$

4. BOUNDARY CONDITIONS

The boundary conditions at the plane $z = 0$ are

$$\sigma_{yz} = \sigma'_{yz}\ , \quad \sigma_{zz} = \sigma'_{zz}\ , \quad u_y = u'_y\ , \quad \text{and} \quad u_z = u'_z\ . \tag{45}$$

Further, if the heat flux is not exchanged at the interface, then

$$q_z = 0 \;, \quad \text{at} \quad z = 0 \;. \tag{46}$$

It is noticed from Table 1 that the source coefficients S_1 and S_2 have different values according to $z > -h$ and $z < -h$. Let S_1' and S_2' be the values of S_1 and S_2 respectively, for $z > -h$. The boundary conditions 45 and 46 yield the system

$$mB_1 + kB_2 - kB_3 + kC_1 + kC_2 = \left(S_1' - S_2' + S_2'kh\right)e^{-kh} \;, \tag{47}$$

$$kB_1 + kB_2 - kC_1 = \left(S_1' + S_2'kh\right)e^{-kh} \;, \tag{48}$$

$$kB_1 + kB_2 + 2k\left(\upsilon_u - 1\right)B_3 - \mu_r kC_1 - 2\mu_r k\left(1-\upsilon'\right)C_2 = \mu_r\left(S_1' + S_2'kh - 2S_2' + 2S_2'\upsilon'\right)e^{-kh} \;, \tag{49}$$

$$mB_1 + kB_2 + k\left(1 - 2\upsilon_u\right)B_3 + \mu_r kC_1 - \mu_r k\left(1-2\upsilon'\right)C_2 = \mu_r\left(S_1' + S_2'kh + S_2' - 2S_2'\upsilon'\right)e^{-kh} \;, \tag{50}$$

$$mA_1 + kA_2 = 0 \;, \tag{51}$$

where $\mu_r = \mu/\mu'$.

On solving these equations, we have

$$\begin{gathered}
A_1 = \frac{\Omega}{2\eta}Q(k+m)S_2'e^{-kh} \,, \qquad A_2 = -\frac{m}{k}A_1 \,, \\
B_1 = \frac{\Omega}{k-m}QS_2'e^{-kh},\; B_2 = \left[-\frac{P_2}{k}\left(S_1' - \frac{S_2'}{2} + S_2'kh\right) + \frac{QS_2'}{2k}\left(1 - \frac{k+m}{k-m}\Omega\right)\right]e^{-kh},\; B_3 = \frac{Q}{k}S_2'e^{-kh}, \\
C_1 = \left[-\frac{P_1}{k}\left(S_1' + S_2'kh\right) + \frac{S_2'}{2k}\left(P_2 + (1+\Omega)Q\right)\right]e^{-kh}, \quad C_2 = \frac{P_1}{k}(2S_1' - S_2' + 2S_2'kh)e^{-kh},
\end{gathered} \tag{52}$$

where

$$\begin{gathered}
P_1 = \frac{1-\mu_r}{1+3\mu_r - 4\mu_r\upsilon'} \;, \quad P_2 = P_1 - 1 \;, \quad P_3 = \frac{4\upsilon_u - 3 - \mu_r}{1-\mu_r} \;, \\
Q = \frac{P_2}{P_1(P_3 + \Omega)} \;, \quad \Omega = \frac{k^2\gamma}{m(m+k)} \;, \quad \gamma = \frac{2(\upsilon - \upsilon_u)}{1-\upsilon} \;.
\end{gathered} \tag{53}$$

Substituting the values of A_i, B_i, C_i's from Eqs. 52 in Eqs. 27-29, 33-34, 40-44, and 25, we get the integral expressions for the stress components and displacement components in Medium I and II, and the temperature difference in Medium I in terms of the source coefficients S_1' and S_2'.

These integrals can be solved numerically for arbitrary values of ω. However, analytical solutions can be found for two particular cases:

Case (i) $\omega \to \infty$ which further implies that no net flow of heat takes place, *i.e.*, the adiabatic condition.

Case (ii) $\omega \to 0$ which further implies that $\theta \to 0$, *i.e.*, the isothermal condition.

5. VERTICAL DIP SLIP DISLOCATION

Following Maruyama (1966), the double couple $(yz) + (zy)$ is equivalent to a vertical dip slip dislocation so that its moment can be represented as

$$D_{yz} = \mu' b\, ds \ , \tag{54}$$

where b is the slip and ds is the width of the line dislocation.

From Table 1, we have

$$S_1' = 0\,, \quad S_2' = \alpha' \frac{D_{yz}}{\pi} = \frac{D_{yz}}{2\pi(1-\upsilon')} \ , \tag{55}$$

with the stipulation that in the representation of integrals, the upper sign is to be selected.

The results for the two limiting cases, $\omega \to \infty$ and $\omega \to 0$, are obtained in analytical form as follows:

Case (i) Adiabatic case

$$U = \alpha' \frac{D_{yz}}{\pi} \left[\frac{1}{2}\left(P_2 + Q_2\right) \tan^{-1}\left(\frac{y}{z+h} \right) + \left(-P_2 h + Q_2 z\right) \frac{y}{R_1^2} \right] , \tag{56}$$

$$\sigma_{yy} = \frac{\alpha' D_{yz}}{\pi} \frac{y}{R_1^4} \left[P_2\left(z+3h\right) - Q_2\left(5z+3h\right) + 8\left(Q_2 z - P_2 h\right) \frac{(z+h)^2}{R_1^2} \right] , \tag{57}$$

$$\sigma_{yz} = \frac{\alpha' D_{yz}}{\pi} \frac{1}{R_1^2} \left[\frac{1}{2}(Q_2 - P_2) + \left\{ P_2(z+7h) - Q_2(7z+h) \right\} \frac{(z+h)}{R_1^2} + \frac{8(Q_2 z - P_2 h)(z+h)^3}{R_1^4} \right], \tag{58}$$

$$\sigma_{zz} = -\frac{\alpha' D_{yz}}{\pi} \frac{y}{R_1^4} \left[P_2(z+3h) - Q_2(z-h) + 8\left(Q_2 z - P_2 h\right) \frac{(z+h)^2}{R_1^2} \right] , \tag{59}$$

$$\varepsilon_{yy} = \frac{\alpha' D_{yz}}{2\mu\pi} \frac{y}{R_1^4} \left[P_2(z+3h) - Q_2\left(5z+3h + \left(\frac{\alpha_0 \gamma}{\eta} - 4\upsilon \right)(z+h) \right) + 8\left(Q_2 z - P_2 h\right) \frac{(z+h)^2}{R_1^2} \right], \tag{60}$$

$$\varepsilon_{yz}=\frac{\alpha' D_{yz}}{2\mu\pi}\frac{1}{R_1^2}\left[\frac{1}{2}(Q_2-P_2)+\left\{P_2(z+7h)-Q_2(7z+h)\right\}\frac{(z+h)}{R_1^2}+\frac{8(Q_2z-P_2h)(z+h)^3}{R_1^4}\right], \tag{61}$$

$$\varepsilon_{zz}=-\frac{\alpha' D_{yz}}{2\mu\pi}\frac{y}{R_1^4}\left[P_2(z+3h)-Q_2\left((z-h)+\left(4\upsilon-\frac{\alpha_0\gamma}{\eta}\right)(z+h)\right)+8\left(Q_2z-P_2h\right)\frac{(z+h)^2}{R_1^2}\right], \tag{62}$$

$$u_y=\frac{\alpha' D_{yz}}{2\mu\pi}\frac{1}{R_1^2}\left[-\frac{1}{2}\left[P_2(z+3h)+Q_2(h-z)-4Q_4(z+h)\right]-2\left(Q_2z-P_2h\right)\frac{(z+h)^2}{R_1^2}\right], \tag{63}$$

$$u_z=\frac{\alpha' D_{yz}}{2\mu\pi}\frac{y}{R_1^2}\left[\frac{1}{2}\left(P_2-Q_2+4Q_4\right)+2\left(Q_2z-P_2h\right)\frac{(z+h)}{R_1^2}\right], \tag{64}$$

$$\theta=-\frac{\alpha' D_{yz}}{\pi}\left(\frac{\gamma}{\eta}\right)Q_2\frac{y(z+h)}{R_1^4}, \tag{65}$$

where $R_1^2=y^2+(z+h)^2$, $Q_2=P_2/P_1P_3$, and $Q_4=Q_2(1-\upsilon_u)$.

For the above limiting case, the solutions for the elastic half space are obtained as follows:

$$\Phi=\frac{\alpha' D_{yz}}{\pi}\left[y(z+h)\frac{1}{R_1^2}+\frac{1}{2}\left(P_2+Q_2\right)\tan^{-1}\left(\frac{y}{h-z}\right)-P_1\frac{y(z+h)}{R_2^2}+4P_1h\frac{yz(h-z)}{R_2^4}\right], \tag{66}$$

$$\begin{aligned}\sigma'_{yy}=\frac{\alpha' D_{yz}y}{\pi}\Bigg[&2\left(-3+4\frac{(z+h)^2}{R_1^2}\right)\frac{(z+h)}{R_1^4}+\left(P_2+Q_2\right)\frac{(h-z)}{R_2^4}-2P_1(5h-3z)\frac{1}{R_2^4}\\&+8P_1\left(h-z\right)\left(z^2+3h^2-10hz\right)\frac{1}{R_2^6}+96P_1hz\frac{(h-z)^3}{R_2^8}\Bigg],\end{aligned} \tag{67}$$

$$\begin{aligned}\sigma'_{zz}=\frac{\alpha' D_{yz}y}{\pi}\Bigg[&2\left(1-4\frac{(z+h)^2}{R_1^2}\right)\frac{(z+h)}{R_1^4}-\Big(2P_1(z+h)+(P_2+Q_2)(h-z)\\&-8P_1(h-z)(h^2-z^2+6hz)\frac{1}{R_2^2}+96P_1hz\frac{(h-z)^3}{R_2^4}\Big)\frac{1}{R_2^4}\Bigg],\end{aligned} \tag{68}$$

$$\begin{aligned}\sigma'_{yz}=\frac{\alpha' D_{yz}}{\pi}\Bigg[&\left(1-8\left(\frac{z+h}{R_1}\right)^2+8\left(\frac{z+h}{R_1}\right)^4\right)\frac{1}{R_1^2}+\Bigg(\frac{1}{2}\left(P_2+Q_2-2P_1\right)+\left(8P_1-P_2-Q_2\right)\frac{(h-z)^2}{R_2^2}\\&-12P_1hz\frac{1}{R_2^2}-8P_1\frac{(h-z)^4}{R_2^4}\Bigg)\frac{1}{R_2^2}+96P_1hz\frac{(h-z)^2}{R_2^6}\left(1-\left(\frac{h-z}{R_2}\right)^2\right)\Bigg],\end{aligned} \tag{69}$$

$$\varepsilon'_{yy} = \frac{\alpha' D_{yz} y}{2\mu'\pi}\left[2\left(-3+2\upsilon+4\frac{(z+h)^2}{R_1^2}\right)\frac{(z+h)}{R_1^4}+(P_2+Q_2)\frac{(h-z)}{R_2^4}\right.$$
$$-2P_1\left(5h-3z-\upsilon(6\mathrm{h}-2z)\right)\frac{1}{R_2^4}$$
$$\left.+8P_1(h-z)\left(z^2+3h^2-10hz-4\upsilon h(\mathrm{h}-\mathrm{z})\right)\frac{1}{R_2^6}+96P_1hz\frac{(h-z)^3}{R_2^8}\right], \quad (70)$$

$$\varepsilon'_{zz} = \frac{\alpha' D_{yz} y}{2\mu'\pi}\left[2\left(1+2\upsilon-4\frac{(z+h)^2}{R_1^2}\right)\frac{(z+h)}{R_1^4}-\left\{2P_1\left((z+h)-\upsilon(6h-2z)\right)+(P_2+Q_2)(h-z)\right.\right.$$
$$\left.\left.-8P_1(h-z)\left(h^2-z^2+6hz-4\upsilon(h-z)\right)\frac{1}{R_2^2}+96P_1hz\frac{(h-z)^3}{R_2^4}\right\}\frac{1}{R_2^4}\right], \quad (71)$$

$$\varepsilon'_{yz} = \frac{\alpha' D_{yz}}{2\mu'\pi}\left[\left(1-8\left(\frac{z+h}{R_1}\right)^2+8\left(\frac{z+h}{R_1}\right)^4\right)\frac{1}{R_1^2}+\left(\frac{1}{2}\left(P_2+Q_2-2P_1\right)+\left(8P_1-P_2-Q_2\right)\frac{(h-z)^2}{R_2^2}\right.\right.$$
$$\left.\left.-12P_1hz\frac{1}{R_2^2}-8P_1\frac{(h-z)^4}{R_2^4}\right)\frac{1}{R_2^2}+96P_1hz\frac{(h-z)^2}{R_2^6}\left(1-\left(\frac{h-z}{R_2}\right)^2\right)\right], \quad (72)$$

$$u'_y = \frac{\alpha' D_{yz}}{2\mu'\pi}\left[\left(3-2\upsilon'-2\frac{(z+h)^2}{R_1^2}\right)\frac{(z+h)}{R_1^2}-\left(\frac{1}{2}(P_2+Q_2)(h-z)+P_1(h+z)\right.\right.$$
$$\left.+2(1-\upsilon')\; P_1(z-3h)\right)\frac{1}{R_2^2}$$
$$\left.+2P_1\left(h^2-z^2+6hz-4(1-\upsilon')h(h-z)\right)\frac{(h-z)}{R_2^4}-16P_1hz\frac{(h-z)^3}{R_2^6}\right], \quad (73)$$

$$u'_z = \frac{\alpha' D_{yz} y}{2\mu'\pi}\left[\left((1-2\upsilon')+2\frac{(z+h)^2}{R_1^2}\right)\frac{1}{R_1^2}-\left(\frac{1}{2}(P_2+Q_2)+P_1(1-2\upsilon')\right)\frac{1}{R_2^2}\right.$$
$$\left.+2P_1\left(3h^2-z^2-4\upsilon' h(h-z)\right)\frac{1}{R_2^4}-16P_1hz\frac{(h-z)^2}{R_2^6}\right], \quad (74)$$

where $R_2^2 = y^2+(z-h)^2$.

Case (ii) Isothermal case

To obtain the results for this particular case, we define

$$P_4 = \frac{4\upsilon-3-\mu_r}{1-\mu_r} \quad Q_1 = \frac{P_2}{P_1P_4} \quad \text{and} \quad Q_3 = (1-\upsilon)Q_1 \; . \quad (75)$$

The expressions for stress components and displacement components for the present case of isothermal are similar to that for the Case (i) if we replace Q_2 by Q_1 and Q_4 by Q_3. These results coincide with the corresponding expressions for a source in an elastic half space in welded contact with another elastic half space (Singh *et al.* 1992).

6. NUMERICAL RESULTS AND DISCUSSION

Equations 57-64 and 67-74 can be used for computing the stresses, strain and displacements in the two half spaces under adiabatic (thermal equilibrium) conditions. The temperature difference is given by Eq. 65. To obtain the results for the stresses, strain, and displacements under isothermal conditions, Q_2 and Q_4 are changed to Q_1 and Q_3 respectively, in Eqs. 57-64 and 67-74. Following Aki and Richards (1980) and Ahrens (1995), the parameters for thermoelastic medium (Pyrope rich garnet) are taken as

$$\mu = 8.51514\times(10)^{10}\,\mathrm{kg\,m^{-1}s^{-2}},\ \lambda = 11.4508\times(10)^{10}\,\mathrm{kg\,m^{-1}s^{-2}},\ \alpha_t = 3.11\times(10)^{-5}\,\mathrm{K^{-1}},$$
$$\rho = 3620\,\mathrm{kg\,m^{-3}},\ T_0 = 1000\,\mathrm{K},\ C_e = 1076\,\mathrm{m^2K^{-1}s^{-2}},\ \ \beta = (3\lambda + 2\mu)\alpha_t\,. \tag{76}$$

For the elastic half space, the Poisson ratio (υ') is taken as 0.25. To make the quantities dimensionless, the followings are defined

$$\begin{aligned} &Y = \frac{y}{h}, \quad Z = \frac{z}{h}, \quad T = \frac{2ct}{h^2}, \quad U_i' = \frac{h}{bds}u_i\,, \\ &\Theta = \frac{h^2}{\mu' bds}\theta, \quad \Sigma_{ij} = \frac{h^2}{\mu' bds}\sigma_{ij}\,, \quad \Sigma_{ij}' = \frac{h^2}{\mu' bds}\sigma_{ij}'\,. \end{aligned} \tag{77}$$

The displacements, strain and stresses generated by a vertical dip-slip dislocation located at a point $(0,0,-h)$ of the elastic half space are computed.

For $z = 0$, the displacement components for both the limiting cases, adiabatic and isothermal, are computed and shown in Fig. 2 for $\mu_r = 0.5$. Here μ_r is the ratio of rigidity of thermoelastic and elastic half spaces. For $\mu_r = 2$, the displacement components are compared in Fig. 3. It is noticed that the difference between adiabatic and isothermal deformations is more significant when the thermoelastic half space is more rigid than the elastic half space. The more rigid the elastic half space, the larger the horizontal and vertical displacements are.

Assuming that $\mu_r = 2$, the variation of the dimensionless stresses (Σ_{yy}, Σ_{zz}, and Σ_{yz}) with dimensionless horizontal distance (Y) from the fault is shown in Figs. 4a, 5a, and 6a for $z = 0$ and that for $z = h$ is shown in Figs. 4b, 5b, and 6b. At the interface $z = 0$, the stresses Σ_{zz} and Σ_{yz} first decrease with Y and then increase steadily when horizontal distance is a little

(a) (b)

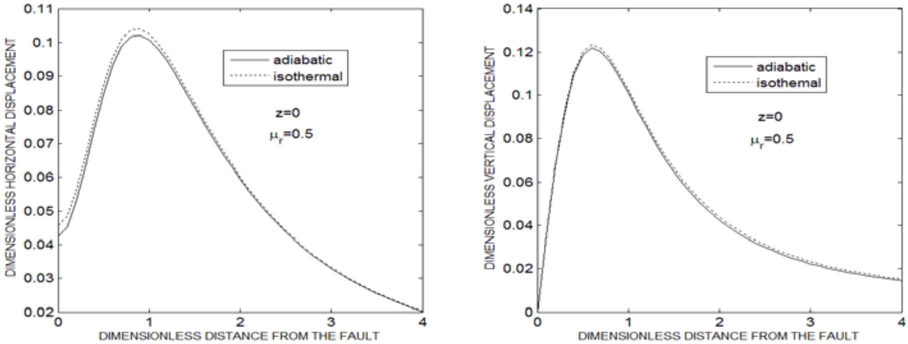

Fig. 2. Variation of horizontal and vertical displacements at the interface $z = 0$ with horizontal distance from the fault for $\mu_r = 0.5$.

(a) (b)

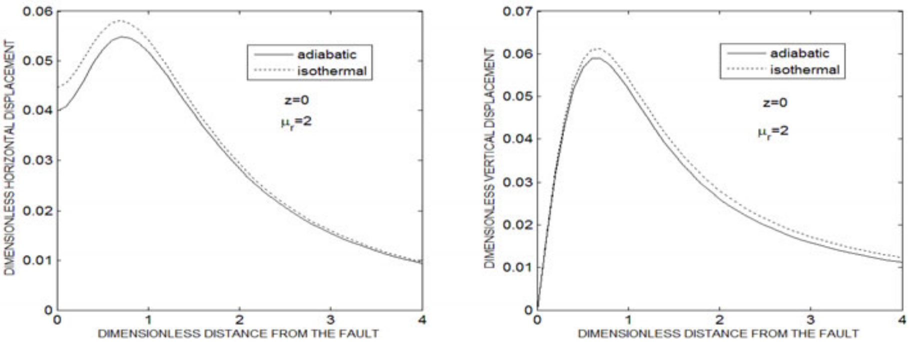

Fig. 3. Variation of horizontal and vertical displacements at the interface $z = 0$ with horizontal distance from the fault for $\mu_r = 2$.

(a) (b)

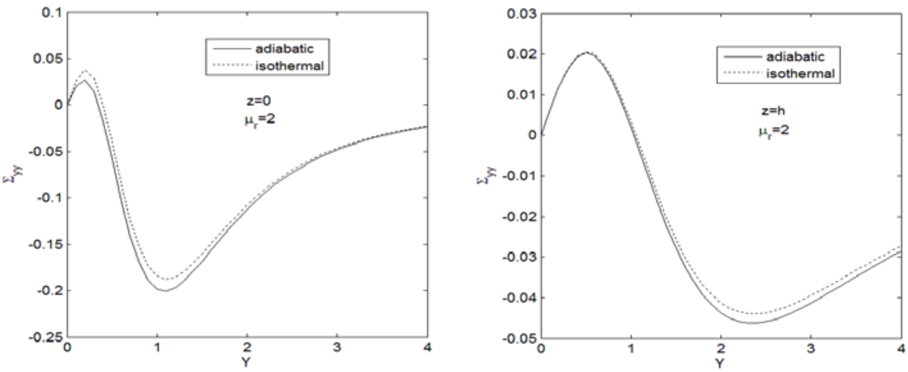

Fig. 4. Variation in dimensionless stress Σ_{yy} in the thermoelastic half space with horizontal distance from the fault $z = 0$ (a), and $z = h$ (b).

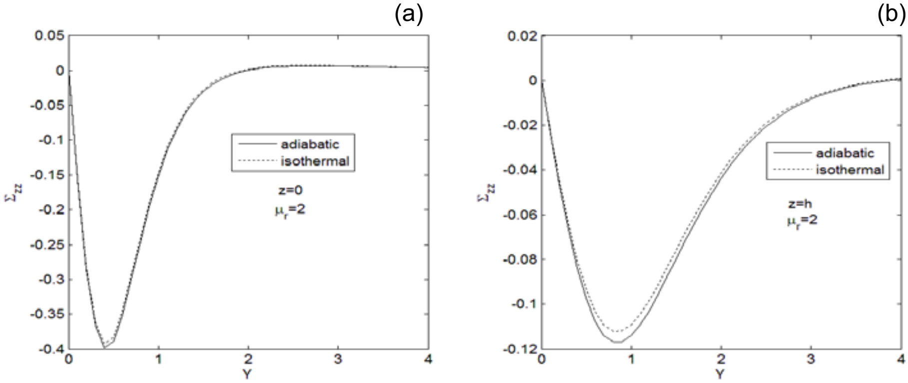

Fig. 5. Variation in dimensionless stress Σ_{zz} in the thermoelastic half space with horizontal distance from the fault $z = 0$ (a), and $z = h$ (b).

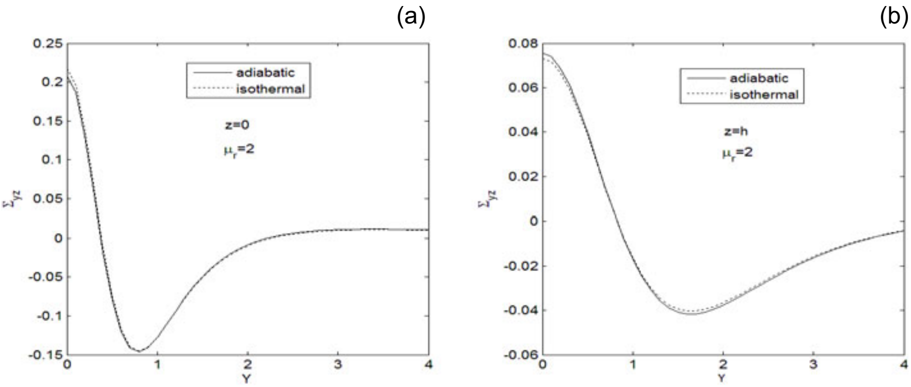

Fig. 6. Variation in dimensionless stress Σ_{yz} in the thermoelastic half space with horizontal distance from the fault $z = 0$ (a), and $z = h$ (b).

less than the depth of the source. As the horizontal distance increases further, *i.e.*, more than twice of the source depth, Σ_{zz} and Σ_{yz} approach to zero. However, Σ_{yy} first increases then decreases and then again increases with Y. The variation pattern of Σ_{yy}, Σ_{zz}, and Σ_{yz} gets smoother for $z = h$, as evident from Figs. 4b-6b. In Figure 7, depth profiles of the stresses Σ_{yy}, Σ_{zz}, and Σ_{yz} are exhibited for $y = h$, $\mu_r = 2$. The stress Σ_{yy} has a maximum value near the plane of source, *i.e.*, $z = -h$. As it goes away from the plane of source towards the interface, it firstly decreases and then increases. It experiences a discontinuity at the interface. Below the plane $z = h$ and above the plane $z = -3h$, the stress Σ_{yy} becomes stable and approaches to zero. In the case of Σ_{yz} and Σ_{zz}, the stresses are continuous at the interface, as expected from the boundary conditions. As we move away from the interface in the elastic medium, Σ_{zz} increases up to a little before the source plane $z = -h$, decreases and

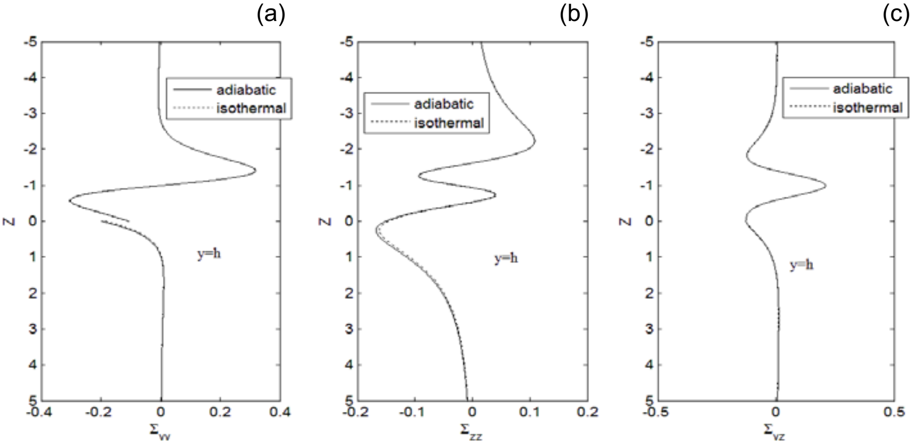

Fig. 7. Variation in dimensionless stresses Σ_{yy} (a), Σ_{zz} (b), and Σ_{yz} (c) with distance from the interface for $y = h$.

increases rapidly up to $z = -2h$, then smoothly decreases and approaches to zero. Similarly, in the thermoelastic half space, it increases smoothly and approaches to zero. The stress Σ_{yz} is greatest on the plane of source, decreases up to a distance h and then increases and approach to zero which is a physically plausible situation also. It is symmetric about the plane of source. No major difference in the variation of the stresses for the two limiting cases is noticed.

From the Eqs. 25, 27-29, 33-34, and 40-44, we get the integral expressions for the temperature, displacements, and stresses at any point in each of the two half spaces caused by a vertical dip slip dislocation located at the point $(0, 0, -h)$ of the elastic half space in $k - \omega$ domain. On replacing $(-i\omega)$ by s, we get the solutions in Fourier–Laplace transform domain, where s is the Laplace transforming variable. Two integrations are required to be performed to get the solution in the space time domain. Schapery (1962) proposed a very simple and efficient approximate formula for finding Laplace inversion numerically. Accordingly, it can be written as

$$\theta(t) \approx [s\overline{\theta}(s)]_{s=1/(2t)} \ , \tag{78}$$

where $\overline{\theta}(s)$ is the Laplace transform of $\theta(t)$.

Inverse Fourier transform is computed numerically. Due to exponential decay, the integrands decrease very rapidly with k.

Figure 8 demonstrates the variation of temperature with time at different depths. It is noticed that the deviation is significant near the interface and the temperature difference approaches to zero as time increases at all depth.

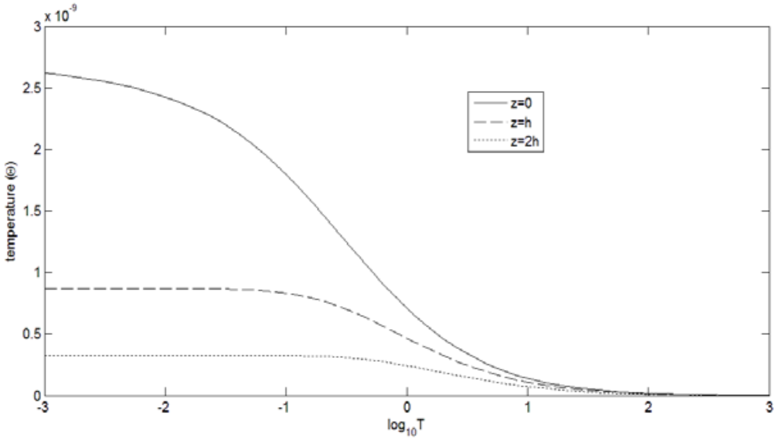

Fig. 8. Diffusion of the temperature difference Θ with T for $y = h$ and $z = 0, h, 2h$.

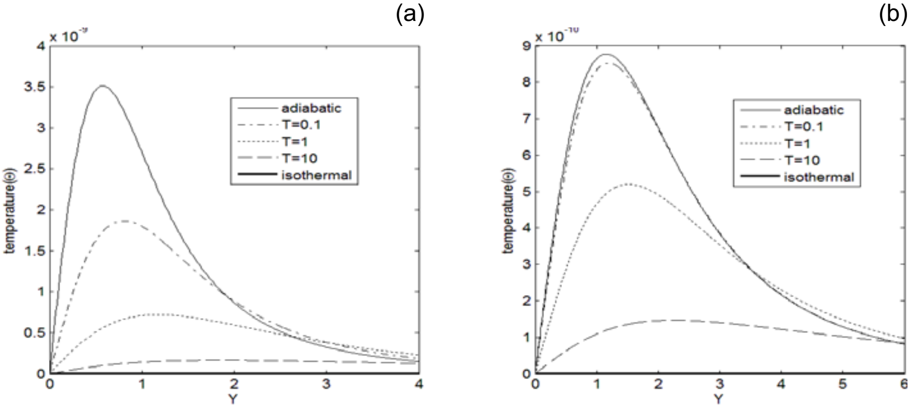

Fig. 9. Variation of the temperature difference Θ with the horizontal distance Y from the fault for $y = h$ at five times $T = 0, 0.1, 1, 10, \infty$ for $z = 0$ (a), and $z = h$ (b).

Temperature difference's variation with Y for different times $T = 0$ (adiabatic), 0.1, 1, 10, ∞ (isothermal), for $z = 0$ and $z = h$ is shown in Fig. 9. As expected, the temperature difference is found zero in the isothermal state. The point of maxima of the temperature difference moves away from the source with time. The temperature difference at different times is more significant on the interface. For all the times, the curves tend to merge for large Y. As T increases, maximum value of temperature difference decreases and maxima travels rightwards with Y.

Figure 10 depicts the depth profile of temperature difference at different times: $T = 0$ (adiabatic), 0.1, 1, 10, ∞ (isothermal). Temperature difference is greatest on the interface and strongly depends on time. As the distance from the interface increases, the temperature difference diffuses rapidly.

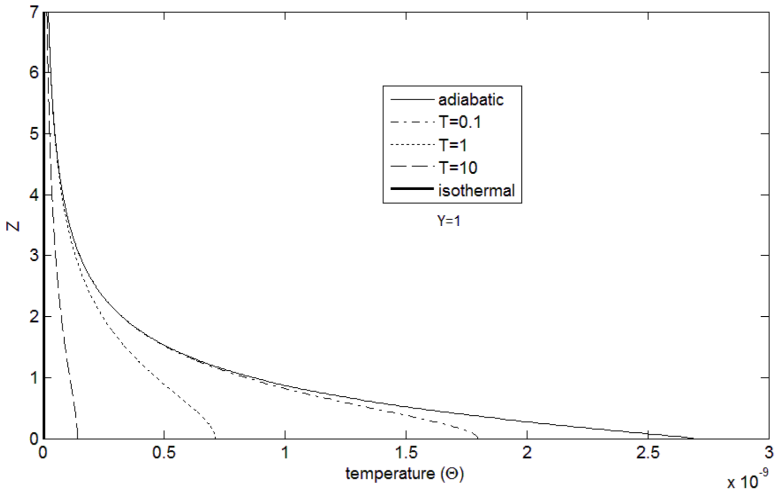

Fig. 10. Variation of the temperature difference Θ with the distance from the interface for $y = h$ at $T = 0, 0.1, 1, 10, \infty$.

Figures 11-15 exhibit time history of dimensionless displacements and stresses for $y = h$: (a) $z = 0$, and (b) $z = 2h$. It is noticed that, at the interface, horizontal displacement and Σ_{yz} decrease slowly with T and then increase, but the vertical displacement and stresses Σ_{yy} and Σ_{zz} increase with time. At $z = 2h$, the horizontal displacement and Σ_{zz} increase with time but the vertical displacement, stresses Σ_{yy} and Σ_{yz} firstly decrease then increase. It is noticed that as the distance from the interface increases, the point of minima of the displacements and stresses move rightward along the time. Also, the variation in displacements and stresses is significant in the range $T = 0.01$ to $T = 100$.

The stress Σ_{yy}'s variation with temperature and with horizontal distance from the fault is shown in Fig. 16. Similarly, the stresses profiles of Σ_{zz} and Σ_{yz} are shown in the Figs. 17 and 18. It can be concluded from these graphs that temperature distribution does not have a major role in the determination of stresses in the thermoelastic half space except in the vicinity of the fault plane. In Fig. 19, the stress profiles with temperature and distance from the interface are depicted. These graphs also confirm the observations about stress variation with Z made earlier.

Deformation in elastic medium is presented in Figs. 20-23.Variation of horizontal and vertical displacements at $z = -1.5h$ with horizontal distance from the fault are presented in Fig. 20 and that at $z = -5h$ are presented in Fig. 21. Horizontal displacement first decreases and then increases and approaches to zero. Vertical displacement first increases, then deceases and

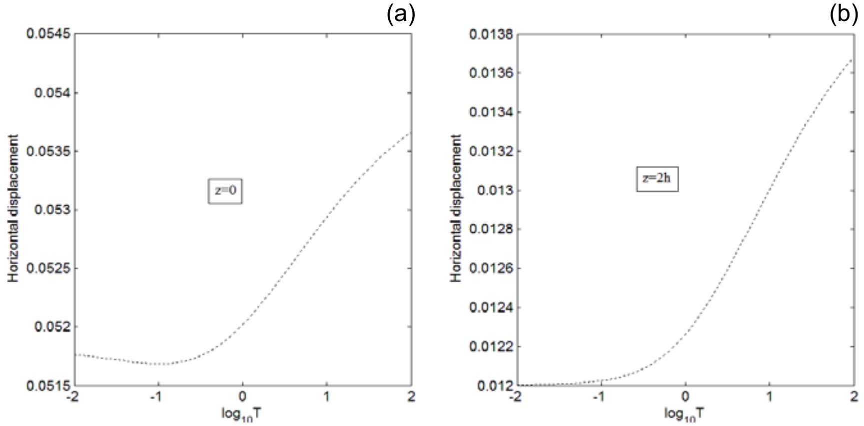

Fig. 11. Variation of horizontal displacement with time T: (a) $z = 0$, and (b) $z = 2h$.

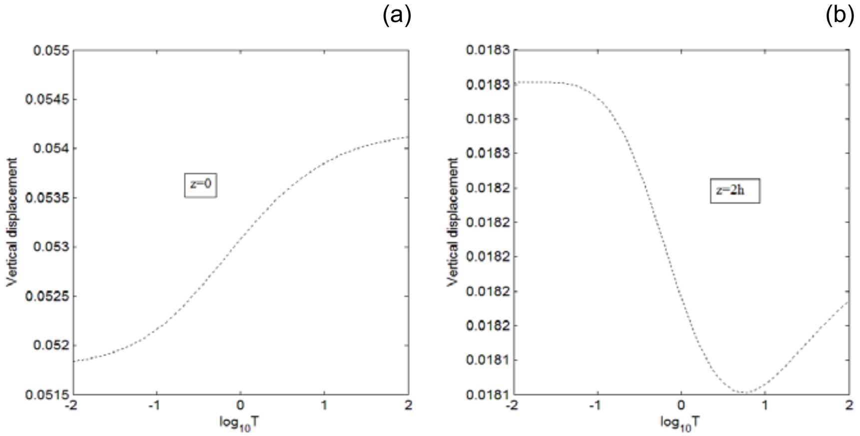

Fig. 12. Variation of vertical displacement with time T: (a) $z = 0$, and (b) $z = 2h$.

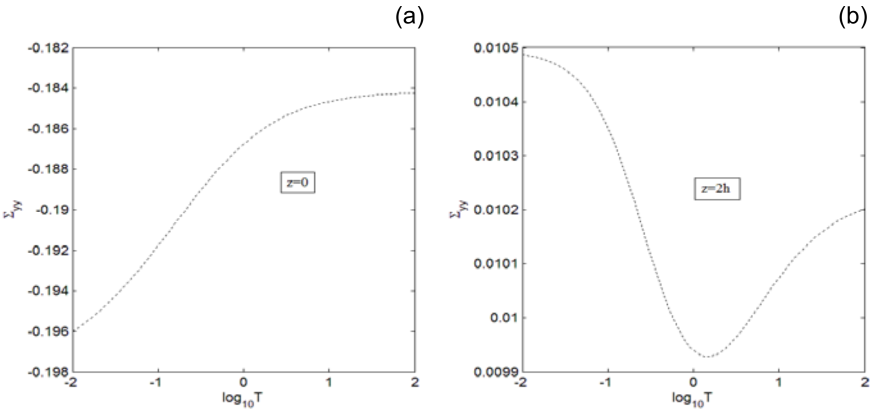

Fig. 13. Variation of stress Σ_{yy} with time T: (a) $z = 0$, and (b) $z = 2h$.

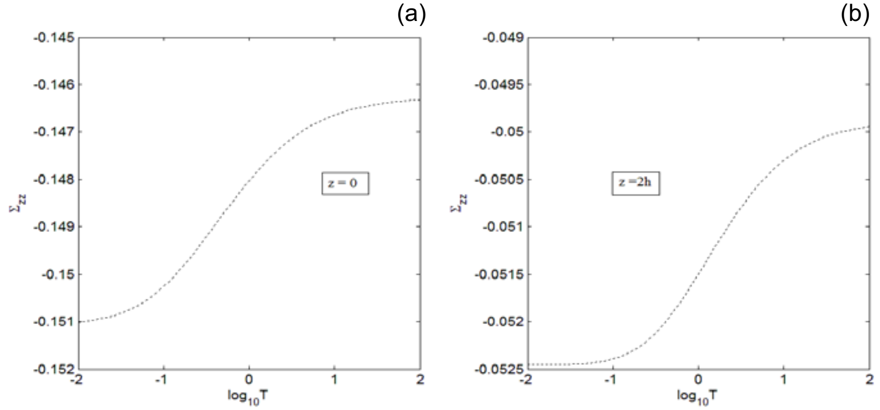

Fig. 14. Variation of stress Σ_{zz} with time T: (a) $z = 0$, and (b) $z = 2h$.

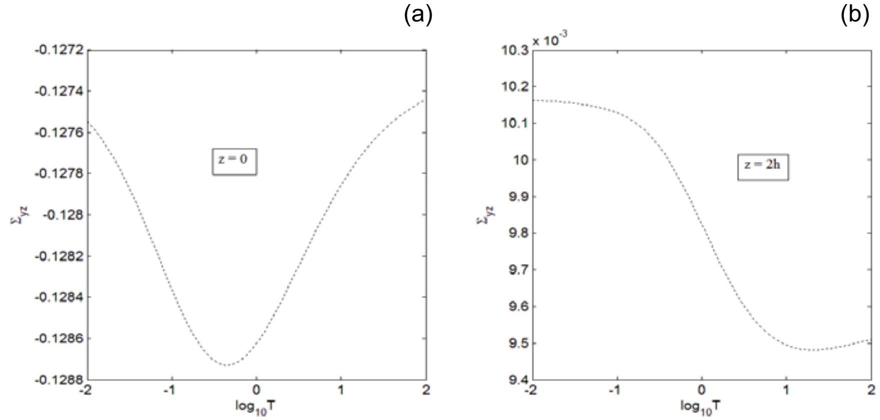

Fig. 15. Variation of stress Σ_{yz} with time T: (a) $z = 0$, and (b) $z = 2h$.

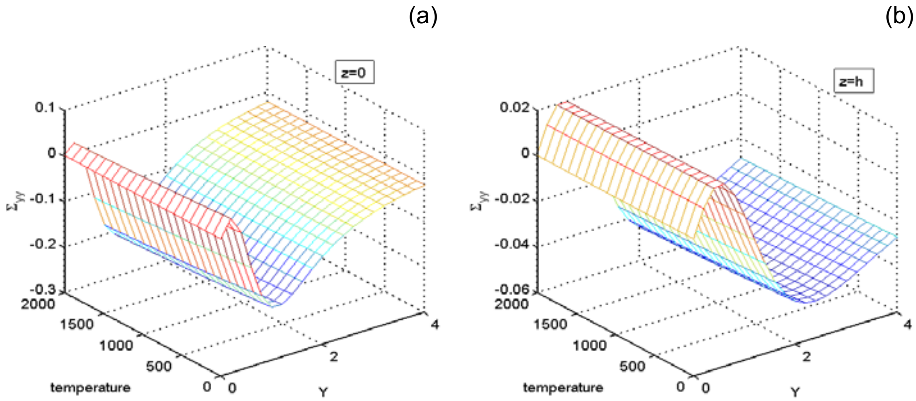

Fig. 16. Variation of stresses Σ_{yy} with temperature and distance from fault $z = 0$ (a), and $z = h$ (b).

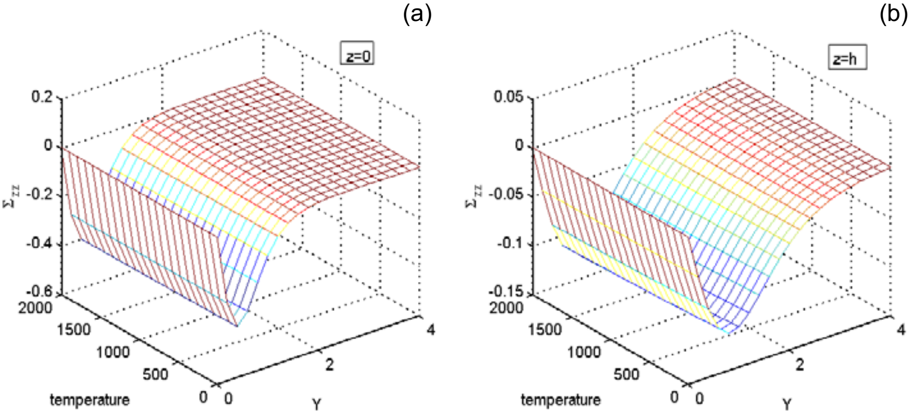

Fig. 17. Variation of stresses Σ_{zz} with temperature and distance from fault $z = 0$ (a), and $z = h$ (b).

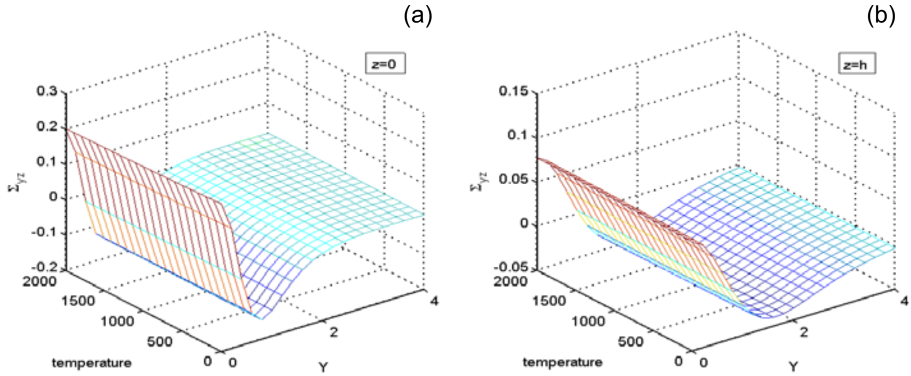

Fig. 18. Variation of stresses Σ_{yz} with temperature and distance from fault $z = 0$ (a), and $z = h$ (b).

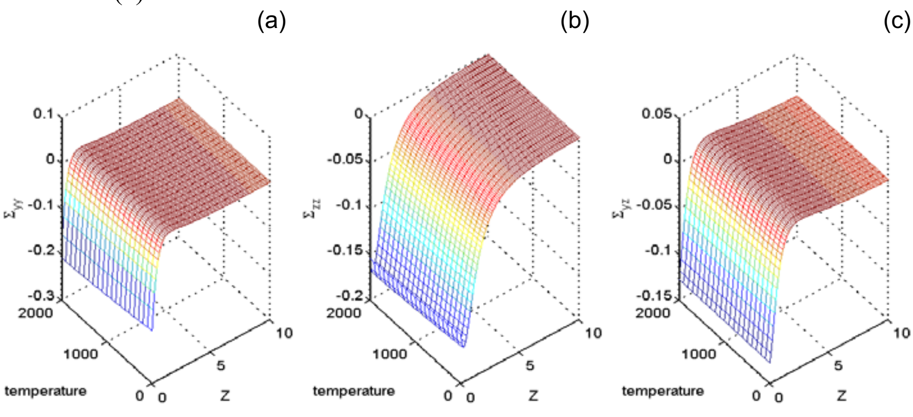

Fig. 19. Variation of stresses Σ_{yy} (a), Σ_{zz} (b), and Σ_{yz} (c) with temperature and distance from interface for $y = h$.

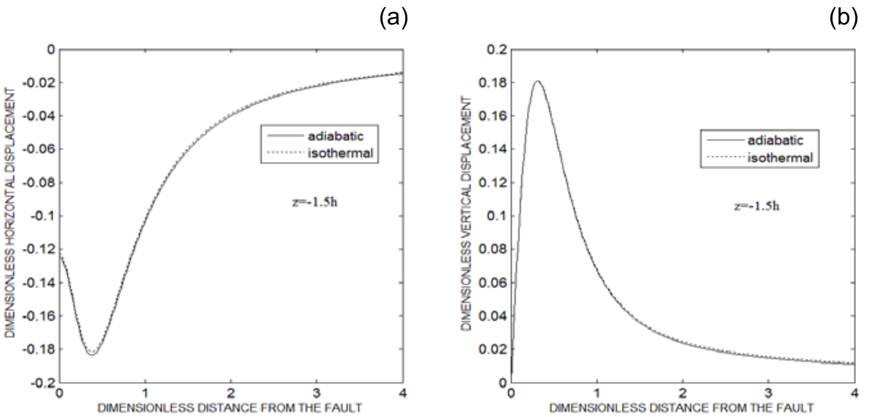

Fig. 20. Variation of horizontal and vertical displacements at $z=-1.5h$ with horizontal distance from the fault.

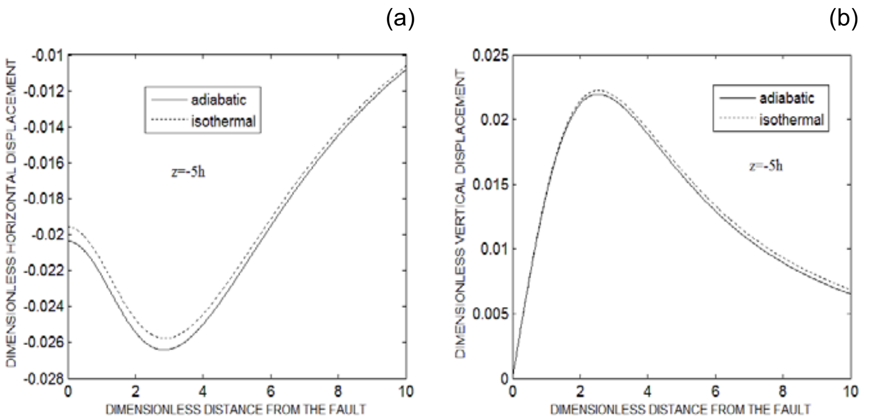

Fig. 21. Variation of horizontal and vertical displacements at $z=-5h$ with horizontal distance from the fault.

approaches to zero. It is noticed that difference in the two extreme cases (adiabatic and isothermal) is more significant at $z=-5h$ than $z=-1.5h$ but the displacements are more significant near the plane of source (*i.e.*, $z=-1.5h$).

Variation of the stresses $\Sigma'_{yy}, \Sigma'_{zz}, \Sigma'_{yz}$ at $z=-1.5h$ with horizontal distance from the fault are presented in Fig. 22a, b and that at $z=-5h$ are presented in Fig. 23a, b. The difference in the limiting cases is significant at far distance from the source. There is a sharp stress drop in elastic half space, *i.e.*, the region containing the fault in comparison to the other half space. At a sufficient distance from the source, the shear displacement increases steadily and the longitudinal displacement decreases steadily.

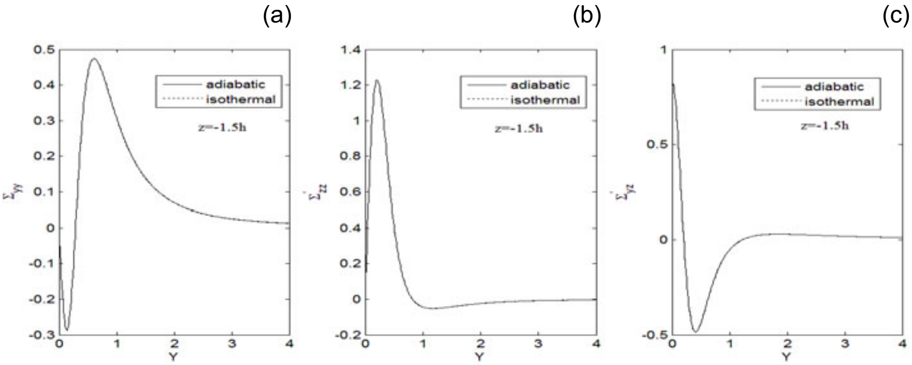

Fig. 22. Variation of stresses Σ'_{yy} (a), Σ'_{zz} (b), and Σ'_{yz} (c) at $z = -1.5h$ with horizontal distance from the fault.

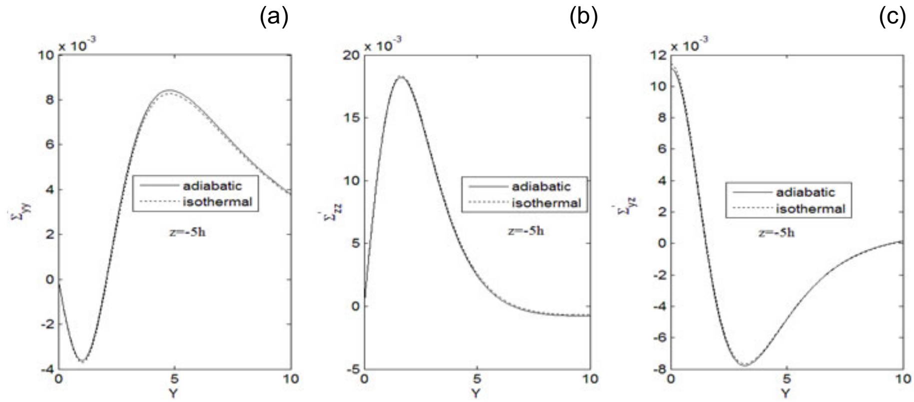

Fig. 23. Variation of the stresses Σ'_{yy} (a), Σ'_{zz} (b), and Σ'_{yz} (c) at $z = -5h$ with horizontal distance from the fault.

The effect of thermoelasticity in the deformation of elastic medium is more significant when the source is nearer to the interface $z = 0$. If the elastic medium is considered as the crustal layer of the Earth and mantle layer is modeled as thermoelastic medium, then due to the fault occurring in the crust near the mantle, the effect of thermoelasticity is significant on the Earth's surface.

List of parameters

Symbol	Description
x, y, z	Cartesian coordinates
t	time
u_i	displacement components of thermoelastic medium
h	distance of the source from interface
σ_{ij}	stress tensor of thermoelastic medium
ε_{ij}	strain tensor of thermoelastic medium
δ_{ij}	Kronecker delta
λ, μ	Lame's constants of thermoelastic medium
α_t	coefficient of linear thermal expansion
$\beta = (3\lambda + 2\mu)\alpha_t$	thermoelastic coupling coefficient
θ	difference between absolute temperature and temperature at the natural state
υ	Poisson's ratio of thermoelastic medium
λ_0	thermal conductivity
C_e	specific heat
ρ	density
T_0	temperature of the medium at natural state
q_i	components of heat flux
ω	frequency
u_i'	displacement components of elastic medium
μ'	shear modulus of elastic medium
υ'	Poisson's ratio of elastic medium
σ_{ij}'	stress tensor of elastic medium
μ_r	ratio of rigidity of thermoelastic and elastic mediums
Y, Z	dimensionless Cartesian coordinates
T	dimensionless time
U_i'	dimensionless displacement components
Θ	dimensionless temperature difference
Σ_{ij}	dimensionless stress tensor of thermoelastic medium
Σ_{ij}'	dimensionless stress tensor of elastic medium

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