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ANTI-PLANE DEFORMATION IN GREEN-NAGHDI (TYPE III) THERMOELASTIC MEDIUM

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Anti-plane problems in elastic, viscoelastic, functionally graded material, and thermoelastic medium have been discussed by researchers in the past. The anti-plane problem in the context of Green-Naghdi (Type III) thermoelasticity has been unexplored. In the present work, a crack in a strip of Green Nagdhi (Type III) thermoelastic medium is discussed under anti-plane shear conditions. The lower boundary of the strip is fixed and it is displaced along the upper boundary. The crack surface is assumed to be traction-free. The expressions of displacement, temperature, and shear stress are obtained. The values of these expressions are then obtained using MATLAB software and the values are then plotted against horizontal distance. The effect of the width of the strip on the components is shown through graphical results. It is found that the width of the strip affects all the physical quantities. The shearing stress along the width of the strip is less oscillatory as compared to the shearing stress along the length of the strip.

Key words: crack, Green-Naghdi, anti-plane, shear stress, temperature distribution.

1. Introduction

In the initial years, thermoelasticity theories were introduced by researchers [1-3]. Green and Nagdhi [4-6] explored the theory of thermoelasticity by introducing type I, type II, and type III theories. In these theories proposed by Green and Naghdi entropy equality was considered instead of entropy inequality taken in previous theories. Different researchers have explored the Green-Naghdi theory of thermoelasticity in the past namely Quintanilla [7, 8], Bargmann *et al.* [9], Aouadi *et al.* [10], Kumar *et al.* [11], Othman and Eraki [12], Ezzat *et al.* [13], Aouadi *et al.* [14], Conti *et al.* [15], Abouelregal [16], Sarkar and Atwa [17], Atwa [18], Abbas [19], Ailawalia *et al.* [20]. A lot of work has been done in the field of thermoelastic theories. It may not be possible to acknowledge all the work but a few prominent problems discussed in the past have been acknowledged by the authors. Pany *et al.* [21] studied wave propagation in orthogonally supported periodic curved panels. Abbas and Othman [22] investigated propagation of plane waves in a thermo-microstretch elastic solid half-space. Abbas [23] studied a problem on thermoelastic interactions in a functional graded material due to thermal shock in the context of the fractional order three-phase lag model. Marin *et al.* [24] derived some results in Moore-Gibson-Thompson thermoelasticity of dipolar bodies. Abbas along with his co-workers explored problems in semiconducting thermoelastic medium [25, 26]. Recently, Lotfy *et al.* [27] investigated the stochastic plasma-mechanical-elastic wave propagation at the boundary of an elastic half-space in a semiconductor material using photo-thermoelasticity theory.

The anti-plane shear crack problems have been extensively studied in the past since these types of problems help to understand the nature of the crack problem. Some of the earlier works on anti-plane problems include Rice [28], Paulino *et al.* [29], Erdogan [30], Ang *et al.* [31], Atkinson and Chen [32]. The anti-plane problems in the field of thermoelasticity have also been discussed by Pettinger and Abeyaratne [33, 34], and Zhou and Shui [35, 36]. Researchers have also studied different types of anti-plane problems in inhomogeneous media [37-43].

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Anti-plane problems in elastic [29], viscoelastic [32], functionally graded material [30, 37-43], thermoelastic medium [33-36] have been discussed by researchers. The anti-plane problem in the context of Green-Naghdi (Type III) thermoelasticity has been unexplored. The current research deals with the investigation of the effect of shear stress in an infinite homogeneous thermoelastic strip of Green-Naghdi (Type III). Expressions for stress, displacement, and temperature are obtained by analytical technique. A numerical example is solved to complement the analytical results. The graphical results are shown for different values of the width of the thermoelastic strip.

2. Basic equations

An infinite homogeneous thermoelastic strip of Green Naghdi (Type III) is considered (Fig.1). The lower surface of the strip represented by $y=-h$ is fixed. The upper surface of the strip $(y=h)$ is displaced as given by $u_3(t)=w(t)=u_0 f(t)$, where u_0 is a constant and $f(t)$ is a non-dimensional function of time. The crack is assumed to lie on the $x-$axis. This crack is of infinite extent along the $z-$axis. The crack surface remains traction-free.

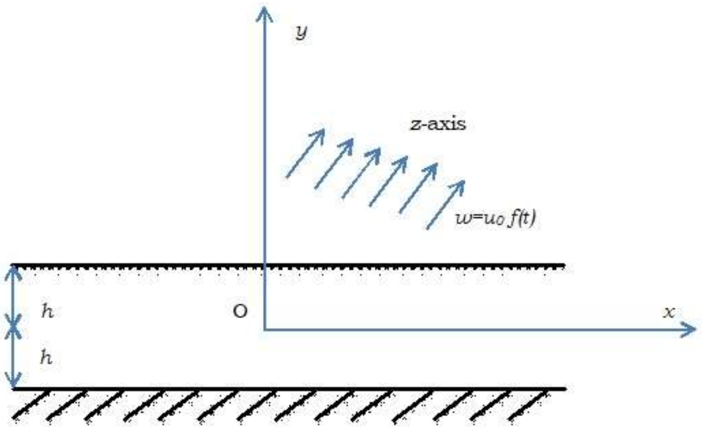

Fig.1. A uniform anti-plane displacement $w=u_0 f(t)$ and a constant thermal source act along the upper boundary $(y=h)$ of the strip.

The field equations, constitutive relations, and heat conduction equation under Green-Naghdi (Type III) homogeneous thermoelastic medium are expressed as follows [6]:

$$\rho\ddot{u}_i=\mu u_{i,kk}+(\lambda+\mu)u_{k,ik}-\frac{\beta}{k_T}T_{,i}\,, \tag{2.1}$$

$$\sigma_{ij}=2\mu e_{ij}+\lambda e_{kk}\,\delta_{ij}-\frac{\beta}{k_T}T\delta_{ij}\,, \tag{2.2}$$

$$h_i=K_1\frac{\partial T}{\partial x_i}\,,\quad U=\frac{\beta T_0}{\rho k_T}e_{kk}+C^*T, \tag{2.3}$$

$$e_{ij}=\frac{u_{i,j}+u_{j,i}}{2}\,, \tag{2.4}$$

$$K_1 T_{,ii} + K_2 \dot{T}_{,ii} - \rho C^* \dot{T} = \vartheta T_0 \ddot{u}_{i,i}. \tag{2.5}$$

3. Problem definition

A two-dimensional antiplane shear fracture in Green-Naghdi (Type III) thermoelastic medium is considered. The components of displacement vector $\vec{u} = (u_1, u_2, u_3)$ are functions of $x, y,$ and t, since the deformation of the medium is parallel to the $x - y$ plane.

Under anti-plane shear conditions, the only non-vanishing field variables are

$$u_3(x,y,t) = w(x,y,t), \quad \sigma_{xz}(x,y,t) = \sigma_x(x,y,t), \quad \sigma_{yz}(x,y,t) = \sigma_y(x,y,t).$$

For simplicity, new notations for displacement and stresses have been used.
Hence the considered Eqs (2.1) and (2.5) for a two-dimensional problem may be written as:

$$\mu \nabla^2 w = \rho \frac{\partial^2 w}{\partial t^2}, \tag{3.1}$$

$$K_1 \nabla^2 T + K_2 \nabla^2 \frac{\partial T}{\partial t} - \rho C^* \frac{\partial^2 T}{\partial t^2} = 0. \tag{3.2}$$

Also, the stress components follow from Eq.(2.2):

$$\sigma_x = \mu \frac{\partial w}{\partial x}, \tag{3.3}$$

$$\sigma_y = \mu \frac{\partial w}{\partial y}. \tag{3.4}$$

Further, to simplify the numerical computations, the following dimensionless variables are introduced,

$$x' = \frac{1}{c_1 t^*} x, \quad y = \frac{1}{c_1 t^*} y, \quad w' = \frac{1}{c_1 t^*} w, \quad t' = \frac{t}{t^*}, \quad \sigma'_{ij} = \frac{\sigma_{ij}}{\mu}, \quad T' = \frac{\vartheta T}{(\lambda + 2\mu)} \tag{3.5}$$

where $c_1^2 = \frac{\lambda + 2\mu}{\rho}$, $t^* = \frac{K_1}{\rho C^* c_1^2}$.
Using Eq.(3.5) in Eqs (3.1)-(3.4), the equations are:

$$\mu \nabla^2 w = \frac{\rho c_1^2}{\mu} \frac{\partial^2 w}{\partial t^2}, \tag{3.6}$$

$$\frac{K_1}{\rho c_1^2} \nabla^2 T + \frac{K_2}{c_1^2 t^*} \nabla^2 \frac{\partial T}{\partial t} - \rho C^* \frac{\partial^2 T}{\partial t^2} = 0, \tag{3.7}$$

$$\sigma_x = \frac{\partial w}{\partial x}\,, \tag{3.8}$$

$$\sigma_y = \frac{\partial w}{\partial y}. \tag{3.9}$$

4. Problem solution

The response of physical variables may be studied by expressing them in the form of normal modes as proposed by Cinelli and Pilkey [44]:

$$\left[w,\sigma_{ij},T\right]=\left[\bar{w},\bar{\sigma}_{ij},\bar{T}\right](y)e^{\omega t+ibx} \tag{4.1}$$

where ω is a complex time constant and b is the wave number in the x-direction.

The advantage of normal mode analysis is that it provides an exact solution without imposing conditions on the quantities and may be applied to large systems as well.

Using Eq.(4.1) in Eqs (3.6)-(3.9), two independent wave equations in terms of $\bar{w}$ and $\bar{T}$ are obtained as:

$$\left(\frac{d^2}{dy^2}-m_1^2\right)\bar{w}=0, \tag{4.2}$$

$$\left(\frac{d^2}{dy^2}-m_2^2\right)\bar{T}=0 \tag{4.3}$$

where

$$m_1^2=b^2+\frac{\rho c_1^2}{\mu}\omega^2, \quad m_2^2=b^2+\frac{\rho C^*}{a_{11}}\omega^2, \quad a_{11}=\frac{1}{c_1^2}\left[K_1+\frac{K_2\omega}{t^*}\right]. \tag{4.4}$$

The solution of wave Eqs (4.2) and (4.3) may be expressed as

$$\bar{w}=A_1e^{-m_1y}+A_2e^{m_1y}, \tag{4.5}$$

$$\bar{T}=A_3e^{-m_2y}+A_4e^{m_2y}. \tag{4.6}$$

5. Boundary conditions

To understand the behavior of thermoelastic medium, boundary conditions play a vital role. Properly defined boundary conditions ensure that the considered problem relates to the real-world model which further leads to more reliable results.

The appropriate conditions along the boundary are:

- The lower boundary of the strip is fixed

$$w=0,\ y=-h\,;$$

- The upper boundary of the strip is displaced

$$w = u_0 \, e^{\omega t}, \; y = h \; ;$$

- A thermal source acts along the upper boundary of the strip (5.1)

$$T = P_0 \, e^{\omega t}, \; y = h \; ;$$

- The temperature field is continuous across the boundary

$$T\left(x, 0^-\right) = T\left(x, 0^+\right).$$

With the boundary conditions mentioned above, the following non-homogenous system of equations is attained:

$$A_1 e^{m_1 h} + A_2 e^{-m_1 h} = 0, \tag{5.2}$$

$$A_1 e^{-m_1 h} + A_2 e^{m_1 h} = u_0, \tag{5.3}$$

$$A_3 e^{-m_2 h} + A_4 e^{m_2 h} = P_0, \tag{5.4}$$

$$A_3 - A_4 = 0. \tag{5.5}$$

The above non-homogenous system can be solved by simple mathematical calculations. The values of $A_i \left(i = 1, 2, 3, 4\right)$ are then substituted in the expressions (4.5), and (4.6) to evaluate the components of displacement, stress, and temperature distribution using Eqs (3.8)-(3.9).

6. Numerical computation

To support the theoretical results, a numerical example is presented. MATLAB software is used for numerical calculations.

Magnesium crystal is chosen as the material for numerical evaluation. The physical constants are taken from Dhaliwal and Singh [45],

$$\lambda = 2.17 \times 10^{10} \frac{N}{m^2}, \quad \mu = 3.278 \times 10^{10} \frac{N}{m^2}, \quad \beta = 2.68 \times 10^6 \, N / m^2 \;, \quad C^* = 1.04 \times 10^3 \frac{J}{kg},$$

$$\vartheta = 2.68 \times 10^4 \frac{N}{m^2}, \quad K_1 = 1.7 \times 10^2 \frac{W}{m}, \quad K_2 = 0.5, \quad \rho = 1.7 \times 10^3 \frac{kg}{m^3}, \quad T_0 = 298\,K.$$

The calculations for the numerical analysis are carried out by taking $u_0 = P_0 = 1.0$ on the surface $y = 1.0$ at $t = 0.1$. The graphical results so obtained for the components of displacement, stress components, and temperature are shown in Figs 2 to 5 assuming that $\omega = \omega_0 + i\omega_1$ with $\omega_0 = -0.3$, $\omega_1 = 0.2$ and $b = 0.3$.

7. Discussions

It is observed from the analytical results that two independent waves namely, displacement wave and thermal wave exit in the medium. The graphical results show that the width of the strip affects all the physical quantities. The value of displacement decreases sharply in the range $0 \le x \le 10.0$ for $h = 0.1$. However, these variations are opposite as the value of h increases (i.e $h = 0.5$ and 1.0). It is observed from Fig.2, that the values of displacement increase sharply in the range $0 \le x \le 10.0$ for $h = 0.5$ and 1.0. The variation of stress σ_x is oscillatory irrespective of width of the strip. It is interesting to see that the magnitude of the oscillation of stress σ_x is inversely proportional to the width of the strip. These variations of stress σ_x are shown in Fig.3.

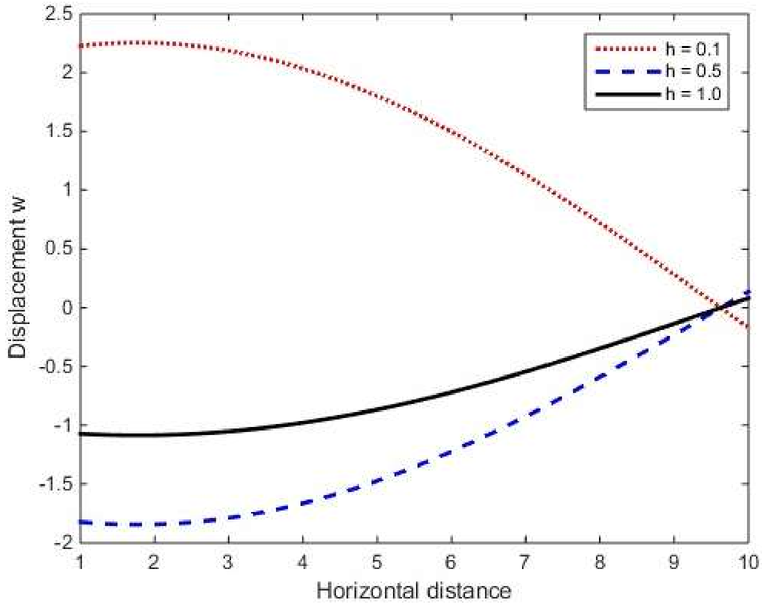

Fig.2. Variation of displacement w with horizontal distance x.

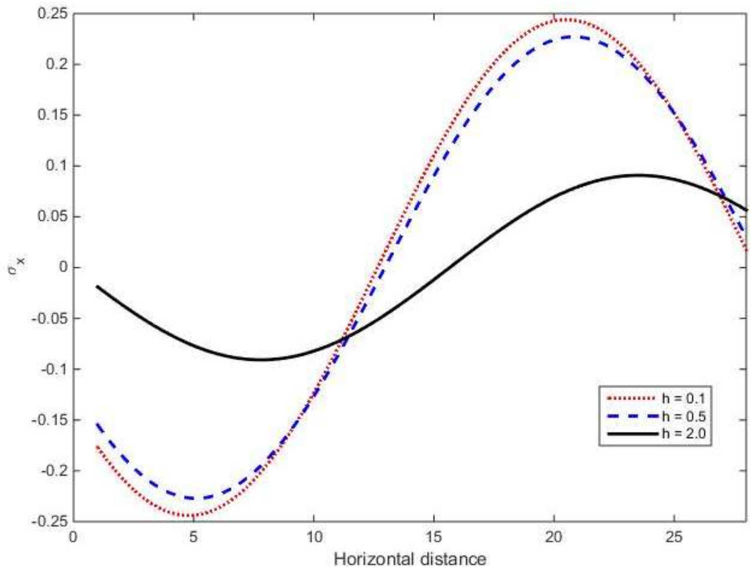

Fig.3. Variation of stress σ_x with horizontal distance x.

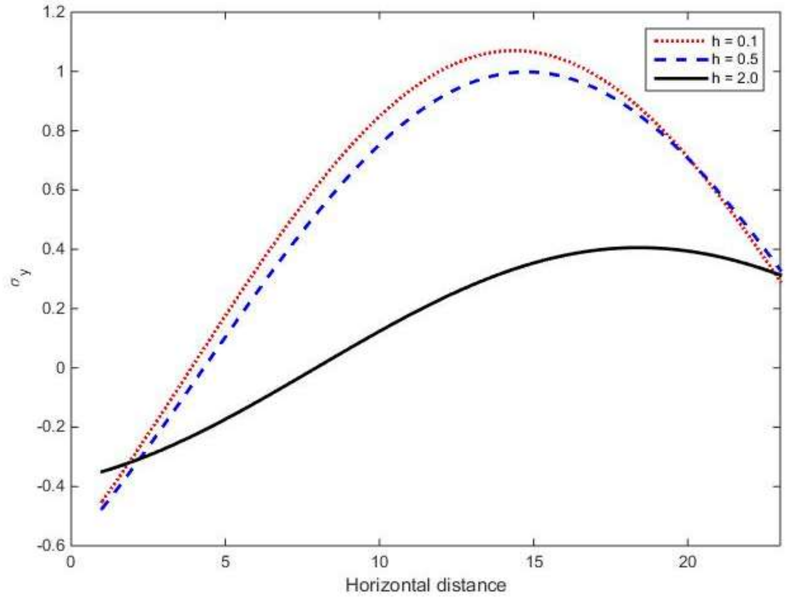

Fig.4. Variation of stress σ_y with horizontal distance *x*.

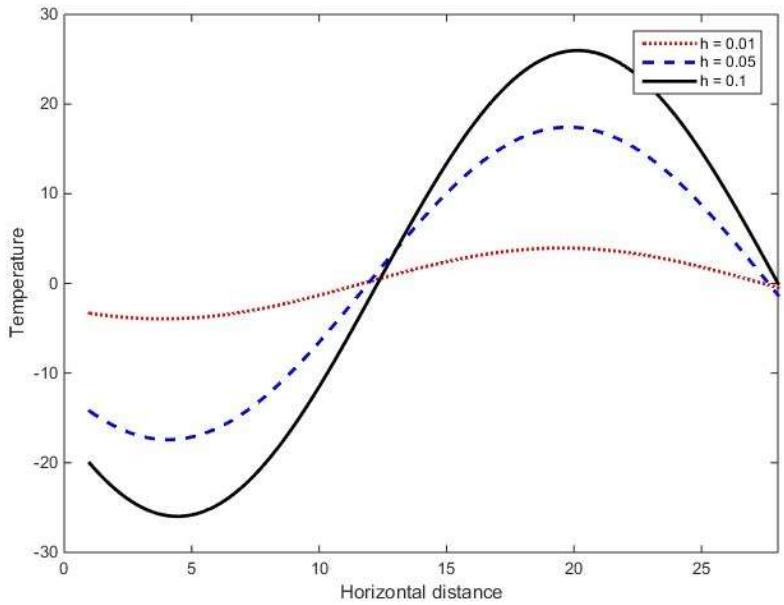

Fig.5. Variation of temperature field T with horizontal distance *x*.

The values of stress σ_y increase in the range $0 \le x \le 10.0$ for different values of width of strip. This increase in the value of stress σ_y becomes sharper as the width of the strip decrease. This variation of stress σ_y is shown in Fig.4. The variation of the temperature field is also oscillatory similar to the variation in stress σ_x but contrary to the variation of stress σ_x, the magnitude of oscillation is directly proportional to the width of the strip. Hence, there is more variation in temperature change with width of the strip. These variations of temperature fields for different strip widths are shown in Fig.5.

8. Conclusion

The effect of shear stress in an infinite homogeneous thermoelastic strip of Green Naghdi (Type III) is investigated. The analytical and numerical results conclude that:

1. An independent displacement wave and thermal wave exit in the medium.
2. The width of the strip affects all the physical quantities.
3. The variation of stress σ_x is oscillatory and the magnitude of oscillation is inversely proportional to the width of the strip.
4. The shearing stress σ_{yz} is less oscillatory as compared to the shearing stress σ_{xz}.
5. The variation of the temperature field is also oscillatory but the magnitude of oscillation is directly proportional to the width of the strip.
6. The problem has wide applications in the field of fracture mechanics, earthquake engineering, acoustic wave propagation, thermal stress analysis. etc.
7. The present study may be extended to study the anti-plane problems on the interface of two dissimilar media.
8. However the anti-plane problems restricts the model to simple geometries whereas the complex three dimensional shapes cannot be analysed using these assumptions.

Nomenclature

C^* – specific heat at constant strain
e_{ij} – strain components
e_{kk} – cubical dilatation
h_i – heat flux
K_1 – thermal conductivity
K_2 – material characteristic of the theory
k_T – isothermal compressibility
T – temperature above the reference temperature T_0
T_0 – reference temperature
U – specific internal energy
u_i – displacement components
β – constant of thermal expansion
δ_{ij} – Kronecker delta
λ,μ – Lame's coefficients
ρ – density of solid
σ_{ij} – stress components
$\vartheta = (3\lambda + 2\mu)\beta$ – thermal modulus

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