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Finite Element Modeling of Thermoelastic Interaction in an Unbounded Orthotropic Medium Containing a Cylindrical Cavity

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Abstract: This study investigates the coupled thermoelastic behavior of an orthotropic medium containing a cylindrical cavity within the framework of generalized thermoelasticity with two thermal relaxation times. The governing problem is solved numerically using the finite element method, with the thermal conductivity assumed to be constant. A quadratic finite element formulation is adopted to discretize the medium and approximate the resulting field variables. Numerical solutions for the physical quantities are derived under the influence of an exponentially decaying heat flux applied to the surface. The numerical results are presented graphically to elucidate the influence of thermal relaxation times and the duration of pulsed heat flux on the distributions of the relevant thermoelastic field variables. The findings provide insight into the coupled thermal and mechanical responses of orthotropic materials under the specified boundary conditions.

Keywords: Finite element analysis; cylindrical cavity; orthotropic thermoelastic medium; thermal relaxation times.

1 Introduction

Orthotropic materials constitute an important class of anisotropic solids whose mechanical and thermal properties differ along three mutually perpendicular principal directions. Owing to their directional dependence, these materials exhibit distinct responses to thermal and mechanical loading, making their analysis essential in various engineering applications. Over recent decades, generalized thermoelasticity has attracted considerable attention from researchers because of its ability to describe coupled thermal and mechanical phenomena more realistically than classical thermoelastic theories. These models have applications in continuum mechanics, nuclear technology, aerospace engineering, high-energy particle accelerators, acoustics, and other fields involving thermally induced deformation and wave propagation.

The development of thermoelastic theories has progressed from classical coupled formulations to generalized models that account for finite-speed thermal disturbances. Biot [1] introduced the coupled theory of thermoelasticity to overcome limitations associated with the uncoupled formulation by incorporating the interaction between the temperature field and elastic deformation. Subsequently, Lord and Shulman [2] proposed a generalized thermoelastic model incorporating a single thermal relaxation time. Green and Lindsay [3] have obtained the second generalized thermo-elastic model in the case of two thermal relaxation times. Dhaliwal and Sherief [4] extended this framework to accommodate anisotropic materials, thereby broadening its applicability to solids with direction-dependent properties.

Subsequent research has investigated various aspects of generalized thermoelastic behavior under different physical conditions and constitutive assumptions. Singh [5] examined wave propagation in materials containing voids within generalized thermoelastic frameworks. Alesemi [6] analyzed plane-wave propagation in anisotropic magnetothermoelastic media governed by the Lord–Shulman (LS) theory, accounting for Coriolis and centrifugal effects. Zenkour and Abbas [7] investigated magnetic-field influences on fiber-reinforced anisotropic

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plates using the Green–Naghdi (GN) theory. In a related contribution, Zenkour and Abbas [8] employed a finite element formulation to study magnetic-field effects in an infinite functionally graded thermoelastic cylinder. Abbas and Zenkour [9] explored the combined influences of initial stress and rotation on fiber-reinforced anisotropic materials within the Green–Naghdi framework.

The Green–Lindsay (GL) theory and related formulations incorporating two relaxation times have been applied to a wide range of coupled thermoelastic problems. Alzahrani and Abbas [10] investigated thermoelastic interactions in porous media subjected to pulsed heat flux using a fractional-order GL model, while Allam et al. [11] examined the reflection of P and SV waves from the free surface of a thermoelastic diffusion solid under electromagnetic fields and initial stress. Modified Green–Lindsay formulations were employed by Tayel et al. [12] and Mohamed et al. [13] to study illumination-induced responses in two-dimensional semi-infinite thermoelastic media, with the latter incorporating rotation. Related investigations addressed magneto-photo-thermoelastic interactions in a slender strip with hereditary characteristics [14], the response of a semiconductor to a focused laser beam [15], and generalized photo-thermoelastic coupling in a semiconductor plate [16]. From a theoretical perspective, Sherief and Hussein [17] developed a fundamental solution for thermoelasticity with two relaxation times in an infinite, spherically symmetric domain. Further applications include electromagneto-thermoelastic interactions in an orthotropic slab [18], thermal-shock plane waves in a conducting half-space [19], and the combined effects of rotation and thermal shock in a perfectly conducting elastic half-space [20]. Collectively, these studies demonstrate the broad applicability of GL-based and two-relaxation-time formulations to thermal, mechanical, electromagnetic, and optical coupling in diverse material systems.

Other investigations have focused on alternative heat-conduction models and specialized geometries. Kar and Kanoria [21] examined three-phase-lag effects in a functionally graded orthotropic hollow sphere. Kaur and Lata [22] employed the Green–Naghdi type III theory to investigate axisymmetric deformation in a transversely isotropic magnetothermoelastic solid subjected to inclined loading. Abbas and Abd-alla [23] studied the influence of thermal relaxation parameters on thermoelastic interactions in an infinite orthotropic medium containing a cylindrical cavity. Biswas et al. [24] analyzed the thermal-shock response of magnetothermoelastic orthotropic materials using a three-phase-lag model. Furthermore, Biswas and Mukhopadhyay [25] investigated Rayleigh-wave propagation in orthotropic media with phase-lag effects through an eigenfunction-expansion method.

Research has also addressed wave propagation and coupled-field phenomena in more complex material systems. Sharma et al. [26] examined thermal conductivity and diffusivity in a two-temperature thermoelastic-diffusion plate with spatially varying thermal conductivity. Biswas [27] examined Rayleigh waves in a porous, nonlocal orthotropic thermoelastic layer resting on a porous, nonlocal orthotropic thermoelastic half-space. Mondal and Sur [28] investigated photothermoelastic wave propagation and memory-dependent responses in an orthotropic semiconductor containing a spherical cavity. Said [29] compared three theoretical models using an eigenvalue technique to investigate rotating magnetothermoelastic media characterized by variable thermal conductivity. Hobiny and Abbas [30] studied generalized thermoelastic interactions induced by pulsed heating in a two-dimensional orthotropic material. Additional contributions addressing generalized thermoelastic problems under diverse constitutive theories and boundary conditions are documented in [31–57], demonstrating the breadth of ongoing research in this area.

Accordingly, the present study investigates thermoelastic interactions in an orthotropic medium containing a cylindrical cavity under pulsed heat flux. The analysis is conducted within the framework of generalized thermoelasticity incorporating two thermal relaxation times. The governing equations are solved numerically using the finite element method, with quadratic elements employed to discretize the medium. The resulting distributions of the relevant physical quantities are presented graphically to examine how variations in thermal relaxation and pulsed heat flux times influences the thermoelastic responses. The findings contribute to a better understanding of transient thermomechanical behavior in orthotropic structures containing cavities and may support the analysis of engineering components exposed to severe thermal conditions.

2 Formulation of the Problem

Consider an orthotropic thermoelastic medium governed by the generalized theory of thermoelasticity [3, 4]. In the absence of body forces and internal heat sources, the equations of motion can be formulated as follows:

$$\sigma_{ij,j} = \rho \frac{\partial^2 u_i}{\partial t^2}, \tag{1}$$

where ρ is the mass density, σ_{ij} denote the components of stress and u_i are the displacement components. The stress–strain temperature equations can be given by

$$\sigma_{ij} = c_{ijkl} e_{kl} - \gamma_i \left(1 + \tau_1 \frac{\partial}{\partial t}\right)(T - T_o)\,\delta_{ij}, \tag{2}$$

where T is the temperature increase above the reference temperature, c_{ijkl} are the elastic constants, τ_o and τ_1 are the thermal relaxation times, γ_i are the thermal moduli, T_o is the reference temperature, and e_{kl} are the components of strain. The strain–displacement relations can be given by

$$e_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right). \tag{3}$$

The governing heat conduction equation, formulated within the framework of generalized thermoelasticity, can

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be written as follows:

$$(K_{jj}T_{,j})_{,j} = \rho c_e \left(1+\tau_o \frac{\partial}{\partial t}\right)\frac{\partial T}{\partial t} + \gamma_{jj} T_o \frac{\partial u_{j,j}}{\partial t}, \quad (4)$$

where K_{jj} are the thermal conductivity components and c_e is the specific heat.

Consider an infinite orthotropic medium containing a cylindrical cavity of radius a, occupying the region $a \le r < \infty$. The thermoelastic response is assumed to exhibit axial symmetry, with all field variables depending exclusively on the radial coordinate r and time t. Within the cylindrical coordinate system (r,θ,z), the displacement field is restricted to the radial direction, such that $u_r = u(r,t)$, while the circumferential and axial displacement components vanish. Under these assumptions, the nonzero components of the infinitesimal strain tensor are expressed as follows:

$$e_{rr} = \frac{\partial u}{\partial r}, \quad e_{\theta\theta} = \frac{u}{r}. \quad (5)$$

Substituting the radial and circumferential strain components e_{rr}, $e_{\theta\theta}$ into the fundamental governing equations and incorporating the assumed axisymmetric displacement field, the resulting thermoelastic relations can be expressed as follows:

$$\sigma_{rr} = c_{11}\frac{\partial u}{\partial r} + c_{12}\frac{u}{r} - \gamma_{11}\left(1+\tau_1\frac{\partial}{\partial t}\right)T, \quad (6)$$

$$\sigma_{\theta\theta} = c_{12}\frac{\partial u}{\partial r} + c_{22}\frac{u}{r} - \gamma_{22}\left(1+\tau_1\frac{\partial}{\partial t}\right)T, \quad (7)$$

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{1}{r}(\sigma_{rr}-\sigma_{\theta\theta}) = \rho\frac{\partial^2 u}{\partial t^2}, \quad (8)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right) = \rho c_e\left(\frac{\partial T}{\partial t} + \tau_o\frac{\partial^2 T}{\partial t^2}\right) + \gamma_{11}T_o\frac{\partial u}{\partial r} + \gamma_{22}T_o\frac{u}{r}. \quad (9)$$

3 Applications

The initial conditions can be expressed by:

$$u(r,0)=0, \quad \frac{\partial u(r,0)}{\partial t}=0, \quad T(r,0)=0, \quad \frac{\partial T(r,0)}{\partial t}=0. \quad (10)$$

While the boundary conditions are given as:

$$K\frac{\partial T(r,t)}{\partial r}\bigg|_{r=a} = -q_o\frac{t^2 e^{-\frac{t}{t_p}}}{16t_p^2}, \quad u(a,t)=0, \quad (11)$$

where q_o denotes the constant heat flux and t_p is the characteristic pulse duration of the heat flux. To facilitate the mathematical analysis and simplify the governing equations, the physical variables are expressed in dimensionless form by introducing suitable characteristic scales:

$$(t^\circ,\tau_o^\circ,\tau_1^\circ) = \omega c^2(t,\tau_o,\tau_1), \quad T^\circ = \frac{T-T_o}{T_o},$$
$$(\sigma_{rr}^\circ,\sigma_{\theta\theta}^\circ) = \frac{(\sigma_{rr},\sigma_{\theta\theta})}{c_{11}}, \quad (r^\circ,u^\circ) = \omega c(r,u), \quad (12)$$

where $\omega = \frac{\rho c_e}{K_o}$ and $c^2 = \frac{c_{11}}{\rho}$.

By introducing the dimensionless variables and parameters defined in Eq. (12) into the fundamental governing equations, the coupled thermomechanical system can be reformulated in a dimensionless framework. For mathematical convenience and clarity of notation, the superscript $\circ$ denoting dimensionless quantities is omitted throughout the subsequent analysis. Accordingly, the resulting governing equations can be expressed as follows:

$$\sigma_{rr} = \frac{\partial u}{\partial r} + f_1\frac{u}{r} - f_2\left(1+\tau_1\frac{\partial}{\partial t}\right)T,$$
$$\sigma_{\theta\theta} = f_1\frac{\partial u}{\partial r} + f_3\frac{u}{r} - f_4\left(1+\tau_1\frac{\partial}{\partial t}\right)T, \quad (13)$$

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - f_3\frac{u}{r^2} - f_2\left(1+\tau_1\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial r} + \frac{f_4-f_2}{r}\left(1+\tau_1\frac{\partial}{\partial t}\right)T = \frac{\partial^2 u}{\partial t^2}, \quad (14)$$

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{\partial T}{\partial t} + \tau_o\frac{\partial^2 T}{\partial t^2} + f_5\frac{\partial u}{\partial r} + f_6\frac{u}{r}, \quad (15)$$

where

$$f_1 = \frac{c_{12}}{c_{11}}, \quad f_2 = \frac{\gamma_{11}T_o}{c_{11}}, \quad f_3 = \frac{c_{22}}{c_{11}},$$
$$f_4 = \frac{\gamma_{22}T_o}{c_{11}}, \quad f_5 = \frac{\gamma_{11}}{\omega K_o}, \quad f_6 = \frac{\gamma_{22}}{\omega K_o}.$$

4 Finite Element Scheme

The finite element method (FEM) is employed to obtain numerical solutions to the coupled governing equations of generalized thermoelasticity. The computational domain is discretized into a finite number of elements, within which the displacement and temperature fields are approximated using suitable interpolation functions. Accordingly, the radial displacement u and temperature T are represented in terms of their nodal values as

$$u = \sum_{j=1}^{n} N_j u_j(t), \quad T = \sum_{j=1}^{n} N_j T_j(t). \quad (16)$$

Here, n denotes the number of nodes associated with each element, N_j represents the corresponding shape function, and $u_j(t)$ and $T_j(t)$ are the time-dependent nodal values of displacement and temperature, respectively. The Galerkin weighted-residual approach is adopted to establish the finite element equations. In this formulation, the same interpolation functions are employed to approximate both the primary field variables and their associated virtual variations. Thus, the displacement and temperature test functions are expressed as

$$\delta u = \sum_{j=1}^{n} N_j \delta u_j, \quad \delta T = \sum_{j=1}^{n} N_j \delta T_j. \quad (17)$$

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For the present analysis, three-node quadratic elements are introduced to discretize the one-dimensional radial domain. Each element is mapped onto a standard parent element defined by the local coordinate $\chi \in [-1,1]$. The corresponding quadratic interpolation functions are given by

$$N_1 = \frac{1}{2}(\chi^2 - \chi), \quad N_2 = 1 - \chi^2, \quad N_3 = \frac{1}{2}(\chi^2 + \chi). \tag{18}$$

The weak forms of the governing equations are obtained by multiplying Eqs. (14) and (15) by the appropriate test functions and integrating over the computational domain. Applying integration by parts to the spatial derivative terms reduces the order of differentiation and introduces the corresponding boundary contributions. Consequently, the variational formulation associated with the displacement field becomes

$$\int_a^\infty \delta u \left[\frac{\partial^2 u}{\partial t^2} - \frac{1}{r}\frac{\partial u}{\partial r} + f_3 \frac{u}{r^2} + f_2\left(1+\tau_1\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial r} - \frac{f_4 - f_2}{r}\left(1+\tau_1\frac{\partial}{\partial t}\right)T\right] dr + \int_a^\infty \frac{\partial \delta u}{\partial r}\frac{\partial u}{\partial r} dr = \left[\delta u \frac{\partial u}{\partial r}\right]_a^\infty. \tag{19}$$

Similarly, the weak formulation corresponding to the generalized heat conduction equation, incorporating temperature-dependent thermal conductivity, is expressed as

$$\int_a^\infty \frac{\partial \delta T}{\partial r}\frac{\partial T}{\partial r} dr + \int_a^\infty \delta T\left[\frac{\partial T}{\partial t} + \tau_o \frac{\partial^2 T}{\partial t^2} + f_5 \frac{\partial u}{\partial r} + f_6 \frac{u}{r} - \frac{1}{r}\frac{\partial T}{\partial r}\right] dr = \left[\delta T \frac{\partial T}{\partial r}\right]_a^\infty. \tag{20}$$

Substituting the finite element approximations into the weak formulations leads to a coupled system of algebraic and differential equations governing the nodal displacement and temperature variables. The resulting element matrices and vectors are assembled into a global system while incorporating the prescribed initial and boundary conditions. Finally, the temporal derivatives are discretized using an implicit time-integration scheme to evaluate the transient thermoelastic response. This computational framework enables the numerical determination of temperature, radial displacement, and stress distributions throughout the medium.

5 Numerical Results

To demonstrate the applicability of the proposed theoretical formulation and evaluate the resulting numerical solutions, an orthotropic cobalt-based material is selected as the representative medium for the computational analysis. The material is characterized by its relevant thermal and mechanical properties, which are incorporated into the governing equations to investigate the coupled thermoelastic response. The numerical simulations are performed using the finite element method developed in the preceding section, allowing the spatial and temporal variations of the physical field variables to be examined. For consistency with the material model and to facilitate comparison with existing studies, the physical constants employed in the numerical calculations are adopted from Ref. [58] and are specified as follows:

$$\begin{aligned}
&c_{11} = 3.71 \times 10^{11}\,\mathrm{N\cdot m^{-2}}, \quad c_{12} = 1.65 \times 10^{11}\,\mathrm{N\cdot m^{-2}},\\
&c_{22} = 3.581 \times 10^{11}\,\mathrm{N\cdot m^{-2}}, \quad \rho = 8836\,\mathrm{kg\cdot m^{-3}},\\
&T_o = 298\,\mathrm{K}, \quad c_e = 427\,\mathrm{J\cdot kg^{-1}\cdot K^{-1}},\\
&K_o = 100\,\mathrm{W\cdot m^{-1}\cdot K^{-1}}, \quad a = 1,\\
&\gamma_{11} = 7.04 \times 10^{6}\,\mathrm{N\cdot m^{-2}\cdot K^{-1}},\\
&\gamma_{22} = 6.9 \times 10^{6}\,\mathrm{N\cdot m^{-2}\cdot K^{-1}},\\
&\tau_o = 0.05, \quad t = 0.2, \quad t_p = 0.15.
\end{aligned}$$

Based on the above data, the computations of physical quantities (numerically) with respect to the radial distance r are carried out for two different cases:

1. Investigating the difference between the classical coupled thermoelasticity (CT) model ($\tau_o = \tau_1 = 0$) and the Green–Lindsay (GL) model ($\tau_1 \geq \tau_o > 0$) as shown in Figs. 1–4.
2. Investigating the influence of the characteristic pulse duration t_p ($t_p = 0.15, 0.20, 0.25$) on the field variables under the Green–Lindsay model as shown in Figs. 5–8.

Figures 1 and 5 illustrate the effects of the thermoelastic models and the characteristic pulse duration t_p on the temperature variation T. It is observed that the temperature attains its maximum value at the inner boundary of the cavity ($r = a$) due to the applied thermal boundary condition and decays monotonically toward zero as r increases, confirming the wave nature of thermal propagation with finite speed under the generalized theories.

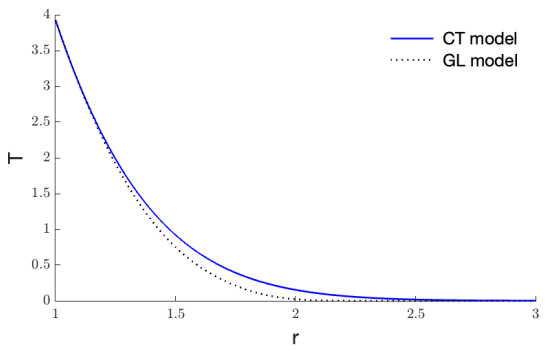


Fig. 1: The temperature variation T through the radial distance r under CT and GL models.

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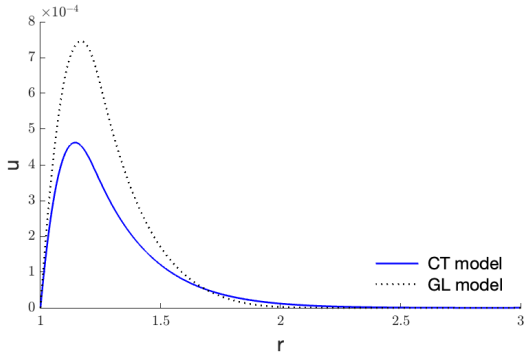


Fig. 2: The variation of radial displacement u through r under CT and GL models.

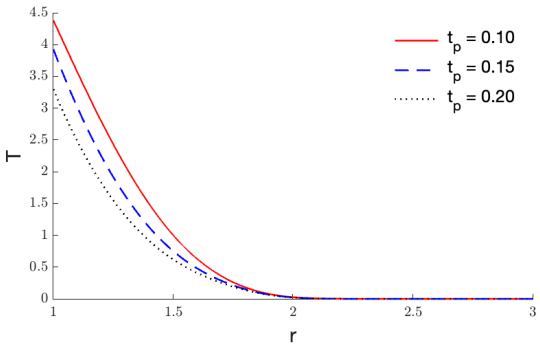


Fig. 5: The temperature variation T through r for three values of t_p.

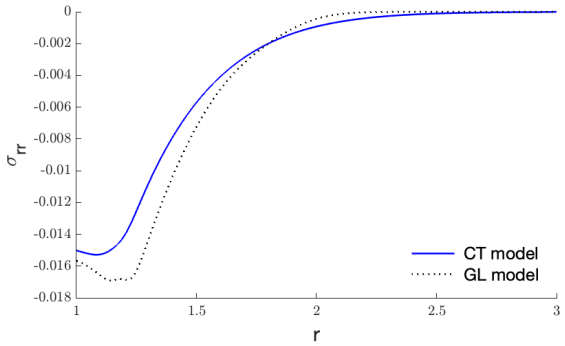


Fig. 3: The variation of radial stress σ_{rr} through r under CT and GL models.

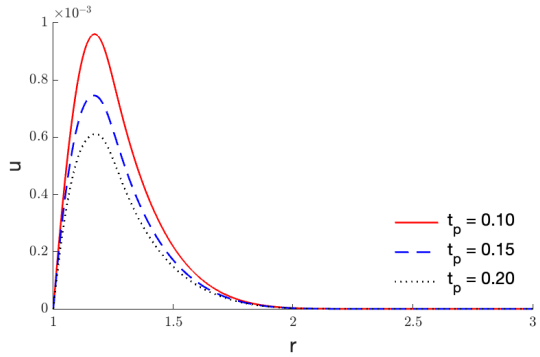


Fig. 6: The variation of radial displacement u through r for three values of t_p.

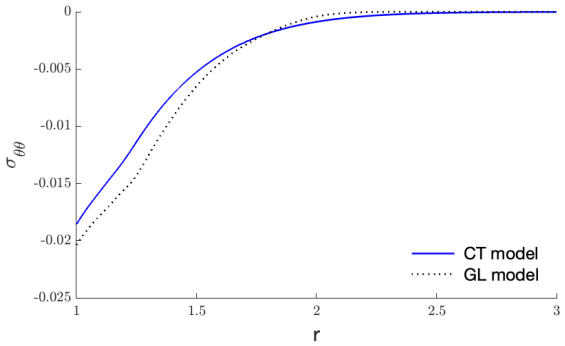


Fig. 4: The variation of hoop stress $\sigma_{\theta\theta}$ through r under CT and GL models.

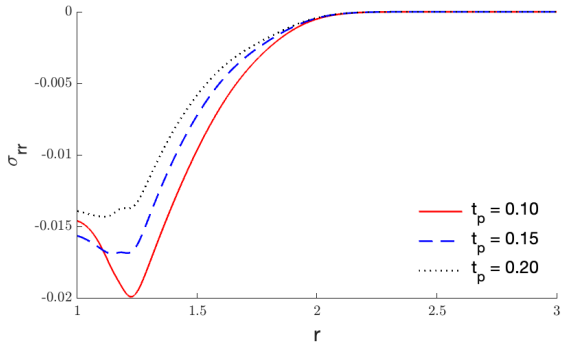


Fig. 7: The variation of radial stress σ_{rr} through r for three values of t_p.

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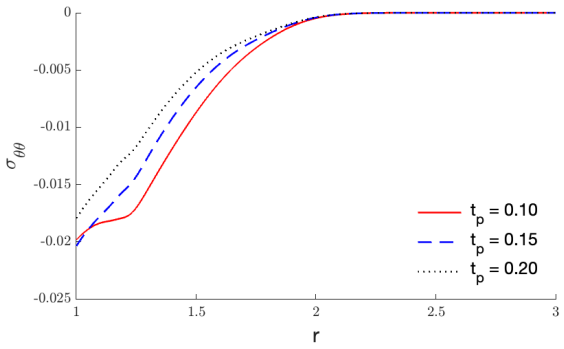


Fig. 8: The variation of sheer stress $\sigma_{\theta\theta}$ through r for three values of t_p.

Figures 2 and 6 illustrate the effects of the thermoelastic model and the characteristic pulse duration t_p on the radial displacement u. As indicated by the boundary condition, the displacement satisfies $u(a,t) = 0$ at the surface of the cylindrical cavity. The displacement increases rapidly to reach a peak value in the vicinity of the cavity and subsequently decreases gradually to zero at deeper regions within the unbounded medium.

Figures 3 and 7 illustrate the effects of the thermoelastic model and the characteristic pulse duration t_p on the radial stress distribution σ_{rr}. The radial stress starts from zero or tensile values at the boundary and smoothly attenuates to zero at large distances, showing strong sensitivity to the thermal relaxation parameters.

Figures 4 and 8 illustrate the effects of the thermoelastic model and the characteristic pulse duration t_p on the hoop stress $\sigma_{\theta\theta}$. Compressive stress develops near the cavity surface due to the sudden localized thermal expansion, followed by wave attenuation into the interior of the material.

6 Conclusion

The transient thermoelastic response of an orthotropic unbounded medium with a cylindrical cavity under pulsed heat flux is investigated in this work. The governing equations are formulated within the framework of generalized thermoelasticity with two thermal relaxation times (Green–Lindsay model) and solved numerically using the finite element method with three-node quadratic elements. The numerical computations demonstrate that:

–Thermal relaxation times have a significant influence on the wave propagation speeds and magnitudes of temperature, displacement, and stress components.
–The characteristic duration of the pulsed heat flux t_p plays a crucial role in controlling the peak amplitudes and penetration depth of the thermomechanical disturbances.
–The finite element formulation with quadratic interpolation functions provides an effective and stable numerical approach for solving coupled transient thermoelastic problems in orthotropic media.

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