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Numerical Solution of a Three-Dimensional Coupled Thermoplastic Problem Based on Deformation Theory

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Abstract:

The coupled thermodynamic boundary problem of thermo plasticity is formulated on the basis of the Ilyushin theory of small elastoplastic deformations. Note that the related problem consists of the equation of motion, which determines the relations of the Ilyushin in deformation theory and the equation of heat influx with the corresponding initial and boundary conditions. In the article, for the problem under consideration, two types of finite difference equations are constructed, namely, explicit schemes reduced to recurrence relations and implicit ones usually solved by the use of the sweep method. Comparisons of numerical results obtained by the two methods show their sufficient proximity, which ensures the reliability of the results obtained.

Keywords: Coupled, thermoplastic, dynamic, theory of deformations, displacement, temperature, explicit, implicit

1. Introduction

The study of the processes of deformation of structures and their elements taking into account thermal and mechanical factors plays an important role in many applied problems of science and technology. These thermomechanical deformation processes are described by the equations of the theory of elasticity (plasticity) and the equation of heat influx in the form of a coupled system of four differential equations for the components of the displacement vector and temperature. Due to the complexity, with some restrictions on the rate of flow of the deformation process, the first three equations of this system can be considered separately from the heat influx equations, in the form of unrelated problems of thermoelasticity (thermoplasticity). Numerical methods for solving unrelated problems of thermoelasticity and thermoplasticity are well studied in the literature [2, 4, 5, 7].

The related problems of thermoelasticity and thermoplasticity are an important and rapidly developing direction of the mechanics of a deformable solid [1]. A related boundary value problem consists of the equation of motion, which determines the relations of the theory of plasticity and the equation of heat influx. It should be noted that the system of partial differential equations consists of three equations of motion of a hyperbolic type and one equation of heat inflow of a parabolic type.

In the general case, the system of differential equations is non-linear and causes difficulties in the study. Even in the one-dimensional case, the coupled problem of thermoplasticity does not lend itself to an analytical solution, except for some isolated particular cases.

The proposed article is devoted to the numerical solution of a three-dimensional dynamic coupled problem of thermo plasticity for an isotropic parallelepiped. On the basis of the finite difference method, explicit and implicit grid equations are written [6]. To solve the implicit grid equations, the method of sweeping in three directions is used [3]. An explicit scheme is reduced to recurrence relations for calculating the desired quantities. On the basis of two methods, numerical results were obtained and graphs were constructed characterizing the change in displacements and temperatures relative to time and coordinate axes. Comparisons show that the numerical results of the coupled thermoplastic problem, obtained on the basis of explicit and implicit schemes, are quite close.

2. Problem Statement

Thermodynamic coupled boundary value problem of thermo plasticity consists of the equations of motion [5]

$$\sigma_{ij,j} + X_i = \rho \ddot{u}_i, \quad (1)$$

the defining relation of the theory of small elastoplastic deformations of Ilyushin [3] (taking into account the temperature):

$$\sigma_{ij} = K(\theta - 3\alpha\vartheta)\delta_{ij} + \frac{\sigma_u}{\varepsilon_u} e_{ij}, \quad (2)$$

differentiated heat conduction equation for isotropic materials [1]

$$\lambda_0 T_{,ii} - C_\varepsilon \dot{T} - \alpha\gamma T_0 \cdot \dot{\varepsilon}_{ij} = 0, \quad (3)$$

and differentiated Cauchy relations

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + v_{j,i}), \quad (4)$$

with initial

$$\begin{aligned} u_i|_{t=t_0} &= \varphi_{u,k}, \quad \dot{u}_i|_{t=t_0} = \psi_{u,k}, \quad v_j|_{t=t_0} = \varphi_{v,k}, \quad \dot{v}_j|_{t=t_0} = \psi_{v,k}, \\ w_k|_{t=t_0} &= \varphi_{w,k}, \quad \dot{w}_k|_{t=t_0} = \psi_{w,k}, \quad T|_{t=t_0} = T_0, \end{aligned} \quad (5)$$

and boundary conditions

$$u_i|_{\Sigma_1} = u_i^0, \quad v_i|_{\Sigma_1} = v_i^0, \quad w_i|_{\Sigma_1} = w_i^0, \quad T|_{\Sigma_1} = \bar{T}_0, \quad \sigma_{ij} n_j|_{\Sigma_2} = S_i^0, \quad (6)$$

where e_{ij} — deviator of the strain tensor, $\theta = \varepsilon_{kk}$ — spherical part of strain tensor [4], T — temperature difference, C_ε — heat at a constant temperature, α — thermal expansion coefficient, λ_0 — the heat flow coefficient, λ, μ — Lamé constants, σ_u, ε_u — intensity of stress and strain tensors.

In the case of a piecewise linear approximation of the deformation diagram, the defining relation (2) takes the form

$$\sigma_{ij} = \lambda\theta\delta_{ij} + 2\mu\varepsilon_{ij} - 2(\mu - \mu')(1 - \frac{\varepsilon_u^*}{\varepsilon_u}) - \alpha\gamma(T - T_0), \quad (7)$$

where

$$\varepsilon_u = \sqrt{\frac{1}{2}e_{ij}e_{ij}}, \quad e_{ij} = \varepsilon_{ij} - \theta/3, \quad \theta = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}.$$

Substituting equation (7.4) into (1), after some transformations, we can find the equations of motion with respect to displacement

$$\begin{cases} (\lambda + 2\mu)\frac{\partial^2 u}{\partial x^2} + \mu\frac{\partial^2 u}{\partial y^2} + \mu\frac{\partial^2 u}{\partial z^2} + (\lambda + \mu)\frac{\partial^2 v}{\partial x\partial y} + (\lambda + \mu)\frac{\partial^2 w}{\partial x\partial z} - \xi - \alpha\gamma\frac{\partial T}{\partial x} = \rho\frac{\partial^2 u}{\partial t^2}, \\ \mu\frac{\partial^2 v}{\partial x^2} + (\lambda + 2\mu)\frac{\partial^2 v}{\partial y^2} + \mu\frac{\partial^2 v}{\partial z^2} + (\lambda + \mu)\frac{\partial^2 u}{\partial x\partial y} + (\lambda + \mu)\frac{\partial^2 w}{\partial y\partial z} - \xi - \alpha\gamma\frac{\partial T}{\partial y} = \rho\frac{\partial^2 v}{\partial t^2}, \\ \mu\frac{\partial^2 w}{\partial x^2} + \mu\frac{\partial^2 w}{\partial y^2} + (\lambda + 2\mu)\frac{\partial^2 w}{\partial z^2} + (\lambda + \mu)\frac{\partial^2 u}{\partial x\partial z} + (\lambda + \mu)\frac{\partial^2 v}{\partial y\partial z} - \xi - \alpha\gamma\frac{\partial T}{\partial z} = \rho\frac{\partial^2 w}{\partial t^2}, \end{cases} \quad (8)$$

and heat flow equation

$$\lambda_0\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) - C_\varepsilon \frac{\partial T}{\partial t} - T_0\alpha\gamma\left(\frac{\partial^2 u}{\partial x\partial t} + \frac{\partial^2 v}{\partial y\partial t} + \frac{\partial^2 w}{\partial z\partial t}\right) = 0, \quad (9)$$

with corresponding initial and boundary conditions of the form:

$$\begin{aligned}
u|_{t=0} &= \varphi_1, \frac{\partial u}{\partial t}|_{t=0} = \psi_1, \frac{\partial u}{\partial t}|_{t=0} = \psi_1, u|_{x=0} = u_0, u|_{x=\ell} = \bar{u}_0, \\
v|_{t=0} &= \varphi_2, \frac{\partial v}{\partial t}|_{t=0} = \psi_2, v|_{x=0} = v_0, v|_{x=\ell} = \bar{v}_0, \\
w|_{t=0} &= \varphi_3, \frac{\partial w}{\partial t}|_{t=0} = \psi_2, w|_{x=0} = w_0, w|_{x=\ell} = \bar{w}_0, \\
T|_{t=0} &= T_0, T|_{x=0} = T_1, T|_{x=\ell} = T_2;
\end{aligned} \tag{10}$$

where $\gamma = 3\lambda + 2\mu$; $\xi = 2(\mu - \mu')\varepsilon_u^* \left[\frac{\partial}{\partial x} \left(\frac{1}{\varepsilon_u} \right) + \frac{\partial}{\partial y} \left(\frac{1}{\varepsilon_u} \right) + \frac{\partial}{\partial z} \left(\frac{1}{\varepsilon_u} \right) \right]$;

$\lambda, \mu, \mu', \alpha, C_\varepsilon, \lambda_0$ – known constants, ℓ_1, ℓ_2, ℓ_3 – parallelepiped component, $\varphi_s, \psi_s, T_0, T_1, T_2$ – set values ($s = 1..3$).

3. Construction of Explicit and Implicit Finite Difference Equations

Now we turn to the numerical solution of the bound boundary problem of thermoplasticity by the method of finite difference differences. In order to solve equations (8-10), we consider the following discretized region $\Omega \{a \leq x, y, z \leq b\}$ by the grid region $\Omega \{x_i = ih_1; y_j = jh_2; z_k = kh_3\}$ $h_m = l_m / N_m; \{i = 1..N_1; j = 1..N_2; k = 1..N_3; m = 1..3\}$ in accordance with each nodal value $t_l = \tau l; l = 0..M$ along the time axis.

Further, replacing the derivatives in equations (8-9) by difference relations [10, 11], we obtain for the first equation of system (8)

$$\begin{aligned}
&(\lambda + 2\mu) \frac{u_{i+1,j,k}^s - 2u_{i,j,k}^s + u_{i-1,j,k}^s}{h_1^2} + \mu \frac{u_{i,j+1,k}^s - 2u_{i,j,k}^s + u_{i,j-1,k}^s}{h_2^2} + \\
&\mu \frac{u_{i,j,k+1}^s - 2u_{i,j,k}^s + u_{i,j,k-1}^s}{h_3^2} + (\lambda + \mu) \frac{v_{i+1,j+1,k}^s - v_{i+1,j-1,k}^s - v_{i-1,j+1,k}^s + v_{i-1,j-1,k}^s}{4h_1h_2} - \\
&\xi_{ijk}^s - \alpha\gamma \frac{T_{i+1,j,k}^{s-1} - T_{i-1,j,k}^{s-1}}{2h_1} + (\lambda + \mu) \frac{w_{i+1,j,k+1}^s - w_{i+1,j,k-1}^s - w_{i-1,j,k+1}^s + w_{i-1,j,k-1}^s}{4h_1h_3} \\
&= \rho \frac{u_{i,j,k}^{s+1} - 2u_{i,j,k}^s + u_{i,j,k}^{s-1}}{\tau^2}.
\end{aligned} \tag{11}$$

The other two equations v and w are found in a similar way, and equation (9) takes the following form

$$\begin{aligned}
&\lambda_0 \left(\frac{T_{i+1,j,k}^s - 2T_{i,j,k}^s + T_{i-1,j,k}^s}{h_1^2} + \frac{T_{i,j+1,k}^s - 2T_{i,j,k}^s + T_{i,j-1,k}^s}{h_2^2} + \frac{T_{i,j,k+1}^s - 2T_{i,j,k}^s + T_{i,j,k-1}^s}{h_3^2} \right) - \\
&-\alpha\gamma T_0 \left(\frac{u_{i+1,j,k}^{s+1} - u_{i-1,j,k}^{s+1} - u_{i+1,j,k}^{s-1} + u_{i-1,j,k}^{s-1}}{4h_1\tau} + \frac{v_{i,j+1,k}^{s+1} - v_{i,j-1,k}^{s+1} - v_{i,j+1,k}^{s-1} + v_{i,j-1,k}^{s-1}}{4h_2\tau} + \right. \\
&\left. -\alpha\gamma T_0 \frac{w_{i,j,k+1}^{s+1} - w_{i,j,k-1}^{s+1} - w_{i,j,k+1}^{s-1} + w_{i,j,k-1}^{s-1}}{4h_3\tau} - C_\varepsilon \frac{T_{i,j,k}^{s+1} - T_{i,j,k}^{s-1}}{2\tau} = 0.
\end{aligned} \tag{12}$$

Solving the difference equations (11-12) with respect to $u_{i,j,k}^{s+1}$, $v_{i,j,k}^{s+1}$, $w_{i,j,k}^{s+1}$ and $T_{i,j,k}^{s+1}$ respectively, we obtain

$$\begin{aligned}
u_{i,j,k}^{s+1} = & \frac{\tau^2}{\rho} ((\lambda + 2\mu) \frac{u_{i+1,j,k}^s - 2u_{i,j,k}^s + u_{i-1,j,k}^s}{h_1^2} + \mu \frac{u_{i,j+1,k}^s - 2u_{i,j,k}^s + u_{i,j-1,k}^s}{h_2^2} + \\
& + \mu \frac{u_{i,j,k+1}^s - 2u_{i,j,k}^s + u_{i,j,k-1}^s}{h_3^2} + (\lambda + \mu) (\frac{v_{i+1,j+1,k}^s - v_{i+1,j-1,k}^s - v_{i-1,j+1,k}^s + v_{i-1,j-1,k}^s}{4h_1h_2} + \\
& + \frac{w_{i+1,j,k+1}^s - w_{i+1,j,k-1}^s - w_{i-1,j,k+1}^s + w_{i-1,j,k-1}^s}{4h_1h_3}) - \xi_{ijk}^s - \\
& - \alpha\gamma \frac{T_{i+1,j,k}^{s-1} - T_{i-1,j,k}^{s-1}}{2h_1} + 2u_{i,j,k}^s - u_{i,j,k}^{s-1},
\end{aligned} \quad (13)$$

$$\begin{aligned}
T_{i,j,k}^{s+1} = & \frac{2\tau}{C_\varepsilon} (\alpha\gamma T_0 (\frac{u_{i+1,j,k}^{s+1} - u_{i-1,j,k}^{s+1} - u_{i+1,j,k}^{s-1} + u_{i-1,j,k}^{s-1}}{4h_1\tau} + \\
& + \frac{v_{i,j+1,k}^{s+1} - v_{i,j-1,k}^{s+1} - v_{i,j+1,k}^{s-1} + v_{i,j-1,k}^{s-1}}{4h_2\tau} + \frac{w_{i,j,k+1}^{s+1} - w_{i,j,k-1}^{s+1} - w_{i,j,k+1}^{s-1} + w_{i,j,k-1}^{s-1}}{4h_3\tau}) \\
& - \lambda_0 (\frac{T_{i+1,j,k}^s - 2T_{i,j,k}^s + T_{i-1,j,k}^s}{h_1^2} + \frac{T_{i,j+1,k}^s - 2T_{i,j,k}^s + T_{i,j-1,k}^s}{h_2^2} + \\
& + \frac{T_{i,j,k+1}^s - 2T_{i,j,k}^s + T_{i,j,k-1}^s}{h_3^2})) + T_{i,j,k}^{s-1}
\end{aligned} \quad (14)$$

Solving the difference equations (13-14) are explicit schemes, they can be solved with respect to $u_{i,j,k}^{s+1}$, $v_{i,j,k}^{s+1}$, $w_{i,j,k}^{s+1}$ and find explicit formulas for determining the desired quantities. Explicit schemes have certain disadvantages associated with the size of the grid step. To avoid this drawback, you can build an implicit scheme with the following form

$$a_{ijk} u_{i+1,j,k}^{s+1} + b_{ijk} u_{i,j,k}^{s+1} + c_{ijk} u_{i-1,j,k}^{s+1} = f_{ijk}, \quad (15)$$

Where

$$\begin{aligned}
a_{ijk} = & \frac{\lambda + 2\mu}{h_1^2}, b_{ijk} = -2 \frac{(\lambda + 2\mu)}{h_1^2} - \frac{\rho}{\tau^2}, c_{ijk} = \frac{\lambda + 2\mu}{h_1^2}, \\
f_{ijk} = & \alpha\gamma \frac{T_{i+1,j,k}^{s-1} - T_{i-1,j,k}^{s-1}}{2h_1} + \xi_{ijk}^s - \mu \frac{u_{i,j+1,k}^s - 2u_{i,j,k}^s + u_{i,j-1,k}^s}{h_2^2} - \mu \frac{u_{i,j,k+1}^s - 2u_{i,j,k}^s + u_{i,j,k-1}^s}{h_3^2} - \\
& - (\lambda + \mu) (\frac{v_{i+1,j+1,k}^s - v_{i+1,j-1,k}^s - v_{i-1,j+1,k}^s + v_{i-1,j-1,k}^s}{4h_1h_2} + \\
& + \frac{w_{i+1,j,k+1}^s - w_{i+1,j,k-1}^s - w_{i-1,j,k+1}^s + w_{i-1,j,k-1}^s}{4h_1h_3}) + \rho \frac{u_{i,j,k-1}^{s-1} - 2u_{i,j,k}^{s-1}}{\tau^2}.
\end{aligned}$$

In a similar way, difference equation (12) can be reduced to the form

$$a_{ijk} T_{i+1,j,k}^{s+1} + b_{ijk} T_{i,j,k}^{s+1} + c_{ijk} T_{i-1,j,k}^{s+1} = f_{ijk}, \quad (16)$$

where

$$a_{ijk} = \frac{\lambda_0}{h_1^2}, b_{ijk} = -2 \frac{\lambda_0}{h_1^2} - \frac{C_\varepsilon}{2\tau}, c_{ijk} = \frac{\lambda_0}{h_1^2},$$

$$f_{ijk} = \alpha \gamma T_0 \left(\frac{u_{i+1,j,k}^{s+1} - u_{i-1,j,k}^{s+1} - u_{i+1,j,k}^{s-1} + u_{i-1,j,k}^{s-1}}{4h_1\tau} + \frac{v_{i,j+1,k}^{s+1} - v_{i,j-1,k}^{s+1} - v_{i,j+1,k}^{s-1} + v_{i,j-1,k}^{s-1}}{4h_2\tau} + \right. \\ \left. + \frac{w_{i,j,k+1}^{s+1} - w_{i,j,k-1}^{s+1} - w_{i,j,k+1}^{s-1} + w_{i,j,k-1}^{s-1}}{4h_3\tau} \right) - \frac{C_\varepsilon}{2\tau} T_{i,j,k}^{s+1} - \\ - \lambda_0 \left(\frac{T_{i,j+1,k}^s - 2T_{i,j,k}^s + T_{i,j-1,k}^s}{h_2^2} + \frac{T_{i,j,k+1}^s - 2T_{i,j,k}^s + T_{i,j,k-1}^s}{h_3^2} \right).$$

Starting from the second layer, we find the values of displacements $u_{i,j,k}^{s+1}$, $v_{i,j,k}^{s+1}$, $w_{i,j,k}^{s+1}$ and temperature $T_{i,j,k}^{s+1}$ using the iterative formulas (15) - (16), and we find the values of these functions on the first layer by the method [8]. The joint solution of the equations of thermo elasticity with the equations of thermal conductivity allow a more adequate description of the process of thermoelastic state under the influence of mechanical and thermal influences [9].

4. Test TASK

As an example, the related problem of thermo-elastic-plasticity (1-6) was solved, with the indicated initial:

$$u(x, y, z, t)|_{t=0} = 0, \quad v(x, y, z, t)|_{t=0} = 0, \quad w(x, y, z, t)|_{t=0} = 0, \\ \frac{\partial u(x, y, z, t)}{\partial t} \Big|_{t=0} = 0, \quad \frac{\partial v(x, y, z, t)}{\partial t} \Big|_{t=0} = 0, \quad \frac{\partial w(x, y, z, t)}{\partial t} \Big|_{t=0} = 0,$$

$$T(x, y, z, t)|_{t=0} = T_0;$$

and boundary conditions:

$$u(x, y, z, t)|_{x,y,z=0} = 0, \quad u(x, y, z, t)|_{x,y,z=1} = 0, \\ v(x, y, z, t)|_{x,y,z=0} = 0, \quad v(x, y, z, t)|_{x,y,z=1} = 0, \\ w(x, y, z, t)|_{x,y,z=0} = 0, \quad w(x, y, z, t)|_{x,y,z=1} = 0,$$

$$T(x, y, z, t)|_{x=0} = T_0 + T_0 \cdot \sin(\pi x) \cdot \sin(\pi y),$$

$$T(x, y, z, t)|_{x=\ell} = T_0 + T_0 \cdot \sin(\pi x) \cdot \sin(\pi y),$$

$$T(x, y, z, t)|_{y=0} = T_0, \quad T(x, y, z, t)|_{y=\ell} = T_0,$$

$$T(x, y, z, t)|_{z=0} = T_0, \quad T(x, y, z, t)|_{z=\ell} = T_0,$$

with the following values of constants:

$$\lambda = 1, \lambda_0 = 1, \alpha = 0.05, \mu = 0.5, \mu' = 0.3, \rho = 1, C_\varepsilon = 3.5,$$

$$T_0 = 90, h = 0.1, \tau = 0.01, n = 10, \ell_i = 1, \quad i = \overline{1..3};$$

x y	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	0	0	0	0	0	0	0	0	0	0	0
0,01	0	0,0093	0,0177	0,0243	0,0286	0,0301	0,0286	0,0244	0,0177	0,0093	0
0,02	0	0,0177	0,0337	0,0463	0,0545	0,0573	0,0545	0,0463	0,0337	0,0177	0
0,03	0	0,0243	0,0463	0,0638	0,075	0,0788	0,075	0,0638	0,0463	0,0243	0
0,04	0	0,0286	0,0545	0,075	0,0881	0,0926	0,0881	0,075	0,0545	0,0286	0
0,05	0	0,0301	0,0573	0,0788	0,0926	0,0974	0,0926	0,0788	0,0573	0,0301	0
0,06	0	0,0286	0,0545	0,075	0,0881	0,0926	0,0881	0,075	0,0545	0,0286	0
0,07	0	0,0243	0,0463	0,0638	0,075	0,0788	0,075	0,0638	0,0463	0,0243	0
0,08	0	0,0177	0,0337	0,0463	0,0545	0,0573	0,0545	0,0463	0,0337	0,0177	0
0,09	0	0,0093	0,0177	0,0244	0,0286	0,0301	0,0286	0,0243	0,0177	0,0093	0
0,1	0	0	0	0	0	0	0	0	0	0	0

Table 1: Displacements $U(x, y, z_n, t_n)$ (Sweep Method)

x y	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	0	0	0	0	0	0	0	0	0	0	0
0,01	0	0,0093	0,0177	0,0243	0,0286	0,0301	0,0286	0,0243	0,0177	0,0093	0
0,02	0	0,0177	0,0336	0,0463	0,0544	0,0572	0,0544	0,0463	0,0336	0,0177	0
0,03	0	0,0243	0,0463	0,0637	0,0749	0,0788	0,0749	0,0637	0,0463	0,0243	0
0,04	0	0,0286	0,0544	0,0749	0,0881	0,0926	0,0881	0,0749	0,0544	0,0286	0
0,05	0	0,0301	0,0572	0,0788	0,0926	0,0974	0,0926	0,0788	0,0572	0,0301	0
0,06	0	0,0286	0,0544	0,0749	0,0881	0,0926	0,0881	0,0749	0,0544	0,0286	0
0,07	0	0,0243	0,0463	0,0637	0,0749	0,0788	0,0749	0,0637	0,0463	0,0243	0
0,08	0	0,0177	0,0336	0,0463	0,0544	0,0572	0,0544	0,0463	0,0336	0,0177	0
0,09	0	0,0093	0,0177	0,0243	0,0286	0,0301	0,0286	0,0243	0,0177	0,0093	0
0,1	0	0	0	0	0	0	0	0	0	0	0

Table 2: Displacements $U(x, y, zn, tn)$ (Mesh Method)

x y	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	0	0	0	0	0	0	0	0	0	0	0
0,01	0	-0,0055	-0,0048	-0,0035	-0,0018	0	0,0018	0,0035	0,0048	0,0055	0
0,02	0	-0,0104	-0,0091	-0,0066	-0,0035	0	0,0035	0,0066	0,0091	0,0104	0
0,03	0	-0,0142	-0,0125	-0,0091	-0,0048	0	0,0048	0,0091	0,0125	0,0142	0
0,04	0	-0,0167	-0,0146	-0,0106	-0,0056	0	0,0056	0,0106	0,0146	0,0167	0
0,05	0	-0,0176	-0,0154	-0,0112	-0,0059	0	0,0059	0,0112	0,0154	0,0176	0
0,06	0	-0,0167	-0,0146	-0,0106	-0,0056	0	0,0056	0,0106	0,0146	0,0167	0
0,07	0	-0,0142	-0,0125	-0,0091	-0,0048	0	0,0048	0,0091	0,0125	0,0142	0
0,08	0	-0,0104	-0,0091	-0,0066	-0,0035	0	0,0035	0,0066	0,0091	0,0104	0
0,09	0	-0,0055	-0,0048	-0,0035	-0,0018	0	0,0018	0,0035	0,0048	0,0055	0
0,1	0	0	0	0	0	0	0	0	0	0	0

Table 3: Displacements $V(x, y, zn, tn)$ (Sweep Method)

x y	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	0	0	0	0	0	0	0	0	0	0	0
0,01	0	-0,0056	-0,0049	-0,0035	-0,0019	0	0,0019	0,0035	0,0049	0,0056	0
0,02	0	-0,0104	-0,0091	-0,0066	-0,0035	0	0,0035	0,0066	0,0091	0,0104	0
0,03	0	-0,0143	-0,0125	-0,0091	-0,0048	0	0,0048	0,0091	0,0125	0,0143	0
0,04	0	-0,0168	-0,0147	-0,0107	-0,0056	0	0,0056	0,0107	0,0147	0,0168	0
0,05	0	-0,0177	-0,0155	-0,0113	-0,0059	0	0,0059	0,0113	0,0155	0,0177	0
0,06	0	-0,0168	-0,0147	-0,0107	-0,0056	0	0,0056	0,0107	0,0147	0,0168	0
0,07	0	-0,0143	-0,0125	-0,0091	-0,0048	0	0,0048	0,0091	0,0125	0,0143	0
0,08	0	-0,0104	-0,0091	-0,0066	-0,0035	0	0,0035	0,0066	0,0091	0,0104	0
0,09	0	-0,0056	-0,0049	-0,0035	-0,0019	0	0,0019	0,0035	0,0049	0,0056	0
0,1	0	0	0	0	0	0	0	0	0	0	0

Table 4: Displacements $V(x, y, zn, tn)$ (Mesh Method)

x y	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	0	0	0	0	0	0	0	0	0	0	0
0,01	0	-0,0054	-0,0102	-0,014	-0,0165	-0,0173	-0,0165	-0,014	-0,0102	-0,0054	0
0,02	0	-0,0048	-0,009	-0,0124	-0,0146	-0,0154	-0,0146	-0,0124	-0,009	-0,0048	0
0,03	0	-0,0035	-0,0066	-0,009	-0,0106	-0,0112	-0,0106	-0,009	-0,0066	-0,0035	0
0,04	0	-0,0018	-0,0035	-0,0048	-0,0056	-0,0059	-0,0056	-0,0048	-0,0035	-0,0018	0
0,05	0	0	0	0	0	0	0	0	0	0	0
0,06	0	0,0018	0,0035	0,0048	0,0056	0,0059	0,0056	0,0048	0,0035	0,0018	0
0,07	0	0,0035	0,0066	0,009	0,0106	0,0112	0,0106	0,009	0,0066	0,0035	0
0,08	0	0,0048	0,009	0,0124	0,0146	0,0154	0,0146	0,0124	0,009	0,0048	0
0,09	0	0,0054	0,0102	0,014	0,0165	0,0173	0,0165	0,014	0,0102	0,0054	0
0,1	0	0	0	0	0	0	0	0	0	0	0

Table 5: Displacements $w(X, Y, Zn, Tn)$ (Sweep Method)

$\begin{matrix} x \\ y \end{matrix}$	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	0	0	0	0	0	0	0	0	0	0	0
0,01	0	-	-	-	-	-	-	-	-	-	0
		0,0055	0,0104	0,0143	0,0168	0,0177	0,0168	0,0143	0,0104	0,0055	
0,02	0	-	-	-	-	-	-	-	-	-	0
		0,0048	0,0091	0,0125	0,0147	0,0155	0,0147	0,0125	0,0091	0,0048	
0,03	0	-	-	-	-	-	-	-	-	-	0
		0,0035	0,0066	0,0091	0,0107	0,0113	0,0107	0,0091	0,0066	0,0035	
0,04	0	-	-	-	-	-	-	-	-	-	0
		0,0019	0,0035	0,0048	0,0056	0,0059	0,0056	0,0048	0,0035	0,0019	
0,05	0	0	0	0	0	0	0	0	0	0	0
0,06	0	0,0019	0,0035	0,0048	0,0056	0,0059	0,0056	0,0048	0,0035	0,0019	0
0,07	0	0,0035	0,0066	0,0091	0,0107	0,0113	0,0107	0,0091	0,0066	0,0035	0
0,08	0	0,0048	0,0091	0,0125	0,0147	0,0155	0,0147	0,0125	0,0091	0,0048	0
0,09	0	0,0055	0,0104	0,0143	0,0168	0,0177	0,0168	0,0143	0,0104	0,0055	0
0,1	0	0	0	0	0	0	0	0	0	0	0

Table 6: Displacements $W(x, y, zn, tn)$ (Mesh Method)

$\begin{matrix} x \\ y \end{matrix}$	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	90	90	90	90	90	90	90	90	90	90	90
0,01	90	94,45	98,39	101,53	103,55	104,25	103,55	101,53	98,39	94,45	90
0,02	90	98,39	105,82	111,74	115,54	116,86	115,55	111,74	105,82	98,39	90
0,03	90	101,54	111,74	119,87	125,09	126,89	125,09	119,87	111,74	101,54	90
0,04	90	103,56	115,54	125,09	131,22	133,33	131,22	125,09	115,54	103,56	90
0,05	90	104,26	116,85	126,89	133,33	135,55	133,33	126,89	116,85	104,26	90
0,06	90	103,56	115,54	125,09	131,22	133,33	131,22	125,09	115,54	103,56	90
0,07	90	101,54	111,74	119,87	125,09	126,89	125,09	119,87	111,74	101,54	90
0,08	90	98,39	105,82	111,74	115,55	116,86	115,54	111,74	105,82	98,39	90
0,09	90	94,45	98,39	101,53	103,55	104,25	103,55	101,53	98,39	94,45	90
0,1	90	90	90	90	90	90	90	90	90	90	90

Table 7: Temperature $T(x, y, zn, tn)$ (Sweep Method)

$\begin{matrix} x \\ y \end{matrix}$	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
0	90	90	90	90	90	90	90	90	90	90	90
0,01	90	94,48	98,46	101,64	103,68	104,38	103,68	101,64	98,46	94,48	90
0,02	90	98,4	105,86	111,8	115,61	116,93	115,61	111,8	105,86	98,4	90
0,03	90	101,55	111,82	119,97	125,21	127,02	125,21	119,97	111,82	101,55	90
0,04	90	103,57	115,63	125,21	131,37	133,49	131,37	125,21	115,63	103,57	90
0,05	90	104,27	116,95	127,02	133,49	135,71	133,49	127,02	116,95	104,27	90
0,06	90	103,57	115,63	125,21	131,37	133,49	131,37	125,21	115,63	103,57	90
0,07	90	101,55	111,82	119,97	125,21	127,02	125,21	119,97	111,82	101,55	90
0,08	90	98,4	105,86	111,8	115,61	116,93	115,61	111,8	105,86	98,4	90
0,09	90	94,48	98,46	101,64	103,68	104,38	103,68	101,64	98,46	94,48	90
0,1	90	90	90	90	90	90	90	90	90	90	90

Table 8: Temperature $T(x, y, zn, tn)$ (Mesh Method)

Figure 1: Temperature $T(x, y, z, t_n)$

Figure 2: Displacements $U(x, y, z, t_n)$

Figure 3: Displacements $V(x, y, z, t_n)$

Figure 4: Displacements $W(x, y, z, t_n)$

5. Conclusion

A comparison of the numerical results in Tables 1-8 and Figures 1-4 shows that the values of the components of displacements and temperature obtained by explicit (explicit scheme) and implicit (sweep method) finite-difference schemes are constructed and solved using the exclusion method and recurrence formulas [10-14] for displacements u , v , w and temperature T . For the numerical solution of finite-difference equations, software was developed in C #, integrated with MathCAD [15].

A comparison of the numerical results obtained when solving two methods of three-dimensional coupled boundary value problems of thermoplasticity shows good agreement.

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