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Determination Of Inverse Creep Of Infinite Hereditarily Elastoplastic Plate With Hole After Instantaneous Removal Of Internal Pressuremammadova M.A

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ABSTRACT
In this paper we define the stress, deformation, and displacement (including residual) components which have infinite hereditarily elastoplastic plate with circular hole after instantaneous removal of uniform pressure applied along the contour of the given hole under the general conditions that loading and instantaneous unloading processes are described by the Volterra type nonlinear relations of second kind.
Keywords: elastoplasticity, inverse creep, deformation, stress, internal pressure

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I. INTRODUCTION.

The infinite plate with circular hole of radius a is under uniform pressure $p(t)$ applied to the contour of the given hole. Let the plate have field of the temperature T homogeneous and independent of time t.The material of plate is close to mechanically incompressible one and its properties are described by the relations of hereditary elastoplasticity. These relations at loading from the natural state (at the first loading) coincide with the known physical nonlinear relations of the V.V.Moskvitin [1] hereditary elasticity

$$2G_0 e_{ij}^{(1)} = f^{(1)}\left(\sigma_+^{(1)}\right) s_{ij}^{(1)} + \int_0^t \Gamma(t-\tau) f^{(1)}\left(\sigma_+^{(1)}\right) s_{ij}^{(1)}(\tau)\, d\tau, \quad (1)$$

$$\theta^{(1)} = 3\alpha T. \quad (2)$$

Here the upper index denotes the number of loading. Besides, it is denoted in (1) and (2): G_0 is instantaneous modulus of elasticity; $e_{ij} = \varepsilon_{ij} - \varepsilon\delta_{ij}$ is strain deviator ε_{ij}; $\varepsilon_{ij} = \varepsilon_{ij}\delta_{ij}/3$ is mean deformation; δ_{ij} is a Kronecker symbol; $\theta = 3\varepsilon$ is relative volume change; α is a coefficient of linear thermal expansion; $s_{ij} = \sigma_{\iota\varphi} - \sigma\delta_{ij}$ is stress deviator σ_{ij}; $\sigma = \sigma_{ij}\delta_{ij}/3$ is mean stress; $\sigma_+ = \left(\frac{3}{2}s_{ij}s_{ij}\right)^{1/2}$ is stress intensity; $\Gamma(t)$ is a hereditary function - creeping kernel; $f(\sigma_+)$ is a function of physical nonlinearity. Note that in enumeration of the denoted quantities the upper indices are omitted.

II. STATEMENT OF A PROBLEM.

Suppose that the known assumptions which are taken in analysis of plates within elasticity, remains valid in the case of plate from hereditarily elastoplastic material. Hence, we can conclude that the plane axisymmetric stressed state is realized in the considered plate.

We use the cylindrical coordinate system (r,φ,z). At that we have

$$\sigma_{zz}^{(1)} = \sigma_z^{(1)} = 0;\ \sigma_{rz}^{(1)} = 0;\ \sigma_{r\varphi}^{(1)} = 0;\ \sigma_{\varphi z}^{(1)} = 0;\ \sigma_{rr}^{(1)} = \sigma_r^{(1)} \neq 0;$$

$$\sigma_{\varphi\varphi}^{(1)} = \sigma_\varphi^{(1)} \neq 0;\ \varepsilon_{r\varphi}^{(1)} = 0;\ \varepsilon_{rz}^{(1)} = 0;\ \varepsilon_{\varphi z}^{(1)} = 0;\ \varepsilon_{rr}^{(1)} = \varepsilon_r^{(1)} \neq 0;$$

$$\varepsilon_{\varphi\varphi}^{(1)} = \varepsilon_\varphi^{(1)} \neq 0;\ \varepsilon_{zz}^{(1)} = \varepsilon_z^{(1)} \neq 0.$$

In our problem $\varepsilon^{(1)} = \frac{1}{3}\theta^{(1)} = \frac{1}{3}\left(\varepsilon_r^{(1)} + \varepsilon_\varphi^{(1)} + \varepsilon_z^{(1)}\right) = \alpha T;\ \sigma^{(1)} = \frac{1}{3}\left(\sigma_r^{(1)} + \sigma_\varphi^{(1)}\right).$

For the stress intensity σ_+ we have

$$\sigma_+^{(1)} = \left(\sigma_r^{(1)2} - \sigma_r^{(1)}\sigma_\varphi^{(1)} + \sigma_\varphi^{(1)2}\right)^{1/2}. \quad (3)$$

The following relations also hold

$$e_r^{(1)} = \varepsilon_r^{(1)} - \alpha T;\ e_\varphi^{(1)} = \varepsilon_\varphi^{(1)} - \alpha T;\ \varepsilon_z^{(1)} = \varepsilon_z^{(1)} - \alpha T;$$

$$s_r^{(1)} = \frac{1}{3}\left(2\sigma_r^{(1)} - \sigma_\varphi^{(1)}\right);\ s_\varphi = \frac{1}{3}\left(2\sigma_\varphi^{(1)} - \sigma_r^{(1)}\right);\ s_z = -\frac{1}{3}\left(\sigma_r^{(1)} - \sigma_\varphi^{(1)}\right).$$

The following equations follow from (1) subject to the last relations

$$2G_0\left(\varepsilon_\varphi^{(1)} - \varepsilon_r^{(1)}\right) = f^{(1)}\left(\sigma_+^{(1)}\right)\left(\sigma_\varphi^{(1)} - \sigma_r^{(1)}\right) + \int_0^t \Gamma(t-\tau) f^{(1)}\left(\sigma_+^{(1)}\right)\left(\sigma_\varphi^{(1)} - \sigma_r^{(1)}\right)d\tau, \quad (4)$$

$$6G_0\left(\varepsilon_\varphi^{(1)} - \varepsilon_r^{(1)} - 2\alpha T\right) = f^{(1)}\left(\sigma_+^{(1)}\right)\left(\sigma_\varphi^{(1)} + \sigma_r^{(1)}\right) + \int_0^t \Gamma(t-\tau) f^{(1)}\left(\sigma_+^{(1)}\right)\left(\sigma_\varphi^{(1)} + \sigma_r^{(1)}\right)d\tau, \quad (5)$$

where $\sigma_+^{(1)}$ is expressed by formula (3).

For defining the unknown components at the first loading we add the following missing relations to (4) and (5)

$$\varepsilon_r^{(1)} + \varepsilon_\varphi^{(1)} + \varepsilon_z^{(1)} = 3\alpha T \quad (6)$$

$$\frac{\partial \sigma_r^{(1)}}{\partial r} + \frac{\sigma_r^{(1)} - \sigma_\varphi^{(1)}}{r} = 0 \quad (7)$$

$$\frac{\partial \varepsilon_\varphi^{(1)}}{\partial r} + \frac{\varepsilon_\varphi^{(1)} - \varepsilon_r^{(1)}}{r} = 0 \quad (8)$$

$$\sigma_r^{(1)}\Big|_{r=a} = -p(t);\ \sigma_r^{(1)}\Big|_{r\to\infty} \to 0. \quad (9)$$

In the paper [2] we obtained the approximated analytic solution of problem (4)-(9) under the condition $f^{(1)}\left(\sigma_+^{(1)}\right) = 1 + A_1\left(\sigma_+^{(1)}\right)^{\gamma_1}$, where A_1 and γ_1 are the known coefficients which can be defined from experiments. We write this solution

$$\sigma_r^{(1)} \approx -\left(\frac{a}{r}\right)^2 p(t) - \frac{A_1 3^{1+\gamma_1/2}\left(\frac{a}{r}\right)^2}{4(1+\gamma_1)}\left[1 - \left(\frac{a}{r}\right)^{2\gamma_1}\right]p^{1+\gamma_1}(t) \quad (10)$$

$$\sigma_\varphi^{(1)} \approx \left(\frac{a}{r}\right)^2 p(t) + \frac{A_1 3^{1+\gamma_1/2}\left(\frac{a}{r}\right)^2}{4(1+\gamma_1)}\left[1 - (1+2\gamma_1)\left(\frac{a}{r}\right)^{2\gamma_1}\right]p^{1+\gamma_1}(t) \quad (11)$$

$$\varepsilon_r^{(1)} \approx \alpha T - \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p^* - \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 \frac{A_1 3^{\gamma_1/2}}{4(1+\gamma_1)}\left[3 - 2\gamma_1\left(\frac{a}{r}\right)^{2\gamma_1}\right]\left(p^{1+\gamma_1}\right)^* \quad (12)$$

$$\varepsilon_\varphi^{(1)} \approx \alpha T + \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p^* + \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 \frac{A_1 3^{\gamma_1/2}}{4(1+\gamma_1)}\left[3 + \left(\frac{a}{r}\right)^{2\gamma_1}\right]\left(p^{1+\gamma_1}\right)^* \quad (13)$$

$$\varepsilon_z^{(1)} \approx \alpha T - \frac{A_1 3^{\gamma_1/2}(1+2\gamma_1)}{8G_0(1+\gamma_1)}\left(\frac{a}{r}\right)^{2(1+\gamma_1)}\left(p^{1+\gamma_1}\right)^*. \quad (14)$$

Here

$$p^* = p(t) + \int_0^t \Gamma(t-\tau)p(\tau)d\tau;\ \left(p^{1+\gamma_1}\right)^* = p^{1+\gamma_1}(t) + \int_0^t \Gamma(t-\tau)p^{1+\gamma_1}(\tau)d\tau.$$

II. Solution of a problem. Let at time $t = t_1$ the pressure in plate is instantaneously removed.
In this case there occurs loading -phenomenon of inverse creeping at the points of plate. Let the plate have the stresses $\sigma_r^{(2)}(r,t),\ \sigma_\varphi^{(2)}(r,t)$ deformations $\varepsilon_r^{(2)}(r,t)$, $\varepsilon_\varphi^{(2)}(r,t)$, $\varepsilon_z^{(2)}(r,t)$ at times $t > t_1$. Let us define these stress and deformation components. Following V.V.Moskvitin [1] weintroducethedifferences

$$\sigma_r^*(x,t) = \sigma_r^{(1)}(x,t) - \sigma_r^{(2)}(x,t);\ \sigma_\varphi^*(x,t) = \sigma_\varphi^{(1)}(x,t) - \sigma_\varphi^{(2)}(x,t);$$
$$\varepsilon_r^*(x,t) = \varepsilon_r^{(1)}(x,t) - \varepsilon_r^{(2)}(x,t);\ \varepsilon_\varphi^*(x,t) = \varepsilon_\varphi^{(1)}(x,t) - \varepsilon_\varphi^{(2)}(x,t); \quad (15)$$
$$\varepsilon_z^*(x,t) = \varepsilon_z^{(1)}(x,t) - \varepsilon_z^{(2)}(x,t).$$

where $t > t_1$ .Here $\sigma_r^{(1)}(x,t), \sigma_\varphi^{(1)}(x,t), \varepsilon_r^{(1)}(x,t),\ \varepsilon_\varphi^{(1)}(x,t), \varepsilon_z^{(1)}(x,t)$ are determined as stress and deformation components which should arise in the considered plate at initial stress by the pressure $p(t)$ monotonically changing on the segment $0 \le t \le t_1$ and remaining unchangeable and equal to $p(t_1)$ for $t < t_1$.

Suppose that the unloading processes are also described by V.V. Moskvitin's nonlinear relations [1]. In this case the equations analogous to (4) and (5) will be in the following form

$$2G_0\left(\varepsilon_{\varphi^*}-\varepsilon_{r^*}\right)=f_*(\sigma_{+*})\left(\sigma_{\varphi^*}-\sigma_{r^*}\right)+$$
$$+\int_0^{t_*}\Gamma(t_*-\tau)f_*(\sigma_{+*}(\tau))\left(\sigma_{\varphi^*}(\tau)-\sigma_{r^*}(\tau)\right)d\tau \quad (16)$$

$$6G_0\left(\varepsilon_{\varphi^*}-\varepsilon_{r^*}\right)=f_*(\sigma_{+*})\left(\sigma_{\varphi^*}-\sigma_{r^*}\right)+$$
$$+\int_0^{t_*}\Gamma(t_*-\tau)f_*(\sigma_{+*}(\tau))\left(\sigma_{\varphi^*}(\tau)-\sigma_{r^*}(\tau)\right)d\tau \quad (17)$$

Here $t_*=t-t_1$ besides

$$\varepsilon_{r*}=\varepsilon_{r*}(r,t_*)=\varepsilon_r^*(r,t_1+t_*)=\varepsilon_r^*(r,t)$$

.... (18)

$$\sigma_{r*}=\sigma_{r*}(r,t_*)=\sigma_r^*(r,t_1+t_*)=\sigma_r^*(r,t)$$

$$\sigma_{+*}=\sigma_{+*}(r,t_*)=\sigma_+^*(r,t_1+t_*)=\sigma_+^*(r,t)=\left(\sigma_r^{*2}-\sigma_r^*\sigma_\varphi^*+\sigma_\varphi^{*2}\right)^{1/2}.$$

We add the following missing relations to (16), (17)

$$\varepsilon_{r*}+\varepsilon_{\varphi*}+\varepsilon_{z*}=0 \quad (19)$$

$$\frac{\partial\sigma_{r*}}{\partial r}+\frac{\sigma_{r*}-\sigma_{\varphi*}}{r}=0 \quad (20)$$

$$\frac{\partial\varepsilon_{\varphi*}}{\partial r}+\frac{\varepsilon_{\varphi*}-\varepsilon_{r*}}{r}=0 \quad (21)$$

$$\sigma_{r*}\big|_{r=a}=-p(t_1)H(t_*);\quad \sigma_{r*}\big|_{r\to\infty}\to 0 \quad (22)$$

where $H(t_*)$ is a Heaviside unit function

$$H(t_*)=\begin{cases}0, & t_*<0\\ 1, & t_*\geq 0\end{cases}.$$

Now for definiteness we take the function $f_*(\sigma_{+*})$ in the form $f_*(\sigma_{+*})=1+A_*(\sigma_{+*})^{\gamma_*}$, where A_* and γ_* axe constants of material. By theorem on V.V.Moskvitin's variable loading [1], comparing relations (16), (17), (19)-(22) with corresponding relations (4)-(9) allowing for (18) we define

$$\sigma_r^*\approx-\left(\frac{a}{r}\right)^2p(t_1)-\frac{A_*3^{1+\gamma_*/2}\left(\frac{a}{r}\right)^2}{4(1+\gamma_*)}\left[1-\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{1+\gamma_*}(t_1) \quad (23)$$

$$\sigma_\varphi^*\approx\left(\frac{a}{r}\right)^2p(t_1)+\frac{A_*3^{1+\gamma_*/2}\left(\frac{a}{r}\right)^2}{4(1+\gamma_*)}\left[1-(1+2\gamma_*)\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{1+\gamma_*}(t_1) \quad (24)$$

$$\varepsilon_r^*\approx-\frac{1}{2G_0}\left(\frac{a}{r}\right)^2p(t_1)J(t_*)\left\{1+\frac{A_*3^{\gamma_*/2}}{4(1+\gamma_*)}\left[3-2\gamma_*\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)\right\} \quad (25)\ (26)\ (27)$$

$$\varepsilon_\varphi^*\approx+\frac{1}{2G_0}\left(\frac{a}{r}\right)^2p(t_1)J(t_*)\left\{1+\frac{A_*3^{\gamma_*/2}}{4(1+\gamma_*)}\left[3+\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)\right\} \quad (26)$$

$$\varepsilon_z^*\approx-\frac{A_*3^{\gamma_*/2}(1+2\gamma_*)}{8G_0(1+\gamma_*)}\left(\frac{a}{r}\right)^{2(1+\gamma_*)}p^{1+\gamma_*}(t_1)J(t_*) \quad (27)$$

where $J(t_*)=1+\int_0^{t_*}\Gamma(\xi)d\xi$.

Now it is possible to determine on the basis of relations (15) the stress and deformation components which hold in the considered plate in the case of its inverse creeping (after instantaneously removal of uniform pressure at time $t=t_1$):

$$\sigma_r^{(2)} \approx -\left(\frac{a}{r}\right)^2 p(t_1)\left\{\frac{A_1 3^{1+\gamma_1/2}}{4(1+\gamma_1)}\left[1-\left(\frac{a}{r}\right)^{2\gamma_1}\right]p^{\gamma_1}(t_1)-\right.$$
$$\left.-\frac{A_* 3^{1+\gamma_*/2}}{4(1+\gamma_*)}\left[1-\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)\right\} \quad (28)$$

$$\sigma_\varphi^{(2)} \approx -\left(\frac{a}{r}\right)^2 p(t_1)\left\{\frac{A_1 3^{1+\gamma_1/2}}{4(1+\gamma_1)}\left[1-(1+2\gamma_1)\left(\frac{a}{r}\right)^{2\gamma_1}\right]p^{\gamma_1}(t_1)-\right.$$
$$\left.-\frac{A_* 3^{1+\gamma_*/2}}{4(1+\gamma_*)}\left[1-(1+2\gamma_*)\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)\right\} \quad (29)$$

$$\varepsilon_r^{(2)} \approx \alpha T - \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p(t_1)\left\{J(t)-J(t-t_1)+\frac{A_1 3^{\gamma_1/2}}{4(1+\gamma_1)}\left[3-2\gamma_1\left(\frac{a}{r}\right)^{2\gamma_1}\right]\times\right.$$
$$\left.\times p^{\gamma_1}(t_1)J(t)-\frac{A_* 3^{\gamma_*/2}}{4(1+\gamma_*)}\left[3-2\gamma_*\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)J(t-t_1)\right\} \quad (30)$$

$$\varepsilon_\varphi^{(2)} \approx \alpha T + \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p(t_1)\left\{J(t)-J(t-t_1)+\frac{A_1 3^{\gamma_1/2}}{4(1+\gamma_1)}\left[3+\left(\frac{a}{r}\right)^{2\gamma_1}\right]\times\right.$$
$$\left.\times p^{\gamma_1}(t_1)J(t)-\frac{A_* 3^{\gamma_*/2}}{4(1+\gamma_*)}\left[3+\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)J(t-t_1)\right\} \quad (31)$$

$$\varepsilon_z^{(2)} \approx \alpha T - \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p(t_1)\left\{\frac{A_1 3^{\gamma_1/2}(1+2\gamma_1)}{4(1+\gamma_1)}\left(\frac{a}{r}\right)^{2\gamma_1} p^{\gamma_1}(t_1)J(t)-\right.$$
$$\left.-\frac{A_* 3^{\gamma_*/2}(1+2\gamma_*)}{4(1+\gamma_*)}\left(\frac{a}{r}\right)^{2\gamma_*} p^{\gamma_*}(t_1)J(t-t_1)\right\}. \quad (32)$$

Formulae (28)-(32) determine the stress and deformation components that the considered plate has at any $t \geq t_1$ i.e., after instantaneous removal of pressure at the moment $t = t_1$.

A unique component $u^{(2)}$ at $t \geq t_1$ is determined by the formula $u^{(2)} = re_\varphi^{(2)}$ where $e_\varphi^{(2)}$ is represented by formula (31). Note that as $t \to \infty$ formulae (28)-(31) determine the residual stress and deformation. The residual stresses σ_r^0 and σ_φ^0 are expressed by formulae (28) and (29), since these relations do not depend on $t: \sigma_r^0 = \sigma_r^{(2)}, \sigma_\varphi^0 = \sigma_\varphi^{(2)}$. Let

$$J_0 = 1 + \int_0^\infty \Gamma(\xi)d\xi$$

then $\lim_{t\to\infty}(J(t) - J(t-t_1)) = 0$.

Subject to these relations from (30), (31) and (32) we obtain the expressions for residual deformations $\varepsilon_r^0, \varepsilon_\varphi^0, \varepsilon_z^0$

$$\varepsilon_r^0 \approx \alpha T - \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p(t_1)J_0\left\{\frac{A_1 3^{\gamma_1/2}}{4(1+\gamma_1)}\left[3-2\gamma_1\left(\frac{a}{r}\right)^{2\gamma_1}\right]\times\right.$$
$$\left.\times p^{\gamma_1}(t_1)-\frac{A_* 3^{\gamma_*/2}}{4(1+\gamma_*)}\left[3-2\gamma_*\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)\right\} \quad (33)$$

$$\varepsilon_\varphi^0 \approx \alpha T + \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p(t_1)J_0\left\{\frac{A_1 3^{\gamma_1/2}}{4(1+\gamma_1)}\left[3+\left(\frac{a}{r}\right)^{2\gamma_1}\right]\times\right.$$
$$\left.\times p^{\gamma_1}(t_1)-\frac{A_* 3^{\gamma_*/2}}{4(1+\gamma_*)}\left[3+\left(\frac{a}{r}\right)^{2\gamma_*}\right]p^{\gamma_*}(t_1)\right\} \quad (34)$$

$$\varepsilon_z^0 \approx \alpha T - \frac{1}{2G_0}\left(\frac{a}{r}\right)^2 p(t_1)J_0\left\{\frac{A_1 3^{\gamma_1/2}(1+2\gamma_1)}{4(1+\gamma_1)}\left(\frac{a}{r}\right)^{2\gamma_1} p^{\gamma_1}(t_1)-\right.$$
$$\left.-\frac{A_* 3^{\gamma_*/2}(1+2\gamma_*)}{4(1+\gamma_*)}\left(\frac{a}{r}\right)^{2\gamma_*} p^{\gamma_*}(t_1)\right\} \quad (35)$$

The residual displacement u^0 will be $u^0 = r\varepsilon_\varphi^0$ where ε_φ^0 is determined by formula (34).

Let us consider the cases $\varepsilon_z^0(a)$ and $u^0(a)$ being of interest. From (35) at $r = a$ we have

$$\varepsilon_z^0(a) = \alpha T - \frac{P(t_1)}{2G_0}J_0\left[\frac{A_1 3^{\gamma_1}(1+2\gamma_1)}{4(1+\gamma_1)}p^{\gamma_1}(t_1)-\frac{A_* 3^{\gamma_*/2}(1+2\gamma_*)}{4(1+\gamma_*)}p^{\gamma_*}(t_1)\right] \quad (36)$$

Now by using (34) we define $u^0(a)$

$$u^0(a) = a\varepsilon_z^0(a) = a\alpha T + \frac{P(t_1)J_0}{2G_0}\left[\frac{A_1 3^{\gamma_1/2}}{1+\gamma_1}p^{\gamma_1}(t_1)-\frac{A_* 3^{\gamma_*/2}}{1+\gamma_*}p^{\gamma_*}(t_1)\right]. \quad (37)$$

For description of loading processes and instantaneous unloading of the considered plate we used nonlinear relations above. If unloading process occurs by law of physical linear hereditary elasticity, then in obtained solutions (28)-(37) we should take $A_* = 0$.

III. CONCLUSION.

For some verification of the obtained relations, we assume that the loading and instantaneous unloading processes are described by the linear relations of hereditary elasticity. Following the physical reasons in this case without solution of the corresponding problems we can confirm that the residual stresses must be equal to zero: $\sigma_r^0 = 0, \sigma_\varphi^0 = 0$, and the residual deformations must be equal to $\varepsilon_r^0 = \varepsilon_\varphi^0 = \varepsilon_z^0 = \alpha T$, since the temperature unloading does not occur. We get these results by using formulae (28),(29),(33),(34),(35) if in these formulae we assume $A_1 = A_* = 0$ which holds in the case of linear relations of hereditary elasticity.

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