BOUNDARY-CONTACT PROBLEMS OF THERMOELASTICITY OF BINARY MIXTURES FOR A MULTILAYER RING AND CIRCLE

I. Tsagareli, D. Toradze

Iv.Javakhishvili Tbilisi State University

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Abstract

. In this work, solutions of boundary-contact problems of statics of thermoelasticity theory, for multilayer ring and circle are constructed explicitly in the form of series.

Key words and phrases: Thermoelastic mixture, boundary-contact problems, multilayer ring and circle.

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A circle is considered which consists of concentric rings D_k $(k = 2, 3, ..., l)$ and of circle D_1 .Each D_k ring is bounded by circumferences S_{k-1} and S_k , which have a common center at the origin of coordinates and R_{k-1} and R_k are the radii. It is supposed that different rings are filled with different two-component elastic mixture.

1. First, let us consider a problem, when we have not D_1 circle - D_1 is empty. Let us find a regular vector $U^k(x) = (u^k(x), u_3^k(x))$ in the ring D_k , which satisfies:

a) the system of equation ([1],[2]) of statics of the theory of thermoelastic mixture:

$$
\begin{gathered}
a_1^k\Delta(u^k)^1(x) + b_1^k graddiv(u^k)^1(x) + c^k\Delta(u^k)^2(x) \\
+d^k graddiv(u^k)^2(x) = \gamma_1^k gradu_3^k \\
c^k\Delta(u^k)^1(x) + d^k graddiv(u^k)^1(x) + a_2^k\Delta(u^k)^2(x) \\
+b_2^k graddiv(u^k)^2(x) = \gamma_2^k gradu_3^k, \\
\Delta u_3^k(x) = 0;
\end{gathered} \tag{1}
$$

b) boundary conditions on the circumference S_{k-1} [3]:

$$
\begin{gathered}
(u_n^k(z))^- - (u_n^{k-1}(z))^+ = 0, \\
(u_s^k(z))^- = 0, (u_s^{k-1}(z))^+ = 0,
\end{gathered} \tag{2}
$$

$$\Big[R^k(\partial_z,n)U^k(z)\Big]_n^- - \Big[R^{k-1}(\partial_z,n)U^{k-1}(z)\Big]_n^+ = 0, k=3,4,...,l; z\in S_{k-1};$$

$$(u_3^k(z))^- - (u_3^{k-1}(z))^+ = f_3^{k-1}(z), \Big[\frac{du_3^k(z)}{dn(z)}\Big]^- - \Big[\frac{du_3^{k-1}(z)}{dn(z)}\Big]^+ = f_4^{k-1}(z);$$
$k=2,3,...l;$

(3)

c) boundary conditions on the circumferences S_1 and S_l :

$$\begin{aligned} &(R^2(\partial_z,n)U^2(z))_n^- = f^1(z), \quad (u_s^2(z))^- = 0, z\in S_1,\\ &(R^l(\partial_z,n)U^l(z))_n^+ = f^l(z), \quad (u_s^l(z))^+ = 0, z\in S_l, \end{aligned} \tag{4}$$

$$\begin{aligned} &u_3^2(z)^- = f_3^1, \quad z\in S_1,\\ &u_3^l(z)^+ = f_3^l, \quad z\in S_l, \end{aligned} \tag{5}$$

where $u^k(x) = ((u^k)^1(x),(u^k)^2(x)),(u^k)^i(x) = ((u_1^k)^i(x),(u_2^k)^i(x))$-is the partial displacement vector at the point x, $x\in D_k$, $i=1,2$; $u_3^k(x)$-is the change of temperature; $R^k(\partial_x,n)U^k(x) =$

$([R^k(\partial_x,n)U^k(x)]^1,[R^k(\partial_z,n)U^k(x)]^2)$, $[R^k(\partial_x,n)U^k(x)]^i =$

$([R^k(\partial_x,n)U^k(x)]_1^i,[R^k(\partial_x,n)U^k(x)]_2^i)$- is the partial thermostres vector in D_k

$$[R^k(\partial_x,n)U^k(x)]_p^i = [P^k(\partial_x,n)u^k(x)]_p^i - \gamma_i^k n_p(x)u_3^k(x), \tag{6}$$

$P^k(\partial_x,n)u^k(x)$-is a stress vector of elastic mixture [2], $f^j = [(f^j)^1,(f^j)^2]$, $j = 1,2$; $i,p=1,2$; $n=(n_1,n_2)$, $s=(-n_2,n_1)$; $a_1^k,b_1^k,c^k,d^k,a_2^k,b_2^k,\gamma_1^k,\gamma_2^k$-are the known constants [1,2] defining elastic and thermal properties in D_k; A_n and A_s- are normal and tangential components of the vector A, respectively.

As we are solving a problem of statics, we cam solve separately problem $[(1)_3,(3),(5)]$. To find the changes of temperature u_3 and separately the problem[(1),(2),(4)]- to find $u^k(x)$ displacement vector.

First we will solve the problem $[(1)_3,(3),(5)]$. Let us suppose that the functions $f_3^j(z)$ and $f_4^{k-1}(z)$ are expanded into Fourier Series ($j = 1,2,...,l$, $k=3,4,...,l$).

The solution of the equation$(1)_3$ in the ring D_k can be written as follows

[4]:

$$u_3^k(x) = \frac{1}{2}a^k(ln\frac{r}{R_k}(u_{03}^k)^- + ln\frac{R_{k-1}}{r}(u_{03}^k)^+)+$$

$$\sum_{m=1}^{\infty} b^k([(\frac{R_{k-1}}{r})^m - (\frac{rR_{k-1}}{R_k^2})^m](u_{m3}^k)^- + [(\frac{r}{R_k})^m - (\frac{R_{k-1}^2}{rR_k})^m](u_{m3}^k)^+),$$

$$k = 2, 3, ..., l, \tag{7}$$

where $a^k = \dfrac{1}{lnR_{k-1} - lnR_k}$, $\quad b^k = \dfrac{1}{1 - (\frac{R_{k-1}}{R_k})^{2m}}$, $\quad (u_{m3}^k)^\pm$- is the Fourier coefficient of the functions given on the boundary S_{k-1}:

$$(u_{m3}^k)^\pm(z) = \frac{1}{\pi}\int_0^{2\pi}(u_3^k)^\pm(\theta)cosm(\theta - \psi)d\theta,$$

$z = (R_k, \psi)$, $\quad y = (R_k, \theta)$, $\quad y \in [0; 2\pi]$. Let us consider unknown $(u_{m3}^k)^+$. If we take into consideration (3) and (5) and put (7) into $(3)_2$ for each m, we obtain an system equations for $(u_{m3}^k)^+$. When $m = 0$, we obtain:

$$\begin{array}{l}
(a^2 + a^3)(u_{03}^2)^+ - a^3(u_{03}^3)^+ = R_2 f_{04}^2 - a^3 f_{03}^2 + a^2 f_{03}^1, \quad k = 3,\\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
-a^{k-1}(u_{03}^{k-2})^+ + (a^{k-1} + a^k)(u_{03}^{k-1})^+ - a^k(u_{03}^k)^+ =\\
R_{k-1}f_{04}^{k-1} + a^{k-1}f_{03}^{k-2} - a^k f_{03}^k, \quad k = 4, 5, ..., l-1,\\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
-a^{l-1}(u_{03}^{l-2})^+ + (a^{l-1} + a^l)(u_{03}^{l-1})^+ =\\
a^l f_{03}^l + R_{l-1}f_{04}^{l-1} + a^{l-1}f_{03}^{l-2} - a^l f_{03}^{l-1}, \quad k = l
\end{array} \tag{8}$$

and when $m = 1, 2, ...$, we have:

$$\begin{array}{l}
(s_m^2 + s_m^3)(u_{m3}^2)^+ - \sigma_m^3(u_{m3}^3)^+ =\\
-R_2 f_{m4}^2 + \sigma^2 f_{m3}^1 - s_m^3 f_{m3}^2, \quad k = 3,\\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
-\sigma_m^{k-1}(u_{m3}^{k-2})^+ + (s_m^{k-1} + s_m^k)(u_{m3}^{k-1})^+ - \sigma_m^k(u_{m3}^k)^+ =\\
-R_{k-1}f_{m4}^{k-1} + \sigma_m^{k-1}f_{m3}^{k-2} - s_m^k f_{m3}^{k-1}, \quad k = 4, 5, ..., l-1,\\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
-\sigma_m^{l-1}(u_{m3}^{l-2})^+ + (s_m^{l-1} + s_m^l)(u_{m3}^{l-1})^+ =\\
-R_{l-1}f_{m4}^{l-1} + \sigma_m^{l-1}f_{m3}^{l-2} + \sigma_m^l f_{m3}^{l-1} - s_m^l f_{m3}^{l-1}, \quad k = l,
\end{array} \tag{9}$$

where $s_m^k = b^k m[1 + (\frac{R_{k-1}}{R_k})^{2m}] \neq 0$, $\sigma_m^k = 2b^k m(\frac{R_{k-1}}{R_k})^m \neq 0$, $k = 2, 3, ..., l$. By direct computation, it is proved that the determinants of the systems (8) and (9) differ from zero. If we substitute the solutions of the systems (8) and (9) into (7), we obtain solutions of problems $[(1)_3,(3),(5)]$ for each k. Let us solve the problem [(1),(2),(4)]. Let us introduce the functions in the domain D_k [5]:

$$v_i^k(x)=r(u_n^k)^i(x)=x_1(u_1^k)^i(x)+x_2(u_2^k)^i(x),$$
$$v_{i+2}^k(x)=r(u_s^k)^i(x)=-x_2(u_1^k)^i(x)+x_1(u_2^k)^i(x), \tag{10}$$

$$X_i^k(x)=r^2[P^k(\partial_x,n)u^k(x)]_n^i, \quad X_{i+2}^k(x)=r^2[P^k(\partial_x,n)u^k(x)]_s^i, \quad i=1,2. \tag{11}$$

By means of v_j^k $(j=1,2,3,4)$ the functions X_i^k rewrite:

$$X_1^k(x)=\varepsilon_1^k r^2\theta_1^k(x)+\varepsilon_2^k r^2\theta_2^k(x)-\varepsilon_1^k v_1^k(x)-\varepsilon_2^k v_2^k(x)-2\varepsilon_4^k\partial_\psi v_3^k(x)-2\varepsilon_5^k\partial_\psi v_4^k(x);$$

$$X_2^k(x)=\varepsilon_2^k r^2\theta_1^k(x)+\varepsilon_3^k r^2\theta_2^k(x)-\varepsilon_2^k(x)v_1^k(x)-\varepsilon_3^k(x)v_2^k(x)-2\varepsilon_5^k\partial_\psi v_3^k(x)-2\varepsilon_6^k\partial_\psi v_4^k(x); \tag{12}$$

the conditions (2) :

$$(v_i^k)^-(z)-(v_i^{k-1})^+(z)=0,$$
$$(v_{i+2}^k)^-(z)=0,(v_{i+2}^{k-1})^+(z)=0, \quad k=3,4,...,l;$$
$$(X_i^k)^-(z)-(X_i^{k-1})^+(z)=R_{k-1}^2\gamma_i^k(u_3^k)^-(z)- \tag{13}$$
$$R_{k-1}^2\gamma_i^{k-1}(u_3^{k-1})^+(z)\equiv\Psi_3^{k-1^i}(z), \quad z\in S_{k-1}, \quad k=3,4,...,l.$$

and the conditions (4):

$$(X_i^2)^-(z)=R_1^2(f^1)^i(z)+R_1^2\gamma_i^2(u_3^2)^-(z)\equiv\varphi_i^1(z),$$
$$(v_{i+2}^2)^-(z)=0, \quad z\in S_1;$$
$$(X_i^l)^+(z)=R_l^2(f^l)^i(z)+R_l^2\gamma_i^l(u_3^l)^+(z)\equiv\varphi_i^l(z), \tag{14}$$
$$(v_{i+2}^l)^+(z)=0, \quad z\in S_l,$$

where $\varepsilon_1^k=a_1^k+b_1^k$, $\varepsilon_2^k=c^k+d^k$, $\varepsilon_3^k=a_2^k+b_2^k$, $\varepsilon_4^k=a_1^k+\lambda_5^k$, $\varepsilon_5^k=c^k-\lambda_5^k$, $\varepsilon_6^k=a_2^k+\lambda_5^k$, $\theta_i^k=\frac{1}{r}\partial_r v_i^k+\frac{1}{r^2}\partial_\psi v_{i+2}^k$, $r^2=x_1^2+x_2^2$, $x=(r,\psi)$. v_p^k values are to be sought. Let us suppose that functions v_p^k expanded into the Fourier Series

$$(v_p^k)^\pm=\frac{1}{2}(v_{0p}^k)^\pm+\sum_{m=1}^{\infty}(v_{mp}^k)^\pm, \quad p=1,2,3,4; \quad k=1,2,...,l.$$

We should seek the solution of the problem in each ring D_k in the form [6]:

$$v_i^k(r,\psi) = a^k(r)(v_{0i}^k)^- + b^k(r)(v_{0i}^k)^+ + h_i^k(r)((u_{03}^k)^- - (u_{03}^k)^+)+$$

$$\sum_{m=1}^{\infty}[K_m^k(r)(v_{mi}^k)^-(\psi) + T_m^k(r)(v_{mi}^k)^+(\psi)] + \sum_{m=1}^{\infty}[(H_{m1}^k)^i(r)(\gamma_{m1}^k)^-(\psi)+$$

$$(L_{m1}^k)^i(r)(\gamma_{m1}^k)^+(\psi) + (H_{m2}^k)^i(r)(\gamma_{m2}^k)^-(\psi) + (L_{m2}^k)^i(r)(\gamma_{m2}^k)^+(\psi)],$$

$$v_j^k(r,\psi) = a^k(r)(v_{0j}^k)^- + b^k(r)(v_{0j}^k)^+ + \sum_{m=1}^{\infty}[K_m^k(r)(v_{mj}^k)^-(\psi)+$$

$$T_m^k(r)(v_{mj}^k)^+(\psi)] + \sum_{m=1}^{\infty}[\frac{\partial}{\partial_\psi}[(H_{m1}^k)^j(r)(\gamma_{m1}^k)^-(\psi) + (L_{m1}^k)^j(r){\gamma_{m1}^k}^+(\psi)+$$

$$(H_{m2}^k)^j(r){\gamma_{m2}^k}^-(\psi) + (L_{m2}^k)^j(r)(\gamma_{m2}^k)^+(\psi)]],$$

$$i = 1,2, \quad j = i+2, \quad k = 1,2,...,l-1, \tag{15}$$

where

$$a^k(r) = \frac{R_{k-1}^2 - r^2}{2(R_k^2 - R_{k-1}^2)}, \quad b^k(r) = \frac{r^2 - R_{k-1}^2}{2(R_k^2 - R_{k-1}^2)}, \quad a^k(R_{k-1}) = b^k(R_k) = \frac{1}{2},$$

$$a^k(R_k) = b^k(R_{k-1}) = 0, \quad h_i^k(r) = -\frac{P_0^k}{2d_1^k(lnR_{k-1} - lnR_k)}[n_3^k(r) + 2n_i^k],$$

$$n_1^k = \gamma_1^k(a_2^k + b_2^k) - \gamma_2^k(c^k + d^k), \quad n_2^k = \gamma_2^k(a_1^k + b_1^k) - \gamma_1^k(c^k + d^k),$$

$$n_3^k = [R_k^2 lnR_k - R_{k-1}^2 lnR_{k-1} - (R_k^2 - R_{k-1}^2)]\frac{2n_1^k}{R_k^2 - R_{k-1}^2},$$

$$h_i^k(R_{k-1}) = h_i^k(R_k) = 0, \quad (\gamma_{mi}^k)^- = \frac{1}{R_{k-1}^2}[\sigma_m^k(v_{mi}^k)^+ - s_m^k(v_{mi}^k)^- +$$

$$R_{k-1}(t_{mi}^k)^- + \frac{\partial}{\partial\psi}(v_{i+2,m}^k)^-], (\gamma_{mi}^k)^+ = \frac{1}{R_k^2}[\sigma_m^k(v_{mi}^k)^- - \sigma_m^k(v_{mi}^k)^- +$$

$$s_m^k(v_{mi}^k)^+ + R_k(t_{mi}^k)^+ + \frac{\partial}{\partial\psi}(v_{i+2,m}^k)^+],$$

$$(t_{mi}^k)^- = -e_4^k m(C_m^k(\psi)[\frac{\partial}{\partial r}P_m^k(r)]_{r=R_p} - D_m^k(\psi)[\frac{\partial}{\partial r}Q_m^k(r)]_{r=R_p}),$$

$$(t_{mi}^k)^+ = -e_5^k m(C_m^k(\psi)[\frac{\partial}{\partial r}P_m^k(r)]_{r=R_p} - D_m^k(\psi)[\frac{\partial}{\partial r}Q_m^k(r)]_{r=R_p}),$$

$$p = k-1, k, \quad e_4^k = \frac{1}{d_1^k}(a_2^k\gamma_1^k - c^k\gamma_2^k), e_5^k = \frac{1}{d_1^k}(a_1^k\gamma_2^k - c^k\gamma_1^k),$$

$$C_m^k = b^k[{u_{m3}^k}^- - (\frac{R_{k-1}}{R_k})^m {u_{m3}^k}^+], \quad D_m^k = b^k[{u_{m3}^k}^+ - (\frac{R_{k-1}}{R_k})^m (u_{m3}^k)^-],$$

$$d_1^k = a_1^k a_2^k - (c^k)^2 > 0; \quad \alpha_m^k = \frac{R_k^2 - R_{k-1}^2}{1 - (\frac{R_{k-1}}{R_k})^{2m}}, \quad P_m^k(r) =$$

$$\frac{1}{4(m-1)}[\alpha_m^k(\frac{R_{k-1}r}{R_k^2})^m + (R_k^2 - r^2 - \alpha_m^k)(\frac{R_{k-1}}{r})^m], \quad m = 2, 3...,$$

$$Q_m^k(r) = \frac{1}{4(m+1)}[\alpha_m^k(\frac{R_{k-1}^2}{R_k r})^m - (R_{k-1}^2 - r^2 + \alpha_m^k)(\frac{r}{R_k})^m],$$

$$m = 1, 2, .., k = 1, 2, ..., l.$$

Let us put (13) into (15) and at the same time, take into consideration (12) and (14). Lo obtain a system of linear algebraic equations for each m for $(v_{mi}^k)^+$. The determinant of this system differs from zero, because the above formulated problem has the unique solution. If we solve this system, then the values $(v_{mi}^k)^-$ will be determined from the conditions (13). By means of the values $(v_{mi}^k)^+$ and $(v_{mi}^k)^-, i = 1, 2$, we will find the values of the functions $v_q^k(q = 1, 2, 3, 4)$, from (15) and from (10) finally we will obtain:

$$(u_1^k)^i = \frac{1}{r^2}(x_1 v_i^k - x_2 v_{i+2}^k),$$

$$(u_2^k)^i = \frac{1}{r^2}(x_2 v_i^k + x_1 v_{i+2}^k), \quad i = 1, 2.$$

So, by (16) and (7) formulae for each ring D_k we will obtain the solution of raised problem - $U^k(x) = ((u_1^k)^1, (u_2^k)^1, (u_1^k)^2, (u_2^k)^2, u_3^k)$ vector value. We will conclude from (15) and (7) formulae that:

$$|(v_{mq}^k)^{\pm}| \le \frac{1}{m^4}, \quad |(v_{m3}^k)^{\pm}| \le \frac{1}{m^3}, \quad m = 1, 2, ..., q = 1, 2, 3, 4; \quad k = 1, 2, ...l. \tag{16}$$

For the absolute and uniform convergency of series (15) and (7) and their first and second order derivatives it is sufficient(including the boundary) to fulfill the inequality : $f^p(z) \in C^4(S_p)$, $f_3^k(z) \in C^3(S_k)$, $f_4^k(z) \in$

$C^2(S_k)$,
$p = 1, l; \quad k = 1, 2, ..., l.$

2. The problems for compound circle may be solved analogously, i.e. when circle D_1 is not empty and is filled with elastic mixture.Representation of the harmonic function $u_3^1(x)$ in the domain D_1 is known [4]:

$$u_3^1(x) = \frac{1}{2}(u_{03}^1)^+ + \sum_{m=1}^{\infty}(\frac{r}{R_1})^m(u_{m3}^1)^+, x \in D_1,$$

where

$$(u_{m3}^1)^+(z) = \frac{1}{\pi}\int_0^{2\pi}(u_3^1)^+(\theta)cosm(\theta - \psi)d\theta, m = 0, 1, ..., z = (R_k, \psi), z \in S_1,$$

the functions $v_j^1(x)$ in the domain D_1 we can represent as:

$$v_i^1(r, \psi) = \frac{1}{2}(\frac{r}{R_1})^2(v_{0i}^1)^+ + \sum_{m=1}^{\infty}[(\frac{r}{R_1})^m(v_{mi}^1)^+ +$$

$$Z_m(r)[H_{mi}^1(\gamma_{m1}^1)^+ + L_{mi}^1(\gamma_{m2}^1)^+ - e_4^1 m\delta_m^1(u_{m3}^1)^+]],$$

$$v_j^1(r, \psi) = \frac{1}{2}(\frac{r}{R_1})^2(v_{0j}^1)^+ + \sum_{m=1}^{\infty}[(\frac{r}{R_1})^m(v_{mj}^1)^+ +$$

$$\frac{1}{m}Z_m(r)[M_{mj}^1(\gamma_{m1}^1)^+ + N_{mj}^1\gamma_{m2}^1 + e_5^1 m\delta_m^1(u_{m3}^1)^+]],$$

where the values

$$Z_m(r) = \frac{R_1^2 - r^2}{4(m+1)\delta_m^1}, Z_m(R_1) = 0, \quad \delta_m^1 = (2 + e_1^1)(2 + e_3^1) - e_2^1 e_6^1,$$

$$\gamma_{mi}^1 = \frac{2(m+1)}{R_1^2}[(v_{mi}^1)^+ + \frac{1}{m}\frac{\partial}{\partial\psi}(v_{mj}^1)^+ - e_{i+3}(u_{m3})^+],$$

$$e_1^1 = \frac{1}{d_1^1}(a_2^1 b_1^1 - c^1 d^1), \quad e_2^1 = \frac{1}{d_1^1}(a_2^1 d^1 - c^1 b_2^1), \quad e_3^1 = \frac{1}{d_1^1}(a_1^1 b_2^1 - c^1 d^1),$$

$$e_4^1 = \frac{1}{d_1^1}(a_1^1 d^1 - c^1 b_1^1), \quad A_1^1 \equiv e_6^1 = \frac{1}{d_1^1}(a_1^1 d^1 - c^1 b_1^1).$$

$H_{mi}^1, L_{mi}^1, M_{mj}^1, N_{mj}^1$-are depending on elastic and thermal constants of the mixture and on the radius R_1, $j = i + 2, i = 1, 2$.

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