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ASUPRA UNOR CURBE SPECIALE PE SUPRAFAȚA DE REFERINȚĂ A UNEI CONGRUENȚE DE DREPTE. II

Rezumat

În articolul precedent din această serie [9] am studiat proprietățile unei curbe $C: x^i = x^i(s)$, $(i = 1, 2, 3)$, pe suprafața de referință $S: x^i = x^i(u^\alpha)$, $(\alpha = 1, 2)$ a unei congruențe de drepte reprezentată prin vectorul unitar cu componente contravariante $\lambda^i = \lambda^i(u^\alpha)$ care este astfel că $d\lambda^i/ds$ este perpendicular pe X^i (componentele contravariante ale normalei la S. Scopul articolului de față este de a studia unele proprietăți ale acestei curbe.

ON THE GENERAL PROBLEM OF ORTHOTROPIC BEAMS LOADED ON THE LATERAL SURFACE AND ON THE ENDS

BY

C. I. BORȘ

To the memory of professor Mendel Haimovici

1. Introduction. The problem of loaded beams on the ends and for which the lateral surface is free from tractions is known as Saint-Venant problem. The problem of loaded beams on the lateral surface when the tractions do not varie with the axial coordinate is known as Almansi-Michell problem and when the lateral surface tractions have polinomial forms with respect to axial coordinate the problem is known as Almansi problem.

The Saint-Venant problem is well-known. Concerning the Almansi-Michell and Almansi problem we know some papers, some of them for the isotropic case [1], [5], [7], [8] and others for the anisotropic case [2], [3], [6], [7].

Generally, there are finded solutions which satisfy the conditions on the lateral surface; the end conditions are passed into account of Saint-Venant problem

In this paper, we shall consider an elastic beam limited by two planes $x_3 = 0$, $x_3 = h (h > 0)$ and by a cylindrical surface $\mathcal{F}$.

We shall denote by $\mathcal{V}$ the domain occupied by the beam and by S the domain and also the area of a cross-section of the beam.

We shall take the axes of x_1, x_2, x_3 such that

$$\iint_S x_1\, d\sigma = 0, \quad \iint_S x_2\, d\sigma = 0, \quad \iint_S x_1 x_2\, d\sigma = 0.$$

All this means that x_3-axis is the central-line of the beam and the axes x_1 and x_2 are the principal axes of inertia of the end $x_3 = 0$.

Here, we shall improve the results of the paper [3], so that the finded solution will satisfy in addition to the lateral surface conditions, also the end conditions although we shall utilize the same structure of solution and the number of the unknown functions will be kept.

The solution will be given for the case when the material of the beam is orthotropic but it can be generalized for the anisotropic materials with one plane of elastic symmetry and also can be particularized for the isotropic case.

2. Statement of the studied problem. We suppose that there are no body forces so that the equilibrium equations can be written in the form

$$\sigma_{ij,j} = 0 \quad \text{in } \mathcal{V}^{*}. \tag{2.1}$$

We supose also that the tractions applied on the lateral surface are given by

$$\sigma_{ij}\, n_j = \sum_{k=0}^{n} \tau_i^{(k)}(x_1, x_2)\, x_3^k \quad \text{on } \mathcal{F}, \tag{2.2}$$

where the functions $\tau_i^{(k)}$ are given and n_i are the direction cosines of the exterior normal to the surface $\mathcal{F}$.

On the end $x_3 = 0$, there are given the resultant and the resultant moment of the tractions applied on this end:

$$R = R\,(R_1, R_2, R_3), \quad \mathfrak{M} = \mathfrak{M}\,(\mathfrak{M}_1, \mathfrak{M}_2, \mathfrak{M}_3) \quad \text{on } x_3 = 0, \tag{2.3}$$

where R_1, R_2, R_3 are the given components of the resultant and $\mathfrak{M}_1, \mathfrak{M}_2, \mathfrak{M}_3$ are the components of the resultant moment.

On the end $x_3 = h$, there are applied tractions so that the beam is in equilibrium.

We shall call *the general problem of the beams* the problem defined by (2.1), (2.2) and (2.3).

The material of the beam being supposed orthotropic, the relations between the stress components σ_{ij} and the strain components γ_{ij} are taken in the form

$$\begin{cases} \sigma_{11} = A\gamma_{11} + H\gamma_{22} + G\gamma_{33}, \\ \sigma_{22} = H\gamma_{11} + B\gamma_{22} + F\gamma_{33}, \\ \sigma_{33} = G\gamma_{11} + F\gamma_{22} + C\gamma_{33}, \\ \sigma_{23} = L\gamma_{23}, \quad \sigma_{31} = M\gamma_{31}, \quad \sigma_{12} = D\gamma_{12}, \end{cases} \tag{2.4}$$

where $A, B, \ldots, L, M, D$ are moduli of elasticity.

* We use the summation convention over repeated indices. The index j after comma indicates partial differentiation with respect to x_j.

We shall express the components of strain γ_{ij} in terms of stress components σ_{ij} in the form

$$\begin{cases} E\gamma_{11} = \nu_{11}\sigma_{11} + \nu_{12}\sigma_{22} - \nu_1\sigma_{33}, \\ E\gamma_{22} = \nu_{12}\sigma_{11} + \nu_{22}\sigma_{22} - \nu_2\sigma_{33}, \\ E\gamma_{33} = -\nu_1\sigma_{11} - \nu_2\sigma_{22} + \sigma_{33}, \\ L\gamma_{23} = \sigma_{23}, \quad M\gamma_{31} = \sigma_{31}, \quad D\gamma_{12} = \sigma_{12}, \end{cases} \tag{2.5}$$

where the coefficients of strain E, ν_{ij}, ν_i may be expressed in terms of moduli of elasticity [4].

The components γ_{ij} are given in terms of the displacement components u_i by

$$\begin{cases} \gamma_{ii} = u_{i,i} \quad \text{(not summed)}, \\ \gamma_{ij} = u_{i,j} + u_{j,i} \quad (i \neq j). \end{cases} \tag{2.6}$$

3. Solution of the stated problem. We shall try to solve the problem defined by (2.1), (2.2) and (2.3). To that purpose let us suppose that the component of displacements u_i are of the form

$$\begin{cases} u_\alpha = \displaystyle\sum_{k=0}^{n+2} \left[\Theta_k^{(\alpha)} + a_k^{(\alpha)} \frac{x_3^2}{(k+1)(k+2)} \right] x_3^k + \sum_{k=0}^{n} \psi_k^{(\alpha)} x_3^k, \\ u_3 = -\displaystyle\sum_{k=0}^{n+2} \frac{1}{k+1} (a_k^{(1)} x_1 + a_k^{(2)} x_2 - A_k) x_3^{k+1} + \sum_{k=0}^{n+1} \omega_k x_3^k, \end{cases} \tag{3.1}$$

where

$$\Theta_k = \frac{1}{2} a_k^{(\alpha)} (\nu_\alpha x_\alpha^2 - \nu_\beta x_\beta^2) + a_k^{(\beta)} \nu_\alpha x_1 x_2 + (-1)^\alpha c_k x_\beta - A_k \nu_\alpha x_\alpha$$

$$(\alpha, \beta = 1, 2;\ \alpha \neq \beta;\ \text{not summed}),$$

$\psi_k^{(\alpha)}(x_1, x_2)$, $\omega_k(x_1, x_2)$ are unknown functions and $a_k^{(\alpha)}$, A_k, c_k are constants which must be determined.

If we denote by $\tau_{ij}^{(k)}$ the stresses corresponding to the displacements $u_\alpha^{(k)} = \psi_k^{(\alpha)}$, $u_3^{(k)} = 0$ then, taken into account (2.6) and (2.4) we find that the stresses of the displacements (3.1) are given by

$$
(3.2)\quad \begin{cases}
\sigma_{11} = \sum\limits_{k=0}^{n} \tau_{11}^{(k)} x_3^k + G \sum\limits_{k=0}^{n+1} k\omega_k x_3^{k-1}, \\
\sigma_{22} = \sum\limits_{k=0}^{n} \tau_{22}^{(k)} x_3^k + F \sum\limits_{k=0}^{n+1} k\omega_k x_3^{k-1}, \\
\sigma_{33} = \sum\limits_{k=0}^{n} \tau_{33}^{(k)} x_3^k + C \sum\limits_{k=0}^{n+1} k\omega_k x_3^{k-1} - E \sum\limits_{k=0}^{n+2} (a_k^{(1)} x_1 + a_k^{(2)} x_2 - A_k) x_3^k, \\
\sigma_{23} = L \left\{ \sum\limits_{k=0}^{n+1} \omega_{k,2} x_3^k + \sum\limits_{k=0}^{n} k\psi_k^{(2)} x_3^{k-1} + \sum\limits_{k=0}^{n+2} k\Theta_k^{(2)} x_3^{k-1} \right\}, \\
\sigma_{31} = M \left\{ \sum\limits_{k=0}^{n+1} \omega_{k,1} x_3^k + \sum\limits_{k=0}^{n} k\psi_k^{(1)} x_3^{k-1} + \sum\limits_{k=0}^{n+2} k\Theta_k^{(1)} x_3^{k-1} \right\}, \\
\sigma_{12} = \sum\limits_{k=0}^{n} \tau_{12}^{(k)} x_3^k .
\end{cases}
$$

By introducing the stresses (3.2) into the equilibrium equations (2.1) and equating with zero the coefficients of x_3 at the same power we obtian

$$
(3.3)\quad \begin{cases}
\tau_{11,1}^{(k)} + \tau_{12,2}^{(k)} + (k+1)\left[(G+M)\omega_{k+1,1} + M(k+2)(\psi_{k+2}^{(1)} + \Theta_{k+2}^{(1)})\right] = 0, \\
\tau_{12,1}^{(k)} + \tau_{22,2}^{(k)} + (k+1)\left[(F+L)\omega_{k+1,2} + L(k+2)(\psi_{k+2}^{(2)} + \Theta_{k+2}^{(2)})\right] = 0 \quad \text{in } S,
\end{cases}
$$

and

$$
(3.4)\quad \begin{aligned}
&\Delta\omega_k + (k+1)\left[M(\psi_{k+1}^{(1)} + \Theta_{k+1}^{(1)})_{,1} + L(\psi_{k+1}^{(2)} + \Theta_{k+1}^{(2)})_{,2} + \right. \\
&\left. + \tau_{33}^{(k+1)} + C(k+2)\omega_{k+2} - E(a_{k+1}^{(1)} x_1 + a_{k+1}^{(2)} x_2 - A_{k+1})\right] = 0 \quad \text{in } S,
\end{aligned}
$$

where

$$
\Delta = M \frac{\partial^2}{\partial x_1^2} + L \frac{\partial^2}{\partial x_2^2}.
$$

By the same way from the boundary conditions (2.2) we get

$$
(3.5)\quad \begin{cases}
\tau_{11}^{(k)} n_1 + \tau_{12}^{(k)} n_2 = \tau_1^{(k)} - G(k+1)\omega_{k+1} n_1, \\
\tau_{12}^{(k)} n_1 + \tau_{22}^{(k)} n_2 = \tau_2^{(k)} - F(k+1)\omega_{k+1} n_2 \quad \text{on } \Gamma
\end{cases}
$$

and

$$
(3.6)\quad \mathfrak{D}\omega_k = \tau_3^{(k)} - (k+1)\left[M(\psi_{k+1}^{(1)} + \Theta_{k+1}^{(1)}) n_1 + L(\psi_{k+1}^{(2)} + \Theta_{k+1}^{(2)}) n_2\right] \quad \text{on } \Gamma,
$$

where the operator $\mathfrak{D}$ is given by

$$
\mathfrak{D} = M n_1 \frac{\partial}{\partial x_1} + L n_2 \frac{\partial}{\partial x_2}.
$$

Now, let us determine the constants A_k, $a_k^{(\alpha)}$ and c_k.

The condition of existence of the function ω_k requires that

$$
\int_\Gamma \mathfrak{D}\omega_k \, ds - \iint_S \Delta\omega_k \, d\sigma = 0.
$$

From this equation, by using (3.4) and (3.6), it is easily to obtain

$$
(3.7)\quad ESA_{k+1} = -\frac{1}{k+1} \int_\Gamma \tau_3^{(k)} \, ds - \iint_S \left[\tau_{33}^{(k+1)} + C(k+2)\,\omega_{k+2}\right] d\sigma,
$$

$$
(k = 0, 1, 2, \ldots, n+1).
$$

The constant A_0 is not contained in (3.7). It will be determined from the end-conditions (2.3).

The equations (3.3) and (3.5) define a plane problem with body forces for the stresses $\tau_{\alpha\beta}^{(k)}$ ($\alpha, \beta = 1, 2$; $k = 0, 1, \ldots, n$). The solution of this plane problem gives the stress components $\tau_{\alpha\beta}^{(k)}$ and also the functions $\psi_k^{(\alpha)}$ because these functions are the components of displacements in this plane problem.

In order to examine the existence of solution of the mentioned plane problem let us consider a particular solution $\overset{*}{\tau}{}_{\alpha\beta}^{(k)}$ of the equation (3.3) and let us put down

$$
\tau_{\alpha\beta}^{(k)} = \tilde{\tau}_{\alpha\beta}^{(k)} + \overset{*}{\tau}{}_{\alpha\beta}^{(k)}.
$$

The new components $\tilde{\tau}_{\alpha\beta}^{(k)}$ will satisfy the equations

$$
(3.8)\quad \tilde{\tau}_{\alpha\beta,\beta}^{(k)} = 0 \quad \text{in} \quad S,
$$

and the boundary conditions

$$
(3.9)\quad \tilde{\tau}_{\alpha\beta}^{(k)} n_\beta = p_\alpha^{(k)} \quad \text{on } \Gamma \ (\alpha, \beta = 1, 2),
$$

where

$$
p_1^{(k)} = \tau_1^{(k)} - G(k+1)\omega_{k+1} n_1 - \overset{*}{\tau}{}_{1\beta}^{(k)} n_\beta ,
$$

$$
p_2^{(k)} = \tau_2^{(k)} - F(k+1)\omega_{k+1} n_2 - \overset{*}{\tau}{}_{2\beta}^{(k)} n_\beta .
$$

The equations (3.8) and (3.9) define an orthotropic plane problem without body forces.

The necessary and sufficient conditions for the existence of the solution of the problem (3.8), (3.9) are given by

$$\int_\Gamma p_\alpha^{(k)}\, ds = 0 \quad (\alpha = 1, 2), \int_\Gamma (x_1 p_2^{(k)} - x_2 p_1^{(k)}) ds = 0. \tag{3.10}$$

These conditions allow to determine the constants $a_{k+1}^{(\alpha)}$, c_{k+1} before to know the function ω_k.

For that purpose we shall take into account the fact that for any function ψ which satisfiy the equation $\Delta\psi = 0$ we have

$$\int_\Gamma \omega_k \mathfrak{D}\psi ds = \int_\Gamma \psi \mathfrak{D}\omega_k ds - \iint_S \psi \Delta\omega_k\, d\sigma$$

and from this equation we can deduce the following formulae

$$\int_\Gamma M\omega_k n_1 ds = \int_\Gamma x_1 \mathfrak{D}\omega_k ds - \iint_S x_1 \Delta\omega_k d\sigma,$$

$$\int_\Gamma L\omega_k n_2 ds = \int_\Gamma x_2 \mathfrak{D}\omega_k ds - \iint_S x_2 \Delta\omega_k d\sigma, \tag{3.11}$$

$$\int_\Gamma (Mx_2 n_1 - Lx_1 n_2)\omega_k ds = \int_\Gamma \varphi \mathfrak{D}\omega_k ds - \iint_S \varphi\Delta\omega_k d\sigma,$$

where φ is the function of torsion defined by [4]:

$$\Delta\varphi = 0 \quad \text{in } S,$$

$$\mathfrak{D}\varphi = Mx_2 n_1 - Lx_1 n_2 \quad \text{on } \Gamma.$$

If we take into account (3.4) and (3.6) the formulae (3.11) become

$$\int_\Gamma M\omega_{k+1} n_1 ds = \iint_S M\omega_{k+1,1} d\sigma = \int_\Gamma \tau_3^{(k+1)} x_1 ds - (k+2)EI_{22} a_{k+2}^{(1)} +$$

$$+ (k+2)\left\{\iint_S [\tau_{33}^{(k+2)} + C(k+3)\omega_{k+3}] x_1 d\sigma - \iint_S M(\psi_{k+2}^{(1)} + \Theta_{k+2}^{(1)}) d\sigma\right\},$$

$$\int_\Gamma L\omega_{k+1} n_2 ds = \iint_S L\omega_{k+1,2}\, d\sigma = \int_\Gamma \tau_3^{(k+1)} x_2 ds - (k+2)EI_{11} a_{k+2}^{(2)} +$$

$$+ (k+2)\left\{\iint_S [\tau_{33}^{(k+2)} + C(k+3)\omega_{k+3}] x_2 d\sigma - \iint_S L(\psi_{k+2}^{(2)} + \Theta_{k+2}^{(2)}) d\sigma\right\},$$

$$\int_\Gamma (Mx_2 n_1 - Lx_1 n_2)\omega_{k+1} ds = \iint_S (Mx_2\omega_{k+1,1} - Lx_1\omega_{k+1,2})\, d\sigma =$$

$$= \int_\Gamma \tau_3^{(k+1)} \varphi ds + (k+2)\iint_S [\tau_{33}^{(k+2)} + C(k+3)\omega_{k+3} -$$

$$- E(a_{k+2}^{(1)} x_1 + a_{k+2}^{(2)} x_2 - A_{k+2})]\varphi d\sigma -$$

$$- (k+2)\iint_S [M(\psi_{k+2}^{(1)} + \Theta_{k+2}^{(1)})\varphi_{,1} + L(\psi_{k+2}^{(2)} + \Theta_{k+2}^{(2)})\varphi_{,2}]\, d\sigma.$$

By using the above formulae, from the conditions (3.10) we obtain immediately

$$EI_{\beta\beta}\, a_{k+2}^{(\alpha)} = \frac{1}{(k+1)(k+2)} \int_\Gamma [\tau_\alpha^{(k)} + (k+1) x_\alpha \tau_3^{(k+1)}] ds +$$

$$\iint_S [\tau_{33}^{(k+2)} + C(k+3)\omega_{k+3}] x_\alpha d\sigma,$$

$$D_t\, c_{k+2} = \frac{1}{(k+1)(k+2)} \int_\Gamma [x_2 \tau_1^{(k)} - x_1 \tau_2^{(k)} + (k+1)\varphi\tau_3^{(k+1)}]\, ds + \tag{3.12}$$

$$+ \iint_S [\tau_{33}^{(k+2)} + C(k+3)\omega_{k+3} - E(a_{k+2}^{(1)} x_1 + a_{k+2}^{(2)} x_2 - A_{k+2})]\varphi d\sigma -$$

$$- \iint_S [M(\varphi_{,1} - x_2)(\psi_{k+2}^{(1)} + \widetilde{\Theta}_{k+2}^{(1)}) + L(\varphi_{,2} + x_1)(\psi_{k+2}^{(2)} + \widetilde{\Theta}_{k+2}^{(2)})] d\sigma,$$

where

$$I_{\alpha\alpha} = \iint_S x_\beta^2\, d\sigma \quad (\alpha, \beta = 1, 2;\ \alpha \neq \beta;\ \text{not summed}),$$

$$D_t = \iint_S (Lx_1^2 + Mx_2^2 + Lx_1\varphi_{,2} - Mx_2\varphi_{,1}) d\sigma > 0 \quad \text{(see [4])},$$

$\widetilde{\Theta}_k^{(\alpha)}$ is obtained from $\Theta_k^{(\alpha)}$ by droping out the term of c_k.

From the end-conditions we still must determine the constants A_1, $a_1^{(\alpha)}$, $a_0^{(\alpha)}$ and c_1. The constant c_0 may be taken as zero.

From the end conditions (2.3) we have

$$
(3.13)\quad \begin{cases} R_\alpha = -\iint\limits_S \sigma_{\alpha 3} d\sigma, \quad R_3 = -\iint\limits_S \sigma_{33}\, d\sigma, \\ \mathfrak{M}_\alpha = (-1)^\alpha \iint\limits_S \sigma_{33} x_\beta d\sigma, \ \mathfrak{M}_3 = -\iint\limits_S (x_1\sigma_{23} - x_2\,\sigma_{31}) d\sigma, \end{cases}
$$

the stresses σ_{ij} being taken for $x_3 = 0$.

By using (3.2), from the above formulae, we get

$$
SEA_0 = -R_3 - \iint\limits_S (\tau_{33}^{(0)} + C\omega_1)\, d\sigma,
$$

$$
EI_{\beta\beta}\, a_1^{(\alpha)} = R_\alpha + \int\limits_\Gamma \tau_3^{(0)} x_\alpha\, ds + \iint\limits_S (\tau_{33}^{(1)} + 2C\omega_2) x_\alpha d\sigma,
$$

$$
D_t c_1 = -\mathfrak{M}_3 + \int\limits_\Gamma \tau_3^{(0)}\, \varphi ds + \iint\limits_S [\tau_{33}^{(1)} + 2C(\omega_2 - E(a_1^{(1)} x_1 + a_1^{(2)} x_2 - A_1)]\varphi d\sigma -
$$

$$
-\iint\limits_S [M(\varphi_{,1} - x_2)(\psi_1^{(1)} + \tilde{\Theta}_1^{(1)}) + L(\varphi_{,2} + x_1)(\psi_1^{(2)} + \tilde{\Theta}_1^{(2)})] d\sigma,
$$

$$
EI_{\beta\beta}\, a_0^{(\alpha)} = (-1)^\alpha \mathfrak{M}_\beta + \iint\limits_S (\tau_{33}^{(0)} + C\omega_1)\, x_\alpha\, d\sigma.
$$

Ewerywhere, in this paper, we must remember that [see Eq. (3.1)]

$$
(3.14)\qquad \omega_{n+1+p} = \psi_{n+p}^{(\alpha)} = \tau_{ij}^{(n+p)} = \tau_i^{(n+p)} = 0 \quad (p = 1, 2, \ldots).
$$

It is easy to see that we must perform the calculus in the following order: taking into account (3.14) we can determine the constants A_{n+2}, $a_{n+2}^{(\alpha)}$, c_{n+2} from the formulae (3.7) and (3.12); the function ω_{n+1} solving the problem (3.4), (3.6) for $k = n + 1$; the functions $\psi_n^{(\alpha)}$ solving the problem (3.3), (3.5) for $k = n$. After that we determine A_{n+1}, $a_{n+1}^{(\alpha)}$, c_{n+1}, ω_n, $\psi_{n-1}^{(\alpha)}$ and so on.

We point out that from the given solution, by adequate particularizations we can obtain the solution for any component of the Saint-Venant problem. As an example let us recover, in the given solution, the classical problem of torsion. In this case we have

$$
\mathfrak{M}_3 \neq 0, \ \tau_i^{(k)} = 0 \ (i = 1, 2, 3;\ k = 0, 1, \ldots, n),
$$

$$
R_1 = R_2 = R_3 = \mathfrak{M}_1 = \mathfrak{M}_2 = 0.
$$

It is easy to see that, in these conditions, all functions and constants are zero excepting ω_0 and c_1. From the equations (3.4) and (3.6) we get

$$
\Delta\omega_0 = 0 \quad \text{in } S,
$$

$$
\mathfrak{D}\omega_0 = c_1(Mx_2n_1 - Lx_1n_2) \quad \text{on } \Gamma
$$

and this means that the function ω_0 coincides with the function $c_1\varphi$. By the same way we can obtain all the other problems.

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ASUPRA PROBLEMEI GENERALE A BARELOR ORTOTROPE ÎNCĂRCATE PE SUPRAFAŢA LATERALĂ ŞI PE CAPETE

Rezumat

În articol se dă o metodă pentru a rezolva problema definită de (2.1) (2.2), (2.3). Rezultatele obţinute pot fi generalizate pentru bare anizotrope cu un plan de simetrie elastică şi de asemenea pot fi particularizate pentru a obţine cazul izotrop. Metoda dată este o generalizare naturală a metodei lui Saint-Venant pentru problema clasică a torsiunii.