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AXISYMMETRIC BEND OF THE LITHOSPHERIC PLATE OF THE EXPONENTIAL PROFILE

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Earth 's seismic and volcanic activity is related to plate tectonics. Thin elastic surface plates form a lithosphere which experience different loads. The article considers a new model of the stress-strain state of the axisymmetric lithospheric plate of exponential profile in a non-uniform temperature field and under the influence of transverse forces. Novelty of solution of this problem lies in study by method of partial sampling of nonlinear differential equation with non-uniform coefficients when the lithospheric plate is bent. There are obtained regularities of change of radial force and bending moments under action of radial uniformly distributed load and volumetric centrifugal forces, as well as a result of temperature heating. A graphic analysis indicates the non-linear nature of their distribution, which significantly affects the shape of a curved plate.

Key words: transverse forces, temperature field, lithospheric plate, exponential profile, axisymmetric bend.

ЭКСПОНЕНЦИАЛДЫ ПРОФИЛЬДІ ЛИТОСФЕРАЛЫҚ ПЛИТАНЫҢ ОСЬСИММЕТРИЯЛЫҚ ИІЛУІ

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Жердің сейсмикалық және вулканикалық белсенділігі плиталар тектоникасымен байланысты. Жұқа серпімді жер үсті плиталар литосфераны құрайды, оларға әр түрлі жүктемелер әсер етеді. Мақалада көлденең күштер мен температуралық өріс әсерінен экспоненциалды профильді литосфералық плитаның кернеулі-деформацияланған күйінің жаңа моделі қарастырылады. Аталмыш міндетті шешудің жаңалығы - литосфералық плита иілу кезіндегі бір текті емес коэффициенттерімен сызықтық емес дифференциалдық теңдеуді ішінара дискреттеу әдісімен зерттеу. Радиалды біркалыпты бөлінген жүктеме мен көлемдік ортадан тепкіш күштер әсерінен, сондай-ақ температуралық қыздыру нәтижесінде радиалды күштер мен иілуші моменттер өзгеру заңдылықтары алынған. Жүргізілген графикалық талдау олардың таралуының бейсызықтық екенін көрсетеді, ол иілген плитаның қалпына елеулі әсерін тигізеді.

Негізгі сөздер: көлденең күш, температуралық өріс, литосфералық плита, экспоненциалдық профиль, осьсимметриялық иілу.

ОСЕСИММЕТРИЧНЫЙ ИЗГИБ ЛИТОСФЕРНОЙ ПЛИТЫ ЭКСПОНЕНЦИАЛЬНОГО ПРОФИЛЯ

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Сейсмическая и вулканическая активность Земли связана с тектоникой плит. Тонкие упругие поверхностные плиты образуют литосферу, которые испытывают действие разного рода нагрузок. В статье рассмотрена новая модель напряженно-деформированного состояния осесимметричной литосферной плиты экспоненциального профиля в неоднородном температурном поле и под воздействием поперечных сил. Новизна решения данной задачи состоит в исследовании методом частичной дискретизации нелинейного дифференциального уравнения с неоднородными коэффициентами изгиба литосферной плиты. Получены закономерности изменения радиальной силы и изгибающих моментов под действием радиальной равномерно распределенной нагрузки и объемных центробежных сил, а также в результате температурного нагрева. Проведенный графический анализ указывает на нелинейный характер их распределения, что существенно влияет на форму изогнутой плиты.

Ключевые слова: поперечные силы, температурное поле, литосферная плита, экспоненциальный профиль, осесимметричный изгиб.

Introduction

The plate tectonics model implies the stiffness of near-surface rocks and their elastic behavior at geological scales of time. Thin resilient surface plates form a lithosphere which floats on the underlying relative liquid mantle. The plates experience various loads, such as the weight of volcanoes and seamounts, so that they bend. For the study of such geological phenomena, the theory of bending of plates under the influence of applied forces and moments of forces is applicable. With this theory it is also possible to explain the occurrence of series of folds in mountain belts, as the formation of folds can be seen as deformations of elastic plates under the action of horizontal compressive forces. The theory of plate bending is used to simulate formation blasting over magmatic intrusions [1-3].

Objects and research methods

Consider axisymmetric bending of non-uniform elastic lithospheric plate of variable thickness of exponential profile in non-uniform temperature field by partial sampling method [4]. The basic differential equations of quasi-static equilibrium are reduced to the next second-order differential equation with respect to angular displacement

$$\frac{d^2\vartheta}{dr^2}+\left(\frac{1}{r}+\frac{1}{D_M}\frac{dD_M}{dr}\right)\frac{d\vartheta}{dr}+\left(\frac{\nu}{rD_M}\frac{dD_M}{dr}-\frac{1}{r^2}\right)\vartheta+ \\ +\frac{1}{rD_M}(\int q_r rdr-c)-\frac{1+\nu}{D_M}\frac{d}{dr}(\chi_T D_M)=0, \quad (1)$$

where $\vartheta=-\frac{\partial w}{\partial r}$ - angular movement, w – deflection, D_M – cylindrical rigidity of a bend, ν – Poisson's coefficient, r – position of midplane point before its deformation, χ_T – thermal deformation due to non-uniform heating, q_r – intensity of cross forces.

An edge task is set when a circular plate of variable thickness with a rigidly embedded inner contour $r=r_1$ is loaded along its outer contour $r=r_2$. Boundary conditions will take the form

$$M_r(r_2)=0, \\ \vartheta(r_1)=0. \quad (2)$$

Let the plate be subjected to uneven heating. In the case of linear heat propagation $\alpha_T T$ in the thickness of the plate the thermal deformation is approximated in the form of

$$\chi_T=\frac{1}{h}\sum_{j=0}^{n}\Delta\varepsilon_j r^j \quad (3)$$

In addition, let the plate of variable thickness rigidly embedded on the inner office $r=r_1$ be loaded uniformly distributed along the surface by transverse forces of intensity q_0 and along the contour $r=r_2$ by transverse force Q

$$q_z=\sum_{j=0}^{n}q_j r^j,\ q_z=q_0$$

$$q_1=q_2=q_3...=0,\ C=Qr_0+0{,}5q_0r_0^2. \quad (4)$$

Then the general solution of equation (1) under an arbitrary law of change in plate thickness will be

$$\vartheta=B+A\int e^{-\int\xi(r)dr}dr+ \\ +\int e^{-\int\xi(r)dr}\left(\int[\eta(r)+\varsigma(r)+\varphi(r)]e^{-\int\xi(r)dr}dr\right)dr \quad (5)$$

where

$$\eta(r)=-\nu\sum\left[\ln\frac{D_N(r_K)}{D_{ON}}\frac{\vartheta(r_{k-1})}{r_{k-1}}\delta(r-r_{k-1})-\ln\frac{D_M(r_k)}{D_{ON}}\frac{\vartheta(r_k)}{r_{k+1}}\delta(r-r_k)\right]- \\ -\sum\left[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\delta(r-r_{k-1})-\left(\frac{1}{r_k}\right)\vartheta(r_k)\delta(r-r_k)\right]; \quad (6)$$

$$\xi(r)=\frac{1}{r}+\frac{1}{D_M}\frac{dD_M}{dr};\quad \varphi(r)=-\frac{1+\nu}{D_M}\frac{d}{dr}(\chi_T D_M);\quad \varsigma(r)=-\frac{1}{rD_M}(\int q_z rdr-C). \quad (7)$$

Arbitrary coefficients A and B are determined by boundary conditions (2).

By taking into account the first three members in (3) and the first member in (4), the general solution of equation (1) for the adopted plate stiffness law will take the form

$$\vartheta = B + Ar_0\left(\ln\frac{r}{r_0} + \frac{r}{r_0} + \frac{r^2}{4r_0^2} + \frac{r^3}{18r_0^3} + \frac{r^4}{96r_0^4} + \frac{r^5}{600r_0^5} + \ldots\right) + \frac{(1+\nu)r_0^2}{h_0}$$

$$\left\{\Delta\varepsilon_1\left[e^{-\frac{r}{3r_0}}\left(3\frac{r}{r_0} - \frac{9}{2}\right) + \frac{9}{4}\left(\ln\frac{r}{r_0} + \frac{r}{3r_0} + \frac{r^2}{36r_0^2} + \frac{r^3}{486r_0^3} + \ldots\right)\right] + \frac{\Delta\varepsilon_0}{r_0}\left[3e^{\frac{4}{3r_0}} + \frac{9}{2}\right.\right.$$

$$\left.\left.\left(\ln\frac{r}{r_0} + \frac{r}{3r_0} - \frac{r^2}{36r_0^2} + \frac{r^3}{486r_0^3} + \ldots\right)\right]\right\} - J_1(r)\left\{\nu\sum\left[\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_{k-1})}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r - r_{k-1}) - \right.\right.$$

$$\left. - \ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_k)}{r_0}e^{-\frac{r_k}{r_0}}H(r - r_k)\right] + \sum\left[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\frac{r_{k-1}}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r - r_{k-1}) - \right. \qquad (8)$$

$$\left.\left. - \left(-\frac{1}{r_k}\right)\vartheta(r_k)e^{-\frac{r_k}{r_0}}H(r - r_k)\right]\right\} + \frac{q_0 r_0^3}{6D_0}e^{\frac{r}{r_0}}\left[1 + 2\frac{r}{r_0} - \left(\frac{r}{r_0}\right)^2\right] + \frac{Qr^2}{D_0}e^{\frac{r}{r_0}}$$

$$\frac{d\vartheta}{dr} = A\frac{r}{r_0}e^{\frac{r}{r_0}} + \frac{(1+\nu)r^2}{h_0 r}e^{\frac{r}{3r_0}}\left[\left(\frac{9}{2} + \frac{3}{2}\frac{r}{r_0} + \frac{r^2}{r_0^2}\right)\Delta\varepsilon_1 + \left(\frac{r}{r_0} + \frac{3}{2}\right)\frac{\Delta\varepsilon_0}{r_0}\right] + \frac{q_0 r_0^2}{3D_0}e^{\frac{r}{r_0}} + \frac{Qr_0}{D_0}e^{\frac{r}{r_0}} -$$

$$\frac{r}{r_0}e^{\frac{r}{r_0}}\left\{\nu\sum\left[\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_{k-1})}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r - r_{k-1}) - \ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_k)}{r_0}e^{-\frac{r_k}{r_0}}H(r - r_k)\right] + \right. \qquad (9)$$

$$\left.\sum\left[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\frac{r_{k-1}}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r - r_{k-1}) - \left(-\frac{1}{r_k}\right)\vartheta(r_k)e^{-\frac{r_k}{r_0}}H(r - r_k)\right]\right\}$$

At that, from boundary condition (2) we get expressions for arbitrary constant

$$A = -0{,}1713\frac{q_0 r_0^2}{D_0} - 0{,}41745\frac{Qr_0}{D_0} - 1{,}8552\frac{\Delta\varepsilon_0}{h_0} - 3.034\frac{r_0}{h_0}\cdot\Delta\varepsilon_1,$$

$$B = -0{,}596\frac{q_0 r_0^3}{D_0} - 2{,}0235\frac{Qr_0^{\ 2}}{D_0} - 3{,}2633\frac{r_0}{h_0}\Delta\varepsilon_0 - 5{,}07757\frac{r_0^{\ 2}}{h_0}\cdot\Delta\varepsilon_1.$$

Bending moments defined by the following ratios

$$\left.\begin{aligned} M_r &= D_M\left[\frac{d\vartheta}{dr} + \frac{\nu}{r}\vartheta - (1+\nu)\chi_T\right] \\ M_\theta &= D_M\left[\nu\frac{d\vartheta}{dr} + \frac{1}{r}\vartheta - (1+\nu)\chi_T\right] \end{aligned}\right\} \qquad (10)$$

will take a form

$$M_r = D_M\left\{\left(-0{,}1713\frac{q_0 r_0^2}{D_0} - 0{,}41745\frac{Qr_0}{D_0} - 1{,}8552\frac{\Delta\varepsilon_0}{h_0} - 3.034\frac{r_0}{h_0}\cdot\Delta\varepsilon_1\right)\frac{r}{r_0}e^{\frac{r}{r_0}} + \frac{(1+v)r^2}{h_0 r}e^{\frac{r}{3r_0}}\right.$$

$$\left[\left(\frac{9}{2}+\frac{3}{2}\frac{r}{r_0}+\frac{r^2}{r_0^2}\right)\Delta\varepsilon_1 + \left(\frac{r}{r_0}+\frac{3}{2}\right)\frac{\Delta\varepsilon_0}{r_0}\right] + \frac{q_0 r_0^2}{3D_0}e^{\frac{r}{r_0}} + \frac{Qr_0}{D_0}e^{\frac{r}{r_0}} - \frac{r}{r_0}e^{\frac{r}{r_0}}$$

$$\left\{v\sum\left[\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_{k-1})}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1}) - \ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_k)}{r_0}e^{-\frac{r_k}{r_0}}H(r-r_k)\right] + \right.$$

$$\left.\sum\left[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\frac{r_{k-1}}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1}) - \left(-\frac{1}{r_k}\right)\vartheta(r_k)e^{-\frac{r_k}{r_0}}H(r-r_k)\right]\right\} -$$

$$-\frac{v}{r}\left(\left(-0{,}596\frac{q_0 r_0^2}{D_0} - 2{,}0235\frac{Qr_0}{D_0} - 3{,}2633\frac{r_0}{h_0}\Delta\varepsilon_0 - 5{,}07757\frac{r_0^{\,2}}{h_0}\cdot\Delta\varepsilon_1\right) + \right.$$

$$+\left(-0{,}1713\frac{q_0 r_0^2}{D_0} - 0{,}41745\frac{Qr_0}{D_0} - 1{,}8552\frac{\Delta\varepsilon_0}{h_0} - 3.034\frac{r_0}{h_0}\cdot\Delta\varepsilon_1\right)r_0\,\cdot$$

$$\left(\ln\frac{r}{r_0}+\frac{r}{r_0}+\frac{r^2}{4r_0^2}+\frac{r^3}{18r_0^3}+\frac{r^4}{96r_0^4}+\frac{r^5}{600r_0^5}+\ldots\right) + \frac{(1+v)r_0^2}{h_0}$$

$$\left\{\Delta\varepsilon_1\left[e^{-\frac{r}{3r_0}}\left(3\frac{r}{r_0}-\frac{9}{2}\right)+\frac{9}{4}\left(\ln\frac{r}{r_0}+\frac{r}{3r_0}+\frac{r^2}{36r_0^2}+\frac{r^3}{486r_0^3}+\ldots\right)\right] + \right.$$

$$\left.+\frac{\Delta\varepsilon_0}{r_0}\left[3e^{\frac{4}{3r_0}}+\frac{9}{2}\left(\ln\frac{r}{r_0}+\frac{r}{3r_0}-\frac{r^2}{36r_0^2}+\frac{r^3}{486r_0^3}+\ldots\right)\right]\right\} -$$

$$-J_1(r)\left\{v\sum\left[\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_{k-1})}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1}) - \right.\right.$$

$$\left.-\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_k)}{r_0}e^{-\frac{r_k}{r_0}}H(r-r_k)\right] + \sum\left[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\frac{r_{k-1}}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1}) - \right.$$

$$\left.\left.-\left(-\frac{1}{r_k}\right)\vartheta(r_k)e^{-\frac{r_k}{r_0}}H(r-r_k)\right]\right\} + \frac{q_0 r_0^3}{6D_0}e^{\frac{r}{r_0}}\left[1+2\frac{r}{r_0}-\left(\frac{r}{r_0}\right)^2\right] + \frac{Qr^2}{D_0}e^{\frac{r}{r_0}}\Bigg) - -(1+v)\frac{1}{h}(\Delta\varepsilon_0 + \Delta\varepsilon_0 r)\Bigg\}$$

$$M_\theta = D_M\left\{\left(-0{,}1713\frac{q_0 r_0^2}{D_0} - 0{,}41745\frac{Qr_0}{D_0} - 1{,}8552\frac{\Delta\varepsilon_0}{h_0} - 3.034\frac{r_0}{h_0}\cdot\Delta\varepsilon_1\right)\frac{r}{r_0}e^{\frac{r}{r_0}} + \frac{(1+v)r^2}{h_0 r}e^{\frac{r}{3r_0}}\right.$$

$$\left[\left(\frac{9}{2}+\frac{3}{2}\frac{r}{r_0}+\frac{r^2}{r_0^2}\right)\Delta\varepsilon_1 + \left(\frac{r}{r_0}+\frac{3}{2}\right)\frac{\Delta\varepsilon_0}{r_0}\right] + \frac{q_0 r_0^2}{3D_0}e^{\frac{r}{r_0}} + \frac{Qr_0}{D_0}e^{\frac{r}{r_0}} - \frac{r}{r_0}e^{\frac{r}{r_0}}$$

$$\left\{v\sum\left[\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_{k-1})}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1}) - \ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_k)}{r_0}e^{-\frac{r_k}{r_0}}H(r-r_k)\right] + \right.$$

$$\left.+\sum\left[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\frac{r_{k-1}}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1}) - \left(-\frac{1}{r_k}\right)\vartheta(r_k)e^{-\frac{r_k}{r_0}}H(r-r_k)\right]\right\} -$$

$$-\frac{1}{r}\Bigg(\left(-0{,}596\frac{q_0r_0^2}{D_0}-2{,}0235\frac{Qr_0}{D_0}-3{,}2633\frac{r_0}{h_0}\Delta\varepsilon_0-5{,}07757\frac{r_0^2}{h_0}\cdot\Delta\varepsilon_1\right)+$$

$$+\left(-0{,}1713\frac{q_0r_0^2}{D_0}-0{,}41745\frac{Qr_0}{D_0}-1{,}8552\frac{\Delta\varepsilon_0}{h_0}-3.034\frac{r_0}{h_0}\cdot\Delta\varepsilon_1\right)r_0\cdot$$

$$\left(\ln\frac{r}{r_0}+\frac{r}{r_0}+\frac{r^2}{4r_0^2}+\frac{r^3}{18r_0^3}+\frac{r^4}{96r_0^4}+\frac{r^5}{600r_0^5}+\dots\right)+\frac{(1+v)r_0^2}{h_0}$$

$$\Bigg\{\Delta\varepsilon_1\left[e^{-\frac{r}{3r_0}}\left(3\frac{r}{r_0}-\frac{9}{2}\right)+\frac{9}{4}\left(\ln\frac{r}{r_0}+\frac{r}{3r_0}+\frac{r^2}{36r_0^2}+\frac{r^3}{486r_0^3}+\dots\right)\right]+\frac{\Delta\varepsilon_0}{r_0}\Bigg[3e^{\frac{4}{3r_0}}+\frac{9}{2}$$

$$\left(\ln\frac{r}{r_0}+\frac{r}{3r_0}-\frac{r^2}{36r_0^2}+\frac{r^3}{486r_0^3}+\dots\right)\Bigg]\Bigg\}-J_1(r)\Bigg\{v\sum\Bigg[\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_{k-1})}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1})-$$

$$-\ln\frac{D_M(r_k)}{D_{OM}}\frac{\vartheta(r_k)}{r_0}e^{-\frac{r_k}{r_0}}H(r-r_k)\Bigg]+\sum\Bigg[\left(\frac{1}{r_k}\right)\vartheta(r_{k-1})\frac{r_{k-1}}{r_0}e^{-\frac{r_{k-1}}{r_0}}H(r-r_{k-1})-$$

$$-\left(-\frac{1}{r_k}\right)\vartheta(r_k)e^{-\frac{r_k}{r_0}}H(r-r_k)\Bigg]\Bigg\}+\frac{q_0r_0^3}{6D_0}e^{\frac{r}{r_0}}\left[1+2\frac{r}{r_0}-\left(\frac{r}{r_0}\right)^2\right]+\frac{Qr^2}{D_0}e^{\frac{r}{r_0}}\Bigg)-(1+v)\frac{1}{h}(\Delta\varepsilon_0+\Delta\varepsilon_0 r)\Bigg\}$$

Results and their discussion

The application of the partial sampling method has made it possible to solve the problem for any law of changing mechanical characteristics. On the basis of the found solution and numerical analysis for stress-deformed state of the lithospheric plate under the action of radial uniformly distributed load and volumetric centrifugal forces, as well as a result of temperature heating, patterns of change of radial force and bending moments are found, which are shown in the form of graphs in Figures 1-2.

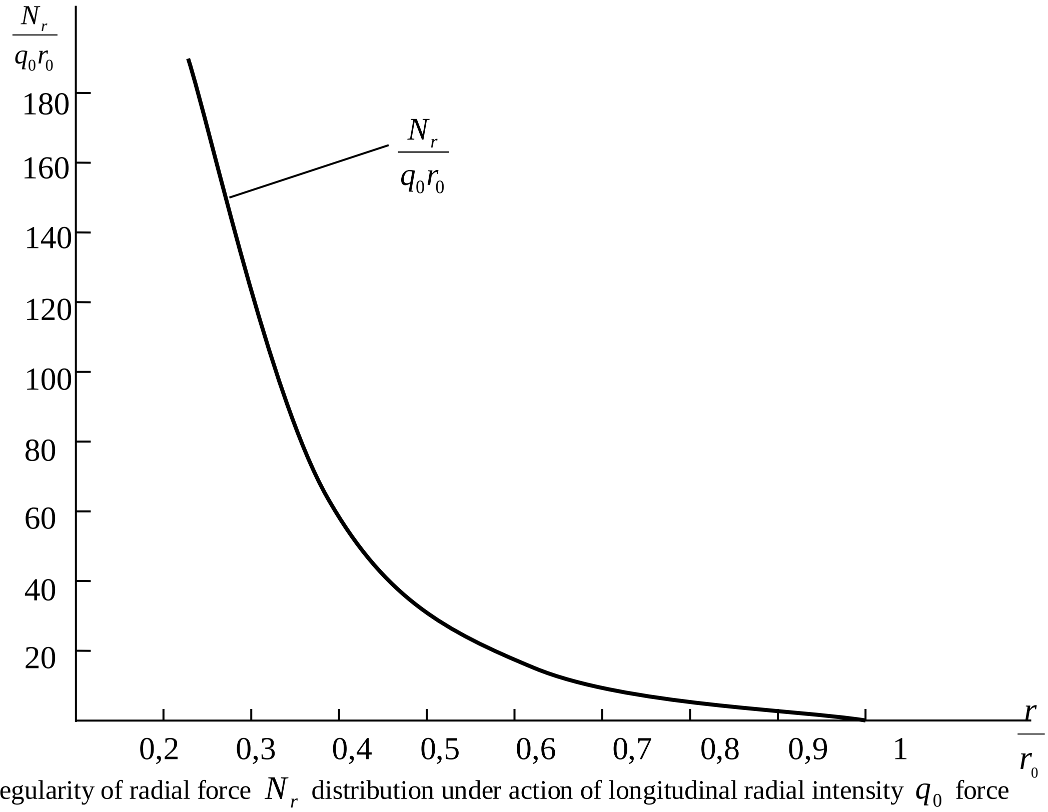

Figure 1 - Regularity of radial force N_r distribution under action of longitudinal radial intensity q_0 force

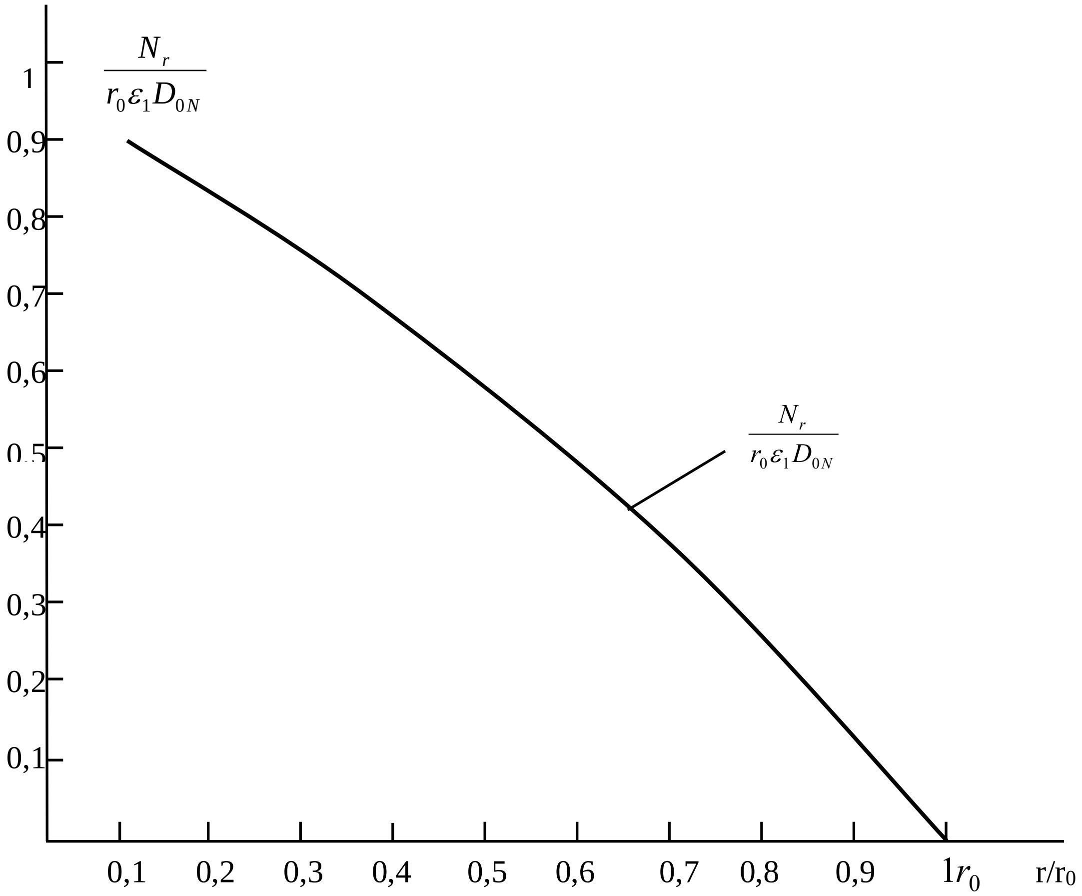

Figure 2 - Law of change of radial force N_r of the plate subjected to temperature heating

Conclusion

New model of stress-strain state of axisymmetric lithospheric plate of exponential profile in non-uniform temperature field and under action of transverse forces is proposed.

To solve the nonlinear differential equation with non-uniform bending coefficients of the lithospheric plate, the partial sampling method was applied for the first time.

Obtained regularities of change of radial force and bending moments under action of radial uniformly distributed load and volumetric centri-fugal forces, and also as a result of temperature heating characterize stressed-deformed state of plate. Graphical analysis indicates the nonlinear nature of their distribution.

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