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The study of the stress-strain state of an elastically supported compressed strip*

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Abstract

An analysis has been conducted on the continuous dependence of the function describing the behavior of the real structure on the characteristics of initial imperfections. A condition has been obtained, imposed on the parameter of external influence and the stiffness coefficient of the foundation, when that is violated, the shape of the cross-section of the strip will no longer be close to a rectangle, i.e. the strip loses shape stability. During the study, the parameters of external influences remained independent.

Keywords: elastic strip, elastic support, continuous dependence, stability.

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Introduction. During the operation of products, various internal processes occur, which can lead to changes in the geometric and physical parameters. However, when designing such products, it is typically assumed that these changes are insignificant. Additionally, during production, there are tolerances for the geometric dimensions of parts as well as for their mechanical, physical, and chemical properties [1–5]. By conducting a study based on a mathematical model, it is assumed that such imperfections do not have a significant effect on the stress-strain state. Thus, the solution describing the stress-strain state is continuously dependent on the initial data (imperfections) [1].

The works on this problem include studies of the stability on the solution of quasi-static problems [2–4]. In most studies, the load parameters ceased to be independent at a certain stage of research and a loading trajectory was introduced.

In this study, an analysis of the continuous dependence of the solution for the state of a compressed elastically supported strip on the functions that characterize the geometry of its cross-section was carried out.

1. Problem statement. Consider a strip made of elastic material. The shape of the cross-section is rectangular. The classical model of a one-parameter Winkler foundation with stiffness coefficient k was chosen as the foundation model. The strip is compressed along the side edges by forces, which makes it impossible to set the exact boundary conditions for the normal stresses. Let them be reduced to the main vector equal to modulus $2ph$, where p is the parameter of external influence, and h is the cross-section height. Similar situations arise, for example, if the load is a concentrated force or a distributed force is applied along a line running along the strip.

Let the upper and lower edges of the strip before deformation be characterized by the following functions:

$$y = (-1)^i (h + f(x)), \quad x \in [-l; l],\ i = 1, 2,$$

and after deformation:

$$y = g_i(x), \quad x \in [-l; l],\ i = 1, 2,$$

where $f(x)$, $g_i(x) \in C^1[-l; l]$; $i = 1$ corresponds to the upper edge of the strip, $i = 2$ corresponds to the bottom edge. In the case of plane strain, the stress-strain state of the strip is described by solving the following problem [6]:

$$\begin{aligned} &\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau}{\partial y} = 0, \qquad \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau}{\partial x} = 0, \\ &\sigma_x = \lambda\theta + 2\mu\frac{\partial u}{\partial x}, \quad \sigma_y = \lambda\theta + 2\mu\frac{\partial v}{\partial y}, \\ &\tau = \mu\Big(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\Big), \quad \theta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \end{aligned} \tag{1}$$

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with boundary conditions:

$$\tau_n\Big|_{y=g_i(x)} = 0, \quad \sigma_n\Big|_{y=g_i(x)} = k(g_i(x) - y_i(x)), \quad i = 1, 2, \tag{2}$$

$$\begin{gathered} \int_{\eta_1}^{\eta_2} \sigma_x dy = \int_{\eta_3}^{\eta_4} \sigma_x dy = -2ph, \\ \int_{\eta_1}^{\eta_2} \sigma_x y dy = \int_{\eta_3}^{\eta_4} \sigma_x y dy = \int_{\xi_1}^{\xi_2} v dy = \int_{\xi_3}^{\xi_4} v dy = 0, \end{gathered} \tag{3}$$

where

$$\begin{array}{ll} \xi_1 = -h - f(l), & \xi_2 = h + f(l), \\ \xi_3 = -h - f(-l), & \xi_2 = h + f(-l), \\ \eta_1 = -h - f(l) + v(l, \xi_1), & \eta_2 = h + f(l) + v(l, \xi_2), \\ \eta_3 = -h - f(-l) + v(-l, \xi_3), & \eta_4 = h + f(-l) + v(-l, \xi_4). \end{array}$$

For $f(x) = 0$ the problem (1)–(3) admits the solution

$$\begin{aligned} & v = v^{(0)} = \varepsilon_y^0 y, \quad \varepsilon_y^0 = -\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\lambda}{\lambda^2 - (kh + 2\mu + \lambda)(2\mu + \lambda)} p}; \\ & u = u^{(0)} = \frac{kh + 2\mu + \lambda}{\lambda} \varepsilon_y^0 x; \\ & \sigma_x = \sigma_x^{(0)} = -\frac{\lambda^2 - (kh + 2\mu + \lambda)(2\mu + \lambda)}{\lambda} \varepsilon_y^0; \\ & \sigma_y = \sigma_y^{(0)} = -kh\varepsilon_y^0; \qquad \tau = \tau^{(0)} = 0. \end{aligned} \tag{4}$$

If the functions that are the solution of problems (1)–(3), depend continuously[1] on $f(x)$ for $f(x) = f_0(x) \equiv 0$, then we obtain that, when there is a small difference in the unloaded state between the cross-sectional shape of the strip and a rectangle ($|f(x)| \ll h$), the stress-strain state after loading is close to (4). In particular, the shape of the cross-section of the strip remains close to rectangular.

2. The study of continuous dependence. Let us determine the conditions under which the solutions of problems (1)–(3) continuously depend on $f(x)$ for $f(x) \equiv 0$. To do this, as shown in [7, 8], it is necessary to compose the following problem regarding auxiliary functionsit is necessary to compose the following task regarding auxiliary functions which are indicated by a prime:

$$\begin{aligned} & \frac{\partial \sigma_x'}{\partial x} + \frac{\partial \tau'}{\partial y} = 0, \qquad \frac{\partial \sigma_y'}{\partial y} + \frac{\partial \tau'}{\partial x} = 0, \\ & \sigma_x' = \lambda\theta' + 2\mu \frac{\partial u'}{\partial x}, \qquad \sigma_y' = \lambda\theta' + 2\mu \frac{\partial v'}{\partial y}, \\ & \tau' = \mu\Big(\frac{\partial v'}{\partial x} + \frac{\partial u'}{\partial y}\Big), \quad \theta' = \frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y}; \end{aligned} \tag{5}$$

[1]By the continuous dependence of the solution of the original problem on $f(x)$ it is meant here that the solution found for $f(x)$ from a sufficiently small neighborhood of $f_0(x)$, will differ little from the one corresponding to the given $f_0(x)$ [10, the result arising from the implicit function theorem; p. 492]. In this paper we consider the case when $f_0(x) \equiv 0$.

$$\begin{aligned}&(\tau_n^0+\tau_n')\big|_{y=g_i^0(x)+g_i'(x)}=0,\\&(\sigma_n^0+\sigma_n')\big|_{y=g_i^0(x)+g_i'(x)}=k\big(v^0(\bar\varphi_i^0+\bar\varphi'_i,h)+v'(\bar\varphi_i^0+\bar\varphi'_i,h)\big),\quad i=1,2;\end{aligned}\tag{6}$$

$$\begin{aligned}&\int_{\eta_1^0+\eta_1'}^{\eta_2^0+\eta_2'}(\sigma_x^0+\sigma_x')dy=\int_{\eta_3^0+\eta_3'}^{\eta_4^0+\eta_4'}(\sigma_x^0+\sigma_x')dy=-2ph,\\&\int_{\eta_1^0+\eta_1'}^{\eta_2^0+\eta_2'}(\sigma_x^0+\sigma_x')ydy=\int_{\eta_3^0+\eta_3'}^{\eta_4^0+\eta_4'}(\sigma_x^0+\sigma_x')ydy=0,\\&\int_{\xi_1^0}^{\xi_2^0}(v^0+v')dy=\int_{\xi_3^0}^{\xi_4^0}(v^0+v')dy=0,\end{aligned}\tag{7}$$

where

$$\begin{aligned}&g_1^0=(1+\varepsilon_y^0)h, && g_2^0=-(1+\varepsilon_y^0)h;\\&\bar\varphi_1^0=\bar\varphi_2^0=\frac{x}{1+\varepsilon_x^0};\\&\bar\varphi'_1=u'\Big(\frac{x}{1+\varepsilon_x^0},+h\Big), && \bar\varphi'_2=u'\Big(\frac{x}{1+\varepsilon_x^0},-h\Big);\\&g_1'=v'\Big(\frac{x}{1+\varepsilon_x^0},h\Big), && g_2'=v'\Big(\frac{x}{1+\varepsilon_x^0},-h\Big);\\&q_1'=u'\Big(l,\frac{y}{1+\varepsilon_y^0}\Big), && q_2'=u'\Big(-l,\frac{y}{1+\varepsilon_y^0}\Big);\\&\xi_1^0=-h,\quad \xi_2^0=h, && \xi_3^0=-h,\quad \xi_4^0=h;\\&\eta_1^0=-h+v^0(l,-h), && \eta_2^0=h+v^0(l,h),\\&\eta_3^0=-h+v^0(-l,-h), && \eta_4^0=h+v^0(-l,h);\\&\eta_1'=v'(l,-h), && \eta_2'=v'(l,h),\\&\eta_3'=v'(-l,-h), && \eta_4'=v'(-l,h).\end{aligned}\tag{8}$$

For the solution of the original problem to depend continuously on the function $f(x)$ for $f(x)\equiv 0$ it is necessary that the homogeneous problem corresponding to linearized (5)–(8), admits only a trivial solution [8, 11]. It is quite difficult to conduct research on the general case; therefore we will consider a case that often occurs in practice when $p/\mu\ll 1$. Then the deformations will also be small ($|\varepsilon_y^0|\ll 1$, $|\varepsilon_x^0|\ll 1$).

This allows the linearized boundary conditions [11], corresponding to (6) and (7), to replace by the following approximate ones (here, it is already taken into account that (4) is the solution of the problem (1)–(3) for $f(x)=0$):

for $y=\pm h$:

$$\tau'-(\sigma_x^{(0)}+\sigma_y^{(0)})\frac{\partial v'}{\partial x}=\sigma_y'+kv'=0;\tag{9}$$

for $x=\pm l$:

$$\begin{aligned}&\sigma_x^{(0)}h\big(v'(x,h)+v'(x,-h)\big)\int_{-h}^{h}(\sigma_x'(x,y)ydy=0,\\&\big(v'(x,h)-v'(x,-h)\big)\int_{-h}^{h}(\sigma_x'(x,y)dy=0,\\&\int_{-h}^{h}v'(x,y)ydy=0.\end{aligned}\tag{10}$$

The general solution of the system of equations from (5) is presented in the form [2]

$$u' = q(\eta)\cos ax, \quad v' = r(\eta)\sin ax, \quad \eta = ay. \tag{11}$$

As a result of substituting (11) into (5), we obtained a system for finding unknown functions $q(\eta)$, $r(\eta)$:

$$\mu\frac{d^2q}{d\eta^2} - (\lambda+2\mu)q + (\lambda+\mu)\frac{dr}{d\eta} = 0, \quad (\lambda+2\mu)\frac{d^2r}{d\eta^2} - \mu r - (\lambda+\mu)\frac{dq}{d\eta} = 0.$$

From here we obtain

$$q(\eta) = C_1 \operatorname{ch}\eta + C_2 \operatorname{sh}\eta + C_3\eta\operatorname{ch}\eta + C_4\eta\operatorname{sh}\eta,$$
$$r(\eta) = (C_2 - a_1C_3)\operatorname{ch}\eta + (C_1 - a_1C_4)\operatorname{sh}\eta + C_1\eta\operatorname{ch}\eta + C_3\eta\operatorname{sh}\eta,$$

where $a_1 = (\lambda+3\mu)/(\lambda+\mu)$; C_1, C_2, C_3, C_4 are arbitrary constants.

From (5) and (11) follows

$$\sigma_x' = a\Big(\lambda\frac{dr}{d\eta} - (\lambda+2\mu)q\Big)\sin ax.$$

Then the boundary conditions (10) are satisfied when $a = \pi n/l$. For other unknowns we obtain

$$\begin{aligned} \sigma_y' &= a\Big((\lambda+2\mu)\frac{dr}{d\eta} - \lambda q\Big)\sin ax, \\ \tau' &= a\mu\Big(\frac{dq}{d\eta} + r\Big)\cos ax. \end{aligned} \tag{12}$$

As a result of substituting (11), (12) into the boundary conditions (9) we obtain the following system of equations:

$$\begin{aligned} \alpha_{11}C_1 + \alpha_{12}C_2 + \alpha_{13}C_3 + \alpha_{14}C_4 &= 0, \\ -\alpha_{11}C_1 + \alpha_{12}C_2 + \alpha_{13}C_3 - \alpha_{14}C_4 &= 0, \\ \alpha_{31}C_1 + \alpha_{32}C_2 + \alpha_{33}C_3 + \alpha_{34}C_4 &= 0, \\ \alpha_{41}C_1 + \alpha_{42}C_2 + \alpha_{43}C_3 + \alpha_{44}C_4 &= 0; \end{aligned} \tag{13}$$

$$\begin{aligned}
&\alpha_{11} = (2\mu - \sigma_x^{(0)} - \sigma_y^{(0)})\operatorname{sh}\beta, \qquad \alpha_{12} = (2\mu - \sigma_x^{(0)} - \sigma_y^{(0)})\operatorname{ch}\beta, \\
&\alpha_{13} = \big(1 + a_1(1+\sigma_x^{(0)} + \sigma_y^{(0)})\big)\operatorname{ch}\beta + \beta(1 - \sigma_x^{(0)} - \sigma_y^{(0)})\operatorname{sh}\beta, \\
&\alpha_{14} = (1 - \sigma_x^{(0)} - \sigma_y^{(0)})\operatorname{ch}\beta + \big(1 - a_1(\sigma_x^{(0)} + \sigma_y^{(0)})\big)\operatorname{sh}\beta, \\
&\alpha_{31} = 2\mu\operatorname{ch}\beta + \frac{k}{a}\operatorname{sh}\beta, \qquad \alpha_{32} = 2\mu\operatorname{sh}\beta + \frac{k}{a}\operatorname{ch}\beta, \\
&\alpha_{33} = \Big((\lambda+2\mu)(1-a_1) + \beta\frac{k}{a}\Big)\operatorname{sh}\beta + \Big(2\mu\beta - a_1\frac{k}{a}\Big)\operatorname{ch}\beta, \\
&\alpha_{34} = \Big((\lambda+2\mu)(1-a_1) + \beta\frac{k}{a}\Big)\operatorname{ch}\beta + \Big(2\mu\beta - a_1\frac{k}{a}\Big)\operatorname{sh}\beta, \\
&\alpha_{41} = 2\mu\operatorname{ch}\beta - \frac{k}{a}\operatorname{sh}\beta, \qquad \alpha_{42} = -2\mu\operatorname{sh}\beta + \frac{k}{a}\operatorname{ch}\beta, \\
&\alpha_{43} = \Big(-(\lambda+2\mu)(1-a_1) + \beta\frac{k}{a}\Big)\operatorname{sh}\beta - \Big(2\mu\beta + a_1\frac{k}{a}\Big)\operatorname{ch}\beta, \\
&\alpha_{44} = \Big((\lambda+2\mu)(1-a_1) - \beta\frac{k}{a}\Big)\operatorname{ch}\beta + \Big(2\mu\beta + a_1\frac{k}{a}\Big)\operatorname{sh}\beta,
\end{aligned} \tag{14}$$

where $\beta = ah$.

From (13) and (14) we have a relation that, when satisfied, the problem (5), (9), (10) has a non-trivial solution:

$$\begin{vmatrix} \alpha_{13} & \alpha_{33} \\ \alpha_{12} & \alpha_{32} \end{vmatrix} \cdot \begin{vmatrix} \alpha_{11} & \alpha_{14} \\ \alpha_{41} & \alpha_{44} \end{vmatrix} + \begin{vmatrix} \alpha_{12} & \alpha_{42} \\ \alpha_{13} & \alpha_{43} \end{vmatrix} \cdot \begin{vmatrix} \alpha_{11} & \alpha_{14} \\ \alpha_{31} & \alpha_{34} \end{vmatrix} = 0. \tag{15}$$

Conclusions. Equation (15) is the equation of a curve at the points where the continuous dependence of the solution of the original problems (1)–(3) on $f(x)$ is violated when $f(x) \equiv 0$. In particular, (15) determines the critical values of the external action parameter p and the stiffness parameter of the foundation k. On the plane of these parameters, equation (15) sets a statically special curve when crossing by the loading trajectory, in which the shape of the cross-section will no longer be close to rectangular (the strip loses stability).

Competing interests. We declare that we have no conflict of interest regarding the authorship and publication of this article.

Authors' contributions and responsibilities. N.V. Minaeva: Idea of study; Formulation of research objectives; Analysis of research results; Writing — review & editing. Yu.I. Skalko: Mathematical modeling of deformation of an elastically supported strip, loaded with compressive forces on the side edges, for which it is impossible to establish exact boundary conditions for normal stresses; Processing and analysis of modeling results. V.S. Safronov: Interpretation of the obtained results; Writing — review & editing. S.Yu. Gridnev: Continuous dependence study; Interpretation of results; Writing — review & editing. E.E. Alexandrova: Conducting research using symbolic mathematics packages; Writing — review & editing. The authors are fully responsible for submitting the final manuscript for printing. The final version of the manuscript has been approved by all authors.

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Исследование напряженно-деформированного состояния упругоподкрепленной сжатой полосы*

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Аннотация

Проведен анализ непрерывной зависимости функции, описывающей поведение реальной конструкции, от характеристик начальных несовершенств. Получено условие, накладываемое на параметр внешнего воздействия и коэффициент жесткости основания, при нарушении которого форма поперечного сечения полосы уже не будет близкой к прямоугольнику, т.е. полоса теряет устойчивость формы. При проведении исследования параметры внешних воздействий оставались независимыми.

Ключевые слова: упругая полоса, упругое подкрепление, непрерывная зависимость, устойчивость.

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Авторский вклад и ответственность. Н.В. Минаева — идея исследования; постановка задач исследования; анализ результатов исследований; работа с переработанным вариантом рукописи. Ю.И. Скалько — математическое моделирование деформирование упругоподкрепленной полосы, нагруженной по боковым кромкам сжимающими усилиями, при которых невозможна постановка точных граничных условий для нормальных напряжений; обработка и анализ результатов моделирования. В.С. Сафронов — интерпретация полученных результатов; подготовка первичного варианта рукописи; работа с черновиком и переработанным вариантом рукописи. С.Ю. Гриднев — исследование непрерывной зависимости; интерпретация результатов; работа с черновиком и переработанным вариантом рукописи. Е.Е. Александрова — проведение исследований с использованием пакетов символьной математики; обработка и анализ результатов моделирования; работа с переработанным вариантом рукописи. Авторы несут полную ответственность за предоставление окончательной рукописи в печать. Окончательная версия рукописи была одобрена всеми авторами.

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