Strength analysis of a cutting kinked curve plate with clamped free edges of a chisel type deep tiller

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Abstract. Currently existing chisel type deep tillers have a number of disadvantages. The authors propose a research of the strength of a deformer system element of an experimental chisel type deep tiller in the form of kinked plates with clamped-free edges. The present paper analyses the possibility of lengthening of the horizontal elements of the deep tiller shank deformer system without loss of their strength and significant change in their thickness. A mathematical model of a thin elastic homogeneous isotropic plate with clamped-free edges was used. A modified model of the kinked plate is proposed, which has not been investigated earlier. The presented problem is solved numerically. Calculation is performed in the first approximation for the stress-strain state of two isotropic fixed kinked plates with clamped medial edges, symmetrically fixed on a vertical shank, set obliquely to the vertical axis, having equal stiffness and constant cross-section along the entire length (volume objective). It is found that the reduction of the actual plate thickness by more than 1/3 of the design thickness is the most dangerous case. This result leads to failure of a separate fragment of the kinked plate. The proposed thickness of 2 mm does not immediately result in failure of a separate fragment of the part. The plate of the investigated form, made of C255 grade steel, will not provide sufficient strength of the part and its fixing on the deep tiller’s shank. The paper proves the possibility of using kinked plates of the given shape having a variable thickness profile.

1. Introduction

Deep tillers exist in a vast variety of designs today. For example, these designs include inclined shanks, as well as inclined shanks with cutting elements attached to them – chisel type deep tillers. A known type is also featuring soil disrupters with a closed contour as a system of straining deformers - volumetric deep tillers. Such soil disrupters are characterized by working width up to 3 m and ripping depth, mainly up to 0.5 m, rarely up to 0.6 m (deep tiller of a volumetric type - up to 0.8 m). As the working width increases, the number of shanks increases too, thus significantly increasing the weight of the tool assembly. This increases traction resistance [1–3].

In an effort to increase working width, depth and tillage quality, existing devices are becoming more complex, whereby their reliability is decreasing. These soil tillage mechanical systems are mostly over-energetic. In addition, it must be taken into account that the possibilities of deep tillage of soil up to a depth of 50 cm or more are limited by environment of their application. If the working width of a
mounted deep tiller is to be increased without adding shanks, the horizontal elements of the deformer systems, positioned on the depth of 30 cm and more, have to be lengthened. This change in the geometry of horizontal elements of the deformer system leads to a loss of their strength. To avoid excessive profile thickness and arrangement of additional reinforcing stiffness ribs, we create horizontal elements of the chisel type deep tiller deformer system in the form of a plate with a given curvature. Consequently, we assume that such kinked curvature serves as a stiffness rib and produces more deformations when passing through the cultivated layer, and therefore, we arrive at increased quality of soil crumbling. In this case, there is a need to study such modified elements of the deformer systems in deep tillers, representing them in the form of kinked plates of a non-smooth profile [4].

2. Materials and methods

Many authors have studied mathematical models of thin elastic homogeneous isotropic plates with clamped-free edges. There is a known method of solving the elasticity of plates with pinched edges by N.I. Muskhelishvili, the solution of which is equivalent to the first basic plane problem of the theory of elasticity. M.V. Sukhoterin carried out the closest studies for the case of a cantilever plate, and by K.O. Lomteva [5]. In her work, she considers a rectangular plate with plane dimensions $a \times 2b$, constant thickness $h$, loaded with uniform pressure of intensity $q_0$ (Figure 1), clamped at all edges. Assuming that the plate has a stiffener rib located in the middle of the plate parallel to the OX axis. The stiffener rib and the plate can be made of different materials. $E_r I_r$ is the stiffness of the rib, where $E_r$ is the Young’s modulus of the rib material; $I_r$ is the moment of inertia of the rib section. Based on this, the plate has a stiffness jump along the line $Y = b$, i.e. heterogeneous structure.

![Figure 1. Rectangular plate $a \times 2b$, clamped on all edges, with the central stiffness rib](image)

To simplify the computational model, instead of the whole plate, it is allowed to study its half – let us mentally conduct a section along the stiffening rib and consider the lower part. On this axis, let us put the condition of absence of angular deflection and generalized shearing forces (conjugation conditions). The differential equation of bending in relative coordinates is as follows:

$$\nabla^2 \nabla^2 W = -q/D.$$  

(1)

It can also be represented in dimensionless form through the relative deflection $w$. Hence, a mathematical model of the problem is formulated: to find the function $w(x,y)$, satisfying the differential bending equation:

$$\nabla^2 \nabla^2 W = -1;$$  

(2)

and boundary conditions:
\[ w|_{y=0} = 0; \quad \frac{\partial w}{\partial y} |_{y=0} = 0; \]

\[ w|_{x=\pm \frac{y}{2}} = 0; \quad \frac{\partial w}{\partial x} |_{x=\pm \frac{y}{2}} = 0; \]

\[ \frac{\partial w}{\partial y} |_{y=1} = 0; \quad V^*_y = -\left(\frac{\partial^4 w}{\partial y^4} + (2 - \nu) \frac{\partial^3 w}{\partial x^2 \partial y^2} + \frac{1}{2} \frac{E^3}{\nu} \frac{\partial^4 w}{\partial x^4}\right) |_{y=1} = 0. \]

where: \( \nabla^2 \) is two-dimensional Laplace operator;
\( w = \frac{WD}{q_0 h^4} \) is a differential deflection of the plate;
\( W \) is the absolute deflection of the plate;
\( q_0 \) is the uniform transverse load;
\( D = \frac{E h^3}{12 (1 - \nu^2)} \) is the cylindrical stiffness of the plate material;
\( E \) is the Young’s modulus of the plate material;
\( \nu \) is the Poisson’s ratio;
\( G = \frac{1}{2} \frac{E h^4}{E^3} \) is the relative stiffness of the rib half.

The bending equation (1) is the Germain-Lagrange equation:
\[ \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial x^4} = \frac{q}{D}, \]
written in dimensionless form. Boundary conditions (2) and (3) express the conditions for the absence of deflections of the clamped edges and their rotation angles. Conditions (4) are conjugation conditions: the rotation angles of the section along the rib axis and the generalized shearing forces \( V^*_y \) must be equal to zero. The second condition (4) is essentially a bending equation of the beam bending, for which the transverse load is the shear force from the side of the plate. However, the last condition contains the fourth derivative of the deflection, and this leads to certain difficulties in constructing the solution and obtaining numerical results [5]. But in our formulation, the problem acquires a more particular case, which has not been investigated previously.

Let us carry out a refined calculation: how the strength characteristics of tilling horizontal elements of the deformer system of the chisel type deep tiller’s shanks will be changed without loss of their strength at 2 mm thick kinked profile plates. Previously, the authors carried out preliminary calculation of the strength of such plates for a thickness of 3 mm.

Let us represent the horizontal parts of the deformer system of a chisel type deep tiller with increased working width as kinked plates having a non-planar inflection of the profile at an angle of 90°, symmetrically located on the lateral free edges of the plates. Consequently, we formulate a problem for calculating by numerical method the stress-strain state of isotropic plates of a non-smooth kinked profile with an inflection on the outer edge, with only the medial edges clamped, symmetrically mounted on a vertical shank, arranged obliquely to the vertical axis, with equal stiffness and constant cross-section along the entire length (volumetric problem). Modern methods and solutions have not been fully applied to our statement of the problem previously.

![Figure 2. General view and arrangement of kinked plates](image-url)
The shape of the kinked plates under study is shown in Figure 2 (assuming that the angle $\theta=45^\circ$). To estimate the strength criteria from the ratio between width and the optimum thickness of inclined steel plates of finite dimensions, kinked profile, with rigidly jammed medial edges, constant cross-section, and equal rigidity (Figure 1). For this purpose, the Structure CAD (SCAD) software package was used. Finite-element modeling with respect to static and dynamic loads was performed. In the formulation of a numerical calculation, the primary aim was to establish the adequacy of a solid-state model of the stress-strain state of isotropic kinky-angled inclined steel plates of constant section with a rigid restraint on the medial part. As a result, various stress-strain states of inclined isotropic plates have been calculated. They have a kinked profile of constant section and are symmetrically arranged on the shank - clamping of the medial parts. The plates have equal stiffness at a thickness of 2 mm, the value of which depends on their strength properties under standard working conditions in the elastic zone of the material.

![Figure 3. Finite element model](image)

The calculation of the stress-strain state assumed the construction of an adequate calculation model at various operating parameters. The number of elements and the number of ensemble nodes is 104 and 132, respectively. Coding of initial information was performed in terms of the incremental method taking into account fragmental representation of kinked plates in the form of objects of a simple geometric form - plates (see figure 3).

In the formulation of the numerical calculation of the pipeline without characteristic defects, the aim was to establish the adequacy of the solid model of the stress-strain state of kinked plates at the maximum head (the resistance of the tilled soil layer) [4, 6].

3. Results and Discussion
Processing of the obtained simulation results showed an increase in deformations by 1.5 - 2 times: relative to X axis (figure 4), relative to Y axis (Figure 5) and relative to Z axis (figure 6) in comparison with the previous study of 2 mm thick kinked plates. Specifically, the appearance of the strain diagrams and the values of arising stresses on figures 5 and 6 are almost identical. At the same time, the obtained values do not overlap the strength reserve of the kinked plates of the investigated shape, without taking into account the rheological resistance properties of the plate material.
The biggest deformations occur in the horizontal parts of the kinked plates, since, in general, they work as a beam, rigidly fixed cantilevered beam and have a bending deflection with an upward direction. There is also an increase in deformations in the plate fracture area; there is a pattern of total deformations as at torsion (Figure 5).

On the total strain diagram (figure 7) the limit values in the places of attachment to the shank of the plate deflection along the length are obtained. From the results obtained it can be seen that inward compression of the sides occurs, as in the study of 3 mm thick kinked plates of this shape. However, in all presented cases (Figures 4 - 7) the strain values in the vertical part of the kinked plates are not changed significantly, compared to the 3 mm thick plates. Consequently, there is an opportunity to investigate a kinked plate with a variable cross-section - the horizontal part is 3.5 mm and the vertical part is 2 mm.
Based on the results of numerical experiments, typical zones of the plate, which may contain the same types of characteristic damage, have been identified. This makes it possible to model the finite dimensions of kinked plates with optimal thickness of the investigated form, providing strength during the subsequent full-scale studies.

4. Conclusion
As a result of preliminary analysis, the stress-strain state of inclined steel plates of finite dimensions, kinked profile is considered. The plates have rigidly clamped medial edges, equal stiffness and constant cross-section along the entire length, under different combinations of loads. The kinked plates are made of C255 grade steel.

From the data obtained, it has been found that:
1) the proposed thickness of 2 mm does not immediately lead to the failure of an individual fragment of the detail;
2) taking into account the rheology of loading influence and material resistance, it is possible to draw a conclusion that the plate of the investigated shape will not provide sufficient durability of a detail and its fastening on a shank of the deep tiller;

3) it is necessary to either change the steel grade of kinked plates with the aim of a threefold increase in material strength or to increase the thickness of such kinked plates not less than 3.5 mm in further research;

4) it is possible to use the kinked plates of this form with variable thickness profile - horizontal part not less than 3.5 mm and vertical part not less than 2 mm.

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