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ESTIMATION OF THE LOAD CAPACITY AND THE STRAIN-STRESS STATE OF ROD TRANSPORTERS

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Summary. *In the paper, an analytical study of the stress-strain state of the structural system of the rod conveyor of root harvesting machine with the maximum load arbitrarily distributed on the conveyor belt is performed. Rod conveyors are one of the main nodes for transporting and separating root crops through the technological channel of root harvesting machines, for loading them into a hopper and onto a vehicle. Structurally, they form an endless grid that surrounds the leading and driven sprockets or pulleys and supporting rollers. The entire structure of the conveyor is attached to the frame, which rests on the main frame of the harvesting unit. The shape and parameters of the rod conveyor are chosen depending on the layout of the unit and the required performance. Reasons for wear and failure of rod conveyors: deviation of the belt during operation, intensive wear of the holding elements in the places of their attachment to the traction elements and the traction elements themselves. It was found that the degree of wear of the left and right runs is different, as a confirmation of the unevenness of the load on the belt during operation. The uneven load of the conveyor is caused both by the transported pile of root crops and by the design features of the conveyor itself, in particular, uneven tension of runs, deviations during installation of shafts, installation of sprockets or pulleys, support rollers, etc. External loads acting on structural elements of agricultural machines are variable quantities. This should be taken into account when determining the stress-strain state of structures. It is possible to estimate the stress-strain state of complex structures of root-harvesting machines, their elements, and search for their optimal parameters, provided that the force factors in the sections of the elements are determined under full stress. In this way, it is possible to optimise the designs of such machines in terms of material consumption and work resource. The proposed method makes it possible to estimate the stress-strain state of rod conveyor elements according to operating conditions and the possible ways of their further improvement.*

Key words*: bar conveyor, unevenly distributed load, stress-strain state, dangerous area.*

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Statement of the problem. Analysis of the researches on the wear of working bodies of agricultural machinery and the constructive solutions on increasing of the wear resistance of rod conveyors of root crops harvesting machines shows the necessity of improving the existing designs of rod conveyors. This can be reached by means of creating the mathematic model which would consider the uneven load on the width and length of these transporters as well as the wear of the elements.

Analysis of available research. Many researchers have performed detailed analysis of the constructions and operating conditions of rod conveyors. The main parameters of the constructions of rod conveyors intended for cleaning root crops from the soil are substantiated. The design parameters of both the conveyors themselves and their drives are determined; the interaxial distances, number of teeth of the drive sprockets, shafts rotation ratio, angle of inclination to the horizon, pitch and height of scrapers, the distance between the rods, web speed are justified. Most of these parameters were set based on the conditions of the maximum capacity of the conveyor, minimal damage to root crops and normal transportation of the pile. There are researches on determining the productivity of rod conveyors depending on the yield of roots or leaves. The conditions of scattering of root crops when they drop from the conveyor are considered. The interaction of root crops with scrapers to ensure their separation from the canvas during

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transportation has been studied in order to intensify cleaning. The interaction of root crops with each other during their transportation by the conveyor belt is theoretically substantiated in order to reduce possible injuries, etc. [2, 8, 15]. Rod conveyors for which the impulse load was simulated in order to take into account the unevenness of its loading by root crops and to consider the wear of its elements, were studied [14]. In the available researches which deal with justification and selection of the main parameters of the designs of rod conveyors-cleaners, the load on the conveyor was not considered simultaneously from the entire pile. Unevenness of its load with root crops or leaves along its length or width was not taken into account.

Objectives of the research is to create the mathematic model which would take into account the unevenness of the load on the rod conveyor web, i.e. simultaneously on the whole pile, and to determine the most loaded cross-sections for further improvement of the design of such conveyors.

Formulation of the problem. To evaluate the stress-strain state of structures of rod conveyors of root crops harvesting machines and their elements in order to find their optimal parameters. This is achievable provided that the force factors in the cross-sections of the elements are determined under the full stress state. Thanks to the obtained results, it is possible to optimise the designs of the conveyors of such machines in terms of material capacity and work resource.

Reliability of the process of digging up root crops depends on the durability of individual elements and assembly units of harvesting machines, for this it is important to know the real state of load of the working bodies of such machines. Based on the study of the stress-strain state of the elements of individual units of machines, it is possible to improve their designs.

Results of the research. One of the main parts for transporting and separating root crops (beetroot, potato, etc.) and leaves inside root and sprout harvesting machines, for loading them into a hopper, onto a vehicle are rod conveyors. They are made of steel rods installed with a certain step and attached to flexible elements: sleeve-roller chains or rubber belts. Structurally, they form an endless grid that surrounds the leading and driven sprockets or pulleys and supporting drums. To maintain the transported mass, finger scrapers are installed on the belts at a certain distance. The entire structure of the conveyor is attached to the frame, which rests on the main frame of the harvesting unit. The transported mass is cleaned by sieving through bars. The shape and parameters of the rod conveyor are selected depending on the layout of the unit and the required performance [2, 8, 16].

Advantages of rod conveyors: simple and cheap design, high transport capacity, the possibility of moving the pile at an angle and over a considerable distance, high-quality implementation of the technological process of root cleaning on sandy soils. Disadvantages: a large number of moving structural elements, inability to separate strong soil clods from the roots, poor cleaning quality on clay soils, low reliability due to rapid wear of the friction parts of the joining elements.

From the analysis of the operating conditions of rod conveyors [2, 8, 15, 16], the causes of failures and their failure were determined: warping of the belt during operation, intensive wear of the holding elements in the places of their attachment to the traction elements and the traction elements themselves. It was found that the degree of wear of the left and right runs is different, as a proof of unevenness of the load on the belt during operation.

The load on the belt of rod conveyors is caused by the transported pile of root crops, which is a mechanical mixture of root crops and soil, that enters the working surface of the conveyor together with leaves and plant residues, or without them, depending on the harvesting technology. Physical and mechanical properties of pile components are characterized by the following indicators: rolling and sliding friction coefficients, various geometric parameters, density, stiffness, breaking force, critical fall speed at which mass damage occurs, etc. [2, 10, 16].

The change in parameters characterizing the pile is caused by soil and climatic conditions, the variety of root crops, phases of development, degree of their rapeness, and the methods of agricultural technology. The size and shape of the roots depend on the crop, temperature and water conditions during the growth period, soil type, etc. At the time of harvesting sugar beets, the mass of root crops is 400–600 g, the average yield is 65 t/ha, the diameter of root crops is within 40–180 mm, the average root crops are 90–110 mm; technical length of roots is 80–370 mm, average values are 220–250 mm; leaves is mainly 30–40% of the mass of the plant; the length of the bunch of leaves is 250–600 mm, average values are 350–400 mm, under favorable conditions the yield of leaves exceeds the yield of roots, the bulk density of the collected leaves is 190–210 kg/m3 [10, 12, 13].

During technological process, the conveyor belt is subjected to loads from root crops, soil clods, plant remains that fall onto the conveyor together with root crops (Fig. 1).

The load from one layer of transported mass of root crops per unit area of the rod cleaner is assumed to be 300–500 N [14, 16].

The reasons for the unevenness of the load of rod conveyors are directly related to changes in both external and internal influences. The higher the percentage of soil moisture, the more sticky soil remains on the roots, the higher the soil hardness and moisture, the higher the percentage of soil clods (loose soil) in the collected pile. These factors have a direct impact on the formation of load unevenness of rod conveyors. With a high yield and favorable soil conditions, the load of the conveyor from external factors will approach a uniform one. The greater the range of the yield difference and the higher the coefficient of variation, the greater the unevenness of the load on the conveyor, especially along its width. All this causes the greatest impact on the forces arising in the traction elements of the conveyor itself [2, 8, 10, 14, 15, 16].

The unevenness of the conveyor load is caused both by the transported mass and by the design features of the conveyor itself, in particular, uneven tension of the runs, deviations during the installation of shafts, installation of sprockets or pulleys, support drums.

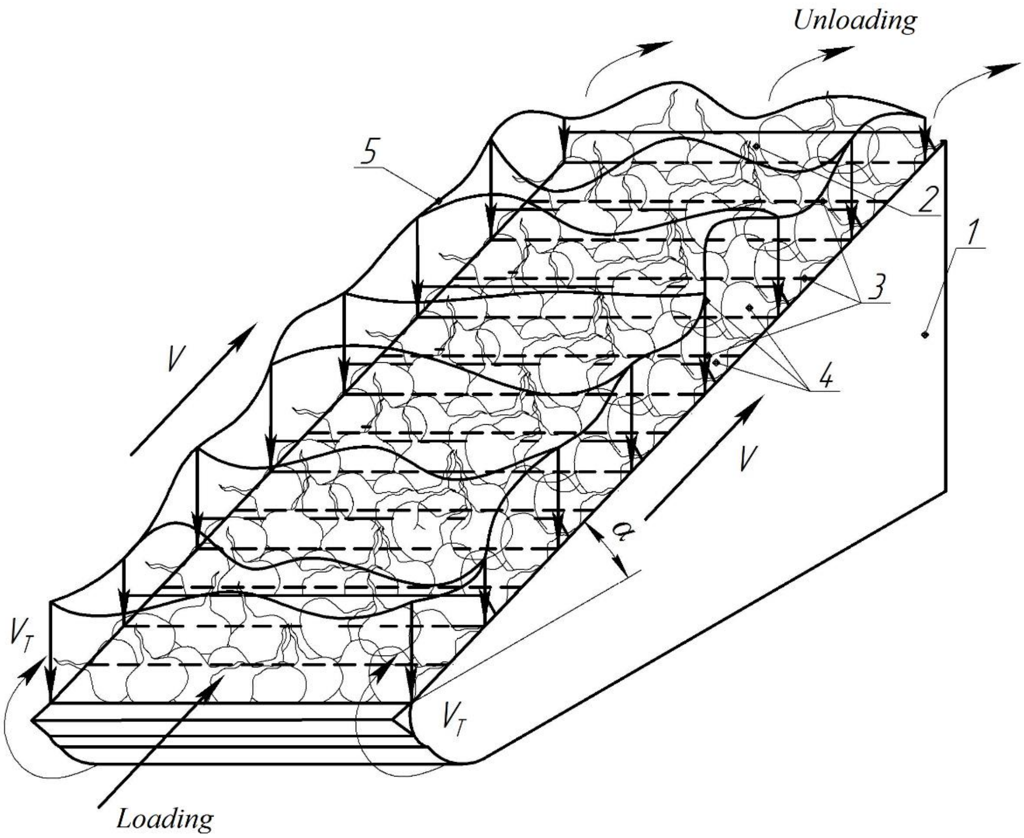


Figure 1. Schematization of the calculation model of the conveyor belt load 1 – frame; 2 – scraper; 3 – rod; 4 – root crops; 5 – load on the canvas $q(S)$

For the study, we will choose a longitudinal conveyor with scrapers with the length 2.4 m, width 0.9 m, the angle of inclination of the conveyor to the horizon 550, the step between the sections of the bars on which the scrapers are fixed 0.3 m, the linear speed of the conveyor 1.14 m/s, the number of rows collected by the machine in one pass is 6, the row width is 45 cm [2, 8, 14, 15].

In case of loading the middle part of the conveyor with the mass of roots, provided that the necessary requirements are met when installing the conveyor, its traction elements will be loaded equally, that is, the forces will be equal to half of the external weight. Let us assume for these conditions a parabolic shape of the load (Fig. 2 a, c). When the transported mass is displaced from the middle part of the conveyor, which happens in most cases, the forces arising in the traction elements are redistributed. In case when installation is not sufficiently accurate, this leads to their significant wear, moreover, the left and right runs wear differently. The unevenness of the forces on the supports leads to uneven wear of the runs of the traction elements of the conveyor and, subsequently, to distortion of the belt. Skews are the main drawback in the operation of such conveyors, which causes a significant change in the nature of their load. For such a case, we will assume a triangular shape of the load (Fig. 2 b).

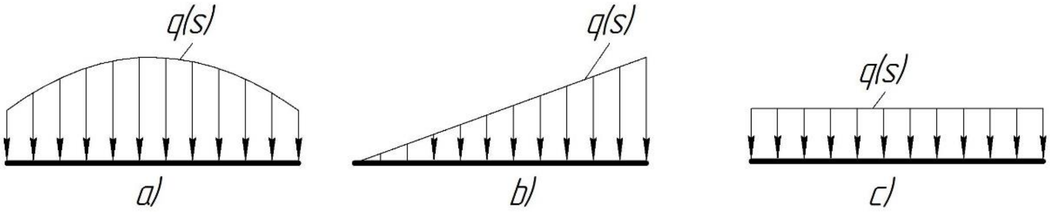
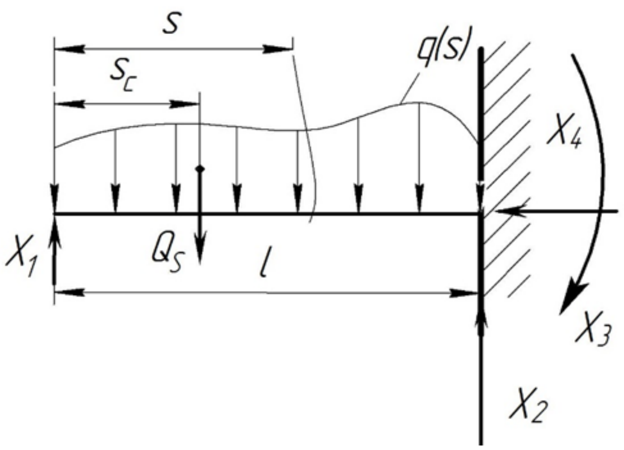


Figure 2. Characteristic diagrams of the distribution of external loads on the belt of belt conveyor

Since the kinematics of root crops transportation by rod conveyors is of repeated-periodic character, the unevenly distributed load in the transverse-longitudinal plane on the conveyor belt presented in the form of a parabolic or triangular shape will approximate the real load conditions of such a conveyor. Load types can replace each other during the operation of the harvesting machine depending on external influences and the design features of the conveyor.

Calculation model for the conveyor width, depending on the fastening of holding elements (rods) to the traction elements, is presented with a certain tolerance [11]: fastening on one side is considered a rigid pinch, on the opposite side – one hinged support (Fig. 3).



$q(S)$ – function of the load intensity of the rod conveyor distributed across the width;
S_C – coordinates of the gravity center of the point of application of uniform force Q_S

Figure 3. Schematization of the calculation model by conveyor width

The solution to the problem of determining the internal power factors for such a load scheme will be based on the modification of the minimum potential energy method in combination with the development of a mathematical model that takes into account the unevenness of the distributed load on the conveyor belts, i.e. according to real operating conditions.

The methodology for calculating the structures of rod conveyors of harvesting machines, taking into account the features of fastening their elements under the action of unevenly distributed load, which is based on the modified method of the minimum potential energy of deformation contains [14]: a developed mathematical model that describes the nature of the load of the rigid elements of the conveyor in an arbitrary form, i.e. in the conditions similar to real conveyor load conditions; calculated schemes of rigid elements of the conveyor were built with the approximation of the load to parabolic and triangular shape; expressions of deformation potential energy function for calculation schemes; equations for determining the unknown force factors included in the expressions of the function of the potential energy of deformation; determination of the stress-strain state of conveyor elements in the form of distribution characteristics.

Under the condition of uniform movement of the bar conveyor and its uniform load with the transported pile, the load from the traction elements (belts) to the bars is transferred almost uniformly. In real operation conditions, the parallel runs of the conveyor move unequally due to the deviation of belt lengths, size of rolls (pulleys), difference in belt tension, non-parallelism of the leading and driven shafts, random distribution of the pile of root crops along conveyor width. There are also cases of roots getting stuck on one or the other side of the conveyor, most often the beet root gets stuck between the side of the conveyor and the scraper finger for a short time. All this leads to skewing of the conveyor and a significant change in the load pattern of the belt at the point of connection of the bar with the belt. The load on the rivets is redistributed, which significantly reduces the durability of the conveyor.

The reason is that the conveyor mechanism has «extra» ties, that is, the connection of the rod with the conveyor belts is statically indeterminate. In the process of operation, the conveyor does not self-adjust, so the skewing of the runs leads to an increase in the force at the intersections of the connection of the rod and the belt.

External loads acting on structural elements of agricultural machines are variable quantities. This should be taken into account when determining the stress-strain state of structures.

Classical methods of determining the strain-stress state of complex flat spatially loaded structural systems give significant errors. Therefore, both when calculating frames and when calculating conveyors, it is reasonable to accept certain assumptions, by means of which two problems can be solved. The first is the determination of external power factors, the second is the determination of internal power factors [5, 6]. Solving such problems on PC using well-known application software packages, in which calculation models are built using the finite element method (FEM), is complicated by the ambiguity of specifying an variable external load. This leads to errors in determining the internal force factors in metal structures. The advantages of using FEM compared to traditional numerical methods in determining the strain-stress state of load-bearing machine-building metal structures are the simplicity of algorithmization, the possibility of fully automating the formulation of equations with obtaining results without any combined systems.

The theoretical and experimental studies of root-harvesting machines, various types of screw conveyors and their working bodies [1, 2, 3, 6, 7, 8, 14] showed that it is necessary to conduct a set of researches to establish the optimal parameters of the supporting structures of these machines. An increase in the coefficient of their strength margin leads to an increase in the material intensity of machine structures and their working bodies, which causes an increase in energy consumption for the technological process and other negative consequences.

Since the distribution of root crops on the conveyor belt in most cases is uneven, another model of loading of the rod conveyor belt is proposed [11]. An arbitrary schematization of distribution of external loads on the conveyor belt is shown in Figure 3.

Since the kinematics of root crops transportation is repeated-periodic in nature, the calculation model for the width of the conveyor, that is, for the length of each rod, can be presented as a beam with different fastening of the ends [14, 15]. To determine the internal force factors in all calculation schemes, an assumption is made: the fastening on one side is considered to be a rigid pinch, on the opposite side it is one-hinge support. That is, the jioning of conveyor bars is statically indeterminate.

Complex, statically indeterminate systems lead to certain difficulties in manufacturing technology: compliance with the accuracy of the dimensions of links consisting of several parts, each of which has a certain manufacturing tolerance; connection tolerances, etc. Along with this, the elimination of «extra» ties does not lead to an increase in the transverse displacements of the mechanism. The geometry of the links also changes during the operation of the conveyor due to the settlement of the frame structure, wear and tear and adjustment of the clearance of the kinematic pairs, elastic deformations, etc.

When constructing a statically determined system [9], the distribution of forces and changes in the size of the links do not affect the operation of the mechanism in general. In addition, such mechanisms reduce the complexity of manufacturing, increase reliability in operation, although production costs may be higher.

In order to study the internal force factors and estimate the stress-strain state of the improved rod conveyor, the intensity of distribution of real load across the width of the elementary section of the conveyor belt is shown in Figure 2. The shape of the load is assumed to be close to parabolic (the most loaded middle part is the most likely case during operation), triangular (distortion of the canvas), rectangular (evenly distributed).

The external load from the transported mass of root crops actually has an arbitrary shape. Taking into account the unevenness of distribution, the load on the belts of rod conveyor is described by the dependence [3, 7]

$$Q_S = \int_0^S q(S)\, dS , \tag{1}$$

where Q_S is the equivalent force of the distributed load acting on the conveyor bar (Figure 3), $Q_S = 500$ N.

To determine the internal force factors of a statically indeterminate system, which is the calculation model of the conveyor, we will apply the modified method of the minimum potential energy of deformation of the system [1, 3, 5, 11].

The coordinate of the gravity center of the point of application of uniform force Q_S is determined as follows

$$S_C = S - \frac{\int_0^S q(S) \cdot S\, dS}{\int_0^S q(S)\, dS} . \tag{2}$$

Function of bending moments

$$M(S) = X_1 \cdot S - M_S(q), \tag{3}$$

where $M_S(q)$ is the function of bending moment from the load $q(S)$

$$M_S(q) = Q_S \cdot (S - S_C) = \int_0^S q(S)\, dS \cdot \left\{ S - \frac{\int_0^S q(S) \cdot S \, dS}{\int_0^S q(S)\, dS} \right\}, \tag{4}$$

X_1 is the force in the support fixation;
Q_S is the uniform force of distributed load $q(S)$ which acts at the conveyor part with the length S

$$Q_S = \int_0^S q(S)\, dS \,. \tag{5}$$

Dependence (3) makes it possible to write down the functions for determining the internal force factors for any form of fastening of the supporting elements (rods) of the conveyor belt from an arbitrary external load.

A mathematical model was built, namely, dependencies (1)–(3) taking into account (4), which describes the unevenness of the load on the conveyor belt. When considering it, the change of the unevenly distributed load in the transverse-longitudinal plane is taken into account as a function of the load of an arbitrary shape, which is the closest to the real conditions of the actual load.

We formulate the expression of the potential energy function from the bending deformation for the calculation scheme (see Fig. 3):

$$U(M) = \frac{1}{2EI}\int_0^l [M(S)]^2 \, dS = \frac{1}{2EI}\int_0^l [X_1 \cdot S - M_S(q)]^2 dS \,, \tag{6}$$

where *E* is the modulus of elasticity of the material of the beam;
I is the axial inertia moment of the area of the beam (rod) cross-section.

Considering the statics equations, we obtain:

$$X_1 = \frac{1}{l}\left(Q_S (l - S_C) - X_3\right). \tag{7}$$

Based on Leibniz formula, we differentiate the integral function by the parameter X_3, and set the obtained value to zero [2]:

$$\frac{\partial U}{\partial X_3} = 0 \,. \tag{8}$$

From here we determine the unknown force X_3.

To determine the static uncertainty of complex rod systems, as in the case of rod conveyors, the modified method of the minimum potential energy of deformation is effective, which greatly simplifies the solution of such problems and is conveniently algorithmized. The main advantage of the method is that after putting down the expression of the potential energy of deformation as a function of the sought parameters $U(Q, M, K)$, which has the property of additivity, it is possible to use individual energy components depending on the structural system and its load [3, 5]. Solving the resulting equations, which include the required parameters, is performed using the Wolfram Mathematica 7 software.

Figure 4 shows the characteristics of the distribution of internal force factors for typical distribution schemes of external loads on the belt of belt conveyor.

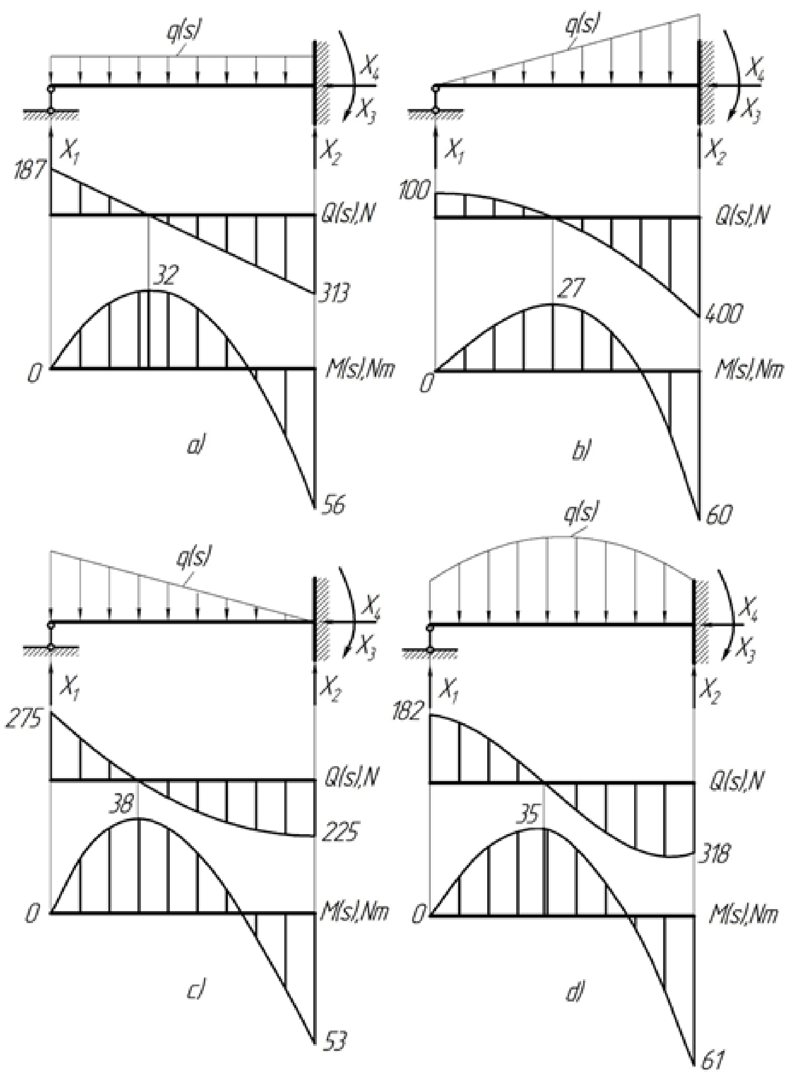


Figure 4. The nature of the distribution of internal force factors for the accepted schemes of external load on the belt of belt conveyor

Conclusions. The proposed method makes it possible to evaluate the stress-strain state of the elements of rod conveyors according to operating conditions with the possibility of further improvement of their designs.

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ОЦІНЮВАННЯ НАВАНТАЖЕНОСТІ ТА НАПРУЖЕНО-ДЕФОРМІВНОГО СТАНУ ПРУТКОВИХ ТРАНСПОРТЕРІВ

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Резюме. *Виконано аналітичне дослідження напружено-деформівного стану конструктивної системи пруткового транспортера коренезбиральної машини з максимальним навантаженням, довільно розподіленим на полотні транспортера. Пруткові транспортери є одними з основних вузлів для* *транспортування й сепарації коренеплодів технологічним руслом коренезбиральних машин для завантаження їх у бункер і на транспортний засіб. Конструктивно вони утворюють нескінченне решітчасте полотно, яке огинає ведучі й ведені зірочки або шківи й підтримуючі ролики. Уся конструкція транспортера кріпиться до рами, яка опирається на основну раму збирального агрегату. Форму і параметри пруткового транспортера вибирають залежно від схеми компонування агрегат й необхідної продуктивності. Причини відмов та виходу з ладу пруткових транспортерів: перекоси полотна під час роботи, інтенсивне зношування тримких елементів у місцях кріплення їх до тягових елементів і самих тяглових елементів. Виявлено, що ступінь зношування лівої і правої гілок різний, як підтвердження нерівномірності навантаження на полотно під час роботи. Нерівномірність навантаження транспортера викликана як транспортованим ворохом коренеплодів, так і особливостями конструкції самого транспортера, зокрема нерівномірним натягом гілок, відхиленнями при монтажі валів, встановленні зірочок чи шківів, опорних роликів та ін. Зовнішні навантаження, що діють на елементи конструкцій сільськогосподарських машин, є змінними величинами. Це потрібно враховувати, визначаючи напружено-деформівний стан конструкцій. Виконати оцінювання напружено-деформівного стану складних конструкцій коренезбиральних машин, їх елементів, та пошуку їх оптимальних параметрів можна за умови визначення силових факторів у перетинах елементів за повним напруженим станом. Цим можна досягти оптимізації конструкцій таких машин за матеріаломісткістю й ресурсом роботи. Запропонована методика дає можливість оцінити напружено-деформівний стан елементів пруткових транспортерів відповідно до умов експлуатації з можливістю подальшого їх удосконалення.*

Ключові слова: *прутковий транспортер, нерівномірнорозподілене навантаження, напружено-деформівний стан, небезпечний перетин.*

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