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MONITORING OF THE ELEMENTS STABILITY OF BUILDING CONSTRUCTIONS BY MEANS OF EXAMPLE OF VERTICAL ELASTIC ROD OF HIGH FLEXIBILITY

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The article is related to the field of geodetic and engineering construction monitoring of building structures in the form of rod systems. It investigates the measurement accuracy of the compression deformation of the rod. As an example, there is considered a vertical rectilinear rod of high flexibility, loaded with a longitudinal axial force. There is explained the accuracy with which it is necessary to measure the displacement of the rod end during the deformation. There is laid out the calculation of the maximum stress deviation based on the stability and flexibility of the rod.

Keywords: vertical rod, deformation, critical stresses, unstable equilibrium, accuracy of measurements, geodetic monitoring.

1. Relevance of the topic

In the structural mechanics, many loadbearing structures of buildings and constructions are considered in the form of rod systems consisting of vertical, horizontal or inclined straight and curvilinear rods interconnected in nodes. The main purpose of the rods is to perceive axial load and bending moment. For example, the rod system is a frame of a high-rise building, bridge design, columns and farms of industrial buildings, towers, watchtowers, etc.

Science of calculation and manufacturing technologies allow to create modern building constructions that can work reliably in certain external conditions under certain external influences. Countermeasure to environment changes and to external influences on the elements is provided by material, size, reserve of strength, stiffness and stability. With increasing of the adverse changes, this may be insufficient. In order to take measures up to time and prevent impending destructions, it is necessary to know which real stress-strain states the structures are in, and if they are far from critical loads and stresses. Conclusion can be done only on the basis of full-scale measurements. Accordingly, geodesic, geotechnical and engineering monitoring are conducted to do this [1].

2. Formulation of the problem

The objective of this article is to show by means of the example of an vertical elastic rod of high flexibility subjected to longitudinal compressive loads, the degree of responsibility and the accuracy needed to conduct geodesic monitoring of building constructions, from the point of view of their stiffness.

3. Analysis of researches and publications

This article discusses the accuracy of measuring the deformation of the compression of the elastic rod, which is a part of the geometrical stable construction. The source [2] estimates the peculiarity of the work of geometrical stability systems statically determinate and statically indeterminate ones for organizing geodesic monitoring of loadbearing structures of buildings. There are defined the tasks of geodesic monitoring of various types of constructions. There are shown the dependences of the a priori calculation of the accuracy on the type of structures, carried out in the monitoring preparation. In the source [4], there was developed the principle of the fundamental calculation of a priori measuring accuracy of the stretching element deformation of the building construction in the form of a vertical rod. In the source [3] there was carried out the calculation of the RMSE measurement (root mean square error) of the deformation of the rod stretching according to parameters depending on the material and on the stresses arising in it under load. There was demonstrated the possibility of measuring the stretching deformation with accuracy obtained from the calculation.

4. Presentation of preliminary material

To ensure reliability, elements of building constructions (EBC) are calculated for strength, stiffness and stability. When calculating stability, it is assumed that the maximum load on the element will not exceed the permissible load, which is determined by the critical load and the stability coefficient [6]. However, if the external load begins to come close to the critical values, the construction elements may lose their stability with all the consequences resulting from here. Stability is the ability of the element to preserve the specified spatial position and the form of equilibrium under external influences.

Load-bearing EBCs are made of steel of various grades, concrete and other materials. For engineering calculations (including those related to our competence), it is necessary to know the mechanical characteristics of the materials used. They are determined experimentally by testing standard samples for tension, compression, bending and torsion [7]. For example, compression tests of short samples are carried out on special machines (presses) that record the magnitude of the compressive force and the magnitude of the absolute shortening of the sample with the help of sensors. The oscilloscope plots the relationship between the applied force F and the absolute deformation Δl. For practical use, a compression diagram is designed by plotting stresses σ and relative deformations L along the coordinate axes.

The compression diagram of plastic materials, for example, low-carbon steel, is similar to the load-elongation diagram that we described in work [4]. At the stage of elastic deformations, the graph lines practically coincide and

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have the same proportionality and elasticity limits, up to the flow stress. The differences begin in the area close to the flow point, but this is already the beginning of large permanent (plastic) deformations, which quickly lead to distructure. The compression diagram of a short rod made of ST3 mild steel is shown in Fig. 1(c).

Line 0-1 shows that the relative compressive strains are directly proportional to the normal stresses arising in the sections of the element due to the application of compressive stress. At the stage of 0-1 elastic deformations according to Hooke's law $L = \sigma/E$. At stage 1-2, the deformations are still elastic, but already nonlinear. Beyond the elastic limit (point 2), the stage of permanent deformations begins, passing into the stage of material flow [6].

A short sample is a rod with the ratio of length to diameter less than 5. Short rods are rods with low flexibility [9]. They fail to operate mainly due to loss of strength, and not loss of stability. However, for many elements of modern structures, the length significantly exceeds the size of the cross-section. Such elements are considered to be relatively long and thin.

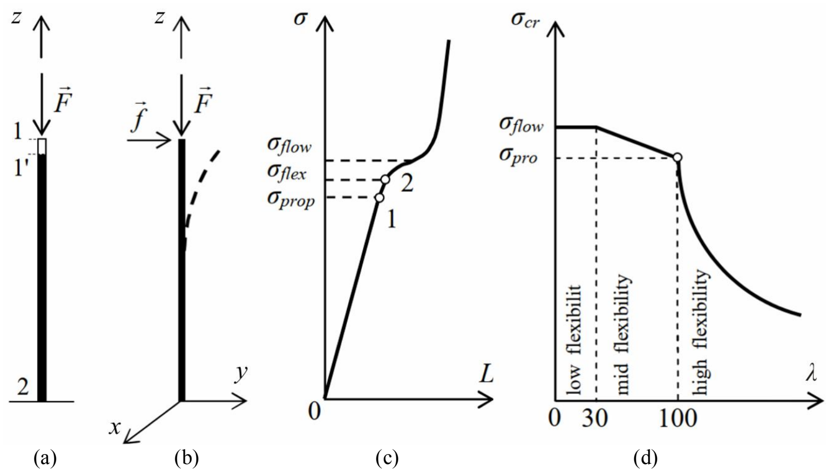

Fig. 1. Stability of the rod: (a) a vertical rod loaded with an axial compressive stress; (b) bifurcation of the equilibrium state of the rod; (c) diagram of the compression of the rod; (d) critical stress diagram

The behavior of long elements under the influence of an axial compressive stress turns out to be fundamentally different from that of short ones. The experience demonstrates that the rod, under the influence of an axial compressive load not exceeding the permissible design values, retains its original form of equilibrium and stability. At the same time, it works in the area of elastic compression deformations. An example is a vertical fixed rod, which has a rectilinear form of equilibrium, loaded with an axial stress, which maintains its stability (Fig. 1(a)).

When the increase of the load reaches some specific values, then it comes to a state of the element when the form of equilibrium becomes unstable, i.e. at any moment, with a slight external influence, it (the form of equilibrium) can turn from rectilinear into curvilinear one. This is followed by large displacements, permanent deformations and finally destruction. There are some possible cases of the element, having lost stability, turning into the mode of sustained oscillations. A danger of loss of stability is meant by its sudden beginning, almost immediately beyond the elastic limit, when the strength of the material is far from being exhausted [8].

There is no need to prove the importance of monitoring when a construction with similar structures is settled, for example, in the zone of development of negative natural and anthropogenic processes. As a result, the load on some elements may increase to critical values due to uneven horizontal and vertical displacement and inclination of the structure, including vibrations, etc. The degree and nature of the development of dangerous exogenous and endogenous processes and their influence on a given spatial position of the structure is determined by the results of geotechnical and geodetic monitoring [1]. At the same time, the complex of engineering and technical measurements should demonstrate, with the necessary completeness, reliability and accuracy of the value, the nature and dynamics of changes in the external load on the elements of the structure, the change in internal forces and stresses in them, the development of deformations (changes in the size and shape of equilibrium).

5. Presentation of the main material

Initially, with the completion of construction, the structure of the construction, all bearing elements, and the entire construction as a whole, must be in a state of elastic equilibrium, which is considered initial at the time tn. The prevailing conditions, external loads, equilibrium of forces and moments of forces, determine their initial stress-strain state (SSS)n and spatial position (shape, dimensions, internal forces and stresses, degree of deformation, etc.), which must meet the calculated values.

During the use of a building, almost every element of the building structure is exposed to the disturbing influences of forces which are external to it, striving lose its initial state of equilibrium. If the disturbing influences are temporary, and the deformations are elastic, then the element returns to the initial state of equilibrium and (SSS)n. If there was a redistribution of the force influence for example as a result of uneven settlement, uneven horizontal displacement, roll, bending or other factors, then the stress-strain state of the elements will change, and at the time tk ,they will be in a new state - (SSS)k.

Let us consider a single element of the building construction - a vertical metal rod operating to compression, which length significantly exceeds its transverse dimensions (long rod). Let’s assume that there is provided in advance a constant monitoring of the deformation and its stress-strain state during the installation and subsequent operation. Therefore, at the first stage, the stage of manufacturing, the ends of the rod are fixed with deformation marks and the length l between them is measured with the RMSE ml (root mean square error). At the second stage - the stage of installation (the stage of the initial loading of the rod), the rod was placed in the designed vertical position ($z1 = l1\text{-}2;\ z2 = 0$) and fixed on a perfectly solid non-deformable foundation (Fig. 1(a)).

We measured the coordinates of points 1 and 2 with accuracy $m_{Z1}=m_{Z2}=m_Z$. Without load, the rod has a zero stress-strain state, i.e. (SSS)0 (excluding its own weight). This state of the bar corresponds to the zero point of the diagram, when there is no load, no stresses and no deformations. Next, a vertical axial load was applied to the rod (the direction of the force vector coincides with the direction of the bar axis), which corresponds to the calculated values, and, on the basis of which, it was calculated for strength, stiffness and stability. The element has acquired elastic deformations, retaining its rectilinear form of equilibrium. In this case, point 2 remained restrained, and point 1 shifted and took position 1'. The coordinate of this point was measured (by the method of engineering geodesy), then $\Delta l = z1 - z1'$ (Δl can be also measured using a strain indicator). Thereby, the rod became a part of the support rod system, having obtained the initial stress-strain state, i.e. at the moment of time *tn*, it is in a stable initial state of equilibrium: under the influence of the calculated axial load, it retains its rectilinear shape, and the stresses in the sections are notably less than the proportionality limit σ_{pr}. And this initial state is fixed by means measuring the initial deformations and initial stresses.

The stresses start to increase if the load starts to increase, i.e. longitudinal compressive force *F*. Deformations start to increase proportionally.

The accuracy with which it is necessary to measure the displacement of the end of the rod during deformation is carried out in the source [4]. There was developed a dependency:

$$m_z = \frac{l}{3\sqrt{2}E}\delta_\sigma , \tag{1}$$

from which it can be seen that the RMSE of the displacement measurement depends on how to choose the extreme deviation of the stress in the sections of the rod made of a certain material. Deviation δ_σ is the limiting error to determine the stresses in the rod, which we can afford, realizing that the accuracy of measuring the displacements of deformation marks will not render possible passing the known limit of elastic deformations. In this work, the choice of δ_σ is done basing on the stability and flexibility of the rod.

It all depends on the magnitude of the external force, and by growing it can lead the rod into the so-called state of indifference. This force is called critical. Being in indifferent state, when ($F = F_{crt}$), two forms of equilibrium are inherent in the rod: rectilinear and curvilinear (bifurcation of equilibrium states) [6, 8]. If the magnitude of the force exceeds the critical value (for the reasons mentioned above), then the equilibrium will become so unstable that even a slight disturbance can cause the rod to bend (Fig. 1(b)). The errors can be such factor, for example the errors in the relative position of the force vector and an element of a building structure, manufacturing errors and others [5]. The increase in the load and the approach of the element to an unstable state must be "seen" by the monitoring system in order to somehow prevent this and destruction. But the deformations in the elements of building structures are small, and the stresses corresponding to them are great, therefore in the monitoring system there must be installed instruments of appropriate high-precision measurements. One of these tools is a preliminary calculation of the required measurement accuracy, which we consider.

The critical force corresponds to the critical stress, which depends on the elastic properties of the material and on the flexibility of the rod [6; 8]:

$$\sigma_{cr} = \frac{\pi^2 E}{\lambda^2}, \tag{2}$$

where λ – rod flexibility parameter.

Each element of a building construction functioning in compression and depending on its geometric and physical values has more or less flexibility. Long rods are more flexible, short ones are less flexible. Accordingly, there is the concept of medium flexibility. There is no clear physical boundary between them, however, it is necessary to know quite definitely when the critical stress occurs at a given flexibility of the rod and then basing on this calculate the accuracy. Fig. 1(d) demonstrates the dependence [6, 8] of critical stresses on the flexibility of the rod, which is known in the strength of materials. The graph shows that if the critical stresses are higher than the proportionality limit, while λ <100, then the rods are considered to be of medium or low flexibility. Medium rods are more stable elements than the long ones, since the ratio of length and transverse dimensions is not so well expressed. For this category of the rods, the critical stresses are between the proportional limit and the flow stress. Short rods, i.e. rods with very little flexibility, when compressed, are destroyed due to loss of strength, and for them the critical stress will be the flow stress (for plastic materials).

If critical stresses arise in the load up to the proportionality limit (inclusive), i.e. $\sigma_{cr} \leq \sigma_{prop}$, then the rods are considered to be of great flexibility. The stability calculation for them is carried out under the condition of linear elastic deformations. In our work, we consider just this kind of rods, since they are sensitive to loss of stability. The graph shows that as the flexibility of the rod increases (λ>100), the level of critical stresses for it decreases, i.e. it can lose stability even in the area of elastic deformations at stresses lower than σ prop.

The critical stress corresponds to the bifurcation state of the rod, i.e. transitional state between stable and unstable equilibrium. From a stable equilibrium the rod passes into indifferent equilibrium and then into an unstable equilibrium. Thus, it is possible to mark a certain state, a certain range of values that precede the critical stress. On this basis, we find the limiting deviation δσ. Let us set the stress interval, which width is

$$k\delta\sigma, \tag{3}$$

where $\delta\sigma = \sigma_{cr} - \sigma l$; σ_l – lower boundary of the interval; $0 < k \leq 1$.

Let us present the length of this interval as the limiting random deviation of stresses, followed by the law of normal distribution. Then, substituting (3) into formula (1), we obtain

$$m_z = \frac{l}{3\sqrt{2}E} k\delta\sigma. \tag{4}$$

Let us consider an example for a 5 m long rod made of steel grade ST3. For the steel ST3 the modulus of elasticity is E =2,1·10^5; proportionality limit σ_{prop}= 200 MPa; elastic limit σ_{el} = 210 MPa; flow stress $\sigma_{f.st}$ = 240 MPa. With the parameter of rod flexibility λ = 100, the critical stress will be at the point of the proportionality limit. Let us take the interval $\delta\sigma$ = 10 MPa and k = 1 [3], then m_z = 0.06 mm.

6. Conclusions

Bearing rod structures of buildings and constructions operating in real conditions differ from "ideal" by their being "distorted" in general by manufacturing and installation errors, incomplete consideration of external influences and other factors. The rod system has sufficient strength and stiffness to resist it and in a deformed state under calculated external loads it has a given form of equilibrium and a state of elastic equilibrium between external and internal forces.

Elastic equilibrium for a given rod system is stable if the increase in the external load does not exceed some limiting values for it and the deformations remain elastic. That is, a structure that has initial deviations in size, geometry, spatial position, which undergoes the increasing of load, leaves the state of equilibrium, but tends to return to its original state.

If the external load reaches the critical values and the system becomes unstable, then errors in the relative position of the system elements can provoke a rapid development of residual deformations and a rapid change in the initial form of equilibrium, up to the destruction of the load-bearing elements.

It follows that special attention should be paid to the accuracy of geodetic and installation works, because of:

- unreasoned errors in the position of elements can play a fatal role, putting the system in an unstable state to destructive changes;
- unreasoned errors in measuring displacements with increasing deformations and stresses will not allow to detect the approach of the system to an unstable stress-strain state.

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МОНІТОРИНГ СТІЙКОСТІ ЕЛЕМЕНТІВ БУДІВЕЛЬНИХ КОНСТРУКЦІЙ НА ПРИКЛАДІ ВЕРТИКАЛЬНОГО ПРУЖНЬОГО СТРИЖНЯ ВЕЛИКОЇ ГНУЧКОСТІ

Стаття відноситься до області геодезичного та інженерно-будівельного моніторингу будівельних конструкцій у вигляді стрижневих систем. Досліджується точність виміру деформації стягнення стрижня. У якості прикладу розглянуто вертикальний прямолінійний стрижень великої гнучкості, навантажений повздовжньою вертикальною силою. Досвід свідчить, що стрижень під дією осьового стискаючого навантаження, що не перевищує допустимих розрахункових значень, зберігає початкову форму рівноваги та стійкість. При цьому він працює у рамках пружних деформацій стиснення. При збільшенні навантаження до критичних значень настає такий стан елемента, коли форма рівноваги стає нестійкою, і в будь-який момент при незначній сторонній дії або в результаті похибок положення, вона може з прямолінійної перетворитися на криволінійну. Це супроводжується великими переміщеннями та залишковими деформаціями. Робиться наголос на важливості моніторингу, коли спорудження з подібними конструкціями виявляється, наприклад, у зоні розвитку негативних природних та антропогенних процесів. В результаті навантаження на деякі елементи може збільшитись до критичних значень за рахунок нерівномірного горизонтального та вертикального зсуву та нахилу споруди, у тому числі вібрацій тощо. Акцентується увага на тому, що комплекс інженерно-технічних вимірювань повинен показати з необхідною повнотою, достовірністю та точністю величини, характер та динаміку змін зовнішнього навантаження на елементи споруди, зміну внутрішніх зусиль та напружень у них, розвиток деформацій (зміна розмірів та форми рівноваги). Обгрунтовується точність, з якою необхідно вимірювати рух кінця стрижня під час деформації. Виведено залежність, з якої видно, що середня квадратична похибка виміру переміщення залежить від того, яким чином обрано граничне відхилення напруги в перерізах стрижня з певного матеріалу. Обгрунтовано розрахунок граничного відхилення напруги, виходячи із стійкості та гнучкості стрижня.

Ключові слова: вертикальний стрижень, деформація, критична напруга, нестійка рівновага, точність вимірювань, геодезичний моніторинг.

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MONITORING OF THE ELEMENTS STABILITY OF BUILDING CONSTRUCTIONS BY MEANS OF EXAMPLE OF VERTICAL ELASTIC ROD OF HIGH FLEXIBILITY

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Keywords: vertical rod, deformation, critical stresses, unstable equilibrium, accuracy of measurements, geodetic monitoring.

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Досліджується точність виміру деформації висотної будівлі у вигляді стягненого стрижня.
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The article considers the accuracy of measuring the deformation of a high-rise building in the form of a curved rod.
Fig. 1. Ref. 9.

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Рассматривается точность измерения деформации высотного здания в виде изогнутого стержня.
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