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ACTUAL ELASTICITY MODULE VALUES OF STRUCTURAL MATERIALS AND METHODS FOR THEIR DETERMINATION

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Ensuring the reliable operation of structural elements using modern materials places increasingly high demands on the accuracy of assessing their key characteristics. One of the most important of these is the elastic modulus of the material. An analysis of methods for determining this modulus was carried out. It has been shown that the main methods, developed at the beginning of the 19th century, are still used today as basic methods without taking into account the characteristics of modern composite materials. It is also shown that the simplifications previously adopted in determining elastic moduli from tensile experiments are not justified. They lead to fictitious values of elastic moduli even for isotropic materials. Analytical dependencies are proposed for obtaining reliable values for this class of materials, which are well confirmed experimentally. It has been proven that these dependencies are unacceptable for determining the elastic moduli of anisotropic materials without taking into account the characteristics of the latter. The methods for determining the elastic moduli for two types of composite materials are presented: monotropic and orthotropic. These methods provide good agreement with experimental values. It is shown that the methods used to date for determining the elastic moduli of structural materials give significantly overestimated values of the determined characteristics compared to the actual ones. In the paper a proposal for determining a modified Young's modulus is presented, which could be more precise and, thus the spread of experimental data could be reduced.

Keywords: composite, modulus of elasticity, tension, experimental determination

INTRODUCTION

Expanding the scope of application of new types of composite materials in structural components is inextricably linked to ensuring their reliability and safety. The latter are usually based on various standards and methods that establish reliable and stable values for the main characteristics of the material. One of the main and most important characteristics for structural components is the elastic modulus of the material, for which a method has been developed worldwide [1]. Its author, Thomas Young, was the first to describe the determination of the elastic modulus of an isotropic material under tension and published it in 1807. This method is based on relative longitudinal deformation corresponding to a given longitudinal stress. The method described by Thomas Young is currently used as the basis for various standards and methods for determining the elastic moduli of not only isotropic but also anisotropic materials [2-5]. It should be noted that the determination of reliable characteristics of isotropic materials has attracted the attention of many prominent scientists, such as R. Hooke, S. Poisson, D. Cauchy, A. Lame, and others. Thanks to their work, Young's method has been improved. The concept of Poisson's ratio has been introduced into it. Experiments to determine Young's modulus have been expanded, which are carried out quite simply by means of tensile tests. However, the modulus of elasticity is determined to date without change for materials of any class as

$$E = \frac{\sigma_x}{\varepsilon_x}, \tag{1}$$

where ε_x is the longitudinal deformation corresponding to specified stress σx under uniaxial tension. The equation presented shows that the value of the modulus of elasticity is determined only by the deformation in the x-direction at a given stress in the same stress. Nevertheless, such elongation of the element in the x-axis direction is accompanied by narrowing in the transverse direction (compression). This is clearly confirmed by test data for both isotropic and anisotropic materials. The corresponding modulus of elasticity, called Young's modulus, is usually given in technical literature as a value characterising the elastic properties of a material [6], i.e. it is the main characteristic of a material, without which it is difficult to determine its other important characteristics. Moreover, the modulus of elasticity determined from tensile or compression tests is the most reliable characteristic of a material. Therefore, its value must be determined carefully, taking into account the influence of all the possible factors, including the factor of sample narrowing. At the same time, it is necessary to take into account the equation of the relationship between deformation and stress for the class of materials under consideration. Theoretically, it is determined from the equation relating deformation and stress for the material in question under linear stress conditions. For isotropic materials, this relationship is represented as [7]:

$$\left.\begin{aligned} \varepsilon_x &= \frac{1}{E}\left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right] \\ \varepsilon_y &= \frac{1}{E}\left[\sigma_y - \nu\left(\sigma_x + \sigma_z\right)\right] \\ \varepsilon_z &= \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_x + \sigma_y\right)\right] \end{aligned}\right\} \tag{2}$$

Here, deformations in the accepted coordinate axes x, y, z are denoted by ε_x, ε_y, ε_z, and stresses by σ_x, σ_y, σ_z; ν is Poisson's ratio; E is the elastic modulus of the material.

In the case of tension in the x-axis direction, there is a linear stress state in which $\sigma_y = 0$; $\sigma_z = 0$. In this case, Equations (2) take the form:

$$\left.\begin{aligned} \varepsilon_x &= \frac{1}{E}\sigma_x \\ \varepsilon_y &= -\frac{1}{E}\nu\sigma_x \\ \varepsilon_z &= -\frac{1}{E}\nu\sigma_x \end{aligned}\right\} \tag{3}$$

In this case, to find the total deformations, the method of superimposing the deformation components caused by each of the stresses acting on the sample, or the superposition method, is used [7]. In the case of tension under consideration, the determined components of deformations from narrowing in the transverse direction, using the noted superposition method, are determined according to (3). Deformation in the direction of the x-axis is determined as

$$\varepsilon = \frac{\sigma_x}{E} - \frac{\sigma_x \nu}{E} - \frac{\sigma_x \nu}{E} \tag{4}$$

It is worth noting the following factors here:

Firstly, the deformation superposition method used gives excellent results not only for the simple linear stress state mentioned above, but also for complex states with simultaneous exposure to stresses σ_x, σ_y, σ_z, uniformly distributed across the element's edges, which is confirmed by numerous experimental measurements [7].

Secondly, the above-mentioned work also outlines the reasons for using the simple expression in (1) to determine the modulus of elasticity of materials employed in engineering structures. The reasons given do not contain sufficient justification, but Equation (1) is still used to this day.

The need to take into account the factor of material narrowing is also noted in literature [8], where it is concluded that the transverse deformation coefficient under uniaxial stress reflects the actual kinetics of the deformation process in the transverse and longitudinal directions and, therefore, is a kinetic parameter. According to [8], this issue is practically not addressed in either educational literature or scientific publications. Based on the above, we consider it necessary to note the influence of this shrinkage on one of the most important characteristics of the material.

It should be noted here that all deformations are measured during the experiment, and Poisson's ratio is determined from the data obtained. The ratios on the right-hand side of (3) are used to calculate the deformations under consideration. The modulus of elasticity can be determined by two methods: using the measured values of all three deformations based on (4), or by calculating the deformation values according to (3). In the first case, from (4) we obtain:

$$\varepsilon_x = \frac{\sigma_x}{E} - \varepsilon_y - \varepsilon_z, \tag{5}$$

where from

$$E = \frac{\sigma_x}{\varepsilon_x + \varepsilon_y + \varepsilon_z} = \frac{\sigma_x}{\varepsilon}, \tag{6}$$

where

$$\varepsilon = \varepsilon_x + \varepsilon_y + \varepsilon_z. \tag{7}$$

This is the total deformation from σ_x. In the second case, Equation (6) for the modulus of elasticity also applies from (4), but all the deformations included in (7) are calculated from (3). The third option for determining the modulus of elasticity can be obtained from the solution of Equations (2) with respect to stresses σ_x, σ_y, σ_z. For example, according to [7]:

$$\sigma_x = \frac{\nu E}{(1+\nu)(1-2\nu)}\varepsilon + \frac{E}{1+\nu}\varepsilon_x. \tag{8}$$

The values ε_x, ε_y, ε_z can be measured experimentally or calculated as shown above. Transverse strains ε_y, ε_z, as can be seen from (7), increase the value of ε and, consequently, reduce the value of the elastic modulus calculated according to (1), bringing it to its actual value.

Nonetheless, to date, when experimentally determining the elastic moduli of structural materials, the values of transverse deformations are generally not taken into account. This is despite the development of anisotropic structural materials and their widespread use in load-bearing components. New methods for the analytical determination of elastic moduli have been developed for these materials, which accurately and clearly include transverse deformations. Examples of this can be found in works [9-15]. The lack of consideration of the influence of transverse deformations when determining elastic moduli is due to the fact that at the time of widespread use of isotropic materials in engineering structures, the elastic moduli of these materials had very high values compared to the permissible stresses, and the noted deformations were very small [7]. At the same time, the fact that the smaller the value of longitudinal deformation, the greater the value of the modulus of elasticity at the same value of the corresponding stress σ_x, was overlooked. As already noted, the exclusion of transverse deformations contributes to a decrease in the value of longitudinal relative deformation [7]. Failure to take their values into account creates fictitious increased values of Young's modulus. Firstly, and secondly, this does not contribute to ensuring reliable operation of the product. There is practical interest in assessing the importance of adopting such a simplification. For isotropic materials, no additional practical actions are required. It is sufficient to compare the values of E determined by Equation (1), let us denote it as $\bar{E}$, and (6):

$$\frac{\bar{E}}{E} = 1 + 2\nu. \tag{9}$$

Equation (9) shows that the difference between the compared values is quite significant. It should also be noted that Equation (1) is unacceptable for determining the elastic moduli of anisotropic materials owing to the difference between the relationship between deformations and stresses in them and in isotropic materials.

No data on verification of the influence of the adopted simplifications on the determined values of the elasticity moduli of the considered isotropic materials was found in the literature. An analysis of published works related to the methods and standards for determining the elasticity moduli of structural materials shows that there are no critical comments or suggestions for their improvement. Various standards based solely on longitudinal deformation and the corresponding stress are still in use today [2-4]. The main focus in published works on the subject under consideration is on modifying and testing previously developed methods, the main parameter of which is the maximum deflection during transverse bending tests [16-19]. However, deflection under bending is not a characteristic of the material [1] as it depends on many external factors. Therefore, it is not appropriate to analyse research on this topic here. The greatest attention and practical interest in the issue under consideration are attracted by the estimation of the error in the value of the elastic modulus of an isotropic material under tension, determined by the commonly used method, without taking into account the transverse deformations of the sample, as well as the assessment of the acceptability of the proposed methods for determining the elastic moduli of structural materials, taking into account transverse deformations. The methods currently used to determine the elastic moduli of isotropic materials have a reliable theoretical basis developed by the classics of elasticity theory. Therefore, the most acceptable solution to the problems identified is a detailed analysis of both the analytical basis of the methods used and their experimental verification. First and foremost, this applies to modern methods for determining the elastic moduli of isotropic materials. They are also utilised for composites of all types, without taking into account either their structural features or the relationship between deformations and stresses in them [20-22].

Considering the above, let us examine in more detail the methods for determining the elastic modulus of certain types of materials.

ANALYSIS OF ANALYTICAL BASIS OF METHOD FOR DETERMINING MODULI OF ELASTICITY OF CONSTRUCTION MATERIALS UNDER TENSION

Monotropic body

The relationship between deformations and stresses for a coordinate system with the *x*-axis coinciding with the direction of the fibres can be represented as [21, 22]:

$$\left.\begin{aligned} \varepsilon_x &= -\frac{\nu_{xz}}{E}\sigma_z - \frac{\nu_{xy}}{E}\sigma_y + \frac{1}{E_x}\sigma_x \\ \varepsilon_y &= -\frac{\nu_{yz}}{E}\sigma_z + \frac{1}{E}\sigma_y - \frac{\nu_{yx}}{E_x}\sigma_x \\ \varepsilon_z &= \frac{1}{E}\sigma_z - \frac{\nu_{zy}}{E}\sigma_y - \frac{\nu_{zx}}{E_x}\sigma_x \end{aligned}\right\}. \tag{10}$$

Here, the *yz* plane is the plane of isotropy; *E* is the modulus of elasticity for directions in the plane of isotropy; the first index in Poisson's ratio denotes the direction of contraction, and the second denotes the direction of force action during tension. The following relationship also applies: $\nu_{xz} E_x = \nu_{zx} E$, where Ex is the modulus of elasticity for the direction perpendicular to the plane of isotropy.

When stretched in the direction of the *x*-axis: $\sigma_y = 0$; $\sigma_z = 0$. Equations (10) in this case are represented as:

$$\left.\begin{aligned} \varepsilon_x &= \frac{\sigma_x}{E_x} \\ \varepsilon_y &= -\frac{\nu_{yx}}{E_x}\sigma_x \\ \varepsilon_z &= -\frac{\nu_{zx}}{E_x}\sigma_y \end{aligned}\right\}. \tag{11}$$

Performing similar actions for isotropic materials, we have: values of deformation components ε_x, ε_y, ε_z, measured during the tensile experiment in the first case, and calculated in the second. Using the dependence for ε_x from Equations (10) and the measured deformation components obtained in the first case, we have:

$$E_x = \frac{\sigma_x}{\varepsilon_x+\varepsilon_y+\varepsilon_z}, \tag{12}$$

in the second case

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \frac{\nu_{yx}\sigma_x}{E_x} - \frac{\nu_{zx}\sigma_x}{E_x}, \tag{13}$$

but y_z is the plane of isotropy; therefore $\nu_{yx} = \nu_{zx}$, then

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \frac{2\nu_{yx}\sigma_x}{E_x} = \frac{\sigma_x}{E_x} - 2\varepsilon_y, \tag{14}$$

where from

$$E_x = \frac{\sigma_x}{\varepsilon_x+2\varepsilon_y}. \tag{15}$$

That is, in the first and second variants, the elasticity modules have identical values and represent the actual value in the direction of reinforcement of the monotropic material:

$$\frac{\bar{E}}{E_x} = \frac{\varepsilon_x+2\varepsilon_y}{\varepsilon_x} = 1 + 2\nu_{yx}. \tag{16}$$

Orthotropic body

This is the most important case of elastic symmetry and the most common among modern composite materials. Assuming that the three mutually perpendicular planes of elastic symmetry are perpendicular to the corresponding coordinate axes *x*, *y*, *z*, the relationship between deformations and stresses can be represented as follows [21]:

$$\left.\begin{aligned} \varepsilon_x &= \frac{1}{E_x}\sigma_x - \frac{\nu_{xy}}{E_y}\sigma_y - \frac{\nu_{xz}}{E_z}\sigma_z \\ \varepsilon_y &= \frac{1}{E_y}\sigma_y - \frac{\nu_{yx}}{E_x}\sigma_x - \frac{\nu_{yz}}{E_z}\sigma_z \\ \varepsilon_z &= \frac{1}{E_z}\sigma_z - \frac{\nu_{zx}}{E_x}\sigma_x - \frac{\nu_{zy}}{E_y}\sigma_y \end{aligned}\right\}. \tag{17}$$

As before, the following dependencies apply here: $E_y\nu_{yx} = E_x\nu_{xy}$; $E_z\nu_{zy} = E_y\nu_{yz}$; $E_x\nu_{xz} = E_z\nu_{zx}$. When stretched in the direction of the *x*-axis, a linear stress state occurs, i.e. σ_y_= 0; σ_z_= 0. In this case, from (17) we have:

$$\left.\begin{aligned}\varepsilon_x &= \frac{1}{E_x}\sigma_x\\ \varepsilon_y &= -\frac{\nu_{yx}}{E_x}\sigma_x\\ \varepsilon_z &= -\frac{\nu_{zx}}{E_x}\sigma_x\end{aligned}\right\}. \qquad (18)$$

Using the same techniques as for the two classes of materials discussed above, we obtain, in the first case, a dependence analogous to (12). Thus, $\frac{\bar{E}}{E} = 1 + \nu_{yx} + \nu_{zx}$. For composite materials with equilibrium fibre orientation, e.g. 1:1, ν_{zx} has the highest Poisson's ratio value on the end surface and, consequently, its influence on the determined characteristic value is also the greatest. Its value does not exceed the Poisson's ratio of a unidirectional material with the same overall reinforcement coefficient when loaded in the direction of the fibres.

In the second case, replacing the deformation components with their ratios given in (18), we have the same relationship as in the first case, that is $\frac{\bar{E}}{E} = 1 + \nu_{yx} + \nu_{zx}$.

The data presented show that methods for determining the elastic moduli of isotropic materials are applicable to anisotropic materials only when the peculiarities of the relationships between stresses and strains in them are taken into account.

ANALYTICAL DATA EVALUATION

An experimental study of the established factor was conducted on the three most studied and widely used structural materials: isotropic, monotropic, and orthotropic. Rectangular steel strips with dimensions (b × h) of 16.8 mm × 5.8 mm and 10.0 × 10.0 mm were used as isotropic materials. Their lengths were 250 mm and 150 mm, respectively. Samples for the other two types of material were cut from glass fibre-based plates in the form of unidirectional (1:0) and orthogonally reinforced (1:1) structures. The thickness of the plates ranged from 2 mm to 13 mm. The samples were manufactured and the tensile tests were conducted in accordance with ASTM D3039M and GOST R56785-2015. The samples were loaded on an MTS 809.40 testing machine. The samples were secured using hydraulic wedge grips. The machine is equipped with software that allows data to be obtained in both digital and graphical formats. Foil strain gauges with a base of 6 mm and 15 mm were used to measure deformations. Strain gauges were attached to the samples to measure the longitudinal and transverse deformations on two perpendicular edges of the sample and were arranged in a similar manner. All the samples were loaded within a stress range that did not exceed the linear dependence of their deformations on stress. These dependencies are not presented here as they have been well studied, and the nature of these dependencies for various materials is presented in many publications, see, for example, [23, 24]. Thus, in [23], for carbon-plastics and carbon-glass-plastics with different reinforcement patterns, deformation diagrams are given for tensile testing, taken both in the direction of reinforcement and at an angle of 45° to it.

Analysis of the dependencies shown indicates that even a small amount of reinforcement in the direction of the applied load or at a slight angle to it leads to linear dependence $\sigma \sim \varepsilon$ up to failure. In [17, 23], it is shown that the deformation diagrams of all oriented composites under tension and compression along the fibres can be considered linear in the first approximation up to failure of the material.

It should be noted that the general approach to methods for determining the elastic moduli of isotropic materials was and remains the same for anisotropic materials. The acceptability of the presented methods for isotropic materials opens up the existing theoretical basis for the development of methods for determining the elastic moduli of other structural materials. The main task is to assess the correctness of their use and further practical dissemination. An important factor in solving this task is to establish the magnitude of error in determining the elasticity modules of structural materials using existing methods. It is a cause for concern that the error leads to significantly overestimated values of elasticity modules.

EXPERIMENTAL EVALUATION OF ACCEPTABILITY OF PRESENTED METHODS

The results of testing isotropic samples are as follows: P = 10.0 KN; $\sigma_x = 0.1026$ GPa; $\varepsilon_x = 0.040$ %;

$$\varepsilon_y = \varepsilon_z = 0.012\ \%;\ \nu = 0.30.$$

Calculation of the modulus of elasticity based on the given data yields:

$$E = \frac{\sigma_x}{\varepsilon_x+\varepsilon_y+\varepsilon_z} = \frac{0.1026}{0.0004+0.00012+0.00012} = 160.313 \text{ GPa}$$

The modulus of elasticity, determined according to existing standards (Equation (1)), is:

$$\bar{E} = \frac{\sigma_x}{\varepsilon_x} = \frac{0.1026}{0.0004} = 256.500 \text{ GPa. Thus } \frac{\bar{E}}{E} = \frac{256.500}{160.313} = 1.60$$

The second option for calculating the modulus of elasticity using deformation components determined by Equations (13): $\varepsilon_y = \varepsilon_z = \frac{\nu\sigma_x}{E_x} = \frac{0.30\times 0.1026}{256.5} = 0.00012$ mm; $\varepsilon_x = 0.0004$ mm

$$E = \frac{\sigma_x}{\varepsilon_x+\varepsilon_y+\varepsilon_z} = \frac{0.1026}{0.00064} = 160.313 \text{ GPa}$$

Thus, both presented methods of calculating the modulus of elasticity give the same values and are in excellent agreement with the presented calculated value.

The third method of determining *E* from Equation (8), where all the deformations and stresses have already been noted is: $\sigma_x = \frac{0.3E}{1.3\times 0.4}0.00064 + \frac{E}{1.3}0.0004 = 0.000677E$ GPa; consequently

$$E = \frac{0.1026}{0.000677} = 151.551 \text{ GPa}$$

Monotropic material – unidirectional fibreglass

Unidirectional fibreglass was used in an experiment to test the tensile strength in the direction of reinforcement, i.e. in the direction of the *x*-axis. The test results are as follows: $\sigma_x = 1.196$ GPa; $\varepsilon_x = 2.390$ %; $\varepsilon_y = 0.654$ %; $\varepsilon_z = 0.654$ %; $\nu_{yx} = 0.274$, where $\nu_{yx} = \nu_{zx}$

The expression for the modulus of elasticity in the first case is given by Equation (12): $E_x = \frac{\sigma_x}{\varepsilon_x+\varepsilon_y+\varepsilon_z} = \frac{1{,}196}{0.037} = 32.324$ GPa. The modulus of elasticity, determined in accordance with the standards used, is equal to: $\bar{E}_x = \frac{\sigma_x}{\varepsilon_x} = \frac{1.196}{0.0239} = 50.040$ GPa. Its ratio in relation to the value calculated using Equation (12) is as follows: $\frac{\bar{E}_x}{E_x} = \frac{50.040}{32.324} = 1.55$.

In the second case, the components of deformations ε_y and ε_z are determined based on Equation (14):

$$\varepsilon_y = \frac{\nu_{yx}\sigma_x}{E_x}\text{ ; }\varepsilon_z = \frac{\nu_{zx}\sigma_x}{E_x}\text{ ; in the plane of isotropy}$$

$$\varepsilon_y = \varepsilon_z = \frac{0.274\times 1.196}{50.04} = 0.0063 \text{ mm.}$$

Consequently $E_x = \frac{1.196}{0.037} = 32.324$ GPa. Both options give identical values for the modulus of elasticity in the direction of reinforcement.

Orthotropic material

On fibreglass samples (1:1): *b* = 10.2 mm; *h* = 12.9 mm; *P* = 3.3 KN; $\sigma_x = 0.0251$ GPa, deformations were measured simultaneously on two faces of the sample, in the reinforcement plane: $\varepsilon_x = 0.1072\%$; $\varepsilon_y = 0.0181\%$, and on the end face *zx*: $\varepsilon_x = 0.1073$ %; $\varepsilon_z = 0.0362\%$; $\nu_{xy} = 0.165$; $\nu_{zx} = 0.340$; $\nu_{yx} = 0.169$.

The modulus of elasticity in the first case was determined by Equation (12): $E_x = \frac{\sigma_x}{\varepsilon_x+\varepsilon_y+\varepsilon_z} = \frac{0.0251}{0.00162} = 15.494$ GPa. The value of the modulus of elasticity, determined by the methods used in the form of $\bar{E}_x = \frac{\sigma_x}{\varepsilon_x} = \frac{0.0251}{0.001073} = 23.392$ GPa. $\frac{\bar{E}_x}{E_x} = \frac{23.392}{15.494} = 1.510$

In the second case, we have the values of the deformation components calculated according to Equation (18):

$\varepsilon_x = 0.1073\%$; $\varepsilon_y = 0.0181\%$; $\varepsilon_z = 0.0362\%$.

$E_x = \frac{0.0251}{0.00162} = 15.494$ GPa

Thus, the values of the modulus of elasticity determined from the calculated deformation components and from the deformation components measured during the experiment are identical.

CONCLUSIONS

Analysis of the data obtained gives grounds for the following conclusions:

- Three options for determining the elastic moduli of isotropic materials from tensile experiments were proposed, which are based on the experimental and calculated values of deformations at given stress values. The calculated values obtained are in excellent agreement with the experimental ones.

- It was established that the proposed methods take into account all the factors affecting the determined values of elastic moduli; therefore, they are real values for the materials under consideration.
- It was shown that the experimental methods and standards currently used in tensile tests on anisotropic materials give significantly overestimated values for their elastic moduli. These values are fictitious.
- The standards currently used to determine reliable values for elastic moduli do not contribute to ensuring the reliable operation of structural components.
- Similar methods, taking into account the relationship between stress and strain, have also been proposed for composite materials. Experimental testing has shown that they are highly suitable for this class of materials.
- It should be added that the values of the modulus of elasticity for samples made of steel and monotropic fibreglass are 1.6 times higher than their true values.

As the results of the experiments show, the use of current standards leads to overestimated values of elastic moduli for all types of materials considered. The methods proposed in this work allow accurate values of elastic moduli to be obtained for all materials considered.

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