Analysis of strain state prismatic samples for mechanical testing of the biaxial stretching method digital image correlation

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Abstract. The paper deals with the experimental-calculated analysis of the deformed state of a prismatic type sample for mechanical laboratory tests designed to evaluate the strength of a material under a biaxial stress state. A description is given of the advantages of the deformation scheme of this sample, which contributes to a reduction in the technical requirements for the test machines used for performing the test procedures. The distribution of deformation fields of the prismatic sample surface studied is obtained by processing the speckle images of the on-board experiment by the method of correlation of digital images in the Vic-3D system, at the stage of elastic deformation. Their comparison with the results of numerical simulation by the finite element method at control points of the surface of the deformed sample is performed. The discrepancy between the results of the full-scale experiment and the given numerical simulation at the control points did not exceed 14%. Conclusions are formulated for the subsequent use of the results obtained.

1. Introduction
A design estimate of the reliability of assemblies and structural components can be provided if reliable experimental information is available on the strength of their elements. Such an assessment should be carried out for those types of stress-strain state (SSS) in the source of destruction that occur during the action on the part of the operational load. Known methods for modeling the strength characteristics of structural parts are based on the study of the deformation processes of a series of typical laboratory samples tested under standard loading conditions [1, 2]. The results of these tests can then be taken into account as weight factors in the so-called combined strength criteria, for example, Jagn-Buzhinsky, Drucker-Prager, Pisarenko-Lebedev et al. [1-4]. From this point of view, the factor limiting the accuracy of applying the combined strength criteria is the difference between the real type of SSS of the estimated design and the type of SSS of typical samples that give information on the strength of the material with strictly limited types of SSS [3]. In addition, the need for the preliminary determination of the strength characteristics included in the combined strength criteria and the corresponding variety of laboratory test techniques complicate the practical application of a refined assessment of the reliability of assemblies and structural components. In particular, when testing to simulate a biaxial stress state, it is necessary to use cross-shaped patterns [5, 6, 7]. The paper deals with the experimental-calculated analysis of the deformed state of the proposed prismatic-type
laboratory sample (prismatic sample) [8], intended to evaluate the strength of a material under a complex stress state, allowing to reproduce the state of biaxial stretching over a wide range of principal stresses under the action of a unidirectional test force.

2. Description of the prismatic sample deformation scheme

When carrying out mechanical tests, the prismatic sample 1 (see Figure 1) is supported by its ends on the end supports 5 and simultaneously by L-shaped projections 2 with support bevels 3 - on the prismatic support 4. In this case, the contact interaction of the bevel occurs 3 with a prismatic support 4 having the same bevel angles. Under the influence of the test force 7 applied to the central zone 8, a longitudinal bending of the sample occurs and in the working zone (the lower surface of the horizontal bar of the L-shaped step) positive principal stresses $\sigma_1$ arise, which are tensile stresses acting in the longitudinal direction for a prismatic sample direction (Figure 1, view I). Simultaneously, during the loading process, the displacement of the lower part of the protrusions 2 also occurs in the direction of the transverse plane of symmetry of the sample. The displacement is caused by the slip of the support bevel 3 of the L-shaped projections 2 along the inclined support surface of the prismatic support 4. At this displacement, due to the structural shape of the lower part of the L-shaped protrusion, it bends in the transverse plane of symmetry of the sample and positive the main stresses $\sigma_2$, the level of which depends on the geometric parameters of the L-shaped projections 2. The stress $\sigma_3$ in the working zone (stresses in the direction normal to the bottom surface of the lateral projection) are close in the test to zero, which creates a biaxial tension.

The described scheme of deformation allows to simplify the corresponding equipment used in the testing process and to reduce the requirements for the number of drives of the testing machine. Varying the basic design parameters of the prismatic sample (the width and height of the prismatic part, the height and thickness of the lateral protrusion, the radius of the tilt transition, the angle of the
lateral support slant), allows creating in the work zone the necessary SSS that simulates the SSS of the original design under study.

3. Experimental research
Together, these elements and the test sample, shown in Figure 1, allowed to develop a laboratory bench for mechanical testing, presented in Figure 2. To create tensile longitudinal stresses $\sigma_1$ caused by longitudinal bending of the prismatic specimen, monolithic end supports are created (Figure 2), and for creating transverse tensile stresses $\sigma_2$ caused by sliding of the support bevels of the L-shaped projections of the sample along the inclined support surface, the support of the prismatic shape is made (Figure 2). This support is a massive prism in the central part of which a longitudinal groove with inclined support surfaces is made, the angles of which are the same as those of the side projections of the test specimen.

![Figure 2. Laboratory bench for mechanical testing (a) and the dimensions (b) of the experimental prismatic sample (the numbering of the elements corresponds to Figure 1)](image)

Mechanical tests were carried out on an electromechanical machine Instron 5989. The registration of displacement and deformation fields was carried out using the method of correlating digital images (DIC) [9, 10]. When recording the displacement and deformation fields, the Vic-3D Correlated Solutions digital optical system was used, the mathematical apparatus of which is based on the method of correlation of digital images. The system includes two digital black-and-white cameras with a resolution of 1.4 MPix, a backlight system, a set of calibration tables, specialized software for adjusting and controlling the shooting process (Vic-Snap) and subsequent mathematical image processing (Vic-3D).
A constructive version of the sample with geometric parameters, shown in Figure 2b. Samples were made from strip rolled bar steel 50CrV4 by milling on 5-coordinate machine tool with numerical control of DMU-80 type. The working and supporting surfaces were subjected to finishing treatment to achieve roughness parameters of these surfaces in accordance with the requirements of the standard [11]. The investigation of the deformation zones of a prismatic sample was carried out at a constant loading rate of 2 mm / min. In Figure 3a shows the appearance of the working body of the Instron 5989 test machine with a test specimen (initial state), figure 3b is the final elastically deformed state of the sample.

The definition of deformation fields with Vic-3D was as follows. The moment of time corresponding to the test force causing elastic deformation of the material was fixed and then the corresponding number of the speckle image frame was determined from the available per second storyboard of the entire test process in Vic-3D. In Vic-3D, this image is processed - the displacement and deformation components are calculated relative to the original (reference) frame using the DIC [9]. In the course of the experiment, the dynamics of changes in the displacements of the speckle structure were carried out by means of continuous fixation of the images of the lateral surface of the sample. In this case, the fixing rate was set at 1 frame per second, which makes it possible to obtain a detailed picture of the deformation state during the entire test period. The processes of loading and fixing images were synchronized in time. This made it possible to determine the deformation characteristics of the surface under investigation at any instant of time to within a second and correlate them with the current test force obtained as a force / displacement curve of the loading device. The results of processing are displayed on the computer screen in the form of a multicoloured palette, each color of which corresponds to its value of the displacement or deformation field.

On the linear portion of the loading diagram of the prismatic specimen, the value of the test force equal to $F = 70 \pm 1$ kN was recorded and located just above half the length of this section. According to the available second-by-second storyboard of the entire test process in the Vic-3D system, the number of the speckle image frame corresponding to the set $F$ was set equal to $t = 130$ seconds. In Figure 4 shows the displacement, calculated as a result of the processing in Vic-3D, corresponding to the deformed state of the sample at the stage of elastic deformation, giving an idea of the pattern of the distribution of the longitudinal $\varepsilon_{xx}$ deformation fields (see Figure 4a) and axial $\varepsilon_{yy}$ deformations (see Figure 4b).
Figure 4. The experimental elastically deformed state of a prismatic sample with the distribution of longitudinal $\varepsilon_{xx}$ (a) and axial $\varepsilon_{yy}$ (b) deformations.
4. Calculation research

Analysis of the experimental and calculated data on the deformed state of the sample in question was carried out based on the results of a numerical experiment with the specification of boundary conditions that maximally simulate the testing process. A feature of the process of numerical modelling of the SSS of the samples was the consideration of the contact nature of the elastic interaction of the sample with its supports [14]. The results of a numerical analysis of the computational model of a laboratory bench with boundary conditions for the conjugation of its elements are discussed in detail in [12, 13]. The test force in the numerical experiment corresponded to the indications of the dynamometer of the testing machine (70 kN). In Figure 5 presents the results of finite element modelling of the elastic deformation process performed in the MSC.NASTRAN-MSC.PATRAN software package.

![Figure 5](image-url)

**Figure 5.** The distribution of the fields of the numerical values of the longitudinal $\epsilon_{xx}$ (a) and axial $\epsilon_{yy}$ (b) deformations at the stage of elastic deformations
5. Processing Results
Comparing the obtained results of the full-scale experiment using the Vic-3D system (Figure 4) with the data of numerical simulation (Figure 5) at the stage of elastic deformation, it is seen that the distribution of the field components of longitudinal $\varepsilon_{xx}$ and axial $\varepsilon_{yy}$ deformations have qualitative similarities. To quantify the reliability of the calculated and experimental deformations available for fixation by the Vic-3D system in the process of elastic deformation of a prismatic sample, the values of these deformations at the reference points of the lateral surface of the deformed sample are compared. The control points are tied to the lateral surface of the sample in a specific way. In the calculated finite element model, the control points are tied to the coordinates of the grid mesh nodes, and on the speckle image processed in the Vic-3D the point coordinate is determined by the shape and size of the speckle image interest area (i.e., the area for which the speckle displacement analysis is assigned). In Figure 6 is a diagram of the arrangement of control points in which the values of the displacement and deformation components were measured and compared.

As a measure of the relative error of the discrepancy between the compared values of $\eta$, we considered the ratio

$$\eta = \frac{\chi_{dic} - \chi_{fem}}{\chi_{dic}} \times 100\%$$

where $\chi_{dic}$ - experimental value of the compared value, obtained by means of a method of correlation of digital images, $\chi_{fem}$ - the calculated value of the compared value, obtained with the help of FEM. In Figure 7 presents the results of a quantitative comparison of the values of the experimental and calculated displacements and deformations at all 14 control points of the lateral surface of the prismatic sample for various components.
The results shown in Figure 7, in aggregate show that the characteristics of displacements and deformations of the surface of the prismatic sample, obtained by numerical simulation on the FEM and as a result of processing digital images of the full-scale experiment in the Vic-3D system, have a discrepancy not exceeding 14%.

6. Conclusion

It is experimentally shown that the developed mathematical model of elastic deformation of prismatic samples on the basis of FEM allows to estimate the characteristics of SSS in their working zones with an error of no more than 14%. This circumstance makes it possible to apply the developed computational models of the specified samples for the realization of various purposes, in particular, for carrying out variant computational studies to identify patterns of deformation of prismatic samples from their basic geometric parameters. Revealing of the indicated regularities will allow to carry out the reasonable choice of geometrical sizes of samples for reproduction of the required ratio of the main stresses of biaxial stretching and the subsequent determination of the strength characteristics of the material in this state.

7. References

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