Investigation of the stress state of flat truss rods. Numerical and physical modeling

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Abstract. The paper presents the results of an experimental numerical study of the stress state of the rods of a flat truss and the results of the analytical calculation. The values of internal forces and stresses in the truss model were obtained using the SCAD software package, as well as experimentally using the polarization-optical method. The finite element method (FEM) is used to calculate two plane truss models. In the first case, the truss was modeled by rod elements, in the second – by plates. The fields of normal, tangential and principal stresses are obtained. With their help there were found the longitudinal internal forces in the rods of the farm. The interference bands in the model of a flat truss are obtained by the method of photoelasticity. Stresses are calculated with their help. The quantitative and qualitative analysis of the stress state, described in the numerical and physical experiment, is carried out.

1. Introduction
A truss is a structure consisting of perfectly rectilinear rods connected in nodes by ideal cylindrical hinges and working to perceive only the nodal load. The practice of calculations shows that replacing the hinge nodes in the farm with hard ones with this method of loading does not affect the stress-strain state of the structure. To determine the efforts in the rods of the trusses and movements there are many methods and specialized programs [1-15]. However, in all cases the truss is calculated as a rod structure with a constant longitudinal force within a single rod.

The point of interest is the stress state of a flat truss with rigid nodes under a nodal load transfer. For the study were used a numerical and physical experiment. As for the numerical determination of voltages, there is no high guarantee that they will be determined exactly. Solutions of such tasks, obtained with the help of software systems, require experimental checks. There are a number of experimental methods for studying stresses [16]. In this work, we used the polarization-optical method for studying stresses, namely the photoelasticity method [17–18].

2. Physical experiment
In work the facility PPU-7 (polarization-projection facility) was used. In order to study the stress state of a flat truss, a model was made of a polarization-optical material - epoxy resin (modulus of elasticity \( E = 3000 \) MPa, Poisson's ratio \( \nu = 0.38 \), price of a material band by stress \( \sigma_0^{1,0} = 1.4 \) MPa·cm). The sample thickness is 5 mm, its dimensions in mm are presented at Figure 1, and the loading diagram is shown at Figure 2.
The studies were performed using the photoelasticity method for direct radiography. During the experiment, there were obtained pictures of interference bands. A fragment of the interference band pattern for a model of epoxy resin is shown in Fig. 3, the pattern of the bands corresponds to a load of 0.4 kN. On the photo 1, 2, 3, ... denote the numbers of the stripes. Dark stripes correspond to the whole number of the strip, and light stripes – to the half.

On a fragment of the interference band pattern (Fig. 3) it can be seen that the rods are loaded unevenly. The stresses with the greatest magnitude appear under force (at the top on the vertical axis of symmetry). The most loaded is a horizontal rod located in the lower belt of the farm under power. Analyzing the pattern of interference bands, we can conclude that the normal stresses in the cross sections of the rods are not constant values. If they were constant, then a single-colored picture within each rod would be observed in the photo. In this case, we have bands of a different order. This suggests that the rods undergo eccentric tension (compression). With all this, assessing the order of the
bands and their location within the rod, we can conclude that the eccentricity that occurs is insignificant. Using the data of the photoelasticity method, we calculated normal stresses in the rods of the truss model. The determination of stresses was calculated on the contour of the rod by multiplying the number of the strip by the price of the strip of material by the stresses. Such an approach is simple and convenient and is often used to determine stresses near geometric concentrators [19, 20]. The absolute values of the voltages found in this way are shown at Figure 3.

3. Numerical experiment

The finite element method (FEM) with the use of the SCAD software package was used to calculate two flat truss models. In the first case, the truss was modeled with rod elements (Fig. 4a), in the second - with plates (Fig. 4b). The triangulation of the plates is made of standard quadrangular elements, possibly rectangular in shape, one of the sides of which is oriented along the longitudinal axis of the truss rod, the cell size is 1x1 mm. Both models are loaded with a concentrated force applied to the node of the upper belt located on the axis of symmetry of the structure, node 6. The magnitude of the force was 0.4 kN. The material of the models, dimensions and their geometry are taken as in a physical experiment. The extreme left and right nodes of the lower chord of the trusses (nodes 1 and 4) are fixed from linear displacements. In the model specified by the core elements, no hinges were inserted in the nodes of their connections, i.e. farm knots are tough. In a truss modeled with plates, the joints of the elements are also rigid. As a result, two truss models with rigid nodes, working on the beam scheme, were obtained.

![Figure 4. Load patterns of computational models](image)

Fig. 5 shows the plot of the longitudinal forces in the truss rods. The efforts in the truss are obtained by a numerical method; they fully correspond to the similar efforts for a hinged truss under the same conditions of fastening and load, which can be obtained by methods of structural mechanics. As expected, with the beam operation, the truss structure is obtained: the upper belt is compressed, the lower one is stretched, the ascending braces are compressed, the descending ones are stretched.
Figure 5. The forces in the truss rods (kN) obtained by the SCAD software package

According to the formula for determining stresses under axial tension-compression, using the received forces, the values of normal stresses in truss rods are determined. The values of the resulting stresses are shown in Fig. 6.

Figure 6. Normal stresses in truss rods (MPa) obtained by the SCAD software package

Fig. 7 shows the stress fields $\sigma_1$, $\sigma_3$, and $\tau_{xy}$ in the truss model, given with plates. In the upper zone of the truss, the stresses are negative, in the lower zone - positive, which coincides with the calculation of the truss, as a core structure, by methods of structural mechanics. The stresses in the bracings also coincide in sign with the calculation of the rod diagram.

Figure 7. Stress fields obtained by the SCAD software package: $\sigma_1$, kN/mm$^2$ (a), $\sigma_3$, kN/mm$^2$ (b), $\tau_{xy}$, kN/mm$^2$ (c).
Figure 8. The forces in the truss rods (kN) obtained analytically.

Using stresses $\sigma_x$, oriented along the axis of the truss rod, longitudinal forces were found in the elements of the second model (Table 1). Longitudinal forces in the truss, given by the plates, vary slightly along the length of the element and differ from the values obtained by analytic methods of structural mechanics (Fig. 8) by 5-10%.

Table 1

| Stress in the truss rods | $N_{1,2}$ [kN] | $N_{2,5}$ [kN] | $N_{6,5}$ [kN] | $N_{1,5}$ [kN] | $N_{2,5}$ [kN] | $N_{2,6}$ [kN] |
|-------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Model in Fig. 5a        | 0.14           | 0.39           | -0.26          | -0.24          | 0.23           | -0.24          |
| Model in Fig. 5b        | 0.14           | 0.36           | -0.26          | -0.21          | 0.22           | -0.22          |
| % of divergence         | 4.97           | 7.62           | 0.59           | 12.38          | 4.12           | 9.51           |

4. Conclusions

Using the photoelasticity method, we obtained pictures of interference bands in a truss model. It should be noted that the picture of interference bands, in fact, is a field of tangential stresses in the model plane. It can be compared with the stress field obtained through the software package and shown at Fig. 7. Analyzing Fig. 3 and Fig. 7, it can be concluded that there is no qualitative correspondence between them. The finite element method found the efforts in the farm, that was made of the core elements and plates. The difference in the longitudinal forces in the structural elements obtained using these models is insignificant and is within the limits of the accuracy of engineering calculations. Comparison of the results of numerical and physical modeling showed good correspondence of the stresses in the rods of the trusses. The maximum divergence is within 12%, which is close to the experimental error. Despite the qualitative difference in the stress state of the truss rods, which, by and large, are plates in this work, this does not affect the quantitative assessment of the stresses.

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