Compression test results of CFS structural members

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Abstract. The subject of the study is the stress-strain state of a cold-formed steel structural members under axial compression. The aim is to experimentally study the behavior of a sample from a cold-formed thin-walled profile in axial compression with stress control. A mechanical method was used to test compression samples on a universal testing machine, a strain gauge method for measuring relative deformations by strain gauges with data collection in the registration unit. The processing of the test results was carried out using the methods of the theory of elasticity. As a result of the tests carried out, a qualitative picture of the deformation of the sample was obtained, the values of relative deformations at specific points of the cross sections of the sample; as a result of processing the data obtained, the main normal stresses at the points of the cross sections of the element were determined. As conclusions, an assessment of the reliability of the results obtained based on the nonlinear theory of plates is given; a conclusion is made about the inapplicability of the strain gauge method to the analysis of the behavior of thin-walled steel profiles. A promising study is the study of fields of relative deformations by non-contact optical methods.

1 Introduction

The building Russian specification [1] for the design and calculation of CFS structural members introduces many assumptions for determining their bearing capacity by the analytical method. Therefore, one of the ways to determine the real work of a structure is experimental studies. The main controlled parameters in the course of experimental studies of steel thin-walled profiles are linear displacements and the critical load of buckling. However, the main criterion for the reliability of building structures are stresses. To date, the main method for controlling the stresses of a test sample is the strain gauge method, which allows obtaining data on the stress level through strain at one specific point of the element's cross section. For CFS members, the key factors are not only the numerical value of stresses and their distribution over the profile's cross section, but also the change in stress fields over time. Obtaining these data is especially important for the analysis of the stress-strain state of the element in the non-linear stage.
Experimental studies of steel thin-walled profiles were carried out by Russian [2, 3, 4, 5] and foreign [6, 7, 8, 9, 10] authors. The publication [2] presents the results of tests of a single C-shaped CFS-profile for stability under the action of an axial force. To control displacements and strains, the authors used the strain gauge method. The samples were brought to destruction, their non-linear effect was analyzed. In the course of studies of the paired C-shaped profile [4] on the action of the axial force, linear displacements were controlled using linear displacement sensors and dial indicators. Stresses in the sample and its non-linear effect were not analyzed. During experimental stability studies of a sample with a non-constant cross-sectional shape [3], a visual assessment of the form of buckling and control of the corresponding critical load was carried out. Publications [6, 7] present the results of studies of short specimens of single C- and Z-shaped profiles on the action of a moment in two planes and an axial force. The control of linear displacements was carried out by linear displacement sensors, visual assessment was made of the conformity of the deformed scheme of the tested sample with the results of a numerical experiment. A similar approach was used in the studies of Wang C., Keerthan P., Li Y. [8,9, 10], however, in the studies of Wang C. [8], the stresses at two points of the section wall were additionally assessed using the strain gauge method. This fact is associated with the specifics of the task and the object of study. In the course of the experiment conducted by E. V. Zenkov [5], a combined approach to fixing the parameters was applied. Linear deformations were controlled by dial indicators, strains were controlled by strain gauge in combination with the non-contact optical method of the Vic-3D system. This approach made it possible to comprehensively assess the stress-strain state of the profile and obtain a complete figure of the relative deformations of the investigated field of the sample wall. When solving the problem numerically by the finite element method, various approaches are used [10, 11, 12, 13, 14, 15]. The publication [10, 11] presents the results of finite element analysis in the ANSYS software package using the shell element Shell181, which is a 4-node element with six degrees of freedom at each node. A similar approach to choosing a finite element type is given in the article by S. Farzanian at al. [12]. In publication [13], the stability of short samples was studied. The material of the elements is specified according to the isotropic bilinear model. The Arc Length Method was used to analyze the non-linear effect and determine the load of collapse mechanism. However, studies by Quach [14] state that this method may not work for local instabilities, it is recommended to use dynamic analysis or artificial damping [15, 16, 17].

2 Methods

As an object of research, a small-scale model of a rack made of a PPN profile 27x28x0.6 mm long L = 250 mm, with a ratio L/h = 9.2. The steel grade of samples 08ps according to GOST 14918-2020 was adopted. The tests were carried out under axial compression conditions. Tests were carried out for three samples, one of which had mechanical damage. Mechanical damage consisted in linear deformation of the shelves, numerically equal to e0=L/50 for each shelf. The geometrical parameters of the sample cross-section and the design scheme are shown in Fig. 1.
The test was carried out on a universal testing machine of the MIM series. The samples were fixed through the nodal elements in the grips of the testing machine. The connection in the nodes was carried out with bolts with a diameter of 4 mm, the number of bolts was taken from the premise of the need to exclude the malleability of the connection.

2.1 Finite element method

The finite element model was developed using the ANSYS software package and can be described as follows:

1. Finite element type is SOLID185, which is a 6-node element with six degrees of freedom at each node. The element has large deflection, and large strain capability. It is important for non-linear effect and accuracy of results.
2. The end conditions of the samples included 4 mm thick steel additional elements. Connections of additional elements and a sample are bonded connections. This is done in order to exclude the ductility of the ends, as this is important for the analysis.
3. Material of the elements is a steel. Properties were Young's modulus $E = 2.1\text{GPa}$, Poisson's ratio $\nu = 0.3$.
4. Material model was bilinear isotropic with hardening effect. A tangent modulus was 1450 MPa.
5. The axial load was applied to the center of gravity of the column head.
6. Hardening material and initial geometric imperfections of the samples were not taken into account.
7. For approximation of the ultimate limit load and collapse mechanism was used analysis or artificial damping.
8. Residual stresses were not considered for analysis.
9. The analysis steps included elastic analysis, determination of buckling modes and critical loads, non-linear analysis and determination ultimate limit load and collapse mechanism.

The finite elemental model is shown in figure 2.
2.2 Experimental method

The relative deformations were measured using strain gages of type 11 KP-5-120- A-12-C with a nominal resistance $R = 120 \, \Omega$ and a base of 5 mm. The strain gauges were located in two sections of the sample along the height of the element at a distance of 7 cm from the lower and upper ends. The location of the sensors along the height of the element is assumed based on numerical modeling of the sample. The relative deformations were measured in the shelves and the wall of the cross-section of the sample. The location of the sensors along the cross section is taken in the form of a three-element rectangular socket (Fig. 3, a), the direction of the sensors A, C (Fig. 3, b) is taken according to the trajectories of the main tensions.

Loading was carried out with a constant speed of movement of the loading traverse of 1 mm/min, fixation of relative deformations was carried out using a multi-channel recorder "Terem-4.1" with a frequency of once per second. The samples were brought to destruction.
The controlled parameters were the critical buckling load and the load of collapse mechanism. The test results were processed using standard methods of elasticity theory.

3 Results

As a result of testing of three samples, qualitative pictures of deformations with buckling were obtained (Fig. 4).

![Fig. 4](image)

- a) deformation of sample No. 1
- b) deformation of sample No. 2
- c) deformation of sample with mechanical damage No. 3

The collapse load was 2.12 kN and 2.00 kN for samples No. 1 and No. 2; for sample No. 3 with mechanical damage - 0.89 kN. The critical buckling load for the samples without damage was 1.50 kN. Graphs of the load dependence on linear vertical displacements are shown in Fig. 5.

![Graph](image)
As a result of processing, the values of the principal stresses at the cross-section points of samples $\sigma_1$ and $\sigma_3$ were obtained. The principal stresses for flange No. 1 were: $\sigma_1 = 131$ MPa, $\sigma_3 = -108$ MPa; for flange No. 2: $\sigma_1 = 126$ MPa, $\sigma_3 = -103$ MPa; for the web: $\sigma_1 = -203$ MPa, $\sigma_3 = -241$ MPa. Graphs of the dependence of the principal stresses on the load for sample No. 1 in the upper one are shown in Fig. 6. The nature of the dependence of the stresses on the load in the flanges is identical, the stress values are close in value, and therefore, the graph is conditionally not shown for the second flange.

The maximum equivalent stresses determined in accordance with the Mises theory were 207 MPa for flange No. 1, 199 MPa for flange No. 2, and 224 MPa for the web.
Based on the results of the finite element analysis, the deformation figure of the sample and the principal stresses were obtained. The mode of buckling coincides with the experimental results (Fig. 7, a). The principal stresses for flange No. 1 were: $\sigma_1 = 114 \text{ MPa}$, $\sigma_3 = -169 \text{ MPa}$; for flange No. 2: $\sigma_1 = 113 \text{ MPa}$, $\sigma_3 = -168 \text{ MPa}$; for the web: $\sigma_1 = 126 \text{ MPa}$, $\sigma_3 = -40 \text{ MPa}$. The minimum principal stresses are shown in the figure 7, b. The maximum principal stresses are shown in the figure 7, c.

![Fig. 7.](image)

**4 Conclusions**

A qualitative analysis of the deformations of the loss of stability showed that the experimental sample is characterized first by a loss of stability of the cross-section shape, then by a loss of the overall stability of the element. These correspond to the theoretical prerequisites for medium-length elements with a ratio of $L/h=10$.

The forms of stability loss during the experiment also correspond to the results of numerical modeling.

The equivalent stresses at the moment of the loss of stability of the form are 75 MPa; the stress values obtained analytically are: 22 MPa for the bending-torsional form of the loss of stability; 25 MPa for the torsional form of the loss of stability; 132 MPa for the bending form of the loss of stability in the plane of the least rigidity; 245 MPa for the bending form of the loss of stability in planes of the greatest rigidity. Flexural-torsional and torsional forms of loss of stability for the test sample were not observed, while the logical ratio of the stress values of the actual at the time of loss of stability of the cross-section shape and theoretical for the general form of loss of stability is observed.

Initial geometric imperfections and mechanical damage have a significant impact on the bearing capacity. The damaged sample No. 3 almost immediately passed into the nonlinear stage of operation, the destructive load for this sample was 40% of the destructive load for samples without initial deformations.

The cross-sectional stress analysis showed that the stresses obtained for the sample wall exceed the stresses obtained for the shelves. This is explained by the location of the strain gages: they are located along the wall near the bend angle, along the shelf - near the free edge.

The results of numerical simulation give a significant error in comparison with the experimental results. The obtained stresses are less than in the numerical simulation, but the
deformation figure is preserved. This may be due to the unaccounted for actual compliance of the joints and the peculiarities of the strain gauge method.

The obtained result confirms one of the main disadvantages of the strain gauge method: fixing the values of relative deformations by this method is performed only at the point of the element where the strain gauge is located. Therefore, this approach does not allow a comprehensive analysis of the stress state of a thin-walled element.

References

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