Improving the Efficiency of I-Beams with a Thin Transverse Corrugated Web Plate

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Abstract. The article describes a way to increase the stability of the transversely corrugated thin web plate of an I-beam due to the use of a double corrugation profile (multi-corrugation). The results of a numerical experiment (performed at LIRA-CAD software) of a large-scale models of beams with transversely corrugated web plates of various profiles (including double corrugation profile), with identical spans, cross sections, boundary conditions, loads, and material characteristics are presented. Distribution diagram of normal and shear stresses in cross sections, deflections, and the forms of buckling of corrugated web plates with safety factors for various models are presented. Based on the calculation results, a comparative analysis of the stress-strain state of the beam models was completed.

1. Introduction
Cross corrugation of individual elements of thin sheet structures has long been used in aircraft structures (corrugated web plates of wing spars), ship structures (corrugated bulkheads, corrugated hatches, corrugated panels of the hulls), building structures (columns, beams, arches, truss elements) and bridge structures (corrugated web plates of superficial combined structures).

The founder of experimental and theoretical research in Russia in the field of corrugated structures is V. N. Gornov. In 1936, he conducted the first full-scale test of welded beams with a thin transverse corrugated web plate, making conclusions about the high efficiency of this type of structure [1]. In the USA, the first work was published by A. F. Fraser in 1956 [2], proposing a practical calculation of a beam with several wavy web plates, which were used in the construction of an airplane wing.

Currently, the most common corrugated structural element is a welded beam of an I-section, the thin web plate of which is continuously corrugated by transverse corrugations of inclined, wavy, parabolic, or trapezoidal profiles. Giving the spatial shape of the web plate allows you to increase its stability, and by reducing its thickness to reduce the consumption of material [1-18].

The work of I-section beams with a thin cross-corrugated web plate has some differences from the work of classical plane-stepped beams. So the transversely corrugated web plate, at most of its height, behaves like a "bellows" of the accordion and practically does not perceive efforts in the direction across the corrugations, only sections of the web plate near the flanges work, and with sharply decaying diagrams of normal stresses with distance from the flanges. At the same time, the entire transverse force is perceived by the cross-corrugated web plate section, and the distribution of shear stresses along the web plate height is uniform and practically independent of the corrugation profile [3, 4, 6, 7, 10, 11, 17, 18]. The work of corrugated beam flanges also has some features. Many researchers [3, 5, 6, 9, 12-15, 16, 18] based on the modeling and testing of beams with a corrugated web plate, concluded that the
normal stresses in the beam flanges are distributed unevenly and significantly depend on the profile of the corrugations.

2. Statement of the problem

The most common and economical type of cross-section of bar-shaped metal building structures in design practice remains a welded or rolled double tee, the web plates of which, according to the requirements of ensuring local stability, are assigned relatively thick, which makes the cross-section of a bent rod economically irrational. The mass of the I-beam is significantly reduced if the thickness of its web plate is assigned from the conditions of strength, and to ensure local stability, the web plate is given a spatial shape.

The aim of this work is to improve the design of a steel I-beam with a thin transverse corrugated web plate to increase the local stability of the latter.

To achieve this goal, the following tasks are solved:
- increase the local stability of the corrugated web plate due to the use of a double profile of corrugation (multi-corrugation);
- evaluate the stress-strain state of beams with classical web plate corrugation and a double web-plate corrugation profile;
- assess the stability of the corrugated web plates by means of the LIRA-CAD software package;
- conduct a comparative analysis of the results of the study.

3. Methods

It is proposed to increase the stability of the corrugated web plate of an I-beam due to the use of a double corrugation profile. According to [8], the thickness of the corrugated web plate is assigned according to the strength conditions (for shear or local compression), and its stability is ensured by the size of the corrugations, while there are two types of buckling:
- loss of “general” web plate stability, accompanied by buckling of the corrugated web plate at its entire height as flat or buckling of several corrugations (observed in the supporting areas with significant transverse forces);
- loss of “local” web plate stability, accompanied by bulging of individual sections of the corrugations (observed with significant concentrated forces).

To obtain a double corrugation profile, you can use a simple installation (Figure 1), consisting of rolls with removable petals. The manufacture of a web plate with a double corrugation profile is carried out in two stages. At the first stage, a (small) sinusoidal profile is formed, at the second, a large-sized profile along the triangular generatrix.

![Figure 1. Production of a web plate of an I-beam with a double corrugation profile: a - forming a sinusoidal (first) profile with small dimensions of the corrugations; b - additional molding of a triangular (second) profile with large corrugations](image-url)
The critical state of the web plates and the stress-strain state of the elements of the cross-section of beams with the same length (5.4 m) and cross-section (flanges 170x10 mm, web plate 400x2.0 mm) and with the modifications of the transverse corrugations in the web plates shown in Table 1 was estimated on the calculated finite-elemental models using the LIRA-CAD software package.

**Table 1.** Modifications for transverse corrugation of the beam web plate.

| Web plate profile | Spatial model | Type of web plate profile, corrugation parameters |
|-------------------|---------------|--------------------------------------------------|
| Triangular        |               | corrugation half-wave length 180 mm              |
|                   |               | corrugation half-wave height 30 mm              |
| Sinusoidal        |               | corrugation half-wave length 180 mm              |
|                   |               | corrugation half-wave height 30 mm              |
| Sinusoidal-triangular |          | corrugation half-waves length 21 and 180 mm    |
|                   |               | corrugation half-waves height 5 mm and 30 mm   |

In the design models of beams, their elements are represented by a set of small-sized lamellar finite elements of four-node FE 44 and three-node FE 42. Dividing of the flanges at the same time ensured the presence of nodes on the contact lines of the flanges with the web plate. Fragments of the considered finite element models are presented in Figure 2.

**Figure 2.** Fragments of finite element models of beams: a - web plate with a triangular profile of the corrugations; b - web plate sinusoidal profile of the corrugations; c - web plate with a sinusoidal-triangular profile of the corrugations.
The load on the beams was applied according to two schemes:
- Scheme 1 - evenly distributed along the entire length of the beam with a value of 45 kN / m. This beam loading scheme was used to estimate the stress-strain state of the elements of their sections and the “general” web plate stability;
- Scheme 2 - locally with a value of 40.5 kN (with a conditional distribution length of 100 mm) with a step of 0.9 m along the length of the beams. This beam loading scheme was used to estimate the stress-strain state of the elements of their sections and the “local” web plate stability.

The critical state of the web plates of the beams was evaluated using the LIRA-CAD method for assessing stability under the condition that the system operates in the elastic region [19], where the task of calculating the stability reduces to determining the critical parameter $k$. The physical meaning of the critical parameter of structural stability loss is that if we increase the loads acting on the structure $k$ times, the system will lose stability. In LIRA-CAD, it is assumed that the distribution of forces (stresses) is known from the solution of the linear static problem, while all the loads applied to the system and internal forces grow in proportion to the parameter $k$. The solution to the problem is to determine the numerical parameter $k$ at which stability loss occurs.

The main calculation results from a uniformly distributed load for the three options for transverse corrugation of the beam web plates are presented in Table 2. The main calculation results from the concentrated loads for the three options for transverse corrugation of the beam web plates are presented in Table 3.

**Table 2.** The results of the calculation of beams when loading them with a uniformly distributed load.

| Web plate profile        | Triangular | Sinusoidal | Sinusoidal triangular |
|--------------------------|------------|------------|-----------------------|
| Web plate buckling form  |            |            |                       |
| $k$                      | 1,04484    | 2,49857    | 4,21065               |
| Deflection in the middle of the span, mm | 20,5 | 20,7 | 21,1 |
| Normal stresses in the cross sections of the middle of the span, MPa | upper row for the symmetric section, lower row for the asymmetric section | | | |
Tangent stresses in cross sections at the adjacent section, MPa (upper row for symmetric section, lower row for asymmetric section)

Table 3. The results of the calculation of beams when loading them with local loads.

| Web plate profile           | Triangular | Sinusoidal | Sinusoidal triangular |
|----------------------------|------------|------------|-----------------------|
| k                          | 1.07896    | 2.55268    | 4.53349               |
| Deflection in the middle of the span, mm | 20.1 | 20.3 | 20.7 |
| Isofields of normal stress under concentrated force, MPa | \(\sigma_{\text{max}} = -184\) | \(\sigma_{\text{max}} = -190\) | \(\sigma_{\text{max}} = -201\) |
4. Conclusions
Based on the analysis of the results obtained, the following conclusions can be drawn:
- a corrugated web plate with a sinusoidal triangular type of corrugations has the highest stability loss coefficients of the considered options \( k = 4.21065 \) - with a loss of "general" stability and \( k = 4.53349 \) - with a loss of "local" stability), which confirms the effectiveness of the application multipleting, due to which the "general" and "local" web plate stability is additionally increased;
- a beam with a triangular profile of the corrugations is the least deformative of the considered options, which is caused by a more intensive involvement of the web plate (web plate sections) in the work for longitudinal efforts;
- the normal stresses in the girder flanges are distributed unevenly, which is caused by the periodic displacement of the web plate from the axis of the rod and the occurrence of local additional bending-twisting forces from the action of the main forces [20], while the normal stresses at the edges of the overhangs in the girders of a beam with a sinusoid-triangular type of corrugations have the smallest spread;
- the distribution of shear stresses on the web plates is uniform and does not depend on the profile of the corrugations.
Thus, the use of a double corrugation profile significantly increases the stability of the corrugated web plate of the I-beam, which ensures a more rational use of its material.

5. References
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