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КОМПЛЕКСНІ ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ЛЕГКИХ СТАЛЕВИХ ТА СТАЛЕЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ ІЗ Z-ПОДІБНИХ ПРОФІЛІВ, ЩО ПРАЦЮЮТЬ В УМОВАХ СКЛАДНОГО НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ

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Анотація. Праця присвячена аналізу особливостей роботи легких сталевих та сталезалізобетонних конструкцій, що працюють в умовах складного напружено-деформованого стану, в тому числі – у вузлах з'єднань елементів та при дії згину з крученням. Наведені результати проведеного циклу експериментальних досліджень такого типу конструктивних елементів, виконаних із Z-подібних профілів. На основі серії експериментальних досліджень встановлено характер роботи балок із Z-подібних елементів, з'єднаних за допомогою накладок та болтів. Експериментально обґрунтовано ефективність використання ЛСТК в поєднанні з легкими теплоізоляційними бетонам (легких сталезалізобетонних конструкцій – ЛСЖБК) з метою підвищення місцевої стійкості конструкцій із тонкостінних сталевих профілів в умовах складних видів деформування – роботи на згин із крученням, а також запропоновані способи анкерування частин комплексного перерізу.

Ключові слова: легкі сталеві конструкції, тонкостінні холодноформовані сталеві профілі, Z-подібні профілі, болтові з'єднання на накладках, легкі теплоізоляційні бетони, комплексні конструкції, анкерні засоби, складні види деформування, згин з крученням.

КОМПЛЕКСНЫЕ ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ЛЕГКИХ СТАЛЬНЫХ И СТАЛЕЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ИЗ Z-ОБРАЗНЫХ ПРОФИЛЕЙ, РАБОТАЮЩИХ В УСЛОВИЯХ СЛОЖНОГО НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ

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Аннотация. Статья посвящена анализу особенностей работы легких стальных и сталежелезобетонных конструкций, работающих в условиях сложного напряженно-деформированного состояния, в том числе – в узлах соединения элементов и при действии изгиба с кручением. Приведены результаты проведенного цикла экспериментальных исследований такого типа конструктивных элементов, выполненных из Z-образных профилей. На основе серии экспериментальных исследований установлен характер работы балок из Z-образных элементов, соединенных с помощью накладок и болтов.

Экспериментально обосновано эффективность использования ЛСТК в сочетании с лёгкими теплоизоляционными бетонами (легких сталежелезобетонных конструкций – ЛСЖБК) с целью повышения местной устойчивости конструкций из тонкостенных стальных профилей в условиях сложных видов деформирования – работы на изгиб с кручением, а также предложены способы анкеровки частей комплексного сечения.

Ключевые слова: легкие стальные конструкции, тонкостенные холодноформованные гнутые стальные профили, Z-образные профили, болтовые соединения на накладках, легкие теплоизоляционные бетоны, комплексные конструкции, анкерные средства, сложные виды деформирования, изгиб с кручением.

COMPLEX EXPERIMENTAL INVESTIGATION INTO LIGHT STEEL AND STEEL-CONCRETE COMPOSITE STRUCTURES MADE OF Z-SHAPED SECTIONS UNDER COMPOUND STRESS

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Abstract. The paper is devoted to the analysis of peculiarities of structural behavior of light steel and composite structures under compound stress, including joints and influence of bending with torsion. The results of an experimental test cycle on such structural elements made of Z-shaped elements are derived. Structural behavior character of beams made of bolted Z-shaped elements with onlays is determined on the basis of a series of experimental research. The efficiency of using light steel thin-walled structures with light insulating concrete (light composite structures) for the purpose of local stability enhancement of thin-walled steel profiles under complex deformations – bending with torsion, – has been experimentally corroborated. Complex sections anchorage methods have been proposed.

Keywords: lightweight steel structures, thin-walled cold-formed steel structural profiles, Z-shape sections, sleeved bolted joints,lightweightinsulating concrete, composite structures, anchoring, complex types of deformation, bending with torsion.

Actuality of research on a theme of behavior of load-bearing structures with cold-formed thin-walled steel profiles

In modern construction practice of Ukraine and foreign countries constructions using steel thin-walled cold-formed profiles (cold-formed structures – CFS) [9, 14, 16] are becoming more common. Among the most common types of cross-sections of cold-formed profiles should be allocated the C-sections used primarily as load-bearing structures of ceilings and walls of low-rise buildings, as well as Z-shaped (Z-profiles), the scope of which are purlins and wall coverings.

Despite the fact that the design of LSF in the recent literature is given a lot of attention [11, 12, 15], today there are still a number of unresolved issues, including the calculation and design of connections of elements, in particular bolted joints. It should be noted that unlike other countries in Ukraine there is no needed national regulatory framework devoted to the design of light steel structures, which will surely slow down their implementation in modern construction practice in Ukraine. In European standards [8] the calculation rules for determining the bearing capacity of individual connections are provided for elements such as bolts, screws, rivets, while no recommendations concerning the behavior of the bolted connections under bending. In general, the use of CFS in the load-bearing structures has a number of features caused primarily by their thickness and specific form of section and consequently some signatures of this type of elements: the possibility of local buckling of flanges and walls under bending due to axial compression; the necessity to considering a bending torsion during deformation analysis owing to the work of flexural and compressed members with eccentricities; significant thermal conductivity of solid profiles which leads to forming of heat-conducting inclusions. In this connection, one of the ways to increase the carrying capacity of this type of structural elements may be filling them with a lightweight concrete. In this case, the complex structure formed in this manner (in fact — lightweight composite structure [10, 13]) allows using the advantages of each of the components in the most efficient way by combining a carrier and heat-insulating functions.

Thus, the main objectives of these studies are to obtain data on the features of the sleeved bolted connections of CFS, and experimentally validate the efficiency of using the CFS combined with lightweight concrete (light composite structures) in order to increase the local stability of thin-walled steel profiles under complex types of deformation – work under bending with torsion.

To achieve the objectives within these studies was conducted a series of experiments, the testing program included experiments on sleeved bolted joints of CFS and complex light steel-concretecomposite structures working under bending with torsion.

Analysis of behavior of sleeved bolted connections of cold-formed elements

In order to expand the use of cold-formed structural elements, in Poltava NTU a series of experiments to study the behavior of bolted joints of thin-walled steel profiles was conducted.

This article presents the main findings of the experimental study of joints of Z-profiles with sleeves.

Analysis of regulatory documents [8] shows that the rules for determining the carrying capacity are represented there for single elements such as bolts, screws, rivets, while there are no recommendations regarding the behavior of bolted connections under bending.

However, static operation of bolting system is critical in the design of structures, as this significantly influences the bearing capacity of the structure as a whole. Nevertheless, nonlinear behavior of joints is hard to predict due to the intermittent properties of an attachment point.

In [4, 6, 7], the authors noted that the use of extra onlays or connecting plates (muffs) in the joints leads to the appearance of considerable nonlinear properties when uploading. Recognizing the fact that they are difficult to quantify accurately, the authors developed simplified methods for determining the rotational stiffness of sleeved joint. The proposed method uses an ideal elastic-plastic model of the «moment-angle of rotation» to verify the results of the test. However, experimental data was not sufficient for the rotational stiffness or resistance moment of sleeved connections formulae derivation.

Comparatively to the sleeved joints, much more attention to the research of overlapped joints is given in the literature [1–3, 5]. The first who has presented the research results was Bryan [1] proposing to use the linear model for joint stiffness. He suggested that the center of rotation coincides with the center of group of bolts, and the amount of force in the joint is proportional to the element mounting distance from the center of rotation. Despite sufficient ease of use, this model overlooks the nonlinear properties of connection and ignores the complex work of a joint as a whole, considering only the connection of two bolted steel overlapped plates.

However, in the studies of connections of overlapped Z-profiles performed Chung and Ho [3, 5] it was concluded that the bending stiffness at the initial stage of loading is greater than at its final stage. It is also noted that the resistance moment of the joint may be increased by increasing the overlap to the height of a profile ratio.The authors propose the conception of flexural stiffness – a. The flexural stiffness of the connection is usually compared to the corresponding solid sample, and the ratio of these values actually determines the effective flexural stiffness $a = (EI)_i / EI$, (where $(EI)_i$ is the value of connection's stiffness during uploading and EI is the control value of stiffness). Dubina [2] proposed a calculation method for the initial evaluation of the flexural stiffness of bolted joints in CFS considering their main type of failure – crushing.

Thus, in the literature discussed above rather little attention is given to the study of sleeved connections of cold-formed Z-profiles, despite the wide experience of their practical using.

To study the structural behavior of sleeved bolted joints a 700 mm beams were made using coupled Z-sections connected via self-tapping selfdrilling screws set with a pitch about 200–230 mm. Junction of the composite beams was carried by plates (pads) of a thickness of 2 mm using a precision 5.8 M8 bolts. On Figure 1 the following dimensions and designations are described: ℓ = 1 200 mm; a = 350 mm; b = 500 mm; D-1, D-2 – deflectometers installed in-plane and out-of-plane of loading of beams respectively, G-1,G-2 – dial gauges mounted on the lower flanges of Z-profile to measure the opening width of the joint. Loading was carried out in steps of 100 kg until the failure of connection.

In total, to study the strength and deformation characteristics of bolted joints 5 samples loaded with two symmetrical forces were tested.

Adopted bending test methodology simulated mechanical loading conditions typical for many design elements and reveals the properties of the surface layers, the most stressed at failure. The samples were loaded on the scheme of pure bending (Fig. 1a).Results of the bending test (Fig. 2) are represented on P-f plot,where P – bending load and f – displacement.

As a result of experimental research authors compiled a brief description of the behavior of connections in the following samples:

- B-1: the maximum beam deflection was 8.6 mm and the joint opening width was more than 11 mm at the failure load of 1 960 kg. Fracture occurred as a shear of the bolt in the tensioned zone of the beam (Fig. 3a).
- B-3: fracture mode – a shear of the lower bolt in the tension zone of the beam, the maximum deflection was 27 mm, the width of the joint opening – more than 13 mm besides the beam gap of 10 mm. Considerable damages of the thread can be seen on the body of the bolts as a result of a complex work of connection. Failure load was equal to 2 000 kg (Fig. 3b). When comparing the carrying capacity of the beam with no gaps in the joint B-1 and B-2 beam with a gap of 10 mm, it can be seen that the gap does not effects on the bearing capacity but significantly increased the deformability of the beam at the initial loads.
- B-4: fracture mode – a shear of the lower bolt in the tension zone of the beam, the maximum deflection was 28 mm, the width of the joint opening – more than 13 mm besides the beam gap of 10 mm. Considerable damages of the thread can be seen on the body of the bolts as a result of a complex work of connection. Load had an amount of 1 480 kg at the fracture. The presence of the washers significantly affected on the carrying capacity since the thickness of the shear pack acting on the bolt's body considerably increased, which in turn had a way negative impact on the carrying capacity in comparison with beams B-1 and B-3, and accelerated the shear of the bolt (Fig. 3c).
- B-5: fracture mode – shear of the upwardmost bolt, the maximum deflection was 32 mm, the width of the joint opening – more than 13 mm besides the beam gap of 10 mm. Failure load was equal to 1 520 kg. Structural behavior of connection was similar to the B-4 specimen (Fig. 3d).
- B-6: shear of the lower bolt in the tension zone of the beam, the maximum deflection was 25.5 mm, the width of the joint opening – more

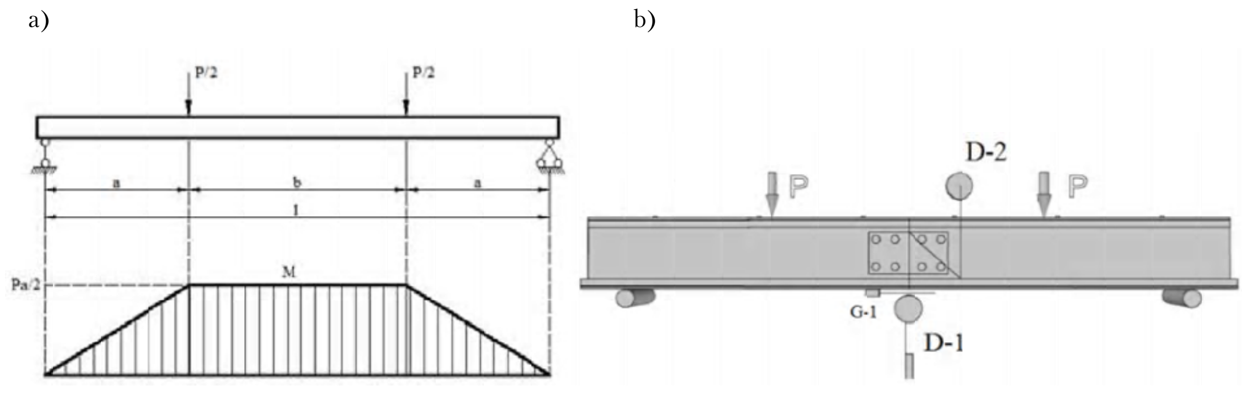


Figure 1. Test model: a) design model of a bending test; b) measuring devices layout.

Table 1. Geometrical properties of complex beams' cross-sections

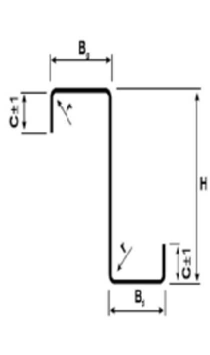
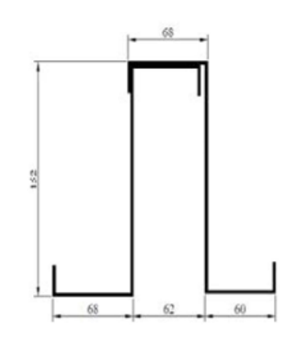
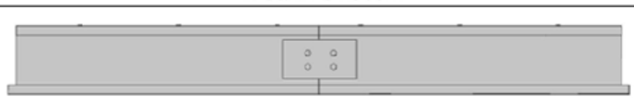
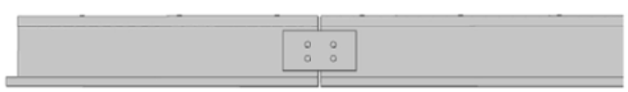
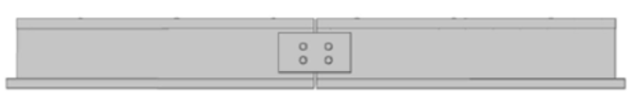
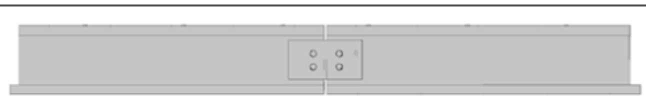
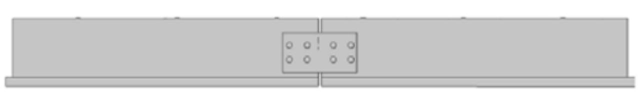
<table>
<tr><th>Cross-section</th><th>Description</th><th>Complex beam cross-section</th><th colspan="2">Parameter</th><th>Value</th></tr>
<tr><td rowspan="6"></td><td>H=150mm</td><td rowspan="6"></td><td rowspan="2">A</td><td rowspan="2">Cross-section area</td><td rowspan="2">12.27 cm^2</td></tr>
<tr><td>B_d=60mm</td></tr>
<tr><td>B_g=68mm</td><td>I_y</td><td>Moment of inertia aboutcentral axis Y1</td><td>445.92 cm^4</td></tr>
<tr><td>C=20mm</td><td>I_z</td><td>Moment of inertia about central axis Z1</td><td>244.10 cm^4</td></tr>
<tr><td>t=2mm</td><td>y_m</td><td>Gravity center coordinate on Y axis</td><td>11.47 cm</td></tr>
<tr><td>A=6,03 cm^2</td><td>z_m</td><td>Gravity center coordinate on Z axis</td><td>9.12 cm</td></tr>
</table>

Table 2. Bolted connections specimens family

	Beam sketch	Connection properties
B-1		Number of bolts: 8pcs. Gap: none Washers: none
B-3		Number of bolts: 8pcs. Gap: 10mm Washers: none
B-4		Number of bolts: 8pcs. Gap: 10mm Washers: 24mm
B-5		Number of bolts: 8pcs. Gap: 10mm Washers: 16mm
B-6		Number of bolts: 16pcs. Gap: 10mm Washers: none

than 13 mm besides the beam gap of 10 mm. Considerable damages of the thread can be seen on the body of the bolts as a result of a complex work of connection. Load had an amount of 3 200 kg at the fracture (Fig. 3e).

Based on the results of the tests, the following conclusions can be drawn:

– the fracture of bolted joint occurs over the action of the bending moment in the beam, while its cross-section remains geometrically unchanged under load. Effective flexural stiffness of connection is mainly governed by the length of the sleeve and the number of bolts disposed thereon;

– basing on the experience of preceding research it is planned to develop a computational method for determining the stiffness of the joints of this type and to conduct a further research.

Experimental studies on light steel-concrete composite structures using thin-walled cold-formed profiles

With a view of a more effective use of CFS in modern construction (increasing the carrying capacity while reducing the thermal conductivity) the authors propose to fill the open cavities of thin-walled

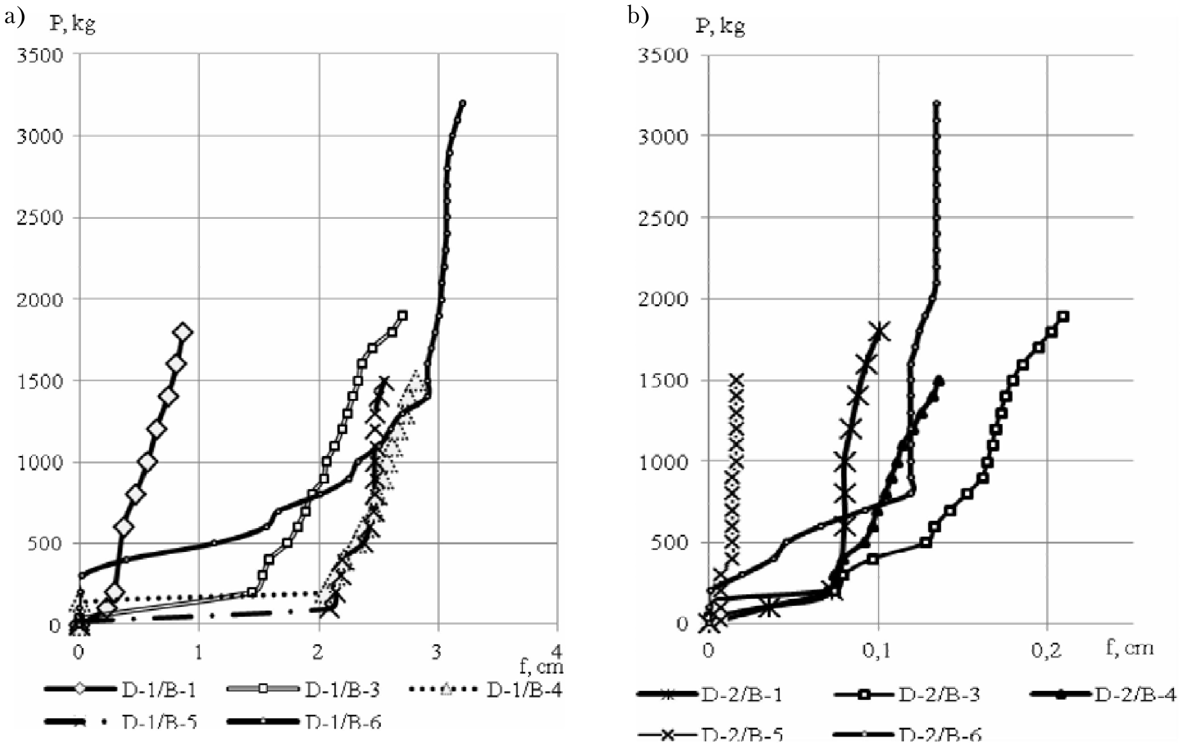


Figure 2. Test curve: a) load to displacement dependence on D-1 deflectometer; b) load to out-of-plane displacement dependence on D-2 deflectometer.

Figure 3. Testing of specimens: a) B-1; b) B-3; c) B-4; d) B-5; e) B-6.

steel structures with light insulating concrete, creating light steel-concrete composite structures.

In order to study this issue, experimental research were carried out in Poltava NTU which included the testing of unfilled profiles (CFz family) and sections filled with concrete – complex light steel-concrete composite structures (CFCz family), see Fig. 4.

All specimens were composite beams made of two Z-profiles interconnected with self-tapping screws, open cavity of which was filled with polystyrene concrete with up to 10 kg/m³ density. Thus, thin-walled steel profiles operate as external sheet reinforcement in a complex steel-concrete structure (see Table 3). To provide joint action of cold-formed profiles with concrete several ways of anchoring of elements of complex cross-section were developed using horizontal (CFCzv family) and vertical V– shaped anchors (CFCzl family). All specimens were a cantilever beams with rigid attachment on support tested on bending with torsion. On the free edge of beams the concentrated load was applied with a shoulder of 0,2 m, which creates torque (Fig. 5).

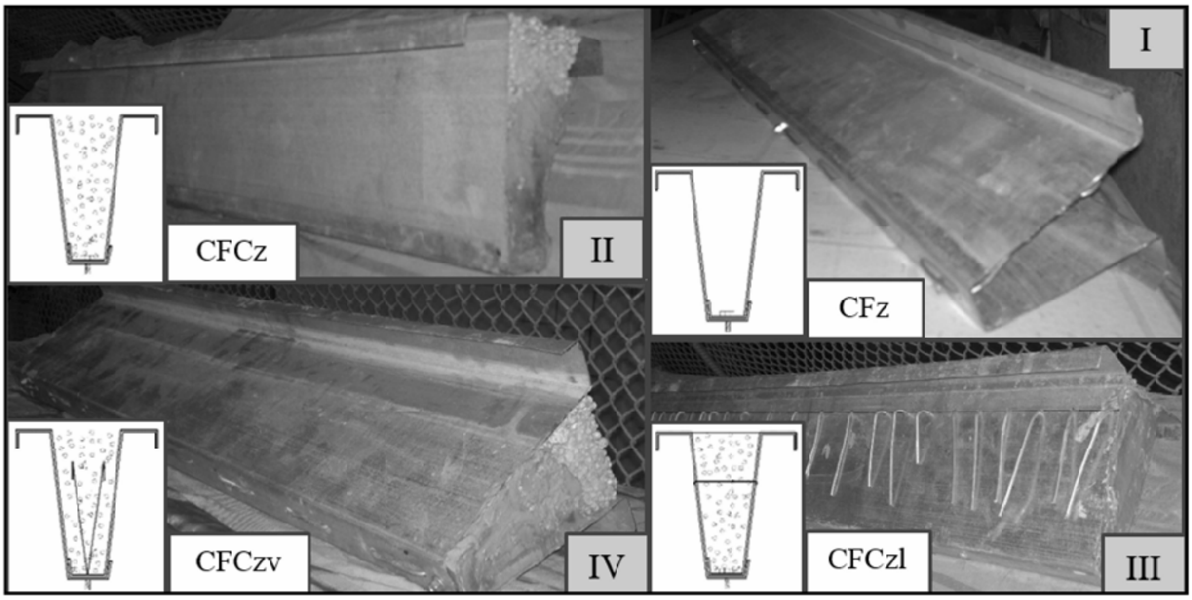


Figure 4. Experimental specimens' general view.

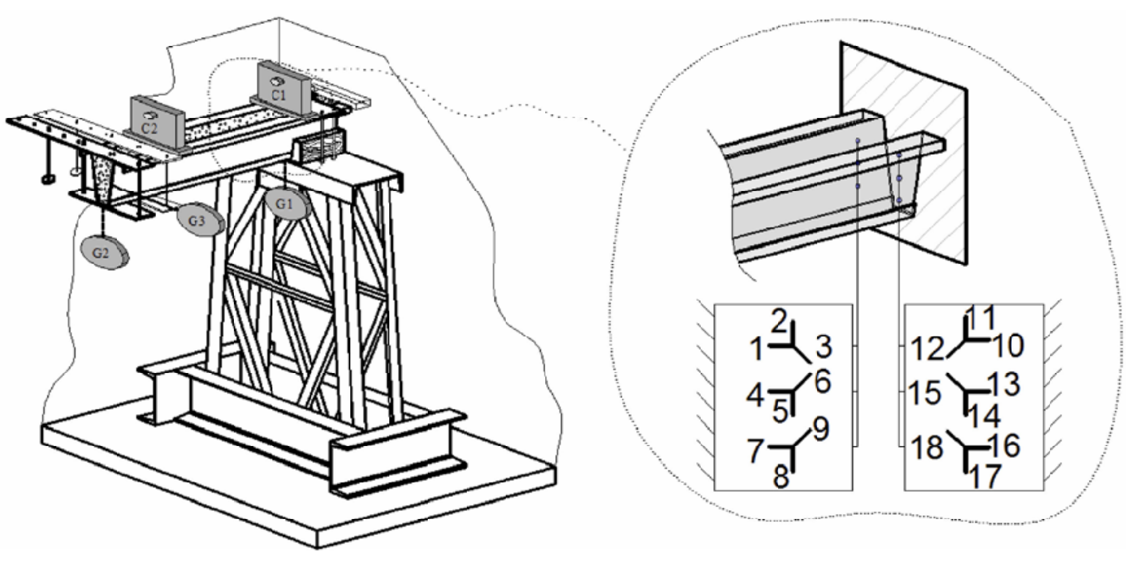
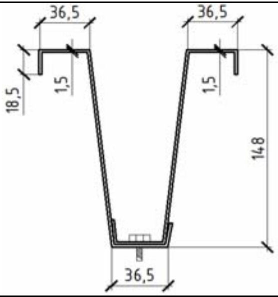
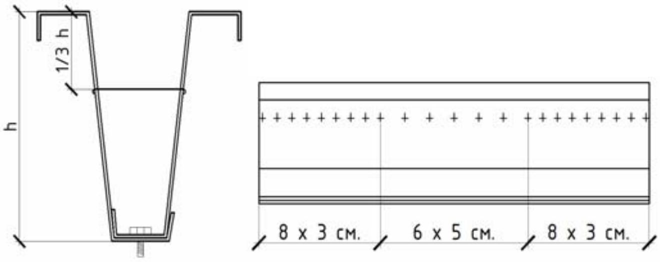
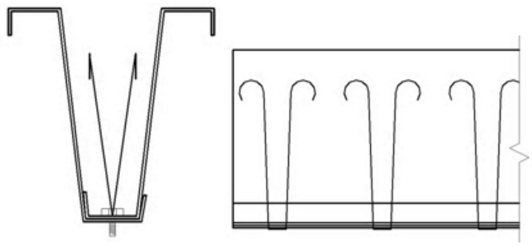


Figure 5. Experimental setup and measuring devices layout.

Table 3. Experimental specimens' description

<table>
<tr><th>Family (type)</th><th>External sheet reinforcement cross-section</th><th>Photo</th></tr>
<tr><td>I (CFz)</td><td rowspan="2">
</td><td rowspan="2"></td></tr>
<tr><td>II (CFCz)</td></tr>
<tr><td>III
(CFCzl)</td><td>
</td><td></td></tr>
<tr><td>IV
(CFCzv)</td><td></td><td></td></tr>
</table>

Thus, the adopted experimental research program allows simulating a structural behavior of elements of facade beams and girders of low-rise buildings and other structures that are subjected to asymmetric loading and work in a complex stress-strain state.

During the test, deflections of the specimens were measured with two deflectometers installed in perpendicular planes, twist angles measurement was carried out using two clinometers allocated along the beam length, and resistance strain rosette gages were used to determine the strains. As a result of the tests it was found that filling CFS with light polystyrene concrete almost doubles the load-bearing capacity when using the beams in bending with torsion. Moreover, the proposed type of light composite beams were characterized by considerably lower (compared with unfilled steel samples) displacements at equal loading (Fig. 6).

Analyzing the work of experimental specimens it should be noted that light steel-concrete composite beams without anchoring devices (CFCz type II family) were characterized by a disturbance of the joint work of the external steel reinforcement and concrete filling observed in the early stages of loading, accompanied by delamination of the steel profile (wall) prior to the formation of the first cracks in the concrete. On the load-displacement plot (Fig. 6) the solid line shows the elastic stage – up to formation of the first cracks in the concrete. In general, for complex steel-concrete beams a more plastic structural behavior nature was observed comparing to the unfilled specimens.

Regarding the proposed ways of anchoring components of a complex cross-section, it can be concluded that using a horizontal anchors (CFCzl type III specimen) is more effective considering a 27 % greater bearing capacity comparing with the V-shaped anchors (CFCzv type IV family) and 46 % greater than that of the elements without anchoring (CFCz type II family). Similar conclusions

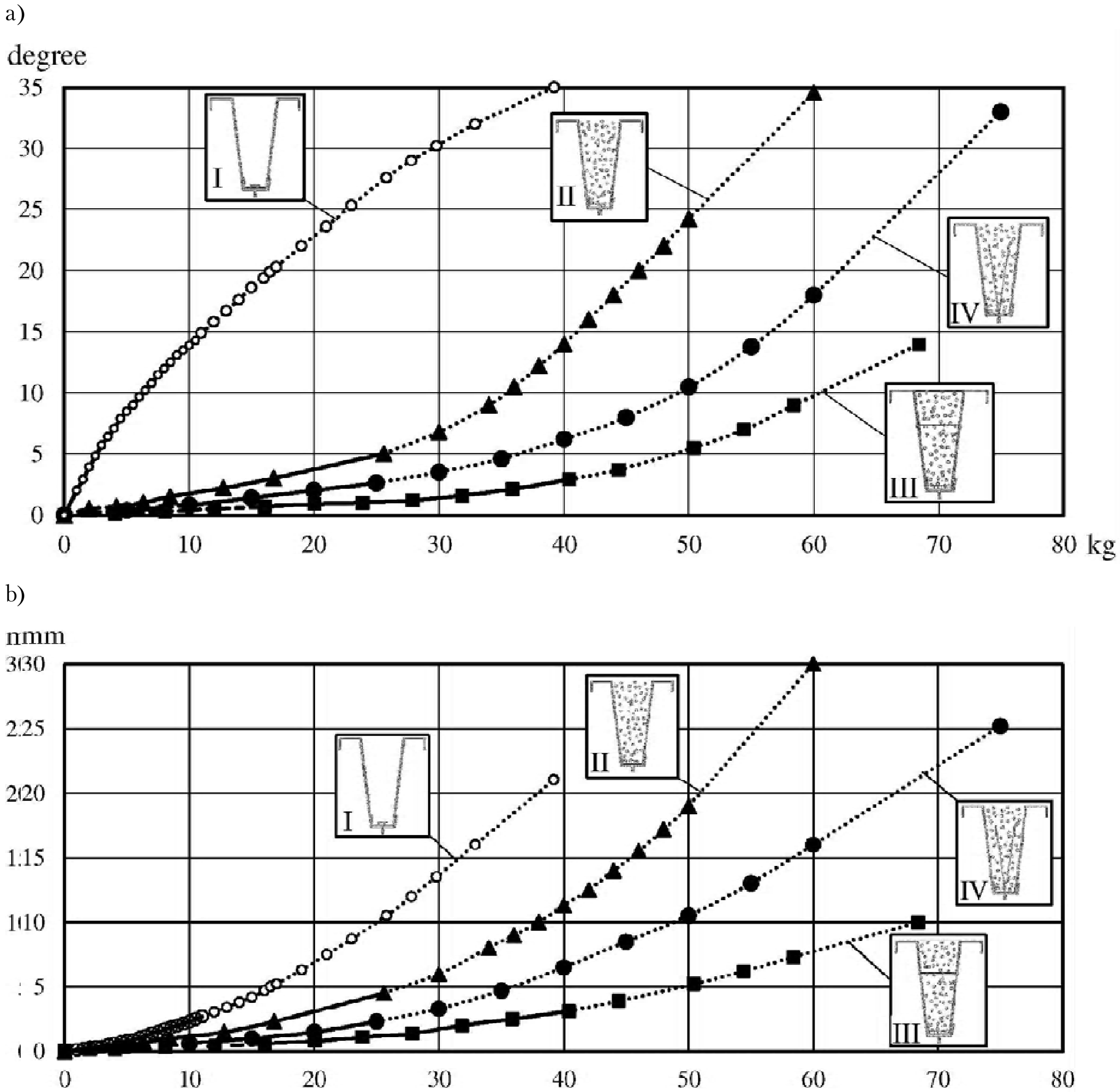


Figure 6. Experimental dependence of displacements of light steel (type I) and complex (type II—IV) beams on loading: a) twisting angle to load plot; b) vertical deflection to load plot.

can be drawn by analyzing the displacements of prototypes (Fig. 6) and their structural behavior under load. It should also be noted that although the samples with various types of anchors are characterized with a former cracking, it was not accompanied by delamination of a steel shell, which confirms the consistency of the whole operation of complex cross-section until fracture.

Thus, the results of experimental studies confirms the possibility of taking into account an operation of light heat-insulating concrete when designing the composite beams with CFS, which is especially important for the design of roofing structures. The absence of sufficient anchorage of steel and concrete parts of the complex cross-section significantly reduces the load-carrying capacity and increases the deformability of the composite element as a whole.

Conclusions

The results of experimental studies on the complex light steel and composite structures made of Z-shaped cold-formed profiles, operating in a complex stress-strain state, including joints of elements and action of bending with torsion allows concluding:

1. The fracture of bolted connection of a beam takes place in consequence of the bending moment while the beam cross-section remains geometrically unchanged under load.
2. Effective flexural stiffness of connection is mainly governed by the length of the sleeve and the number of bolts disposed thereon.
3. Filling CFS with light polystyrene concrete almost doubles the load-bearing capacity when using the beams in bending with torsion.
4. Lack of sufficient anchorage of steel and concrete parts of the complex cross-section significantly reduces the load-carrying capacity and increases the deformability of the composite steel-concrete element as a whole. From this viewpoint, it is quite effective to use the proposed horizontal anchors which 1.5 times increases the bearing capacity of the beams under bending with torsion.
5. An operation of light heat-insulating concrete should be taken into account when designing the composite steel-concrete beams with CFS, which is especially important for design of roofing structures.

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