Spatial Roof Slab with Belts of Strip Batten Elements

S. V. Grigorev, I. Y. Petukhova, N. I. Marchuk, V. I. Palagushkin, and A. V. Maksimov
School of Engineering and Construction, Siberian Federal University, 82 Svobodny, Krasnoyarsk, 660041 Russia
Email: karen0878@yandex.ru, iypetuhova@mail.ru, t9131708548@gmail.com, palagushkin53@mail.ru and 954195@mail.ru

Abstract**—Spatial Roof Slabs (SRS) are developed, numerically calculated and designed of the full-scale SRS by the authors. Main dimensions: length-6 m., width-1.32 m., height-0.6 m, with insulation and waterproofing layer placed on the top chord SRS for the climatic construction area - Dudinka town. For the experimental research, the reduced model of the SRS was calculated, designed and manufactured, in accordance with the similarity coefficient of 3.33, with dimensions: length 1.8 m, width 0.4 m, height 0.18 m. Experimental research were carried out, as a result the performance capability of this construction was proved and precision of efforts of research and numerical experiment are acceptable was revealed.**

Index Terms**—spatial roof slab, SRS, strip battens, tips, decreased model, batten elements**

I. INTRODUCTION

In modern construction, the most promising direction is the use of spatial roof slabs. Compared to planar structures, spatial slabs are lighter, less resource demanding, and affordable. The closest analogue according to the technical solution is lens-shaped coating blocks with belts made of profiled metal sheet [1, 2] of curved shape, which work together. The belts are bent in the form of a square parabola with the maximum bend in the center-the form that is most rational for the perception of the span moment, the joint work of the belt sheets is provided by the racks and braces from bent corners located between them, and at the ends of the block, the corrugations of the upper belt are placed in the corrugations of the lower belt and are connected to each other by contact spot welding along the entire contacting surface . In addition to saving materials obtained as a result of the inclusion of a profiled sheet in the work as the main load-bearing element, a significant reduction is achieved when using steel corrugated sheeting as a roof, due to the exclusion of roofing work, That is, this design uses the principle of combining load-bearing and enclosing functions.

To compare the technical and economic characteristics, consider a lenticular coating block with a span of 12 m and a width of 3 m, the upper and lower belts of profiled sheets S44-1000-0.8 according to GOST 24045-94 are curved in the shape of a square parabola and connected to the racks using self-tapping screws. The maximum structural height in the center of the block is 0.6 m. The step of the racks is 1 m. The profiled sheets of the lower and upper belts are arranged with a wide shelf up, and a narrow one – down. This is done in order to reduce the area of distribution of normal compressive stresses in the shelves of the profiled sheet, which are a criterion for local loss of its stability. The main disadvantage of this technical solution is the high cost of a metal profiled sheet, from which the belts of the structure are made. In addition, this design is relatively more time-consuming to manufacture.

Construction of interest is spatial roof slab (SRS) with belts of strip batten elements (Fig. 1, 2 3) – is a combined modular unit and can be used in industrial and agricultural construction. The ability to transport structures in folded form (with the belts not pushed apart in height) with the additional blocks assembling on the construction site (pushing the belts in height and placing struts and braces between them) allows using these structures in remote areas, for example, in the Far North.

II. GOAL OF RESEARCH

Goal of research is to create an effective coating design by reducing the cost, material consumption and weight of the coating by giving the structure the most effective space form, using lighter and less expensive materials, and a tenuous belt structure.

The goal is achieved by the fact that in the roof slab (Fig. 1, 2, 3), which includes the upper (1) and lower (2) batten belts of rectangular cross section, bent longitudinally in the form of a square parabola, and intermediate elements (3) - solid or through-section struts located between the slab belts. Vertical cross braces made of wooden rods (4) are located between the struts. The tenuous spatial structure is created by the fact that the strip elements of the belts alternate with each other. At the ends of the roof slab, tips (5) with holes are attached to the ends of each of the strip elements of the belts. The tips are fastened together in the crosswise direction by use of a through rod (6) passing through the holes of the tips. The tips with holes allow the belt elements to rotate relative to each other around the crosswise axis passing through the support part of the roof

---

Manuscript received June 2, 2021; revised July 18, 2021; accepted August 5, 2021.

doi: 10.18178/ijscer.10.4.144-149

slab, when the upper and lower belts are pushed apart during its manufacture. A patent for the invention [3] defends this technical solution.

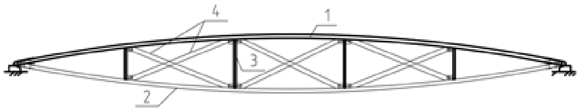


Figure 1. SRS, side view.

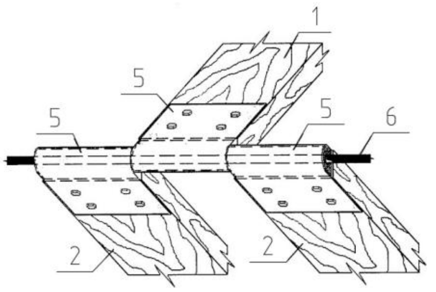


Figure 2. The variation of node connection of belts SRS.

Figure 3. 3D–model SRS of strip batten elements.

III. THEORETICAL RESEARCH

Previously, the calculation was performed in the SCAD PC, and the design of the full-scale coating plate. Main dimensions: length L=6,0 m, width B=1,32 m, height H= 0,6 m, step of struts 1,2 m (quantity 4 PCs.), elements of the upper and lower belt-boards made of material-2nd grade pine [4]. Nominal case conditions according to the construction area- Dudinka town. Uniformly distributed equal-sided and one-sided snow loads [5], the load from the insulation and coating, as well as the stresses caused by the original bending of the belt elements were taken into account in the calculation.

The stresses from the structural bending of the belts were determined as for a single-span articulated beam loaded with a uniformly distributed load, expressed from the deflection formula fmax = 5 q L4 /384 EI, from this formula we express the load q and find its value for fmax = 300 mm (0.5 N is the value of the structural bending of the belts). We will determine the internal forces and stresses from this load, and then add these stresses to the stresses obtained in the SRS belts as a result of static calculation in the SCAD software package.

The calculation results are shown in Fig. 4, 5, 6. As a result of the calculation, the cross section of the belt elements (165 x 40 mm) and struts (thickness t=21 mm) was found. The cross section of the braces is 20x50 mm. The least favorable was the combination of loads with a one-sided snow load (the load combination C2), the maximum displacement in this case was -28.23 mm, the maximum compressing stress in the upper belt was 8 MPa, and the maximum tensile stress in the lower belt was 2.86 MPa.

According to the numerical experiment data the reduced model of the SRS [6, 7, 8] was calculated, designed and manufactured. A physical model can be considered an installation in which complete or incomplete modeling and, accordingly, physical similarity are carried out, so that all the essential characteristics of a full-scale object can be obtained from the characteristics of the model by multiplying by scale coefficients. A physical model differs from a full-scale object in its size, but the processes occurring in it do not differ in nature from the processes occurring in nature (that is, it is a copy of a physically real system).

Similarity criteria can be found if its mathematical description is known, or at least the set of parameters that can characterize the phenomenon under study in this problem and under these conditions. From the point of view of using the methods of similarity theory, the phenomenon of the stress-strain state of the spatial coating plate can be attributed to the phenomenon of the second group – a phenomenon that has been studied so much that it is only possible to list the physical quantities essential for this phenomenon.

These values are:

− linear dimensions, the similarity of which expresses the similarity coefficient of geometric parameters:

$$k^{similarity}=\frac{L}{L_m}=\frac{B}{B_m}=\frac{H}{H_m}=\frac{t_b}{t_{b.m}}=\frac{b_b}{b_{b.m}}$$

where L, B and H – geometric dimensions of the natural-size structure;

L_m, B_m and H_m – geometric dimensions of the reduced model;

t_b and b_b – geometric dimensions of the cross-section of the elements of the construction belts of natural size;

$t_{b.m}$ and $b_{b.m}$ – geometric dimensions of the cross-section of the elements of the belts of a reduced design;

− maximum deflections;

− maximum effort.

The determining control of the plate design is a check for rigidity. Therefore, the determining criterion of similarity is the criterion of equal stiffness:

$$\frac{f}{L}=\frac{f_m}{L_m}$$

where f and f_m– the maximum deflections of the full-size design and the reduced design, respectively.

The coefficient of similarity of geometric parameters for the manufacture of a reduced model of a plate intended for full-scale tests of $k_{similarity}$= 3.33.

Accordingly, the dimensions of the reduced model will be: length 1.8 m, width 0.4 m, height 0.18 m.

IV. THE MANUFACTURE OF A REDUCED MODEL

Before testing the reduced model, the belt coupling unit (the metal tip of the belt element of the reduced model, connected to the wooden belt element with a 50x10 mm cross-section with four M5 bolts) was tested for tension in order to identify the value of the critical load at which the wood will split along the section weakened by the bolts and compare this value with the force in the lower belt element from the calculated load.

The tip was fixed on the hook of the crane beam, and a loading platform was suspended from the wooden element. Loading took place with concrete blocks of 100x400x600 mm in size and weighing 60 kg, as well as full-bodied clay bricks with an average weight of 3.3 kg.

Loading took place in stages (the values given are calculated without taking into account the weight of the slings and slinging devices):

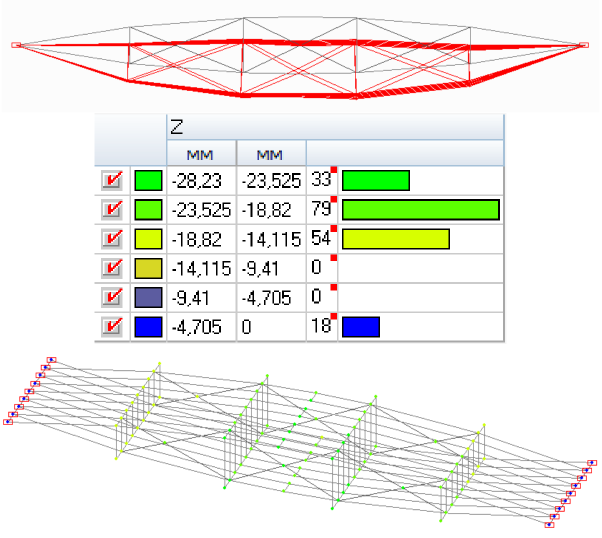
1 stage – 1 plate = 60 kg;
2 stage – 1 plate and 3 bricks = 69.9 kg;
3 stage – 1 plate and 6 bricks = 79.8 kg;
4 stage – 1 plate and 9 bricks = 89.7 kg;
5 stage – 1 plate and 12 bricks = 99.6 kg;
6 stage – 1 slab and 15 bricks = 109.5 kg.

Then the steps were repeated: the bricks were removed and the next slab was laid instead.

After loading each stage, the connection was maintained for 20 minutes under load.

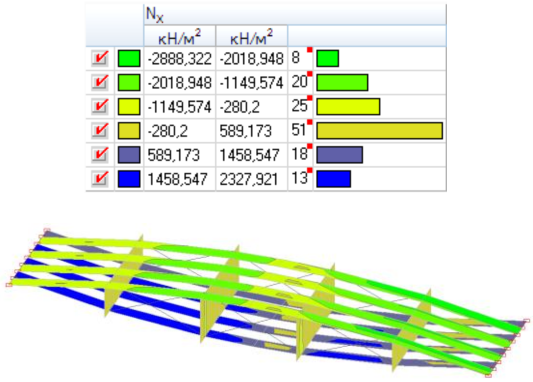
The destruction occurred at the moment when 6 concrete blocks and 3 bricks were suspended from the tip. Taking into account the weight of the slings, the total load on the tip was 415.9 kg (4.07 kN), which is 3.15 times higher than the force from the design load in the lower belt element equal to 1.29 kN, therefore, the strength of the bolted connection is ensured under the action of the design load.

The manufacture of a reduced model of the SRS was in the following manner. To pine boards with dimensions of 180x50x10 mm, acting as upper and lower belts, using four M5 bolts arranged in a staggered state. Tips were attached-bent painted metal plates with a thickness of 1 mm and a total length of 150 mm [9] with a gap for a metal rod-threaded bar with a diameter of 1 cm and a length of 61 cm with a free length of 3 cm from the belts.



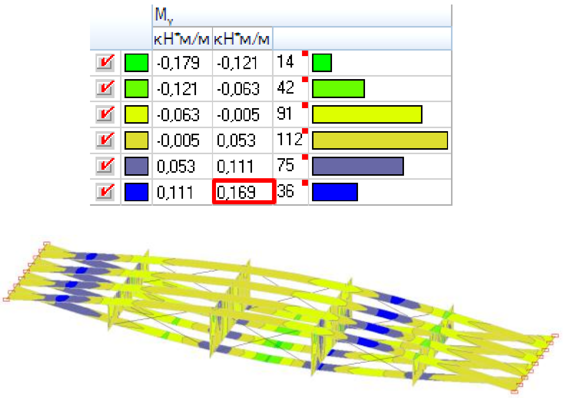
		Z			
		мм	мм		
☑	🟩	-28,23	-23,525	33	🟩
☑	🟩	-23,525	-18,82	79	🟩
☑	🟨	-18,82	-14,115	54	🟨
☑	🟨	-14,115	-9,41	0	
☑	🟦	-9,41	-4,705	0	
☑	🟦	-4,705	0	18	🟦

Figure 4. Deformed model displacement at load combination C2.



		N_x			
		кН/м²	кН/м²		
☑	🟩	-2888,322	-2018,948	8	🟩
☑	🟩	-2018,948	-1149,574	20	🟩
☑	🟨	-1149,574	-280,2	25	🟨
☑	🟨	-280,2	589,173	51	🟨
☑	🟦	589,173	1458,547	18	🟦
☑	🟦	1458,547	2327,921	13	🟦

Figure 5. Stress field Nx at load combination C2.



		M_y			
		кН*м/м	кН*м/м		
☑	🟩	-0,179	-0,121	14	🟩
☑	🟩	-0,121	-0,063	42	🟩
☑	🟨	-0,063	-0,005	91	🟨
☑	🟨	-0,005	0,053	112	🟨
☑	🟦	0,053	0,111	75	🟦
☑	🟦	0,111	0,169	36	🟦

Figure 6. Stress field My at load combination C2.

Then the belts were laid on a horizontal surface and connected to each other in the crosswise direction of the plate by passing a threaded bar through the holes. Then the strip elements were pushed apart relative to each other by turning around the threaded bar axis and struts were placed between them (plywood strips 2.1 cm thick, 40 cm length and 16.1 cm and 10.4 cm height) in the amount of 4 PCs at a distance of 36 cm from each other and from the supports. After that, cross-shaped braces (wooden bars with a cross section of 25x25 mm) were placed on both sides of the SRS model.

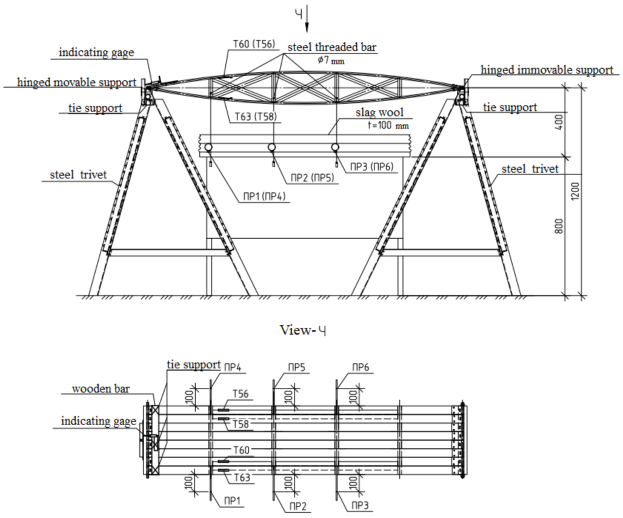


Figure 7. Pattern array of indicators: ПР1-ПР6 – flexometers; T56-T63 – resistive strain sensors.

V. FIELD RESEARCH

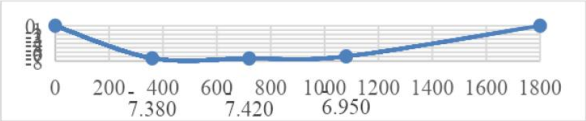
The decreased model (SRS) with belts of strip batten elements was manufactured and tested, according to the recommendations [10]:

- under equal-sided load - when the action of standard load, which equals 1.64 kN/m2. Calculated load is 2,26 kN/m2 (at load combination C1)

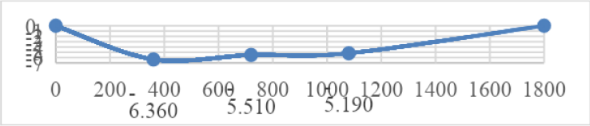
- under one-sided load - when the action of standard load, which equals 1,26 kN/m2 on the less loaded side (nearer to the hinged immovable support) and 2.01 kN/m2 on the more loaded side (nearer to the hinged movable support). Calculated load are 1,74 kN/m2 on the less loaded side and 2,79 kN/m2 on the more loaded side. (at load combination C2)

There are the testing bed and pattern array of indicators on Fig. 8.

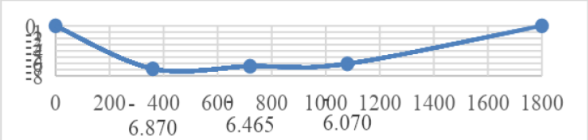
Figure 8. Loading decreased model SRS distributed one-sided load, equaled 1,5 $q_{calculated}$ (4,185 [kN/m^2]/ 2,61 [kN/m^2]).



far side



middle side



near side

Figure 9. Lines of deflections at one-sided load $q_{standard}$, [*mm*].

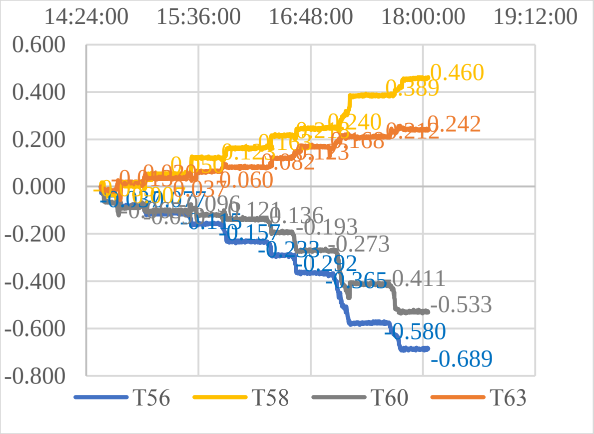


Figure 10. Stress at one-sided load (C2) on resistive strain sensors, [kg(f) /*mm*^{2}], indicated by microprocessor multi-channel strain-measuring system 64.01-1.

VI. THE FIELD AND THEORETICAL RESEARCHES REVIEW

In analyzing resulting diagrams of variation deflections (Fig. 11), it is apparent that the model becomes skewed. There is the same effect in the efforts of numerical experiments. This is explained by the fact of asymmetry belts location: on width the model is started by top chord element and ended by a bottom chord. The choice of a scheme with an asymmetric arrangement of belt elements in both the decreased model and the full-scale construction is due to the fact that in this way it is easier to place the slabs in order along the span of the building. Thanks to the covering, the load will be partially relocated to adjoining slabs, and the skew will be minimized. It is also obvious that the symmetrical location of the belt elements, when the slab begins and ends with an element of the upper belt or an element of the lower belt, eliminates skew.

In addition, there is a slight deflexion in the middle of the construction model (less than 1 mm). The same effect is observed in the efforts of numerical experiments and is due to the arched shape of the belts: when the load is applied, the upper belt deflects down in the extreme sectors, but deflects up in the middle sector and "pulls" the lowest belt in the middle sector up through the support pillars.

The maximum uniformly distributed equal-sided load of decreased model SRS is 3,73 [kN/m2], that is corresponds to the limit load factor - 1,65 from calculated load.

The maximum uniformly distributed equal-sided load of decreased model SRS is 7,23 [kN/m2] from the more loaded side and is 4,44 [kN/m2] from the less loaded side, that is corresponds to the limit load factor - 1,5 from calculated load on Fig. 8.

TABLE I. EFFORTS OF NUMERICAL EXPERIMENT AND RESEARCH

Indicator name	Efforts of numerical experiment	Efforts of research	Variance percentage , [%]
$f_{standard}$ C1, [*mm*]	-8,454	-7,03	17
$f_{standard}$ C2, [*mm*]	-8,527	-7,42	13
$f_{calculated}$ C1, [*mm*]	-11,392	-9,83	14
$f_{calculated}$ C2, [*mm*]	-11,814	-11,50	3
$X_{standard}$ C1, [*mm*]	0,381	0,45	15

$X_{standard}$ C2, [mm]	0,35	0,420	17
$X_{calculated}$ C1, [mm]	0,545	0,66	17
$X_{calculated}$ C2, [mm]	0,501	0,550	9
$\sigma_X(T56)_{standard}$ C1, [MPa]	-1,326	-1,465	9
$\sigma_X(T58)_{standard}$ C1, [MPa]	1,482	1,724	14
$\sigma_X(T60)_{standard}$ C1, [MPa]	-0,428	-0,468	8
$\sigma_X(T63)_{standard}$ C1, [MPa]	0,520	0,573	9
$\sigma_X(T56)_{standard}$ C2, [MPa]	-1,74	-1,95	11
$\sigma_X(T58)_{standard}$ C2, [MPa]	1,733	1,894	9
$\sigma_X(T60)_{standard}$ C2, [MPa]	-0,583	-0,695	16
$\sigma_X(T63)_{standard}$ C2, [MPa]	0,885	0,924	4
$\sigma_X(T56)_{calculated}$ C1, [MPa]	-1,844	-2,090	12
$\sigma_X(T58)_{calculated}$ C1, [MPa]	1,843	2,105	12
$\sigma_X(T60)_{calculated}$ C1, [MPa]	-0,859	-1,010	15
$\sigma_X(T63)_{calculated}$ C1, [MPa]	1,064	1,152	8
$\sigma_X(T56)_{calculated}$ C2, [MPa]	-3,003	-3,27	8
$\sigma_X(T58)_{calculated}$ C2, [MPa]	2,574	2,708	5
$\sigma_X(T60)_{calculated}$ C2, [MPa]	-1,704	-1,99	14
$\sigma_X(T63)_{calculated}$ C2, [MPa]	1,528	1,76	13

Notes to the Table I:

- In the efforts of numerical experiment presented compressing stress on the bottom fiber and tension stresses on the top fiber appropriately the specifics of the resisting strain sensors location.
- Maximum deflections of numerical experiment and research are given in Table I.

VII. KEY INSIGHTS

In analyzing charts on Fig. 9 and 10 and Table I, leading us to the conclusion that the stiffness of the tested model in the SCAD PC is above than design diagram stiffness (probably, the real modulus of elasticity of the model is higher than standard one, which was accepted upon an analysis). Conversely, the stresses from tests are higher than calculated stresses, this can be explained by the fact that stresses distribution take place irregularly due to knots –they are stress raisers.

In addition, there are not large error of measurement deflexions on the nearest and the farthest model sides by virtue of fixing the flexometer hair on pins (are located in 10 cm from a model). However, in compare to the obtained values of deflections, the error is insignificant.

Overall, precision of efforts of research and numerical experiment are acceptable, the maximum percentage of disparity is 17 %, and this indicates the performance capability of this construction.

VIII. FURTHER RESEARCHES DIRECTION

In the future, experimental and theoretical studies of a spatial coating plate with belts of plank strip elements are planned, in which the internal space between the belts is filled with an expanding hardening composition (for example, foam insulation). The adhesion of the hardened material to the inner surface of the belts significantly increases their stability.In this case, the principle of combining the functions of the material is used, that is, the hardened composition performs the functions of insulation and plays the role of intermediate elements, in addition, the gaps between the belt elements of the upper belt are filled and a solid surface is formed for laying the waterproofing layer. There is an analog of such a design with belts made of profiled sheets and filling the internal space between them with a hardening compound [11].

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Sergey Grigoriev created the ideas of a lenticular design with alternating belts of wooden strip elements curved alternately up and down in the shape of a square parabola and with racks and braces installed between the belts, defended the idea with a patent, led scientific research, participated in calculations, design work and experimental research, analyzed the results of calculations and experimental research. Nikolai Marchuk was responsible for numerical studies of the spatial scheme of the full-scale 6-meter structure and the reduced model, analyzed and processed the results of the calculation. Inna Petukhova engaged in designing a full-scale 6-meter structure and a reduced model. Alexander Maksimov and Vladimir Palagushkin made a node connection of a reduced model of the structure and conducted tests of the node, made a reduced model of the structure, developed test programs and conducted experimental studies.

REFERENCES

[1] Author's certificate for an invention 1479584A1 USSR. Spatial rood slab and the method of its installation/ Krasnoyarsk PromstroyNIIproekt; V. P. Grigoriev, S. V. Grigoryev. 1989.

[2] Lenticular blocks of coating from a metal profiled sheet: dissertation candidate of technical sciences: 05.23.01 / Grigoriev, S. V. - Novosibirsk, 1995.

[3] S. V. Grigorev, L. V. Endzhievskii, V. P. Grigorev, A.IU. Maryshev, O.F. Novikov Patent RU2163283C2, 1999.

[4] SP 64.13330.2017 Timber structures. The updated edition of SNiP 2.25-80* (with Amendments No. 1, 2).

[5] SP 20.13330.2016 Loads and actions. The updated edition of SNiP 2.01.07-85* (with Amendments No. 1, 2).

[6] Fundamentals of scientific research: a manual for students of technical disciplines / G. M. Kuzemkina. - Gomel: UO "BelGUT", 2005. - 82 p.

[7] Testing of building structures on models. The section "Theory and reliability of models" / V. N. Mastachenko. - Moscow, 1972.

[8] Questions of similarity of intensified reinforced concrete beams in experiments on reduced scale models / S. V. Bokarev, S. V. Efimov / /Science studies: theoretical and scientific-practical internet journal/ / FSBEI HPE STU. - Novosibirsk, 2014. - Issue 5 (24). – 55 p.

[9] SP 16.13330.2017 Steel construction. The updated edition of SNiP 2.23-81* (with Amendments No. 1, 2).
[10] The recommendations for testing wooden structures. tsniisk im. V. A. Kucherenko. - M: Stroyizdat, 1976. - 28 p.
[11] L. V. Endzhievskii, S. V. Grigorev, V. P. Grigorev, O. F. Novikov Patent RU2134753C1, 1999.

Sergey Grigoriev is an Associate Professor of the Building Structures and Controlled Systems Department of the School of Engineering and Construction, Siberian Federal University.

In 1995, he defended his thesis work on the topic: «Lenticular coating blocks made of metal profiled sheet» and received the degree of Candidate of Technical Sciences. Research interests are development of new types of building structures, methods of their calculation and research.

During the period of his career, 26 scientific papers were published, including 7 patents and 11 educational and methodological developments and manuals.

Inna Petukhova is an Associate Professor of the Building Structures and Controlled Systems Department of the School of Engineering and Construction, Siberian Federal University.

In 1978, he was awarded the degree of Candidate of Technical Sciences in the specialty «Construction Mechanics». In 1982, by the decision of the Higher Attestation Commission, he was awarded the title of associate professor in the Department of Building Structures.

Research interests: light metal structures.

She co-authored 32 scientific articles, including those included in the journals of the Scopus database, and 41 methodological manuals for students of the specialties «Industrial and Civil Construction», «Expertise and Real Estate Management». Awarded the title «Honored Teacher of the Krasnoyarsk Territory».

Nikolai Marchuk is an Associate Professor of the Building Structures and Controlled Systems Department of the School of Engineering and Construction, Siberian Federal University.

Teaching experience in SibFU is 48 years. In 1985, he defended his PhD thesis on the topic «Calculation of flexible ribbed elastic-plastic shells by the variational-difference method».

He was honored RAASN diplomas in 2004 and 2005. Honorary medal in honor of the anniversary of V. G. Shukhov. In 2007, he was awarded the RAASN medal for the development of the textbook «Modern aspects of active learning».

Research interests: solving problems of regulating and managing the VAT of structures, optimization and optimal design of structures using the ANSYS software package, calculation and research of buildings and structures for seismic impacts based on the SCAD and ANSYS calculation software systems.

During the period of work, more than 100 scientific publications and 20 educational and methodological developments and manuals were published.

Vladimir Palagushkin is an Associate Professor of the Building Structures and Controlled Systems Department of the School of Engineering and Construction, Siberian Federal University. In 2002 he received the degree of Candidate of Technical Sciences, in 2005 he was awarded the academic title of associate Professor. Currently, his research interests include the development of methods for calculating and actively controlling the stress-strain state of building structure elements. He has published more than 40 peer-reviewed journal articles and more than 20 reports at international conferences, as well as two monographs.

Awarded the Gold Medal of the Russian Academy of Architecture and Construction Sciences (2007).

Alexander Maksimov is an Associate Professor of the Building Structures and Controlled Systems Department of the School of Engineering and Construction, Siberian Federal University.

He has the Post-graduate course of KPI in 1986-1989, scientific supervisor, Doctor of Technical Sciences, professor. Abovsky N. P. Defended his PhD thesis in 1995 on the topic «Identification of parameters of computational schemes of non-analogous anisotropic shells».

Associate Professor of the Department of «Construction Mechanics» from 1996 to the present moment. Work experience as an associate professor is 25 years, the total work experience in the university is 40 years.He is an author of more than 80 printed works and publications.